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Convergence of V2X communication systems and next generation networks

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Abstract. The main goals of the new generation of Vehicle-to-everything (V2X) communication systems is to increase the public safety trying to achieve the accident-free milestone, increase traffic efficiency and lower the carbon emissions for a cleaner environment, improve traffic flow in intersections and on the highways, more efficient parking system, improve fuel efficiency and ultimately enabling self-driving vehicles. Due to multiple research and standardization institutions in Europe and US, two different technologies have emerged, namely C-ITS (Europe – ITS-G5) and DSRC (US – WAVE) based on 802.11p. Both are fully standardized, tested and ready for mass deployment. As the science evolves at an always accelerating pace, a new technology, C-V2X (LTE/Cellular based V2X) is being developed and it started taking the spotlight from already mature and well tested technologies but with less convergence towards 5G. The foundation for connected and automated cars is an optimal technology that is scalable and can evolve in the years to come. C-V2X allows its users to communicate leveraging the existing LTE infrastructure and in future, the 5G mobile network. In this paper we will make a brief introduction on existing technologies, we will present and analyze the standardization landscape and the capabilities of existing technologies. Furthermore, we discuss the proposals for spectrum harmonization followed by pros and cons of legacy and new V2X technologies highlighting the pressure of different automotive and industry associations on steering the development and deployment of these V2X communication systems.

1. Introduction

The present article gives a good overview of standards for cellular and legacy V2X technologies as well as potential future directions. First section is an introduction into V2X landscape and necessity of standardization. The other sections of the article are organized as follows: Section 2 presents the standardization landscape, analyzing key organizations and the development status, Section 3 gives an overview of spectrum usage harmonization attempts, while Section 4 provides trends and directions for future releases, the road towards cellular V2X communication in Europe and in the U.S. Finally, Section 5 offers a conclusion of the article.

1.1. State-of-the-art

Either it takes the form of combat sports or two technology confronting each other vying to become an industry standard, “Everyone loves a fight!" says the president of Ultimate Fighting Championship (UFC). This is the main purpose of this article, to give the best overview of these two technology

confrontation, between Wi-Fi-based 802.11p and cellular C-V2X, as they vie to represent vehicle-to-everything (V2X) communications on a global scale.
The 802.11p standard also defines how to exchange data through a link without the need to establish a basic service set (BSS), without the need of association and authentication procedures to exchange data.

DSRC uses IEEE 802.11p, which is an approved amendment to the IEEE 802.11 standard and adds wireless access in vehicular environments (WAVE). It offers low-latency (down to 2-ms) communication of safety messages between vehicles and between vehicles and infrastructure like roadside units.

C-ITS is the IEEE 802.11p equivalent protocol stack in Europe, covering PHY and MAC, named also ITS-G5. Similar to DSRC, it operates in the 5.9-GHz band as well. DSRC and C-ITS facilitates the communication for vehicle-to-infrastructure (V2I) and vehicle-to-pedestrian (V2P). This gives the vehicle additional awareness on top of what's provided by advances in RADAR, LIDAR and advanced camera systems. A strong challenger to DSRC and C-ITS for V2X has emerged from the cellular industry, namely Cellular-V2X. Similar to 802.11p based communications, C-V2X direct communications supports active safety and enhance situational awareness by detecting and exchanging information using low-latency transmission in the 5.9-GHz ITS band for vehicle-to-vehicle (V2V) as well as V2I and V2P scenarios. C-V2X can also function without the assistance of network and has a higher range than DSRC/C-ITS, that exceeds one mile, even in areas where mobile network connection is not available.

C-V2X can combine the communication capabilities of roadside units (RSUs) with the cellular network to help improve safety and support autonomous driving. The roadside units will use a high-throughput connection, as they are static with other cars on the road to build dynamic high quality maps using cameras and many data sensors on board, and share them with nearby vehicles as needed [1].

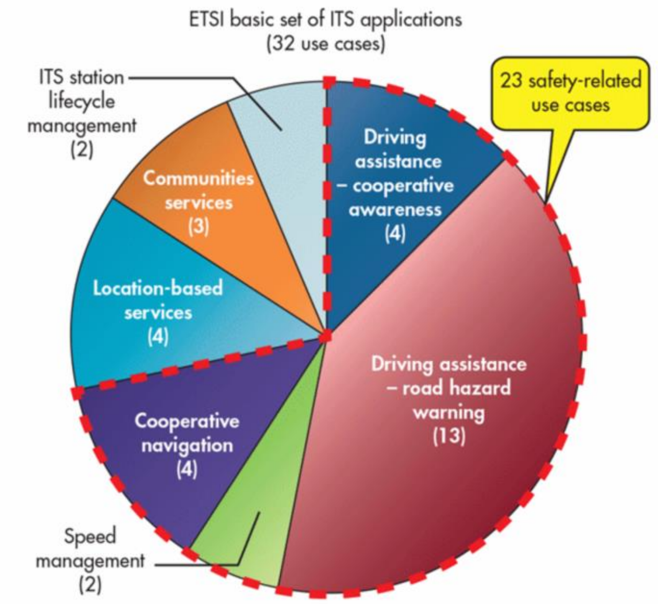

Figure 1. ETSI basic set of ITS applications

Figure 1 give a brief overview of the use cases covered. V2X is using wireless connectivity to enable connected vehicles to achieve "Cooperative Awareness" for the realization of the "Basic Set of ITS Applications" as defined by ETSI (European Telecommunications Standards Institute) [2].

1.2. Necessity of standardization

A standardization process for wireless vehicular communication ensures, as in any other domains, not only interoperability but also supports regulations and legislation in the legal framework, and creates larger markets for global products.

An essential requirement for the worldwide deployment of V2X communication systems are global standards, which provide regulations to ensure interconnectivity among V2X sub-systems and components as well as interoperability of implementations from different vendors. Additionally, global standards also serve for many other purposes, like: open standards create trust for customers in products and services, create global markets compared to proprietary systems, help to lower development and maintenance costs, and increase competition between vendors helping to lower the production costs.

