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Interworking of DSRC and Cellular Network Technologies for V2X Communications: A Survey

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***Abstract*—Vehicle-to-anything (V2X) communications refer to information exchange between a vehicle and various elements of the intelligent transportation system, including other vehicles, pedestrians, Internet gateways, and transport infrastructure (such as traffic lights and signs). The technology has a great potential of enabling a variety of novel applications for road safety, passenger infotainment, car manufacturer services, and vehicle traffic optimization. Today, V2X communications is based on one of two main technologies: dedicated short range communications (DSRC) and cellular networks. However, in the near future, it is not expected that a single technology can support such a variety of expected V2X applications for a large number of vehicles. Hence, interworking between DSRC and cellular network technologies for efficient V2X communications is proposed. This paper surveys potential DSRC and cellular interworking solutions for efficient V2X communications. Firstly, we highlight the limitations of each technology in supporting V2X applications. Then, we review potential DSRC-cellular hybrid architectures, together with the main interworking challenges resulting from vehicle mobility, such as vertical handover and network selection issues. Also, we provide an overview of the global DSRC standards, the existing V2X research and development platforms, and the V2X products already adopted and deployed in vehicles by car manufactures, as an attempt to align academic research with automotive industrial activities. Finally, we suggest some open research issues for future V2X communications based on interworking of DSRC and cellular network technologies.**

I. Introduction

During the information age, the motor vehicle has evolved from a simple mechanical device to a smart body of sensors that can measure different attributes, enhancing both vehicle safety and driver/passenger experience. Motor vehicles are now safer and smarter than they have ever been. However, our transportation system still suffers from major problems. The fast growth of metropolitan areas has been accompanied with an increasing influx of vehicular traffic to and from big cities. As a result, urban roads and highways are plagued by traffic congestions and road crashes, resulting in serious socio-economic problems. The latest report from the United States (U.S.) National Highway Traffic Safety Administration (NHTSA) has listed the annual casualties of motor vehicle crashes with a total of 32,999 fatalities and 3.9 million injuries on the roadways of the U.S., mounting the annual economical loss to $836 billion [1]. Furthermore, in 2014, traffic jams caused highway users in the U.S. to spend extra unnecessary 6.9 billion hours on roads to consume additional 3.1 billion gallons of fuel, adding up to an annual economical loss of $160 billion [2]. The statistical highway data from 1982 to 2014 show that these problems will continue to increase unless drastic new policy and technological measures are taken [2]. To address these problems, there have been worldwide efforts from auto companies, academic institutions, and government agencies to provide the vehicles and the transport infrastructure with communication capabilities, thus enabling vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian communications, which are collectively referred to as vehicle-to-x (V2X) communications, as recently defined by the 3rd Generation Partnership Project (3GPP) group [3]. The use of V2X communications together with existing vehicle sensing capabilities has a great potential of enabling many advanced applications for road safety, passenger infotainment, manufacturer services, and vehicle traffic optimization. Examples of such applications include cooperative collision warning, intersection collision avoidance, in-vehicle Internet access, point-of-interest notification, and remote vehicle diagnostics [4]–[7]. V2X communications elevate the collaboration among vehicles, pedestrians, and transport infrastructure, which promises to eliminate 80% of the current road crashes and helps fostering automobile and telecommunication industries for a smarter and safer ground transportation system [8].

There are two potential solutions to support V2X communications: dedicated short range communications (DSRC) and cellular network technologies. Although there is no globally agreed-on definition for DSRC, DSRC generally refers to a wireless technology used for automotive and intelligent transportation system (ITS) applications via short-range exchange of information among DSRC devices such as a) onboard units (OBUs) located inside the vehicles, b) road-side units (RSUs) placed on the side of the road, or c) hand-held devices carried by pedestrians. To promote the development of DSRC technology, different spectrum management organizations, such as the U.S. Federal Communication Commission (FCC), have allocated radio spectrum bands to be exclusively used for DSRC-based applications. Also, in 2014, the U.S. NHTSA announced that it had been working with the U.S. Department of Transportation (DOT) on regulations that will eventually mandate vehicular communication capabilities in new light vehicles by 2017 [8]. Along these steps, in 2015, the U.S. DOT has announced that it is investing up to $42 million in new V2X pilot projects in three U.S. cities [9].

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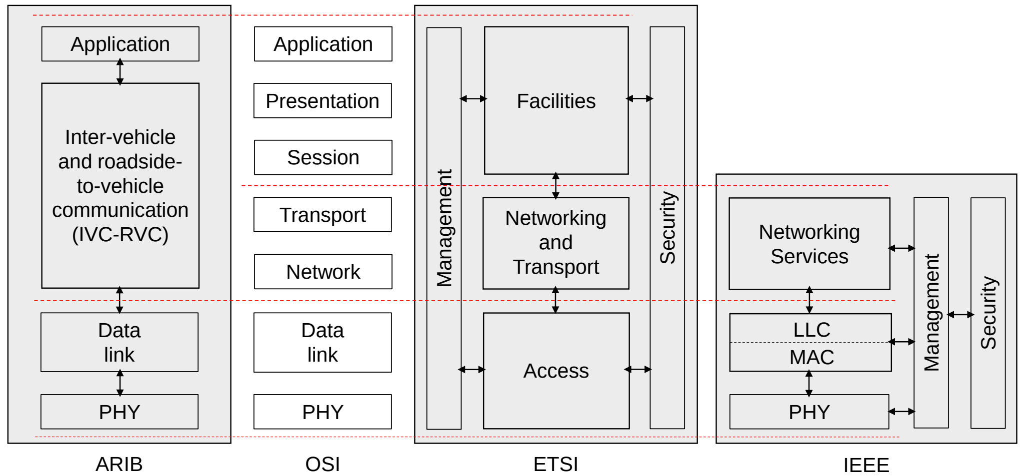

Fig. 1: Vehicular network architectures as defined in the standards IEEE 1609.0 (North America), ETSI EN 302 665 (Europe), and ARIB STD-T109 (Japan), in comparison with the Open System Interconnection (OSI) reference model

As part of the pilot project, New York City is installing the DSRC technology in a) up to 10,000 city-owned vehicles (e.g., buses and limousines), b) traffic signals on selected avenues in Manhattan and Brooklyn, and c) a number of RSUs on a major highway in Manhattan [9]. However, the ability of DSRC to support reliable and efficient V2X communications has been shaken by research results that revealed its poor performance, especially in high vehicle density scenarios. Furthermore, the allocated DSRC radio spectrum alone is not expected to meet the high data traffic demand for in-vehicle Internet access, which is foreseen to be dominated by data-hungry video applications (Cisco forecasts that the consumer Internet video traffic will be 80–90% of all consumer Internet traffic in 2019 [10]). The limitations of DSRC and the recent advancement in cellular network technologies have motivated the research community to investigate cellular-based V2X communications [3]. Cellular networks provide an off-the-shelf potential solution for V2X communications, which can make use of a high capacity, large cell coverage range, and widely deployed infrastructure. Car manufacturers have been sprinting to be part of the huge ITS market, which was globally valued at $43.47 billion in 2013 [11]. This market is expected to witness a rapid growth in the near future to reach $100.92 billion by 2018, growing at a compound annual growth rate (CAGR) of 18.35 percent [11]. As a result, different car manufacturers (e.g., GM and BMW) have relied on the deployed cellular networks to provide their vehicles with communication services, mainly targeting infotainment applications and a few V2I-based safety applications. However, the centralized nature of cellular networks limits their ability to support low-latency V2V communications which can jeopardize the effectiveness of safety applications. Furthermore, it is unclear whether or not the cellular network capacity alone can accommodate V2X data traffic along with the increasing data traffic load from its legacy cellular users, particularly with the expected 10-fold increase in the global mobile data between 2013 and 2018 [10]. Consequently, the research community has recently been looking into exploiting a hybrid DSRC-cellular architecture to support reliable and efficient V2X communications.

In this paper, we review the current V2X communication technologies, present various DSRC-cellular hybrid architectures, discuss the interworking challenges between the two technologies, and survey commercially available V2X products. Firstly, we give an overview of the global DSRC standards and clarify the limitations of providing V2X communications solely based on either DSRC or cellular networks. Secondly, we present potential hybrid DSRC-cellular architectures and the corresponding rules that govern the use of the two technologies by different type of network nodes. Then, we discuss interworking issues of DSRC-cellular network solutions characterized by the mobility management challenges, mainly in terms of vertical handover and network selection schemes. Thirdly, we summarize the commercially available development platforms, which can be utilized for implementation and testing of V2X systems, as well as the deployed V2X products in newly manufactured vehicles and the supported applications provided by the deploying car manufacturers. Finally, we highlight open issues related to the DSRC-cellular interworking for future V2X communications.

