applied sciences

MDPI

Review

Review of V2X–IoT Standards and Frameworks for ITS Applications

Karolis Kiela [1,*], Vaidotas Barzdenas [2], Marijan Jurgo [1], Vytautas Macaitis [1], Justas Rafanavicius [2], Aleksandr Vasjanov [2], Leonid Kladovscikov [2] and Romualdas Navickas [1]

1 Micro and Nanoelectronics Systems Design and Research Laboratory, Vilnius Gediminas Technical University, 10257 Vilnius, Lithuania; marijan.jurgo@vgtu.lt (M.J.); vytautas.macaitis@vgtu.lt (V.M.); romualdas.navickas@vgtu.lt (R.N.)

2 Department of Computer Science and Communications Technologies, Vilnius Gediminas Technical University, Naugarduko str. 41, 03227 Vilnius, Lithuania; vaidotas.barzdenas@vgtu.lt (V.B.); justas.rafanavicius@stud.vgtu.lt (J.R.); aleksandr.vasjanov@vgtu.lt (A.V.); leonid.kladovscikov@vgtu.lt (L.K.)

* Correspondence: karolis.kiela@vgtu.lt; Tel.: +370-610-10191

Received: 11 May 2020; Accepted: 17 June 2020; Published: 23 June 2020

Abstract: The intelligent transport system (ITS) has become one of the most globally researched topics with a lot of investment and development resources being dedicated into it due to its foreseen impact on the economic growth of the transport sector. Currently there are two main vehicle-to-everything (V2X) technologies, whose primary application is focused on ITS, backed up by the key players of various automotive, telecommunication and transport industries: dedicated short-range communications (DSRC) and cellular vehicle-to-everything (C-V2X), respectively based on IEEE 802.11p and 3GPP LTE/5G NR. While DSRC already has deployments, C-V2X is expected to see larger scale trails and deployments in 2020. In this work, the authors provide insight and review into two main V2X technologies, DSRC and C-V2X, their core parameters, shortcomings and limitations, and explore the need for integration of IoT-based technologies into modern ITS solutions. A comprehensive overview and analysis of currently commercially available V2X products, their sub-blocks and features is provided.

Keywords: V2X; DSRC; C-V2X; 5G NR; ITS; IoT

1. Introduction

The transport sector is one of the most important economic sectors and sources of income, both in Europe and globally. The European Union (EU) transport sector alone (services, manufacturing, maintenance, construction, etc.) generates more than 9% of EU gross value added (GVA), with transport services alone representing 5% which is equal to EUR 662 billion. More than 20 million people work in this sector, making up more than 9% of the EU workforce [1]. However, a rapid development of this sector faces significant challenges and problems: ways of reducing the number of crashes of road and air transport, greenhouse effect caused by gas emissions, the dependency from fossil fuel, ways of maximizing and effectively exploiting vehicles as well as increasing the skills of the drivers, and many other important and relevant issues.

One way to address the latter problems of the transport sector is to create and introduce an intelligent transport system (ITS). It is hard to clearly define what ITS is, however, these systems are often understood as the use of information and communication technologies in transport to solve various problems in the transport sector. For these reasons, the term ITS may cover a very wide range of transport sectors. As a term, it has been approved and has been officially used in the USA and Japan since 1991, and in Europe, since the year 1994 in the First ITS World Congress held in Paris, France [2].

By far one of the most essential problems from those listed above, which is present in all countries worldwide, is the aim to reduce the number of fatalities and casualties in road accidents. For example, only during 2018, 25,100 people died on the EU's roads, which is 200 less than in 2017 (−1%) and 6400 less than in 2010 (−21%) [3]. While this trend is encouraging, it may be too small to achieve the EU goal of halving the number of road deaths by the period of 2010–2020, and having zero road deaths by 2050 ("Vision Zero") [4,5]. In addition, it is estimated that there were over 135,000 seriously injured people, among whom, a large proportion was of vulnerable road participants in 2018: pedestrians, cyclists and motorcyclists [3]. Deaths and road injuries affect not only the victims but also society as a whole and its economic development. It is estimated that the EU socio-economic costs, which are devoted to the rehabilitation and healthcare of injured persons, compensation for victims and other areas, reach EUR 120 billion per year [6]. Additionally, there are other occurrences of losses due to time spent in traffic jams, the amount of fuel consumed and increased air pollution. For example, traffic jam-related problem costs in Europe are estimated to amount to more than EUR 130 billion every year [7]. Trends and statistics show that the number of vehicles in Europe is annually growing (the increase in passenger vehicles: 1–2%, goods transportation vehicles: 4–7%). The potential for urban infrastructure development is limited and, as the number of vehicles grows, the problem of traffic jams in cities will become more and more relevant. For the latter reasons, these challenges will only continue to increase unless drastic new political and technological measures are taken.

In order to address the above-mentioned problems, both automotive and communications companies, as well as science and government institutions worldwide, are working to develop a variety of vehicle communication networks. There can be different vehicle communication Network types depending on the participants that exchange data. Networks, consisting of mobile nodes which are strictly moving vehicles communicating directly with each other, are called vehicle-to-vehicle (V2V). Vehicle-to-infrastructure (V2I) or pedestrians (V2P) networks are formed when moving vehicles communicate with either roadside infrastructure or pedestrians. If the vehicle communicates with IT networks and/or data centers, the network type becomes vehicle-to-network (V2N). A common term that combines all these types of communication, providing vehicle links with various recipients, is called vehicle-to-everything (V2X).

The already mentioned "Road Safety Program 2011–2020" [5] states, that one of the seven strategic goals is to boost smart technology in order to enable data and information exchange between vehicles, pedestrians and inter-roadside infrastructure (for example, to receive real-time information on speed limits, traffic flows, traffic jams, pedestrians on road, etc.). As a result, the EU encourages both research institutions and business companies to develop new ITSs, to carry out their deployment, research and further development by allocating investments from different funds.

The use of V2X communications, along with the existing possibilities of modern vehicles, could not only solve the abovementioned issues but would also offer better quality public transport services, better road quality, more efficient logistics solutions, efficient use of transport infrastructure, especially accurate electronic maps, various vehicle manufacturers and vehicles services, and many other, relevant and innovative solutions and services. Some examples of such future services are provided by CAR2CAR Communication Consortium (a consortium of major car manufacturers), in their published manifesto: various safety warnings, improved and complete route guidance and navigation, green light optimal speed recommendation, V2V merging assistance, Internet access in vehicles, informing the driver of relevant and important issues, remote diagnostics of vehicles and many others [8].

There are currently two data transfer technologies that can be used in V2X systems: dedicated short-range communications (DSRC) technology and cellular vehicle-to-everything (C-V2X) communication technologies. The DSRC technologies are used for data transfer between vehicles, inter-roadside infrastructure and pedestrians when its distance is limited to a few hundred meters. Data exchange is carried out between devices installed in DSRC communication system vehicles, called on board units (OBU), and roadside equipped devices, called road side units (RSU), as well as pedestrians' portable mobile devices. Many world governments are currently supporting and investing in the deployment and research of DSRC's communication technologies. For example, in 2016 the US Department of Transportation (DOT) announced that it will invest USD 45 million into three DSRC technology pilot projects, in accordance with the Connected Vehicle Pilot Deployment Program. The aim of the program is to promote V2X innovation by combining research and practical engineering solutions. For example, New York City's Department of Transportation has planned to introduce V2V technological solutions to 8000 city-owned vehicles and V2I technological solutions in several streets of Manhattan and Brooklyn as a part of this pilot project [9].

Another example, this time in Europe, in September 2014 the Collective Transport Society of Porto (Portugal) and the municipality of Porto started offering free Wi-Fi service to their passengers in the city. Over 600 vehicles, including entire public bus fleet, taxis and municipal service vehicles have been equipped with OBUs and routers that transmit and receive Internet data via one of two possible data paths [10]. Priority is given to DSRC communication technology, which has 55 access points/RSUs (April 2016 data) in different parts of the city that connect directly or via multiple buses OBUs. If data transfer via DSRC is not available, the data are transferred over via cellular Long Term Evolution (LTE) networks.

However, a lot of published research data have shown that DSRC technologies face reliability, efficiency, and productivity problems with high traffic volumes. Furthermore, DSRC communication technologies are not designed to transfer large amounts of data and access the Internet in vehicles. In addition, taking into account that in 2022, 82% of the total bandwidth will be used for video sharing data, this problem will be even more acute and sensitive [11]. Due to the limitations of the latest DSRC technologies, great attention is paid to cellular V2X communication technologies. The C-V2X connection allows for increased coverage of streams of data transmitted, however, each cellular station broadcasts information to all devices within its coverage, and those devices communicate with the station using unicast. A growing number of vehicles is increasing the number of unicast streams, thereby straining network resources, which, in turn, results in greater messaging latency. In the case of traffic safety, data transmission latency is one of the key, critical and minimizable parameters. Being aware that the number of mobile users and data transfer amounts since 2017 have been increasing and will still be increasing until 2022 several times [11], it remains unclear whether the current mobile, cellular network infrastructure will be capable of transmitting data via C-V2X communication technology within the permissible latency. For the latter reasons, it is necessary to look for DSRC and C-V2X architectural solutions that support reliable and efficient V2X connections. In order to carry out research on DSRC and C-V2X communication technologies, it is necessary to develop integrated circuits [12–21] and, on their basis, development platforms supporting all possible V2X communication technologies.

This article consists of four chapters. In the first chapter, the main standards of DSRC and C-V2X technology are reviewed, including their regulated spectrum bands and the intended use. Essential shortcomings and limitations of DSRC and C-V2X technologies by revealing the need for the conjuncture of these technologies and the creation of hybrid architectures are also presented in this chapter. Subsequently, the second chapter provides a comprehensive review of commercially available systems, R&D platforms, and transceivers, that can be used for V2X system development, deployment and testing. An analysis of commercial products features and functions is carried out, which needs to be taken into account when a versatile V2X–IoT framework for ITS applications is being developed. The final chapter concludes the presentation of the essential V2X and IoT progress that has been spotted over the recent years and summarizes suggestions for further research and technology development.

