

Future Trends in Connected and Autonomous Vehicles: Enabling Communications and Processing Technologies

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ABSTRACT With significant advancements in information and communication technologies, connected and autonomous vehicles (CAVs) can provide improved transportation services. At present, a variety of technologies, such as vehicular networks, communication interfaces, and modern hardware devices enable CAVs to support reliable, safe, and quality transportation system options with improved performance and increased effectiveness. In this paper, we carefully explore a set of distinguished state-of-the-art CAV systems with a focus on On-board Computational Unit (OBCU) hardware architectures, communication technologies, deployment challenges, and performance aspects. The exploration critically identifies important area transformations and anticipates future trends influencing CAV communications and processing requirements. To that end, we propose the design of a future generic OBCU architecture that can be customized with appealing features and used in CAVs.

INDEX TERMS Vehicle-to-everything, vehicular ad hoc networks, Internet of Things, embedded systems, processing technology, on-board units.

I. INTRODUCTION

Vehicular crashes and traffic congestion are serious socio-economic problems faced by many metropolitan cities. World Health Organization reported 1.35 million deaths globally due to vehicular crashes in 2016 [1]. By supporting autonomous driving and connecting vehicles promptly, these problems can be mitigated. CAVs aid the effort to eliminate car crashes, alleviate traffic congestion, maximize vehicle awareness, lower fuel consumption and gas emissions, and provide a safer and more comfortable experience. Great strides have been made over the last decades in the fields of wireless technology and vehicular communication to achieve the goal of autonomous and connected driving [2]–[4].

Connected vehicle technologies largely depend on Vehicular Ad Hoc Networks (VANETs) for transmission awareness or basic security messaging. On the other hand, autonomous vehicles combine different technologies to

achieve the desired autonomy level. Society of Automotive Engineers (SAE) International's J3016 standard foresees six levels of automation. At Level 0, there is *no automation* but some momentary safety warning features and driver-assist systems such as blind-spot detection, lane departure warning, cruise control, and the automatic emergency braking are included. Level 1—*driver assistance* includes features that are present in most modern vehicles today such as adaptive cruise control and lane-keeping assistance. The inclusion of additional self-control features, like steering and acceleration/deceleration control, which still requires a human driver to do everything else and monitor road conditions, leads to Level 2—*partial automation* of the vehicle. Under Level 3—*conditional automation*, the vehicle will be able to navigate complex traffic situations, obey traffic signs without driver's intervention but would require, instantly, a human driver to take control upon the request of an engaged feature. With Level 4—*high automation*, a vehicle is expected to completely analyze its environment and drive on its own even if a human driver does not respond appropriately to a

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request to intervene. At Level 5—*full automation*, the vehicle will carry passengers only and human intervention will be eliminated [5].

Efficient vehicular connectivity techniques for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications can open the door to highly safe, efficient, and sustainable transportation systems in the future. Recently, Long-Term Evolution (LTE) systems, as well as 5G initiatives, are undergoing an evolution to support Vehicle-to-Everything (V2X) communication. V2X enables vehicles to communicate with other vehicles, pedestrians, infrastructure, and networks. Optimizing traffic flow and collision mitigation are some of the most important target application areas that V2X communications, and accordingly connected vehicles, aim to support [6].

Modern Intelligent Transportation Systems (ITS) provide advanced localization, navigation, communication, networking, context-awareness, and decision-making support to its constituents including CAVs. Road-side units (RSUs) and vehicle onboard units (OBUs) are cornerstone devices in a typical ITS. Modern RSUs comprise automotive sensors, V2X communication modules, and processors for driver-assisted systems and communication equipment. Modern automobiles require the embedding of numerous Electronic Control Units (ECUs) that range in complexity and may include engine, restraint, driver seat, rear view camera, side obstacle, driver door, keyless entry, and more control units. At present, the scope of On-board Computational Units (OBCUs) is beyond traditional OBUs and ECUs, where OBCUs aim to support on-board diagnostics, infotainment, advanced driver assistance, autonomous driving, and inter-vehicle and intra-vehicle connectivity. The hardware architecture of a present-day OBCU includes processors, memory, onboard storage, multiple communication interfaces, navigation module, displays, and networking bus systems. Such hardware units are usually supported by application programming interfaces and software development kits. Indeed, OBCUs can benefit from the availability of powerful automotive-grade and off-the-shelf hardware components, such as the Arduino Project and Raspberry Pi (RPi) boards. Field Programmable Gate Arrays (FPGAs), Graphics Processing Units (GPUs), and Microcontroller Units (MCUs) are modern embedded hardware devices that can facilitate effective OBCU implementations.

While CAVs provide several benefits, it is important to note that a vehicular environment is challenging primarily due to the dense population of user equipment, computationally intensive tasks, and the communication of real-time information. To achieve their fullest potential, it is essential to incorporate multiple state-of-the-art technologies focused on efficient and accurate perception, planning, control, and ultra-low latency communication while designing solutions for CAVs. In this paper, we study a set of distinguished recent systems and contributions that were reported under CAVs. The selected articles appeared with distinguished publishers, such as the Institute of Electrical and Electronics

Engineers (IEEE) and Elsevier. The articles were carefully selected to cover important trends, methods, and approaches; hence, they are representative articles and do not constitute an exhaustive list. The objectives of the paper are as follows:

- 1) Explore a set of distinguished recent CAV investigations with a focus on communications and processing technologies, system deployments, hardware architectures, and computational and performance aspects.
- 2) Identify important area transformations, open issues, and accordingly derive pointers to future research.
- 3) Develop a future OBCU hardware system architecture that can be customized and adapted for CAVs.

This paper is structured so that the following section presents key communications and processing aspects of CAVs. Then, the architectures of OBCUs and the future trends influencing CAV communications and processing requirements are explored. The later section presents the development of a future OBCU architecture that can be customized and adopted within CAVs. Finally, the last section concludes the paper.

II. KEY COMMUNICATIONS AND PROCESSING ASPECTS OF CAVS

In this section, key aspects of in-vehicle and V2X communication technologies, and the computational challenges of autonomous driving are briefly examined. Modern communication standards provide opportunities to improve CAV performance, but at the same time, they pose stringent computational demands. Moreover, autonomous driving further adds to the computational burden of CAVs. Understanding modern communications and computational aspects of CAVs, and how they influence the design of OBCUs (as discussed in the later sections), is of major importance.

