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Automated Vehicle Marshalling: The First Functionally Safe V2X Service for Connected Automated Driving

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ABSTRACT Automated Vehicle Marshalling (AVM) is an innovative technology poised to transform the automotive industry by enabling automated vehicles to be wirelessly controlled within geofenced areas while ensuring guaranteed Functional Safety (FuSa). Significant investments from major automakers and suppliers are driving the advancement of this SAE Level 4 driverless technology. Standardization is a crucial prerequisite for the widespread deployment of AVM, requiring collaboration among academia, international standardization bodies (e.g., ISO, ETSI, SAE), and industry consortia such as VDA and 5GAA. This article outlines the current standardization efforts and deployment status of AVM, elaborates on core vehicle motion control mechanisms, FuSa principles, communication interfaces, message formats, and spectrum requirements. Through this comprehensive examination, the article aims to address how AVM can be seamlessly integrated into future Intelligent Transportation System (ITS) ecosystems. As the automotive industry progresses toward greater automation and connectivity, AVM represents a major advancement in automated vehicle maneuvering and control for manufacturing plants, logistics depots, parking facilities, and charging stations.

INDEX TERMS AVM, AVP, V2X, 5G, ITS, functional safety, standardization, SAE L4.

I. INTRODUCTION

One of the main drivers of today's technology development is the increasing societal demand for mobility. In 2023, the global number of registered vehicles reached 1.5 billion, approximately doubling every 25 years [1], [2], [3]. The World Health Organization (WHO), in its Global Plan for the Decade of Action for Road Safety 2021–2030, estimates that road traffic injuries will total 500 million between 2021 and 2030, with 13 million resulting in fatalities [4]. Rising traffic densities additionally lead to higher times spent in traffic jams, accounting for a yearly average per driver of 42h in the US and 31h in Europe. This equates to nearly a full workweek lost each year. In its recently released *REPORT on the new EU Urban Mobility Framework* the European Parliament estimates the total cost to society from transport to EUR 987 billion a year, of which EUR 270 billion can be attributed to congestion [5]. After arrival, car drivers spend another 55h on average searching for a parking space in European and American cities every year [6].

To address these challenges, authorities worldwide are placing their hopes in the development of Intelligent Transportation Systems (ITS), with a strong focus on connected and automated driving technologies. The exchange of information between traffic participants by means of Vehicle-to-Everything (V2X) communication is seen as one of their main enablers. To ensure interoperability, standardization mandates have been issued in the different regions of the world. Some of the leading regional Standards Developing Organizations (SDOs) for ITS are ETSI (EU), SAE (US), and C-SAE (CN), with further standardization requests in the ITS domain issued to the international SDOs ISO, CEN/CENELEC, IEC, IEEE, and ITU among others (cf., e.g., the ITS section of the *Rolling Plan for ICT standardization 2024* of the European Commission [7]). SDO partnerships like 3GPP and industrial alliances such as 5GAA and the C2C-CC support the development process.

Early V2X services, often referred to as Day 1 services, have reached maturity and are currently being deployed. In Europe for instance, the two flagship V2X services of the ETSI TC ITS Rel-1 specifications Cooperative Awareness and Decentralized Environmental Notification have been deployed by Volkswagen since 2019 using ITS-G5 as access layer technology. Cooperative Awareness allows traffic participants to share their kinematic and attitude state with other connected ITS stations, while the Decentralized Environmental Notification Service enables them to warn others of critical situations. Both services have their analogues in other regions of the world.

Currently a new set of Day 2 standards is being developed globally. In Europe the specification of these standards is taking place in the scope of ETSI TC ITS Rel-2, which is planned to be released in 2025. While enhancing the mentioned Rel-1 services and upgrading them to Rel-2 compliance, new services, such as Collective Perception and Vulnerable Road User (VRU) Awareness, will be introduced. Collective Perception, also known as Sensor Sharing or Cooperative Sensing, enables the exchange of environmental information, such as detected objects or perceived regions. VRU Awareness on the other side, is the VRU-based pendant to Cooperative Awareness, enabling VRUs, such as pedestrians or bicycles to inform surrounding ITS stations of their kinematic and attitude states. These services also have their counterparts at SAE and C-SAE.

In 2022 a new service was proposed for incorporation into the ETSI TC ITS Rel-2 bundle: Automated Vehicle Marshalling (AVM), also known as Automated Vehicle Maneuvering. AVM is a specific category of low-speed remote controlled automated driving. It supports various use cases and applications. The first category of AVM use cases includes consumer applications such as Automated Valet Parking (AVP) and Automated Valet Charging (AVC). They allow vehicle owners to hand over control of their vehicles to a Remote Vehicle Operation (RVO) offering different services, such as autonomous charging, washing, and parking, before being picked up again at a defined place and time. Beyond private vehicle applications, these use cases (schematically depicted in Fig. 1(a)) are gaining traction in commercial real estate, where automated parking solutions help optimize space usage and enhance property value. This integration supports real estate developers in reducing infrastructure needs while offering a premium amenity for tenants [8]. Another category of AVM use cases are production use cases, including Self-Navigating Automotive Production (SNAP [9]) for control of vehicles in the production lines, Automated Factory Marshalling (AFM) or Automated Plant Marshalling (APM) for maneuvering of already assembled vehicles in the factory. Another category of AVM use cases belongs to the area of logistics. New vehicles must be transported to their target markets, as shown in Fig. 1(b), or may be driven through depots autonomously, e.g., with Automated Depot Marshalling (ADM), as depicted in Fig. 1(c). In the following the term AVM is used as umbrella-term for the technology to refer to all variations generically. Notably, this technology is not limited to passenger vehicles; it can also be applied to autonomous trucks, mobile robots, and vessels, among others.

To ensure interoperability between different car manufacturers and RVO system providers AVM is developed in a joint effort by various SDOs and industrial alliances, such as ISO, VDA, ETSI, SAE and 5GAA. ISO-23374-1 categorizes AVM[1] into three types based on their functional allocation between the vehicle and the RVO [10]:

- Type 1 (Vehicle-Centric Control): the vehicle handles all tasks related to route planning and navigation, using its own sensors and systems, while the RVO provides only basic support like positioning assistance.
- Type 2 (Infrastructure-Centric Control): the RVO is responsible for both route planning and navigation, with the vehicle following the RVO's commands, reducing the complexity needed onboard the vehicle.
- Type 3 (Hybrid Approach): responsibilities are shared between the vehicle and RVO, e.g., with the RVO planning the route, and the vehicle managing specific navigation tasks such as localization.

This ISO categorization standardizes the control allocation between RVO and vehicles, enabling varied implementations for different use cases. While Types 1 and 2 have clear

1.ISO-23374-1 uses the term Automated Valet Parking System (AVPS), as it was introduced based on the AVP use case.

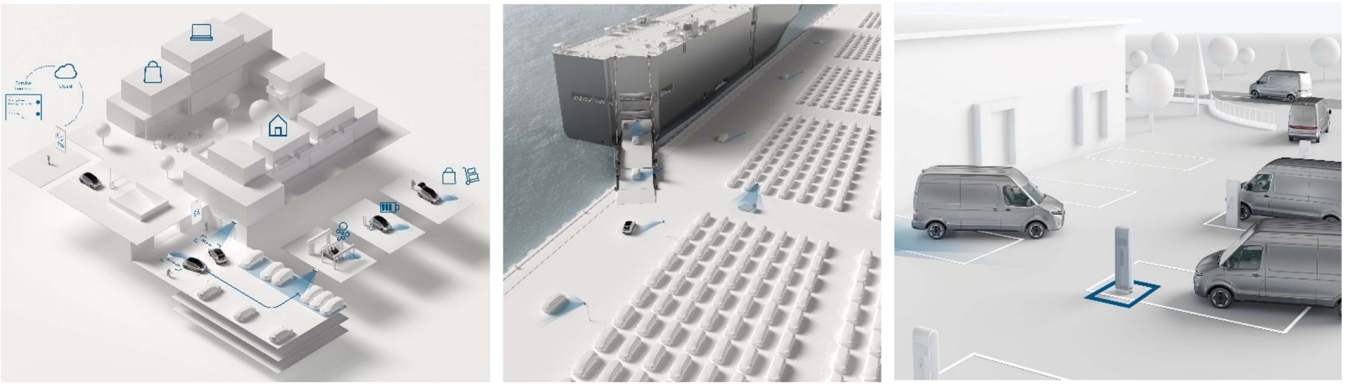


FIGURE 1. Exemplary AVM-enabled use cases including (a) parking, carwash and charging, (b) shipment, and (c) depot logistics.

FIGURE 2. AVP pilot developed by Mercedes and Bosch [18].

FIGURE 3. Ford Escape test vehicle guided by Bosch smart infrastructure sensors through Bedrock's Assembly Garage in Detroit [20].

FIGURE 4. Audi e-tron Sportback starting an AVP process initiated via app, driving through an automatic car wash facility before parking [22].

FIGURE 5. Mercedes-Benz EQS 580 demonstrating AVP at InterContinental Los Angeles Downtown hotel, Los Angeles [24].

roles, Type 3's flexibility demands careful consideration of responsibility and liability.

The German Association of the Automotive Industry (VDA) plays a key role in developing interface specifications for AVM, based on real-world implementation experience to ensure practicality and widespread adoption. Meanwhile, 5GAA focuses on leveraging 5G-V2X technologies to enable AVM, supporting its deployment in vehicles and parking facilities. Additionally, 5GAA collaborates with SDOs to develop interoperability test specifications and system profiles, ensuring seamless operation across different platforms [11].

AVM communication specifications, including message formats and generation management, are being standardized in ETSI TS 103 882 [12] in Europe and in SAE J3292 [13] in the US. In China the National Technical Committee of Auto Standardization (NTCAS) and China-SAE (C-SAE) have been working on a series of AVM related standards, such as T/CSAE 156-2020, T/CSAE 261-2022, T/CSAE 304-2023.

Despite regional differences, these standards aim to define the architecture, communication protocols, and safety requirements for AVM systems. SAE J3292 and ETSI TS 103 882, for example, align closely in their approach to message formats and communication, ensuring consistent guidance for AVM deployment. Infrastructure plays a key role across all standards, managing vehicle navigation and safety. Global harmonization of these standards is essential for ensuring

FIGURE 6. BMW G70 being maneuvered through BMW's production plant in Dingolfing by the AFM system [25].

FIGURE 7. Six of the seven AVP-capable Mercedes-Benz series vehicles [29].

FIGURE 8. Continental Automated Vehicle Maneuvering [31].

AVM systems can be deployed reliably and interoperably across diverse environments.

