Vehicular Wireless Communication Standards: Challenges and Comparison

Review Paper

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Abstract *– Autonomous vehicles (AVs) are the future of mobility. Safe and reliable AVs are required for widespread adoption by a community which is only possible if these AVs can communicate with each other & with other entities in a highly efficient way. AVs require ultra-reliable communications for safety-critical applications to ensure safe driving. Existing vehicular communication standards, i.e., IEEE 802.11p (DSRC), ITS-G5, & LTE, etc., do not meet the requirements of high throughput, ultra-high reliability, and ultra-low latency along with other issues. To address these challenges, IEEE 802.11bd & 5G NR-V2X standards provide more efficient and reliable communication, however, these standards are in the developing stage. Existing literature generally discusses the features of these standards only and does not discuss the drawbacks. Similarly, existing literature does not discuss the comparison between these standards or discusses a comparison between any two standards only. However, this work comprehensively describes different issues/challenges faced by these standards. This work also comprehensively provides a comparison among these standards along with their salient features. The work also describes spectrum management issues comprehensively, i.e., interoperability issues, co-existence with Wi-Fi, etc. The work also describes different other issues comprehensively along with recommendations. The work describes that 802.11bd and 5G NR are the two potential future standards for efficient vehicle communications; however, these standards must be able to provide backward compatibility, interoperability, and co-existence with current and previous standards.*

Keywords*: Intelligent Transportation System (C-ITS); LTE (C-V2X); IEEE802.11p (DSRC), IEEE 802.11bd, 5GNR-V2X, ITS-G5*

1. INTRODUCTION

Autonomous vehicles (AVs) are the future of transportation mobility due to their increased traffic safety, fuel efficiency, better use of infrastructure, and other promising features. These AVs use different vehicular networks (one of the applications of Mobile ad-hoc networks- MANETs) to communicate with each other due to their high speed, short communication time, and highly dynamic topologies [1]. However, many of these standards (networks) are not able to meet the requirements, i.e., ultra-high reliability, ultra- low latency, etc., of vehicular communications. Therefore, new protocols, mechanisms, and standards are required to guarantee the highest reliability and interoperability among different vehicular networks, i.e., cooperative intelligent transportation system (C-ITS), etc., for safe and reliable driving [2]. Different types of wireless communications (also known as V2X communication) may be performed by a vehicle with different entities as shown in Fig.1. [3].

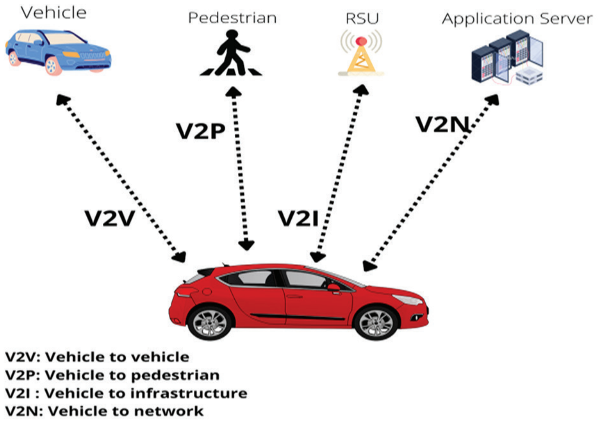


Fig. 1. Vehicle-to-everything (V2X) [3]

Sensors are heavily used in vehicles to assist human drivers to perform various applications as sensors are not prone to tiredness, deflection, or sentiment like humans. However, sensors have also limited sight as humans. Therefore, vehicles equipped with sensors are also unable to coordinate efficiently with other vehicles in highly mobile environments [4]. However, C-ITS have no such issues and can also be used to reduce traffic jamming, traffic accidents, and other transportation-related environmental issues. CC-ITS also provides cooperative collision warning, traffic management, infotainment, etc., which makes autonomous vehicles (AVs) capable to share their driving information, ultimately making transportation safer and more reliable [4]. Two primary messages, i.e., cooperative awareness message (CAM) and decentralized environmental notification message (DENM), etc., are used to provide information related to speed, location, and other features of C-ITS [4, 5]. The basic set of C-ITS applications is shown in Fig.2. [3].

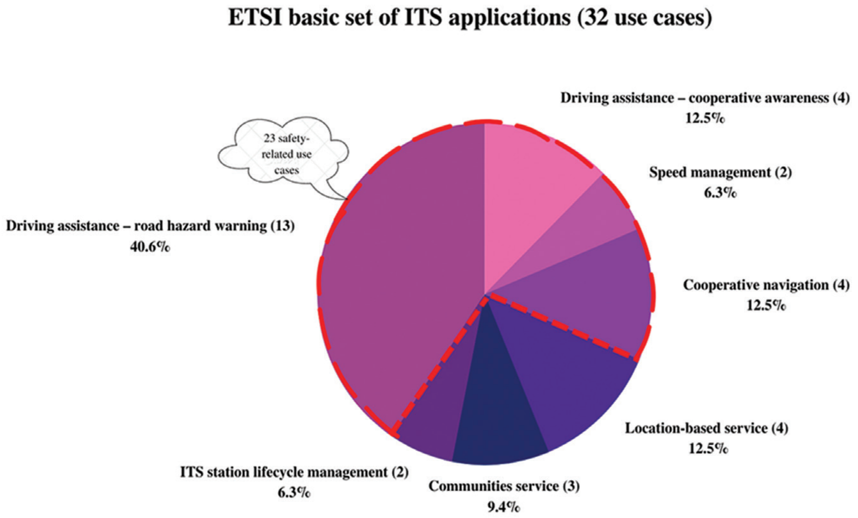


Fig. 2. ITS applications defined by ETSI (European Telecommunications Standards Institute) [3]

Traditional Wi-Fi-based approaches cannot be used for V2X communications as they have many challenges such as high power consumption, packet delivery rate issues and high latency, etc. Also, traditional Wi-Fi standards do not support high mobility applications, which is one of the fundamental requirements for vehicle communication. To overcome these shortcomings/challenges, many standards have been developed to support ITS applications such as Dynamic short-range communication (DSRC), long-term evolution-LTE (C-V2X), 5G NR-V2X, etc. [6]. However, which technology is best for V2X is another issue. No one would like to ride a car that uses technology not compatible with a technology used by a nearby moving car. Similarly, if the government standardizes one specific technology, it would stop the potential benefits of other technologies. It is also very difficult for the industry and the community to elicit all the possible benefits of new technology in the early stages of development. Therefore, delays may occur in choosing the best communication technology among vehicles which will ultimately also delay the commercial deployment of AVs [6, 7]. The evolution of V2X communication is shown in Fig.3. [8].

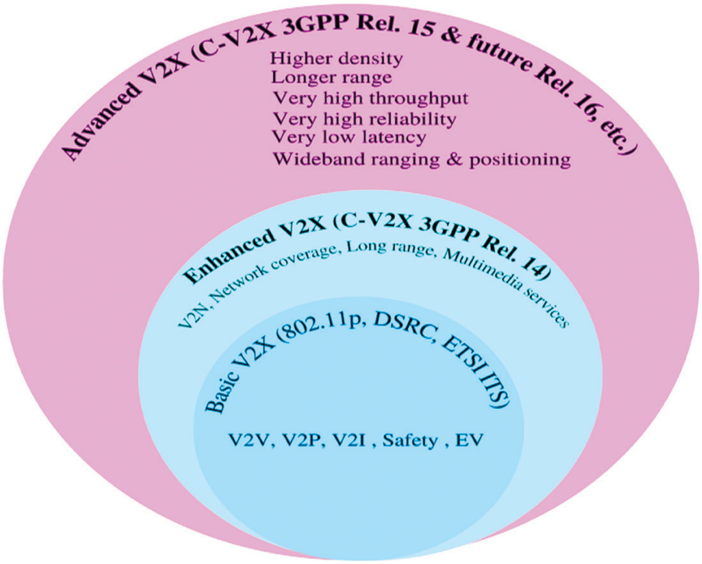


Fig. 3. V2X Evolution [8]

The existing V2X communication systems, i.e., IEEE 802.11p (DSRC), intelligent transportation systems (ITS-G5) & LTE (C-V2X), etc., have many issues and challenges. Similarly, the advanced V2X systems, i.e., IEEE 802.11bd, 5G NR-V2X, etc., also have many issues. The existing literature generally describes the features of these standards only. The existing literature also does not describe the issues/challenges and/or comparison between these standards or discuss challenges/comparison for any two standards only [4, 5, 9, 10, 11, 12, 13, 14]. However, this work comprehensively provides an overview of the different issues/challenges faced by these standards. This work also comprehensively provides a comparison among these communication standards along with their salient features. The overall structure of this work is shown in Fig.4.