2. Standardization landscape

Historically speaking, standardization in Europe and in the U.S. has developed in parallel with many overlaps, mainly because the activities were supported by different SDOs, research and development programs, as well as promoted by different stakeholders. In the end, these different paths led to different sets of standards. These two approaches are C-ITS (Cooperative Intelligent Transportation Systems) in Europe and DSRC (Dedicated Short Range Communication) in the U.S. ITU (International Telecommunication Union) and 3GPP (3rd Generation Partnership Project) have initiated first standardization studies. This article focuses on the most relevant standards planned for deployment in the next years, and namely the standardization of C-ITS in Europe, DSRC in the U.S. and C-V2X with PC5 interface as a global standard [2].

2.1. Global overview

Policy and rule makers in many countries around the globe have been preparing policies on V2X for some time, reflecting the fact that technologies for cooperative driving are continuously evolving, and automated vehicles are already being introduced in the market. More work is still needed in the areas of security/privacy, conformance, public awareness and economic sustainability for investors, since these kinds of deployment require involvement from many parties, like the state, regional and local governments and road authorities together with the private sector.

In Europe, the modernization and digitalization of transport and the use of intelligent transport systems (ITS) has increasing interest from the European Committee, due to the many benefits, like increase of road safety, address gas emission and traffic congestion issues, and support jobs and economic growth in the transportation sector.

Back in August 2008, the EC published the Decision 2008/671/EC [3] to allocate the frequency band 5875–5905MHz (30MHz) for safety-related applications of ITS, and adopted the ITS Action Plan COM(2008)886 [4], with the initiatives to accelerate and coordinate the deployment of ITS systems on roads and in auto vehicles in the EU.

In July 2010, a legal framework, Directive 2010/40/EU [5], was adopted to accelerate the deployment of ITS across Europe, with the V2I link defined as a key priority area.

The major SDOs active in Europe in the C-ITS development area are ETSI (European Telecommunications Standards Institute) and CEN (European Committee for Standardization) with their Technical Committees (CEN TC 278 – Intelligent Transport Systems) [6]. CEN works closely with ISO to produces joint specifications. Supported by a mandate of the European Commission (EC) [7], ETSI and CEN have created a stable and consistent set of standards for a minimal deployment of V2X communication system, which was supposed to be taken as basis for European deployment. ETSI focused on specifications and requirements for the communication system and V2V applications while CEN mainly focused on standards for V2I applications. The European standardization efforts are going in parallel with activities of the Car-2-Car Communication Consortium (C2C-CC) [8], an industry consortium of automobile manufacturers, equipment suppliers, and research organizations like ERTICO [9], a European organization of public and private stakeholders, and ETSI CTI (Center for Testing and Interoperability). The C2C-CC has developed a customized profile of the European C-ITS Release 1 that is restricting the large set of developed standards and complements missing specifications.

In 2013, automobile manufacturers in C2C-CC signed an agreement for the adaptation of the V2X C-ITS system. Deployment plans were developed in the Amsterdam Group, a strategic alliance with stakeholders from C-ITS ecosystem in Europe, with the objective to facilitate joint deployment of cooperative ITS in Europe. The Amsterdam Group includes umbrella organizations like CEDR–ASECAP–POLIS, representing stakeholders of the ITS infrastructure on highways, cities and traffic management, and the C2C-CC. There were many pilot deployment projects supporting the system introduction and concept demonstration. A trilateral C-ITS corridor that interconnects Vienna–Frankfurt–Rotterdam is planned to be equipped with roadwork protection systems for highways until end of 2018 [10] [11] [12].

In November 2014, the EC launched a C-ITS Deployment Platform, a multilateral framework involving national authorities and C-ITS stakeholders (not including the cellular mobile sector) to identify the remaining barriers and to propose solutions for the commercial deployment of C-ITS systems in the EU zone.

The initial phase of the C-ITS Platform (2014–2016) has focused on the development of a common vision on the interoperability deployment of the system in the EU, including the identification of key technical, legal and commercial issues and the development of policy recommendations to address these issues. The first phase has ended with publication of an technical and strategical expert report in January 2016 [13], which was complemented by a "cost vs. benefit" analysis and a public consultation on this topic.

In July 2016, the C-ITS Platform second phase started. The main objective was to further develop a shared vision on the interoperable deployment of C-ITS systems in the EU, by defining the common technical and legal framework to address key issues on security, data protection, compliance assessment and hybrid communication identified in the first phase, and by investigating further the benefits that C-ITS could bring in terms of autonomous driving. The 5GAA (5G Automotive Association) attended two C-ITS Platform meetings as guests during year 2017. The second phase ended with the publication of an expert report in September 2017 [14].

In parallel, the EC has adopted and is open to various other policies which are relevant for connected, cooperative and automated mobility within EU zone. In particular, "5G for Europe: An Action Plan" – COM(2016)588 [15] calls for the availability of 5G along main European transportation paths.

In October 2017, the Radio Spectrum Committee (composed of the EC and representatives of regulators from EU Member States) approved a new mandate for CEPT (European Conference of Postal and Telecommunications) to study an extension of the ITS-safety related spectrum band 5.9GHz, with the possibility to extend the dedicated ITS spectrum to 50MHz in bandwidth (from 30MHz currently). The document recognizes recent developments in relation to Cellular (LTE) based V2X specification for ITS, which could underpin the path to 5G connectivity for the automotive and road transport sectors. The EC also recognizes that the two V2V radio systems (IEEE 802.11p and C-V2X PC5) cannot inter-communicate with each other due to different radio access techniques. CEPT shall deliver a final report on the topic of harmonization and coexistence by March 2019 [16].

U.S. was the first to assign a dedicated spectrum in the 5.9GHz band for DSRC-based V2X services, but unfortunately there has been a huge delay between the spectrum being assigned, and being put into use. In October 1999, the United States Federal Communications Commission (FCC) allocated 75 MHz of spectrum in the 5.9 GHz band to be used by intelligent transportation systems (ITS).

In the U.S., the relevant SDOs for V2X communications are IEEE (Institute of Electrical and Electronics Engineers) and SAE (Society of Automotive Engineers). Specifically, the 802.11 Wireless LAN and the 1609 Standards were developed by working groups from IEEE, while the DSRC was developed by the technical committee from SAE. IEEE has developed the IEEE 1609 standard family of protocols [17] on top of the IEEE 802.11 PHY and MAC layers. This combination of IEEE 802.11 and 1609 standards is also known as WAVE (Wireless Access for Vehicular Environment). Additional layers coming above the protocol stack, like V2X message sets and related performance requirements, are specified by SAE. Altogether, the WAVE standards, V2X message sets and performance requirements build a consistent set of standards ready for basic functionality commercial deployment.