A. COMMUNICATION STANDARDS OF CONNECTED VEHICLES

Among in-vehicle networks, the most widely used ones are local interconnection network (LIN), controller area network (CAN), FlexRay, media-oriented systems transport (MOST), and Ethernet [7]. While LIN network is the easiest to deploy and offers low cost, it is often used in less time-critical low-speed communication, such as battery monitoring and temperature sensors. CAN, the most dominant among automotive networks is a low-cost, medium fault tolerance network that is widely deployed in engine controllers, transmission units, climate controllers, etc. At a significantly higher cost, FlexRay offers much faster speeds and greater fault-tolerance that are usually required in applications such as chassis control, safety radar, and supplementary restraint system. MOST network also offers high-speed and is specifically optimized for in-vehicle multimedia, navigation system, and infotainment data transmission. Wired Ethernet offers high speed but is relatively new to production cars; it has seen limited application in ECUs, cameras, and entertainment units. With the implementation of various advanced features on many newer vehicles that require high bandwidth such as

advanced driver assistance system (ADAS) and multimedia functions, the Ethernet network is a promising candidate to dominate the next generation of in-vehicle networks.

V2X communication enables the exchange of information between vehicles as well as any other entity within the vehicle network infrastructure to improve road safety, increase the efficient flow of traffic, and provide additional traveler information services. The Third Generation Partnership Project (3GPP) has specified several use case categories for V2X such as cooperative maneuvering (e.g. lane merging, lane changing, intersection management), cooperative perception (e.g. see-through, lifted seat or bird's eye vision), cooperative safety (e.g. real-time situational awareness, warnings for traffic jam, traffic light violations, vulnerable pedestrian protection), autonomous navigation (e.g. real-time high definition map updates with precise context, convoy driving, speed harmonization), vehicle platooning and remote driving (e.g. automated parking) [8]. Several challenges are faced by V2X communications due to specific deployed conditions such as data exchange between high-speed vehicles, vehicles crossing from other directions, and between vehicles and roadside infrastructure. More importantly, for the advanced V2X use cases, the latency and reliability requirements are extremely stringent, as compared to the basic safety applications [9].

Currently, two main radio access technologies (RATs) that enable V2X communication exist: the dedicated short-range communications (DSRC) based on IEEE 802.11p and Cellular V2X (C-V2X) technology based on 3GPP LTE/5G new radio (NR). DSRC technology is designed to operate in the 5.9 GHz ITS band and enables data transfer between vehicles, roadside infrastructure, and pedestrians when the communication devices are within a limited distance of each other. Over the years, it has been standardized, implemented, and thoroughly tested for V2X applications, and several auto manufacturers such as Cadillac, Audi, and Volkswagen have already deployed DSRC devices to enable V2V and V2I communications. Research has shown that the range, performance, and reliability of DSRC is adequate for basic safety applications [10]–[13].

In competition to vehicular communication technologies based on IEEE 802.11p, such as DSRC and its European counterpart ITS-G5, 3GPP standardized C-V2X in 2016 as an alternative RAT technology. C-V2X leverages the existing cellular infrastructure as a means for vehicular communication [8]. 3GPP Release 14 defined two complementary communication modes for C-V2X to provide both Wi-Fi and cellular communication. The commercial cellular spectrum is used for vehicles to communicate to the cloud via the mobile network (V2N) for infotainment, telematics, and latency-tolerant informational safety use cases whereas the direct communication or sidelink channel over the PC5 interface is used for the delivery of latency-sensitive communication via the 5.9 GHz ITS spectrum. C-V2X defines two sidelink modes (mode 3 or mode 4). In mode 3, the cellular base station (or eNB) selects and manages the sub-channels

for the direct communication between vehicles whereas, in mode 4, vehicles autonomously select their sub-channels.

Fig. 1 shows typical deployments of DSRC and C-V2X with a variety of connectivity options within smart cities. Research shows that, in comparison to DSRC, C-V2X can provide larger coverage (as depicted in the figure), enhanced reliability, better quality of service (QoS) support, 360° non-line-of-sight (NLOS) awareness, and higher capacity. Both RATs can reliably support basic safety use cases with end-to-end latency requirements of around 100 milliseconds under moderate vehicular density, such as traffic light information and emergency vehicle notifications, road work, and emergency brake warnings. However, both RATs suffer from scalability issues and fail to meet the stringent QoS requirements of more advanced use case groups that include vehicle platooning, high throughput sensor sharing, intent sharing, autonomous and remote driving, and other safety-critical applications [10].

Next-generation of these technologies, IEEE 802.11bd and NR V2X, are being developed with several enhancements that are aimed to support higher density, throughput and reliability, longer range, submeter positioning, and ultra-low latency. Recently, 3GPP Release 16 defined specifications for NR V2X which is designed to supplement C-V2X for supporting advanced use cases. Preliminary studies indicate that NR V2X achieves large gains in comparison to C-V2X under highway scenarios and is close to achieving the QoS requirements for advanced V2X use cases [10].

B. COMPUTATIONAL ASPECTS OF AUTONOMOUS VEHICLES

Smart city initiatives, as supported by modern vehicular communication capabilities, are prime enablers of autonomous driving. Within a smart city environment, the integration of smart “things” with smart vehicles, enables numerous applications that include safe autonomous driving, intelligent transportation, and more [3]. For instance, a modern autonomous vehicle can sense and communicate with its surroundings to ensure safe driving. Furthermore, health-care emergencies of passengers can be detected through wearables and accordingly disseminate an alert to nearby vehicles, communicate with an emergency caregiver, and smoothly navigate through intelligent traffic light signals. An intelligent vehicle can autonomously take protection actions by broadcasting its location and stop the vehicle as well [5], [14].

To fully realize the opportunities of autonomous driving, the supporting infrastructure demands a continuous build-up of computing strength to effectively execute a plethora of applications. Ongoing classic investigations on computational aspects of autonomous driving include traffic control, route optimization, and shareability of service. Autonomous driving puts an additional burden on information processing due to the heavy computations involved in dynamic path planning, cooperative-driving support, and multimedia processing. Modern computing aspects include the task of

