Chapter 5
Cyber-physical Autonomous Vehicular System (CAVS): A MAC Layer Perspective

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5.1 Introduction

In vehicular networking for intelligent transportation, cyber-physical autonomous vehicular system (CAVS) is a promising technology that has been widely considered by governments, autonomous industries, and academic research institutes [60, 73]. CAVS is the synergistic integration of heterogeneous networking, computation, and physical processes in which all vehicles and their components communicate via a vehicular networking platform and are driven in a platoon-based pattern with a closed feedback loop between the cyber process and physical process [63]. The main purpose of the vehicular cyber-physical systems is to incorporate computation, communication, and control to enhance road safety, efficiency, convenience, and high quality of daily life by minimizing traffic congestion and injuries, and improving fuel efficiency while traveling on the road [51].

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Furthermore, with the recent advancement of automation in automotive industries, the vehicular wireless communication becomes an emerging research interest both for automotive industry engineers and researchers [13, 111]. As a consequence, there is an increasing number of required safety features in the modern vehicle such as driver safety, road safety, vehicle to infrastructure recognition, and vehicle-to-vehicle communications. The current generation of vehicles integrates a number of various sensors with the help of different wireless communication protocols to provide real-time communication for those purposes. Incorporating a large number of sensors inside the vehicle provides overall safely support for vehicle as well driver, whereas designing an interoperable, reliable, and flexible communication technology has been the key challenge [83, 116].

A wireless sensor network (WSN) is spatially characterized by various autonomous sensors to supervise physical or environmental conditions, such as remote health monitoring, temperature, sound, pressure, etc. and to simultaneously forward their particular information over a communication network to a sink location [17, 18, 46]. The combination of WSN with internet of things (IoT) enables WSN with either object-oriented or internet-centric resources, which enormously enlarges the capacity of WSN in a large number of sensing and communication applications [53, 55].

Modern smart automobiles are monitored by complex distributed networks made up of a large number of heterogeneous wireless sensor nodes with rich connectivity supplied by central networks and internet [65]. With the rapid improvement of the automobile intelligent system and intelligence and internet connectivity, security and privacy have emerged to be the main challenges for automotive systems [98]. Researchers have shown that by reducing a single control unit, a possible attacker may obtain access to other vehicle controller units via internal communication buses such as controller area network (CAN), and harm critical subsystems [111]. As CAN receives simultaneous connection with IoT resources and service providers, it becomes effortless marks to cyber adversaries, particularly, because, it has never been supposed to handle cyber risks. This makes CAN information susceptible to falsehood assaults that turn into erroneous critical information distribution to users, which in turn leads the system to take improper and hazardous activities or to be unaware of an ongoing attack as was the case in Stuxnet attack [80, 118]. It also enables adversaries to possibly perform destructive instructions on control systems, causing dangerous actions (e.g., disabling the brake system). Therefore, it is crucially important to secure and protect smart automobile functions towards any kinds of cyber-related assaults [80, 117].

CAVS is an integration of physical process and cyber systems via heterogeneous networking and communications. A typical CAVS is shown in Fig. 5.1, comprising physical components (such as vehicles, DSRC/mobile devices, tablets), cyber systems (e.g., data center, traffic control center), and communications (e.g., vehicular networks).

The CAVS industry has noticed a progressive improvement since 2014 and is estimated to continually exhibit a significant growth as shown in Fig. 5.2 [93]. The concept of the CAVS is growing in every industry sector and more and

