Scalable and Heterogeneous ITS Architecture Design for Connected Autonomous Vehicles

Ioannis Mavromatis, Andrea Tassi, Giovanni Rigazzi, Csaba Bali, Robert J. Piechocki, Arthur Richards and Andrew Nix

***Abstract*—Connected and Autonomous Vehicles (CAVs) are excepted to play a crucial role in next-generation Intelligent Transportation Systems (ITSs). Not only is the information exchange fundamental to improve road safety and efficiency, but it also paves the way to a wide spectrum of advanced ITS applications enhancing efficiency, mobility and accessibility. However, highly dynamic network topologies and unpredictable wireless channel conditions entail numerous design challenges and open questions. In this article, we discuss the beneficial interactions between CAVs and ITSs, and propose a novel architecture design paradigm able to accommodate multi-layer application data streams over multiple Radio Access Technologies (RATs).**

***Index Terms*—Connected Autonomous Vehicles, DSRC, LTE-A, LTE Direct, mmWave, layered services, decision-making.**

I. Introduction

The introduction of autonomous vehicles will represent the biggest revolution on our roads since the rise of the internal combustion engine. The benefits include: traffic reduction and increased traffic predictability, better road safety, new mobility options and social inclusion. Recent forecasts estimate that globally the number of people living in urban areas is due to increase to over 66% by 2050[1]. In particular, road congestion determines huge productivity losses. Consider the simple action of searching for a parking space; this represents around 30% of all road traffic in mid-to-large cities, mainly due to two factors:

- a *lack of knowledge* - If the drivers were aware of the presence of a traffic jam, they would try and avoid congested roads by selecting a different route (vehicle rerouting) or they would choose alternative transportation means (road off-loading);
- a *lack of confidence* - Drivers are not aware of the location of the next available parking slot and cannot quickly reach their destinations, wasting time in constantly search for available spaces.

Generally, traditional Intelligent Transportation Systems (ITS) should allow a user: (i) to plan the journey ahead, and (ii) to react to traffic jams by rerouting vehicles. However, given the expected population growth, road congestion needs to be prevented in a more proactive way.

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[1]Source: The United Nations, http://www.un.org/en/development/desa/news/population/world-urbanization-prospects-2014.html.

Next-generation ITSs are expected to bring the paradigm of Mobility-as-a-Service (MaaS) to a whole new level by means of Connected Autonomous Vehicles (CAVs). A key factor in a CAV-based MaaS paradigm is represented by autonomous vehicles that cease to be *autonomous systems* and become *cooperative entities*. Specifically, cooperation among autonomous vehicles is enabled by the sharing of sensory data and manoeuvring intentions in a Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) fashion. For these reasons, MaaS city models based on CAVs have the potential to overcome the users' lack of knowledge and confidence, by means of intelligent continuous route planning systems, and optimized road-resource allocation strategies.

In this article, we propose an advanced ITS framework based on a heterogeneous communication infrastructure, as shown in Fig. 1. The proposed ITS framework enables efficient Vehicle-to-Everything (V2X) communications among CAVs by: i) handling scalable ITS applications consisting of independent data streams, and mapping onto three different V2X layers, and ii) employing multiple Radio Access Technologies (RATs) to deliver each data stream, according to the specific Quality-of-Service (QoS) constraints. We first illustrate the key components of CAVs, identifying various types of information data exchanged between vehicles and infrastructure through wireless connectivity. Then, an overview of the candidate RATs is provided, along with a discussion on their benefits and limitations. Finally, we present our envisioned ITS architecture and examine all its components as well as discuss prospective V2X use cases.

II. Cooperative Decision-Making Agent for CAVs

In an attempt to transform CAVs in cooperative ITS actors, we refer to the architecture shown in Fig. 2a. In particular, the proposed CAV design comprises an *ITS agent* and a *Decision-Making agent* [1]. As will be presented in Section IV, the ITS agent allows each CAV to exchange sensory data and driving intentions with other CAVs and city-level emergency rooms.