What sets AVM apart among Day 2 services is its distinction as the first Functional Safety (FuSa)-enabled V2X service worldwide, with both the RVO and vehicle subsystems developed according to IEC 61508 and ISO 26262 standards, respectively. However, the rapid pace of development and the relatively short time since the initiation of standardization efforts at ETSI and SAE have left some open questions, particularly concerning the application of FuSa concepts to C-ITS and the scalability of AVM services with regard to communication aspects such as spectrum requirements and regulatory compliance.

The paper at hand is intended to resolve these doubts and pave the way of this first FuSa-enabled V2X service into the Day 2 bundle, which is currently being consolidated by the various involved SDOs and supporting alliances around the world.

The remainder of this paper is structured as follows: Section II discusses AVM pilots and the current deployment status. Section III introduces the AVM service and outlines the main Vehicle Motion Control (VMC) mechanisms. Section IV explores the core FuSa concepts and their underlying rationale. Sections V through VIII delve into the communication interface, covering AVM message formats, generation rules, possible protocol stack variants, and security mechanisms. Finally, Section IX provides an in-depth analysis of the technology's spectrum needs, identifies limitations, and proposes potential performance enhancements before concluding in Section X.

II. AVM DEMONSTRATIONS AND DEPLOYMENT

AVM and its previously introduced use cases have been demonstrated in various pilots throughout the last years. Although AVP has been a well-known AVM use case for over a decade, its first major functional advancements emerged around 2015, with the project V-Charge around Volkswagen and Bosch [14][15], BMW's and Continental's demonstration at the Consumer Electronics Show (CES) [16], and the AVP cooperation between Bosch and Mercedes-Benz [17], among others.

A first technological milestone was reached when in 2019, Mercedes-Benz and Bosch obtained the world's first special permit to operate AVP in environments with both automated and manually operated vehicles without human oversight, ensuring seamless integration in real-world mixed-traffic conditions [18] (Fig. 2). The special permit was granted for the automated operation of selected E-Class vehicles in the parking garage of the Mercedes-Benz Museum in Stuttgart.

Only one year later, Mercedes-Benz announced the company started deploying the technology in its S-Class, making the INTELLIGENT PARK PILOT the first SAE Level 4 automated driving function pre-installed in a series vehicle worldwide [19].

The same year, Ford Motor Company, Bedrock and Bosch demonstrated infrastructure-based AVP for the first time in the US [20]. Initially being demonstrated in a Ford Escape test vehicle, an integration into Ford's Co-Pilot360 driver-assist technology stack was envisioned for the future (Fig. 3).

In 2021 the VDA brought together various automakers, namely BMW, CARIAD (with the brands Volkswagen, Audi and Porsche), Ford, Jaguar Land Rover, and Mercedes-Benz, as well as the technology and infrastructure providers Bosch, Continental, Valeo, Kopernikus Automotive and Unikie to demonstrate an interoperable AVP implementation at the IAA mobility fair in Munich [21]. Various use cases were presented to the public, including automated app-based parking, washing, and charging (Fig. 4).

In March 2022, Mercedes and Bosch showcased AVP at the InterContinental Los Angeles Downtown hotel (Fig. 5). The technology is mature and Mercedes is evaluating to expand its pre-installation in series vehicles to the US based on the evolution of the country's market and legislation [23].

FIGURE 9. AFM implemented by CARIAD and Bosch in Audi's production plant in Neckarsulm.

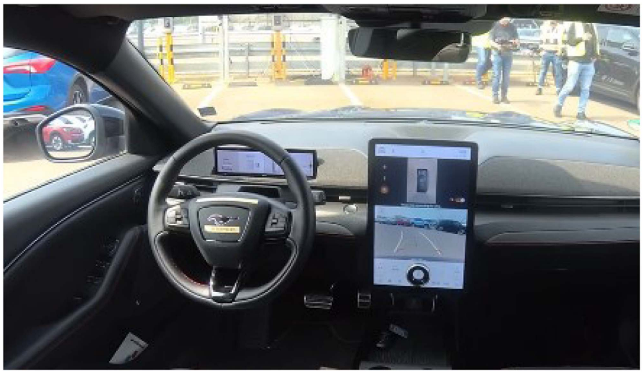


FIGURE 10. A Ford Mach-E 2023 being remotely guided by AVM system at E-Self demonstration in Cologne.

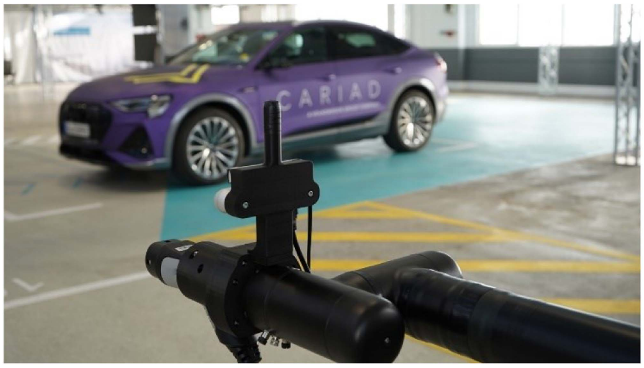


FIGURE 11. Automated Valet Charging as presented on the CES 2024 by Bosch and CARIAD in Las Vegas.

FIGURE 12. Teleoperated Valet Parking as demonstrated on the CES 2024 by Valeo and BMW.

In July 2022 the BMW Group kicked-off the AFM-based Automated Driving In-Plant project (ger. 'Automatisiertes Fahren im Werk', AFW) to enable vehicles fresh off the production line to move autonomously through assembly and to a parking area — ready for their onward journey by train or truck. AFM is part of BMW's iFACTORY and was first trialed on the new BMW 7 Series and the fully electric BMW i7 [25] (Fig. 6).

In November 2022, Germany's Federal Motor Transport Authority (KBA) approved the public use of the AVP system developed by Bosch and Mercedes for series vehicles in Germany [26]. The approval was issued one month after the KBA published a catalogue of technical requirements for AVP [27], based on the new Act on Autonomous Driving passed by the German Federal Ministry for Digital and Transport in 2021 [28]. With this, Mercedes is the world's first car OEM to obtain official approval for the commercial use of a highly automated driverless parking function (SAE level 4) (Fig. 7).

Inspired by this world's premiere, Mercedes has steadily increased the number of AVP-capable series vehicles, amounting to a total of seven by the end of 2023: S-Class, E-Class Saloon, E-Class Estate, EQS Saloon, EQS SUV, EQE Saloon and EQE SUV [29] (Fig. 8).

Another key player counting on a long history in the field of safe infrastructure solutions to increase road safety through sensors placed in the infrastructure is Continental. Besides the presentation of its AVP capabilities at the IAA 2021, Continental demonstrated its AVP Type 1 and AVP Type 2 solutions at the Conti TechShow in 2023 in their own employee parking garage [30]. These technologies and relevant safety concepts are developed and tested in dedicated V2X laboratories located in Continental's indoor and outdoor AVM test facilities.

Besides the ongoing AVP development, Continental has been strengthening its focus on AFM, which is the use-case where Continental currently experiences the highest market demand. With its AVM technology, Continental focuses on the control and orchestration of multiple vehicles simultaneously in vehicle production plants [32].

The same year, in 2023, two other major demonstrations of AFM were presented by CARIAD and Bosch in Audi's production plant in Neckarsulm (see Fig. 9), and by Ford in Cologne (see Fig. 10) . In Neckarsulm, the intelligent infrastructure for the AFM pilot was set up by Bosch in only a few days. For communication a private 5G network provided by Ericsson was used. The system was not only able to operate under the strict precision requirements, expectably resulting in increased efficiency and productivity in the future, but also to gain important insights into the particularities of the in-plant conditions for the functional safety assessment.

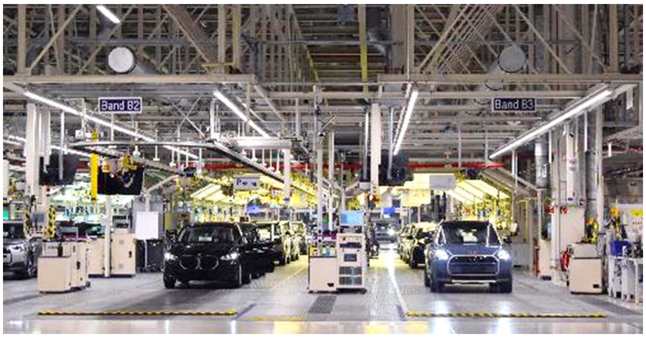


FIGURE 13. AVM-controlled vehicles in BMW's production plant in Leipzig.

Ford's E-self demonstration at Cologne [56] showed a concept around multiple automated vehicles being guided from inside the plant to a parking lot. Ford's implementation of AVM technology follows and supports the ongoing standardization work in SAE J3292 which can operate with both C-V2X[2] and cellular technology.

Similar demonstrations based on ETSI TS 103 882 were developed by Kopernikus [34] and Unikie [35] for two Ford production plants each. Likewise, Volkswagen started cooperations to equip its plant in Wolfsburg with Kopernikus [36] and the VW automotive Seaport in Emden with Unikie [37].

On the 2024 edition of the CES, the largest and most renowned tech event in the world, in Las Vegas, USA, Bosch presented AVM-based AVC. The demonstration was a big success, with Bosch even winning one of the prestigious CES innovation awards [38]. The technology is intended to support drivers of Electric Vehicles (EVs) by automating the charging process. With the expected rapidly growing EV market, drivers will increasingly be confronted with time-consuming queues, tedious charging procedures, and potential penalty fees associated with delayed unplugging. AVC allows to overcome these frustrating experiences by automating the entire charging process, from the vehicle maneuvering to the operation of the charging robots.

During the same event the BMW Group and Valeo, having signed a strategic partnership for the joint development of next-generation automated Level 4 parking solutions in 2023 [39], exhibited their latest AVM-related technology. The fully autonomous AVP solution was additionally extended by teleoperation capabilities, allowing a remote operator to maneuver the vehicle through the parking lot and parking and retrieving it in a carefully controlled manner.

In early 2025, following successful trials and certification for indoor operation at BMW's plant in Dingolfing by TÜV Süd, the AFM system is transitioning into series operation [40]. The system allows newly produced vehicles to navigate autonomously for over one kilometer from the assembly halls through short test courses to final finishing areas, marking a key step toward full automation in production logistics. In cooperation with Hesai, Outsight and Embotech this deployment is powered by one of Europe's largest LIDAR-based infrastructure systems, providing an externally generated environmental model for precise vehicle guidance. The BMW Group is expanding the operation of its AFW technology to additional plants, including Leipzig, Regensburg, and Oxford, with further rollouts expected at the new Debrecen site in Hungary [41].