2. Core ITS Standards

As was mentioned before, ITS not only includes vehicles and their drivers, but also passengers, pedestrians, traffic management specialists, roadside infrastructure, etc. All of these ITS components must be interlinked in order to exchange information and/or retrieve data from the surrounding environment. However, such an ITS system can successfully exchange data only if it is developed in accordance with international standards. At first glance, it may appear simple to identify the standards that describe ITS systems as the International Organization for Standardization (ISO) has a special ITS Committee (ISO/TC 204) [22]. However, the situation is much more complicated because both regional standards, such as the European Telecommunications Standards Institute (ETSI) and the European Committee for Standardization (CEN) standards, as well as national standards, such as those of the Association of Radio Industries and Businesses (ARIB) in Japan, and international ones, must be taken into account. Standards, either national, regional or international, have to operate within a framework of regulations. These are mainly national regulations, managed by such commissions as the United States Federal Communications Commission (FCC), or the Australian Communications and Media Authority (ACMA). The regulations are also complied within the European Union countries, but in order to develop a common market, the European Conference of Postal and Telecommunications Administrations (CEPT) have developed recommendations for the most commonly used ITS frequency bands among the European Union (EU) countries and other CEPT members. At the international level, similar recommendations are also made by the International Telecommunication Union (ITU) (through its ITU Telecommunication and ITU-Radio divisions), whose main objective is to promote global interoperability of standards.

The standards for DSRC, C-V2X technologies and their regulated frequency spectrum bands are discussed in this subsection.

2.1. Standards for Dedicated Short-Range Communications (DSRC) Technology

Dedicated Short-Range Communication (DSRC) technologies are designed for vehicles using short-range wireless radio, for data exchange between vehicles and roadside infrastructure. Both the DSRC term and abbreviation are associated with the 1998 US Federal Communications Commission (FCC) initiative to conclude a regulation for (5.850–5.925) GHz band allocation [23]. Later, with the rapid development of ITS, this term/abbreviation has been increasingly used ever more widely.

Figure 1 shows DSRC frequency bands for ITS in North America, Europe and Japan. Let us consider these spectrum bands and the standards that describe them in more detail.

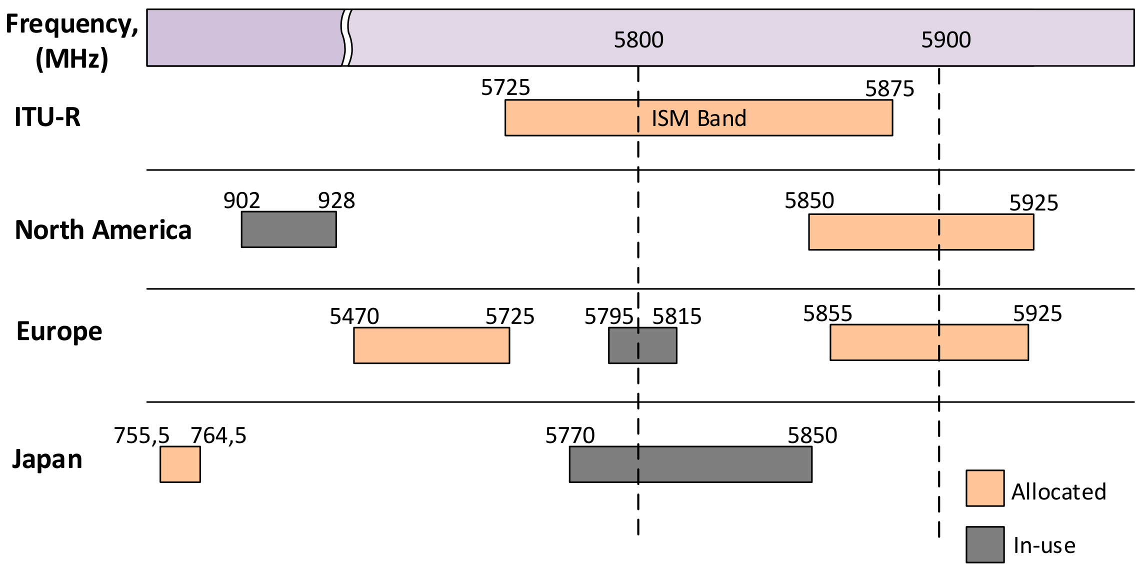

Figure 1. Frequency spectrum bands for Dedicated Short-Range Communications in North America, Europe and Japan.

The International Telecommunication Union (ITU) has developed a number of key recommendations for ITS systems: ITU-R M.1452 [24] and ITU-R M.1453 [25]. The ITU-R M.1452 recommendation specifies system requirements and operational characteristics for millimeter wave radiocommunication systems. The recommendation covers vehicular collision avoidance radars operating in the (76–77) GHz and (77–81) GHz bands and integrated millimeter wave radiocommunication systems for ITS in (57–66) GHz range for V2V and V2I. The ITU-R M.1452 recommendation frequency spectrum bands are not shown in Figure 1. Meanwhile, according to the ITU-R M.1453 recommendation, ITS distinguishes the (5.725–5.875) GHz band and describes two methods for DSRC technologies: active (transceiver) or backscatter (transponder).

Two sections of the DSRC frequency spectrum can be distinguished in North America: (902–928) MHz and (5.850–5.925) GHz. The last band, with a width of 75 MHz, was introduced in October 1999 by the US Federal Communications Commission (FCC). This frequency band was dedicated to a wide range of DSRC communications ITS applications: traffic light management, traffic monitoring, passenger alerting, automatic toll collection, traffic congestion detection and other areas [26]. In 2010, IEEE (Institute of Electrical and Electronics Engineers) completed the development of an improved edition of the IEEE 802.11 protocol, called IEEE 802.11p [27]. The main purpose of this standard was to describe the physical (PHY) and Medium Access Control (MAC) layers for interchanging wireless broadcast messages in a vehicular environment. The IEEE 802.11p standard is based on the IEEE 1609 family of standards for wireless access in vehicular environments, also known as WAVE [28]. As mentioned earlier, this standard allocates the 75 MHz bandwidth at the (5.850–5.925) GHz frequency band, divided into seven channels of 10 MHz, one for the control channel, and the other six reserved for service channels. Meanwhile, the (5.850–5.855) GHz band is reserved for the future uses.

American Society for Testing and Material (ASTM) regulates the physical (PHY) layer description and developed the ASTM E2158-01 standard specification for the North American 902 MHz to 928 MHz frequency band [29]. This band is used for electronic toll collection, commercial and non-commercial vehicle applications. The ASTM E2158-01 standard is not compatible with the above-mentioned IEEE 802.11p DSRC standard.

Three frequency spectrum bands for ITS could be distinguished in Europe: (5.470–5.725) GHz, (5.795–5.815) GHz and (5.855–5.925) GHz. The physical (PHY) and medium access control (MAC) layers of the first and third frequency bands mentioned above are regulated by European Telecommunications Standards Institute (ETSI) standard ETSI ES 202 663 [30]. These frequency bands are further subdivided into sub-categories/classes: the (5.470–5.725) GHz band is classified as ITS-G5C and is intended for the radio local area networks (RLAN, BRAN, WLAN); the (5.855–5.875) GHz band belongs to ITS-G5B and dedicated to ITS non-safety applications; the (5.875–5.905) GHz band is ITS-G5A and dedicated to ITS for safety-related applications; the (5.905–5.925) GHz band is classified as ITS-G5D and reserved for future ITS standard expansion. Similar to the IEEE 802.11p standard, the (5.855–5.925) GHz band is divided into 7 fixed 10 MHz channels, with one dedicated for the control channel and the other six reserved for service channels [31]. Meanwhile, the entire 255 MHz band of the sub-category ITS-G5C is shared with the radio local area network (RLAN) band, used by Wi-Fi devices, and can have 10 MHz or 20 MHz channel spacing.

The physical layer of the (5.795–5.815) GHz band is described by the European Committee for Standardization (CEN) standard CEN EN12253 [32]. This standard specifies the physical parameters for both OBU and RSU, and distinguishes two types of communications: downlink (from RSU to OBU) and uplink (from OBU to RSU). According to this standard, this frequency band is divided into four channels, each having a width of 5 MHz, where the downlink carrier is allocated: 5.7975 GHz, 5.8025 GHz, 5.8075 GHz and 5.8125 GHz. Meanwhile, two possible sub-carrier frequencies can be used in the uplink: an offset of either 1.5 MHz or 2 MHz from the carrier frequency. According to the standard specifications, this frequency band is intended for road transport and traffic telematics systems.

Two frequency bands are distinguished for ITS in Japan: (5.770–5.850) GHz and (755.5–764.5) MHz regulated by the standards of the Association of Radio Industries and Businesses (ARIB). The physical, data and application layers of the first frequency band are described by ARIB STD-T55 [33] and ARIB STD-T75 [34]. This (5.770–5.850) GHz band is divided into 14 channels of 5 MHz, 7 of which are downlink and the remaining 7 are uplink. These standards specify the radio communication interface for the electronic toll collection, passenger information collection, event and disaster information, and various entertainment events. Meanwhile, the use of the 700 MHz radio frequency band is regulated by the ARIB STD-T109 [35] standard and is intended to provide a link between the roadside-to-vehicle communications and the inter-roadside communications. The main purpose of the systems described in this standard is to:

- Reduce the number of accidents on the road;
- Regulate the flow of vehicles;
- Ensure the transmission of information for safe driving and to provide a variety of services.

The ARIB STDT109 standard specifies the (755.5–764.5) MHz band with a center frequency of 760 MHz and a channel width of up to 9 MHz.

DSRC standards shall optimize the resource use of the control plane and/or user plane for transfer of continuous uplink data that requires both a high data rate (e.g., 10 Mbps) and a very low end-to-end latency in the range of 1–10 ms. An earlier paper reports practical latency research results obtained during a moving field test, taking into account the vehicle speed and packet loss percentage [36]. The measured vehicle-to-roadside latency under various conditions averages to 4.3 ms with a maximum value of around 5 ms, which is within the officially approved DSRC standard specifications.

DSRC is a wireless communication method with a limited range in order of tens of meters. In order to establish an active sideling to any roadside device, the speed of the automobile has to be relatively low, so as to allow enough time for switching. One of the proposed solutions is to use extended range DSRC repeater, but this poses another problem [37]. With an increased number of intermediary nodes, transmission delay times are also increased, which limits the use of safety messages.