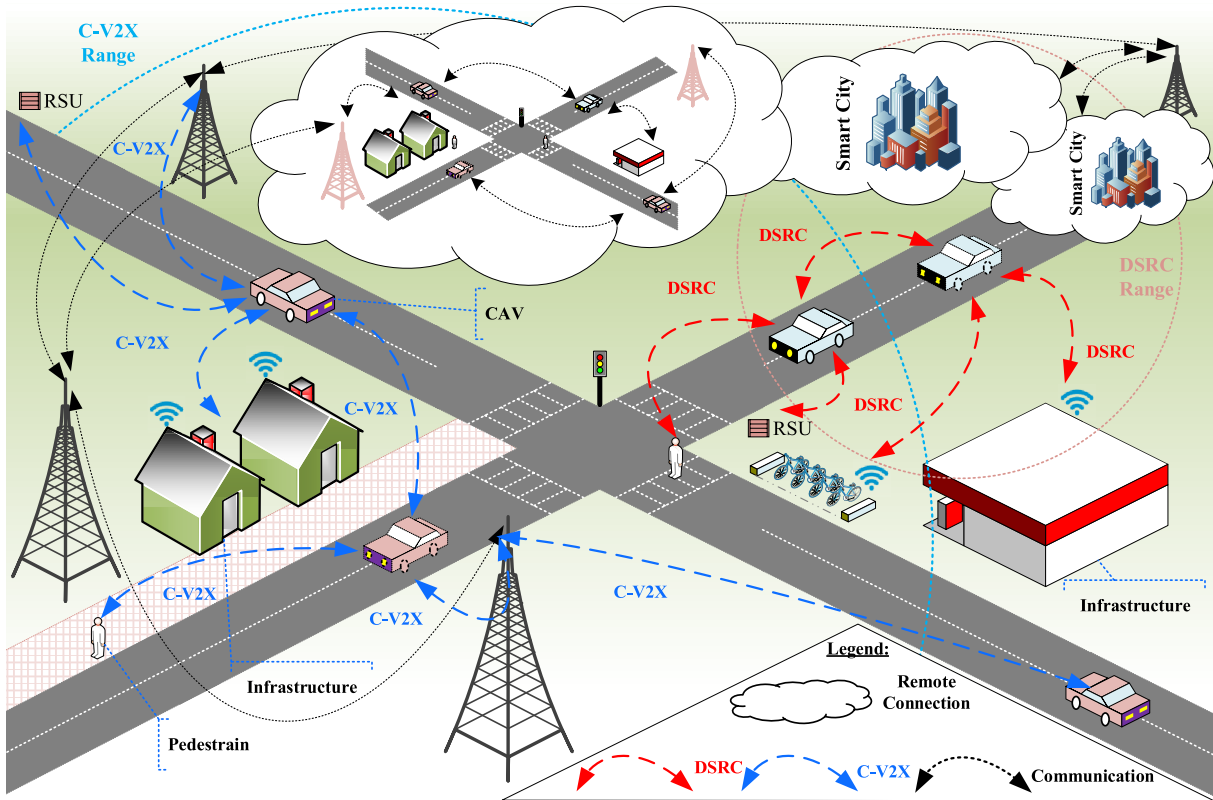


FIGURE 1. A visualization that depicts the typical deployments of DSRC and C-V2X that enables V2V, V2I, V2N, and other connectivity options.

accurate and timely perception to comprehensively understand the environment in proximity. Computer vision has been greatly used in Autonomous Vehicles (AVs) to detect lanes and pedestrians, perform tracking, etc. Typical computer vision technologies, such as machine learning, are utilized to perform complex tasks. Deep Neural Networks have been widely used for computer vision in AVs, such as processing road vision, cityscape, and geometrical reconstruction datasets. State-of-the-art intelligent driving features are now being adopted by a variety of projects, such as Waymo, Tesla Autopilot, and Intel Mobileye autonomous driving systems [15]. Currently, car vendors, such as Toyota and Lexus, are aiming at adding intelligent personal assistance, namely Amazon Alexa, to their cars as an appealing feature of a modern lifestyle.

Table 1 summarizes the investigations of recent studies focused on broader development aspects of CAV systems [3], [4], [7], [15]–[20]. Key features of the surveyed CAV systems and the aspects related to their implementation technologies are highlighted. In addition to identifying the scope of various systems, the table aids the discovery of commonalities and variations in deployment options, architectural considerations, analysis metrics and performance indicators, and complementary improvement opportunities across the surveyed systems.

III. ON-BOARD COMPUTATIONAL UNITS IN CONNECTED AND AUTONOMOUS VEHICLES

The growing effort in creating CAVs enables the development of OBCUs with interesting architectures [21]–[28]. Indeed, tailoring the OBCUs architecture to fit within CAVs is a challenging hardware design task. The ultimate goal is to design OBCUs capable of running tasks that range from simple to computationally intensive autonomous driving algorithms. In addition, CAV OBCU design may demand the support of multiple state-of-the-art communication standards and interfaces to effectively implement the desired level of connectivity.

In ITS, traditional OBUs adopt one or more processors that include MCUs or other general-purpose units with reduced or complex architectures. Standard OBU memory units still comprise the legacy electrically erasable programmable read-only memory (EEPROM), random-access memory (RAM), SD cards, and expanding use of flash memory. Common OBU communication interfaces rely mainly on the use of ZigBee, Bluetooth, Wi-Fi, and LTE for wireless communication and GPS for localization. Other interfaces, such as Ethernet, USB, Controller Area Network Bus (CANBUS), audio, video, and general-purpose input/output (GPIO) are commonly supported. Some OBUs already include support for temperature, accelerometer,

TABLE 1. State-of-the-art enablers of CAVs, architectures, analysis metrics, and open issues.

Ref	Year	Purpose	Analysis	Deployment	Architecture	Open Issues
[21]	2021	Investigating the migration of engine ECU software from single-core to multi-core processors	Core load; core execution time	HYUNDAI engine ECU	Tricore TC275 Multi-core MCU	Integration of multiple ECUs; reduce power consumption
[22]	2021	Designing reconfigurable ECU architecture for secure and dependable automotive CPS	Time; energy; end-to-end delay	Steer-by-wire system	NXP quad-core iMX6Q SABRE development board; Advanced RISC Machines (ARM) Cortex-A9 CPU core; Xilinx automotive grade Spartan-6 FPGA; CANBUS; Operational architecture: Hand wheel, front axle control; hardware force feedback	Authentication; privacy; intelligent decision making
[16]	2020	Developing an OBU for energy-constrained vehicles to efficiently collect data	Signal-to-noise ratio (SNR); block error rate; round-trip delay time; power consumption	Internet of Vehicles (IoV); Urban; cloud services; mobile app.	RPI Zero W; memory; battery; display; USB; serial interface; LoRaWAN; Global Positioning System (GPS); Narrowband Internet of Things (NB-IoT)	Testing; intelligent decision making
[23]	2019	Developing a predictive and adaptive cruise control using a customized ECU	Time delay; fit index; speed	A Volkswagen vehicle, Polo Sedan 2004 with spark-ignition engine 2.0 L	A decentralized architecture of three MCUs; ARM Cortex M3 MCU; ARS300 Radar; CAN network	On-road applications
[17]	2019	Designing a precision cm-level positioning OBU using LTE-V, dead reckoning, and network real time kinematic	Delay; packet loss rate; positioning error	Outdoor V2V	i.MX6Quad processor; flash memory; USB; UART; CANBUS; GPIO; HDMII; SDIO; I2C; LTE-V; Inertial Measurement Unit (IMU)	specialized device
[18]	2018	Developing an OBU with 3-level security architecture for IoVs	Correctness; reliability; failure rate; execution time; time delay; time overhead	IoV; Wireless (WLAN); LTE/5G	MCUs; network cards; Wi-Fi; Bluetooth; CANBUS; serial ports	hardware optimization
[19]	2018	Developing a flexible OBU architecture for sensor data and fleet management	Throughput	V2V and V2I	RPI; GPS; LoRa; Bluetooth; Wi-Fi; power management unit	Physical comm. unit; live-streamed sensor data
[15]	2018	Investigating the relationship between IoV and big data in vehicular environment	QoS; connectivity; performance	Internet; IoT devices; comm. systems	Satellite, Unmanned aerial vehicles (UAVs), terrestrial, social, and sensor networks	Business model for IoV service market; hardware aspects
[4]	2018	Cooperative sensing for improved traffic efficiency; wrong way, hazard, traffic, and priority warnings	Reliability; scalability; latency; coverage; packet success rate; SNR; jitter; vehicle speed	Personal, vehicles, personal, roads, and global and local area distributions	RSUs; OBUs; personal units (such as mobile phones); Wireless sensor network (WSN); gateways; traffic management center	Integration of wireless comm. technologies such as LTE; comm. configurability
[3]	2017	Integrating wearables and intelligent vehicles.	Comm. range; power consumption; safety; security; privacy; reliability;	Wearables and in-vehicle	Sensor nodes; sensors; Personal digital assistant (PDA); smart wearables;	Interoperability; software solutions
[20]	2017	Neighbor-aided localization in vehicular networks	Distance; signal strength; accuracy	NEC LinkBird MX for IEEE 802.11p	RSUs; OBUs; comm. interfaces; mobile phones; road maps; sensors	Applied only in urban scenario
[7]	2016	Identifying in-vehicle networks outlook in terms of achievements and challenges	Speed; tolerance; cost; transmission capacity; jitter; utilization; frame parameters; security strength	In-vehicle	Under hood: vehicle dynamics, power train, power management; Front: anti-theft, active safety, instrument, control; Infotainment: telematics, console; Rear: control	Software aspects
[8]	2016	Identifying LTE evolution features of V2X services	Cost; coverage; robustness to congestion	In-vehicle; road; pedestrian;	ITS server; RSUs; vehicles; users; cellular-based V2X; camera;	High vehicle speed and user equipment densities