The ITS agent interacts with the Decision-Making agent, which comprises a combination of *proprioceptive* (related to the behaviour of the CAV itself, for e.g., inertial measurements and engine status) and *exteroceptive* (related to the environment outside the CAV, for e.g., cameras or proximity sensors) sensing that begins the control loop structure. Fig. 2b shows a suite of possible exteroceptive sensors for an autonomous car. The *Perception* system processes raw sensory outputs into features describing: i) the position and movement of the vehicle [2], ii) the road geometry [3], and iii) the kind

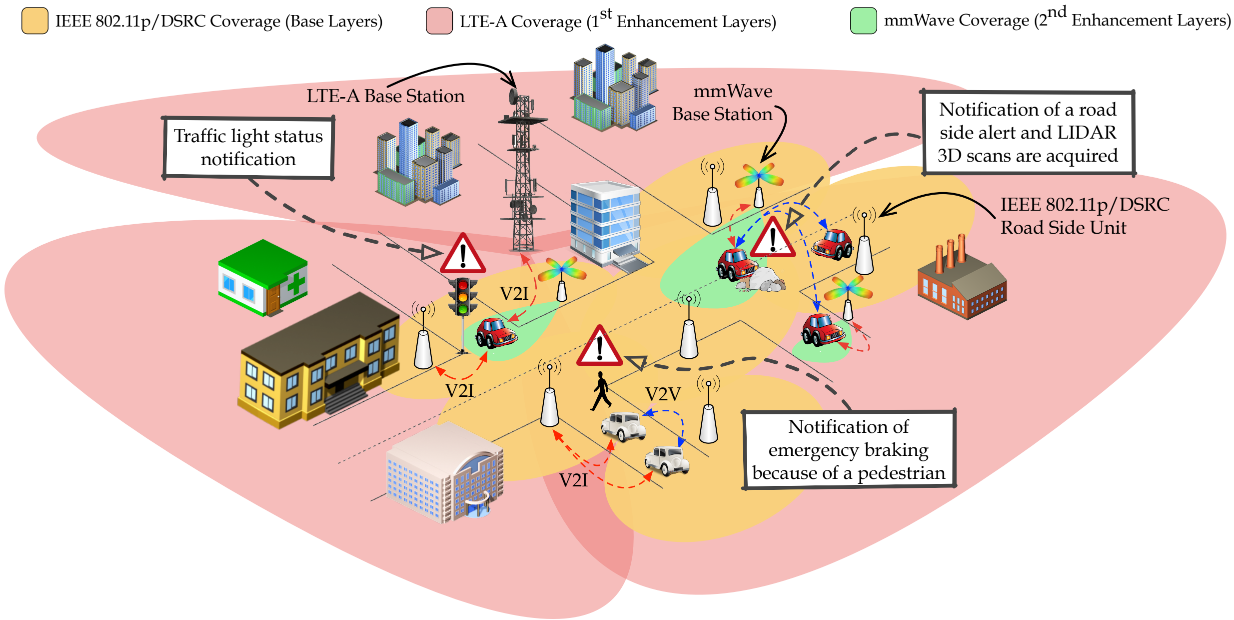
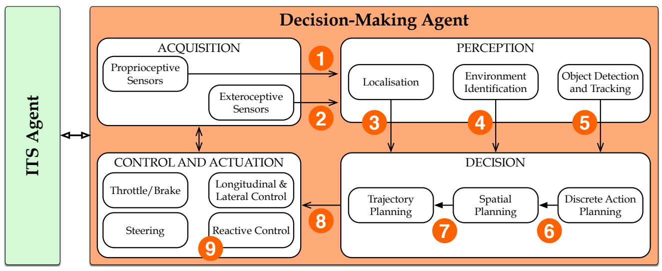


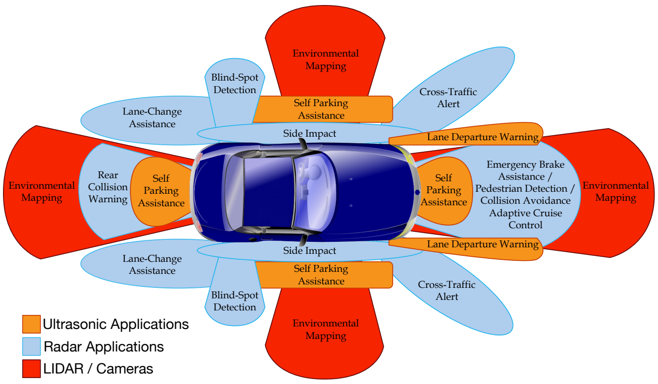
Fig. 1. General overview of the considered system model. The proposed ITS design framework ensures analog-like performance degradation communications among CAVs by means of multi-layer V2X communications over an heterogeneous network infrastructure.

(for e.g., cars, cyclists or pedestrians) and motion of moving objects. The Perception system interacts with the *Decision* system, which takes basic manoeuvring choices (*Discrete action planning*) and determines the path to be followed on a chosen road (*Spatial planning* and *Trajectory planning*) [4], as shown in Fig. 3. Finally, *Control and Actuation* system implements the manoeuvring operations needed to follow the chosen trajectory.