II. V2X Technologies

A. DSRC

As discussed in Section I, an essential technology for realizing V2X communications is DSRC. The DSRC is achieved over reserved radio spectrum bands, which differ in North America, Europe, and Japan, posing incompatibility problems among these regions. Table I shows the DSRC spectrum bands allocated by the U.S. FCC and Industry Canada in North America, the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) in Europe, and the Ministry of Internal Affairs and Communications (MIC) in Japan. Some

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TABLE I: DSRC spectrum bands and standards in North America, Europe, and Japan

Region	Band (MHz)	Channelization	In-use or allocated	Applications	Standard	Scope
North America	902-928[a]	Uplink/downlink channels for active and backscatter systems [12]	In-use	Electronic toll collection and commercial and non-commercial vehicle applications [13]	ASTM E2158-01	Physical (PHY) layer
					[14]	Data link layer
	5850-5925	One 10 MHz control channel, six 10 MHz service channels, and one 5 MHz channel (held in reserve) [15]	Allocated	Road safety, passenger infotainment, manufacturer services, and vehicle traffic optimization applications [5]–[7]	IEEE 1609.0	System architecture
					IEEE 1609.2	Security services
					IEEE 1609.3	Logical link control (LLC), network, and transport layers
					IEEE 1609.4	Multi-channel operation
					IEEE 1609.11	Electronic payment
					IEEE 1609.12	Identifier allocation
					IEEE 802.11-2012	PHY and medium access control (MAC) layers
Europe	5470-5725[b] (ITS-G5C)	Dynamic frequency selection (DFS) of a 10 MHz or 20 MHz service channel [16]	Allocated	ITS applications based on V2I communications [16]	ETSI EN 302 571	Requirements for operation in the 5855-5925 MHz band
					ETSI EN 300 674-1	Requirements for operation in the 5795-5815 MHz band
					ETSI ES 202 663 (ITS-G5)	PHY and MAC layers
	5795-5815	Four 5 MHz channels [17]	In-use	Road transport and traffic telematics [18]	ETSI EN 302 665	Communication architecture
					ETSI EN 302 636-3	Network architecture
					ETSI EN 302 636-4-1	Geographical routing functionality
					ETSI TS 102 636-4-2	Geographical routing based on ITS-G5
	5855-5925	One 10 MHz control channel and six 10 MHz service channels [19]	Allocated	Non-safety applications [5855-5875 MHz (ITS-G5B)], safety applications [5875-5905 MHz (ITS-G5A)], and future ITS applications (5905-5925 MHz) [19]	ETSI EN 302 636-6-1	Transmission of IPv6 packets using geographical routing
					ETSI EN 302 636-5-1	Transport layer
					ETSI EN 302 637-2	Format and handling of cooperative awareness messages (CAMs)
					ETSI EN 302 637-3	Format and handling of decentralized environmental notification messages (DENMs)
Japan	755.5-764.5	Single channel [20]	Allocated	Safety applications [20]	ARIB STD-T109	PHY, data link, application, and IVC-RVC layers[c]
	5770-5850[d]	Seven uplink and seven downlink 5 MHz channels [21]	In-use	Toll collection, passenger entertainment, and information provisioning regarding road conditions, local events, and emergent disasters [22], [23]	ARIB STD-T55	PHY, data link, and application layers[e]
					ARIB STD-T75	
					ARIB STD-T88	Application sub-layer for deployment of multiple DSRC applications based on ARIB STD-T75
					ARIB STD-T110	Application interface for deploying non-IP applications based on ARIB STD-T88 and ARIB STD-T75

[a]This band is currently used only for V2I communications with DSRC-enabled RSUs that control both the uplink and downlink transmissions, based on time division multiple access [12].

[b]This band is only for V2I communications with DSRC-enabled RSUs that act as a dynamic frequency selection (DFS) master, as specified in the ETSI ES 202 663 standard.

[c]The IVC-RVC layer stands for inter-vehicle and roadside-to-vehicle communication layer. The IVC-RVC and application layers, as defined in the ARIB-T109 standard, also specifies the required functionalities of layers 3, 4, 5, and 6 of the OSI reference model, as shown in Fig. 1.

[d]This band is currently used only for V2I-based ITS applications, such as electronic toll collection.

[e]The application layer, as defined in the ARIB STD-T55 and ARIB STD-T77 standards, also specifies the required functionalities of layers 3, 4, 5, and 6 of the OSI reference model.

DSRC bands are currently deployed for applications such as electronic toll collection, e.g., 902-928 MHz (North America), 5795-5815 MHz (Europe), and 5770-5850 MHz (Japan), while the rest of the DSRC allocated spectrum bands are currently not in-use. Each DSRC band is either used as a single frequency channel or divided into multiple channels, depending on the type of V2X applications that should be provided and the supporting communication standards. As shown in Table I, various DSRC standards are developed by different standardization bodies including the Institute of Electrical and Electronics Engineers (IEEE) in North America, the European Telecommunications Standards Institute (ETSI) in Europe, and the Association of Radio Industries and Businesses (ARIB) in Japan. The developed DSRC standards vary significantly from one region to another, based on the operating spectrum band and the proposed vehicular network architectures, as shown in Fig. 1. For instance, while the IEEE 802.11 [24], ITS-G5 [16], and ARIB STD-T109 [20] standards support V2V and V2I communications based on carrier sense multiple access with collision avoidance (CSMA/CA), the ASTM E2158-01 [12], ARIB STD-T55 [22], and ARIB STD-T75 [23] standards are developed only for V2I communications based on time division multiple access (TDMA) and frequency division duplexing (FDD). In addition to the DSRC standards listed

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in Table I, the Society of Automotive Engineers (SAE) has produced the SAE J2735 application layer standard [25]. The standard is a message set dictionary that defines the format of different DSRC application layer messages in both Abstract Syntax Notation One (ASN.1) and Extensible Markup Language (XML) formats. Examples of the messages defined in the SAE J2735 standard include the basic safety message (BSM), signal phase and timing (SPAT) message, and traveler information message (TIM). Also, the SAE is currently developing the J2945 standard to specify the minimum DSRC performance requirements, e.g., message transmission rate, to support the SAE J2735 DSRC message set.

Despite the collaborative efforts from governments, academic institutions, industrial organizations, and standardization bodies in the research and development (R&D) of DSRC, the technology still suffers from some limitations in supporting V2X applications. The first limitation originates from the inherent 'short range' characteristic of DSRC. For instance, to provide in-vehicle Internet access via DSRC Internet gateways deployed along the road sides, a vehicle needs to be within the 'small' coverage region of a gateway (i.e., an RSU), which may happen only for a short time period, especially if the vehicle is moving with a high speed. Such limitation does not exist for cellular network technologies, where the base station (BS) covers a much larger region as compared to that covered by a DSRC Internet gateway. Even when multi-hop communication is employed to extend the coverage of DSRC gateways (by allowing vehicles to relay packets to/from the gateway), the existence of a network path between a vehicle and a gateway at each time instant is not guaranteed, particularly in low vehicle density scenarios. Moreover, even if a network path exists, the packet routing to/from the gateway is a very challenging task given the highly dynamic network topology caused by fast vehicle movement. The network path existence and packet routing issues reduce the suitability of DSRC for any V2X application that requires low latency data dissemination on a large road segment. Another major limitation of DSRC results from the CSMA/CA technique, which is the main contention-based MAC scheme employed by DSRC standards, such as IEEE 802.11. Note that, the current version of the IEEE 802.11 standard [24] incorporates the IEEE 802.11p amendment for wireless access in vehicular environments (WAVE) [26], which is based on the ASTM E2213-03 standard for DSRC medium access control and physical layer specifications [27]. In a high vehicle density scenario, the intensity of channel contention among vehicles increases significantly, resulting in a considerable degradation of the IEEE 802.11 performance, due to a high transmission collision rate and a large channel access delay. Such widely investigated performance degradation of the IEEE 802.11 standard in highly dense scenarios has motivated the current development of the new IEEE 802.11ax amendment, mainly focusing on achieving enhanced network performance in dense deployment of IEEE 802.11 networks. The poor performance of the IEEE 802.11 standard with the increased vehicle density is even more severe in delivering broadcast frames, due to the lack of handshaking and acknowledgement mechanisms, which results in an unreliable broadcast service that is seriously affected by the hidden terminal problem [28]. Such inefficient broadcast service is critically undesired for V2X communications, since all the V2X road safety applications are based on broadcast of safety messages by vehicles and RSUs, both periodically and driven by unusual safety events [5]. Some MAC schemes have been proposed based on distributed TDMA to provide a reliable broadcast service for high priority V2X road safety applications, but none of these protocols has been yet standardized [29] [30].

B. Cellular Technology

The concerns in pure-DSRC V2X communication solutions have raised the interest in the research community to investigate the ability of off-the-shelf cellular technologies (e.g., LTE) to support reliable V2X communications for different applications. There are many enablers for cellular technology to back this interest: a) high network capacity, which enables the support of high bandwidth demand and data-thirsty applications; b) wide cellular coverage range, which reduces the frequency of horizontal handovers since the vehicle-to-BS contact time is relatively long compared to that of the vehicle-to-RSU; and c) mature technology, which eases the implementation and accelerates the deployment of V2X communications. Despite these advantages, there are several challenges that limit the ability of cellular technology to support reliable V2X communications. Due to the centralized control nature of cellular networks, vehicular data need to pass by the BS first, thus limiting its applicability to V2V communications especially for safety applications that have very strict delay requirements[1]. In a unicast mode, a vehicle sends its safety message to a cellular BS, which unicasts the message either to every vehicle in the cell or to the relevant vehicles only[2]. In both cases, studies show that the downlink channel becomes a bottleneck even when there is a small number of vehicles in the cell [42]–[44]. The available broadcast and multicast features that are already supported in the 3GPP standards, namely the multimedia broadcast and multicast services (MBMS) and the evolved MBMS (eMBMS), are promising solutions for safety message dissemination. In a broadcast mode, the BS broadcasts a safety message to all the vehicles in its cell, and it is up to each vehicle to determine the relevance of the received safety message. As a result, vehicles receive many irrelevant messages and conduct unnecessary processing (since the number of vehicles in a BS coverage is much larger than that in the zone of relevance of a safety message [5]). One solution to this problem is to use the multicast service, such that a message is sent to vehicles in a multicast group only. However, this solution can be costly in terms of latency and control signaling overhead associated with the join and leave

[1]Although D2D is a potential solution for V2V communications, it still requires authentication from the BS [3].