proximity, light, gyroscope, elevation, and fuel consumption sensors. Current power units rely mostly on charged batteries; however, developing sustainable options are reported to support energy harvesting.

In [16]–[19], the design of several specialized OBU hardware architectures are presented. Purposes included developing efficient data collection for energy-constrained vehicles [16], accurate positioning [17], improved security for Internet of vehicles (IoVs) [18], and flexible architecture for sensor data and fleet management [19]. All the developed OBUs aimed at enabling advanced connectivity for IoVs [16], [17], V2V [17], [19], and V2I [19]. A variety of modern components are used to design the proposed OBUs. Processors comprised RPis [16], [19], multiple MCUs [18], and multi-core-based processor boards like the i.MX6Quad in [17]. All the presented OBU designs integrated modern communication interfaces, such as LoRoWAN, NB-IoT, LTE-V, etc. The used state-of-the-art processors and communication interfaces aim at effectively supporting CAV requirements. Several commercial OBUs, available in the market from providers, such as Siemens, LEONARDO, Q-Free, LACROIX, etc., exhibit similar architectures as in [16]–[19], with a growing support for advanced connectivity like V2X.

Within modern vehicles, ECUs exhibit an interesting integration of processing and communications technologies to tackle present-time challenges. In [22], the authors present the design and evaluation of a reconfigurable ECU architecture for secure and dependable automotive Cyber-Physical Systems (CPS). The effectiveness was demonstrated by using a steer-by-wire (SBW) application over CAN with flexible data rate as a case study. Brugnolli *et al.* in [23] present a customized ECU for predictive and adaptive cruise control. In another investigation, Moone *et al.* [21] investigates a methodology for migrating engine ECU software from single-core to multi-core processors. More specifically, the target multi-core processor is the Tricore TC275 developed by Infineon. The exploited processing technology to attain reconfiguration in [22] is a Xilinx Automotive Spartan-6 FPGA as supported by an ARM based application processor. Moreover, an NXP quadcore iMX6Q SABRE automotive board was used to implement secure and dependable automotive CPS. The adaptive cruise control ECU in [23] comprised an ARM Cortex MCU, CAN transceivers, and a radar.

An On-Board Diagnostics (OBD) computer system enables real-time monitoring and control of various electronic subsystems and sensors within a vehicle. The current OBD set of standards is known as OBD-II and it is characterized by its ability to assist in vehicle operation monitoring, driver behavior monitoring, emissions testing, and commercial vehicle telematics. Sawan *et al.* in [24] present the design of an OBD-II device that includes an ARM Cortex M0+ MCU and a Bluetooth module to support connectivity with a laptop or tablet. In [25], the OBD-II interpreter ELM327 MCU is used to implement a Wireless OBD-II fleet management system. Wireless connectivity is implemented using a Wi-Fi module. The system also includes a GPS subsystem.

High-end computational devices are critical for effective modern ITS, autonomous driving, and infotainment systems. Common uses, such as object detection, traffic monitoring, recognition, complex optimization, navigation, video processing, sensor fusion, and intelligent decision making can be computationally intensive and demand the use of highly capable hardware resources. Example high-end processing devices that were utilized for ITS and autonomous driving applications include GPUs (such as NVIDIA Tesla, GeForce GTX, Jetson, Tegra, etc.) and FPGAs (such as Xilinx Virtex, Intel Altera Stratix, etc.) [26]. Today's high-end infotainment systems are characterized by their ability to perform parallel computations as supported by multiple processing units, Digital Signal Processors (DSPs), GPUs, and more. For example, Texas Instruments' DRA72x Jacinto 6 Eco infotainment processor includes an ARM Cortex A15, two dual-ARM cortex M4, an SGX544 graphics, a C66x DSP, an HD 1080p video, and radio processors. The system is supported by high-speed interconnect, automotive peripherals, connectivity, display, scalable memory, and storage components. Moreover, it is supported by an embedded security module [27], [28].

Table 1 presents additional descriptions of the investigations [16]–[19], [21]–[23] and their main features.

IV. FUTURE TRENDS INFLUENCING CAV COMMUNICATIONS AND PROCESSING UNITS

Future CAVs pose very challenging communications and processing requirements. The exploration of expectations, challenges, and current technological advancements can highlight interesting area transformations, reveal modern trends, and identify future requirements. In Table 2, pointers to future directions focused on improvements in communications and processing technologies from the explored articles are carefully identified [3], [7], [8], [15]–[17], [19], [29]–[31]. These pointers lay the foundation for the proposed customizable OBCU architecture presented in the next section.