Other downside of DSRC is the distribution of data packets during intensive traffic [37,38]. During these conditions network equipment capacity is maxed out due to increased numbers of connected devices using same radio channels. As a consequence, signal interference and transmission delay is increased, while data transmission rate is decreased. During intense traffic conditions and while using high data rate transmission between devices, device authentication may not be handled properly or not be handled at all. This in turn makes the network vulnerable. This is crucial, as it provides the means to misinform road users using false safety messages (messages about accidents, traffic conditions and traffic management). This in turn may be the reason for new traffic accidents. An upgrade to IEEE 802.11ax-based transceivers for DSRC V2X systems could increase the load handling capability, thus mitigating previously mentioned issues related to overcrowding.

2.2. Standards for 4G- and 5G-Based Cellular (C-V2X) Technology

C-V2X stands for cellular communication for data transmission between vehicles and its environment (V2X). C-V2X technology is regulated by the 3GPP (3rd Generation Partnership Project) international organization, taking into account the growing needs of the automotive industry and the development of the V2X services. Furthermore, automotive, telecommunication, other mobility and transport technology industry-leading companies have created the 5G Automotive Association (5GAA) with the goal to expedite the development and real-world implementation of the C-V2X.

The LTE Advanced Pro V2X services, architectures, radio access network regulations and four use case scenarios (V2V, V2I, V2N, V2P) have been defined in detail in the 3GPP (3rd Generation Partnership Project) Service aspects (“stage 1”) and LTE (Evolved UTRA), LTE-Advanced, LTE-Advanced Pro radio technology series technical specifications and technical reports starting with Release 14. C-V2X communication is based either on a single band using PC5 or inter-band concurrent communication using both PC5 and Uu interfaces. The LTE Uu interface is used for connection to the cellular station, while PC5 interface is used for direct communication between V2X nodes. [38,39]. The initial C-V2X release only supported half duplex PC5 interface on band 47, which coincides with the North America DSRC (5.850–5.925) GHz frequency range, but later specification extensions added support for the Uu interface. For 3GPP Release 15, TS 36.101 specification distinguishes 10 frequency bands for

Uu interface while keeping a single PC5 interface on band 47 [40]. While Uu communication does not support carrier aggregation and is limited to a bandwidth of 20 MHz (10 MHz being used in most cases), PC5 interface can use up to three intra-band carriers with bandwidth options of 10 and 20 MHz, with total bandwidth not exceeding 30 MHz. Frequency bands for the LTE-based C-V2X communication are provided in Table 1.

Table 1. LTE-based C-V2X operating bands.

C-V2X Operating Band	Uplink, MHz	Downlink, MHz	Interface	Maximum Bandwidth, MHz
47	5855–5925		PC5	30 [1]
3	1710–1785	1805–1880	Uu	20
5	824–849	869–894	Uu	20
7	2500–2570	2620–2690	Uu	20
8	880–915	925–960	Uu	10
20	832–862	791–821	Uu	20
28	703–748	758–803	Uu	20
34	2010–2025		Uu	15
39	1880–1920		Uu	20
41	2496–2690		Uu	20
71	663–689	617–652	Uu	20

[1] Using carrier aggregation format 10 + 20 MHz or 10 + 10 + 10 MHz.

3GPP Release 15, TS 36.101 specification chapter 14 describes the main user equipment (UE) parameters; it does not include latency parameters [40]. LTE-based C-V2X service latency requirements are defined by the TS 22.185 specification [41], while insight into specific use cases is provided in TR 22.885 [42]. Crash avoidance-oriented V2V services have the most strict latency requirement—no more than 20 ms. For non-critical V2V services, also for V2P, V2I uses case scenarios where the latency cannot exceed 100 ms and for V2N—no more than 1000 ms.

The 3GPP International Release 16 Specification Set expanded on the C-V2X operating scenarios for the 5G new radio (NR), which include standalone (SA) and non-standalone (NSA) deployments. TS 38.101.1 defines two frequency ranges, FR1 and FR2, where 5G NR-based radio communication could be established [43]. The corresponding frequency ranges are 410 MHz–7125 MHz and 24.25 GHz–52.6 GHz for FR1 and FR2, respectively.

Radio coverage for the Uu sidelink during the initial rollouts of the 5G NR networks will be not as extensive as LTE, hence, C-V2X control should be handled by both with seamless handovers. The PC5 interface is based on both 5G NR and LTE. TR 38.885 provides insight on different operating scenarios, where sidelink communication can be done in both FR1 and FR2 if a common design framework is used [44].

According to TR 38.886, the 5G NR C-V2X operating band n47 should use up to 40 MHz channel bandwidth—a two-fold increase from LTE-based C-V2X [45]. Uu sidelinks remain in the same licensed bands. 5G NR-based C-V2X service latency requirements are in TR 22.886 [46]. The most strict latency requirement is for fully automated driving—no more than 3 ms, with data rates peaking at 1000 Mbps, although most of the communication scenarios maximum end-to-end latencies are given around 20 ms—100 ms (can be as high as 500 ms for non-critical services) and data rates not exceeding 100 Mbps.

Although C-V2X has many advantages that stem from reusing an already developed network infrastructure, its downsides must also be considered. A high number of intermediary nodes for Uu sidelinks means an increase in transmission delays. Message re-transmission is supported by 3GPP standards and intermediary nodes re-transmit messages to all devices in range. Retransmissions puts unnecessary network traffic load on networking equipment, while the retransmission decision process also puts additional load on the processing hardware. One of the proposed solutions is the use of group messages, which allows data transmission only to related devices that are in close proximity [47]. This in turn decreases the load on networking and processing hardware. It is important to state that group messages only solve the problem of data reception from road side units, but the problem of data transmission during overcrowded situations still remains. It is also important to note that C-V2X networks share the same resources as mobile users, which add additional network loading and delay control signals. With the arrival of 5G NR, C-V2X-based communication will have to handle handovers from LTE to 5G NR and vice versa, which adds complexity to system design.

2.3. Hybrid ITS Architecture

Hybrid ITS network architecture is a combination of DSRC and C-V2X networks. ITS network consists of static devices, such as base stations, road infrastructure and dynamic devices, such as automobiles and pedestrian equipment. Such network architectures can be classified as either hierarchical or flat.

Hierarchical hybrid ITS network architecture is based around the concept of assigning network devices to separate levels [48]. Utilization of said levels allows devices to be assigned to separate groups, restrict or grant access to certain features, and send or receive specific information. Usually, devices are classified into public transport and public services, personal transportation and other device groups. In such network architecture, C-V2X is used for communication between public transport and public services, and can also be used for access to the internet. Meanwhile, DSRC-based networks are used for communication between personal transportation and communication between personal and public transportation. A hierarchical hybrid ITS network architecture, where each device is assigned to a certain level which does not change, is called static.

Hierarchical network architectures may also be dynamic, which means that levels, which are assigned to devices, may be updated and reassigned in response to changing network conditions. Dynamic hierarchical network architecture consists of multiple device groups [49–53]. Typically, devices are assigned to groups based on their position on the road. It is important to note, that every group must have a main device. The main device usually is an intermediary node or a device which has high network and computational resources. The goal of the main device is to control the connections and regulate network load. Regular devices (those, which are not main devices) can be connected to more than one main device. This enables regular devices to retransmit data between adjacent device groups. In this case, the C-V2X network is used for communication between main device and base station; communication between main devices; communication between main device and regular devices in its group. The DSRC network is used for connection between regular devices in the same group. The main advantage of this architecture is that the main device can collect information from regular devices and periodically transmit it to the base station or other data-processing device, which reduces the network load. The main disadvantage of this architecture is that the grouping process is lengthy, which limits the deployment capabilities in densely populated areas, such as city centers.

Flat ITS network architecture does not limit the connection type for device interconnections. Connection type between devices is chosen according to the network load, quality and distance. For example, if devices use C-V2X as default, they could switch to DSRC if network conditions change. Both DSRC and C-V2X parameters are constantly updated and the best possible connection method is chosen based on a pre-determined algorithm.

A hybrid ITS network comparison is shown in Table 2.

Table 2. Hybrid ITS network comparison.

Source	Network Topology	Landscape	Use Case Scenario	Purpose
[48]	Hierarchical	Rural	V2X	Video messages
[49]	Hierarchical	City	V2I	Internet
[54]	Hierarchical	City	V2X	Safety messages
[55]	Flat	City	V2V	Travel planning
[56]	Flat	Rural	V2I	Internet

3. Commercial V2X Products

As was already mentioned in the previous chapter, both the automotive industry and the governments, as well as scientific institutions are making significant efforts to develop and promote architectural solutions for hybrid DSRC and C-V2X technologies that would sustain reliable and efficient V2X connections. The design and development of these technologies must not only offer new V2X communication schemes, assess their effectiveness and reliability in various mathematical analyses or computer simulations, but more importantly, demonstrate the real feasibility, i.e., how these theoretical algorithms operate in the real transport environment and whether they can be integrated with the current V2X systems installed by the large vehicle manufacturers. Therefore, this section will review the existing V2X R&D platforms and commercial products that could be used in developing versatile frameworks for ITS applications, research and for equipment deployed on modern vehicles or road infrastructure. In this section, we will also review and analyze on-market radio frequency chips, which could be used to develop new V2X systems that fit the DSRC and C-V2X communication technologies and covering all current standards.

3.1. Commercial V2X Devices

As V2X systems are only beginning to develop more intensely, there are not many commercial devices on the market yet. Tables 3–5 contain comparison of the currently available commercial V2X devices.

The data collected show that these devices are basically divided into three types, usually of different purpose: devices for communication with the road side unit (RSU), which are most often mounted on streets, traffic lights or other near the street infrastructure; the on-board unit (OBU); and small-scale mobile devices or smart device attachments whose primary purpose is to inform pedestrians, cyclists and motorcyclists of current and potential traffic accidents. However, the market is also trying to create universal devices, combining RSU and OBU into one system. An example of such a system could be the Commsignia V2X Evaluation Kit. Another important aspect can also be seen in this comparative analysis. In practice, almost all commercial V2X devices have communication modules only for DSRC communication technologies and consists of two main parts: (1) a radio frequency (RF) transceiver, mainly implementing the IEEE 802.11p standard with the PHY layer, and (2) a connection processor that implements the standard IEEE 802.11p/IEEE 1609.4 MAC layer and other features as well as launching the platform operating system, supporting security, various interfaces and network services in addition to allowing for the installation of user-generated V2X applications, etc. Some devices use a separate application processor to implement the latter functions. Meanwhile, data protection functions are implemented in two ways: using software or hardware-based security solutions. Furthermore, all platforms have GPS modules that are designed for localization, time and synchronization settings.