The considered Decision-Making agent focuses on automated driving issues, which require immediate decision-making, thus reliable communication systems [5], [6]. For each of the listed message-based interactions identified in Fig. 2a, Table I covers the implications of sharing the information content of these messages via a communication system.



(a) Considered Autonomous Driving Architecture



(b) Suite of possible exteroceptive sensors

Fig. 2. Illustration of sensors for automotive applications and the considered autonomous driving architecture.

III. Candidate RATs for V2X communications

To date, three different RATs: the IEEE 802.11p/Dedicated Short Range Communications (DSRC) [7], 3GPP's LTE-Advanced (LTE-A) [8] and millimeter-wave (mmWave) frequency systems [9], have emerged as potential enablers of V2X communications. This section will briefly discuss the pros and cons of these technologies and their impact on vehicular communications. Table II summarizes the main features and the additional capabilities provided by all of the considered communication solutions.

A. IEEE 802.11p/DSRC

IEEE 802.11p/DSRC represents the suite of IEEE 802.11s and IEEE P1609.x standards, describing a system operating in the frequency range 5.850 GHz to 5.925 GHz, with a decentralised architecture that supports V2X communications. The IEEE 802.11p standard defines the PHY and MAC layers. More specifically, on top of the MAC layer, a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) access to the medium, supports different QoS profiles by the Enhanced Distributed Channel Access (EDCA) protocol. The IEEE 802.11p/DSRC implementation of the EDCA is inherited from IEEE 802.11e with little modification. With regards to the PHY layer, the Orthogonal Frequency Division Multiplexing (OFDM) mechanism is adopted, which allows

TABLE I
CHARACTERIZATION OF MESSAGES EXCHANGED AMONG THE ENTITIES WITHIN THE DECISION-MAKING AGENT

Message Type	Example(s)	Data Rate Estimate	Sharing Potentials
1. Proprioceptive sensing	Global Positioning System (GPS)	10 Kbps to 60 Kbps	Simple V2V beaconing will improve reliability of tracking. Could also be augmented with extra information to report accidents or prioritize progress for emergency vehicles.
2. Exteroceptive sensing	Light Detection And Ranging (LIDAR) scans	30 Mbps to 100 Mbps	Sharing raw-sensory data increases field of view, enabling cars to see round corners or remove blind-spot [5]. Also improves reliability of object detection and tracking.
3. Localization	Fused GPS, Inertial Navigation System (INS) and Simultaneous Localisation and Mapping (SLAM) position	10 Kbps to 800 Kbps	Most simply, this could be implemented by means of the same beaconing as in message type 1. Obtained localization features could also be shared to improve navigation quality across many CAVs [2].
4. Environment	Driveability grid or road shape	100 Kbps to 10 Mbps	Sharing processed road data (for e.g., classified map grids or highly parametrized road shapes) offers benefits similar to these associated to the adoption of message type 2.
5. Objects	Positions and velocities of other road users	80 Kbps to 800 Kbps	In addition to an enhanced field of view (similar to the adoption of message type 2), improved reliability and accuracy of tracking.
6. Discrete plans	Intended route choice and turns	1 Kbps to 10 Kbps	Roughly equivalent to flashing indicators, short term route sharing would enable greater cooperation on the road and smoother rides thanks to improved prediction. Knowing the intentions of other road users can improve global performance. May help predict traffic levels and alleviate congestion.
7. Spatial plans	Single path or mesh	80 Kbps to 800 Kbps	Sharing the path enables a simple 'follow the car in front' behaviour, aiding robust decision making, at least as a starting point for a path planner. Can be viewed as an extreme version of what discussed for message type 4, with the road environment distilled to a single driveable path. Could also share spatial planning meshes used to determine routes (see Fig. 3). Meshes can be very costly to produce but likely to be similar over time and cars [4].
8. Trajectories	Single path with time profile	80 Kbps to 800 Kbps	An enhanced form of what discussed for message type 6; this information improves predictability of other road users, reducing the corresponding conservatism in planning and enabling smoother rides during interactions. Can be considered as feed-forward information, known to damp out instabilities in vehicle platoons [6].
9. Reactions	Emergency brake signal	1.5 Kbps	Possibly as an augmentation of beaconing as in message type 1, rapid sharing of sudden braking or other reactive responses will improve response times in traffic, equivalent to brake lights and hazard light signalling.