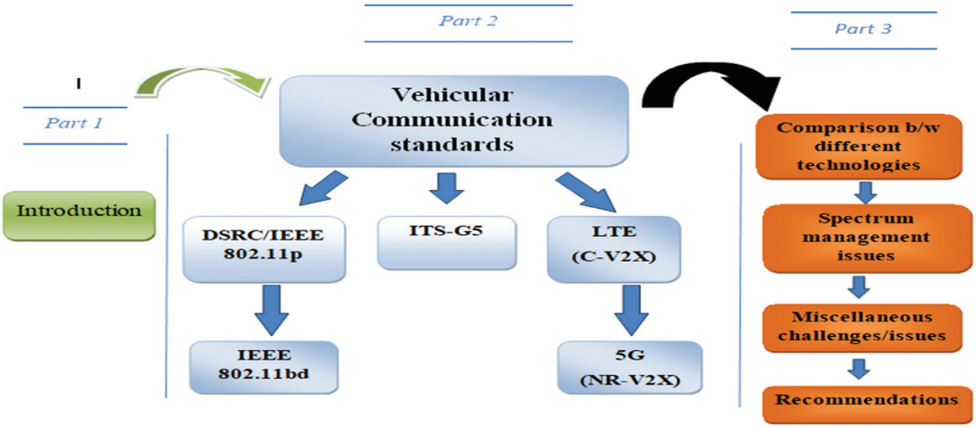


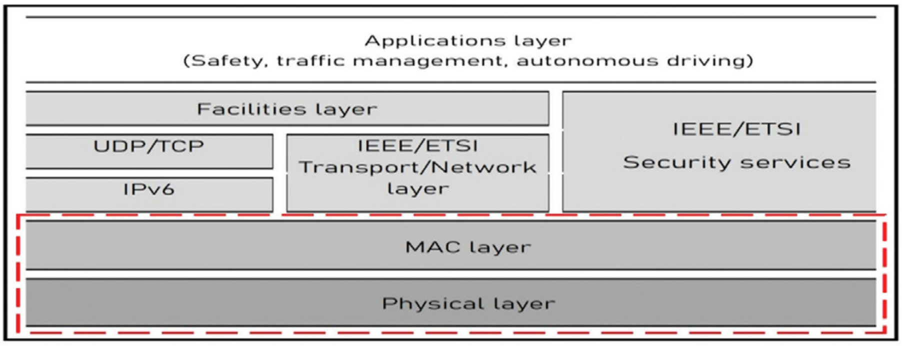
Fig. 4. The overall organization of the research

The paper is arranged as follows. Section II presents the V2X standards. Section III presents a comparison between DSRC (IEEE 802.11p) & LTE (C-V2X). Section IV presents a comparison between IEEE 802.11bd & 5GNR (NR-V2X). Section V presents a comparison between IEEE 802.11p (DSRC) & IEEE 802.11bd. Section VI presents a comparison between LTE (C-V2X) & NR-V2X. Section VII presents a comparison between IEEE WAVE (DSRC) & ITS-G5. Section VIII presents a comparison between ITS-G5 & LTE (C-V2X). Section IX presents spectrum management issues. Section X describes other challenges/issues. Section XI presents recommendations. Section XII presents the conclusion.

The next section presents the vehicular communication standards.

2. VEHICULAR COMMUNICATION STANDARDS

Different vehicular communication standards have been developed in recent years such as DSRC, ITS-G5, LTE (C-V2X), IEEE 802.11bd, 5G NR-V2X, etc. DSRC, ITS-G5, and LTE (C-V2X) operate at a 5.9 GHz unlicensed band. DSRC protocol is developed in the United States and the intelligent transportation system (ITS-G5) protocol is developed by the European telecommunications standards institute (ETSI), respectively. Similarly, C-V2X (a long-term evolution (LTE) based radio access technology (RAT) which facilitates LTE equipped vehicles to function even without cellular infrastructure) has been developed by the 3rd generation partnership project (3GPP). A generalized vehicular communication protocol stack used by DSRC, ITS-G5, and LTE is shown in Fig.5. [2, 10].



IEEE: Institute of Electrical and Electronics Engineers
ETSI: European Telecommunication Standard Institute
UDP: User Datagram Protocol
TCP: Transmission Control Protocol
MAC: Medium Access Control

Fig. 5. Generalized vehicular communication protocol stack [2]

The figure shows that the difference between these standards lies at MAC and PHY layers. DSRC and ITS-G5 use Wi-Fi, whereas LTE uses cellular-based access technology. Moreover, DSRC and ITS-G5 use different access mechanisms in the PHY layers [10, 15]. The next section describes the DSRC protocol.

2.1. DEDICATED SHORT RANGE COMMUNICATIONS (DSRC) - IEEE 802.11P

It is the de-facto standard for V2X communication based on the IEEE 802.11p (modified version of IEEE 802.11) and 1609 Wireless Access in Vehicular Environment (WAVE) protocols in the United States. The protocol stack for DSRC is shown in Fig.6. [5].

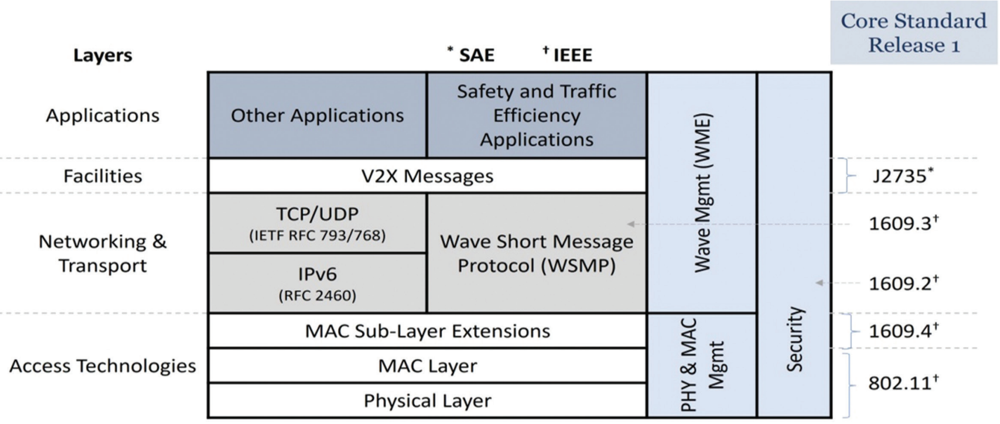


Fig. 6. Protocol stacks & related core standards for DSRC in the USA [5]

The work for DSRC was started in 2004 by the IEEE task group *p* and was approved in 2010. DSRC was the only available V2X technology for a long time. DSRC operates in the 5.9 GHz band ITS applications. The standard supports low latency V2X communications in high mobility scenarios. The standard also supports platooning (i.e., better fuel efficiency and carbon dioxide emissions, etc.) and provides reliable traffic management, i.e., traffic lights, emergency services, etc. Municipal/state governments and auto manufacturers have invested a lot of money to develop this standard and it is ready for deployment as it addresses the most challenging V2X requirements. Any other technology that can fulfill the same requirements would again require huge testing and investment [2, 12, 16].

2.1.2. Issues/challenges

The DSRC has many issues. It is appropriate for short-range messaging, however, it does not provide a strong connection, very high reliability, and very low latency, especially in high mobility environments. DSRC also suffers low data rates, poor scalability, and packet losses when the vehicle's density is high. The standard also needs broader compatibility, merger, and coexistence, i.e., the ability to support safety services, etc. [5, 17].

The next section describes the Long term evolution-LTE (C-V2X) protocol.

2.2. Long term evolution - LTE (C-V2X)

Initially, there was an assumption that cellular technology does not provide vehicular safety applications as it requires low latency, especially at high speed as the messages have to go through the infrastructure. However, the 3GPP developed LTE. In this standard, direct communication among devices was achieved by using proximity services (ProSe). This was done in 3GPP-Release 14 & Release 15 (modes 3 and 4), based on the PC5 interface with or without any involvement of evolved node B (eNB) [10, 12]. The standard uses two different types of communications: network communications which use the Uu interface (radio interface between user equipment & enodeB) and direct communications which use a side link channel over the PC5 interface as shown in Fig.7. [14].

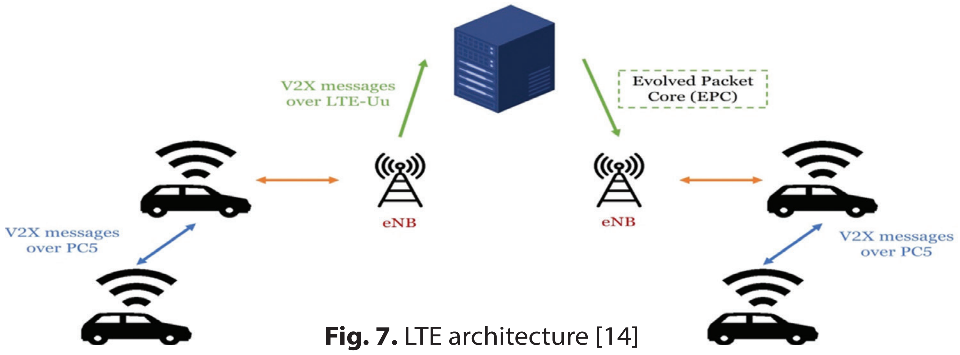


Fig. 7. LTE architecture [14]

Licensed spectrum is used for network communications, while evolved node B (eNodeB) is used to send messages to the vehicle's user equipment (UEs). For direct communication, messages are communicated at 5.9 GHz (unlicensed spectrum). Moreover, modes 3 and 4 (D2D transmission modes) support low-latency vehicular applications by allocating resources in different ways. In mode 3, resources are allocated by eNodeB, while mode 4 allocates resources autonomously without using eNodeB. Therefore, LTE operates at licensed and unlicensed spectrum [2, 12].