In January 2017, the US DoT (Department of Transportation) gave a Notice of Proposed Rulemaking (NPRM) that require all new light vehicles being sold on US market to be capable of V2V communications. It tries to mandate the IEEE 802.11p as the communication technology standard for V2V, and require automotive OEMs to start implementing these specifications and requirements two years after the final rule is adopted, this being around 2019-2020 (although it gave a three-year period to accommodate automotive OEM production lines). The NPRM attracted lots of attention and hundreds of responses, especially from the C-V2X supporters and promoters, but the US DoT has given no indication on when it will proceed.

In parallel, the US DOT's Federal Highway Administration Infrastructure Deployment Guidelines were temporarily published but then withdrawn from public access. These guidelines give specifications about V2I communications, in order to help transportation planners to integrate the technologies that allow their vehicles to communicate with roadside infrastructure.

Unlike in Europe, where deployment is industry-driven and voluntarily, a regulatory decision was expected in the U.S. until 5GPP, Qualcomm and GSMA started to push rule makers for technology neutrality approach. This rulemaking process was planned to be initiated and to make DSRC mandatory, indicating a deployment at the beginning of 2020 [2].

In China no dedicated spectrum was allocated initially for ITS services, but the Ministry of Industry and Information Technology (MIIT) allocated 50MHz in the 5.9GHz band for ITS systems, on a license-exempt basis, like in all other regions.

In November 2016, the Chinese government announced the dedicated allocation of 20MHz (5905–5925MHz) for C-V2X trials in six major cities. It is possible that China will be the first country to launch C-V2X, due to bigger opening to new technologies. Research being conducted for this study suggests that C-V2X commercial launch in China could be in the second half of 2019.

In Japan, the 5.9GHz band was used by a Japanese wireless technology called Electronic Tolling Collection (ETC). Reports show that this band is considered for use to provide V2V and V2I communications, but it is unclear whether a decision will be made soon. Until now, Toyota already deployed a proprietary "ITS Connect" solution in 12 cities.

In September 2016, Ministry of Communications in South Korea allocated 70MHz of spectrum in the 5855–5925MHz band for ITS services on a license-exempt basis, and finally on a technology-neutral basis.

Last year, in September 2017, Australia's telecommunications regulator, ACMA, closed a consultation on the allocation of dedicated spectrum in 5.9GHz band for ITS application, proposing rules to follow a technology-neutral approach [18].

2.2. Wi-Fi based V2X (802.11p)

2.2.1. Dedicated Short Range Communication (DSCR) standards in U.S. DSRC is based on the widely deployed WLAN standard defined in 2012, IEEE 802.11, which defines the physical transmission (PHY) and medium access control (MAC) (Figure 2 shows the overall DSCR protocol stack). PHY and MAC are derived from the former IEEE 802.11a standard, and adapted to the requirements for V2X communication.

Similar to IEEE 802.11a, DSRC operates in the 5 GHz band (U-NII band), but it was shifted from the regular Wi-Fi channels to some dedicated DSRC channels. These channels range from 5.855 GHz to 5.925 GHz, commonly referred as the "5.9 GHz band". The spectrum is further subdivided into 10 MHz channels (see Figure 3).

DSRC uses the Orthogonal Frequency Division Multiplexing (OFDM) scheme, a state-of-the-art widely used multi-carrier transmission scheme which is proven to be robust against interference and fading, and also re-uses the same preamble and the pilot design for synchronization as well as channel estimation. Comparing to the normal usage in Wi-Fi, OFDM operates with "half clock", which reduces the commonly used 20 MHz channel spacing to 10 MHz and doubles the time parameters, particularly the OFDM symbol duration with the cyclic prefix. These changes attribute to the characteristics of the wireless channel in vehicular environments as it can adapt to the inter-carrier interference caused by the Doppler spread due to fast moving vehicles [19].

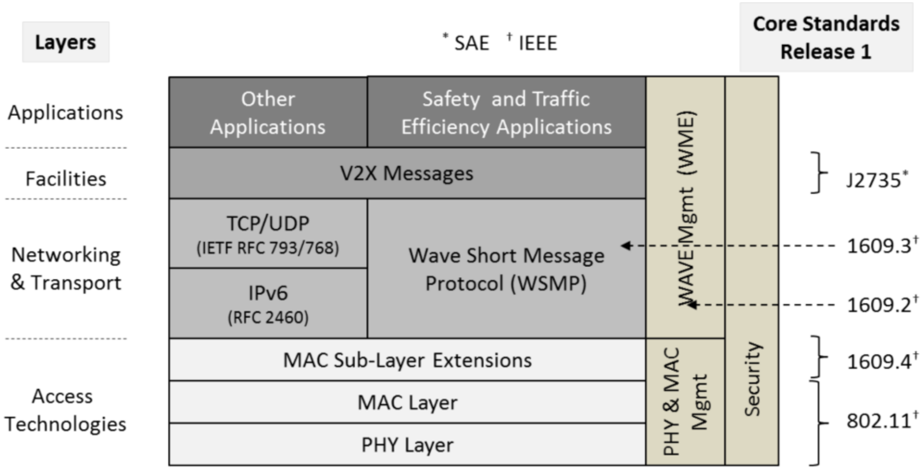

Figure 2. DSRC Protocol stack and related standards in the U.S.

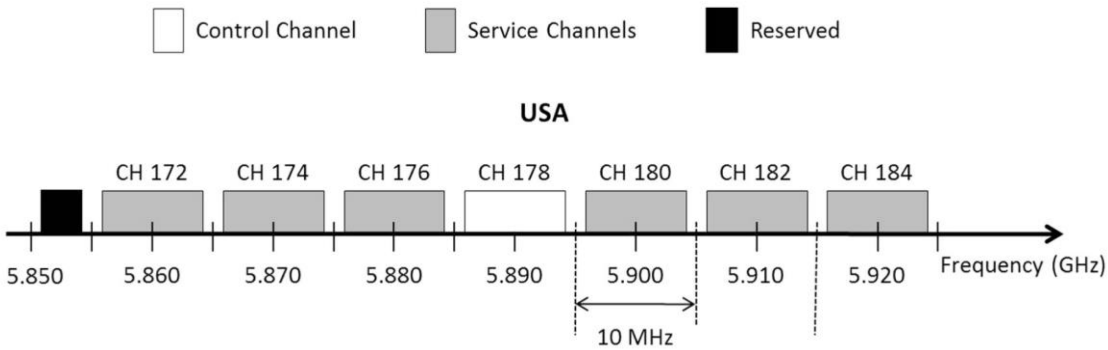

Figure 3. IEEE 802.11p DSRC Channel Frequency Band in U.S.