[2]Using location information, the BS can determine to which vehicles the message is relevant. Different safety applications have different zone of relevance [5].

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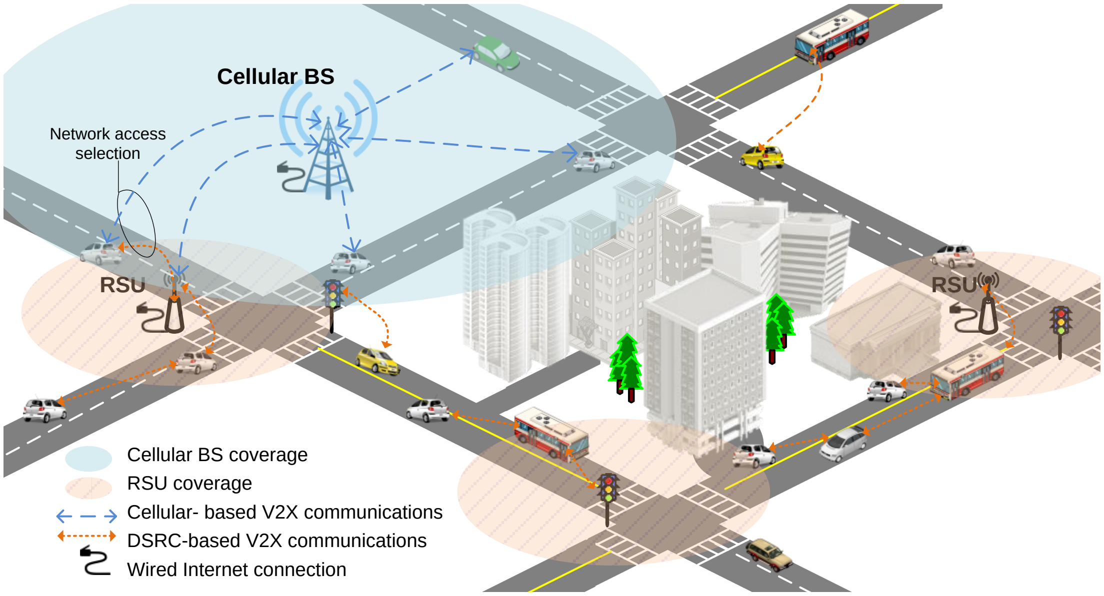

Fig. 2: V2X communications in a DSRC-cellular hybrid urban scenario

procedures of the eMBMS, which are necessary to create a multicast group [45]. Although broadcast/multicast services can reduce the load on the downlink, the uplink channel becomes a bottleneck in a high vehicle density situation, given the fact that uplink transmissions are always achieved using unicast mode [43], [44]. In addition, the performance evaluation of pure-cellular V2X communication solutions need to account for the traditional cellular network traffic (e.g., voice calls), which is generally ignored in existing studies [42]–[44], [46].

III. DSRC-Cellular Interworking

Due to the aforementioned limitations of using a single V2X technology to support efficient and reliable V2X communications, an inclusion of both DSRC and cellular technologies is more viable, as illustrated in Fig. 2. Hybrid solutions that exploit the benefits of both DSRC and cellular technologies have been proposed for vehicular communications. The benefits of making use of the two technologies are as follows. A cellular network can act as a) a backup for vehicular data when V2V multi-hop connections are shattered in a sparse network, b) an access network to the Internet, and c) a backbone network for control message dissemination. For example, the majority of position-based ad-hoc routing protocols in the literature, which are proposed for pure DSRC technology, rely on collecting vehicle information (e.g., GPS location information, vehicle traffic flow condition, etc.) to improve their performance. When such information is scarce or cannot reach source/relay nodes, e.g., due to network fragmentation, ad-hoc routing protocols cannot perform as intended. In this case, cellular networks can be used to connect fragmented network segments, or can be completely relied on to disseminate control-routing information [37], [38]. Also, the currently deployed cellular BSs in urban cities, highways, and rural areas provide a base for in-vehicle Internet access, supporting various infotainment applications [35], [40], [47]. In addition to the enhancement a cellular network can provide to V2X communications, a part of the DSRC spectrum can be utilized opportunistically by cellular networks when cellular-data traffic peaks and V2X-data traffic plummets [48].

A. Hybrid Architecture

Here, we review characteristics of DSRC-cellular hybrid architectures that have been proposed for V2X communications in the literature. In a hybrid DSRC-cellular network, the network nodes are either static (i.e., cellular BSs and RSUs) or mobile (i.e., vehicles), as illustrated in Fig. 3. The static and mobile nodes can be conceptually arranged in a *hierarchical* or *flat* architecture. In the hierarchical architecture, the use of cellular/DSRC technology for V2X communications is restricted to network nodes belonging to specific hierarchical levels[3]. For example, city-owned vehicles, such as transit buses and taxis, may belong to a certain hierarchical level, while the rest of private vehicles may be assigned to a lower level in the hierarchy [31]. In this two-tier hybrid architecture, a city-owned vehicle is equipped with two interfaces: one for access to the cellular network, and the other for communication with other private vehicles (in a lower hierarchical level) via DSRC technology [31]. Such a DSRC-cellular network is said to have a *fixed* hierarchical architecture, since the types of nodes belonging to each level of the hierarchy are pre-selected and do not change with time. On the other hand, in a *dynamic* hierarchy, the nodes are not originally differentiated based on their type and are assumed homogeneous. Then, during network operation, the hierarchical levels are dynamically created and updated based on the variations in network topology, traffic load, etc. One way to achieve a

[3]Usually, restrictions are imposed on the use of cellular technology.

dynamic hierarchy is by employing a node clustering scheme, which groups nearby nodes into a set called *cluster*. Each cluster has cluster head (CH) responsible of maintaining the cluster and managing its network resources. The remaining nodes are called cluster members (CMs), and a CM can belong to multiple clusters. The CH may elect some of its CMs as gateway nodes that facilitate the inter-cluster communications among neighboring clusters. In such a clustered architecture, CHs and gateways create a dynamic hierarchy that can be utilized to relay information to/from the cellular network [32], [34], [35]. For example, a CH can download popular video content from the cellular BS and multicast it using DSRC technology to its CMs [36]. Furthermore, CHs and gateways can aggregate information collected from their CMs before transmitting it to the cellular BS, thus reducing the V2X data traffic load on the cellular network [35]. While a fixed hierarchy provides a simple and time-invariant architecture, it lacks flexibility and robustness to network dynamics (e.g., disconnections and network fragmentation) and sometimes is difficult to implement, such as a public-vehicle-based hierarchy in a non-urban scenario (where public vehicles are sparse) [31]. On the other hand, a cluster-based dynamic hierarchy enables such robustness to network variations, but forming and maintaining node clusters require explicit exchange of messages, which can significantly increase in a highly dynamic vehicular network. Therefore, how to form stable clusters that last for a long time is a major issue to be considered when adopting a cluster-based DSRC-cellular network [49].

Different from a hierarchical architecture, in a flat DSRC-cellular network, the use of cellular or DSRC technology is not restricted to a certain group of nodes. Alternatively, the choice of which technology to employ for V2X communications should be based on the type of transmitted data or on certain performance metrics, which reflect the quality of service (QoS) provisioning, network data-traffic load, or network coverage. For example, the transmission of control packets may be restricted to the cellular network while the forwarding of data traffic is achieved using DSRC [37], [38]. When the V2X communication technology is chosen based on performance metrics, nodes should obtain information updates about both DSRC and cellular systems (e.g., available bandwidth [40] and network connectivity) and the decision is based on the network-selection criteria, as discussed in the following subsection. A classification of the DSRC-cellular hybrid architectures presented in this section is summarized

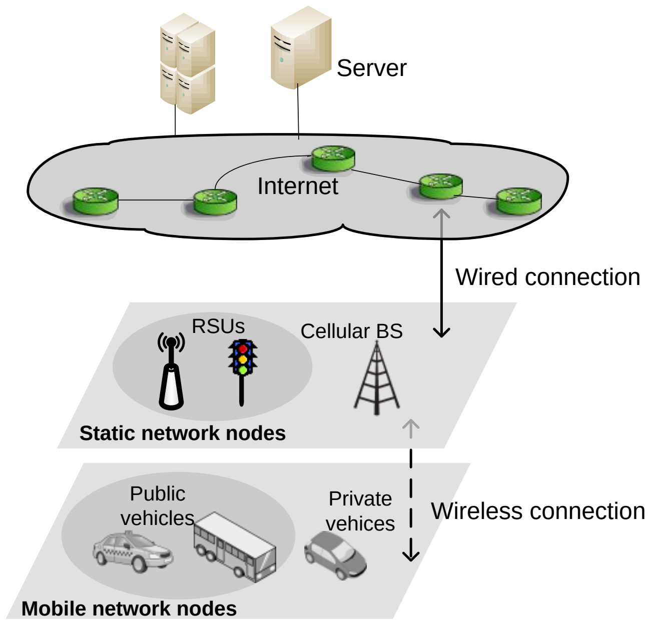

Fig. 3: Network nodes in a DSRC-cellular hybrid architecture

in Table II. In the literature, hybrid architectures have been adopted in various network solutions to support different vehicular applications. Some of these solutions are compared in Table III.