2.2.1. C-V2X (LTE-release 14) issues

a) V2I/I2V related issues

Cellular technology is generally suitable for non-safety-related uses. Similarly, the performance of LTE networks is not clear when the network traffic is very high, especially when roaming conditions for many network operators is not clear. This issue can be solved by using a point-to-multipoint interface, i.e., Multimedia Broadcast/Multicase Service (eMBMS). However, eMBMS is typically designed to support static scenarios, e.g., crowd watching a football match in a stadium. Moreover, handovers and cooperation between mobile network operators (MNOs) are also not well defined due to the presence of data traffic from other applications which might affect I2V applications [5, 18].

b) V2V-related issues

The use of cellular technology for safety-related applications experiences many challenges. Unicast LTE networks cannot handle too much data when some V2V applications produce continuous traffic among vehicles, as cellular networks do not provide high data bandwidth at a low latency across all coverage areas. Although, messages with low bandwidth, i.e., decentralized environmental notification messages (DENM), are supported by the cellular networks at very low latency. However, cellular systems are not capable of supporting these messages under all conditions [18, 19].

c) Timeline for C-V2X

The 5G NR-V2X will be included in Release 16 and onwards (i.e., referred to as 5G) as shown in Fig.8. [20]. By the time, the cellular community addresses all LTE issues, other technologies (e.g., 802.11p) would be already in use and would create tough competition for 5G NR-V2X [18, 19].

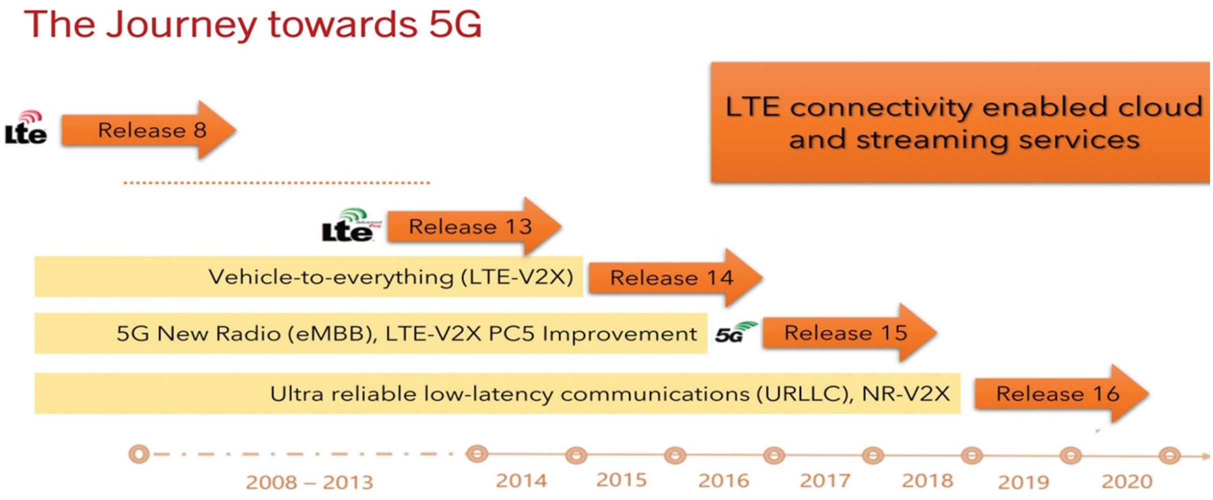


Fig. 8. A journey towards 5G [20]

d) Safety and privacy considerations

The subscriber Identity Module (SIM) card is used for network authentication by cellular networks for the user's

security. However, in the absence of a network, SIMs may not work for network-assisted V2X communication, and 3GPPP has not addressed this issue yet. Similarly, privacy is a growing concern for everyone and there is major opposition to cloud-based systems with this technology. However, privacy is more secure in IEEE 802.11p/bd as there is no cloud system [18, 19].

e) Cellular infrastructure issues

Existing cellular infrastructure does not support many V2X applications as these applications require low latency in high mobility and/or high congestion scenarios. Therefore, improvements and expansion are required for cellular infrastructure. On the other hand, roadside units (RSUs) can be deployed in IEEE 802.11p/bd along with existing infrastructure (traffic lights and traffic signs, etc.) which will reduce costs for near and long-term deployment [18].

f) Standardization issues

It is very difficult for cellular networks to fulfill all the technical and standardization requirements of V2X due to bandwidth issues. However, in IEEE 802.11p/bd, the standard only operates at 5.9 GHz once everything is according to the standards/requirements, i.e., no requirement of subscriptions and roaming agreements, etc. [18, 21].

g) C-V2X security architecture issues

Control functions are provided by eNB and mobility management entity (MME) in LTE. Although efficient, this design does not provide a robust approach for credential management, privacy, and anonymity of involved entities. Moreover, there is limited support for many other functions such as positioning, maneuver changes, platoon formations, etc. Similarly, the safety requirements in LTE applications (e.g., periodic transmission after every 100 msec) are not efficient compared to aperiodic transmission by using large and variable-sized packets [18, 19, 22].

h) Other issues/challenges

There are also many other issues/challenges in Relesae14 such as a high Doppler shift of 2700 Hz, which creates a channel variation even within a sub-frame at a relative speed of 500 Km/hr at 6 GHz; reliability of channel estimation is also very difficult at very high frequency, e.g., there is an offset of up to 1800 Hz at 6 GHz; channel inter-leaver issue exists because of the reuse of other LTE uplink severely impacts the performance of side link data channel in RB/modulation coding scheme. Moreover, the solutions provided are incompatible with Rel-15; the transport block-sized table used in Rel-15 is incompatible with Rel-14; Mode-4 in Rel-14 suffers from high latency and the solution provided in Rel-15 is not compatible with Rel-14; users may miss the safety messages due to half-duplex problem. The solution is only available with 5G NR instead of Release 15. This issue is also not present in ETSI ITS-G5 due to the principle of "listen-before-talk"; LTE is also very sensitive to frequency offsets, e.g., a small subcarrier spacing of 15 kHz, especially at 2 or 3 GHz region is not compatible in the 5.9 GHz band. However, in 5G NR, 3GPP is planning to "unlock" the subcarrier spacing according to the deployment; selecting a suitable modulation scheme (e.g., SC-FDM or OFDM) and changes in signal structure (e.g., additional pilots for better channel estimation) are other issues with Release 14 which need to be solved [5, 18, 19, 21, 22].

To address all the above-mentioned issues would require new approaches and designs requiring time and money [18]. The next section describes the Intelligent Transportation System (ITS-G5) protocol.

2.3. INTELLIGENT TRANSPORTATION SYSTEM (ITS-G5)

This protocol operates in the 5 GHz frequency band and is developed by ETSI. It uses the same PHY layer as in 802.11p, however, it defines different algorithms for channel access [11]. The protocol stack for the ITS-G5 is shown in Fig.9. [5].

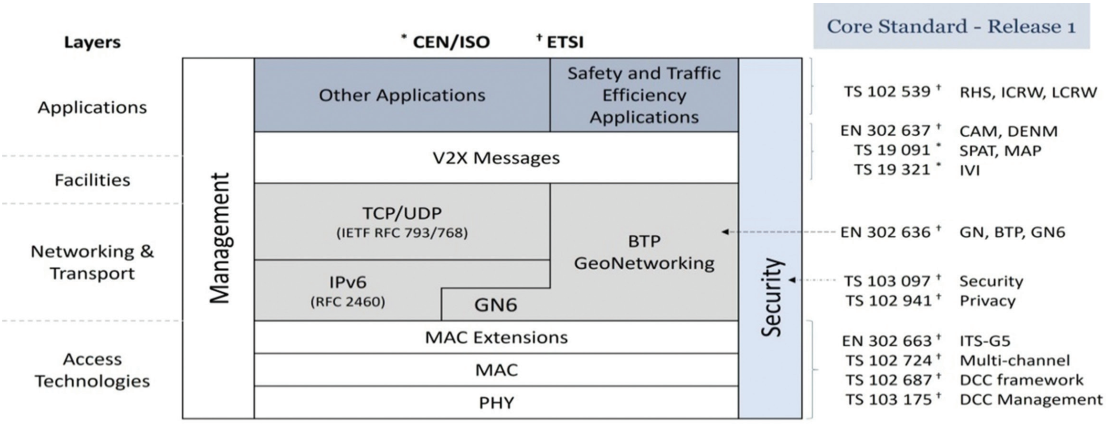


Fig.9. Protocol stacks & related core standards for C-ITS (Europe) [5]

2.3.1. ETSI (ITS-G5) issues

The performance, i.e., end-to-end delay, packet error rates, etc., of the ITS-G5 systems is not well defined under high node density scenarios. Similarly, decentralized congestion control in ITS-G5 introduces local and global oscillation of the state machine. Moreover, the number of received cooperative awareness messages (CAMs) reduces considerably at a high penetration rate, which ultimately reduces the number of known neighbors [23].