Future directions in connected vehicles and networks point at improving network effectiveness and speed, developing software-defined networks, improving network function virtualization, and deploying cost-effective network infrastructure [3], [7], [15]–[17], [19], [29]–[31]. A clear direction in vehicular connectivity is dedicated to developing V2X communication and investigating the expected significance of deploying 5G networks for enhancing system performance and automobile's driving and safety experience. Furthermore, future vehicles need to deal with interoperability issues due to the inability of collaboration among some devices and the absence of seamless real-time end-to-end connectivity. Example solutions include hybridizing communication technologies, supporting social IoT, etc. With social IoT, vehicles adopt a service-oriented architecture where heterogeneous devices can offer or request services and collaborate on behalf of their owners.

To become fully functional and safe, autonomous vehicles need to accurately perceive the environment, negotiate, and

TABLE 2. Pointers to future directions identified in the explored articles with a focus on communications and processing technologies and categorized accordingly. In addition, the pointers are presented in chronological order, per reference and publication year.

Reference and Year	[7] 2016	[8] 2016	[3] 2017	[29] 2017	[30] 2017	[15] 2018	[31] 2018	[19] 2018	[17] 2019	[16] 2020	[22] 2021
Pointers to Future Directions											
<i>Communications</i>											
Developing V2X communication		✓				✓	✓	✓	✓		
Hybridizing communication technologies	✓	✓			✓	✓	✓	✓		✓	
Adopting 5G features						✓					
Improving QoS	✓	✓			✓	✓	✓	✓		✓	✓
Deploying cost-effective networks		✓		✓	✓			✓			
<i>Processing</i>											
Improving environment perception and safety	✓	✓	✓		✓	✓	✓				✓
Embedding security features	✓	✓	✓	✓	✓	✓	✓	✓			✓
Integrating AI, data science techniques, and decision support					✓	✓				✓	✓
Developing context awareness				✓		✓					
Integrating self-X requirements					✓						
Integrating social IoT				✓							
<i>Communications and Processing</i>											
Developing interoperability of services	✓		✓		✓						
Improve practical testing in real scenarios						✓	✓	✓	✓	✓	
Involving diverse stakeholders in R&D	✓		✓			✓	✓				
Integrating ICT cross-domain knowledge			✓		✓	✓					
Developing autonomous energy management	✓										
Improving power harvesting aspects			✓								

act seamlessly. Future directions include improving intelligent context awareness at high levels of intervention and actuation capabilities. To this end, artificial intelligence, data science techniques, and decision support promise major gains. Future emergency features in autonomous vehicles include making smart decisions to apply breaks, changing lanes and routes, and bypassing delicate driving situations at an eliminated chance of human error. As such, improving safety may require several extra sensing devices, in addition to a camera, lidar, sonar, and radar, to be integrated within the supporting computing system. However, the architectural modification must not compromise the simplicity of the developed system including hardware, application software, and operating systems.

The highly pervasive nature of CAVs demands the collection of safety-critical driver information within potentially hostile environments. To that end, strict security measures must be correctly developed and implemented, well-enforced, and kept fresh. Security requirements include protecting data privacy by preventing information leaks and withstanding potential access attacks. Moreover, protecting data integrity is an equally important requirement to ensure non-alteration and non-loss of information. Improvements in security for autonomous and connected vehicles include the development of embedded cryptographic hardware accelerators, adaptive security-QoS schemas, and social-network-based reputation records. Emphasis needs to be put on formally developing security mechanisms and procedures to ensure the correctness of operation. Hardware security, whether under FPGAs or application-specific integrated circuits (ASICs), is indeed an area to explore as related to embedding security in CAVs.

Inspired by the stratification of IoT, future CAV characteristics may include high-order self-reliance, aka Self-X abilities. Such abilities go beyond self-driving to take CAVs to significantly higher levels of autonomy. Notable features include self-healing, -learning, -configuration, -organization, and -optimization; in addition to self-sufficiency in terms of power harvesting and autonomous energy management [30]. This high-level self-reliance and autonomy features, incorporated within CAVs, warrant further exploration but undoubtedly pose additional communications and processing workload.

Testing, verification, and validation are of critical importance in transportation applications as incorrect developments, implementations, or use can lead to loss of life. Two specific important open issues appear to be limitedly addressed in the literature, namely, the practical testing within real scenarios and the integration of formal methods in creating CAVs. Firstly, testing in real scenarios can be best improved by accelerating the creation of testbeds, such as Ann Arbor Connected Vehicle Test Environment (AACVTE) in the United States, Bed Lower Saxony in Germany, etc. Secondly, future research can benefit from the existing wealth of formal methods and mathematical notations at various stages of system development, verification, testing, and validation.

Due to the great requirement for reliability, and with the increasing complexity of applications, formal methods provide a breakthrough in terms of developing unambiguous, clear, and concise system specifications. Formal methods enable a functional analysis of specifications, correct refinement of implementations, and the elimination of possible errors.

Some other pointers of importance to CAV communication and processing technologies are as follows:

- Applying architectural simplifications to arrive at implementations with improved costs, sizes, and performance.
- Integrating Information and Communication Technology (ICT) cross-domain knowledge.
- Involving diverse stakeholders, from academia and the industry, in Research and Development (R&D) effort.

As a future technology, CAV aims at connecting passengers with work, home, police, caregivers, insurance companies, governmental networked services, and other geographically distributed stakeholders. With the recent breakthrough in mobile technology, 5G capabilities will act as a glue among architectural simplifications, mobility, and efficient V2X communications. To illustrate trends, a two-dimensional visualization of future deployments of CAVs is presented in Fig. 2. The figure shows a backend multilayer communication network architecture in one of the dimensions that highlight the trends of rapidly prototyping networked subsystems, their integration, and depicts the adoption of formal verification for dependable development. The backend dimension lists some trending communication technologies as well as some legacy technologies that are expected to remain operational in the future. The frontend dimension in Fig. 2 visualizes the pervasiveness of deployments that can include embedded systems in various applications. The figure captures various features of future CAV supporting systems including mobility, security, and the wide interoperability of services.