The selection of AVM-based technological achievements, demonstrations, pilots and first consumer products presented in this section demonstrates the rapidly growing interest in -and maturity of- the technology. Some AVM use cases have already achieved official approval for commercial use by the corresponding authorities and it is just a matter of time until more will follow.

The next section introduces the architecture and core components of AVM, together with its motion modes and control concepts.

III. AVM SERVICE

The AVM system consists of several subsystems to guide vehicles through facilities like parking garages, depots, and production plants, often including:

- Remote Vehicle Operation (RVO): guides vehicles using the operation interface.
- Operator Backend: manages reservations, sessions, and missions while interfacing with the User Backend and Vehicle Backend.
- Vehicle Backend: provided by the manufacturer, this serves as an intermediary between the vehicle and the Operator Backend.
- User Backend: acts as a broker between users and other subsystems.

As part of the facility's infrastructure, the RVO uses sensors to detect the ego vehicle and surrounding obstacles. The RVO is responsible for planning a safe path for the vehicle while ensuring it interacts safely with its surroundings and avoids collisions.

The AVM system integrates a dual-layer architecture, separating functional motion control from safety mechanisms (Fig. 15). The motion control loop determines the speed and direction of the vehicle, while the safety chain can only decide to stop with maximum deceleration, abort the mission, or continue driving. Different vehicle operation modes are specified by the VDA, including [42]:

- INITIALIZATION: the vehicle initializes and prepares for the mission.
- SAFE_DRIVING: the vehicle possesses a valid *DrivingPermission* and is actively following the path or trajectory commands.
- STANDBY: the vehicle continues in safe driving state but is currently not actively following a path or trajectory.
- TERMINATION: the vehicle leaves safe driving state after finalizing the mission and disconnects from the RVO unless otherwise requested.

2.Throughout this article, the terms C-V2X, LTE-V2X, and NR-V2X refer specifically to the corresponding PC5 sidelink interface for simplicity, deviating from the broader definitions provided by 5GAA [33]. For comparison, 'native cellular' communication via the operator's core network is referred to as the Uu interface.

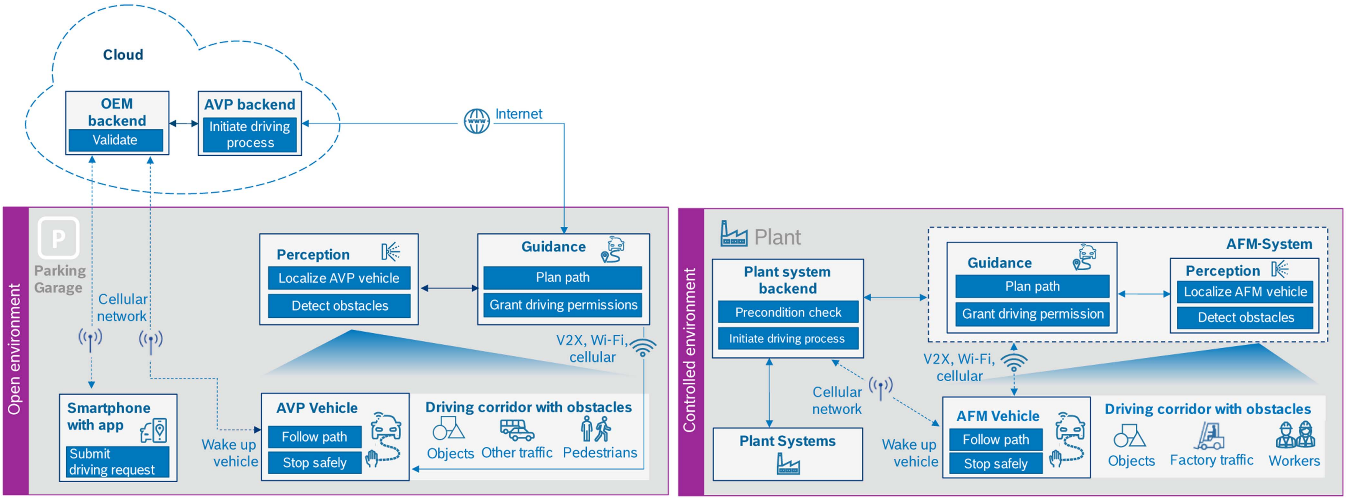


FIGURE 14. AVM system architecture for two of the most prominent use cases, namely AVP and AFM, indicating the key AVM system components.

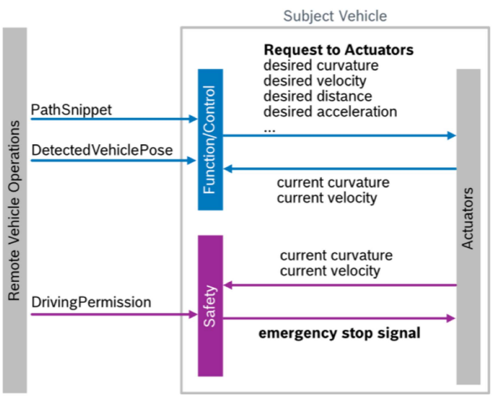


FIGURE 15. Data flow between RVO and vehicle, with separation of function and safety.

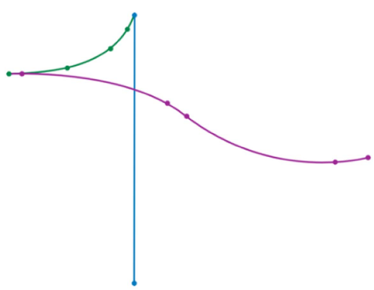


FIGURE 16. Path consisting of 3 *PathSnippets* and 11 *WayPoints*.

To enable precise vehicle maneuvering, AVM incorporates two distinct VMC methods. Both approaches rely on real-time communication between the RVO and vehicle, ensuring safe navigation via continuous path updates or trajectory adjustments, as described in the following two subsections.

A. PATH CONTROL

The path interface is a purely geometrical approach, in which the RVO provides the marshaled vehicle with a path and its current pose. The vehicle is configured to follow the path using its own controller.

For transmission, the path is divided into multiple *PathSnippets* (Fig. 16). The size of each *PathSnippet* varies depending on the current driving situation. Each *PathSnippet* consists of a series of *WayPoints*, which include coordinates (*x*, *y*, and *heading* in the driving facility's coordinate system), a maximum velocity, and an appropriate curvature to help the vehicle controller and make the path smoother.

The RVO sends the vehicle's current pose to the vehicle in a suitable cycle, given in the facility's coordinate system. By knowing its current pose and the *PathSnippet*, the vehicle can determine its position relative to the path and calculate appropriate controller outputs to follow the path. The RVO sends a new *PathSnippet* whenever the vehicle approaches the end of the previous *PathSnippet* or if the situation changes, such as if the vehicle needs to stop smoothly in front of an obstacle or reduce its velocity because of pedestrians walking close by. With this approach, the vehicle can precisely navigate and stop at the end of the path snippet. Communication delays, lost packets, and message generation intervals can be compensated by the vehicle, allowing it to accurately determine its current pose at any time.

B. TRAJECTORY CONTROL

The trajectory interface is a time-based approach. Similar to how a pathway is defined by a *PathSnippet*, the RVO provides a sequence of velocity and curvature commands. These lateral and longitudinal movement commands are executed at equidistant time intervals to help vehicle motion along a straight or curved pathway. Moreover, this approach also provides the vehicle with a certain *distanceToStop* defined along its maneuver pathway so that the vehicle is aware of the displacement it must not exceed. The simplified command structure of the RVO reduces the control and computing power required in the vehicle and thus the concept is adoptable for high-volume applications in the automotive market.

IV. FUNCTIONAL SAFETY ASPECTS

Functional Safety (FuSa) is a critical requirement for AVM, given its operation at SAE Level 4 without human oversight in environments with mixed traffic and various potential obstructions. Hence, any fault in the system can potentially lead to casualties. Two alternative approaches have found their way into standardization and are discussed in the following subsections. They may be adopted by other V2X services in the coming years.

A. PROACTIVE APPROACH

The first approach proactively grants the vehicle authorization to safely maneuver in a mixed-use environment despite an unreliable wireless connection.

1) DRIVING PERMISSION

The core of the proposed safety concept is the continuous and frequent transmission of *DrivingPermissions* from the RVO to the vehicle to ensure controlled maneuvering. A *DrivingPermission* defines a corridor within which the vehicle is permitted to move, specifying maximum velocity, minimum and maximum curvatures, and an expiration time. The RVO calculates the *DrivingPermission* such that the vehicle will not collide with obstacles if it adheres to the specified parameters.

In the event that a vehicle violates any parameter of the *DrivingPermission*, it will come to a stop with maximum deceleration. For example, if the vehicle's velocity exceeds the maximum allowed by the *DrivingPermission*, it will stop with maximum deceleration. Also, if the connection between RVO and vehicle is interrupted, preventing further reception of *DrivingPermissions*, the vehicle initiates a safety stop at maximum deceleration based on the expiration time specified in the last received valid *DrivingPermission*.

2) CLOCK SYNCHRONIZATION

Both the RVO and the vehicle must maintain a safely synchronized clock, meeting a Safety Integrity Level (SIL) rating (IEC 61508) for the RVO and an Automotive Safety Integrity Level (ASIL) rating (ISO 26262) for the vehicle. This synchronization ensures accurate setting and evaluation of *DrivingPermissions* expiration times. The vehicle maintains a reference safety clock and the RVO synchronizes with it, based on a worst-case estimation rather than focusing on precision.

3) END-TO-END PROTECTION OF SAFETY PAYLOADS

End-to-end protection of safety payloads is essential to prevent transmission and processing failures between safety endpoints in the RVO and vehicle from causing safety-critical issues. This is achieved through a checksum mechanism that ensures a sufficiently high probability of detecting bit errors.

Several measures are taken to ensure that safety payloads are reliable and recent:

- Only safety components can calculate a valid checksum for safety payloads, protecting against accidental changes and recalculation of checksums in non-(A)SIL-rated components. The safety checksum algorithm is different from those on other communication layers, and a secret known only to safety components is incorporated when calculating the safety checksums.
- Each safety payload is reliably associated with a specific vehicle by making the secret incorporating in the safety checksums vehicle-specific, protecting against mix-ups in non-safety components.
- Safety payloads are protected against (accidental) replay of previous messages by including timestamps, counters, or by sending them only once per mission. The secret incorporated in the safety checksums also changes for each mission.