It is very difficult to say which standard (DSRC, LTE, and ITS-G5) is better. Currently, DSRC has the advantage as the 5.9 GHz band in the United States is reserved for DSRC for more than a decade now. Until unless, the LTE inventors can convince government regulators that LTE is a technically superior and more flexible alternative than 802.11p, the mandate for 802.11p seems imminent. In Europe, the EU plans to roll out the ITS-G5 system very soon. However, ITS-G5 also intends to use 802.11p as the basis of the radio standard for safety applications. Similarly, the Chinese government is ready to mandate LTE by using the 5905-5925 MHz spectrum. This is important as it would provide minimal standards differences worldwide. In the US, the legislation timeframe for mandating V2V communication is set for 2023 [3].

However, the above-mentioned standards (DSRC, LTE, and ITS-G5) provide vehicle safety applications up to 99% reliability & 100 ms latency only, however, AV driving requires reliability and latency up to 99.99% & 3 ms. Therefore, to meet this challenge, IEEE Task Group 802.11bd (TGbd-enhanced version of DSRC) was formed in Jan. 2019. Similarly, 3GPP is also developing New Radio (NR-V2X) for its Rel. 16 (enhanced version of LTE-V2X), i.e., building on the top of 5G [2, 12].

The next section describes the IEEE 802.11bd (Enhanced version of IEEE 802.11p-DSRC) protocol.

2.4. IEEE 802.11BD (ENHANCED VERSION OF IEEE 802.11P-DSRC)

To meet the requirements of V2X communications and to accomplish the challenges faced by the different standards mentioned above, the work has started to develop the IEEE 802.11bd standard to provide high throughput and low latency, etc. [2]. In this standard, various improvements such as low-density parity-check (LDPC) coding, space-time block coding (STBC), midambles, etc., have been achieved at the PHY and MAC layer protocols of IEEE 802.11n, 802.11ac, and 802.11ax [2]. This standard also improves orthogonal frequency division multiplexing (OFDM) sub-carrier spacing, forward error correction (FEC) coding, channel estimation, etc. Moreover, better spectral efficiency is achieved as compared to 802.11p by using efficient orthogonal frequency-division multiple access (OFDMA) numerologies. However, the reduced sub-carrier spacing affected by channel variations is still an issue [2, 22, 24].

2.4.1. Issues/challenges

There are many issues with the 802.11bd standard which are described below.

a) Interoperability

Interoperability is a critical requirement that 802.11bd must satisfy. For interoperability, 802.11bd & 802.11p must be able to decode each other messages as many auto manufacturers are already installing 802.11p in their AVs [12].

b) Backward compatibility

At least, one mode of 802.11bd must be interoperable with 802.11p for backward compatibility. Design of the PHY and MAC layers of 802.11bd, i.e., space-time block coding, etc., face many constraints due to the interoperability and backward compatibility requirements. Many changes have been made in the frame format to address this issue [12, 24].

c) Coexistence

Coexistence requires 802.11p devices to detect 802.11bd frames as valid frames instead of decoding and vice versa. Coexistence is required when 802.11bd devices send messages only for 802.11bd (not 802.11p). However, in situations where both devices are present, 802.11bd devices can also send messages using only the 802.11p frame format, i.e., even when there is no 802.11p device [12].

d) Fairness

There are many issues of fair and equal access to the physical transmission channel, especially when both 802.11bd and 802.11p equipment are operating in the same vicinity [12].

The next section describes the 5G New Radio (5G NR-V2X) protocol.

2.5. 5G New Radio (5G NR-V2X)

5G is the future of cellular networks. Therefore, 3GPP is working toward the development of the NR-V2X standard to fulfill ultra-reliable and ultra-low latency requirements, i.e., Rel. 16 (enhanced version of LTE-V2X) as shown in Fig.10. [25].

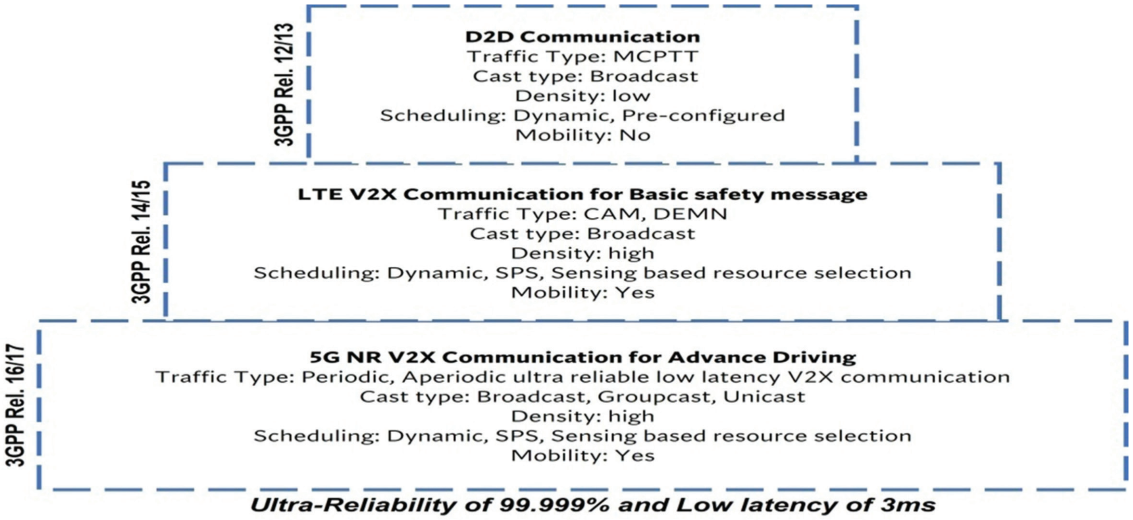


Fig.10. 3GPP Side link Evolution [25]

As compared to LTE, NR-V2X is a function-based architecture that mainly provides service-based access to all involved entities as shown in Fig.11. [25].

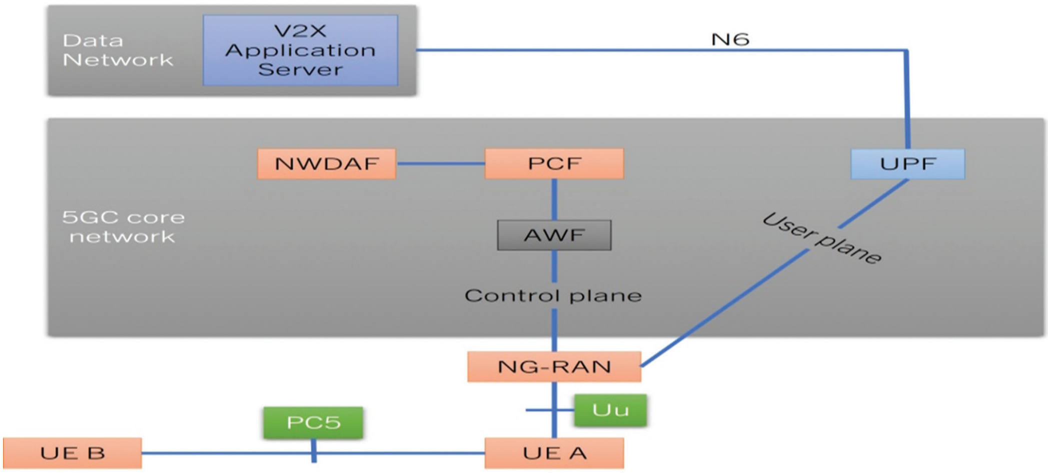


Fig.11. Release 16 V2X architecture within 5G system architecture [25]

The standard uses flexible numerologies, agile frame structure, mm-Wave bands, better channel recovery, and advanced multiple access techniques. It also provides side link communication via the PC5 interface to provide immediate dissemination of vehicles' planned maneuvers. Similarly, NR-V2X will also provide pre-emptive resource scheduling for critical messages, adaptive retransmissions, and support of unicast & groupcast communications [2, 12, 26, 27]. The standard also uses both DFT-spread-OFDM (DFT-s-OFDM) and OFDM as compared to LTE, which is more suitable for high throughput and wide-bandwidth operations with low complexity. For low-budget devices, DFT-s-OFDM provides high efficiency because of its low peak to average power ratio (PAPR). The standard also uses scalable OFDM numerologies which allow the standard to choose between different subcarrier spacing from 15 to 480 kHz. All of the above-mentioned features make NR-V2X more reliable, scalable, and throughput efficient as compared to LTE [28].