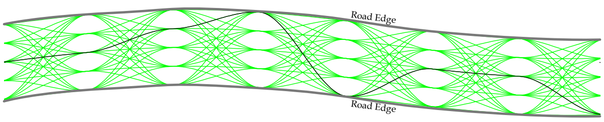


Fig. 3. Example of spatial planning mesh with a single driving path highlighted.

users to achieve a maximum transmission rate of 27 Mbps at a speed of $60\,\mathrm{km\,h^{-1}}$. The reserved 75 MHz of spectrum is divided into seven channels each of 10 MHz bandwidth, where channel 178 (the Control Channel, CCH) is solely intended for broadcasting safety and mission-critical messages, and six channels (the Service Channels, SCHs) are used for all other applications.

Due to the adopted MAC contention mechanism, the density of vehicles per area may have a disruptive impact on the overall end-to-end delay. This is caused by the lack of coordination among the devices, i.e., the number of channel erasures increases more than linearly with vehicle density. As a result, IEEE 802.11p/DSRC tends to be more suitable for transferring low bitrate data streams in vehicular environments characterized by low-to-medium road density and vehicle speed. Examples of IEEE 802.11p/DSRC units for road side (Road Side Unit) and an on-board vehicle deployment (On-Board Unit) are shown in Fig. 4.

B. 3GPP LTE-Advanced

LTE and its major enhancement, LTE-A, represent the 4G cellular communications standards defined by 3GPP to provide high data rate, ubiquitous coverage and global connectivity for mobile cellular users [8]. The air interface can support Time-Division Duplexing (TDD), Frequency-Division Duplexing (FDD), and Half-Duplex FDD, as well as scalable channel bandwidths (1.4 MHz - 20 MHz). Furthermore, a maximum of five component carriers can also be aggregated in LTE-A, leading to a maximum aggregated bandwidth of 100 MHz. Downlink and uplink access technologies are based on Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Division Multiple Access (SC-FDMA), respectively, thus guaranteeing high flexibility and efficiency in frequency-time resource scheduling. Due to advanced Multiple-Input Multiple-Output (MIMO) capabilities, significant spectral efficiency can be obtained, even at high user speeds and under dynamic propagation environments. In addition, high data rates are potentially supported, ranging from 300 Mbps and 75 Mbps in the LTE downlink and uplink respectively, to theoretically 1 Gbps in the case of the LTE-A downlink [10].

Multicast/broadcast services are also fully supported by means of the evolved Multimedia Broadcast and Multicast Service (eMBMS), thus enabling the efficient broadcast of vehicular service messages in cross-traffic assistance applica-

TABLE II
CANDIDATE RAT SOLUTIONS FOR V2X COMMUNICATIONS

RAT / *Feature*	**IEEE 802.11p/DSRC**	**LTE-A**	**mmWave (IEEE 802.11ad)**
Frequency Band	5.85 GHz - 5.925 GHz	450 MHz - 4.99 GHz	57.05 GHz - 64 GHz
Channel Bandwidth	10 MHz	Up to 100 MHz	2.16 GHz
Range	$\leq$ 1 km	$\leq$ 30 km	$\leq$ 50 m
Bit Rate	3 Mbps-27 Mbps	Up to 1 Gbps	Up to 7 Gbps
Latency	$\leq$ 10 ms	100 ms-200 ms	$\leq$ 10 ms
Coverage	Intermittent	Ubiquitous	Intermittent
Mobility Support	$\leq 60\,\mathrm{km\,h^{-1}}$	$\leq 350\,\mathrm{km\,h^{-1}}$	$\leq 60\,\mathrm{km\,h^{-1}}$
QoS Support	Yes	Yes	Yes
Broadcast Support	Yes	Yes	No
V2I Support	Yes	Yes	Yes
V2V Support	Yes	Potentially over LTE Direct	Yes
Relay Mode	Yes	Under investigation	Yes
MIMO	No	Yes	Yes