B. REACTIVE APPROACH

The core of the reactive approach is a dedicated (reactive) emergency stop signal, allowing the RVO to explicitly command vehicles in potentially hazardous situations. In such cases, the drive command must be transmitted and received with a specified minimal inter packet gap. Functionally it is possible to trigger such an emergency case in an event-driven manner, beyond the usual periodic dissemination of the messages. It serves to command the vehicle an immediate maximal deceleration into a safe standstill. Additionally, the concept allows to apply a two-stage braking approach:

1. Depending on the severity of the emergency and the vehicle's speed, the RVO first initiates a pre-charge of the braking system. It applies the brake pads to the brake disk without a visual deceleration of the vehicle.
2. In the second step, full deceleration is initiated, ensuring no delay in braking response and minimizing stopping distance based on the vehicle's initial speed.

The reactive approach requires additional end-to-end protection of the AVM to ensure functional safety. This is achieved by including a checksum computed over the entire message according to Autosar specifications [43]. This allows the endpoints in the signal chain to prove signal integrity of the message bodies including all signals with a Hamming distance of 6.

V. MESSAGE FORMATS

The AVM service defines two messages, one transmitted by the RVO and one by the vehicles. In view of the ongoing standardization efforts at SAE and the first AVM message formats being finalized in Europe, the latter following sections will be based on ETSI TS 103 882 v2.1.1 [12]. The messages used to disseminate the data by the RVO and the vehicles are the Marshalling Infrastructure Message (MIM) and the Marshalling Vehicle Message (MVM), respectively. Both are described in more detail in the following subsections. Note that the SAE J3292 follows a similar approach. However, the SAE names for the two messages are Infrastructure Marshalling Message (IMM) and Vehicle Marshalling Message (VMM) to differentiate them from their ETSI counterparts MIM and MVM, respectively. With some minor differences, function and operation of the SAE messages are quite similar.

header		protocolVersion
		messageID
		stationID
e2eProtection		length
		rollingCounter
		dataID
		crc32
mims	SEQUENCE of Mim	MIMDataControlField OPTIONAL
		SystemManagementData OPTIONAL
		VidRequest OPTIONAL
		DrivingPermission OPTIONAL
		SafetyTimeSyncRequest OPTIONAL
		DriveCommand OPTIONAL
		DetectedVehiclePose OPTIONAL
		ControlInterface OPTIONAL

FIGURE 17. Message format of the MIM.

header	protocolVersion
	messageID
	stationID
e2eProtection	Length
	rollingCounter
	dataID
	crc32
mvm	MVMDataControlField OPTIONAL
	SystemManagementData OPTIONAL
	VehicleState OPTIONAL
	VidResponse OPTIONAL
	SafetyTimeSyncResponse OPTIONAL
	SafeVehicleTypeConfirmation OPTIONAL
	VehicleError OPTIONAL
	VehicleSafetyFeedback OPTIONAL
	VehicleProperties OPTIONAL

FIGURE 18. Message format of the MVM.

A. MIM

The MIM is composed of an *ITS PDU header*, an *AVME2EProtection* container and a *mims* container (see Fig. 17). The *ITS PDU header* is mandatory and common to all Facility-layer V2X services defined by ETSI. It includes the protocol version, the *messageID* (18 in the case of MIM) and the *stationID*.

The *AVME2EProtection* container has been specifically designed to support the reactive FuSa approach introduced in Section III-B. It is mandatory and protects the message transmission in compliance with Autosar e2e protection [43]. To this aim, this container includes the length of the message, a rolling counter identifying the message and iteratively being incremented by 1 with every new MIM generation, an ID of the data originating system, and a Cyclic Redundancy Check (CRC) of 32 bits to detect errors at the receiver side. The *dataID* is a unique identifier for verification of transmitted MIM and MVM.

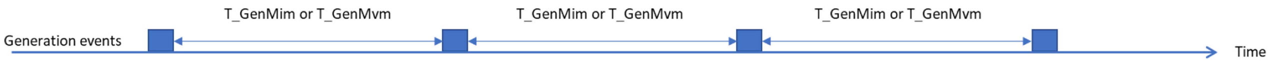
The *mims* container is a sequence of up to 32 *Mim* containers, each of them targeted to a specific vehicle. Each *Mim* contains eight optional elements, as shown in Fig. 17. More specifically, each *Mim* optionally includes a *MIMDataControlField* with control information, such as a specific *checksum*, the *mimGenerationTime* representing the time at which the vehicle container was fully assembled, a rolling counter, and a proprietary extension field. The *Mim* also includes the optional *SystemManagementData* that contains the *sessionID*, *missionID*, *vehicleID* (targeted vehicle), and *facilityID* to identify the road infrastructure. Various such fields are required to uniquely identify various aspects of commanded maneuvers for individual vehicles or in combination.

A *VidRequest* can be used to identify the vehicle during standstill, using a method based on blinking lights. The standard allows for further methods to be added in the future. The *Mim* can also include a *DrivingPermission* with data elements for the vehicle obtaining or denying a permission to drive (e.g., expiration time, maximum speed, and maximum/minimum curvature) and also has its own *checksum*. The *Mim* optionally includes the *SafetyTimeSyncRequest* element to request a safety time synchronization to the vehicle as described in Section III-A. The *DriveCommand* that can also be included in the *Mim* includes data elements for general drive commands, such as the command action (e.g., sleep, drive, wait), the gear request, or the direction indicator request. The *Mim* can also include the *DetectedVehiclePose*, that contains the vehicle's position determined by the infrastructure sensors in a relative two-dimensional coordinate system. Finally, the *Mim* can also include the *ControlInterface* that is used for vehicle motion control. Two different control options are currently supported. The first control method, introduced in Section II-A, is known as *pathControl* and is based on the transmission of a sequence of up to 200 *wayPoints* that the vehicle must follow (cf. Fig. 16). Each *wayPoint* contains an index, the position, speed, curvature, and pitch angle of the vehicle. The second control method, introduced in Section II-B, is known as *trajectoryControl* and is based on the transmission of a trajectory that the vehicle must follow. Each control point (up to 50) in the trajectory includes the curvature, the speed or acceleration of the vehicle. The trajectory can also optionally include up to 50 state points with the position and speed of the vehicle.

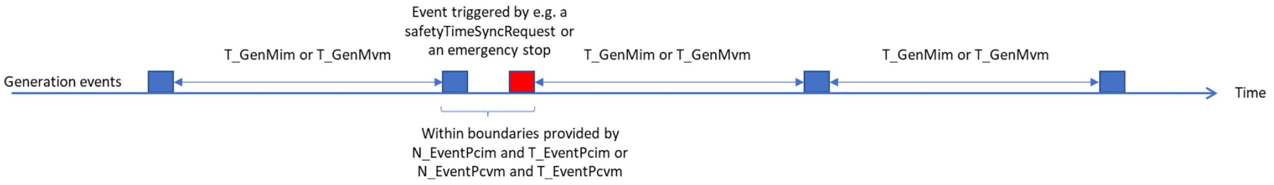
For the generation of a MIM, it is important to note that all data elements included in each *Mim* are optional. The use of these elements depends on the current vehicle operation mode.

B. MVM

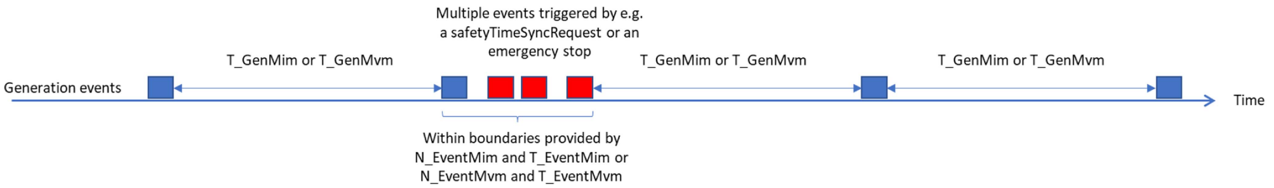
The MVM format is illustrated in Fig. 18 and has a similar structure to the MIM. The MVM uses the same *ITS PDU header* (*messageID* 19 in the case of MVM) and *e2eProtection* containers as the MIM. In addition, the MVM has a *mvm* container that includes 9 optional elements as illustrated in Fig. 18. The first element is the *MVMDataControlField*, that includes a timestamp, up to 10 rolling counters (as a mirror of the rolling counters that have been received



(a) Periodic message generation



(b) Mixed periodic and event-driven message generation



(c) Mixed periodic and multiple event-driven message generation

FIGURE 19. MIM and MVM dissemination modes for different ratios of periodic and event-triggered messages.

with the latest MIMs), and a proprietary extension field. The *mvm* container can also include the *SystemManagementData* that is equal to the one included in the MIM. The *VehicleState* includes information about the vehicle motion status (e.g., operation mode, gear state, direction indicator state, current position, velocity or curvature, among others). The *mvm* container can also include the *VidResponse*, which is sent as a response to the vehicle identification request received through a MIM. Similarly, the *SafetyTimeSyncResponse* is included in the *mvm* container as a response to the *SafetyTimeSynchRequest* sent by the infrastructure. The *mvm* container can additionally include the *SafeVehicleTypeConfirmation* to allow the vehicle to inform the infrastructure about vehicle type and used safety profile. The safety profile specification is an essential component of an interface implementation profile, which is typically defined by industry consortia like the VDA, 5GAA, the C2C-CC or C-ROADS. The *VehicleError* included in the *mvm* container can be used by the vehicle to inform the infrastructure about an error (e.g., path not drivable, onboard vehicle fault, or communication fault). The *vehicleError* includes the *time*, *vehCode* and *customCode*, as well as up to 200 bytes of error description. The *mvm* container could also contain the *VehicleSafetyFeedback* that includes safety information such as the remaining time to start braking, or a list of the safety violations that lead the vehicle to stop. Finally, the *mvm* container also includes the *VehicleProperties*, with information about the vehicle length, width, mass, and speed limit, among others.

VI. MESSAGE GENERATION

An RVO can address one or more vehicles using a single MIM. After successfully receiving at least one MIM a vehicle is allowed to respond with an MVM. In addition to this mandatory message sequence, AVM introduces a novel message generation concept for ETSI TC ITS: a mix of periodic and event-driven messages. By default, AVM messages are generated continuously, similar to relevant V2X messages like CAM and CPM. A schematic visualization of the periodic message generation mode is offered in Fig. 19(a). AVM generates messages every *T_GenMim* and *T_GenMvm*, the maximum inter-message time for MIM and MVM, respectively. These parameters must be set between 100 ms and 1000 ms, depending on the state of the communication channel, leading to periodic message generation rates of 1 to 10 Hz. To this end, ETSI has recently extended the ITS protocol stack by an additional set of standards intended to enable channel awareness on the facility layer [44], [45]. The specified mechanisms provide the AVM service among others with a maximum recommended data rate, which can then be used to increase the transmission reliability, e.g., by adjusting the message rate or size accordingly.