2.5.1. Issues/challenges

a) Security attacks and threats

Security is one of the key issues for NR-V2X. LTE is highly vulnerable to attacks if it is used in NS-5G (Non-Standalone) mode. Similarly, NR-V2X also requires additional security when used in the NS-5G V2X mode for different scenarios (which do not exist for LTE) such as service-based accessibility and edge-based authentications, etc. [29].

b) Irregular placement of gNB

Irregular placement of gNB (counterpart of eNB (tower) & MME of LTE) may cause possible attacks on NR-V2X, especially for authentication and authorization of vehicles. Certificate-based security is provided in semi-autonomous mode or a secure connection is achieved between roadside units (RSUs) and original equipment manufacturer (OEM) to address this issue. However, in fully autonomous mode, the smooth transit between gNBs may be hindered by certificate-based solutions [12, 25].

c) Cell coverage

Cell coverage, network layout, planning, and handover are other areas that may be exploited by the attackers in both intra and inter modes. Although, a lower number of roadside units (RSUs) are used by LTE and NR, however, issues related to universal availability and access management are still there. Similarly, there is no architecture available to provide dynamic RSUs. NR securities also have complex and expensive backward operations for V2X applications [25, 30].

d) Excessive service initiations

Many services can be initiated by an attacker, if he gets access to security reflex functions (SRF).

e) Security reflex function (SRF) positioning

Optimization of the SRF function is another issue in different scenarios. In some scenarios, SRF functions must be placed near original equipment manufacturers (OEM) to have direct control of vehicles by the OEM. However, it violates the principles of edge computing [25, 29].

f) Accurate sensor readings

In all situations, accurate data regarding the vehicle needs to be retrieved by sensors for location and trajectory-based key generations.

g) Credential theft

New approaches are required for the accurate identification of vehicles to avoid any kind of threats to infrastructure (KX), especially in the case of a fake call from vehicles (KV) [25, 30].

h) Configuration attacks

For NS-5G-V2X, configuration attacks are very critical. The receiving entity may be misleading to take wrong decisions by using V2V/V2P broadcasts by the attackers. These attacks may further create routing attacks and session hijacking [25].

i) Perfect forward secrecy

Forward secrecy is violated while capturing a vehicle or doing signature replication by NR, which may enhance credential threats of vehicles to physical threats [29].

j) Insider threats & zero-day attacks

These vulnerabilities are the major reason for the privacy and anonymity issues, which may expose the entire network to other entities further enhancing attacks [31].

k) Privacy protection for unicast & multicast messages over PC5

New identifier(s) (layer 2 identifiers - L2 IDs) are used to update request messages from the user equipment (UE) in case of unicast messages over PC5. L2 IDs can be made blind by an attacker by using long-term V2X IDs and may create track and linkability issues. Similarly, long multicast sessions may create L2 ID tracking in the groupcast, i.e., SA3 WG multicast [25].

l) Issues of eV2X unicast messages over PC5

A man-in-the-middle attack may happen while initiating a direct communication by UE via broadcast to all UEs and interested UEs may reply to establish a unicast communication. This may further lead to eavesdropping on signaling, data traffic, etc. [25].

m) Issues of identifier conversion in group communication

Mapping or configuration is used by UE in the conversion procedure to find out the destination L2 ID. This conversion should be secure; otherwise, an attacker may get access to UE group memberships [25].

n) Setting up multicast security

A man-in-the-middle attack may happen to L2 signaling and UEs may receive wrong or no multicast information at all. As there is no security setup for multicast (groupcast) communication at present [25].

o) UE service authorization and revocation issues

The overall security of all services may be under threat, if service authorization and revocation are not safe over the PC5 [25].

p) Cross-RAT (radio access technology) PC5 control authorization indication

There is no secure procedure for cross-RAT PC5 control authorization, i.e., control of the cellular network for LTE and/or NR side link (via LTE Uu or NR Uu). This may create severe security issues [25].

q) Other miscellaneous issues

There are many other issues/challenges such as ciphertext attacks, these may happen as sensory information is shared without encryption; fresh keys and synchronized patterns should be used to avoid issues such as a replay or de-synchronous attacks; side-channel attacks are difficult to find which may put the entire network under threat by affecting only the vehicle or gNB; locations of certain entities/functions, involving gNB, session management function (SMF), access and mobility function (AMF), etc., are other key issues for the security of NR [25, 30, 31].

Different V2X standards have been discussed in the previous section presenting their brief features, along with their comprehensive challenges and issues.

The next section presents the comparison between 802.11p & LTE.

3. COMPARISON BETWEEN IEEE 802.11p (DSRC) & LTE (C-V2X)

Both standards support various basic vehicular safety applications such as road awareness, traffic situations, emergency vehicle notifications, etc.

3.1. READINESS

IEEE 802.11p is ready to use, while LTE is in its advanced stages with an advantage of the already deployed infrastructure. 802.11p is a mature technology and LTE is the latest technology, and comparative analyses between these are not widely available. A comparison among these technologies is shown in Fig.12. [18].The key difference is that 802.11p uses direct communication, while LTE depends on the presence of the network [18].

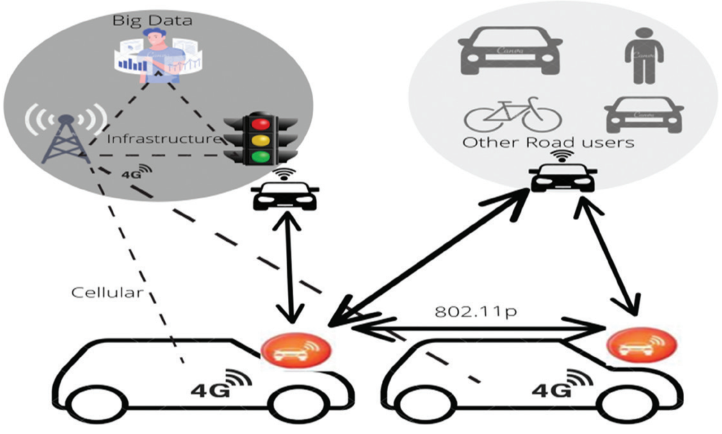


Fig.12. Comparison between IEEE 802.11p & LTE [18]

3.2. LATENCY

Both technologies provide a latency of around 100 milliseconds for low vehicular density scenarios. However, in a high vehicular density scenario, DSRC performance rapidly deteriorates because of packet collisions. Packet collision happens due to simultaneous transmissions and hidden node issues. This issue can be partially addressed by using congestion control approaches [12].

3.3. HIGHER LINK BUDGET

The *side link* mode 4 of LTE performs better than DSRC in terms of a higher link budget. Similarly, *side link* mode 3 of LTE provides efficient utilization of the spectrum. Although, mode 4 provides frequency re-use, the re-use distance is reduced as traffic density increases reducing the performance of LTE [12].

3.4. DELIVERY RATE

Both standards are not capable of providing consistent high data rate transmissions for advanced autonomous driving applications. However, the performance of LTE is better than 802.11p due to the improved PHY layer. Similarly, 802.11p does not provide optimal congestion control mechanisms such as LTE [21].

3.5. PACKET RECEPTION RATIO

At low data traffic, LTE-V2V supports a better packet reception ratio (e.g., up to 10%) as compared to 802.11P. Similarly, LTE-V2V provides a lower update

delay for longer distances (up to 500 meters) as compared to 802.11p (approximately 250 meters) [32].

3.6. RANGE

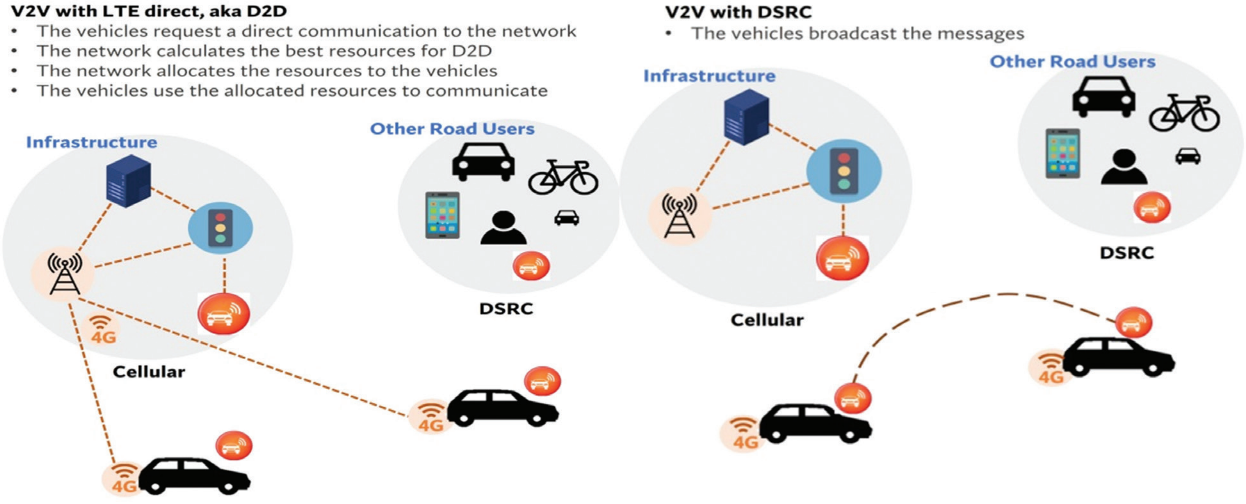
The field trials show that LTE can support reliable communication for distances longer than 1.2 km at a relative speed greater than 430 km/h compared to 802.11p, especially in mode 3 [2, 33].