B. Mobility management

Mobility management is a major issue in the design of DSRC-cellular hybrid solutions for V2X communications. Different from traditional mobile ad hoc networks, the high node mobility in vehicular networks can cause frequent network topology changes and fragmentation [50], [51]. Also, urban roads and highways are highly susceptible to vehicle density variations from time-to-time throughout a day. Moreover, in an urban city with many buildings and high towers, V2X communications can experience intermittent connectivity due to channel fading and shadowing, which is spatially correlated with the fixed obstacle locations [36], [46], [52]. Additionally, high vehicle speeds, especially on highways, can induce spatiotemporal variations in network topology, which directly (or indirectly) affect the performance of network protocols [50], [51]. For example, in a clustered DSRC-cellular hybrid architecture, vehicle mobility can

TABLE II: Classification of potential DSRC-cellular hybrid architectures for V2X communications

DSRC-cellular hybrid architecture	Hierarchical	Fixed	[31]
		Dynamic	[32]–[36]
	Flat	Data-centric	[37], [38]
		Performance-centric	[39][a] [40], [41]

[a]This work uses a clustered infrastructure to perform the DSRC-to-cellular gateway selection; however, the gateway is not necessarily a cluster-backbone node.

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TABLE III: Comparison of proposed DSRC-cellular hybrid solutions for V2X communications

Reference	Cellular technology	DSRC/cellular bandwidth aggregation	Hierarchical or flat architecture	Scenario	Supported vehicular communications	MBMS/eMBMS usage	Application
[31]	LTE	No	Hierarchical	Urban	V2X	Not used	Safety message broadcast
[35]	WiMAX	No	Flat	Highway	V2I	Not used	Internet access
[36]	LTE	Yes	Flat	Highway	V2X	Not used	Video sharing
[38]	UMTS	No	Flat	Urban	V2V	MBMS	Routing
[40]	Generic	Yes	Flat	Urban	V2I	Not used	Internet access
[41]	LTE	No	Flat	Highway	V2I	Not used	Internet access
[47]	UMTS/LTE	No	Hierarchical	Urban	V2I	Not used	Internet access

significantly impact the node cluster stability due to its impact on merging and splitting of the clusters, inflicting high clustering control overhead on the network [49]. As a result, vehicle mobility imposes technical challenges in maintaining V2V connections between vehicular nodes [53] and V2I connections between vehicles and BSs/RSUs [54]. Hence, as vehicles move in and out of the coverage areas of other vehicles, RSUs, and cellular BSs, and change their communication point of attachment (PoA), mobility management aims to provide a seamless communication by efficient handover strategies and network selection schemes, as discussed in the following.

1) Handover strategies

There are two types of handover strategies:

a) horizontal handover–when a data transmission session is transferred from one PoA to another on the same network (using the same access technology) [55], and
b) vertical handover–when a data transmission session is transferred from one PoA to another on a different network (using a different access technology) [56].

For example, a horizontal handover is required to transfer an Internet video streaming session of a vehicle from one RSU to another RSU as the vehicle moves between their coverage ranges [57], [58]. On the other hand, a vertical handover is required when an Internet video streaming session is transferred from an RSU to a cellular BS. Since different access technologies have different characteristics (e.g., frequency band, available bandwidth, and modulation and coding schemes), vertical handover is a more challenging task as compared to horizontal handover. Here, we focus on vertical handover and refer to it simply by handover. The core of DSRC-cellular interworking relies on a proper vertical handover strategy that efficiently manages the transfer of ongoing transmissions from one V2X access technology to the other with a low packet-loss and handover latency.

There are different reasons to perform a handover. Handover triggers include: a) communication disconnection due to movement of V2X communicating nodes out of the communication range of each others [41]; b) signal quality degradation due to relative mobility, channel fading, or interference [41], [59]; or c) availability of several networks in the same time/space, making some networks more appealing than the others in terms of billing cost or available bandwidth (e.g., in the overlapping region of cellular BS and RSU's coverage ranges) [41].

Handover management can be implemented in the data link layer [layer two (L2)] or in the network layer [layer three (L3)]. For cellular-mobile terminals (e.g., hand-held devices used by pedestrians or passengers traveling in vehicles), different L3-mobility management solutions have been proposed to support user mobility and provide seamless Internet access over cellular networks. The Internet Engineering Task Force (IETF) has developed mobile IPv6 [60] (L3-protocol) to enable a user from resuming its Internet connectivity when it moves from one access router (AR) to another, by maintaining its original IP address and acquiring a new care-of-address (CoA) from the new AR. This process of obtaining a new CoA introduces latency as the new CoA needs to get registered at the original router, a process referred to as *Binding*, so that the packets addressed to the node's home address can be *tunnelled* to the node. However, during this handover, a mobile user cannot transmit or receive packets until the CoA registration is acknowledged by its original AR. Using mobile IPv6, data transmissions suffers from handover latency due to the link-switching delay and IPv6 protocol operations, including movement detection, handover initiation, new CoA inquiry, Binding update, duplicate address detection (DAD), and Binding acknowledgement [60]. To address the IPv6 protocol operations' delay, a fast handover mobile IPv6 has also been developed by the IETF that enables early detection of the handover and provides information about the new AR while the mobile node is still connected to its current AR [61]. Information about available access routers can be obtained by L2 mechanisms. Yet, this improved handover strategy suffers from signaling overhead and does not address the link-switching delay. To reduce the involvement of mobile nodes (hosts) in the signaling required for mobility management, IETF has put forward centralized mobility management solutions such as Proxy mobile IPv6 and Network Mobility (NEMO) Basic Support protocol to enable network domain entities or mobile

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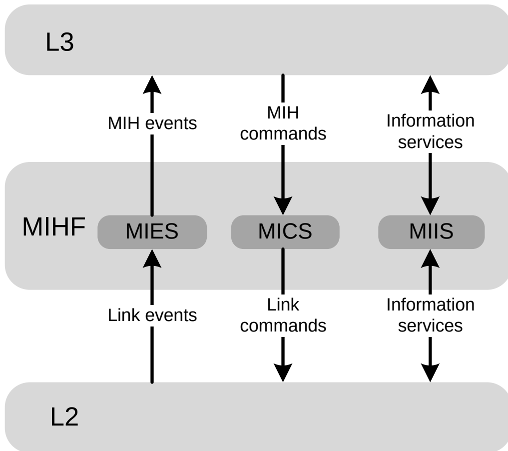

Fig. 4: MIHF entity in the IEEE 802.21 standard [64]

nodes (acting as AR) to collect host information and perform handovers on behalf of hosts [62], [63]. However, the mobile IPv6 protocol and its extensions are not designed for a vehicular environment. Centralized handover management solutions, such as the NEMO Basic Support, in general suffer from high vehicle mobility, as vehicles move out of their *mobile network* and disconnect from the central mobile AR. This issue can be addressed by coexistence of both host-based (distributed) and network-based (centralized) mobility management protocols [47]. Although fast handover mobile IPv6 can perform early L3 handover before L2 handover based on prediction, if the prediction fails and the vehicle does not move to the predicted AR due to unexpected vehicle behaviors, the standard mobile IPv6 procedures are unnecessarily triggered, leading to even more handover latency. One approach to solve this problem is to let a vehicle maintain its original CoA, such that the messages are routed from the original AR to the new AR, and the DAD and Binding processes of the new CoA are performed (in the background) while maintaining continuous IP connectivity [57]. However, the latency mounts as the number of hops between the two ARs increases [57].

The IEEE 802.21-Media independent handover (MIH) standard defines a new MIH function (MIHF) entity between the link layer and the network layer that enables the collection of handover-necessary information between heterogeneous access technologies [64]. The IEEE 802.21 standard specifies three different types of communications with different associated semantics, the so-called MIH services, namely: media independent event services (MIES), media independent command services (MICS), and media independent information services (MIIS), as illustrated in Fig. 4. MIES services support different types of events, such as MAC and PHY state change events, link parameter events, and link transmission events. Before making the handover decision, a mobile node can obtain information about a) its current connection with a point of service (PoS) and b) candidate PoSs with different PoAs. The MICS refers to commands sent from upper layers to inquire about link status information or to configure mobile terminals to facilitate optimal handover policies. Information from the MICS should be combined with network information to support handover decision making. It should be noted that none of the MICS commands affects the routing/forwarding of the user packets, which is done by the upper layer mobility management protocols, such as mobile IPv6. The MIIS provides a framework through which the MIHF can obtain network information (within a geographical area) that is needed in the network selection for a successful handover [64]. To utilize MIHF services for vehicular communications, the MIIS should account for the QoS requirements of different applications (e.g., virtual updates for low-latency online gaming [65]) and of different data flow traffic classes, in order to manage data flow division in L3-mobility management protocols [66]. IPv6-based mobility management solutions (mobile IPv6, NEMO Basic Support, and fast handover Mobile IPv6) for vehicular communications focus on seamless Internet connection. However, for V2X communications that do not involve Internet access, such as in V2V safety message broadcast or V2I content distribution, a mobility management solution should account for the transfer of data transmissions among different access technologies and different types of V2X communications (V2V/V2I), based on the decision made in network selection. For example, the broadcast of safety messages by vehicles and RSUs can switch between DSRC-based broadcast and cellular eMBMS, in a way which guarantees reliable and timely delivery of each safety message to all the intended receivers.