Additionally, the generation of MIMs and MVMs may be triggered by events, such as *safetyTimeSyncRequests* or emergency stops. These events may cause the immediate generation of one (Fig. 19(b)) or more (Fig. 19(c)) new messages, leading to a disruption in the periodic pattern. If a periodic generation interval, *T_GenMim* or *T_GenMvm*, elapses after an event-triggered message, the generation management returns to the periodic generation pattern. This is illustrated in Fig. 19(c) after the third (red colored) event-triggered message.

This hybrid approach optimizes message transmission, improving network reliability and reducing latency by adjusting message frequency based on the operational context. To avoid intentional and unintentional spectrum misuse, as would be the case in a jamming attack or in the presence of a “babbling idiot” (see IEC 61508), the AVM service restricts the number of MIMs generated by an RVO during a time interval *T_EventMim* to *N_EventMim*, with *T_EventMim* $\leq$ *T_GenMim*. Analogous restrictions apply to the generation of MVMs by vehicles. Recommended values for these parameters are specified in Annex C.4 of TS 103 882 [12].

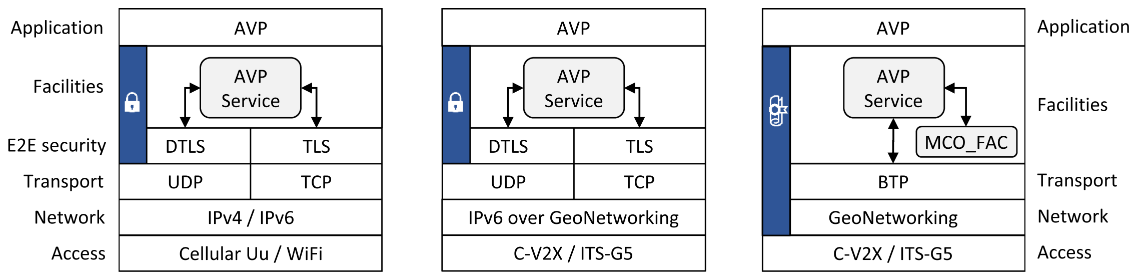


FIGURE 20. AVM protocol stack options as supported by ETSI TS 103 882 v2.1.1.

VII. AVM PROTOCOL STACK

The AVM service was designed to be independent of wireless communication technology to better address the different AVM use cases. Therefore, AVM can make use of any of the protocol stacks options illustrated in Fig. 20. The AVM messages may be generated by the AVM service at the Facilities layer and be sent through the TCP/IP stack over cellular (Uu) or Wi-Fi technologies (Fig. 20, left). With these infrastructure-based wireless technologies, MIM and MVM messages are transmitted in unicast mode. Therefore, in a unicast approach, each MIM contains information about a single target vehicle.

In addition to unicast transmission over cellular and Wi-Fi, AVM messages can also be broadcast over direct short-range V2X technologies, including Wi-Fi-based ITS-G5 (Profile 1: IEEE 802.11-2020, Profile 2: IEEE 802.11-2020 amended by IEEE 802.11bd [46]) or the cellular-based C-V2X technologies LTE-V2X and NR-V2X [47]. In this case, the MIM and MVM messages could be transmitted in broadcast mode at the Access Layer. As illustrated in Fig. 20 (middle), MIM and MVM messages can be transmitted via TCP/IPv6 with GeoNetworking over short-range V2X technologies. Fig. 20 (right) shows a third option in which MIM and MVM are transmitted using BTP (Basic Transport Protocol) and GeoNetworking over short-range V2X technologies (with the AVM service being assigned the ITS-AID 71 [48] and the BTP port number 2026 [49]). In this last case, the MCO_FAC [45] component can be used to provide the AVM service with relevant information regarding the number of available communication resources. This allows to generate messages in a channel-aware fashion. MCO_FAC dynamically manages message transmissions across (one or) multiple radio channels, enabling load balancing and congestion mitigation by offloading data to alternative communication channels as specified in Clause 6.3 of the AVM specifications released by ETSI [12]. For further information regarding MCO_FAC the interested reader is kindly referred to [50].

The deployment of the AVM service through short-range V2X technologies, such as ITS-G5 or LTE-V2X, imposes certain restrictions that must be taken into account. Deployment in the 5.855 MHz to 5.925 MHz frequency band must comply with technical requirements outlined in [51], including transmitter frequency stability, RF output power, and emissions limitations. However, [51] also imposes restrictions on the amount of time that an ITS-Station (ITS-S), vehicle or RVO, can transmit over the radio channel. In particular, [51] mandates that the duty cycle must not exceed 3%, limiting the total transmission time within a 1-second window on each available radio channel. Moreover, the time interval between two consecutive transmissions performed by the same radio equipment is limited to a maximum of 25 ms [51], i.e., the message transmission frequency must not exceed 40 Hz. This minimum time interval increases for CBR (Channel Busy Ratio) levels higher than 0.62 to control congestion as a function of the packet duration and the CBR itself. The CBR is a metric for the channel load caused by all users that represents the fraction of time or bandwidth that a radio channel is busy. These limits restrict the amount of V2X messages that an ITS-S can transmit, and the duration of these messages (which depends on their size and also on transmission parameters such as the modulation and coding scheme). Similarly, limitations on the channel load per transmitter are also imposed under LTE-V2X technology standard based on the packet size [52]. In the case of cellular (Uu) technologies, such channel access restrictions are not imposed. Nevertheless, the duplex scheme, e.g., time or frequency division duplex, and the scheduling rules can still limit the number of resources, in frequency and time, that a vehicle or RVO can use for transmitting the MVM and MIM, respectively. To ensure consistent performance, AVM can leverage network slicing and QoS-flow prioritization, minimizing interference from competing services while maintaining low-latency communication for safety-critical applications.

Short-range V2X technologies also present message size restrictions [52][53]. The maximum size allowed by ITS-G5 is limited by the underlying IEEE 802.11 technology that supports message payloads with up to 2304 bytes [53]. Similarly, the message size in LTE-V2X is limited to 1063 bytes for Onboard Units (OBUs), and 1980 bytes for Roadside Units (RSUs) in 10 MHz channels, considering that the highest MCS is 11 for OBUs and 17 for RSUs following ETSI EN 303 798[3]. When GeoNetworking is used, these sizes are further limited by *itsGnMaxSduSize* corresponding to 1398 bytes according to ETSI EN 302 636-4-1. Similarly, cellular (Uu)

3.The term RSU is commonly used by the ITS community to refer to infrastructure ITS-S. Analogously, OBU is used to refer to mobile ITS-S. For AVM they are part of the RVO and the vehicle, correspondingly.

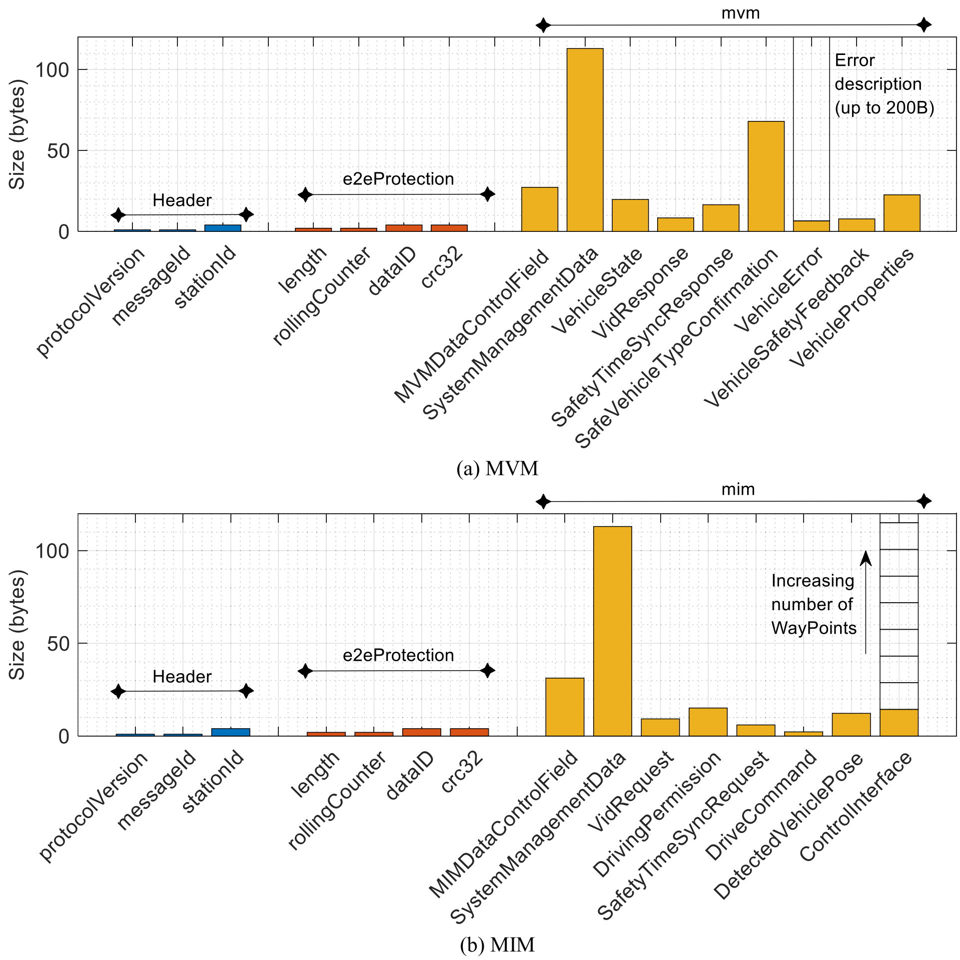


FIGURE 21. Message breakdown of containers and data elements considering all the optional and mandatory containers.

and Wi-Fi-based technologies do not impose specific limitations on the message level but only on the packet level, as defined by the corresponding maximum transmission unit.

VIII. SECURITY AND AUTHENTICATION

For short-range technology, such as ITS-G5 or C-V2X, transmitted MVMs or MIMs will be augmented with IEEE 1609.2 security certificates or certificate digests for authentication upon receipt. In contrast, if a longer-range technology such as cellular communication is used, then transport layer security (TLS) with encryption will be used in a unicast approach between the automated vehicle and RVO. Note that this security will apply on top of the CRC checks for the inner fields in the two messages. Both approaches are depicted in Fig. 20 as part of an AVM protocol stack. An OEM-specific certificate PKI chain can be used to ensure trust and cyber-security of the system. To support interoperability for automated vehicles of different OEMs at an AVM facility, the RVO needs to support independent PKI chains for each OEM.