3.7. MISCELLANEOUS COMPARISONS

Several other comparisons can be made. Such as the comparison that LTE mode 3 performs better than 802.11p & LTE mode 4 because of the better knowledge of node positions and allocations; LTE-V2V mode 4 performs better than 802.11p, especially at larger distances with high density, but with longer update delay; LTE is generally better than 802.11p for standard and non-standard application layer codes, but 802.11p with 16QAM-3/4 is preferable at higher channel load; LTE mode 3 is collision-free; LTE is better than 802.11p on highways, but less in urban areas; LTE provides longer range, enhanced reliability and consistent performance during traffic congestions as compared to 802.11p; the future of LTE is 5G due to better co-existence with other technologies [2, 21, 33, 34, 35].

3.8. IMPORTANT NOTES

Existing literature reveals that LTE performance is better than 802.11p in terms of additional link budget, better resistance to interference, better non-line-of-sight (NLOS) capabilities, and mainly due to the already deployed infrastructure. However, factors such as mobility management, cost, consistency, safety, and scalability are yet to be further evaluated, especially by using different modulation and coding scheme (MCS) strategies as these factors generally penalize 802.11p without proper evaluation [12, 21, 28]. A comparison between LTE and DSRC is shown in Fig.13. [18]. In the cellular case, proper management of the network interference is achieved via full control of direct communication, while in the case of DCRS, a fast execution happens due to the use of the random access protocol, however, wireless resources are used inefficiently.



V2V with LTE direct, aka D2D

- The vehicles request a direct communication to the network
- The network calculates the best resources for D2D
- The network allocates the resources to the vehicles
- The vehicles use the allocated resources to communicate

V2V with DSRC

- The vehicles broadcast the messages

Fig.13. LTE advantages over IEEE 802.11p [18]

The next section presents comparisons between 802.11bd & 5G NR.

4. COMPARISON BETWEEN IEEE 802.11BD & 5G NR-V2X

Both standards provide reliable end services, lower latency, and high throughput. However, their design approach is considerably different.

4.1. BACKWARD COMPATIBILITY

IEEE802.11bd is backward compatible with 802.11p, i.e., devices from both standards can communicate with each other while using the same channel. However, in 5G NR, vehicles using NR can communicate with LTE by using a dual radio system, i.e., one for each technology [4, 12].

4.2. TRANSMISSION RELIABILITY

For the PHY performance, NR-V2X provides better transmission reliability. However, Doppler shifts are a major issue for 802.11bd. Although, mid ambles and extended range preamble significantly improve the performance of 802.11bd, however, NR-V2X is still better due to better channel estimation techniques, lower code rates, and DFT-s-OFDM.

4.3. PACKET ERROR RATES

This error happens in 802.11bd even at high signal-to-noise ratios due to the high Doppler shift for PHY performance [33]. Similarly, more advanced control applications such as the cooperative adaptive cruise control (CACC) system need further investigation for 802.11bd [24].

4.4. TRANSMISSION LATENCY

NR provides better transmission latency than 802.11bd due to the use of the mini slot option. However, NR outperforms LTE when the minimum latency requirement is less than 1 ms.

4.5. DATA RATE

NR provides a four times higher data rate for a packet size of 100 bytes and a 7 Mbps higher data rate for a packet size of 1500 bytes as compared to 802.11bd [24].

4.6. PACKET INTER-ARRIVAL TIME

For this feature, NR is better than 802.11bd due to lower code rates [24].

4.7. PACKET RECEPTION RATIO (PRR)

Taking 90% PRR as a threshold, both LTE & NR are better than 802.11bd because of their very low coding rate. For 100 & 1500 bytes packet size, NR performs better than other standards by providing a higher range. This performance can be further improved by the hybrid automatic repeat request (HARQ) mechanism [24].

4.8. DOPPLER SHIFT

NR-V2X takes care of the Doppler shifts in a better way and outperforms 802.11bd by providing better reliability.

Based on the above discussion, NR performance is better in terms of reliability, latency, data rate, and packet inter-arrival time as compared to 802.11bd. However, many other challenging issues regarding these technologies need to be further investigated, especially the design of PHY and MAC layers.

The next section presents comparisons between 802.11p & 802.11bd.

5. COMPARISON BETWEEN IEEE 802.11P & IEEE 802.11BD

5.1. TRANSMISSION LATENCY

IEEE 802.11bd has a low transmission latency as compared to 802.11p because of higher-order modulation & coding schemes and more data carriers. With packet sizes of 100 & 1500 bytes, 802.11bd achieves 0.1 ms and 0.388 ms transmission latency, respectively [36].

5.2. DATA RATE

IEEE 802.11bd provides a peak data rate of approximately 0.3 Mbps & 8 Mbps for 100 &1500 bytes of packet sizes as compared to 8021.11p because of better channel estimation and coding scheme.

5.3. HIGH DOPPLER SCENARIOS

IEEE 802.11bd provides better performance in high Doppler scenarios as compared to 802.11p [12].

5.4. GAIN COMPARISON

Simulation results show that 802.11bd provides a gain of 3-8 dB instead of 0.5-1.7 dB achieved by 802.11p at a block error rate of 10^{-1}. Similarly, 802.11bd can provide an additional 1-3 dB gain at a block error rate of 10^{-1} by using the parity-based interoperability mechanism [24].

5.5. PACKET ERROR RATE

IEEE 802.11bd provides a gain of 8 dB as compared to 802.11p in terms of packet error rate.

The above discussion shows that 802.11bd is better than 802.11p in every aspect. The next section presents comparisons between LTE & NR-V2X.

6. COMPARISON BETWEEN LTE (C-V2X) & 5G NR-V2X

6.1. DATA RATE

5G NR provides a data rate better than LTE, i.e., 16 & 13 Mbps for 100 & 1500 bytes of packet sizes, because of less control overhead and better bandwidth efficiency [12].

6.2. GAIN

Simulation results show that NR provides much better gain due to 60 kHz sub-carrier spacing compared to LTE, which uses 15 kHz spacing, especially at relatively higher velocities, i.e., 500 *kmph*.

In summary, by using flexible NR numerologies which provide larger sub-carrier spacing and superior link-level performance, NR significantly outperform**s** LTE in every aspect including transmission, latency, reliability, throughput, packet reception ratio, packet error rate, etc. Under highway scenarios, NR almost meets the desired performance requirements for vehicular communication. [24].

The next section presents comparisons between IEEE WAVE (DSRC) & ITS-G5.

7. COMPARISON BETWEEN IEEE WIRELESS ACCESSES IN VEHICULAR ENVIRONMENTS (WAVE) (DSRC) & ETSI (ITS-G5)

A similar, however, not identical approach is used by ETSI in Europe and IEEE WAVE in North America to achieve the required vehicular communications. Both standards are based on 802.11p which operates at 5.9 GHz. However, both standards use different ways to access the available channels, i.e., WAVE uses enhanced distributed channel access (EDCA) subsystems, and ITS-G5 uses models consisting of state machines. Generally, the performance of both systems for many parameters such as end-to-end delay, packet error rates, inefficient channel utilization, etc., is not up to the standard, especially in high node scenarios. Although, ITS-G5 with decentralized congestion control (DCC) may access channels conservatively, however, it performs better than WAVE in most cases**.** Similarly, ITS-G5 performs better than WAVE for packet delivery rates at higher penetration rates, however, approximately only 40% of AVs are detectable by radio receivers at short distances [5, 11, 37**].**

The next section presents comparisons between ITS-G5 & LTE.

8. COMPARISON BETWEEN ITS-G5& LTE (C-V2X)

8.1. READINESS

ITS-G5 is an advanced version of the Wi-Fi standard, while most of the available LTE data are based on numerical simulations. For LTE, different performance classes will be available in the future due to different releases (Rel-14, Rel-15, etc.), which will also create an unfair situation for customers, as Rel-15 cars will have more advanced features as compared to Rel-14 cars [7]. Generally, we can say that LTE (especially Rel-14)) is not ready yet as compared to ITS-G5 as the testing has not been done according to the required standards [38].

8.2 COMPATIBILITY

LTE Rel-15 is not backward compatible with Rel-14, and Rel-14 may be obsolete even before deployed. Similarly, 5G NR technology is not backward compatible with LTE Rel-15 & Rel-14. Therefore, LTE implementation will always be equipped with previous versions in case it relies on services from previous releases, e.g., basic safety messages [7, 38].

8.3 RANGE COMPARISON

Real-time results show that generally, LTE suffers more losses as compared to ITS-G5 in range comparison. However, LTE has a better range in low node concentration due to data rate differences. For high node concentration, ITS-G5 outperforms LTE because of better resource scheduling.