2.2.2. Cooperative – Intelligent Transportation System (C-ITS) standards in Europe. The parallel research and development of V2X communications by different SDOs has led to a different protocol stack in the U.S. and Europe. This section presents the C-ITS standards in Europe in comparison to the DSRC standards. Figure 4 describes the overall protocol stack and the corresponding core standards behind it, keeping the same structure of horizontal layers for access technologies, networking & transport, facilities and V2X messages, applications, and vertical management and security entities for all layers, same as in Figure 2.

ITS-G5 is the IEEE 802.11p DSRC equivalent in the C-ITS stack covering PHY and MAC layers. The last two letters in naming indicate that it operates in the 5 GHz band. It operates in the 5.9 GHz band in channels of 10MHz each, whereas the European spectrum allocation is sub-divided into part A to D (see in Figure 5). ITS-G5A with 30 MHz is the primary frequency band that is dedicated for safety and traffic efficiency applications, ITSG5B has 20 MHz for non-safety application, and ITS-G5C is shared with the RLAN band, while ITS-G5D is reserved for ITS future use [20].

A specific requirement for Europe is that the ITS-G5 spectrum must minimize the interferences to the 5.8 GHz band. However, the key technology features of IEEE-802.11 for DSCR and ITS-G5 are similar. On PHY layer, it applies OFDM with the same parameter set "half clocked" compared to IEEE 802.11a, with an adapted spectrum masks. On MAC layer, ITS-G5 also employs EDCA with CSMA/CA, identical to DSRC, and access categories allow for prioritization of data traffic.

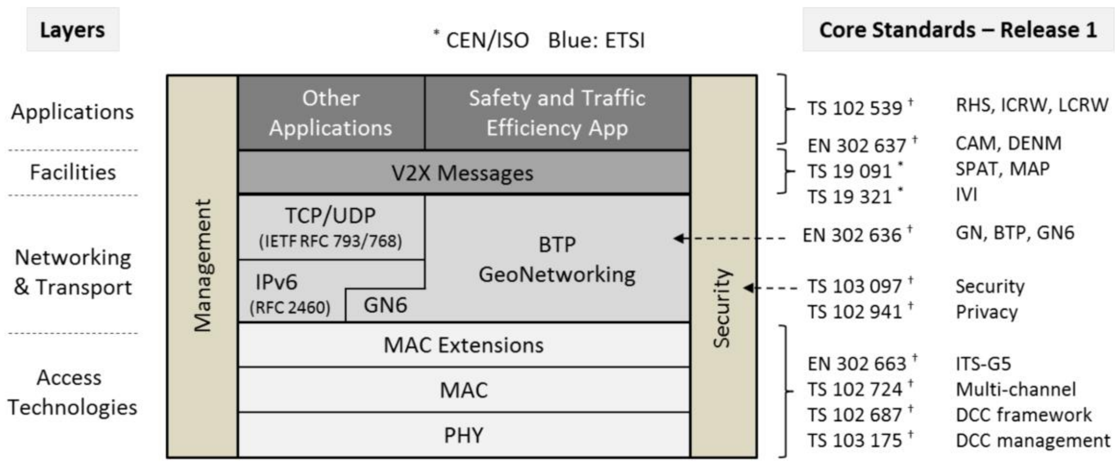

Figure 4. Protocol stack and related core standards for C-ITS in Europe

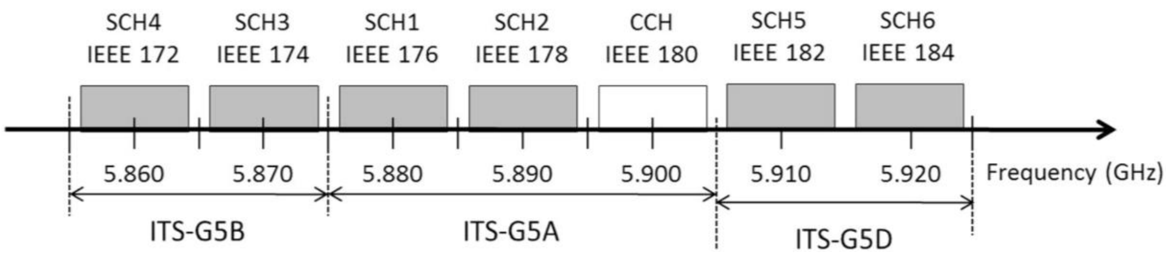

Figure 5. IEEE 802.11p ITS-G5 Channel Frequency Band in Europe

Standards for Networking & Transport and V2X messages also rely on the IP protocol. While the usage of TCP/UDP and IP version 6 is similar, C-ITS specifies a totally different ad-hoc routing protocol with additional function for multi-hop communication, named GeoNetworking described by the ETSI EN 302 636 standard series. Main feature is the utilization of geographical coordinates for addressing and forwarding of messages. The geographical addressing has the advantage of making the packet delivery independent from the communication range of a single wireless hop (which can vary from several 10 meters up to 1 km under line-of-sight conditions found on highways). It enables much more efficient multi-hop routing with low protocol overhead for establishment and maintenance of network routes in a highly dynamic environment with frequent topology changes. This feature provides more technical opportunities in application support, but has the disadvantage of an increased protocol complexity and overhead.

Standards at the Facilities and V2X messages layer define more application-related functionalities specific for European market. The most relevant V2X messages are: Cooperative Awareness Message (CAM) (ETSI EN 302 637-2) [21]. CAM periodically conveys critical information about the state of the vehicle in support of safety and traffic efficiency application. Vehicles receiving CAM messages can track other vehicles positions and movement. It can be considered as an equivalent to the BSM in DSRC protocol stack. Distributed Environmental Notification Message (DENM) (ETSI EN 302 637-3) [22] helps to disseminate safety information in a specific geographical region. Comparing with the

CAM, which is sent periodically by all vehicles, the DENM message transmission has to be triggered by an application, which offers more flexibility.