In addition to the hardware of the V2X devices, the software is just as important. Most of these devices are based on Linux operating systems with the SSH protocol for safe data exchange between the platform and the user. In addition, some manufacturers also provide a graphical user interface for the device and real-time monitoring. To facilitate the development of V2X consumer programs, some manufacturers devices also provide an application development kit (SDK) which, together with application programming interfaces (APIs), allows the user to programmatically implement various V2X devices functions.

Table 3. Commercial V2X devices currently on the market—Part I.

Basic Parameters / Commercial V2X Devices	[57] **Cohda Wireless MK5 OBU**	[58] **Cohda Wireless MK5 RSU**	[59] **LocoMate OBU**	[60] **LocoMate RSU**	[61] **LocoMate ME**	[62] **BlueTOAD Spectra**
RSU/OBU/Mobile	OBU	RSU	OBU	RSU	Mobile	RSU
Supported V2X technologies	DSRC	DSRC	DSRC	DSRC	DSRC	DSRC
RF transceiver chipset	u-blox THEO-P1	u-blox THEO-P1	Atheros AR5414	Atheros AR5414	Atheros AR5414	-
GNSS	Yes	Yes	Yes	Yes	Yes	-
Security	-	-	Software	Software	Software	Software, hardware
Baseband processor chipset	SAF5100	SAF5100	Atheros AR7100	Atheros AR7100	Atheros AR7100	NXP i.MX6
Operating system	Linux	Linux	Linux, SDK with C libraries	Linux, SDK with C libraries	Linux, SDK with C libraries, Android	-
External connectors	Ethernet, USB, CAN, Audio, microSD	Ethernet, USB, Serial Console	Ethernet, USB	Ethernet	-	Ethernet

Note: The "-" symbol in the cells indicates that data could not be found or are not in the system.

Table 4. Commercial V2X devices currently on the market—Part II.

Basic Parameters \ Commercial V2X Devices	[63] **Commsignia V2X Evaluation Kit**	[64] **Commsignia ITS-RS4D**	[65] **Commsignia ITS-OB4-D**	[66] **Unex OBU-201**	[67] **Unex RSU-101**	[68] **Unex OBU-310E**
RSU/OBU/Mobile	RSU/OBU	RSU	OBU	OBU	RSU	OBU
Supported V2X technologies	DSRC	DSRC, C-V2X	DSRC, C-V2X	DSRC	DSRC	DSRC
RF transceiver chipset	Autotalks ATK3100	Qualcomm 9150	Qualcomm 9150	Autotalks ATK3100	Autotalks ATK3100	Autotalks PLUTON2
GNSS	Yes	Yes	Yes	Yes	Yes	Yes
Security	Hardware	Software	Software	Hardware, Infineon SLE97	Hardware, Infineon SLE97	Hardware
Baseband processor chipset	Autotalks ATK4100 and ARM	NXP i.MX6	NXP i.MX6	Autotalks ATK4100	Autotalks ATK4100	Autotalks CRATON2 and ARM
Operating system	-	Linux/RTOS (V2X)	Linux/RTOS (V2X)	ThreadX OS	ThreadX OS	Linux
External connectors	Ethernet, CAN, GPIO, microSD	Ethernet, SIM, USB	Ethernet, USB, SIM, micro SD, HDMI, Audio	RS232, GPIO, CAN, Ethernet, Audio, microSD	Ethernet, CAN, GPIO, RS232	Ethernet, RS232, CAN, USB

Note: The “-” symbol in the cells indicates that data could not be found or are not in the system.

Table 5. Commercial V2X devices currently on the market—Part III.

Commercial V2X Devices / Basic Parameters	[69] **Norbit FZ58058**	[70] **Norbit VTR850**	[71] **Kapsch TrafficCom OBU-TS3306**	[72] **Kapsch TrafficCom RIS-9160**	[73] **Kapsch RIS-9260**	[74] **Huawei LTE-V RSU5201**
RSU/OBU/Mobile	RSU	OBU	OBU	RSU	RSU	RSU
Supported V2X technologies	DSRC	DSRC	DSRC	DSRC	DSRC, C-V2X	C-V2X
RF transceiver chipset	-	-	-	-	Qualcomm 9150	-
GNSS	No	No	Yes	Yes	Yes	Yes
Security	-	-	Hardware	Hardware	Hardware	Software
Baseband processor chipset	-	-	-	-	x86 CPU	-
Operating system	-	-	-	Linux, SDK with C libraries	-	-
External connectors	Ethernet, RS485, RS232, USB	-	USB, CAN, microSD	Ethernet, GPIO	GPIO, microSD, USB	Ethernet, Optical, SIM

Note: The "-" symbol in the cells indicates that data could not be found or are not in the system.

Although the same manufacturer's RSU and OBU devices, the supported standards and protocols are practically identical, and these devices often differ in quantity and type of interfaces, power supply methods and casing and installation structures. For example, OBU's devices have CAN interfaces that can be connected to the vehicle's information systems to obtain various readings from the vehicle's integrated sensors. Meanwhile, RSU and mobile devices do not have such interfaces. Furthermore, the OBU devices are powered from 6V to 24V power supply, as this corresponds to the rated voltage of the vehicle battery. Meanwhile, the power supply of RSU devices comes through the power-over-ethernet (PoE) interface that transfers both data and supply voltage. This interface is widely used and is especially appropriate for the deployment near street installation, combining many different devices to one PoE source. In contrast, mobile devices are powered from smart devices or other external rechargeable batteries. It should also be noted that there are no specific, stringent requirements for the casings of mobile and OBU devices, while the casings of the RSU devices must be compliant with NEMA, IP67 or other environmental protection standards.

As mentioned earlier, practically all commercial V2X devices are dedicated to DSRC communication technologies and do not support C-V2X. This, in turn, restricts further research into the hybrid architectural solutions of these technologies and the development of new V2X systems. The exception could be considered a Qualcomm Snapdragon 602 Automotive Platform and Qualcomm Snapdragon 820 Automotive Platform [75,76], which have LTE, Wi-Fi/DSRC communication modules. However, there are several chipsets of transceivers for these communication technologies: QCA6574, WTR3925, WTR4905 and others. Perhaps for the last-mentioned reasons, Qualcomm develops C-V2X 9150 chipset that will support the C-V2X with the integrated global navigation satellite system (GNSS), and will have an application processor running the ITS stack [77]. ZTE has already announced its future communication with Qualcomm, developing a new generation of C-V2X solutions [78].

3.2. Commercial V2X Chipsets

Following the review of commercially available OBU and RSU platforms on the market, major manufacturers of V2X chipsets are AutoTalks, NXP Semiconductors, and Qualcomm Atheros. For example, the Commsignia V2X Evaluation Kit, Unex OBU-201 and Unex RSU-201 V2X solutions discussed above use AutoTalks V2X chipsets: PLUTON (ATK3100), SECTON and CRATON (ATK4100) [79]. PLUTON is a V2X RF transceiver for the IEEE 802.11p standard with a carrier frequency range from 5.18 GHz to 5.93 GHz. SECTION is a chip designed to implement data security features. Meanwhile, CRATON is a V2X communication processor that processes data from the PLUTON transceiver. Additionally, AutoTalks offers V2X solutions for their latest products, PLUTON2 (ATK3200) and CRATON2 chips. PLUTON2 is a low-power, multi-standard RF transceiver capable of working with both IEEE 802.11p and IEEE 802.11a/b/g/n/ac communication standards. Meanwhile, CRATON2 is a digital communication processor with an integrated V2X hardware security module (eHSM) and a dual-core ARM Cortex A7 processor for middleware and applications. Furthermore, CRATON2 can support IEEE 802.11a/b/g/n/ac standards for external Wi-Fi services. The manufacturer does not provide more detailed specifications for these chips.

Cohda Wireless MK5 OBU and Cohda Wireless MK5 RSUs discussed above-use U-blox THEO-P1 modules with NXP Semiconductors chipsets [80]: TEF5100 is a dual radio multi-band RF transceiver for the IEEE 802.11p standard, but is compliant with Japan's (760 MHz), US and European (5.9 GHz) V2X standards; SAF5100—software-defined radio processor; SXF1800—for data security implementation functions. NXP Semiconductors also offers the DSRC modem SAF5400, which combines transceiver, data security and digital signal processing functions into one system.

LocoMate OBU, LocoMate RSU and LocoMate ME products use Qualcomm's Atheros AR5414 chipset [81], consisting of a dual-band 2.4/5 GHz RF transceiver and a MAC/Baseband communication processor [82]. This chip is also often used in a variety of scientific works that develop and analyze various V2X solutions [83–85].

There are also various chips on the market which, according to their manufacturers, can be used to create various V2X systems. Examples of such manufacturers and their products could be Renesas Electronics (R-Car W2R (R7S720004)), Marvell (88W8987XA), Redpine Signals (WaveCombo module) and Asahi Kasei Microdevices Corporation (AK1553). The technical specifications of the chips provided by these manufacturers are not very detailed, so we will briefly review only their main features.

Company Renesas Electronics produced R-Car W2R (R7S720004) is designed exclusively for IEEE 802.11p standard, and integrates RF transceiver and MAC/Baseband communication processor [86].

Marvell's 88W8987xA chip family has an integrated IEEE 802.11ac (wave2)/IEEE 802.11p transceiver and Bluetooth-5 specifically designed to support the speed, reliability, and quality requirements for IEEE 1609.x wireless access in vehicular environments and DSRC systems [87]. The RF transceiver has two 2.4 GHz and 5 GHz bands. These family chips also integrate WLAN/MAC/Baseband and Bluetooth-Baseband communication processors.

WaveCombo Module is manufactured by Redpine Signals for many IEEE 802.11 standards, including IEEE 802.11p and IEEE 802.154/ZigBee [88]. This module includes an RS8111 chip—a dual-band (2.4/5 GHz) RF transceiver, and a RS9113—MAC Baseband communication processor.

Another interesting product is the Japanese company's Asahi Kasei Microdevices Corporation 5.9 GHz RF transceiver AK1553. This transceiver is compliant with the Arib STD-T75 standard and is designed for ETC2.0 systems [89]. This transceiver requires an external MAC/Baseband communication processor.