8.4 HIGH MOBILITY ENVIRONMENT

ITS-G5 provides high mobility even for long distances by using a turbo-codec compared to LTE, which does not provide the same performance at high speed even with advanced block-based codecs (like LDPC) as these codecs cannot be decoded per symbol [38].

8.5 DATA RATE

LTE performs better than ITS-G5 for the same data rate. Moreover, LTE outperforms ITS-G5 when user density is less than 150 users per km^2, however, performance deteriorates more severely as congestion increases [10].

8.6 LATENCY

Generally, ITS-G5 provides better latency than LTE. Overall, which systems perform better depends on user density and operating range [10].

8.7 END-TO-END DELAY

The E2E delay of ITS services is affected by the handover procedure. However, association and authentication procedures are disabled in ITS-G5, which is an advantage of ITS-G5 over LTE (mode 3).

8.8 OTHER COMPARISONS

ITS-G5 is designed for V2X, whereas LTE (mode 3) is also used for other applications such as video streaming and VoIP. Similarly, undefined communication profiles for LTE, unrealistic timing requirements, non-clarities regarding the number of supported vehicles along with latency issues are additional challenges that have not been evaluated yet. These challenges also prove that LTE is still in the developing stage compared to ITS-G5.

Table.1. presents a generalized comparison of 802.11p, LTE, 5G-NR & 802.11bd [8]

Table.1. Comparison of DSRC, LTE, 5G-NR & 802.11bd [8]

Key Elements	DSRC/IEEE802.11p	C-V2X (LTE)	NR-V2X (Release 15, 16)	IEEE 802.11bd
Operations beyond networks	Yes	Yes	Yes	Yes
Vehicle to Vehicle operation	Yes	Yes	Yes	Yes
Safety-related messages	Yes	Yes	No*	Yes
Vehicle to pedestrian operation	Yes	Yes	Yes	Yes
Vehicle to infrastructure operation	Limited	Yes	Yes	Yes
Multimedia services	No	Yes	Yes	Yes
Network coverage	Limited	Yes	Yes	Yes
Global economies of scale	No	Yes	Yes	Yes
Regulatory/testing efforts	Yes	Limited	No	No
Very high throughput	No	No	Yes	Yes
Very high reliability	No	No	Yes	Yes
Wideband ranging and positioning	No	No	Yes	Yes
Very low latency	No	No	Yes	Yes

*Rel-15 supports all basic safety messaging as Rel-14.
Rel-16 has all features such as Rel-14 & 15 and will support advanced cases by using 5G NR-V2X.

The next section presents the spectrum management issues related to vehicular wireless communication.

9. SPECTRUM MANAGEMENT ISSUES

9.1. HETEROGENEOUS V2X NETWORKS (INTEROPERABILITY CHALLENGES)

Multiple V2X radio access technologies (RATs) may drive different vehicles simultaneously in the same region very soon. However, LTE and DSRC are two different technologies and are not compatible with each other. A true perspective of V2X communications cannot be obtained if vehicles with different technologies are not compatible with each other [2, 12, 39].

9.2. COEXISTENCE OF DSRC & WI-FI

Studies show that the MAC protocols of Wi-Fi & DSRC are considerably similar. However, the current coexistence mechanism may make it more difficult for Wi-Fi users to operate with the same spectrum. Especially, in urban areas, a large number of vehicles equipped with DSRC will always make it difficult for Wi-Fi devices to get access to the spectrum. Moreover, Wi-Fi operation at 5.9 GHz (unlicensed) should only be permitted if it does not create interference with V2X technologies. Coexistence between DSRC & Wi-Fi can potentially be obtained by changing different parameters in the current Wi-Fi standards instead of using conservative back-off mechanisms. DSRC transmitters can only get a high chance of channel access with a larger contention window size and/or spacing between frames of Wi-Fi. The MAC protocol of 802.11bd is also almost the same as 802.11p, which means that the coexistence of DSRC & Wi-Fi may also be appropriate for the coexistence of 802.11bd &Wi-Fi [39, 40].

9.3. COEXISTENCE OF LTE & WI-FI

The MAC protocol of LTE is considerably different from Wi-Fi. Similarly, LTE & Wi-Fi coexistence has not been properly evaluated and the coexistence of DSRC & Wi-Fi cannot be used as a standard for LTE & Wi-Fi coexistence. Therefore a cohesive coexistence approach is required due to the different MAC protocols of DSRC & LTE. The developed approach must also be forward compatible, i.e., LTE & Wi-Fi approach must also be compatible with 5G NR & Wi-Fi coexistence [39, 41]. However, there are still many issues that need to be addressed and are described below:

9.3.1.

For the signal range between -62 dBm and -82 dBm, LTE and Wi-Fi cannot detect each other signals. Therefore, a new mechanism should be designed to detect signals in this range. The performance of LTE and Wi-Fi systems can also decrease up to 40 %, if the SINR is above 10 dB [39].

9.3.2.

LTE-WLAN Aggregation (LWA) effectively minimizes interference between LTE & Wi-Fi as they access channels differently. However, interference while finding data routing between LTE and Wi-Fi radio is still an issue. Similarly, changing traffic situations along with changing the number of Wi-Fi equipment is also a challenge to design efficient flow routing algorithms [39, 42].

9.3.3.

Multefire devices are in the early stage of development and the effect of their transmissions on the Wi-Fi system, especially concerning Wi-Fi & Wi-Fi coexistence still needs further investigation. Similarly, MulteFire devices also get interference from LTE-U (unlicensed LTE systems) and LAA (License Assisted Access) systems due to similar channel access parameters. Therefore, the performance of MulteFire devices needs further evaluation, especially in the presence of unlicensed LTE technologies [39].

9.3.4.

The back-off mechanism in LBT (listen-before-talk) has a significant impact on the balanced sharing of the spectrum between LTE and Wi-Fi. Therefore, more research is required for optimal LBT schemes in the presence of unlicensed LTE devices [39, 40]].

9.4. INTERFERENCE FROM ADJACENT BANDS

V2X RAT technologies are also affected by adjacent bands. In the US, wireless local area networks use the lower side of the 5.9 GHz band. The Federal Communications Commission (FCC) in the US has also proposed to use unlicensed Wi-Fi operations in the 6 GHz band, i.e., the upper side of the 5.9 GHz band. In such scenarios, if a Wi-Fi device is using a nearby channel of a V2X receiver, the noise floor may be elevated, which will reduce the overall performance as the separation between Wi-Fi & ITS channels is less [39, 41].

9.5. COEXISTENCE OF LTE & NR-V2X

NR may coexist with LTE without any backward compatibility due to the use of multiple numerologies. Therefore, designing an efficient coexistence approach is very important. However, studies suggest that the two technologies can coexist by using frequency division multiplexing (FDM) and/or time-division multiplexing (TDM) in separate channels [2, 12].

9.5.1. Coexistence issues while using FDM

In this mechanism, transmissions may overlap in time while using two different radio access technologies. Similarly, if two different radios are used, and if the frequency channels are not sufficiently apart, interference may occur. Furthermore, if the same band (5.9 GHz band) is used, then the overall power radiated by automobiles may be constrained due to defined vehicle regulations, which may also split the power across the two terminals affecting the QoS [2, 12].

9.5.2. Coexistence issues while using TDM

The transmissions occur at different channels and different timings in TDM, however, latency is still an issue for critical messages as the interference of NR may be off when a latency-sensitive message is created. Similarly, time synchronization between LTE & NR is another issue while using TDM. Furthermore, if LTE & NR channels are not sufficiently apart and NR transmits in this case, then sensing cannot be done by LTE due to a half-duplex problem, affecting the LTE sensing-based resource reservation algorithm [2, 12].

9.6. COEXISTENCE ISSUES OF DIFFERENT COMMUNICATION TYPES & PERIODICITIES

QoS requirements may be different for different messages, i.e., broadcast, groupcast, unicast, etc., even transmitted by the same user equipment (UE) in NR. Furthermore, these messages may be periodic or aperiodic. Periodic messages can use LTE *sidelink* mode 4 resource reservation algorithms for out-of-coverage situations, while aperiodic unicast may use different transmission approaches creating different issues. One approach is to solve this issue by using a pre-emption mechanism [2, 12, 40].

9.7. COEXISTENCE ISSUES OF DSCR & CELLULAR NETWORKING

Many issues need to be solved before DSRC-cellular coexistence can be achieved efficiently. These issues generally arise while deploying dynamic vehicular topology which uses small cell deployment for the next-generation cellular networks because of the requirements of effective network selection techniques.

9.8. COEXISTENCE ISSUES OF HETEROGENEOUS WIRELESS SYSTEMS AT 5 GHZ BANDS

Accurate design is required to efficiently detect the signals in the 5.35-5.47 GHz band Wi-Fi access points (APs). Similarly, hidden node problems in the 5.25-5.35 GHz & 5.47-5.725 GHz ranges (due to dynamic frequency selection, and implementation only at AP), and 5.35-5.47 GHz range (due to non-collocated transceivers) are still an issue [19, 39, 43].

9.9. OTHER ISSUES

Safe mechanisms are required to develop for the security of every user in any V2X standard when it coexists with Wi-Fi systems.