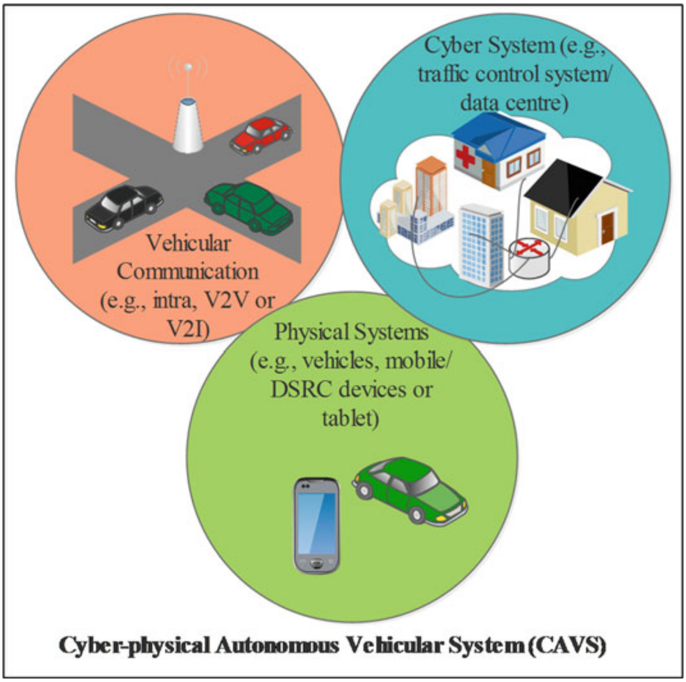
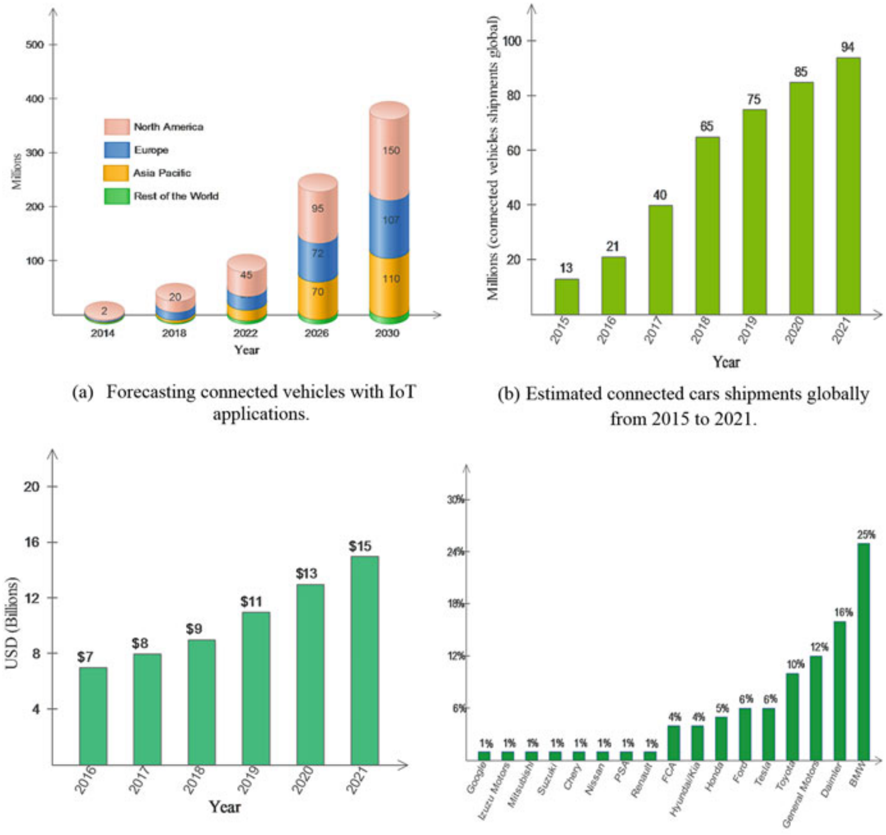


Fig. 5.1 A typical diagram illustrating the concept of vehicular cyber-physical systems using the interactions among system components

more wireless technologies are being incorporated in the emerging IoT protocol stack [28]. Device-to-Device (D2D) communication is innovating in daily basis and envisioned to create a wireless ecosystem of billions of intelligent electronics devices within a single entity named IoT [15]. In the CAVS ecosystem, intelligent devices communicate with each other autonomously to assemble, communicate, and forward heterogeneous information in a multi-hop manner without any human centralized control and collaboration. However, the real-time communication among the intelligent devices is the key leveraging value in CAVS intelligent environment where information is gathered and transformed intelligently. Ultimately, the ability to gather different types of information varies from one device to another, which is particularly driven by assorted networking standards and connectivity challenges [16, 62].

5.2 Impact of CPS on Vehicular Systems

Various automobile manufacturers are spending investment into the cyber-physical system (CPS), and one particular concern is CPS connected automated vehicles.



(a) Forecasting connected vehicles with IoT applications.

(b) Estimated connected cars shipments globally from 2015 to 2021.

(c) Global market potential of connected cars from 2016 to 2021.

(d) Leading connectivity and self-driving automotive vehicle companies.

Fig. 5.2 Estimating and forecasting connecting vehicles due to the emerging growth of CAVS

Business intelligence (BI), a business insider's premium research service, anticipated 94 million connected automobiles to ship in 2021 as shown in Fig. 5.2b, which constitute to 82% of all vehicles transported in the same year. This would represent a compound yearly growth rate of 35% from 21 million connected vehicles in 2016. Automobile marketplaces have successfully observed a flourishing trend and a significant business opportunity for their connected automobiles. BI forecasted 381 million connected cars to be on the road by 2020, up from 36 million in 2015. Furthermore, BI forecasted that this will generate $8.1 trillion from connected automobiles between 2015 and 2020 as shown in Fig. 5.2c.

Automobile manufacturers are becoming interested in heavily investing in their connected automobile initiatives due to a number of reasons. Internet connectivity in vehicles enables automobile manufacturers to introduce software updates in real time, which are extremely worthwhile for after sales service. Moreover, the automobile manufacturers can leverage upon a huge amount of big data from vehicles to analyze the performance and generate invaluable insights on how drivers utilize their vehicles. Furthermore, the vehicle connectivity provides more efficient ways to sell their products and better quality of services to customers. It is expected that in the near future the connected vehicles in the CPS ecosystem produce a big amount of data which will pave the way to ensure the driving safety of fully reliable CAVS via vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications.

Recently, many leading automotive companies have introduced the connected vehicle concept in the CPS ecosystem as shown in Fig. 5.2d according to the KPMG survey of 200 automotive executives. The BMW is the top leading company with other manufacturers including Daimler, General Motors, Toyota, and Tesla being near the top of the list.