Network domains should be separated and secured against each other to minimize the risk of remote attacks. For this purpose, the vehicle's internal IP address space needs to be concealed from the public network, such as from the cellular/MNO network, internet, and OEM backend.

IX. ANALYSIS OF THE AVM SERVICE

A. SCALABILITY ANALYSIS

Fig. 21 breaks down the MVM and MIM into their constituting containers and shows the estimated size of each data element. The number of bits required for a given data element, e, is estimated with the following equation:

$$b_e = \log_2 (n_e) \tag{1}$$

where n_e is the number of different values that the data element can have. Fig. 21(a) shows that all the elements inside the MVM have less than 28 bytes, except the *SystemManagementData*, the *SafetyVehicleTypeConfirmation* and the *VehicleError*. The *SystemManagementData* has up to 113 bytes and contains the required IDs (session, mission, etc.). The *SafetyVehicleTypeConfirmation* has up to 68 bytes and includes information such as the *vehicleType* and its *safetyProfile*. The *vehicleError* includes the *time*, *vehCode* and *customCode*, (yellow color in the figure) as well as up to 200 bytes of error description (transparent bar in the figure).

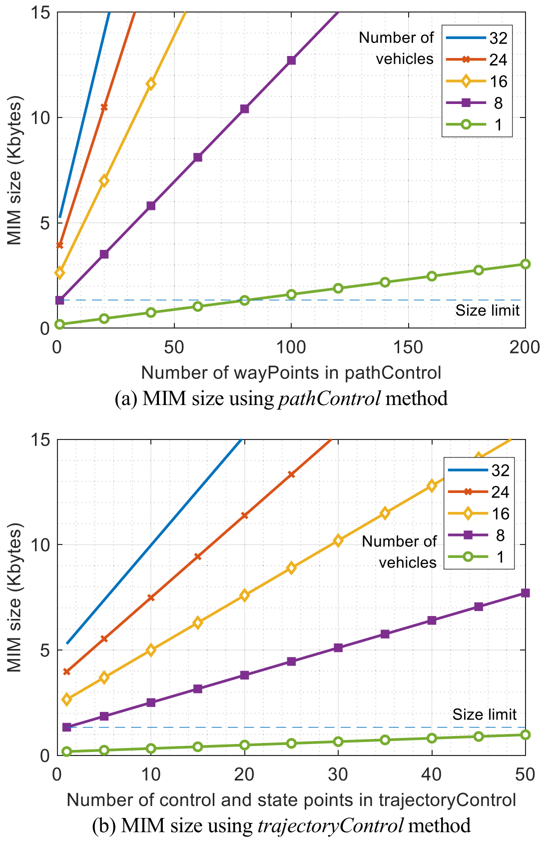


FIGURE 22. MIM size for varying number of vehicles controlled with a single MIM when all the mandatory and optional elements are included.

The maximum MVM size can be therefore around 442 bytes (excluding the *vehicleError* that is only rarely sent).

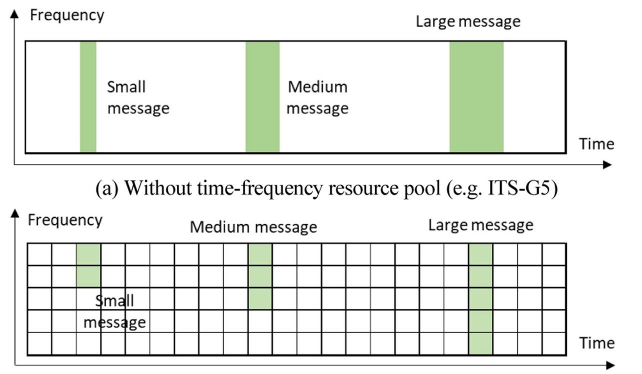
The MIM is shown in Fig. 21(b) with a single *mim* (i.e., with only one vehicle under control) and considering *pathControl* as control method (it influences the size of the *ControlInterface*). As it can be observed in the figure, all the elements have less than 31 bytes except the *SystemManagementData* and the *ControlInterface*. The *ControlInterface* can contain up to 200 *wayPoints*, each of them with up to around 14 bytes.

The size of the MIM is highly dependent on the number of controlled vehicles and the number of *wayPoints* in *pathControl* or *controlPoints* in *trajectoryControl* sent to each vehicle. The MIM size can be up to around 3080 bytes with a single *Mim* container (targeting a single vehicle under control) if all the optional elements are included with 200 *wayPoints* as part of the *ControlInterface*. If the *trajectoryControl* method is used, the maximum number of points is 50 and the MIM size for a single *Mim* is 1031 bytes. Since up to 32 *Mim* containers can be included (one per vehicle under control), the MIM size can be very large. This can be observed in Fig. 22, that shows the MIM size as a function of the number of *Points*, for varying number of vehicles, without adding any protocol header, and including all the optional and mandatory elements. Fig. 22(a) shows the MIM size when the *pathControl* method is used. Fig. 22(b) shows the size of the MIM for the *trajectoryControl* method.

The results in Fig. 22 show that the MIM size can be significantly higher than the limits of the underlying protocol stacks when short-range V2X technologies and the *GeoNetworking* protocol are considered. A potential solution is message segmentation or fragmentation. A V2X message could be segmented at different layers of the protocol stack. When it is segmented by the lower layers, e.g., by the Access layer, all the segments must be correctly received at the destination in order to be able to decode the message by the target AVM service. Thus, ETSI TS 103 882 foresees that the segmentation is performed by the AVM service at the Facilities layer (Fig. 20). In this case, the MIM message could be segmented by separating different *Mims* into different messages, each of them having its own *ITS PDU header* and *e2eProtection* containers. This would ultimately increase the total number of bytes transmitted but would ensure that each segment is actually an independent MIM that can be decoded at the AVM service of the destination, independently of the other segments. However, when a MIM is segmented at the Facilities layer, its segments must still satisfy the time interval limits imposed by [51]. As a consequence, subsequent message segments would be delayed by at least 25 ms, which could cause undesirable effects at the receiver side due to the increase in latency.

With cellular (Uu) and Wi-Fi technology, each MIM is sent in unicast mode, i.e., to only one vehicle under control. Hence, the length of the MIM per controlled vehicle lies within the typical payload size for the *trajectoryControl* method, whereas for the *pathControl* method, the size of the MIM surpasses the typical MTU size when including 200 waypoints. Keeping the MIM size about the same length as for the *trajectoryControl* method, implies reducing the number of waypoints to a total of about 55 waypoints per controlled vehicle. Lower layer segmentation can also be applied, with the potential risk of losing segments over the wireless channel.

Beyond message size limitations, duty cycle constraints also impact the feasibility of large-scale AVM deployments and must thus be considered during the design of the service. The estimation of the duty cycle depends on how the radio resources are organized at the lower layers, because as of today the duty cycle is defined in the time domain only. In this context, wireless technologies with and without time-frequency organization of resources can be differentiated. Without a time-frequency resource pool (i.e., ITS-G5), the message duration and the duty cycle are directly proportional to the message size for a fixed MCS (Modulation and Coding Scheme). This effect can be observed in Fig. 23. However, when a time-frequency resource pool is considered (i.e., with LTE-V2X or 5G NR V2X), the duty cycle is fixed because the message duration is constant and equal to the slot duration. In this case, the duty cycle is maintained when the message size increases as long as the message size fits into the considered slot (see Fig. 23(b)). In 5G NR V2X, the duty cycle consumed



(a) Without time-frequency resource pool (e.g. ITS-G5)

(b) Based on time-frequency resource pool (e.g. LTE-V2X or 5G NR V2X)

FIGURE 23. Organization of time-frequency resources.

by a message would also depend on the numerology, which affects the duration of each slot (0.25 ms, 0.5 ms and 1 ms for numerologies 0, 1 and 2, respectively). In LTE-V2X, it is fixed to 1ms.

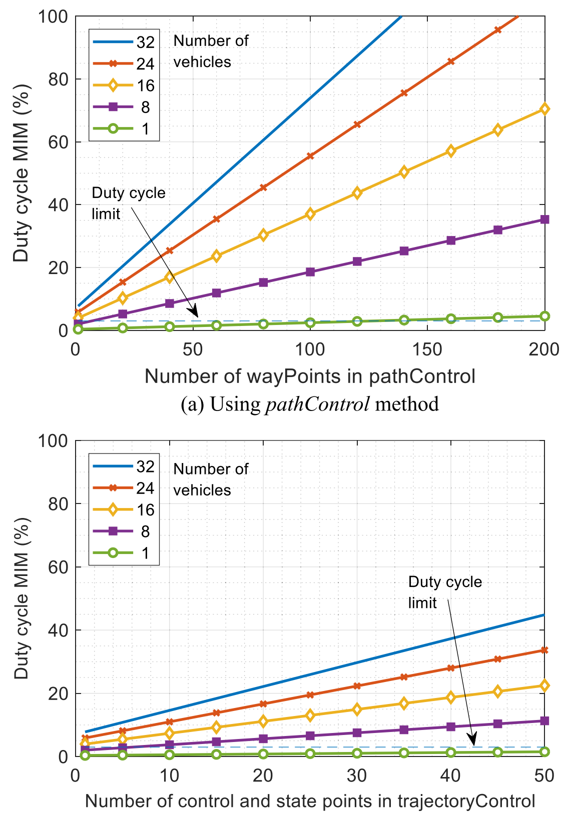
To estimate the duty cycle for wireless technologies without a time-frequency resource pool (e.g., ITS-G5), the following equation was used:

$$dc = \lambda \cdot \left(b_{mim} + b_{btp} + b_{geo}\right) / (bw \cdot e) \qquad (2)$$

where λ is the number of MIMs transmitted per second, and b_{mim}, b_{btp} and b_{geo} are the sizes of the MIM, the BTP header and the GeoNetworking headers, respectively. bw is the channel bandwidth and e is the transmission efficiency, defined as the number of bits (including headers) that can be transmitted per second and per Hertz. In this study, these parameters are configured as $\lambda = 10\,\text{Hz}$ (nominal transmission rate of MIM), $b_{btp} = 32$ bits and $b_{geo} = 480$ bits, $bw = 10\,\text{MHz}$ and $e = 0.55\,\text{b/s/Hz}$ following [54]. The considered value of e corresponds, approximately, to an MCS resulting in a data rate of 6 Mbps with ITS-G5. Fig. 24 plots the estimated duty cycle as a function of the number of vehicles controlled by a MIM. The figure shows that the 3% limit can be easily exceeded as the number of controlled vehicles and *Points* (using *pathControl* or *trajectoryControl* for motion control as described in Section III) augments. Therefore, segmentation is not a solution to reduce the duty cycle. This is the case because each segmented message would require individual protocol headers, and thus a higher number of bits to be transmitted. All the segments would have to satisfy the time interval limits imposed by [51]. Increasing the MCS would augment the transmission efficiency but could decrease the robustness of radio transmissions, negatively impacting the communication range. Choosing higher order MCS would ultimately depend on the careful deployment of the RSU for operating under Line of Sight (LOS) conditions.