For V2I (vehicle-to-infrastructure) communications, additional services are defined to communicate with road users, to control of roadside infrastructure for priority access, preemption in case of emergency and to provide information from the vehicles to the infrastructure (see Table 1).

Table 1 Overview of V2I services based on V2X communication (ETSI TS 103 301 [23])

Service name		Description
IIS	Intersection information service	Provides dynamic information about status of an intersection, such as traffic light state, residual time until traffic light changes, right of way for allowed maneuvers, public transport prioritization
TPS	Topology service	Offers static topology information for intersection or road segment, and paths for pedestrian crossings, for vehicles, public transportation
IVI	In-vehicle information service	Gives mandatory and advisory road signage information inside the vehicle, including static, variable and virtual signs; examples: such as contextual speeds and road works warnings.
SCS	Signal control service	Controls traffic lights for prioritization of public transport and preemption of public safety vehicles
INS	Infrastructure notification service	Informs vehicles and pedestrians about traffic situation, hazards, road works warnings, and other events
IAS	Infrastructure awareness service	Informs vehicles about existence of infrastructure (e.g., for interference management near tolling zones); estimation of traffic situation and flow based on messages from vehicles in vicinity

These services define dedicated messages (see Figure 4), namely the Signal Phase & Timing (SPAT) message for IIS, the MAP message for TPS, and the In-Vehicle Information (IVI). In the signal control service message are bidirectional exchanged. DENM and CAM are also used for infrastructure-related services like INS and IAS.

Similar to the DSRC standards, C-ITS applications are not fully standardized. Only minimum functional and performance requirements for three groups of applications are defined:

- Road hazard signaling (RHS): includes use cases such as emergency vehicle approaching, hazardous location and emergency electronic brake lights;
- Intersection collision risk warning (ICRW): refer to potential vehicle collisions at intersections;
- Longitudinal collision risk warning (LCRW): refer to potential vehicle rear-end/head-on collisions.

2.3. Cellular based V2X (4G and future 5G)

V2V communications are based on device-to-device (D2D) communications defined as part of ProSe services in Release 12 and later in Release 13 of the 3GPP specifications. Sidelink aims to enable D2D communications within legacy cellular-based LTE radio access networks.

In legacy LTE communications, two UEs communicate through the Uu (Over the air) interface and data are always going through the network LTE eNB. Differently, Sidelink enables the direct communication between multiple UEs in proximity of each other using the newly defined PC5 interface, and data does not need to go through the eNB (see Figure 6).

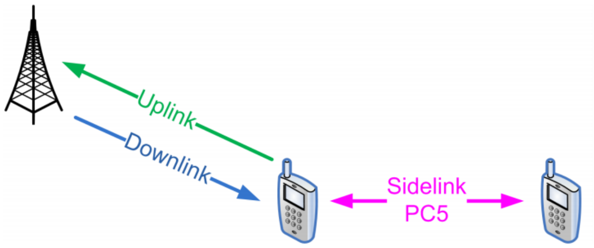

Figure 6. Model of Sidelink PC5 interface

Resources assigned to the PC5 interface are taken from the Uplink resource pool. The reasons for this is, first, the UL subframes are usually less occupied; second, most of the Downlink subframes are never really empty so that they can be reused. Usually there are always at least the cell specific reference signals (CRS) transmitted in all DL subframes.

Based on fundamental link and system level changes, in Cellular V2X communication there are two possible high-level deployment configurations currently defined and illustrated in Figure 7.

In both cases GNSS (Global Navigation Satellite System) is used for time synchronization. This can be seen as a drawback for the C-V2X systems while operating in tunnels or area where GNSS signal is missing.

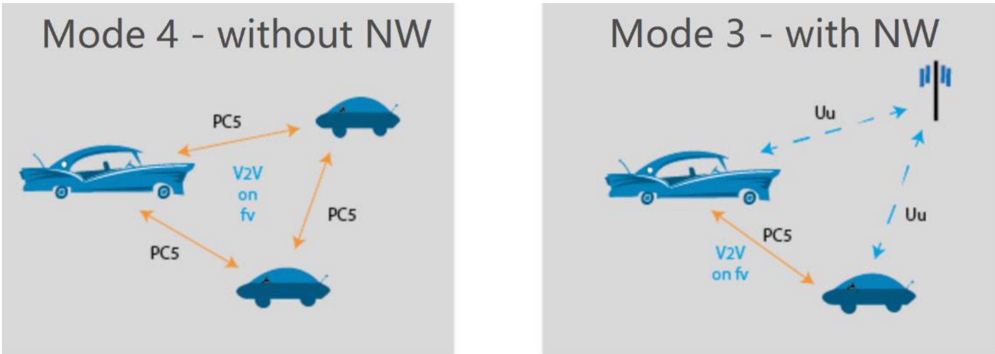

Figure 7. C-V2X deployment modes (Mode 4 – left picture; Mode 3 – right picture)

In “Mode 4”, scheduling and interference management are supported based on distributed algorithms implemented between the vehicles. As specified earlier the distributed algorithm is based on sensing with semi-persistent transmission.

In “Mode 3”, scheduling and interference management are managed by the eNBs via control signaling over the Uu interface. The eNodeB will assign the resources for V2V signaling dynamically [24].

According to the requirements, ProSe communication has to work in regions, where network coverage is missing. Therefore, ProSe communication is specified for the following scenarios (see Figure 10):

- In the “in coverage” case, the network controls the resources used for ProSe so interferences with the cellular traffic are avoided and in addition the ProSe communication may be optimized;
- For the “out-of-coverage” case such a control is not possible. The UE uses resources which are preconfigured, either in the mobile device or in the USIM of the UICC card;
- A special case is given in the “partial coverage” case. Coordination between the network and the preconfigured values is necessary in order to enable communication and to limit the interferences to other UEs at the cell boundary.

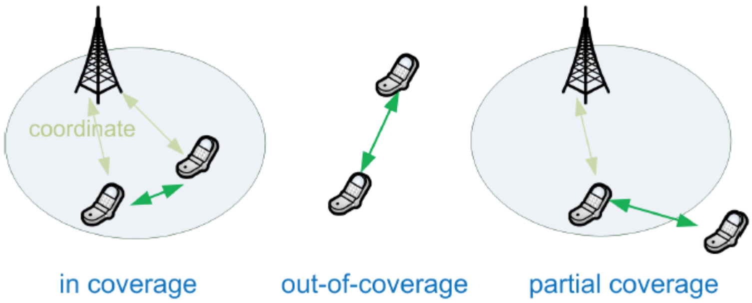

Figure 8. Coverage scenarios

The PC5 air interface, in ProSe communication system, is connectionless. There is no equivalent to the RRC connection procedures from legacy LTE system. Messages are created on the application level of the UE and transmitted with the first opportunity. If a connection is required, it has to be done within the application. For transmission and reception of the associated data packets, the following protocol stack is used (see Figure 9).