V. A CUSTOMIZABLE FUTURE OBCU HARDWARE ARCHITECTURE

Inspired by the explored OBCUs and scenarios of future CAV deployment (See previous sections), a generic OBCU architecture that can be customized and adopted within CAVs is proposed and depicted in Fig. 3. The proposed OBCU architecture is customizable in the sense that it can include a selection of the proposed options as desired by the designer. The developed OBCU has several parts embedded with the future technologies and features identified in Table 1. The OBCU architecture comprises a multiprocessing unit that can be heterogeneous in nature. The heterogeneity comes from the possible embedding of multi-core processors, MCUs, FPGAs, GPUs, DSPs, automotive grade, and other off-the-shelf hardware devices such as RPi, and/or other processing options [26]. Each processor technology enjoys specific characteristics and the choice can be made per application context. For instance, MCUs can be used for performing simple computations, while GPUs and DSPs can run intensive

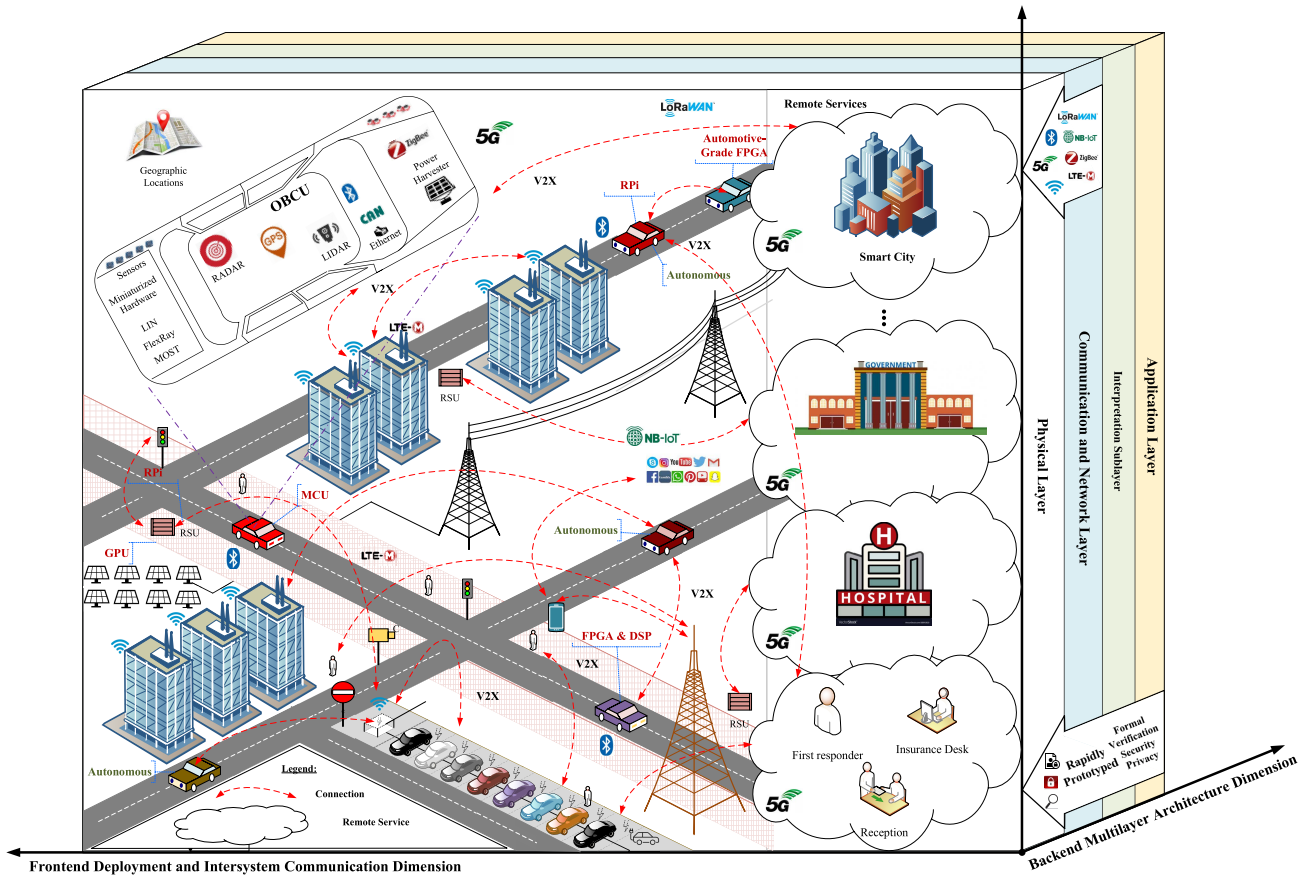


FIGURE 2. A visualization of network architecture and its physical layer that presents a future pervasive deployment in various CAV applications.

graphics and multimedia computations. Furthermore, FPGAs can provide significant implementation flexibility due to reconfigurability. The multiprocessing unit will be supported by specialized co-processing devices that further support some desired requirements, such as safety and context awareness. Future OBCUs will unveil the further integration of AI acceleration, graphics acceleration, embedded security, multimedia processing, run-time reconfiguration, in-system programmability, and optimization-specific units to improve the performance of computations. Modern and future memory/storage units of OBCUs will continue to adopt traditional random access memory (RAM), read-only memory (ROM), Flash Memory, and SD technologies; with their growing speed, increasing size, and economical power requirements. Future OBCUs will be supported by modern applications and functionalities that comprise social IoT, cooperative-driving support, intelligent control, secure flash, secure localization, AI datasets, dynamic path planning, and driver assistance.

Future OBCUs will include arrays of modern sensors that enable improved autonomy. Sensor units like global positioning systems (GPS) will be supported by inertial measurement units (IMUs) for improved localization and navigation. Advanced RADAR and/or LiDAR units scan surroundings and help with planning the behavior of autonomous vehicles.

Moreover, weather, air pollution, and radiation sensor units will be integrated into future OBCU. Radiation sensors will be used to detect and measure beta/gamma ionization in the ambient background. Indeed, OBCUs will still need to support traditional sensors, analog-to-digital converters with high accuracy, and be connected through hardware interfaces and expansion arrays at high speeds with low power consumption.

In terms of off-the-shelf embedded hardware, 5G interfaces are expected to dominate the market and soar in the list of communication devices in high demand. Side by side, modern cellular interfaces, such as NB-IoT and LTE, and non-cellular communication interfaces will support broader scales of coverage, increased mobility, and wider interoperability. Modern non-cellular interfaces comprise LoRaWAN, Wi-Fi, ZigBee, and Bluetooth. Communication interfaces will be backed by tiny, low-power, and powerful transceivers. Legacy in-vehicle interfaces continue to comprise CANBUS, FlexRay, LIN, and MOST. Bluetooth, Ethernet, and even ZigBee will continue to be adopted for in-vehicle communication.