With wireless technologies using a time-frequency resource pool (e.g., LTE-V2X or 5G NR V2X), the duty cycle can be estimated with the following equation:

$$dc = \lambda \cdot \tau \qquad (3)$$



(a) Using *pathControl* method

(b) Using *trajectoryControl* method

FIGURE 24. Duty cycle of the transmission of MIMs at 10 Hz with 0.55 b/s/Hz in a 10 MHz ITS-G5 channel.

where τ is the slot duration ($\tau = 1$ ms for LTE-V2X and $\tau = 0.5$ ms for 5G NR V2X following ETSI [47]). In this equation, dc is expressed as a fraction between 0 and 1. This equation assumes that each message fits in a single slot. Under this assumption, the duty cycle for LTE-V2X transmitting MIMs at 10 Hz is 1%, as long as the MIM sizes are below 1980 bytes including headers (otherwise, it would not fit or would be segmented). LTE-V2X can also operate at 20 Hz message rate, which would translate into a duty cycle of 2%, still below the 3% limit. However, splitting messages generated with 10 Hz to achieve a 20 Hz message rate, half of these messages would be transmitted with a delay of at least 25 ms in order to comply with the imposed time-interval limits. The transmission of MIM at 10 Hz with 5G NR V2X would result in a duty cycle of 0.5%.

A. ADAPTIVE SOLUTION

The large MIM sizes and the duty cycle required to support the control of a large number of vehicles call for a smart selection of the information to be included in each MIM. In this section, a dynamic operation-mode-dependent inclusion of MIM containers is evaluated to satisfy the message size and duty cycle limitations.

The largest data element in the MIM is the *controlInterface* that is included with each *Mim*. It includes the path that the

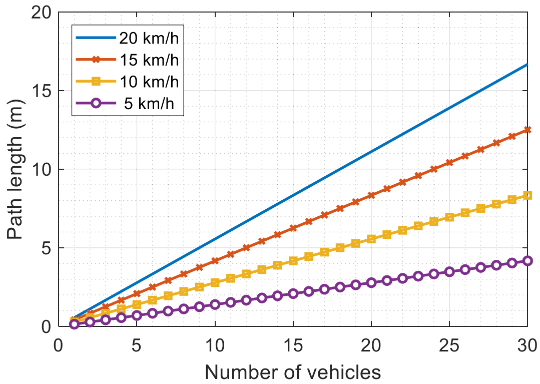


FIGURE 25. **Analysis of the path length needed with the proposed solution that targets to control a single vehicle in each MIM.**

vehicle must follow, as a sequence of *controlPoints* or *wayPoints*. Conveniently, ETSI TS 103 882 allows for dynamic inclusion rules of this data element depending on aspects such as the vehicle speed and shape of the path. A proper design should be able to support the maximum number of vehicles, that is $n_v = 32$. The AVM service should optimize MIM transmission by updating paths only when necessary, reducing redundant communication and conserving bandwidth. A new updated path should be sent before the vehicle reaches the end of the path it is currently following. To reduce the MIM size, the inclusion of only one *controlInterface* (targeting a single vehicle) in each MIM is considered. With this solution, a vehicle will receive a new path from the infrastructure every:

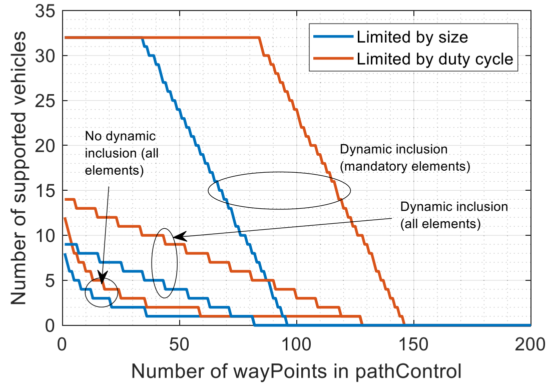
$$T = n_v/\lambda \tag{4}$$

i.e., every $T = 3.2$ seconds when $\lambda = 10$ Hz and $n_v = 32$ vehicles. The path sent to the vehicle with *controlInterface* has to then cover the trajectory of the vehicle during the next T seconds. Therefore, the path length can be computed as:

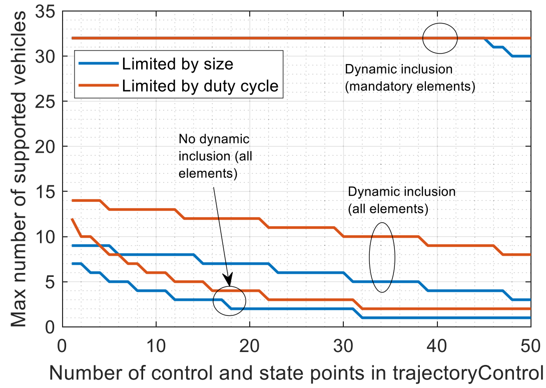
$$p = T \cdot v \tag{5}$$

where v is the vehicle's speed in m/s. The length of the path that should be included in a MIM is illustrated in Fig. 25 for different speeds and number of vehicles, n_v. In a straight path it could correspond to one pose per meter. Assuming a speed of 20 km/h (or 5.6 m/s) during $T = 3.2$ seconds the trajectory of a vehicle could be described with less than 20 *wayPoints*, with few additional points to avoid the vehicle braking at the end. This would mean that roughly 30 *wayPoints* would be required in this case. However, on a curve, a pose is normally required every 0.2m. That would mean that 40 poses on a 90° turn with radius 5m (and a length of 8m) would be required. This analysis shows that receiving a new *controlInterface* every T seconds would be sufficient to adequately support the AVM service.

The remaining containers within a *Mim* are optional (Fig. 17), which opens the door for their dynamic inclusion in the MIM to satisfy the size and duty cycle limitations. During SAFE_DRIVING mode the AVM messages must always include the *SystemManagementData* (with only the *missionID* being mandatory in each message), the *DrivingPermission* and the *DetectedVehiclePose*, in addition to the *controlInterface* following the previous discussion. The *MIMDataControlField* is not strictly required in certain implementations and the *VidRequest* is only needed during initialization. The *SafetyTimeSyncRequest* and the *DriveCommand* are not always required and could be sent e.g., once per second to each vehicle. Under these assumptions, the MIM size and its corresponding duty cycle are significantly reduced. To show the potential of the dynamic inclusion of data elements and containers in the MIM, Fig. 26 shows the number of vehicles that would be supported without exceeding the message size limit (1398 bytes for GeoNetworking) and the duty cycle limit (3%). The figure shows the results for the full MIM message (corresponding to the sizes shown in Fig. 22) and the proposed solution with dynamic inclusion of data elements and containers. When this dynamic inclusion approach is used, the figure differentiates the results with and without the optional elements (i.e., with only the mandatory ones).



(a) Using *pathControl* method



(b) Using *trajectoryControl* method

FIGURE 26. **Number of supported vehicles with and without the dynamic inclusion approach to satisfy the message size and duty cycle limitations. Duty cycle results are depicted for ITS-G5 transmitting at 10 Hz with 0.55 b/s/Hz in a 10 MHz channel.**

The results shown in Fig. 26 demonstrate that the number of supported vehicles can be significantly increased when the dynamic inclusion approach is used. This is particularly the case when only the mandatory elements of the selected

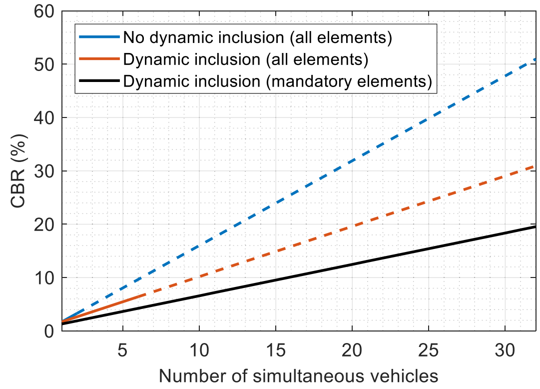


FIGURE 27. **CBR (Channel Busy Ratio) obtained from the transmission of MIM and MVM at 10 Hz with 0.55 b/s/Hz in a 10 MHz channel (applicable to both ITS-G5 and LTE-V2X) with and without dynamic inclusion approach.**

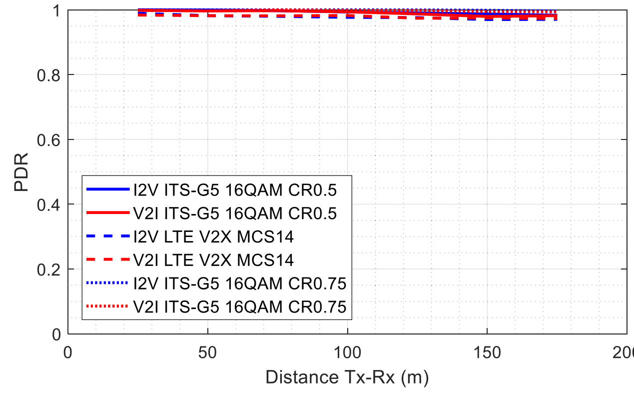


FIGURE 28. **PDR (Packet Delivery Ratio) obtained from the transmission of MIM and MVM at 10 Hz in a 10 MHz ITS-G5 and LTE-V2X channel with the proposed solution.**

containers are included. The figure also shows that the message size limit is more restrictive than the duty cycle limit for the considered transmission efficiency of 0.55 b/s/Hz and message rate (10 Hz). The message size limitation is imposed by the GeoNetworking layer, and it is thus common to ITS-G5 and C-V2X technologies. The results also reveal that more than 30 points could be included in the *mim* and still support the maximum number of 32 vehicles, for both the *pathControl* (Fig. 26(a)) and *trajectoryControl* (Fig. 26(b)) methods.