2) Network selection schemes

As discussed earlier, there are different factors that can trigger a handover. Network selection is the process of making a handover decision based on handover triggers. Handover triggers can be user-centric or network-centric. The former includes a) financial cost: cellular-based network services are currently available to users by subscription fees (i.e., data plans), while DSRC-based networks are likely to be free, especially for safety-related applications; and b) QoS provisioning: the user QoS is generally based on metrics such as the end-to-end delay, packet loss, throughput, and other application-specific requirements such as the video quality in case of video streaming and online-gaming [36], [39], [65]. Network-centric handover triggers include: a) data-traffic priority (vehicular data-traffic is split into classes with different priorities); b) load balancing among different cellular BSs/RSUs according to their capacities [41]; c) fairness guarantees for different users [41], [59]; and d) network throughput maximization, which is a main objective that can trigger handovers as it maximizes the power of the network to support user demands in terms of available bandwidth and required latency. Network selection schemes can utilize user-centric, network-centric, or a combination of both user- and network-centric handover triggers to set a utility/objective function to decide whether or not a handover should be initiated [59]. It should be noted

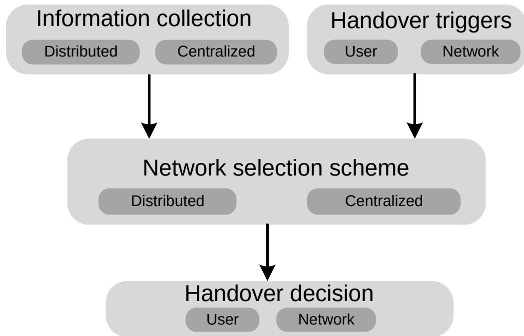

Fig. 5: The logic of network selection based on handover triggers

that a QoS mapping is required between different access technologies [56]. For example, the priorities of vehicular data traffic classes set in the IEEE 1609.4 standard should be mapped to the cellular-technology standard to maintain the expected QoS provisioning level [39].

These user- and network-centric triggers are just measures that drive the handover decision. User and network information should be collected and provided as an input for the network selection scheme to decide whether or not a handover should be initiated, based on the handover triggers, as illustrated in Fig. 5. The process of collecting the handover-related information can be either distributed or centralized. In the distributed approach, each node can rely on the received signal strength (RSS) information from different networks in range as an indicator for the networks' ability to support its QoS requirements [39], [41], [59]. On the other hand, in the centralized approach, a network entity may be responsible for collecting and processing handover-related information, for example by crowd-sourcing vehicle information and uploading it to a cloud or a central controller through cellular BSs/RSUs [41], [59].

Network selection schemes proposed in the literature are either distributed or centralized based on the type of algorithm and the entity that runs the algorithm. For example, game-theoretic approaches are generally distributed, since each vehicle selects its network based on its local information, independently from other vehicles [59]. On the other hand, a centralized entity such as a mobile AR, CH, RSU, BS, or cloud can perform optimization-based network selection on a predefined utility function [40], [41]. A utility function can incorporate different handover triggers, such as network load balancing and fairness [41], QoS requirements for different flow classes [66], or available data rate per vehicle per access technology [59].

The completely distributed network selection based on local information can suffer from bad handover decisions due to limited or inaccurate local information in some vehicles, and from fairness issues as a result of each vehicle trying to optimize its own experience. On the other hand, a central controller with global information can perform an early prediction for the time a vehicle would require a handover and push the handover information to the vehicle [59]. Although the handover information collection and the network selection can be centralized, the handover decision can still be left for the individual nodes to make [59]. This approach gives each node the freedom of decision and the robustness against disconnections from the central controller that is running the selection scheme. In case of a disconnection, a node can decide to initiate a handover based on local information (e.g., RSS from neighboring RSUs/BSs).

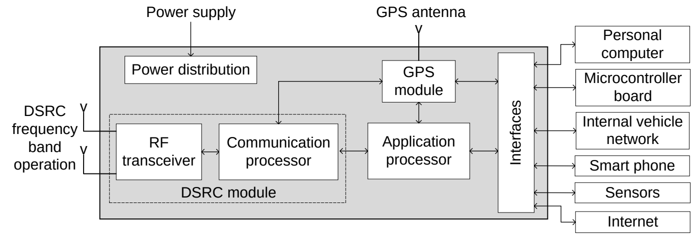

Fig. 6: Illustration of a generic R&D platform for V2X communications

IV. V2X Commercial Products

The tremendous efforts from academia, governments, and automotive industries toward developing V2X communication technology have reached a turning point. It is necessary not only to propose new V2X communication schemes/applications and evaluate their performance via mathematical analysis or computer simulations, but more importantly to show the feasibility and implementation cost of the proposed schemes/applications, how they perform in real vehicular environments, and whether or not they can be integrated with the V2X products that are currently installed in vehicles by leading car manufacturers. Hence, this section provides an overview of the existing V2X communication systems in the market, which are mainly classified into platforms for V2X R&D and products that are already adopted and deployed by automotive companies. While the R&D platforms primarily use DSRC for V2X communications, the V2X products that exist in today's vehicles are mostly based on cellular network technologies. Both categories of commercial V2X systems are discussed separately in the following.

A. R&D Platforms

The R&D platforms aim at providing a solution for developing and testing V2X applications based on DSRC, in order to be used for academic research and field experiments (by government/industry consortiums), or as a reference design for automotive built-in and aftermarket V2X products. Generally, an R&D platform includes a DSRC module, an application processor, a GPS module, and a set of interfaces to external devices and networks, as shown in Fig. 6. The DSRC module consists of a radio frequency (RF) transceiver that operates over the DSRC spectrum, based on the IEEE 802.11p

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standard physical layer, and a communication processor that typically implements the standard IEEE 802.11p/1609.4 MAC layer in multichannel operation. The application processor runs the operating system of the platform, supports security and networking services (mainly according to the IEEE 1609.2/3 standards), and allows for the implementation of user-developed V2X applications based on the DSRC protocol stack. The GPS module provides localization, timing, and synchronization services for both of the DSRC module and the application processor. To facilitate V2X application development, the platform usually comes with a software development kit (SDK), which provides a set of application programming interfaces (APIs) for developers to utilize the various platform features. Due to novelty of the V2X technology, there are only a few V2X R&D platforms currently available. Each platform is equipped with a DSRC module, which is produced by one of three main suppliers, as listed in Table IV, indicating the RF transceiver and communication processor models for each supplier. The commercial R&D platforms include OBUs, RSUs, and portable DSRC devices. While the DSRC protocol stack is similar for an OBU, an RSU, and a portable DSRC device (when produced by the same supplier), these platforms mainly differ in system interface, enclosure type, and power supply method. For instance, an OBU may have a connector to the vehicle controlled area network (CAN) bus (e.g., to receive readings from the vehicle built-in sensors), while an RSU or a portable DSRC device do not require a similar interface. Also, an OBU is usually powered by 12V DC, in order to be plugged-in one of the vehicle's auxiliary power outlets. On the other hand, a portable DSRC device includes a chargeable battery, while an RSU typically has a power over ethernet (PoE) option, which is suitable for street deployment, e.g., to connect multiple RSUs to one PoE switch providing both power supply and backhaul connection. In terms of hardware enclosure, the OBUs and portable devices do not require special enclosure types, unlike the RSUs that need to comply with specific enclosure standards, e.g., NEMA4, for protection against outdoor environmental conditions, such as rain.

From a developer's perspective, the quality of an R&D platform depends not only on the supported DSRC protocol stack, DSRC module features, and interface options, but also on the provided SDK and the method of interactive communication with the platform. Most of the R&D platforms are based on Linux operating system, with a secure shell (SSH) or Telnet server to interact with the platform. Also, some suppliers provide a graphical user interface (GUI) for controling and real-time monitoring of the platform. The SDK commonly provides APIs for configuring the radio interfaces, accessing the networking services of the DSRC protocol stack, reading the location and time information from the GPS module, and communicating with the external devices connected to the platform, e.g., to send information to a smart phone acting as a human-machine interface. Additionally, some SDKs include APIs for encoding and decoding application layer messages, as defined in the SAE J2735 standard, and give sample applications to demonstrate the use of these messages. Table V shows a comparison among the existing V2X R&D platforms, in terms of platform type, DSRC module provider, and supported standards. One feature that is not supported by any of the indicated V2X R&D platforms is the integration of DSRC and cellular network modules on the same platform, in order to implement and test DSRC-cellular interworking schemes, such as for vertical handover. One step toward providing this integrated R&D platform is the Qualcomm Snapdragon 602A system-on-chip (SoC), which includes an LTE modem and a DSRC module, and has a development platform for automotive applications. Also, the 'Connected Car Platform' provided by Lesswire currently includes LTE/UMTS connectivity and expected to integrate a DSRC module in the future.

TABLE IV: Current DSRC module suppliers

DSRC module supplier	RF transceiver	Communication processor
NXP	TEF510x	SAF510x
Autotalks	PLUTON (ATK3100B0)	CRATON (ATK4100A1)
Qualcomm	VIVE QCA65x4	

B. Deployed Products

In order to improve the safety and efficiency of our transportation system, newly manufactured vehicles are equipped with powerful sensing, computing, storage, and processing capabilities. This vehicle intelligence has enabled numerous applications aiming to improve the experience of both drivers and passengers in terms of safety and entertainment. Based on on-board cameras, radars, and sensors, many advanced driver assistance systems (ADAS) already exist in our cars, such as parking assistance, lane change warning, blind spot warning, speed limit information, and so on. In addition, some connected vehicle-related products have been appearing in the market [67]. In the following, we review recent connected vehicle products that have been deployed by some car manufacturers.