Trending CAV features include the ability to benefit from renewable sources as well as harvesting energy within a vehicle. For example, vibration energy can be collected using a piezoelectric energy harvester. In addition, a ball-screw

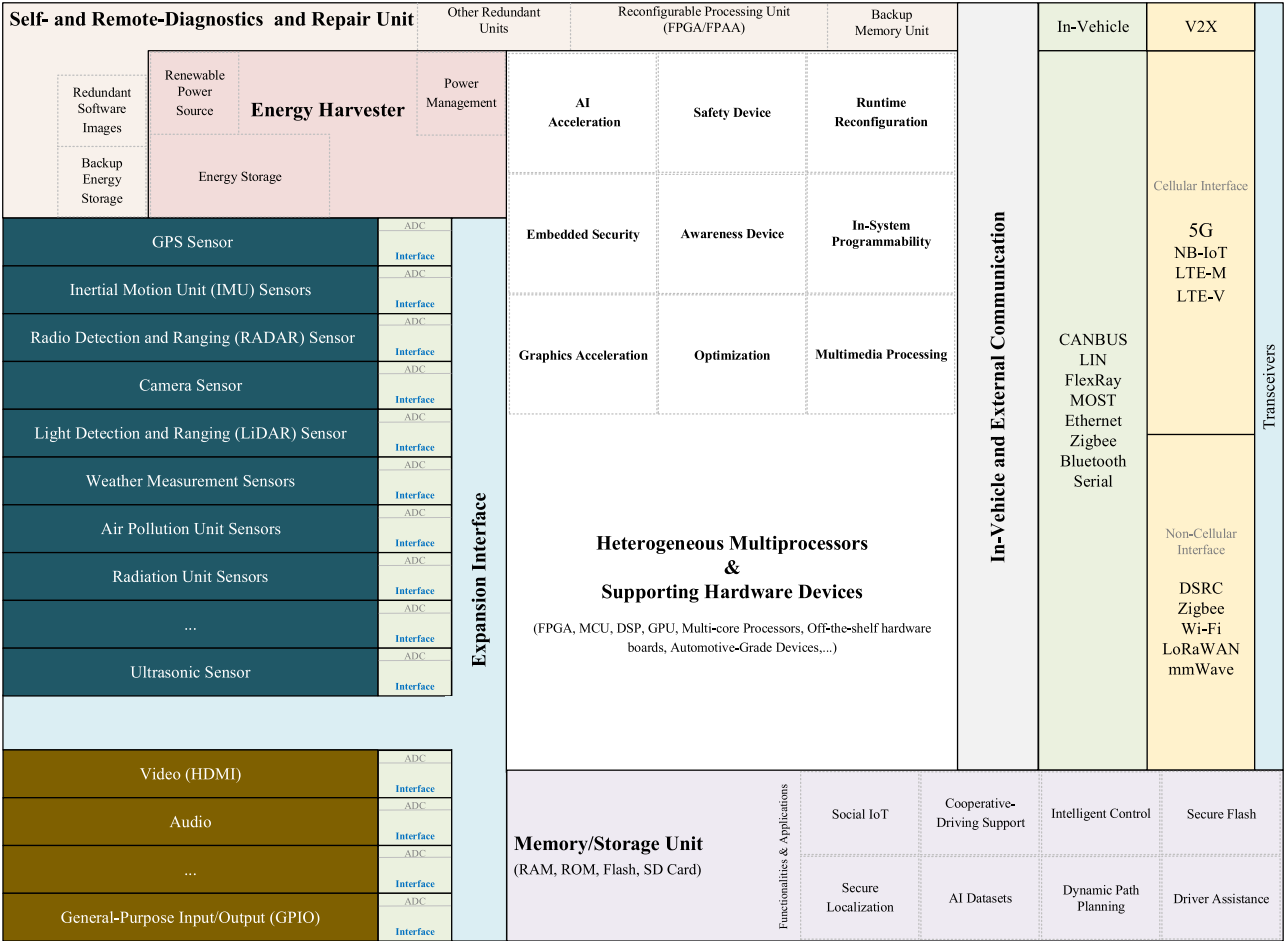


FIGURE 3. Future generic OBCU architecture that can be customized and adopted within CAVs.

electromagnetic damper can be used for regenerating energy from the suspension system of a vehicle. Having smart power management and efficient energy storage units, as part of the OBCU, may be the key to attaining sustainable operation of the vehicle.

Future OBCUs are to support self- and remote-diagnostics and repair through/by other vehicles. Self-healing units can perform self-diagnosis, self-maintenance, and self-repairs. Combining powerful AI techniques with the readily available reconfigurable hardware technologies, such as FPGAs and Field-Programmable Analog Arrays (FPAAs), future OBCUs can have great benefits like dynamically adapting their configuration to respond to failure or a change in functionality.

Legacy QoS indicators, such as throughput, response time, reliability, robustness, power consumption, accuracy, and scalability continue to play a critical role in assuring CAVs quality. However, interesting trending performance indicators include architectural simplifications in terms of system size, portability, and ease of integration. Future efforts need to target the development of business models that capture service quality per cost. Accordingly, users can select a suitable quality option among a menu of CAV services. Other

trending indicators including the correctness of development, level of security and privacy, volume of interoperability and connectivity, and the system safety levels. Integrating aspects of Quality of Experience (QoE) in development calls for the incorporation of indicators, such as satisfaction with the operation, travel behavior, passenger mobility, etc.

VI. CONCLUSION

CAVs are shaping the future of modern transportation and are expected to significantly improve service availability, promote safety, and reduce costs and associated risks. The literature of CAVs is rich in trending investigations whose directions can be carefully singled out to sketch the predominant factors affecting the future. In this paper, a selection of modern investigations is explored to probe area transformations in CAVs with a focus on communications and processing technologies. It is provisioned that future CAVs will pose significant demand on its supporting infrastructure to enable trending applications, such as cooperative driving, social IoT, intelligent control, secure localization, to name but a few. In response to the emerging communication and computational needs, this paper presents the design of a

future generic OBCU that can be customized and used in CAVs. The proposed future OBCU includes fast and dense memory units, non-traditional sensors, modern interfaces for effective V2X communication, and heterogeneous processing units. Furthermore, OBCUs are expected to support intelligent run-time reconfiguration, embedded security, context awareness, and a multitude of specialized accelerators. With no doubt, the effectiveness of CAVs in servicing modern societies can benefit at large from issuing laws, developing standards, and launching international-level joint projects. Recent CAV research investigations still show a limited commitment to practical testing in real scenarios. Ultimately, issues like hybridizing communications and processing technologies remain areas to further explore.