These results confirm that the dynamic inclusion approach effectively balances message size constraints, duty cycle compliance, and network efficiency, making it a viable strategy for large-scale AVM deployments, especially when optional data can be omitted.

Finally, Fig. 27 estimates the CBR as a function of the number of simultaneous vehicles supported by a single RVO with the dynamic inclusion approach previously described that considers a single *controlInterface* per MIM (i.e., targeting one vehicle) using the *pathControl* method, with 30 *wayPoints* (following Fig. 26). The solid parts of the depicted lines represent the supported scenarios, i.e., the scenarios with a number of vehicles below the limits of Fig. 26). The CBR is estimated as the sum of the fraction of bandwidth consumed by the infrastructure and the one consumed by the vehicles, assuming that they are all under coverage. This estimation is independent of the underlying technology (ITS-G5 or LTE-V2X in this paper) since 0.55 b/s/Hz is assumed for both. The MVMs can have up to around 485 bytes (without *vehicleError*), depending on the optional data elements included. Fig. 27 shows the results obtained with and without the dynamic inclusion approach. The figure also compares the CBR with and without the optional elements included in each container. As it can be observed, the CBR can be significantly reduced thanks to the dynamic inclusion approach applied to the MIM, especially when only the mandatory elements are included. Including optional elements raises the CBR, though the increase remains within acceptable thresholds for reliable communication, demonstrating the feasibility of the solution.

The performance of an AVM service has been also evaluated through network simulations using OMNeT++. To this end an AVM scenario (e.g., parking facility, production plant, depot) with 32 vehicles is considered. The RSU/RVO is located in the center to ensure LOS (Line of Sight) conditions with all vehicles. The range of the RSU is 160 m. All vehicles transmit MVMs periodically every 100 ms with 530 bytes (including headers). The RSU transmits MIMs periodically every 100 ms with 1398 bytes (including headers) to satisfy the *itsGnMaxSduSize* limit. This MIM size assumes that the dynamic inclusion approach is applied (a single *controlInterface* per MIM) with the corresponding number of points to satisfy the limit imposed by the GeoNetworking layer. When using LTE-V2X, MVMs and MIMs are transmitted using MCS14 (16QAM with coding rate of approximately 0.6) to be able to support the large size of the MIMs. ITS-G5 does not have this particular coding rate, hence the simulations were carried out with 16QAM and 0.5 coding rate (12 Mbps datarate) and with 16QAM and 0.75 coding rate (18 Mbps datarate).

Fig. 28 shows the PDR (Packet Delivery Ratio) obtained in the conducted simulations as a function of the distance between the transmitter and receiver. The figure plots the PDR for V2I (i.e., MVM) and I2V (i.e., MIM) transmissions. ITS-G5 and LTE-V2X are both able to achieve 98%-99% reception probability because of the relatively short distances, the possibility to plan adequately the deployment of RSUs in parking areas, the low CBR experienced (following Fig. 27) and the practically non-existent hidden-terminal problems in the scenario. In this scenario, the CBR measured with LTE-V2X is 13.2%, while it is equal to 9.6% and 13.7% with ITS-G5 and coding rates of 0.75 and 0.5, respectively.

Another key performance metric for the study of the AVM service is the PIR (Packet Inter-Reception) time. The PIR is defined as the time elapsed between two consecutive packet receptions. The PIR for the k^{th} received packet can be expressed as:

$$PIR\left(k\right) = t_{rx}\left(k\right) - t_{rx}\left(k-1\right) \tag{6}$$

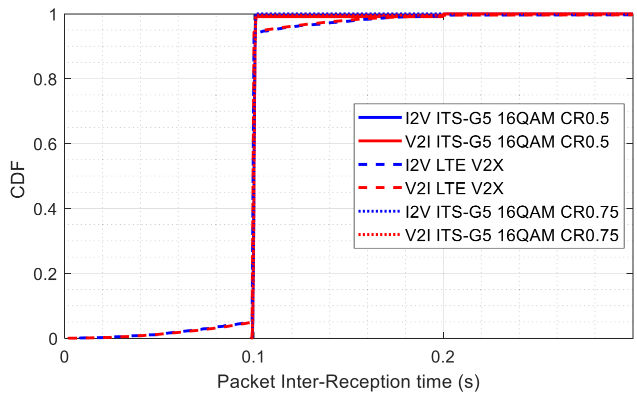


FIGURE 29. CDF (Cumulative Distribution Function) of the Packet Inter-Reception time obtained from the transmission of MIMs and MVMs at 10 Hz in a 10 MHz channel with the proposed solution with ITS-G5 and LTE-V2X.

where $t_{rx}(j)$ is the reception time of packet j^{th}. The packet reception time can be expressed as a function of the packet generation time, plus time needed to access the channel and the propagation time:

$$t_{rx}(k) = t_{gen}(k) + \Delta t_{acc}(k) + \Delta t_{pro}(k) \tag{7}$$

The generation time is the time when the AVM service generates the message. The channel access time is the time interval required by the access layer to access the channel to transmit the message. The propagation time is here considered as the time interval needed to transmit the message plus the time required for the signal to reach the receiver. The propagation time can be considered negligible and constant if packets with constant size and duration, and a fixed distance between transmitter and receiver are considered. Therefore, the PIR of the k^{th} packet can be expressed as:

$$PIR(k) = t_{gen}(k) + \Delta t_{acc}(k) - t_{gen}(k-1) - \Delta t_{acc}(k-1) \tag{8}$$

or equivalently:

$$PIR(k) = 1/\lambda + \Delta t_{acc}(k) - \Delta t_{acc}(k-1) \tag{9}$$

where λ is the message generation frequency in Hz. Assuming a channel access time between certain $\Delta t_{acc}^{\min}$ and $\Delta t_{acc}^{\max}$, the PIR is in the interval $[1/\lambda + \Delta t_{acc}^{\min} - \Delta t_{acc}^{\max}, 1/\lambda + \Delta t_{acc}^{\max} - \Delta t_{acc}^{\min}]$.

Fig. 29 shows the CDF (Cumulative Distribution Function) of the PIR time for MVMs (V2I transmissions) and MIMs (I2V transmissions), and for LTE-V2X and ITS-G5 with different modulation and coding schemes. Since MIMs and MVMs are generated every 100ms and they are received with high probability, the packet inter-reception time is normally around $1/\lambda = 100$ ms. The small differences observed between LTE-V2X and ITS-G5 are produced due to their different channel access times (Δt_{acc}). The channel access time of ITS-G5 depends on the channel load and can be in the order of 2 ms [55]. In our scenario, it is approximately in the interval [0,1] ms and therefore the PIR time is approximately between 99 ms and 101 ms for ITS-G5, in line with (9).

With LTE-V2X, the channel access time, Δt_{acc}, can be considered a random variable between $\Delta t_{acc}^{\min} = 1$ ms and $\Delta t_{acc}^{\max} = 100$ ms since a PDB (Packet Delay Budget) of 100 ms is considered. This random channel access time is kept constant until a resource reselection is produced (once every 10 packets in average, since there are no resource reselections due to changes in packet size or interval in our scenario). While Δt_{acc} is constant, the packet inter-reception time is exactly $1/\lambda = 100$ ms when packets are correctly received, as it can be derived from (9). However, when a resource reselection is produced, a new random channel access time is generated between 1 and 100 ms. Therefore, every time a new resource reselection is produced, the packet inter-reception time is between 1 and 199 ms. The minimum value (1 ms) is obtained when the channel access time of the packet before the reselection is 100 ms and the channel access time of the packet after the reselection is 1 ms. The maximum value (199 ms) is obtained when the channel access time of the packet before the reselection is 1 ms and the channel access time of the packet after the reselection is 100 ms. The results obtained and shown in Fig. 29 match the analysis conducted through (6)–(9) and validate the use of ITS-G5 and LTE-V2X to support the AVM service.

X. CONCLUSION

Automated Vehicle Marshalling (AVM) is a pioneering technology, introducing the world's first functionally safe V2X service. This advancement marks a significant milestone in the evolution of connected automated driving, offering transformative solutions for vehicle marshalling in both controlled and mixed-traffic environments. This work reviewed the current deployment status and AVM-enabled use cases, such as Automated Valet Parking (AVP), Automated Valet Charging (AVC), Automated Factory Marshalling (AFM), and Automated Depot Marshalling (ADM), highlighting the growing maturity and real-world adoption of this technology.

The article further provided the first comprehensive overview of the AVM technology, focusing on core aspects of interoperability and scalability, including Functional Safety (FuSa) mechanisms, communication stack options, regulatory challenges and its worldwide standardization efforts.

A key contribution of this work is the identification and resolution of inefficiencies in data transmission. For example, in vehicle motion control, frequent pose sampling previously resulted in large message sizes and communication bottlenecks. By introducing mechanisms to reduce number of required poses and adapting the data shared via the wireless channel to the respective driving mode, the number of controllable vehicles was substantially increased without compromising safety.

Notably, several findings and enhancements presented in this paper have already been incorporated into AVM-related standards worldwide, underscoring its impact on ongoing standardization efforts. These contributions are pivotal as the industry moves toward deploying AVM at scale.

Looking ahead, ensuring redundant communication channels may become essential to maintain high service availability, particularly in safety-critical scenarios where a secure and reliable data connection is legally mandated. Integrating multiple communication modules and combining ITS-G5 or C-V2X with public or private 5G networks can significantly enhance data transmission reliability, especially in complex environments, and prevent communication breakdowns that might otherwise trigger safety stops.

The safety mechanisms developed for AVM could also be applied to other V2X services. Particularly Collective Perception [57], [58], a service enabling sensor data sharing among traffic participants and infrastructure, would substantially benefit from the transfer of certain AVM mechanisms. For instance, the safeguarded AI-independent perception pipeline could be implemented in a similar manner for infrastructure-based services. Rather than transmitting safeguarded trajectories, safeguarded occupancy states within so-called perception regions and kinematic data of detected objects could be shared. This approach would significantly expand the range of connected automated driving functions. It would support not only functionally safe AVM Type 1 and Type 3 implementations but also all other functions that benefit from safeguarded extended environmental perception.

In conclusion, AVM is at the forefront of connected automated driving, setting the stage for safer, more efficient vehicle management. As the first functionally safe V2X service on a global scale, AVM is not only transforming vehicle maneuvering but also paving the way for future advancements in autonomous driving. Continued collaboration among industry stakeholders, regulators, standardization bodies, and end-users, such as commercial real estate operators and fleet managers, will be vital to fully realizing the potential of AVM and ensuring its successful global deployment.

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