The CPS can be enabled with the advanced of development in wireless technologies, including RFID, smart sensors, communication technologies, and internet protocols. Basically, the main principle is driven by the need of smart sensors to cooperate directly without any human interaction. The recent change in internet-centric phenomena, mobile communications, and overall machine-to-machine (M2M) communication technologies can be seen as the fundamentals of the CPS [4, 81]. In the coming years, the growth of the CPS is predicted through integration of enormous wireless communication technologies to enable unique applications by connecting cyber systems with physical objects together in support of intelligent decision making [105]. Likewise, today's automobiles have an increased range of effective electronic control devices (ECU) and associated distributed sensor and actuator elements [68]. For instance, a significant number of more than 50 sensors are implemented nowadays in a mid-range vehicle, while the industry estimates for any automotive sensor market volumes surpass 665 million devices and 2237 million devices, in the USA and globally, respectively [35]. This represents a multi-billion dollar market in electronic sensors alone in 2007 and the analysts estimated a significantly more than 80% of the latest functions in cars become electronic devices based [3, 84, 85]. As a result, the designing concept, production and installation of the wiring for several of these sensor elements require considerable engineering work. At present, wiring harnessed inside a vehicle with 4000 parts may have weighed up to 40 kg and up to 4 kilometers long [65]. Eliminating or reducing the number of wires may potentially provide mass savings, warranty savings, and overall cost savings. This opportunity also paves the way to enable wireless technology inside the vehicle to monitor its critical parts as envisioned in the concept of intelligent transportation system (ITS). Therefore, the intra-vehicular wireless communication requires an in-depth investigation of various types of wireless communication protocols for integration within the CAVS [83].

Modern automobiles are progressively furnished with a large number of different types of sensors, actuators, and communication protocols and devices (WSNs, 3G/4G, mobile devices, GPS devices, and embedded computers) [66]. Generally, automobiles have been equipped with effective sensing, networking, communication, and data processing capabilities, and can communicate with other automobiles or transfer important information with the external environments over various internet protocols like HTTP or TCP/IP, and next-generation telematics protocols [107]. Consequently, various advanced telematics solutions such as remote security for disabling the engine and remote diagnosis have been designed to improve drivers' safety, efficiency, and enjoyment [30]. The improvements in cloud computing and CAVS have delivered a promising opportunity to further address the increasing intelligent transportation issues, such as heavy traffic, congestion, and vehicle safety [41]. In the recent years, researchers have suggested a few models that use cloud computing for implementing ITSs. For example, a new vehicular cloud architecture called ITS-Cloud was proposed to improve V2V communications and road safety [45].

The integration of sensor devices and various both wired and wireless communication technologies pave the way for us to track the updating status of an object by using the internet. The CPS describes a future in which a number of physical objects and devices around us, such as various sensors, radio frequency identification (RFID) tags, GPS devices, and mobile devices, will be associated to the internet and allows these objects and devices to connect, cooperate, and communicate within social, environmental, and user contexts to reach common goals [20, 41, 125]. As a promising technology, the CAVS is expected to offer appealing possibilities to transform transportation systems and automobile services in the automobile industry [38]. Guerrero-ibanez et al. [41] proposed an idea to use the "unique identifying properties of car registration plates" to connect various things. As vehicles are equipped with increasingly powerful sensing, networking, communication, and data processing capabilities, CAVS technologies can be used to harness these capabilities and share under-utilized resources among vehicles in the parking space or on the road. For example, CAVS technologies can make it possible to track each vehicle's existing location, monitor its movement, and predict its future location [52].

By integrating cloud computing with WSNs, RFID tags, satellite network, and other ITSs technologies, a new generation of CPS-based vehicular data clouds can be improved to bring many business advantages, such as anticipating improved road safety, decreasing road traffic congestion, controlling traffic, and promoting car maintenance or repair [26]. Some exploratory works of using CPS technologies to enhance ITSs have been performed in recent few years [2, 115]. For example, an intelligent informatics system (iDrive system) manufactured by BMW used various sensors and tags to monitor the environment, such as tracking the vehicle location and the road condition, to provide driving directions [8, 45]. Anand et al. and Uden et al. [8, 113] proposed an intelligent internet-of-vehicles system (known as IIOVMS) to collect traffic information from the external environments on an ongoing basis in order to monitor and manage road traffic in real time. He et al. [45] discussed how ITSs could use IoT devices in the vehicle to connect to the cloud and how numerous sensors on the road could be virtualized to leverage the processing capabilities of the cloud. Anand et al. [8] proposed a technology architecture that uses cloud computing, IoT, and middleware technologies to enable innovation of automobile services [123].

WSNs are mainly characterized by the limited resources of the nodes. A holistic network configuration and planning is crucial for the effective uses of the restricted resources. The media access control (MAC) protocol, as a fundamental part of the networking stack, should be configured with respect to the topological structure of the network, the power source of the nodes, and the characteristics and requirements of the running applications [14, 70, 120].