One of the earliest connected vehicle products is General Motors' (GM) OnStar communications system. Using cellular network and GPS technology, OnStar supports V2I communications for many applications including: a) automatic crash response (activated either automatically from on-board sensor information or manually by pressing a button), to connect the driver to a call center to provide the necessary assistance to the vehicle's GPS location; b) diver behavior rewards, to track the driver behavior and connect the driver to insurance companies for special discounts, thus encouraging good driving habits and improving road-safety; c) advanced diagnostics, to collect vehicle information (e.g., transmission, engine, CO2 emissions, brakes, and battery) from the on-board diagnostic (OBD) system and provide real-time proactive alerts appearing on the vehicle's monitor and on the driver's smart phone [through a mobile application (App)]; d) anti-theft program, to locate a vehicle for law enforcement when the vehicle is

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TABLE V: Current R&D platforms

Platform supplier	Platform model			DSRC module supplier	Supported standards			
	OBU	RSU	Portable		IEEE WAVE	ETSI ITS	ARIB STD-T109	SAE J2735
Arada Systems	LocoMate OBU	LocoMate RSU	LocoMate ME	Qualcomm	Yes	No	No	Yes
Autotalks	PANGEA4	-	-	Autotalks	Yes	Yes	Yes	No
Cohda Wireless	MK5-OBU	MK5-RSU	-	NXP	Yes	Yes	No	Yes
Kapsch TrafficCom	EVK-3300 and TS3306	MTX-9450	-	'undisclosed'	Yes	Yes	No	Yes
Savari Networks	MobiWAVE	StreetWAVE	-	Qualcomm	Yes	No	No	Yes

reported missing, prevent the thief from starting/restarting the vehicle by activating *Remote Ignition Block*, and send a *Stolen Vehicle Slowdown* signal to gradually reduce the speed of the stolen vehicle at the request of the law enforcement; and e) mobile WiFi hotspot, to provide easy Internet access to in-vehicle hand-held devices based on an LTE connection. OnStar services are subject to subscription charges, and OnStar Internet access is provided in partnership with a mobile network carrier. For example, currently, AT&T provides this service for GM customers in the U.S. under a data plan (e.g., 1GB data for 20$ per month)[4]. The quality of OnStar's Internet access is contingent on the wireless carrier coverage and technology. As a result, in-vehicle Internet access may suffer from intermittent connectivity as the vehicle drives on the road. Beside cellular-based safety and infotainment services, GM has announced the deployment of DSRC technology in some selected 2017 models to enable V2V communications and support safety applications. Furthermore, GM has introduced new in-vehicle, remote, and smart grid APIs for developers to build mobile applications for connected vehicles.

Another already deployed connected-vehicle product is the BMW's *ConnectedDrive* system. This system is based on Context Aware centralized server architecture, as illustrated in Fig. 7. It focuses on using on-board sensor information collected about the vehicle and the surrounding environment to provide context awareness for the drivers according to their specific tasks. Collected sensor data are fused and processed to infer information that runs different applications, and to generate statistical models that can then be used to enhance the performance of the inference process. Through cellular networks (embedded SIM card), many infotainment applications are supported in ConnectedDrive, providing the driver with weather and news information, online Internet search, and mobile office functions (e.g., email). Mobile Apps on a driver's hand-held device can also be integrated into the vehicle's ConnectedDrive system, thus notifying the driver with calender or social media activities. In addition, the vehicle owner can remotely lock, locate, or heat the vehicle using a mobile application on a hand-held device. Real-time traffic conditions based on GPS information from vehicles and hand-held devices are aggregated and provided to the driver to optimize route choices. Similar to OnStar, BMW ConnectedDrive enables a mobile WiFi hotspot via LTE connection for in-vehicle portable devices to enjoy Internet access. ConnectedDrive services are also subject to subscription charges.

Similar connected vehicle services can be found in Volvo's newly manufactured vehicles with *Sensus* system. The Volvo's Sensus system is based on Ericsson's *Connected Vehicle Cloud*, and is the result of collaboration among Ericsson, AT&T, and Volvo [69]. The Ericsson's connected vehicle cloud solution is built on top of its *Service Enablement Platform*, which connects operators and service providers with customers, and enables cooperation among multiple service providers. With the connected vehicle cloud, not only different applications can be loaded into the vehicle to provide various services to the driver and passengers, but also vehicle information can be integrated with the loaded applications to enhance driver and passenger experience. For example, when a driver wants to find a near-by restaurant, the request and vehicle location information are integrated with a parking application, which can recommend a parking spot that is in accordance to the driving direction and a selected restaurant's location. Since the Ericsson's connected-car solution is cloud-based, the vehicle is always being monitored and the vehicle information is continuously logged. The availability of such

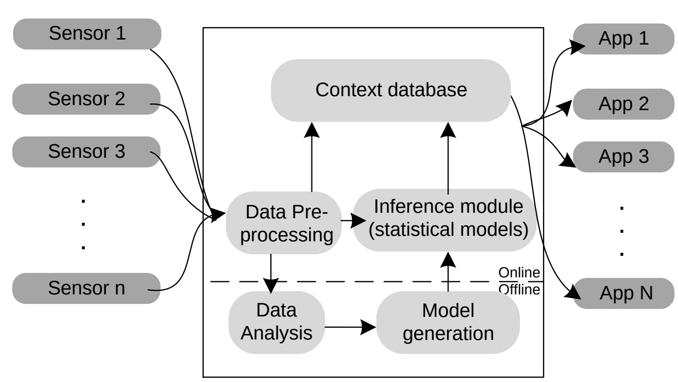

Fig. 7: BMW ConnectedDrive context server architecture [68]

[4]Verizon used to be the service provider for GM's OnStar. Verizon has announced its own connected-vehicle services with plug-in Delphi connect modules by Delphi auto-manufacturer.

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TABLE VI: Comparison of currently deployed connected-vehicle services

Connected vehicle system	WiFi hotspot	Call center	Cloud-based	Wireless vehicle control	Mobile Apps
GM OnStar	Yes	Yes	No	Yes	Yes
BMW ConnectedDrive	Yes	Yes	No	Yes	Yes
Volvo Sensus	No[a]	Yes	Yes	Yes	Yes
Ford SYNC	No[a]	No[b]	Yes	No	Yes

[a]Only available through a paired phone that can act as a hotspot
[b]Only automatic 911 call through paired phone in case of a crash

real-time information can support cloud-based road-condition information dissemination among vehicles. For example, from tires' movement, sensors can detect icy roads and upload this information to the cloud, which disseminates a slippery-road alert to vehicles heading towards that patch. The technology is currently under a 50-1000 car fleet test by Volvo, and is expected to be available to customers within a few years [70]. Cloud-based platforms have been adopted by other car manufacturers. For instance, Ford utilizes the Microsoft's Azure cloud computing platform to perform wireless automatic updates to its SYNC system via WiFi connections. However, Ford SYNC services are only based on a Bluetooth paired-smart phone. The connected-vehicle services discussed in this subsection are compared in Table VI.

V. Discussion and open issues

With the continous technological evolution, both DSRC and cellular technologies are subject to change. Therefore, some (or all) of the limitations, discussed in Section II, that hinder each of the technologies in supporting V2X communications can vanish. New amendments of IEEE802.11 standard and new generations of cellular networks can emerge. In fact, the 3GPP group has recently approved a new working item (WI) specifically to study the feasibility of LTE support for V2X communications and to investigate enhancements to existing cellular services (such as ProSe D2D services) to enable direct and reliable V2V communications [3], [71]. Therefore, DSRC-cellular interworking solutions should take into account the advancements in the DSRC and cellular technologies. For example, as discussed in Subsection II-B, one of the main drives for using cellular network technology to support V2X communications is the large BS coverage range, which bridges the disconnections in a sparse vehicular network and minimizes the number of handovers as a vehicle traverses a road segment. However, the next generation of cellular technology is expected to adopt a smaller BS coverage range in an effort to increase network capacity, further hindering handover management [72]. Therefore, vehicular mobility management strategies should be designed for the expected ultra-dense deployment of small cells in the next cellular network generation, while preserving backward compatibility with current and previous generations.