REFERENCES

- [1] *Global Status Report on Road Safety 2018: Summary*, World Health Org., Geneva, Switzerland, 2018.
- [2] L. Quijano-Sánchez, I. Cantador, M. E. Cortés-Cediel, and O. Gil, "Recommendation systems for smart cities," *Inf. Syst.*, vol. 92, Sep. 2020, Art. no. 101545.
- [3] W. Sun, J. Liu, and H. Zhang, "When smart wearables meet intelligent vehicles: Challenges and future directions," *IEEE Wireless Commun.*, vol. 24, no. 3, pp. 58–65, Jun. 2017.
- [4] J. Ferreira, M. Alam, B. Fernandes, L. Silva, J. Almeida, L. Moura, R. Costa, G. Iovino, and E. Cordiviola, "Cooperative sensing for improved traffic efficiency: The highway field trial," *Comput. Netw.*, vol. 143, pp. 82–97, Oct. 2018.
- [5] I. W. Damaj, D. K. Serhal, L. A. Hamandi, R. N. Zantout, and H. T. Mouftah, "Connected and autonomous electric vehicles: Quality of experience survey and taxonomy," *Veh. Commun.*, vol. 28, Apr. 2021, Art. no. 100312.
- [6] R. Molina-Masegosa, J. Gozalvez, and M. Sepulcre, "Comparison of IEEE 802.11p and LTE-V2X: An evaluation with periodic and aperiodic messages of constant and variable size," *IEEE Access*, vol. 8, pp. 121526–121548, 2020.
- [7] W. Zeng, M. A. S. Khalid, and S. Chowdhury, "In-vehicle networks outlook: Achievements and challenges," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1552–1571, 3rd Quart., 2016.
- [8] H. Seo, K.-D. Lee, S. Yasukawa, Y. Peng, and P. Sartori, "LTE evolution for vehicle-to-everything services," *IEEE Commun. Mag.*, vol. 54, no. 6, pp. 22–28, Jun. 2016.
- [9] S. Maaloul, H. Aniss, M. Kassab, and M. Berbineau, "Classification of C-ITS services in vehicular environments," *IEEE Access*, vol. 9, pp. 117868–117879, 2021.
- [10] G. Naik, B. Choudhury, and J.-M. Park, "IEEE 802.11bd & 5G NR V2X: Evolution of radio access technologies for V2X communications," *IEEE Access*, vol. 7, pp. 70169–70184, 2019.
- [11] Z. H. Mir, J. Toutouh, F. Filali, and Y.-B. Ko, "Enabling DSRC and C-V2X integrated hybrid vehicular networks: Architecture and protocol," *IEEE Access*, vol. 8, pp. 180909–180927, 2020.
- [12] D. Garcia-Roger, E. E. Gonzalez, D. Martin-Sacristan, and J. F. Monserrat, "V2X support in 3GPP specifications: From 4G to 5G and beyond," *IEEE Access*, vol. 8, pp. 190946–190963, 2020.
- [13] T. T. Le and S. Moh, "Comprehensive survey of radio resource allocation schemes for 5G V2X communications," *IEEE Access*, vol. 9, pp. 123117–123133, 2021.
- [14] I. W. Damaj, Y. Iraqi, and H. T. Mouftah, "Modern development technologies and health informatics: Area transformation and future trends," *IEEE Internet Things Mag.*, vol. 3, no. 4, pp. 88–94, Dec. 2020.
- [15] W. Xu, H. Zhou, N. Cheng, F. Lyu, W. Shi, J. Chen, and X. Shen, "Internet of vehicles in big data era," *IEEE/CAA J. Autom. Sinica*, vol. 5, no. 1, pp. 19–35, Jan. 2018.
- [16] J. Santa, L. Bernal-Escobedo, and R. Sanchez-Iborra, "On-board unit to connect personal mobility vehicles to the IoT," *Proc. Comput. Sci.*, vol. 175, pp. 173–180, Jan. 2020.
- [17] H. Kong, W. Chen, S. Fu, H. Zheng, L. Du, and Y. Mao, "OBU design and test analysis with centimeter-level positioning for LTE-V2X," in *Proc. 5th Int. Conf. Transp. Inf. Saf. (ICTIS)*, Jul. 2019, pp. 383–387.
- [18] L. Wang and X. Liu, "NOTSA: Novel OBU with three-level security architecture for internet of vehicles," *IEEE Internet Things J.*, vol. 5, no. 5, pp. 3548–3558, Oct. 2018.
- [19] M. Stevens and I. Nikolaidis, "A flexible on-board unit architecture for sensor data and fleet management services," in *Proc. 9th Int. Conf. Inf. Intell., Syst. Appl. (IISA)*, Jul. 2018, pp. 1–8.
- [20] S. B. Cruz, T. E. Abrudan, Z. Xiao, N. Trigoni, and J. Barros, "Neighbor-aided localization in vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 10, pp. 2693–2702, Oct. 2017.
- [21] J. Y. Moon, D. Y. Kim, J. H. Kim, and J. W. Jeon, "The migration of engine ECU software from single-core to multi-core," *IEEE Access*, vol. 9, pp. 55742–55753, 2021.
- [22] B. Poudel and A. Munir, "Design and evaluation of a reconfigurable ECU architecture for secure and dependable automotive CPS," *IEEE Trans. Depend. Sec. Comput.*, vol. 18, no. 1, pp. 235–252, Jan. 2021.
- [23] M. M. Brugnolli, B. A. Angelico, and A. A. M. Lagana, "Predictive adaptive cruise control using a customized ECU," *IEEE Access*, vol. 7, pp. 55305–55317, 2019.
- [24] P. R. Sawant and Y. B. Mane, "Design and development of on-board diagnostic (OBD) device for cars," in *Proc. 4th Int. Conf. Comput. Commun. Control Autom. (ICCUBE)*, Aug. 2018, pp. 1–4.
- [25] R. Malekian, N. R. Molisane, L. Nair, B. T. Maharaj, and U. A. K. Chude-Okonkwo, "Design and implementation of a wireless OBD II fleet management system," *IEEE Sensors J.*, vol. 17, no. 4, pp. 1154–1164, Feb. 2017.
- [26] I. Damaj, S. K. Al Khatib, T. Naous, W. Lawand, Z. Z. Abdelrazzak, and H. T. Mouftah, "Intelligent transportation systems: A survey on modern hardware devices for the era of machine learning," *J. King Saud Univ., Comput. Inf. Sci.*, Jul. 2021, doi: 10.1016/j.jksuci.2021.07.020.
- [27] J. Rangaraju and M. Watson. (2014). *Today's High-End Infotainment Soon Becoming Mainstream*. [Online]. Available: <https://www.ti.com/lit/wp/spry261/spry261.pdf?ts=1633408461724>
- [28] A. H. Salem, I. W. Damaj, and H. T. Mouftah, "Vehicle as a computational resource: Optimizing quality of experience for connected vehicles in a smart city," *Veh. Commun.*, vol. 33, Jan. 2022, Art. no. 100432. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2214209621001017>
- [29] B. Afzal, M. Umair, G. A. Shah, and E. Ahmed, "Enabling IoT platforms for social IoT applications: Vision, feature mapping, and challenges," *Future Gener. Comput. Syst.*, vol. 92, pp. 718–731, Mar. 2019.
- [30] O. Bello and S. Zeadally, "Toward efficient smartification of the Internet of Things (IoT) services," *Future Gener. Comput. Syst.*, vol. 92, pp. 663–673, Mar. 2019.
- [31] Z. Ning, X. Hu, Z. Chen, M. Zhou, B. Hu, J. Cheng, and M. S. Obaidat, "A cooperative quality-aware service access system for social internet of vehicles," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2506–2517, Aug. 2018.



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