In the subsequent section of this article, some general challenges of MAC protocol development for CAVS are first reviewed. It follows with state-of-the-art MAC protocol concept for the CAVS platform. A proposed framework is then suggested for the future CAVS-enabled vehicular WSN. A conclusion is drawn to highlight the key points discussed in this article.

5.3 Challenges of Developing Reliable MAC Strategies in CAVS

A wide range of issues need to be addressed at different layers of the architecture and from different aspects of system design to improve the CAVS. In this section, some general challenges of wireless MAC design in the CAVS are discussed:

Large-Scale Deployment and Ad Hoc Architecture Most of the networks contain a large number of deployed sensor nodes without a predetermined network infrastructure, which exhibits challenges to provide seamless autonomous connectivity. Developing a suitable technology to design a CAVS from existing technologies requires a comprehensive analysis on communication protocols of the selected technology. In addition, new technology can also be explored for such a network.

Integration with Internet and Other Networks It is a fundamental importance for the CAVS to provide continuous services that allow querying of the network to retrieve useful information from anywhere and at any time. Therefore, the vehicular wireless technology should be remotely accessible from the internet and needs to be integrated with the existing internet protocols.

Resource-Efficient MAC An energy-efficient protocol for wireless communication is important to optimize the network lifetime of the CAVS. The energy saving can be achieved in every feature of the network by combining network functionalities with energy-efficient protocols such as energy-aware routing on network layer and energy-saving mode on MAC layer.

Self-Configuration and Self-Organization MAC The MAC of the existing technologies should have dynamic topology features to avoid the node failure due to mobility and large-scale mobile node deployments that demand self-organizing architectures and protocols. New sensor nodes can be incorporated to replace the failing sensor nodes in the implementation area and, similarly, existing nodes in the network can also be eliminated from the system without impacting the common objective of the application.

Quality of Services As much as possible, the CAVS connection is required to be safe and reliable without minimal human interaction. The QoS provided by the MAC layer corresponds to the accuracy between the data reported to the sink node and what is actually occurring in the physical environment. In the CAVS, it is undesirable to have sensor data with long latency due to processing or communication because they may be outdated and lead to wrong decisions in the monitoring system.

5.4 State-of-the-Art on MAC Design and Development towards Reliable CAVS

Different of technologies to enable the IoT are becoming widely available due to the need to provide a better understanding of our environment [77]. As a result, intelligent devices and networks embedded in various kinds of WSNs are connected and integrated with the IP-based large network [1, 5]. However, many open challenges, mostly the suited protocols and standards, still persist in practical implementation. Specifically, the MAC layer carries a fundamental building block of WSNs to establish the communication link among different network infrastructures [87, 101]. Several relevant classifications of IoT enabled MAC protocols in WSNs have been presented based on operating principles and underlying features to emphasize their opportunities, strengths, and weaknesses [59].

Within a pervasive sensing framework, WSN technologies have been an integral aspect of IoT, which enable sensors and actuators to communicate seamlessly with the environment around us, and to share the information across multiple platforms towards the vision of a smart environment system [22, 56, 114]. Smart connectivity with existing network infrastructures and ubiquitous computation using network resources is an indispensable part of IoT. However, the success of IoT depends on the improvement of the network performance, flexibility, interoperability, reliability, and limited energy consumption of WSNs [106]. Among various network layers, the MAC layer protocols have been received more attention for development towards reliable energy-efficient sensor network architecture. The attributes of the MAC layer significantly impact on the performance, power consumption, and scalability of the sensor network [89].

Since the past few years different wireless sensor MAC protocols have been successfully developed to fulfill the requirement of the growing scale of the WSNs in the CAVS [29, 57, 89]. This article classifies these MAC protocols according to different channel access mechanisms, which include resource sharing methods, contention based, channel polling, scheduling based, and hybrid MAC protocols. As an overview, the main classification of the MAC protocols is given in Fig. 5.3.

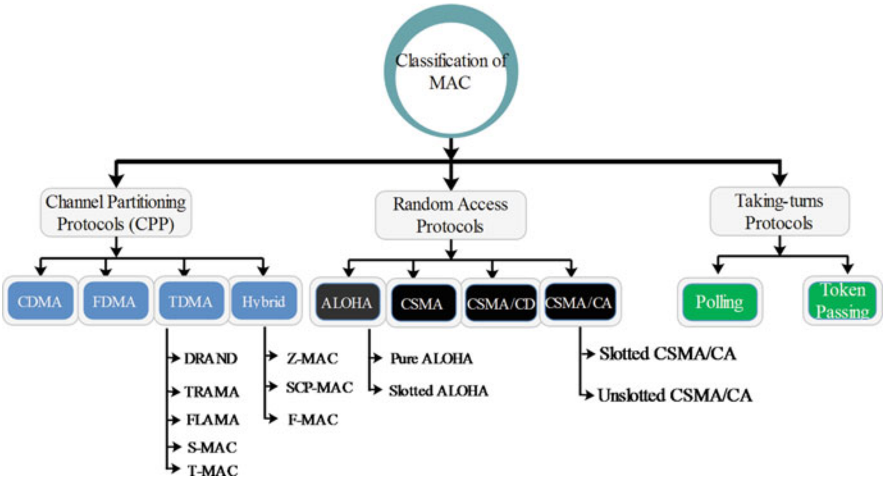


Fig. 5.3 Classification of MAC protocols for CAVS

5.4.1 Channel Partitioning Protocols (CPP)

The resource division method along one or more dimensions for a MAC protocol has been well established. There exist three recognized resource division methods, namely frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA). The FDMA strategy splits the resource into several partitions of channels. TDMA mechanism divides the resource into multiple time slots and the CDMA method separates the resource into a collection of codes in which the same channel is identified by the assigned user [43, 49, 86, 88].