Beside the handover triggers discussed In Subsection III-B, there are other considerations to be taken into account when designing the criteria for network selection between DSRC and cellular technologies. One issue to be considered in network selection criteria is the preference to the network in use. That is, a vehicle-user may prefer to maintain its current network connection than switching to another only for a slight increase in performance or quality of experience. For example, in the system model considered in [41], where a BS coverage range spans the whole highway segment and the RSUs are scattered with non-overlapping coverage ranges along the highway, a vehicle may favor to remain connected to the BS over switching the connection temporarily to an RSU for an incremental enhancement in Internet access. Hence, prediction-based network selection is required to reduce unnecessary frequent handovers as vehicles move in and out of the coverage ranges of RSUs. The time durations of V2V and V2I connections can be predicted through probabilistic models [53], [54] or through cloud-assisted information crowd-sourcing [37], [59]. Another issue of importance to the network selection decisions is the market penetration rate of network technologies. In a scenario where not all the vehicles are enabled with dual-interface for DSRC and cellular network access, fairness issues may arise, especially when network selection and handover decisions are made solely by each vehicle and considering only the vehicle's own preferences. Also, the market penetration of both technologies should be accounted for in the network selection. For example, in safety message broadcast, a V2X technology should be chosen if more source-vehicle neighbors are equipped with the technology, since the safety improves when a larger number of neighboring vehicles receive the safety message on time [55]. The computational complexity of the network selection algorithm should be considered especially for delay sensitive V2X applications. Network selection based on game-theory or optimization methods requires non-trivial computing capabilities. On the other hand, software defined networks (SDNs) are a promising architecture in which the data plane is separated from the control plane. In an SDN, the processes of network detection and selection take place on the control plane, where an SDN controller can further utilize cloud resources and the availability of global network topology information to optimize these processes in a timely fashion

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[37], [59]. However, a low-overhead mechanism is required to collect and maintain an up-to-date database of global network topology information in a highly dynamic vehicular network [37], [59]. Additionally, a backup mechanism should be in place to deal with vehicle disconnections from the central controller [37].

As mentioned in Subsection IV-B, the collaborations among telecommunication companies, car manufacturers, and cloud-service providers have made some connected vehicle services available in the market. The majority of these services bring to the driver a variety of applications that interconnect information from different on-board sensors (Fig. 7), social networks, and home and entreprise networks. Such applications are expected to fuse data obtained from V2X communications, thus elevating their performance. How to enhance existing connected vehicle services with V2X communications information and how to integrate such information in existing ADAS systems need further studies.

VI. Conclusions

V2X communications technology is expected to revolutionize the ground transportation system by providing a safer, smarter, less polluted, and more entertaining environment for people on roads. To support V2X applications for a large number of vehicles, interworking between DSRC and cellular network technologies is a promising approach, which can be based on a flat or a hierarchical DSRC-cellular hybrid architecture. However, in order to efficiently achieve such DSRC-cellular interworking, we need to resolve many technical issues, mainly originating from the highly dynamic vehicular network topology, together with the trend of small-cell deployment in next generation cellular networks, which requires effective vertical handover techniques and network selection schemes. With the current momentum in R&D for V2X communications, the development of future V2X solutions should balance various factors such as the implementation cost, performance in real vehicular environments, and compatibility with the existing V2X systems. Hence, the paper gives an overview about the available V2X R&D platforms to implement and test newly proposed solutions, and the adopted V2X products that exist in today's vehicles. Nevertheless, there is a current need for an R&D platform that integrates DSRC and cellular network modules, in order to develop and evaluate novel DSRC-cellular interworking schemes.

References

[1] L. Blincoe *et al.*, "The economic and societal impact of motor vehicle crashes, 2010 (revised)," U.S. National Highway Traffic Safety Administration (NHTSA), Tech. Rep. DOT HS 812 013, 2015.

[2] D. Schrank, B. Eisele, T. Lomax, and J. Bak, "2015 urban mobility scorecard," Texas A&M Transportation Institute, 2015.

[3] "Study on LTE-based V2X services (release 14)," Third Generation Partnership Project (3GPP), Technical Specification Group Services and System Aspects (TSG SA), 3GPP TR 36.885, 2016.

[4] H. T. Cheng, H. Shan, and W. Zhuang, "Infotainment and road safety service support in vehicular networking: From a communication perspective," *Mechanical Systems and Signal Processing*, vol. 25, no. 6, pp. 2020–2038, 2011.

[5] "Vehicle safety communications project task 3 final report," The CAMP Vehicle Safety Communications Consortium, Tech. Rep. DOT HS 809 859, 2005.

[6] "Vehicle safety communications-applications (VSC-A) final report," The CAMP Vehicle Safety Communications 2 Consortium, Tech. Rep. DOT HS 811 492A, 2011.

[7] R. Baldessari *et al.*, "Car-2-car communication consortium manifesto," Tech. Rep. Version 1.1, 2007. [Online]. Available: https://www.car-2-car.org/index.php?id=31

[8] J. Harding *et al.*, "Vehicle-to-vehicle communications: readiness of V2V technology for application," U.S. National Highway Traffic Safety Administration (NHTSA), Tech. Rep. DOT HS 812 014, 2014.

[9] "Connected vehicle pilot deployment program," U.S. Departement of Transportation (DOT) fact sheet, 2015. [Online]. Available: http://www.its.dot.gov/factsheets/pdf/JPO_CVPilot.pdf

[10] "Cisco visual networking index: forecast and methodology, 2014-2019," Cisco White paper, 2015.

[11] "Global smart transportation market 2014-2018," Technavio report, 2014.

[12] "Standard specification for dedicated short range communication (DSRC) physical layer using microwave in the 902 to 928 MHz band (withdrawn 2010)," American Society for Testing and Materials (ASTM) standard, ASTM E2158-01, 2001.

[13] "DSRC 915MHz: dedicated short range communication at 915 MHz standards group," U.S. Department of Transportation (USDOT), 2015. [Online]. Available: http://www.iteris.com/itsarch/html/standard/dsrc915mhz.htm

[14] "Draft standard for dedicated short range, two-way vehicle to roadside communications equipment," American Society for Testing and Materials (ASTM) draft standard 6, 1996.

[15] "FCC report and order 03-324," U.S. Federal Communications Commission (FCC), 2004. [Online]. Available: https://apps.fcc.gov/edocs_public/attachmatch/FCC-03-324A1.pdf

[16] "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," European Telecommunications Standards Institute (ETSI) standard, ETSI ES 202 663 V1.1.0, 2010. [Online]. Available: http://www.etsi.org/deliver/etsi_es/202600_202699/202663/01.01.00_60/es_202663v010100p.pdf

[17] "Electromagnetic compatibility and radio spectrum matters (ERM); road transport and traffic telematics (RTTT); dedicated short range communication (DSRC) transmission equipment (500 kbit/s / 250 kbit/s) operating in the 5,8 GHz industrial, scientific and medical (ISM) band; part 1: general characteristics and test methods for road side units (RSU) and on-board units (OBU)," European Telecommunications Standards Institute (ETSI) european standard, ETSI EN 300 674-1 V1.2.1, 2004. [Online]. Available: http://www.etsi.org/deliver/etsi_en/300600_300699/30067401/01.02.01_60/en_30067401v010201p.pdf

[18] "ECC/DEC/(02)01: ECC decision of 15 march 2002 on the frequency bands to be designated for the co-ordinated introduction of road transport and traffic telematic systems," European Conference of Postal and Telecommunications Administrations (CEPT), 2002. [Online]. Available: http://www.erodocdb.dk/docs/doc98/official/pdf/Dec0201.pdf

[19] "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," European Telecommunications Standards Institute (ETSI) european standard, ETSI EN 302 571 V1.2.1, 2013. [Online]. Available: http://www.etsi.org/deliver/etsi_en/302500_302599/302571/01.02.01_60/en_302571v010201p.pdf

[20] "700 MHz band intelligent transportation systems," Association of Radio Industries and Businesses (ARIB) standard, ARIB STD-T109, 2012. [Online]. Available: http://www.arib.or.jp/english/html/overview/doc/5-STD-T109v1_2-E1.pdf

[21] "Frequency allocation table 2 (annexes 8.8 and 11.3)," Ministry of Internal Affairs and Communications (MIC) in Japan, 2015. [Online]. Available: http://www.tele.soumu.go.jp/e/adm/freq/search/share/plan.htm

[22] "Dedicated short range communication for transport information and control systems," Association of Radio Industries and Businesses (ARIB) standard, ARIB STD-T55, 1997. [Online]. Available: http://www.arib.or.jp/english/html/overview/doc/5-STD-T55v1_0-E.pdf

[23] "Dedicated short range communication system," Association of Radio Industries and Businesses (ARIB) standard, ARIB STD-T75,

2001. [Online]. Available: http://www.arib.or.jp/english/html/overview/doc/5-STD-T75v1_0-E2.pdf

[24] "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," IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007), pp. 1–2793, 2012.

[25] "Dedicated short range communications (DSRC) message set dictionary," Society of Automotive Engineers (SAE) standard, SAE J2735, 2009.

[26] "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 (amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009), pp. 1–51, 2010.

[27] "Specification for telecommunications and information exchange between roadside and vehicle systems 5 GHz band dedicated short range communications (DSRC) medium access control (MAC) and physical layer (PHY) specifications," American Society for Testing and Materials (ASTM) standard, ASTM E2213, 2003 (2010).

[28] H. A. Omar, W. Zhuang, A. Abdrabou, and L. Li, "Performance evaluation of VeMAC supporting safety applications in vehicular networks," *IEEE Trans. on Emerging Topics in Computing*, vol. 1, no. 1, pp. 69-83, 2013.

[29] H. Omar, W. Zhuang, and L. Li, "VeMAC: a TDMA-based MAC protocol for reliable broadcast in VANETs," *IEEE Trans. Mobile Computing*, vol. 12, no. 9, pp. 1724–1736, 2013.

[30] F. Borgonovo, A. Capone, M. Cesana, and L. Fratta, "ADHOC MAC: new MAC architecture for ad hoc networks providing efficient and reliable point-to-point and broadcast services," *Wireless Networks*, vol. 10, pp. 359–366, 2004.

[31] B. Liu, D. Jia, J. Wang, K. Lu, and L. Wu, "Cloud-assisted safety message dissemination in VANET-cellular heterogeneous wireless network," *IEEE Systems Journal*, in press, 2015.