LTE-Uu interface can be unicast, multicast or broadcast transmitted via MBMS (Multimedia Broadcast/Multicast Services) [14].

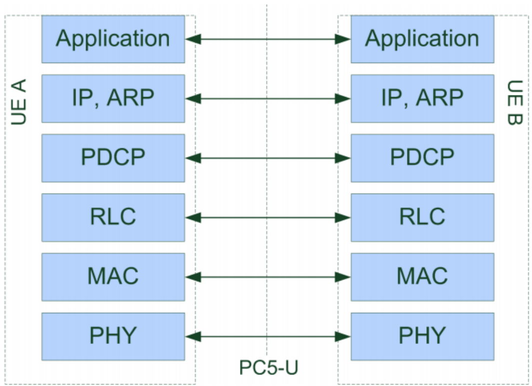

Figure 9. PC5 air interface protocol stack

3GPP Release 14 including C-V2X is a key step to the next generation of cellular technology, namely 5G. Naturally C-V2X is already on a backwards compatible evolution path with enhancements being specified beginning with 3GPP Release 15.

3. Harmonization of spectrum usage

3.1. Technology-neutrality of the regulatory bodie

Considering that FHWA (Federal Highway Administration) in US and European Committee had preferred 802.11p V2X as main technology for enabling C-ITS, the 5GAA association and GSMA asked both regulatory bodies to keep and respect technology neutrality. Regulators shall facilitate interoperability regulations between technologies while the market should decide which one is more suited and optimal for a strong foundation in order to remain sustainable for years to come.

Created in September 2016, 5G Automotive Association (5GAA), a relatively new cross industry association, is committed to support further enhancements of this future proof technology, to make sure that the full potential of the C-V2X technology is reached. This includes leading efforts to address key technical and regulatory issues, as well as integrating vehicle platforms with advanced cellular connectivity, networking and computing solutions [25].

The technology neutral nature of spectrum regulations in Europe means that both LTE-V2X and 802.11p have equal rights to operate in the 5.9 GHz band, subject to compliance with the relevant regulatory technical conditions. 5GAA is a supporter of LTE-V2X as a platform to evolve towards 5G technologies.

3.2. Spectrum harmonization efforts in Europe

C-V2X and 802.11p use different physical layers and medium access control protocols. Therefore, the operation of the two technologies in the 5.9 GHz band and in the same geographic area without an agreed coexistence solution would result in mutually harmful co-channel interference. These interferences can be avoided in the short term by allocating so-called "safe harbor" channels to C-V2X and 802.11p in the 5875-5905 MHz band (see Figure 10). This will encourage stakeholders to further enhance this proposal and come to speedy agreements on this topic for the benefit of the European ITS ecosystem as a whole.

The below regulatory measures all refer to the ETSI Harmonized Standard EN 302 571 [26] which defines requirements for operation of ITS equipment in 5855-5925 MHz, covering the essential requirements of article 3.2 of the Radio Equipment Directive (2014/53/EU). According to ECC (European Communication Committee), ITS equipment complying with EN 302 571 are exempt from individual licensing for operating in this band.

The band 5855-5925 MHz is subject to the following harmonization measures in Europe:

- The European Commission has harmonized the band 5875-5905 MHz for safety-related applications of Intelligent Transport Systems in the European Union via the legally binding Commission Decision 2008/671/EC [3].
- The same harmonization is applied by the ECC via ECC Decision (08)01 [27], which additionally indicates that CEPT administrations shall consider within a future review of this Decision the designation of the frequency sub-band 5905-5925 MHz for an extension of ITS spectrum.
- ECC also recommends, via ECC Recommendation (08)01 [28], that CEPT administrations should make the frequency band 5855-5875 MHz available for ITS non-safety applications.

The proposed spectrum partitioning shall happen in three steps. Finally, partitioning might be complemented by additional technical mechanisms which would allow each of C-V2X and 802.11p to access the remaining 20 MHz in a fair manner, to reduce the risk of harmful co-channel interference.

Harmonization of safety-related applications is shown in Figure 10 below, where the two technologies are referred to as Technology A and Technology B, where the equipment is tuned to operate at 5875-5885 and 5895-5905 MHz, respectively avoiding co-channel interference between the two V2X technologies.

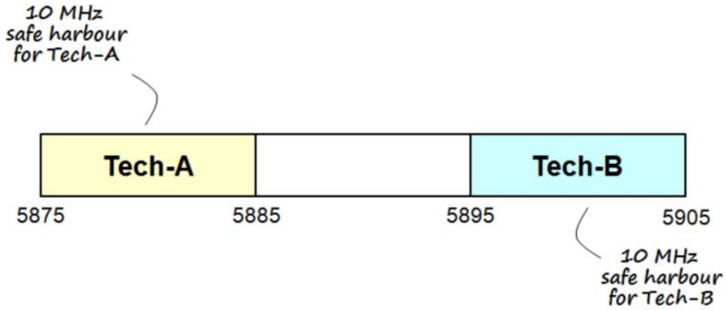

Figure 10. Step1: Partitioning of 5.9 GHz

Figure 11 illustrates Step 2, with a detect-and-vacate solution for C-V2X and 802.11p coexistence. Technology A equipment should operate without any special measures in 5875-5885 MHz. If Technology A equipment needs to transmit in 5885-5895 MHz, then it would need to monitor activity on the relevant channel, and proceed with transmissions if and only if Technology B transmissions are not detected in that channel. A symmetrical procedure would apply to Technology B.