For virtually all of the basic ITS standards, DSRC and C-V2X systems discussed in the previous section, software defined RF transceivers could be suitable. While most software with defined RF transceivers could be suitable for 3G/4G/5G base stations, it should be noted that Multiple-Input-Multiple-Output (MIMO) receiver and transmitter chains usually share the same Local Oscillation (LO) generators, hence, only single standards can be supported at a single time and more than one transceiver must be used in a multistandard V2X system.

In summary, all reviewed RSU, OBU, and RF transceivers are mainly intended to support one or only a few specific standards and are usually single-channel (SISO). This means that multiple, different frequency standards cannot be maintained simultaneously. For the latter reasons, it is necessary to develop new V2X frameworks based on highly versatile hardware both from analog and digital processing point of view. This would enable the development of new hybrid DSRC and C-V2X technologies and systems, and would enable the use of other complementary wireless solutions (for example, IoT-based) in such systems.

4. IoT Standards Applicability in ITS

The Internet of Things (IoT) technology is currently one of the newest and fastest developing directions of information and communication technologies. As evidenced by the global experience of the IoT application and recent research, the scale of services and applications of these technologies in everyday life and business in recent years is steadily increasing and will only increase in the future [90,91]. The International Data Corporation (IDC), an international information technology market research firm, and the European Commission state that "the IoT enables objects sharing information with other objects/members in the network, recognizing events and changes so to react autonomously in an appropriate manner. The IoT therefore builds on communication between things (machines, buildings, cars, animals, etc.) that leads to action and value creation" [92]. Meanwhile, the International Telecommunication Union (ITU) defines the IoT as "a global infrastructure for the information society, enabling advanced services by interconnecting things based on existing and evolving interoperable information and communication technologies" [93]. The research focuses on five major domains that already apply or will apply the IoT technologies: health, living, industry, environment, and transport [90]. The IoT technologies, along with a variety of sensors and image recognition and analysis systems, are already widely used and researched in ITS: identifying and planning traffic flows, analyzing and informing on road events, increasing traffic safety, and so on. Various software and hardware Internet platforms are also being developed to assist the driver. For example, the work [94] integrates methods of combining data from former routes, sensors, image recognition and analysis to identify pedestrians and other transport systems on the road. The work [95] provides a cloud-based smart parking system that analyzes and interprets existing geographic location, car parking facilities, traffic flow and parking space reservation information.

Many different protocols have been developed for the IoT technologies, which are regulated by various organizations such as IEEE, IETF (Internet Engineering Task Force), ITU, 3GPP or various alliances such as Zigbee, LoRa and others. Many of these protocols are already standardized, some are still under development, and some are already patented. Standards in the market that regulate protocols in different frequency bands are intended for short or long data transmission distances, various data rates, power consumption, and so on. As a result, a large number of standards and protocols make it difficult to combine different IoT systems and their further development.

The most common wireless standards in the IoT technologies are the following: Zigbee, LoRaWAN, LTE-M and NB-IoT, IEEE 802.11ah (HaLow) and 802.11af (White-Fi) [96].

The Zigbee standard operates in the unlicensed 2.4 GHz, 915 MHz and 868 MHz bands, and describes wireless network protocols for low-power networked nodes. This standard specifies network and application levels based on the fact that the data channel and the physical layer are developed according to the IEEE 802.15.4 standard. The IoT networks based on this standard are used in systems with low data rates (up to 250 kb/s), the operating distance between nodes is up to 10 m. However, it can work up to 100 m if a lower data rate is used. The Zigbee standard is widely used in intelligent transport systems. For example, in the EMMA (Embedded Middleware in Mobility Applications) project, funded by the European Commission, which involved car and component manufacturers, transport service providers and research institutes, communication between the in-vehicle nodes, cars and road infrastructure was implemented on the Zigbee [97]. There are also more scientific, engineering and practically implemented works that demonstrate the applicability of the Zigbee to intelligent transport systems [98–100].

The LoRaWAN standard is regulated by the LoRa alliance of five hundred companies [101]. Like Zigbee, LoRaWAN is designed for low-speed, low-power networks and their nodes. However, the main difference from Zigbee is that LoRaWAN is for wide-area networks. The range of these networks can vary from 2 to 5 km in the city, up to 15 km in the suburbs and up to 45 km in the rural area. This IoT technology uses license-free sub-gigahertz frequency bands: 169 MHz, 433 MHz, 868 MHz (Europe) and 915 MHz (North America), with data rates ranging from 0.3 kb/s to 50 kb/s [102]. LoRaWAN can also be widely deployed in intelligent transport systems and their infrastructure. For example, South Korean mobile operator SK Telecom deployed a nationwide LoRaWAN network, capable of connecting millions of items (sensors, controllers, and other devices) and implement a new infrastructure for healthcare, renewable energy and autonomous cars [102,103]. It is also planned to install LoRaWAN in the urban street lighting networks to collect environmental and existing road load data and to adjust lighting intensity and reduce energy consumption.

Cellular LTE-M (machine-type communications) and NB-IoT (narrowband Internet of things) standards for the IoT networks are regulated by the 3GPP [104–107]. The main advantage of the LTE-M standard is the global connectivity capability to track moving network nodes over long distances. According to the Global System for Mobile Communications (GSMA), this “technology provides improved both indoor and outdoor coverage, supports massive numbers of low throughput devices, low delay sensitivity, ultra-low device cost, low device power consumption and optimized network architecture” [108]. As the IoT technologies in this standard work on cellular communication networks (LTE bands 1, 2, 3, 4, 5, 12, 13, 20, 25, 26, 28) [109], LTE-M can be used to monitor, control and retrieve information from IoT devices built into many modes of transport: trucks, trains, ships, and so on. Examples of such use are provided in the following references [110,111]. Although LTE networks provide transfer speeds of tens of Mb/s, to reduce power consumption, data rates of LTE-M devices are reduced to 100–380 kb/s [112]. One of the advantages of the LTE-M standard is that in the absence of the LTE network, the system can operate on WCDMA (3G) or GPRS/EDGE (2G) networks.

NB-IoT is also used on multiple LTE bands (1, 2, 3, 4, 5, 8, 11, 12, 13, 14, 17, 18, 19, 20, 25, 26, 28, 31, 66, 70, 71, 72, 73, 74 and 85) [104,106,107] and its range is up to 10 km. However, the IoT technologies based on the NB-IoT standard are more intended for indoor use and where even lower data rates are sufficient (up to 250 kb/s in accordance with 3GPP Release 13). However, there are NB-IoT solutions for parking systems [113], smart street lighting management [114], transport control and tracking systems [115].

IEEE 802.11af (White-Fi) and IEEE 802.11ah (HaLow) standards are also designed for various IoT solutions. The first of these standards works in the VHF and UHF bands from 54 MHz to 790 MHz (470–790 MHz in Europe and 54–698 MHz in United States), data transfer is available from 1.8 Mb/s to 35.6 Mb/s, and the designed coverage is up to 1 km [116]. Meanwhile, IEEE 802.11ah operates in the 863–868 MHz (Europe) and 902–928 MHz (North America) bands, with a coverage of up to one kilometer, and data rates ranging from 150 kb/s to 347 Mb/s [117]. These IoT standards can also be widely used in the design of various engineering solutions for intelligent transport systems [118]. A summary of common wireless standards for IoT is given in Table 6.

Table 6. Summary of common wireless standards for IoT.

Standard	Frequency, MHz	Range	Transfer Rate
Zigbee	915, 868	10–100 m	20–250 kb/s
LoRaWAN	169, 433, 868, 915	2–45 km	3–50 kb/s
LTE-M	700–2100	Global	100–380 kb/s
NB-IoT	450–2100	1–10 km	28–250 kb/s
IEEE 802.11af (White-Fi)	470–790, 54–698	1 km	1.8–35.6 Mb/s
IEEE 802.11ah (HaLow)	863–868, 902–928	1 km	0.15–347 Mb/s

To summarize, it can be said that V2X and IoT technologies are a necessity in the operation of existing and new smart transport systems. This would bring together a number of V2X and IoT standards into one whole and choose the most appropriate communication standard for the intelligent transport systems and the surrounding environment. Therefore, it is necessary to create multi-standard, multi-band transceivers that meet the requirements of both V2X and IoT standards.

5. Discussions

Most of the published research is focused around a single V2X technology and/or isolated use case scenarios where technologies are compared to one another. Results of the review of currently commercially available V2X products also match with the latter findings. The V2X products, frameworks and/or developments kits that are currently available on the market are mostly suited for the applications with a small selection of predefined technologies. Even so, published research data have shown that the performance of the two main V2X technologies degrades as the number of connected devices increases. Application of the upgraded transceivers, which are based on IEEE 802.11ax, could increase the capability of the load handling for the DSRC technology based on IEEE 802.11p standard. It still remains unclear whether the current mobile, cellular network infrastructure will be capable of transmitting data via C-V2X technology within the permissible latency and throughput. It is expected that the gradual deployment of the next-generation cellular network infrastructure, like 5G NR, will increase the capacity and throughput and decrease the latency. Due to the requirement of backward compatibility, communication based on C-V2X will have to include handover procedures between network equipment from different cellular generations, which will increase deployment costs and design complexity of the system

Due to aforementioned reasons, it is necessary to develop solutions, based on highly versatile hardware from analog and digital processing point of view, that enable reliable and efficient technology insensitive V2X communications. Since the two main V2X technologies share some of the frequency spectrum, solutions of hybrid ITS network architecture, which combine DSRC, C-V2X or other complementary wireless solutions (for example IoT-based), are the next logical step. Here, the V2X technology between users is chosen according to the network load, quality, application or other critical parameters and is not limited by the hardware. IoT technologies should also be integrated into the hybrid ITS network. They could be used for offload of the non-critical sensor data, which can help to identify and plan traffic flows, analyze and inform on-road events, and so on. It can be concluded that merging V2X and IoT technologies is a necessity that can help manage and add new features into ITS solutions.

Summing up the overview of DSRC, C-V2X, IoT technologies and their standards, regulations and hardware specifications of the commercial products, it can be concluded that a highly versatile framework that supports several wireless technologies and the extremely wide 54–7125 MHz frequency spectrum is needed for the development of a modern ITS solution. There is no sufficiently flexible framework at the time that can be used to develop new transport communication networks or their architectures and concurrently verify them at the hardware and software level.