[32] A. Benslimane, T. Taleb, and R. Sivaraj, "Dynamic clustering-based adaptive mobile gateway management in integrated VANET3G heterogeneous wireless networks," *IEEE J. Selected Areas in Communications (JSAC)*, vol. 29, no. 3, pp. 559–570, 2011.

[33] R. Sivaraj, A. K. Gopalakrishna, M. G. Chandra, and P. Balamuralidhar, "QoS-enabled group communication in integrated VANET-LTE heterogeneous wireless networks," in *Proc. IEEE WiMob*, 2011, pp. 17–24.

[34] S. Ucar, S. Coleri Ergen, and O. Ozkasap, "Multi-hop cluster based IEEE 802.11p and LTE hybrid architecture for VANET safety message dissemination," *IEEE Trans. Vehicular Technology*, vol. 65, no. 4, pp. 2621–2636, 2015.

[35] K. Yang, S. Ou, H.-H. Chen, and J. He, "A multihop peer-communication protocol with fairness guarantee for IEEE 802.16-based vehicular networks," *IEEE Trans. Vehicular Technology*, vol. 56, no. 6, pp. 3358–3370, 2007.

[36] E. Yaacoub, F. Filali, and A. Abu-Dayya, "QoE enhancement of SVC video streaming over vehicular networks using cooperative LTE/802.11 p communications," *IEEE J. Selected Topics in Signal Processing*, vol. 9, no. 1, pp. 37–49, 2015.

[37] I. Ku, Y. Lu, M. Gerla, F. Ongaro, R. L. Gomes, and E. Cerqueira, "Towards software-defined VANET: architecture and services," in *Proc. IEEE MED-HOC-NET*, 2014, pp. 103–110.

[38] I. Lequerica, P. Ruiz, and V. Cabrera, "Improvement of vehicular communications by using 3G capabilities to disseminate control information," *IEEE Network*, vol. 24, no. 1, pp. 32–38, 2010.

[39] G. El Mouna Zhioua, N. Tabbane, H. Labiod, and S. Tabbane, "A fuzzy multi-metric QoS-balancing gateway selection algorithm in a clustered VANET to LTE advanced hybrid cellular network," *IEEE Trans. Vehicular Technology*, vol. 64, no. 2, pp. 804–817, 2015.

[40] H. Zhang, F. Bai, and X. Ju, "Heterogeneous vehicular wireless networking: a theoretical perspective," in *Proc. IEEE WCNC*, 2015, pp. 1936–1941.

[41] S. Bi, C. Chen, R. Du, and X. Guan, "Proper handover between VANET and cellular network improves Internet access," in *Proc. IEEE VTC*, 2014, pp. 1–5.

[42] G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro, "LTE for vehicular networking: a survey," *IEEE Communications Magazine*, vol. 51, no. 5, pp. 148–157, 2013.

[43] A. Vinel, "3GPP LTE versus IEEE 802.11p/WAVE: which technology is able to support cooperative vehicular safety applications?" *IEEE Wireless Communications Letters*, vol. 1, no. 2, pp. 125–128, 2012.

[44] J. Calabuig, J. Monserrat, D. Gozalvez, and O. Klemp, "Safety on the roads: LTE alternatives for sending ITS messages," *IEEE Vehicular Technology Magazine*, vol. 9, no. 4, pp. 61–70, 2014.

[45] "Multimedia broadcast/multicast service (MBMS); architecture and functional description (release 13)." Third Generation Partnership Project (3GPP), Technical Specification Group Services and System Aspects (TSG SA), 3GPP TS 23.246 V13.0.0, 2015.

[46] T. Mangel, T. Kosch, and H. Hartenstein, "A comparison of UMTS and LTE for vehicular safety communication at intersections," in *Proc. IEEE VNC*, 2010, pp. 293–300.

[47] S. Cespedes and X. Shen, "On achieving seamless IP communications in heterogeneous vehicular networks," *IEEE Trans. Intelligent Transportation Systems*, vol. 16, no. 6, pp. 3223–3237, 2015.

[48] Y. Wang, J. Jose, J. Li, X. Wu, and S. Subramanian, "Opportunistic use of the DSRC spectrum," U.S. Patent App. 13/921,706 US20140378054 A1, 2013.

[49] K. Abboud and W. Zhuang, "Stochastic modeling of single-hop cluster stability in vehicular ad hoc networks," *IEEE Trans. Vehicular Technology*, vol. 65, no. 1, pp. 226–240, 2015.

[50] K. Abboud and W. Zhuang, *Mobility Modeling for Vehicular Communication Networks*, springer Briefs in Computer Science, ISBN 978-3-319-25507-1 DOI: 10.1007/978-3-319-25507-1, 2015.

[51] F. Bai and B. Krishnamachari, "Spatio-temporal variations of vehicle traffic in VANETs: facts and implications," in *Proc. ACM VANET*, 2009, pp. 43–52.

[52] C. Sommer, S. Joerer, M. Segata, O. Tonguz, R. Cigno, and F. Dressler, "How shadowing hurts vehicular communications and how dynamic beaconing can help," *IEEE Trans. Mobile Computing*, vol. 14, no. 7, pp. 1411–1421, 2015.

[53] K. Abboud and W. Zhuang, "Stochastic analysis of a single-hop communication link in vehicular ad hoc networks," *IEEE Trans. Intelligent Transportation Systems*, vol. 15, no. 5, pp. 2297–2307, 2014.

[54] W. Zhang, Y. Chen, Y. Yang, X. Wang, Y. Zhang, X. Hong, and G. Mao, "Multi-hop connectivity probability in infrastructure-based vehicular networks," *IEEE J. Selected Areas in Communications (JSAC)*, vol. 30, no. 4, pp. 740–747, 2012.

[55] E. Hossain, G. Chow, V. C. Leung, R. D. McLeod, J. Mišić, V. W. Wong, and O. Yang, "Vehicular telematics over heterogeneous wireless networks: a survey," *Computer Communications*, vol. 33, no. 7, pp. 775–793, 2010.

[56] S. Fernandes and A. Karmouch, "Vertical mobility management architectures in wireless networks: a comprehensive survey and future directions," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 1, pp. 45–63, 2012.

[57] H. Oh and C.-K. Kim, "A robust handover under analysis of unexpected vehicle behaviors in vehicular ad-hoc network," in *Proc. IEEE VTC*, 2010, pp. 1–7.

[58] K. Zhu, D. Niyato, P. Wang, E. Hossain, and D. In Kim, "Mobility and handoff management in vehicular networks: a survey," *Wireless communications and mobile computing*, vol. 11, no. 4, pp. 459–476, 2011.

[59] K. Xu, K. Wang, R. Amin, J. Martin, and R. Izard, "A fast cloud-based network selection scheme using coalition formation games in vehicular networks," *IEEE Trans. Vehicular Technology*, vol. 64, no. 11, pp. 5327–5339, 2014.

[60] E. C. Perkins *et al.*, "Mobility support in IPv6," Internet Engineering Task Force (IETF) Request for Comments, RFC 3775, 2011.

[61] R. Koodli, "Mobile IPv6 fast handovers," Internet Engineering Task Force (IETF) Request for Comments, RFC 5568, 2009.

[62] E. S. Gundavelli *et al.*, "Proxy mobile IPv6," Internet Engineering Task Force (IETF) Request for Comments, RFC 5213, 2008.

[63] V. Devarapalli *et al.*, "Network mobility (NEMO) basic support protocol," Internet Engineering Task Force (IETF) Request for Comments, RFC 3963, 2005.

[64] A. De La Oliva, A. Banchs, I. Soto, T. Melia, and A. Vidal, "An overview of IEEE 802.21: media-independent handover services," *IEEE Wireless Communications*, vol. 15, no. 4, pp. 96–103, 2008.

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[65] R. I. Meneguette, L. F. Bittencourt, and E. R. Madeira, "User-centric mobility management architecture for vehicular networks." in *Proc. MONAMI*, 2012, pp. 42–56.

[66] R. I. Meneguette, L. F. Bittencourt, and E. R. M. Madeira, "A seamless flow mobility management architecture for vehicular communication networks," *Communications and Networks*, vol. 15, no. 2, pp. 207–216, 2013.

[67] W. Fleming, "Forty-year review of automotive electronics: a unique source of historical information on automotive electronics," *IEEE Vehicular Technology Magazine*, vol. 10, no. 3, pp. 80–90, 2015.

[68] S. Hoch, F. Althoff, and G. Rigoll, "The ConnectedDrive context server – flexible software architecture for a context aware vehicle," in *Advanced Microsystems for Automotive Applications*. Springer, 2007, pp. 201–213.

[69] R. Lanctot, "Strategy analytics insight report: how collaboration is defining the future of the connected car," Ericsson Automotive Multimedia & Communications, 2015.

[70] "Volvo cars puts 1000 test cars to use Scandinavian cloud-based project for sharing road-condition information becomes a reality," Volvo Press Release ID:157065, 2015.

[71] Y. L. Tseng, "LTE-advanced enhancement for vehicular communication," *IEEE Wireless Communications Magazine*, vol. 22, no. 6, pp. 4–7, 2015.

[72] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. Soong, and J. C. Zhang, "What will 5G be?" *IEEE J. Selected Areas in Communications (JSAC)*, vol. 32, no. 6, pp. 1065–1082, 2014.

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