The next section presents different other miscellaneous issues/challenges.

10.MISCELLANEOUS ISSUES & CHALLENGES

10.1. MILLIMETER-WAVE COMMUNICATIONS AND BEAMFORMING

Millimeter-wave (mmWave) provides high throughput at 30-300 GHz band for transmission and can also be reused with less interference. NR & 802.11bd want to use mmWave in the 60 GHz range to accommodate more users. Moreover, multiple antennas can also be used due to the small antenna size with narrowly focused beams (beamforming) to overcome many other challenges, i.e., increasing signal strength and effective range, etc. However, mmWaves are highly attenuated and can only be used for short-range, i.e., 1km. Therefore, multiple hops may be required, which may increase transmission delays. Short wavelength is also sensitive to weather conditions and blocking objects. Moreover, fast-moving communicating nodes also make it difficult to use beamforming in V2X applications [2, 12, 16].

10.2. BACKWARD COMPATIBILITY WITH NEW STANDARDS

New standards should be backward compatible with previous standards, and protocols should be developed to enable seamless interoperability between new and previous standards. If not, there will be numerous vehicles of different standards and interoperability will be a challenge [2].

10.3. AUTONOMOUS/FOG-BASED RESOURCE ALLOCATION

Resource allocation, i.e., time slots in 802.11bd & resource blocks in LTE, etc., is very critical, particularly, when vehicle applications will increase in the future. For efficient communication, a robust autonomous resource allocation scheme (e.g., SB-SPS) or fog RSUs (roadside units) will be required in the future [2].

10.4. MULTI-VENDOR APPLICATION SUPPORT (MVAS)

Multiple vendors will provide V2X communications inside a vehicle for different applications. Therefore, multi-vendor application support (MVAS) is a key requirement for V2X. Efficient designing of layouts, software-defined networking (SDN), network function virtualization (NFV), etc., are required for MVAS.

10.5. AUTONOMOUS ALGORITHM SAFETY (AAS)

Vulnerability is another source of cyber attacks, especially at level 5 (fully autonomous). Therefore, features such as channel security, session management, camouflage detections, risk mitigation, etc., need to be efficiently provided by AAS [2].

10.6. NETWORK CONTROL & SAFETY (NCS)

The tradeoff between network control and safety has a substantial effect on the accomplishment and security of the network for V2X, i.e., attaining MVAS and AAS, as NCS takes care of all security-related issues. Similarly, finding anomalies and avoiding zero-day vulnerabilities are other issues that need to be efficiently analyzed.

10.7. ROGUE DEVICES

Rogue devices **(**which can disable dynamic frequency selection or interrupt functions in the presence of other systems**)** need to be detected, identified, and adjudicated. Moreover, all of these operations should be automatic and less expensive so that they can be easily implemented [39].

10.8. HALF DUPLEXING ISSUE

4G and 5G devices cannot perform the sensing procedure while the device is transmitting due to the constraint of half duplexing. Similarly, the transmissions sent by neighboring vehicles during the same TTI (transmission time interval) cannot be received, even by using different radio base stations [27].

10.9. ORTHOGONALITY ISSUE

The orthogonality issue exists in the frequency domain. Therefore, interference due to in-band emission (IBE) is always present for messages sent at the same TTI, even when nominally orthogonal resources are used [27].

10.10. HANDOVER ISSUES IN LTE & 5GNR

Due to the higher range provided by a large number of available base stations, cellular network technology can be used for V2X continuous network operations in all scenarios with a minimum number of handovers. However, handover management may be a problem with the next-generation cellular technology due to the smaller BS coverage range, especially when network capacity needs to be increased [15].

10.11. NETWORK CHOICE

A little bit of an increase in performance or quality of experience may not prompt a user to change his current network provider to another technology. For example, a user may prefer to remain connected to a BS (which provides a whole highway coverage range) rather than to connect scattered RSUs (which provide non-overlapping coverage ranges along the highway) for slightly better QoS.

10.12. FAIRNESS ISSUES

Fairness issues may also arise in a scenario for vehicles that do not use a dual interface for DSRC & cellular network access, especially for network selection and handover decisions according to the vehicle's preferences. Similarly, for delay-sensitive V2X applications, the computational complexity of the algorithms will be different for different networks. Therefore, it will be safe and secure if the same technology is used by a large number of vehicles, especially for safety broadcast messages which must be received within the defined time limit.

10.13. SECURITY ISSUES REGARDING UNICAST & MULTICAST

The unicast and groupcast modes are enhanced for NR-based PC5. Unicast mode over PC5 uses control plane signaling over two layers (V2X layer and AS layer). Similarly, for security and privacy protection, the groupcast is used by the application layer and UE configuration provisioning for vehicle communications. However, several other issues such as security of eV2X unicast messages over PC5, security of identifier conversion in group communication, multicast security setup, etc., need further research [25].

Based on the previous discussion, the next section presents recommendations.

11. RECOMMENDATIONS

11.1.

Some standards**,** e.g., LTE., already have a large deployed infrastructure as compared to other standards, i.e., DSRC, 802.11bd, etc. However, the performance of these standards on large-scale operations is not proven. If LTE/5G proves better and cheaper in the future than other standards on a large scale, then holding off until more information is available about other standards so that the industry can make a decision seems to be a practical (or at least risk-averse) strategy. On the other hand, standardizing DSRC/802.11bd without properly analyzing LTE/5G can be a mistake. Moreover, if LTE/5G does not prove to be good, then mandating DRSC/802.11bd or any other standard will not be too late. Of course, some costs have to pay due to the time factor, however, it will be less costly than making the opposite mistake [16].

11.2.

C-ITS demands backward compatibility, interoperability, and advanced design for standardizing ITS. Therefore, a hybrid communication approach will be more efficient for the security and safety of the V2X. Therefore, such protocols should be developed that can provide seamless communications with high throughput and low latency in a heterogeneous environment while using any standard, i.e., DSRC, LTE, NR, etc. Another option is to use only one standard (either DSRC or LTE) in an AV for a short period [2, 12].

11.3. BACKUP

There should always be a backup mechanism in case of vehicle disconnections from the central controller, which should be achieved by better collaboration among different service providers.

11.4.

802.11bd and 5G NR are the two potential future standards for vehicle communications. However, spectrum management issues and operational challenges must be pro-actively solved for the efficient co-existence of these two standards.

11.5.

Spectrum management issues need more research to attain seamless interoperability and coexistence among different V2X technologies for secure and efficient operations.

11.6.

Security and safety are the critical aspects of concern when considering the widespread adoption of AVs by the community. Therefore, safe, secure, and reliable algorithms should be developed for efficient V2X communication.

11.7.

All of the above management issues/challenges must be addressed before standardizing any technology to provide secure V2X communications for vehicular technology.

12. CONCLUSION

An efficient and reliable communication standard is required for the communication of AVs with all other entities and their operations. Existing work generally discusses the features and certain performance comparisons of the existing vehicular communication standards without comprehensively describing the drawbacks of these standards. Existing literature also does not provide a comparison between these standards and generally discusses a comparison between two standards only. However, this work comprehensively describes different issues/challenges and comparisons between these standards along with their salient features.

The first contribution of the work is the comprehensive description of the different issues/challenges of these standards, along with their salient features. The second contribution of the work is the presentation of the comparisons among different standards. Another contribution is the detailed description of the spectrum management issues of these technologies. The work also comprehensively presents several miscellaneous challenges to these technologies. In the end, the paper also proposes recommendations that must be taken into account for an efficient V2X communication standard.

The work concludes that theoretically LTE is better than DSRC and does not require large infrastructure investments as compared to DSRC, however, it is still not proven in a large-scale operation. The work also describes that 802.11p, LTE, and ITS-G5 standards are not able to meet the requirements for a reliable and efficient vehicular communication standard, i.e., ultra-high reliability, ultra-low latency, etc. However, two new standards, i.e., 802.11bd and 5G NR-V2X, are the two potential vehicle communication standards as they can meet the requirement of V2X communication, however, issues such as backward compatibility, interoperability, and co-existence with other standards need further evaluation. The work describes that generally, 5G NR performs better than 802.11bd in most of the technical parameters. However, 5G NR and 802.11bd are still in the developing stages. The work also describes that solving spectrum management issues is very critical, especially in the case of co-existence with Wi-Fi and interoperability issues, etc. Similarly, many other challenges such as compatibility, security, highly dynamic vehicular environment, etc., are very important before standardizing any technology.

The work emphasizes that standardizing any one technology without properly analyzing comparative technologies can be a mistake. Delaying is not a big issue when done to investigate an efficient standard. Similarly, standardizing two technologies at the same time in one geographical area can also be very challenging, especially in terms of interoperability, and spectrum management issues. Additionally, implementation cost, road maintenance issues, compatibility, performance in real large-scale environments, etc., must also be evaluated before standardizing any technology. AVs cannot be successful until a secure, safe, and reliable vehicle communication technology is available. Therefore, all the issues related to a standard must be solved before implementation; otherwise the maximum benefits of V2X communication cannot be obtained.

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