TDMA is a synchronous method wherein the users cannot communicate individually and simultaneously. No overlapping time slots are permitted to assorted users to increase the data rate, since it can only access its allocated time slot. TDMA typically adheres to a high power efficiency requirement, which is the most desirable characteristics for low power operating systems, at the expense of reducing the transmission capacity per user [10, 27, 112].

FDMA transmission permits several users to send simultaneously using different frequencies inside a uniform cell per room topology. In a cellular strategy, the data transfer is divided into non-overlapping frequency bands. In orthogonal frequency-division multiple access (OFDMA), users are allocated frequency slots spanning several OFDM symbols and subcarriers. In general, power efficiency is the main disadvantage of FDMA and it worsens as the number of subcarriers increases [32, 79, 89].

For CDMA techniques, the typically used strategies rely on direct sequence distribution where users can receive the exact channel using optical orthogonal codes (OOCs). This corresponds adaptability of adding users and asynchronous accessibility capacity [64]. Users are allowed to transmit at overlapping times and wavelengths. Consequently, it is feasible to implement hybrid systems such as WDMA/CDMA or TDMA/CDMA [44, 67].

5.4.1.1 TDMA Based Protocols

In the TDMA mechanism of a MAC protocol, a channel is accessed by only one user at any time in a same slot [44]. If the other users want to communicate within the same time slot, it will lead to packet losses or network collision. The main drawback of using this scheme in WSNs is the increasing waiting time to transmit, which increases the network vulnerability and reduces network scalability [91]. However, to avoid any data drop or network collision, this MAC strategy is recommended because it can utilize the network resource more effectively [74].

Several MAC strategies based on the TDMA mechanism have been developed over the last few years, which focus on different performances metrics such as energy efficiency and quality of service (QoS), and result in collision-free MAC protocols such as TRAMA [58, 72, 104]. The S-MAC and T-MAC follow the synchronous approach schemes, which tolerate a little schedule misalignment in the network, although they still require a globally synchronized schedule that creates an additional energy overhead [71]. S-MAC is popular as an energy-efficient protocol, but still fails to guarantee to a satisfactory QoS performance in the large-scale network topology [121].

S-MAC utilizes a mixed contention and scheduling scheme for collision avoidance. Furthermore, interfering nodes will go to sleep when they receive control message to avoid overhearing [34]. In S-MAC, lengthy messages will be separated into tiny fragments, which will be sent as a burst. It creates additional messages to send, which need a longer accessibility to the medium. S-MAC is developed primarily to reduce energy consumption at the expense of sacrificing other important performance factors such as fairness, throughput, bandwidth utilization, and latency [33, 61]. Fairness will degrade (from a MAC level perspective) as some nodes with small time frame will require to wait MAC access with adaptive listening in which messages shift two hops in every duty cycle. Consequently, latency becomes higher as more messages are prepared to be sent [24].

T-MAC is designed to achieve a better performance over S-MAC by utilizing a dynamic duty cycle instead of a fixed one [6]. The concept is to transfer all information from one node to another in bursts of adjustable length and introduce sleeping between bursts for additional energy efficiency [40]. It can also decide the duration of the variable load by keeping an optimal time. T-MAC pertains RTS and CTS methods. When RTS cannot obtain a CTS response, it would attempt again before giving up [48]. As in S-MAC, T-MAC can only deliver the information to one single hope for each duty cycle, which results in a large latency [9]. Additionally, T-MAC has an early sleep problem as a node changes to sleep even when a neighbor has some information waiting to be sent. Consequently, the throughput is reduced at the sink nodes [124]. T-MAC can adjust the duty cycle in accordance with the traffic load of the network. It also offers scalability and collision avoidance functionality through a mixed scheduling and contention schemes such as S-MAC [37]. Table 5.1 shows the key principle differences among S-MAC, T-MAC, and DSMAC.

Several wireless MAC protocols that overcome the difficulties of receiving global topology information in the large and scalable networks such as DRAND, PACT, and TRAMA have been proposed in the literature [7, 95, 102]. Flow-aware medium access (FLAMA) is a TDMA based MAC protocol modified from TRAMA, which is prominent for periodic monitoring applications [58]. The main idea of FLAMA is to prevent the overhead corresponding to the exchange of traffic information. As the information movement in periodic reporting applications is rather stable, FLAMA first sets up the flows and then uses a pull-based mechanism so that data is transferred only after being explicitly requested [39, 75].