Author Contributions: Conceptualization, K.K. and V.B.; investigation, M.J., K.K., V.M., A.V. and L.K.; resources, J.R.; writing—original draft preparation, K.K. and V.B.; writing—review and editing, M.J., V.M., R.N., J.R., A.V. and L.K.; visualization, K.K. and V.B.; project administration, R.N.; funding acquisition, R.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Research Council of Lithuania, grant number DOTSUT-235, No. 01.2.2-LMT-K-718-01-0054.

Acknowledgments: The team of authors wishes to express their gratitude to the Research Council of Lithuania for financially supporting this research as a part of "Design and Research of Internet of Things (IoT) Framework Model and Tools for Intelligent Transport Systems" project, grant number DOTSUT-235, No. 01.2.2-LMT-K-718-01-0054.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. European Commission. The Trans-European Transport Network: An EU that Delivers Investments in Smart, Sustainable and Safe Mobility for Jobs and Growth. April 2018. Available online: https://ec.europa.eu/transport/sites/transport/files/2018-eu-that-delivers.pdf (accessed on 17 May 2019).
2. Nowacki, G. Development and Standardization of Intelligent Transport Systems. *TransNav* **2012**, *6*, 403–411.
3. European Commission. 2018 Road Safety Statistics: What is Behind the Figures? April 2019. Available online: http://europa.eu/rapid/press-release_MEMO-19-1990_en.htm (accessed on 17 May 2019).
4. European Commission. EU Strategic Action Plan on Road Safety. 17 May 2018. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar%3A0e8b694e-59b5-11e8-ab41-01aa75ed71a1.0003.02/DOC_2&format=PDF (accessed on 17 May 2019).
5. European Commission. Memo-Road Safety Programme 2011–2020: Detailed Measures. 20 July 2010. Available online: http://europa.eu/rapid/press-release_MEMO-10-343_en.htm (accessed on 17 May 2019).
6. European Commission. Road Safety: Data Show Improvements in 2017 but Renewed Efforts Are Needed for Further Substantial Progress. 10 April 2018. Available online: http://europa.eu/rapid/press-release_IP-18-2761_en.htm (accessed on 17 May 2019).
7. European Commission. Sustainable Urban Mobility: Policy Context. March 2017. Available online: https://ec.europa.eu/transport/sites/transport/files/2017-sustainable-urban-mobility-policy-context.pdf (accessed on 17 May 2019).
8. Baldessari, R. "Car-2-Car Communication Consortium Manifesto," ITS Automotive Nord GmbH, Braunschweig, Germany, Technical Reports Version 1.1. 2007. Available online: https://www.car-2-car.org/fileadmin/documents/General_Documents/C2C-CC_Manifesto_Aug_2007.pdf (accessed on 17 May 2019).
9. "Connected Vehicle Pilot Deployment Program," U.S. Dept. Transp. (DOT), Washington, DC, USA, Fact Sheet. 2015. Available online: http://www.its.dot.gov/factsheets/pdf/JPO_CVPilot.pdf (accessed on 17 May 2019).

10. Veniam, "Smart City Case Study: Creating the World's Largest Network of Connected Vehicles for Smart Cities". April 2016. Available online: http://worldwifiday.com/wp-content/uploads/2016/05/3.-PortoCaseStudy_Letter_2016-04-15.pdf (accessed on 17 May 2019).
11. "Cisco Visual Networking Index: Forecast and Trends, 2017–2022," White Paper. Cisco: San Jose, CA, USA, 27 February 2019. Available online: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/complete-white-paper-c11-481360.pdf (accessed on 17 May 2019).
12. Jurgo, M.; Navickas, R. Structure of all-digital frequency synthesiser for IoT and IoV applications. *Electronics* **2019**, *8*, 29. [CrossRef]
13. Macaitis, V.; Navickas, R. Design of high frequency, low phase noise LC digitally controlled oscillator for 5G intelligent transport systems. *Electronics* **2019**, *8*, 72. [CrossRef]
14. Macaitis, V.; Barzdenas, V.; Navickas, R. Design of 4.48–5.89 GHz LC-VCO in 65 nm RF CMOS Technology. *Elektron. Elektrotech.* **2014**, *20*, 44–47. [CrossRef]
15. Kladovščikov, L.; Navickas, R.; Kiela, K. Self-tuning system for multistandard active RC filters. *Microelectron. J.* **2019**, *90*, 260–266. [CrossRef]
16. Kiela, K.; Navickas, R. A method for continuous tuning of MOSFET–RC filters with extended control range. *J. Electr. Eng.* **2016**, *67*, 449–453. [CrossRef]
17. Jurgo, M.; Kiela, K.; Navickas, R. Design of low noise 10 GHz divide by 16 ... 511 frequency divider. *Elektron. Elektrotech.* **2013**, *19*, 87–90. [CrossRef]
18. Jurgo, M.; Navickas, R. Design of gigahertz tuning range 5 GHz LC digitally controlled oscillator in 0.18 µm CMOS. *J. Electr. Eng.* **2016**, *67*, 143–148. [CrossRef]
19. Charlamov, J.; Navickas, R.; Baškys, A. Phase noise minimization in CMOS voltage controlled oscillators. Acta Physica Polonica A. In Proceedings of the 14th International Symposium on Ultrafast Phenomena in Semiconductors, Vilnius, Lithuania, 23–25 August 2010; Polish Academy of Sciences: Warszawa, Poland, 2011; Volume 119, pp. 234–236.
20. Baškys, A.; Navickas, R.; Šimkevičius, Č. The Fast differential amplifier-based integrated circuit yield analysis technique. *Acta Phys. Pol. A* **2011**, *119*, 259–261. [CrossRef]
21. Barzdėnas, V.; Navickas, R. Leakage current compensation for the 0.13 µm CMOS charge sensitive preamplifier. *Elektron. Elektrotech.* **2007**, *7*, 33–36.
22. International Organization for Standardization. ISO/TC 204 Technical Committees, Intelligent Transport Systems. Available online: https://www.iso.org/committee/54706.html (accessed on 18 June 2020).
23. Federal Communications Commission. FCC Proposes to Allocate Spectrum in 5.9 GHz Range for Intelligent Transportation Systems Uses. (Et Docket No. 98-95). 11 June 1998. Available online: https://transition.fcc.gov/Bureaus/Engineering_Technology/News_Releases/1998/nret8010.html (accessed on 18 June 2020).
24. International Telecommunications Union, ITU-R M.1452-2 Recommendation. Millimetre Wave Vehicular Collision Avoidance Radars and Radiocommunication Systems for Intelligent Transport System Applications. Available online: https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.1452-2-201205-I!!PDF-E.pdf (accessed on 18 June 2020).
25. International Telecommunications Union, ITU-R M.1453-2 Recommendation. Intelligent Transport Systems-Dedicated Short Range Communications at 5.8 GHz. Available online: https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.1453-2-200506-I!!PDF-E.pdf (accessed on 18 June 2020).
26. Federal Communications Commission. FCC Allocates Spectrum in 5.9 GHz Range for Intelligent Transport Systems Uses. 21 October 1999. Available online: https://transition.fcc.gov/Bureaus/Engineering_Technology/News_Releases/1999/nret9006.html (accessed on 18 June 2020).
27. IEEE Standard for Information Technology. Telecommunications and Information Exchange between Systems—Local and Metropolitan Area Networks—Specific Requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment 6: Wireless Access in Vehicular Environments. IEEE Std. 802.11p-2010. Available online: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5514475 (accessed on 18 June 2020).
28. IEEE Standards Association. Standards Development Working Group. IEEE1609—Dedicated Short Range Communication Working Group. Available online: https://standards.ieee.org/develop/wg/1609.html (accessed on 18 June 2020).

29. ASTM International. ASTM E2158-01. Standard Specification for Dedicated Short Range Communication (DSRC) Physical Layer Using Microwave in the 902 to 928 MHz Band (Withdrawn 2010). Available online: https://www.astm.org/Standards/E2158.htm (accessed on 18 June 2020).
30. European Telecommunications Standards Institute. Intelligent Transport Systems (ITS); European Profile Standard for the Physical and Medium Access Control Layer of Intelligent Transport Systems Operating in the 5 GHz Frequency Band, ETSI ES 202 663 V1.1.0. 2010. Available online: http://www.etsi.org/deliver/etsi_es/202600_202699/202663/01.01.00_60/es_202663v010100p.pdf (accessed on 18 June 2020).
31. European Telecommunications Standards Institute. Intelligent Transport Systems (ITS); Radiocommunications Equipment Operating in the 5.855 MHz to 5.925 MHz Frequency Band; Harmonized EN Covering the Essential Requirements of Article 3.2 of the R&TTE Directive, ETSI EN 302 571 V1.2.1. 2013. Available online: http://www.etsi.org/deliver/etsi_en/302500_302599/302571/01.02.01_60/en_302571v010201p.pdf (accessed on 18 June 2020).
32. European Committee for Standardization. Standard: CEN-EN 12253. Road Transport and Traffic Telematics—Dedicated Short-Range Communication-Physical Layer Using Microwave at 5.8 GHz, EN 12253:2004. 2004. Available online: https://standards.globalspec.com/std/453636/cen-en-12253 (accessed on 18 June 2020).
33. Association of Radio Industries and Businesses. Dedicated Shord Range Communication for Transport Information and Control Systems, ARIB Standard, ARIB STD-T55 Version 1.0. Available online: https://www.arib.or.jp/english/html/overview/doc/5-STD-T55v1_0-E.pdf (accessed on 18 June 2020).
34. Association of Radio Industries and Businesses. Dedicated Short Range Communication System, ARIB Standard, ARIB STD-T75, Version 1.0. Available online: https://www.arib.or.jp/english/html/overview/doc/5-STD-T75v1_0-E2.pdf (accessed on 18 June 2020).
35. Association of Radio Industries and Businesses. 700 MHz Band Intelligent Transport Systems, ARIB Standard, ARIB STD-T109 Version 1.3. Available online: https://www.arib.or.jp/english/html/overview/doc/5-STD-T109v1_3-E1.pdf (accessed on 18 June 2020).
36. Lin, C.S.; Chen, B.C.; Lin, J.C. Field Test and Performance Improvement in IEEE 802. 11p V2R/R2V Environments. In Proceedings of the 2010 IEEE International Conference on Communications Workshops, Cape Town, South Africa, 23–27 May 2010; pp. 1–5.
37. Cailean, A.; Cagneau, B.; Chassagne, L.; Popa, V.; Dimian, M. A survey on the usage of DSRC and VLC in communication-based vehicle safety applications. In Proceedings of the 2014 IEEE 21st Symposium on Communications and Vehicular Technology in the Benelux (SCVT), Delft, The Netherlands, 10 November 2014.
38. Qualcomm Technologies. Introduction to Cellular V2X. Available online: https://www.qualcomm.com/media/documents/files/introduction-to-c-v2x.pdf (accessed on 8 June 2020).
39. Wang, J.; Shao, Y.; Ge, Y.; Yu, R. A survey of vehicle to everything (v2x) testing. *Sensors* **2019**, *19*, 334. [CrossRef] [PubMed]
40. Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) Radio Transmission and Reception (Release 15), Tech. Specification Group Radio Access Network (TSG RAN), 3GPP TS 36.101. 2019. Available online: http://www.3gpp.org/ftp//Specs/archive/36_series/36.101/36101-f80.zip (accessed on 26 November 2019).
41. Service Requirements for V2X Services (Release 15), Tech. Specification Group Service & Systems Aspects (TSG SA), 3GPP TS 22.185. 2018. Available online: http://www.3gpp.org/ftp//Specs/archive/22_series/22.185/22185-f00.zip (accessed on 27 November 2019).
42. Study on LTE Support for Vehicle to Everything (V2X) Services (Release 14), Tech. Specification Group Service & Systems Aspects (TSG SA), 3GPP TR 22.885. 2015. Available online: http://www.3gpp.org/ftp/Specs/archive/22_series/22.885/22885-e00.zip (accessed on 9 December 2019).
43. User Equipment (UE) Radio Transmission and Reception; Part 1: Range 1 Standalone (Release 16), Tech. Specification Group Radio Access Network (TSG RAN), 3GPP TR 38.101. 2019. Available online: http://www.3gpp.org/ftp//Specs/archive/38_series/38.101-1/38101-1-g10.zip (accessed on 9 December 2019).
44. Study on NR Vehicle-to-Everything (V2X) (Release 16), Tech. Specification Group Radio Access Network (TSG RAN), 3GPP TR 38.885. 2019. Available online: http://www.3gpp.org/ftp//Specs/archive/38_series/38.885/38885-g00.zip (accessed on 24 November 2019).