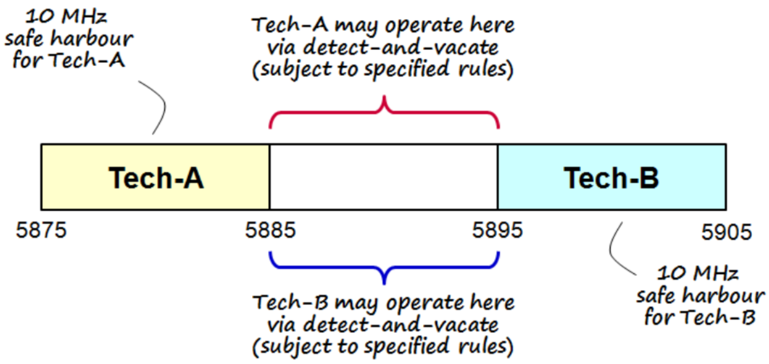

Figure 11. Step2: Partitioning of 5.9GHz with mutual "detect and vacate" techniques for middle 10MHz

Figure 12 illustrates Step 3, with an extended detect-and-vacate solution for C-V2X and 802.11p coexistence. Technology A equipment should operate without any special measures in 5875-5885 MHz. If Technology A equipment needs to transmit in 5885-5905 MHz, then it would need to monitor activity on the relevant channel, and proceed with transmissions if and only if Technology B transmissions are not detected in this channel. A symmetrical procedure would apply to Technology B.

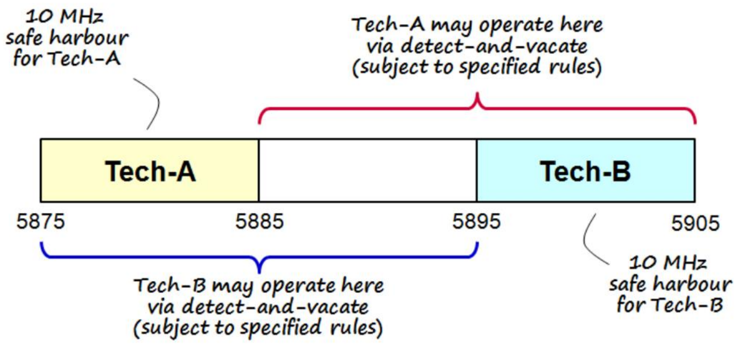

Figure 12. Step3: Partitioning of 5.9GHz with enhanced mutual "detect and vacate" techniques for middle 10MHz

ITS industry to will further develop, and cope with this agreement on the spectrum partitioning, with a view to expedite the successful deployment of C-V2X and 802.11p in the 5.9 GHz band [29].

4. Road to Cellular V2X

C-V2X started to gain momentum once release of 3GPP Rel.14 was published. Following this, studies about the readiness of 802.11p technologies were published and pushed to regulators. These studies were highlighting how C-V2X is only in the early stages of development and it will take many years, by 2020-2021, until readiness for commercial deployment.

In 2016, a European strategy on C-ITS was published, setting out priorities for the deployment of C-ITS, with a goal of deployment by 2019. At that time, the technology being specified was based on the IEEE 802.11p standard, although using C-V2X for V2I, rather than deploying dedicated roadside infrastructure, was recognized as a means of accelerating infrastructure penetration across all roads from the very first launch of C-ITS services. Since then, the mobile industry has developed C-V2X specifications within Release 14 of the 3GPP specifications for LTE/4G, in the expectation that 5G-based C-V2X will be analyzed in 3GPP specifications from Release 16 onwards. Initial 5G deployment, providing enhanced mobile broadband services, will be specified starting from Release 15 [18].

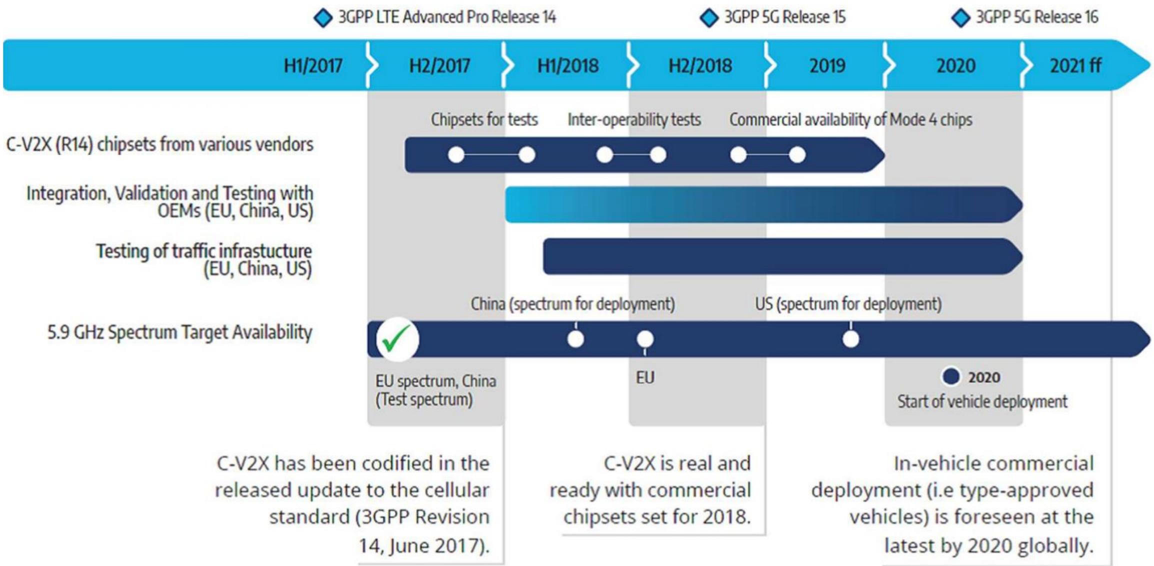

Figure 13. Scenario for C-V2X deployment [18]

The 4 major chipset vendors Intel, Qualcomm, Huawei and Samsung which are members of 5GAA provide almost all of the chipsets used in connected cars today. These vendors are committed to provide C-V2X chipsets and stopped supporting 802.11p standard. The availability of these chipsets will coincide with planned validation and testing of the communication modules by vehicle manufacturers including supportive vendors Audi, Continental, Ford, Nissan, PSA, SAIC and Bosch.

This testing and validation aims to confirm the C-V2X functional capabilities, and V2V communications in particular. These chipset vendors look to build on the successfully tested pre-standard versions from 2015 and 2016, which showed a superior technical advantage in all safety relevant parameters such as vehicle speed, braking distance, scalability and reliability, compared to similar tests performed over IEEE 802.11p based protocols. These validation tests are an essential prerequisite to ensure a successful launch in the second half of 2018 of the first commercial chipsets from Qualcomm [30].