5.4.1.2 FDMA Based Protocols

FDMA is another strategy that provides a collision-free channel. In practice, FDMA needs additional circuitry to dynamically communicate with various radio channels [47]. This operation increases the cost of the sensor nodes, which contradicts with the objective of sensor network systems. Compared to TDMA and CDMA, FDMA is less suitable for operation in low-cost devices [37]. The underlying reason for this is that FDMA capable nodes need extra circuitry to communicate over and change among different radio channels. The complicated band pass filters needed for this operation are reasonably expensive. Another drawback of FDMA that restricts its practical use is the rather strict linearity requirement on the medium [11].

5.4.1.3 CDMA Based Protocols

CDMA also provides a collision-free medium access mechanism. Its main characteristic is the high computational requirement, which is a major barrier for the required energy-efficient sensor networks [82]. To minimize the computational time in the CDMA based wireless sensor networks, there has been limited effort to investigate the computationally feasible source and modulation schemes, particularly signature waveforms, simple receiver models, and other signal synchronization schemes [27]. If it can be shown that the high computational complexity of CDMA can be traded-off with the collision avoidance function, then CDMA protocols might also be regarded as a possible solution for sensor networks [32].

5.4.1.4 Hybrid Protocols

Hybrid MAC protocols are usually a combination of TDMA, FDMA, and CDMA. Protocols that combine TDMA and CDMA such as reservation-based and contention-based hybrid MAC protocols and a TDMA/FDMA based hybrid

Table 5.1 Key principle differences among S-MAC, T-MAC, and DSMAC

References	MAC name	Targeted application	Key design principles	Strengths	Weakness
Huang et al. [47], Rao et al. [90]	S-MAC	Bursty event Multihop	Fixed low duty cycle, Maintain NAV for virtual carrier sensing (virtual clustering) Use physical/virtual carrier sense with randomized carrier sense time, RTS/CTS exchange and NAV to avoid overhearing	Low duty cycle to save energy, virtual clusters to support scalability and self-configuration, overhearing avoidance to save energy, message passing to reduce contention latency	High latency due to periodic sleep, fixed duty cycle not adaptive to dynamic traffic loads
Arifuzzaman et al. [9], Suriyachai et al. [108]	T-MAC	Dynamic traffic loads in time and location, Multihop	Transmit messages in a burst of variable lengths, adaptive duty cycle (ADC) with timeout mechanism dynamically ending the active part, future request-to-send (FRTS), full-buffer priority with threshold control	Save more energy by adaptation to dynamic traffic	ADC increases latency and reduces throughput, difficult to distinguish the communication pattern of a live WS
Doudou et al. [34], Huang et al. [47], Yin et al. [122]	DSMAC	Dynamic traffic loads to meet the application's load	Fully independent duty cycle, so that each node can adapt, in a fully distributed way, to the current surrounding conditions	Energy Efficient, dynamically changes each node's duty cycle	Additional energy overhead

MAC protocol called HYMAC behave like CSMA at low contention levels and switch to TDMA-type operation at high contention levels [109]. Protocols such as the hybrid MAC proposed in [100] combine CSMA with TDMA and FDMA where nodes are allocated a frequency as well as a time frame to send data once they effectively request for bandwidth resources using contention-based transmission. Similar protocols where CSMA-based bandwidth demands are used to decide the assignment of timeslots and codes have also been proposed in [103]. Zebra MAC (Z-MAC) protocol is one of the most widely considered examples in a hybrid scheme, which integrates the strengths of both TDMA and CSMA while offsetting their disadvantages [96, 97]. The Scheduled Channel Polling MAC (SCP-MAC) and Funneling-MAC protocol are other alternative examples of the widely used hybrid MAC schemes [54].

Table 5.2 presents a broad classification of the various hybrid MAC protocols. There are two types of contention-free access scheme, namely Adaptive Collision Free MAC (ACFM) and Cluster-Based RSU Centric Channel Access (CBRC) [44]. The combined approach of contention free and contention-based accesses can be divided into seven types, namely CSMA and Self-Organizing TDMA MAC (CS-TDMA), Space-Orthogonal Frequency-Time Medium Access Control (SOFT-MAC), Hybrid Efficient and Reliable MAC (HER-MAC), Dedicated Multichannel MAC with Adaptive Broadcasting (DMMAC), Clustering-Based Multichannel MAC (CBMMAC), Cluster-Based Medium Access Control Protocol (CBMCS), and Risk-Aware Dynamic MAC (R-MAC) [49].

Liu et al. [67] have proposed energy-efficient hybrid MAC protocols in a single window. In the case of hybrid MAC protocols, protocols based on CSMA/CA and TDMA access techniques provide better performance compared to CSMA/CA based MAC protocols. Hybrid protocols based on FDMA and CDMA better improve the network scalability than the pure FDMA and CDMA protocols. However, the disadvantages of FDMA-based and CDMA-based hybrid protocols are the requirement for expensive hardware and complicated operation and the requirement for power control. As a result, TDMA-based hybrid protocols are the most appealing in the context of IoT enabled communications [67].