45. V2X Services Based on NR; User Equipment (UE) Radio Transmission and Reception (Release 16), Tech. Specification Group Radio Access Network (TSG RAN), 3GPP TR 38.886. 2019. Available online: http://ftp.3gpp.org//Specs/archive/38_series/38.886/38886-040.zip (accessed on 9 December 2019).
46. Study on Enhancement of 3GPP Support for 5G V2X Services (Release 16), Tech. Specification Group Service & Systems Aspects (TSG SA), 3GPP TR 22.886. 2018. Available online: http://www.3gpp.org/ftp//Specs/archive/22_series/22.886/22886-g20.zip (accessed on 9 December 2019).
47. Abboud, K.; Omar, H.; Zhuang, W. Interworking of DSRC and Cellular Network Technologies for V2X Communications: A Survey. *IEEE Trans. Veh. Technol.* **2016**, *65*, 9457–9470. [CrossRef]
48. Yaacoub, E.; Filali, F.; Abu-Dayya, A. QoE Enhancement of SVC Video Streaming Over Vehicular Networks Using Cooperative LTE/802.11p Communications. *IEEE J. Sel. Top. Signal Process.* **2015**, *9*, 37–49. [CrossRef]
49. Cespedes, S.; Shen, X. On Achieving Seamless IP Communications in Heterogeneous Vehicular Networks. *IEEE Trans. Intell. Transp. Syst.* **2015**, *16*, 3223–3237. [CrossRef]
50. Benslimane, A.; Taleb, T.; Sivaraj, R. Dynamic Clustering-Based Adaptive Mobile Gateway Management in Integrated VANET—3G Heterogeneous Wireless Networks. *IEEE J. Sel. Areas Commun.* **2011**, *29*, 559–570. [CrossRef]
51. Sivaraj, R.; Gopalakrishna, A.; Chandra, M.; Balamuralidhar, P. QoS-enabled group communication in integrated VANET-LTE heterogeneous wireless networks. In Proceedings of the 2011 IEEE 7th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Wuhan, China, 10–12 October 2011.
52. Ucar, S.; Ergen, S.; Ozkasap, O. Multihop-Cluster-Based IEEE 802.11p and LTE Hybrid Architecture for VANET Safety Message Dissemination. *IEEE Trans. Veh. Technol.* **2016**, *65*, 2621–2636. [CrossRef]
53. Zhioua, G.; Tabbane, N.; Labiod, H.; Tabbane, S. A Fuzzy Multi-Metric QoS-Balancing Gateway Selection Algorithm in a Clustered VANET to LTE Advanced Hybrid Cellular Network. *IEEE Trans. Veh. Technol.* **2015**, *64*, 804–817. [CrossRef]
54. Liu, B.; Jia, D.; Wang, J.; Lu, K.; Wu, L. Cloud-Assisted Safety Message Dissemination in VANET. *IEEE Syst. J.* **2015**, *11*, 128–139. [CrossRef]
55. Lequerica, I.; Ruiz, P.; Cabrera, V. Improvement of vehicular communications by using 3G capabilities to disseminate control information. *IEEE Netw.* **2010**, *24*, 32–38. [CrossRef]
56. Bi, S.; Chen, C.; Du, R.; Guan, X. Proper Handover between VANET and Cellular Network Improves Internet Access. In Proceedings of the 2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall), Vancouver, BC, Canada, 14–17 September 2014.
57. Cohda Wireless. MK5 OBU Specification. Available online: http://www.neard.ws/wp-content/uploads/2018/11/MK5_OBU_Specification.pdf (accessed on 2 January 2019).
58. Cohda Wireless. MK5 RSU Specification. Available online: http://www.neard.ws/wp-content/uploads/2018/11/MK5_RSU_Specification.pdf (accessed on 2 January 2019).
59. Arada Systems. LocoMate OBU. Available online: http://www.aradasystems.com/wp-content/uploads/2015/06/Arada_datasheet_obu_2.01_2015.pdf (accessed on 2 January 2019).
60. Arada Systems. LocoMate RSU. Available online: http://www.aradasystems.com/wp-content/uploads/2015/05/LocoMate_RSU_Datasheet_v2.0_May2015.pdf (accessed on 2 January 2019).
61. Arada Systems. LocoMate ME, Mobile DSRC for V2X Connectivity. Available online: http://www.aradasystems.com/wp-content/uploads/2014/03/LocoMate_OBU_Datasheet_v2.16-MEREV1.16.pdf (accessed on 2 January 2019).
62. BlueTOAD. Spectra DSRC Roadside Unit. Available online: http://trafficcast.com/spectrarsu/assets/BlueTOAD_SpectraRSU-Cutsheet-April18.pdf (accessed on 2 December 2019).
63. Commsignia. V2X Evaluation Kit. Available online: http://www.commsignia.com/hardware/#datasheet (accessed on 2 January 2019).
64. Commsignia. TS-RS4 (DSRC & C-V2X Dual Mode) for Smart Intersections and Highways. Available online: https://shop.commsignia.com/index.php?route=product/product&path=62&product_id=57 (accessed on 2 December 2019).
65. Commsignia. ITS-OB4 (DSRC & C-V2X Dual Mode)—Aftermarket Safety Device. Available online: https://shop.commsignia.com/index.php?route=product/product&path=61&product_id=54 (accessed on 2 December 2019).

66. Unex. V2X On-Borad Unit, OBU-201 Specification. Available online: https://unex.com.tw/download/5795d321a45b0/36?token=Lge42wsFFlquZJl4LQ25jvVLrkc3tyoEzRomBE55 (accessed on 2 January 2019).
67. Unex. V2X Roadside Unit, RSU-101 Specification. Available online: https://unex.com.tw/download/58ae830239608/56?token=Qpc6sJkF10CxPh6OrrtIGtSc5yXhVHt9NpiNL1BR (accessed on 2 January 2019).
68. Unex. OBU-301E DSRC-V2X On-Board Unit. Available online: https://unex.com.tw/download/5bd033afd5147/71?token=HbS0Ze2sBJjM4bC1jYVjVjI6YlQTFaiwxsyERE9t (accessed on 2 December 2019).
69. Norbit. FZ58058 Road Side Unit (RSU). Available online: https://norbit.com/media/PS-100003-10_Norbit_ITS_FZ58058_datasheet.pdf (accessed on 2 January 2019).
70. Norbit. VTR850-R On-Board Unit (OBU). Available online: https://norbit.com/media/PS-130003-2_Norbit_ITS_VTR850-R_datasheet.pdf (accessed on 2 January 2019).
71. Kapsch TrafficCom. Kapsch OBU-TS3306 On-Board Unit. Available online: https://www.kapsch.net/ktc/downloads/datasheets/in-vehicle/5-9/Kapsch-KTC-DS-OBU-TS3306.pdf?lang=ru-RU (accessed on 2 January 2019).
72. Kapsch TrafficCom. Kapsch RIS-9160. V2X Roadside ITS Station. Available online: https://www.kapsch.net/us/ktc/downloads/datasheets/rf-field/5-9/KTC_DB_RIS-9160_EN_20170609_lowres.pdf?lang=en-US (accessed on 2 January 2019).
73. Kapsch. RIS-9260 V2X Roadside ITS Station. Available online: https://connectedvehicles.kapsch.net/download/KapschRIS-9260datasheet.pdf (accessed on 2 December 2019).
74. Huawei. LTE-V RSU5201 Product Description. Available online: https://carrier.huawei.com/~{}/media/CNBGV2/download/products/wireless-network/c-v2x/lte-v-rsu5201-product-description-en.pdf (accessed on 2 December 2019).
75. Qualcomm. The Qualcomm®Snapdragon™ Automotive Development Platform. Available online: https://www.qualcomm.com/media/documents/files/snapdragon-automotive-development-platform-spec-sheet.pdf (accessed on 2 January 2019).
76. Intrinsic. Snapdragon™ S820Am v2 Automotive Development Platform Based on the Snapdragon™ 820A Automotive Processor. Available online: https://www.intrinsyc.com/automotive-development-platforms/s820am-v2-automotive-development-platform (accessed on 2 January 2019).
77. Qualcomm. Qualcomm 9150 C-V2X Chipset. Available online: https://whttps://www.qualcomm.com/invention/5g/cellular-v2x (accessed on 2 December 2019).
78. Green Car Congress. ZTE C-V2X Module to Use Qualcomm 9150 C-V2X Chipset in Next-Gen Vehicles and Roadside Infrastructure. Available online: http://www.greencarcongress.com/2018/02/20180228-zte.html (accessed on 2 January 2019).
79. Autotalks. V2X Chipset Products. Available online: https://www.auto-talks.com/product/ (accessed on 2 January 2019).
80. NXP Semiconductors. NXP DSRC Safety Modem. Available online: https://www.nxp.com/products/wireless/dsrc-safety-modem:DSRC-MODEM (accessed on 2 January 2019).
81. Arada Systems. Locomate OBU [miniPCI Platform], Multi-Role WAVE Platform for Dedicated Short Range Communication (DSRC). Available online: http://files.moonblink.com/Arada-Locomate-OBU.pdf (accessed on 2 January 2019).
82. Atheros Communication. AR5414 Data Sheet. AR5414 Dual-Band, Multi-Mode MAC/BB/Radio for IEEE 802.11 a/b/g Wireless LAN. Available online: http://atoma.spb.ru/sites/default/files/documents/ar5414_data_sheet_05_04.pdf (accessed on 2 January 2019).
83. Abunei, A.; Comsa, C.; Bogdan, I. Implementation of a Cost-effective V2X hardware and software platform. In Proceedings of the 2016 International Conference on Communications (COMM), Bucharest, Romania, 9–10 June 2016; pp. 367–370.
84. Liu, Z.; Liu, Z.; Meng, Z.; Yang, X.; Pu, L.; Zhang, L. Implementation and performance measurement of a V2X communication system for vehicle and pedestrian safety. *Int. J. Distrib. Sens. Netw.* **2016**, *12*, 1–14. [CrossRef]
85. Mavromatis, I.; Tassi, A.; Piechocki, R.J.; Nix, A. Agile calibration process of full-stack simulation frameworks for V2X communications. In Proceedings of the 2017 IEEE Vehicular Networking Conference (VNC), Torino, Italy, 27–29 November 2017; pp. 89–96.
86. Renesas. R-Car W2R Product Overview. Available online: https://www.renesas.com/eu/en/about/press-center/news/2015/09/20150929-r-car-w2r-specs-en.pdf.https://www.renesas.com/en-eu/solutions/automotive/products/rcar-w2r.html (accessed on 2 January 2019).