An additional safety benefit of C-V2X is the support for Vulnerable Road User (VRU) collision avoidance, with the integration of V2N and V2P (vehicle to pedestrian) functionality. It ensures that a VRU becomes visible to vehicles via V2N utilizing smart phone applications. It will not require the integration of smartphones with C-V2X functionality in the first step of deployment. this feature will be implemented as a second step, for direct V2P communication between vehicles and VRUs. These enhancements will not possible in other V2V and V2I technologies such as DSRC or ITS-G5.

C-V2X also allows for further enhancements by future architecture and design decisions including network slicing, quality of service, edge computing and innovation, leveraging the C-V2X foundation. Rohde & Schwarz, a leading supplier of test and measurement equipment, is enabling vehicles to move to the next level of autonomy by providing initial signaling testing support for cellular vehicle-to-everything (C-V2X). Rohde & Schwarz and Qualcomm have collaborated by testing a pre-commercial Qualcomm 9150 C-V2X chipset, supporting 3GPP Release 14 specifications for PC5 based direct communications with the R&S CMW500 wideband radio communication tester. The 9150 C-V2X chipset is a product of Qualcomm Technologies and operates in bands 46D and 47 for 5.8/5.9GHz ITS spectrum [31].

Both technologies, C-V2X and IEEE 802.11p, have the potential to increase the safety and efficiency in transport. However, with the currently defined C-V2X technology communication, combined with LTE cellular networks for V2N, has the potential to bring additional benefits, including:

- better coverage for V2N, by exploiting existing cellular network coverage

- reduced infrastructure deployment costs and improved service reliability, by using existing mobile infrastructure
- other telematics services in vehicles (e.g. infotainment) to be provided via cellular interface
- increased deployment flexibility, with coverage for both short-range and wide-area applications
- integration with smart-city and other connected-transportation initiatives using cellular
- enhanced security, by usage of mobile subscriber identity module (SIM) cards
- future proof evolution to 5G, facilitating earlier deployment and after-market deployment.

5. Conclusions

By leveraging existing cellular infrastructure and continued industry investment, deployment of C-V2X technology can be achieved at a much lower cost compared to other competing V2X technologies. Consequently, C-V2X technology can save taxpayer money that otherwise would be used for new deployment, maintenance, and upgrade of roadside units utilized by non-cellular technologies.

C-V2X benefits from a higher spectrum efficiency and supports higher ranges compared to non-cellular technologies. Additionally, with support from the existing cellular ecosystem, C-V2X is integrated into the latest cellular standards with a clear upgrade path for future enhanced safety features and migration towards 5G (see Figure 14).

On the other side, the IEEE 802.11p is a ready to deploy technology that could save lives and make the traffic more efficient from today if mass deployed [32]. It has the advantage of many years of research, development and testing [33].

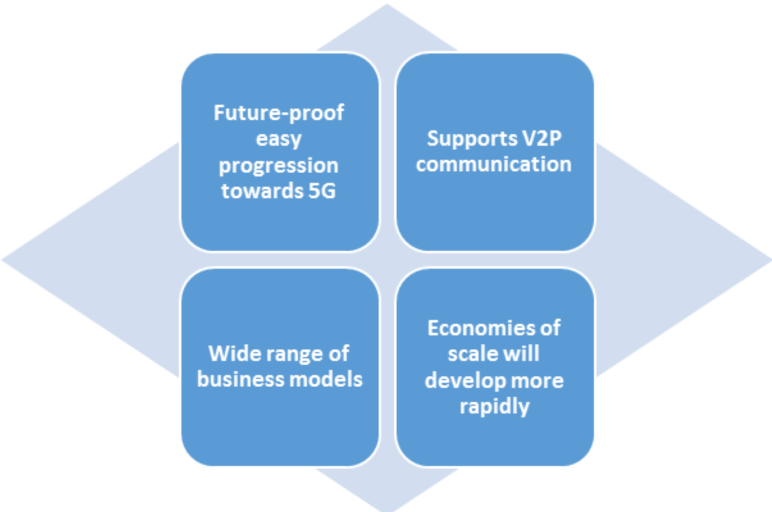

Figure 14. Qualitative benefits of C-V2X and 5G over 802.11p

The path to fully automated vehicles will require coexistence for a period of time between vehicles with no active control systems, different levels of automated vehicles and fully automated vehicles. C-V2X technology will help to enable this coexistence by ensuring that fully automated vehicles and drivers of other levels of automated vehicles can maintain complete awareness surrounding vehicles and other road hazards. C-V2X technology is well positioned to implement the full slate of V2X benefits highlighted in this paper.

Qualcomm was initially a big enabler of DSRC and offered also second-generation 802.11p DSRC chips. Currently their focus switched to cellular V2X, announcing the interruption of 802.11p enabled chipsets.

As until now, the trend is to adopt both 802.11p and C-V2X technologies and let the market decide which one is more suited for commercial deployment and future development and evolution towards 5G.

A "Analysis Mason" study from December 2017 [18] indicates that C-V2X (PC5) outperforms 802.11p by reducing serious injuries and fatalities on the EU roads. This is due to a combination of the superior performance of C-V2X at the radio link level for ad-hoc direct communications between road users, together with the market conditions which better places the deployment of C-V2X in commercial vehicles and smartphones. For these reasons, it is essential that EU regulations remain neutral and do not obstruct the deployment of C-V2X in favor of 802.11p for the provision of direct vehicle communications and between vehicles and VRUs (vulnerable road users).

The absence of interoperability measures at radio link level between C-V2X and 802.11p is unlikely to present a serious barrier to the reduction of accidents on the EU roads in the short to medium term. The low penetration of C-ITS technologies in vehicles in the second half of this decade means that a vehicle equipped with C-V2X or 802.11p is far more likely to interact on the roads with a vehicle that is not equipped with any C-ITS technologies at all. Only starting from the middle of the next decade, when penetration rates are expected to reach a significant level which results in visible impacts on lowering the accident rates. Any regulations from rule-making-bodies which mandate that C-V2X to be backward compatible with 802.11p standards, will only have a limited effect in the early stages of deployment pre-2025. Nevertheless, such regulations will run the risk of unnecessarily obstructing full potential of C-V2X development in favor of 802.11p, thereby obstructing the smooth and rapid adoption of C-V2X and resulting in a higher rate of road injuries and fatalities on the longer term.

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