5.5 Framework on CAVS

All the aforementioned MAC protocols are designed from a general communication point of view. However, MAC on CAVS should be designed to cater specific needs and requirements of vehicular applications. More specifically, the MAC design for a CAVS communication platform depends on the following factors:

Network Components The CAVS consists of various types of components such as onboard sensor nodes for intra-vehicular communications, roadside unit (RSU), which is installed along the road and provides real-time data services to passing vehicles, and different long-range communication enabled devices that can be

Table 5.2 Existing hybrid protocols

References	MAC name	Channels	Mobility	Density	Traffic characteristics	Multi-media application	Real-time application	Data traffic	Experiment	
									Analytical	Simulator
Dang et al.[31]	HERMAC	Multiple	NA	Low	Bidirectional	Yes	Yes	High load	NA	MATLAB
Torabi and Ghahfarokhi [110]	CSTDMA	Multiple	NA	Medium	Bidirectional	Yes	Yes	High load	Packet loss probability	MATLAB
Rezazade et al. [99]	STDMA	Single	High	High	Bidirectional	No	Yes	High load	NA	MATLAB
Wu et al. [119]	SOFTMAC	Single	NA	Low	Unidirectional	Yes	Yes	High load	NA	NA
Lu et al. [69]	DMMAC	Multiple	High	Medium	Unidirectional	NA	Yes	High load	NA	NS-2
Jayaraj et al. [49]	CBMMAC	Multiple	High	Low	Unidirectional	Yes	Yes	Medium	Probabilistic analysis	MATLAB
Nabi et al. [76]	CBMCS	Multiple	High	Low	Unidirectional	Yes	Yes	Medium	NA	C++
Guo et al. [42]	RMAC	Single	High	High	Unidirectional	No	Yes	High	Stochastic collision prevention model	NS-2
Nguyen et al. [78]	HTCMAC	Multiple	NA	Low	Bidirectional	NA	NA	Low, medium	Markov chain based Low,	MATLAB
Cao et al. [23]	Dynamic MAC	Single	NA	Low, high	Unidirectional	NA	NA	Low, medium, high	NA	MATLAB

supported by different technologies like WiMAX or 3G/4G for inter-vehicular communications [50, 92]. It shall be noted that cyber–physical interactions within the CAVS can be divided into two categories, namely intra-vehicular CPS and inter-vehicular CPS. The intra-vehicular CPS provides the kinetic performance of a single vehicle by combining and coordinating all of its components such as various types on board sensor nodes, actuators, and other smart devices into the complex environment. On the other hand, inter-vehicular communication incorporates V2V and V2I communications in which the traffic and vehicular networking are controlled from a CPS design standpoint.

Network Architecture The architecture of CAVS platform can be considered by reviewing some straightforward issues from the vehicular networking perspectives. Recall that there are two types of communications in such an environment, namely V2V [21] and V2I [25]. In V2V communications, vehicles communicate with one other using dedicated short-range communication standards such as DSRC/WAVE, radio frequency identifications (RFID), ZigBee, and Bluetooth [36, 83]. In V2I communications, the vehicles may use medium- or long-range communication technologies such as WiFi, WiMAX, or LTE/LTE-Advance for accessing the resources as shown in Fig. 5.4. The vehicles have specialized units such as onboard units (OBUs), application units, and sensors to communicate with one another and with the nearest fixed base access points. In the intra-vehicular communication, various short-range wireless communications such as Bluetooth, ZigBee, or UWB can be used [13, 68]. A typical network topology for intra-vehicular communication is of star shape. Alternatively, the mesh or cluster tree topology can also be

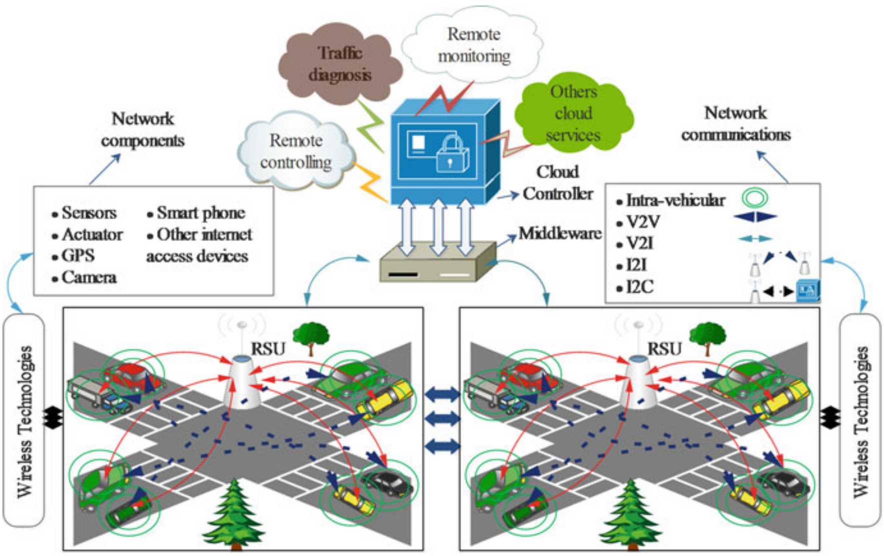


Fig. 5.4 A complete scenario of CAVS platform

employed at the expense of increasing complexity of the network architecture for further maintenance [83]. The long-range communications used for V2V, V2I, infrastructure-to-infrastructure (I2I), and infrastructure-to-controller (I2C) data exchange typically employ mesh topology for their communications. The RSU accesses all the vehicular information from OBU and passes it to the control center through a dedicated middleware that is responsible for maintaining the privacy and security.