87. Marvell. 88W8987xA Wi-Fi, Bluetooth 5 and 802.11p Combo Solutions for Vehicle-to-Everything (V2X) and In-Vehicle Infotainment (IVI). Available online: https://www.marvell.com/documents/pepdlwlnnttwitthagov (accessed on 2 January 2019).
88. Redpine Signals. WaveCombo™ Module Overview. Available online: http://www.redpinesignals.com/Products/802.11p_V2X_Connectivity/802.11p_V2X_Module.php (accessed on 2 January 2019).
89. Asahi Kasei Microdevices Corporation. Overview of 5.9 GHz RF Transceiver with Power Amplifier for ETC. Available online: https://www.akm.com/akm/en/product/datasheet1/?partno=AK1553 (accessed on 2 January 2019).
90. Siow, E.; Tiropanis, T.; Hall, W. Analytics for the Internet of Things: A Survey. *ACM Comput. Surv.* **2018**, *51*, 1–36. [CrossRef]
91. James, M.; Chui, M.; Bisson, P.; Woetzel, J.; Dobbs, R.; Bughin, J.; Aharon, D. *The Internet of Things: Mapping the Value beyond the Hype*; Technical Report; McKinsey Global Institute: New York, NY, USA, 2015; Available online: http://www.mckinsey.com/business-functions/digital-mckinsey/our-insights/the-internet-of-things-the-value-of-digitizing-the-physical-world (accessed on 18 June 2020).
92. Aguzzi, S.; Bradshaw, D.; Canning, M.; Cansfield, M.; Carter, P.; Cattaneo, G.; Gusmeroli, S.; Micheletti, G.; Rotondi, D.; Stevens, R. Definition of a Research and Innovation Policy Leveraging Cloud Computing and IoT. *A study for the European Commission DG Communications Networks, Content & Technology*. Available online: http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=9472 (accessed on 3 December 2019).
93. International Telecommunication Union. *Overview of the Internet of Things*; Technical Report; International Telecommunication Union: Geneva, Switzerland, 2012; Available online: http://www.itu.int/ITU-T/recommendations/rec.aspx?rec=11559 (accessed on 18 June 2020).
94. Danner, J.; Wills, L.; Ruiz, E.M.; Lerner, L.W. Rapid Precedent-Aware Pedestrian and Car Classification on Constrained IoT Platforms. In Proceedings of the 14th ACM/IEEE Symposium on Embedded Systems for Real-Time Multimedia—ESTIMedia 16, Pittsburgh, PA, USA, 6–7 October 2016; pp. 29–36.
95. He, W.; Yan, G.; Xu, L.D. Developing Vehicular Data Cloud Services in the IoT Environment. *IEEE Trans. Ind. Inform.* **2014**, *10*, 1587–1595. [CrossRef]
96. Valerio, P. Top Wireless Standards for IoT Devices. *IoT Times*, 11 April 2018. Available online: https://iot.eetimes.com/top-wireless-standards-for-iot-devices/ (accessed on 3 December 2019).
97. Selvarajah, K.; Tully, A.; Blythe, P. ZigBee for Intelligent Transport System Applications. In Proceedings of the IET Road Transport Information and Control Conference and the ITS United Kingdom Members Conference (RTIC 2008), Manchester, UK, 20–22 May 2008; pp. 1–7.
98. Rhoades, B.B.; Conrad, J.M. A survey of alternate methods and implementations of an intelligent transportation system. In *SoutheastCon 2017*; IEEE: Piscataway, NJ, USA, 2017; pp. 1–8.
99. Fan, H. The Vehicle Positioning Algorithm of the ZigBee Technology. In Proceedings of the 2016 International Symposium on Computer, Consumer and Control (IS3C), Xi'an, China, 4–6 July 2016; pp. 911–914.
100. Lei, Y.; Wang, T.; Wu, J. Vehicles relative positioning based on ZigBee and GPS technology. In Proceedings of the 2016 6th International Conference on Electronics Information and Emergency Communication (ICEIEC), Beijing, China, 17–19 June 2016; pp. 59–62.
101. LoRa Alliance™. Home Page. Available online: https://lora-alliance.org/ (accessed on 3 December 2019).
102. Silva, J.; Rodrigues, J.; Alberti, A. LoRaWAN—A Low Power WAN Protocol for Internet of Things: A Review and Opportunities. In Proceedings of the 2017 2nd International Multidisciplinary Conference on Computer and Energy Science (SpliTech), Split, Croatia, 12–14 July 2018; pp. 1–6.
103. LoRaWAN™ IoT Network Deployed Nationwide in South Korea by SK Telecom Covers 99 Percent of Population. Available online: https://www.semtech.com/company/press/LoRaWAN-IoT-Network-Deployed-Nationwide-in-South-Korea-by-SK-Telecom-Covers-99-Percent-of-Population (accessed on 3 December 2019).
104. Evolution of LTE in Release 13. Available online: http://www.3gpp.org/news-events/3gpp-news/1628-rel13 (accessed on 3 December 2019).
105. Standardization of NB-IOT Completed. Available online: http://www.3gpp.org/news-events/3gpp-news/1785-nb_iot_complete (accessed on 3 December 2019).
106. Release 14. Available online: https://www.3gpp.org/release-14 (accessed on 3 December 2019).
107. Release 15. Available online: https://www.3gpp.org/release-15 (accessed on 3 December 2019).

108. LTE-M Logo GSMA. Available online: https://www.gsma.com/iot/resources/ltem-logo/ (accessed on 3 December 2019).
109. LTE-M Deployment Guide, Gsma. Available online: https://www.gsma.com/iot/wp-content/uploads/2018/04/LTE-M_Deployment_Guide_v2_5Apr2018.pdf (accessed on 3 December 2019).
110. Tang, T.; Dai, K.; Zhang, Y.; Zhao, H.; Jiang, H. Field test results analysis in urban rail transit train ground communication systems of integrated service using LTE-M. In Proceedings of the 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), Rio de Janeiro, Brazil, 1–4 November 2016; pp. 2017–2021.
111. Huawei Introduces LTE-M Offering for Railways. Telecom Asia. Available online: https://www.telecomasia.net/content/huawei-introduces-lte-m-offering-railways (accessed on 3 December 2019).
112. What Is the Difference in Data Throughput between LTE-M/NB-IoT and 3G or 4G? GSMA. Available online: https://www.gsma.com/iot/resources/what-is-the-difference-in-data-throughput-between-lte-m-nb-iot-and-3g-or-4g/ (accessed on 3 December 2019).
113. Smart Parking, Huawei. Available online: https://www.huawei.com/minisite/iot/en/smart-parking.html (accessed on 3 December 2019).
114. Smart Street Lamps, Huawei. Available online: https://www.huawei.com/minisite/iot/en/smart-lighting.html (accessed on 3 December 2019).
115. FM36M1—Special NB-IoT and LTE CATM1 Tracker with High Gain GNSS and IoT/GSM Antennas, Internal Backup Battery, Teltonika. Available online: https://teltonika.lt/product/fm36m1/ (accessed on 3 December 2019).
116. Vujić, D.S.; Dukić, M. Comparison of TDD LTE and IEEE 802.11af Deployment in TVWS Band. In Proceedings of the Sinteza 2017—International Scientific Conference on Information Technology and Data Related Research, Beograd, Serbia, 21 April 2017; pp. 357–363.
117. Domazetovic, B.; Kocan, E.; Mihovska, A. Performance evaluation of IEEE 802.11ah systems. In Proceedings of the 2016 24th Telecommunications Forum (TELFOR), Belgrade, Serbia, 22–23 November 2016; pp. 1–4.
118. Goulianos, A.A.; Abdullah, N.F.; Kong, D.; Mellios, E.; Berkovskyy, D.; Doufexi, A.; Nix, A. Evaluation of 802.11 and LTE for Automotive Applications. In Proceedings of the 2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall), Vancouver, BC, Canada, 14–17 September 2014; pp. 1–5.