CAVS is an integration of physical process and cyber systems via heterogeneous networking and communications. A typical CAVS is shown in Fig. 5.4, which comprises physical components (such as vehicles, DSRC/mobile devices, tablets), cyber systems (e.g., data center, traffic control center), and communications (e.g., vehicular networks).

Communication Technologies

In the CAVS for intelligent transportation systems, vehicles are expected to be able to compute and process the traffic information, and communicate that information with other vehicles, pedestrian, or roadside units (RSUs) using V2V or V2I communications in order to avoid traffic accidents and congestion [115]. For communications among vehicles or between vehicles and RSUs, wireless technology appears to be the most suitable option because the vehicular network topology changes quickly with the speed variation of the vehicles. In order to meet the communication requirements, each vehicle needs to dynamically change operating parameters needed for resilient communications based on the requirements and applications that are intended to support [19].

For intra-vehicular CPS, the short-range wireless technologies such as Bluetooth, ZigBee, or WiFi are suitable. However, due to the increasing number of sensor nodes demanded by intra-vehicular applications, a careful selection of such technologies is crucial for designing intra-vehicular communication. For inter-vehicular communication CPS, the long-range wireless technologies such as WiMAX and LTE are appropriate.

Vehicular networking and communications are considered as principal elements for the vehicular cyber-physical systems to improve the entire traffic safety and efficiency by propagating and analyzing the accurate time-critical information in an appropriate manner [94]. Generally, communications in vehicular CPS rely on vehicle-to-vehicle (V2V) and vehicle-to-roadside (V2R) communications with possible intermediate roadside-to-roadside (R2R) communications [92]. Conventional solutions to these issues use mainly automatic control systems using OBU in individual vehicles without any interaction with other vehicles. However, a recently proposed vehicular communication platform could help coordinate participating vehicles more efficiently and effectively with the assistance from inter-vehicular communications using V2V and/or V2R networking [12].

From the above discussion, it can be stated that according to the communication requirements for CAVS, both short- and long-range communications technology should be considered by addressing the following performance criteria, namely:

- Flexibility and Interoperability
- Safety
- Preparation for the management of quality of service (QoS)
- High Throughput
- Easy Installation and maintenance
- Mobility
- Low Cost
- Coverage

5.6 Open Research Issues

CAVS is still at its primary stage of development towards fully autonomous operations. Key development directions include proper improvement of onboard embedded systems, sensor networks, and communication systems. To develop a fully functioning CAVS platform, some key challenges in the following need to be addressed:

Privacy and Cyber-Security Privacy and security are major problems faced by vehicular communications. Whenever vehicles identification is utilized, the system can be safeguarded by making the involved parties accountable. Nevertheless, whenever vehicle authentication is used, the privacy of owner or driver/renter may be comprised. This basically means that, in vehicular systems, it is important to confirm the identity of the authenticating vehicle to maintain integrity regarding the supplied information. Cyber-attacks are the main security concern in the wireless network architecture used for CAVS. The security vulnerabilities of the vehicular network can cause damages and fatalities to the vehicle and driver.

Heterogeneous Wireless Connectivity The CAVS is integrated with various vehicular devices or access technologies. Heterogeneous wireless connectivity comprises a large number of specialized sensor nodes, in which a subset of the nodes can dynamically set up a self-organizing communication network. Effective management and integration of different heterogeneous networks constitutes to one of the primary challenges in improving the overall quality of service (QoS) in networks with different short-range or long-range wireless connectivity that can access trust information from the vehicular platform.

Delay Sensitivity and QoS The CAVS wireless connectivity is considered one of the most important enabling factors to deliver time-critical communications in a very short time frame.

Platform Independence and Interoperability The CAVS is supposed to be fully automatic and interoperable across different platforms with complex tasks and environments. It is challenging to achieve this where it is required from the manufacturing point of view to assemble different components and systems from different vendors and suppliers.

Small Delay and High-Speed Communication Technology Communication technology for CAVS should have a very small delay and latency requirement (i.e., in the order of microsecond or less) so that sensing and processed information can be used to stabilize the system in a timely manner. This requirement has not been fully met by the existing CAVS-wireless technologies.

High Data Rates The limited data rate of existing wireless technologies is insufficient to manage the requirement of CAVS because of high computational scenarios like videos. It is therefore important to improve existing data rates across all the CAVS-wireless access technologies.

5.7 Conclusion

In this chapter we have studied the CAVS from a MAC layer perspective. We have discussed the incorporation of the concept of IoT on vehicular systems and its impact based on statistical information. In order to address the MAC layer's challenges and issues on CAVS, the detailed state of art was discussed. A framework for CAVS was illustrated and finally the open research issues were described.

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