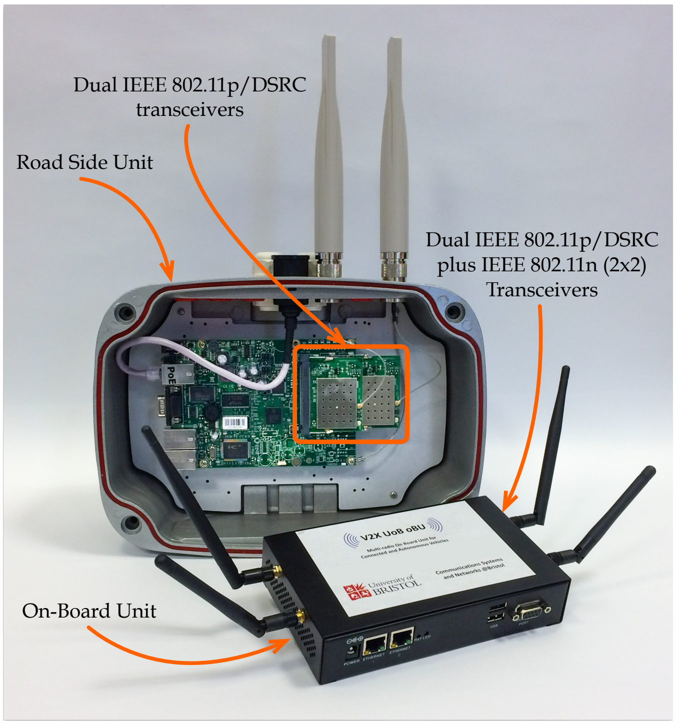


Fig. 4. Low-latency Linux Kernel implementation of IEEE 802.11p/DSRC units we prototyped. The figure shows units designed for a road side and an on-board vehicle deployment.

tions. Along with the eMBMS framework, the most recent introduction of LTE Direct allows virtually any network peer to engage device-to-device (D2D) communications. As a drawback we observe that radio resources hosting LTE Direct traffic need to be centrally allocated by the base stations to which they connect to.

Due to the flat architecture, applications demanding low-to-medium latency requirements can be supported without affecting network scalability. In particular, up to 100 ms end-to-end delay can be reached over an LTE-A network. However, *tactile*-like latency requirements smaller than 10 ms cannot be fulfilled in the presence of higher cellular traffic load. Furthermore, terminals in idle mode need to re-establish a connection with the base station, thus spending additional time to reach the connected state. This leads to severe performance degradation in safety-critical applications [11].

C. Millimeter Waves Systems

Systems based on mmWave are expected to play a pivotal role in fifth generation (5G) cellular systems. Generally, a mmWave system operates in the spectrum between 30 GHz and 300 GHz. For what concerns the application domain of local area networking, the IEEE 802.11ad standard is gaining momentum [12]. In this standard, the carrier frequencies are spread around 60 GHz, with a channelization of 2.16 GHz. In addition, any mmWave system imposes the adoption of large antenna arrays to achieve high array gains through beamforming techniques. The high array gains, along with large channel bandwidths, allow the system to achieve high data rates (typically several gigabits-per-second). IEEE 802.11ad ensures data rates higher than 7 Gbps and an end-to-end latency smaller than 10 ms.

From the signal propagation perspective, Line-of-Sight (LOS) communications are characterized by path loss exponents smaller than 2.8, while Non-Line-of-Sight (NLOS) communications may present much higher path loss exponents. In fact, due to their reduced wavelength, mmWave systems are extremely sensitive to blockages. For these reasons, typical NLOS path loss exponents span between 3.8 and 5.6 [10].

As a prospective 5G wireless solution, mmWave systems proved to be a viable alternative to traditional cellular networks and wireless backhauling systems, while the possibility of using this technology to support the communications in next-generation ITS systems is being extensively investigated. In particular, the European Commission is currently considering the possibility of supporting standardization activities of ITSs based on mmWave systems to be operated across a dedicated band spanning between 63 GHz and 64 GHz [12].

With ideal propagation conditions, mmWave systems significantly outperform vehicular communication systems based on the IEEE 802.11/DSRC and LTE/LTE-A standards. Obviously, large values of penetration loss and errors in the alignment of the antenna beams will have a disruptive impact onto the stability of mmWave links.

IV. Proposed ITS Agent Design for Next-Generation CAVs

This section describes the proposed ITS agent design for next-generation ITSs featuring CAVs by means of heterogeneous communication technologies, as shown in Fig. 5. With regards to Section II, we observe that the ITS agent interacts with the Decision-Making agent to achieve ITS service goals, for instance, by implementing long-term driving manoeuvres (ITS Agent to Decision Making agent signalling) or adapting the service goals in accordance with detected car accidents (Decision Making agent to ITS agent signalling).

Since IEEE 802.11p/DSRC access network does not rely on a core network, this ensures low latencies V2X communications at the cost of a reduced coverage. To this end, it appears natural to relay safety/mission-critical messages via an IEEE 802.11p/DSRC network when: i) they are relevant to surrounding vehicles, ii) are characterised by low data rate, and iii) tolerate a *tactile*-like end-to-end latency. For instance, this is the case of messages signalling that a vehicle triggered its emergency braking system. This information is likely to be relevant only to the immediate surrounding vehicles. On the other hand, if vehicles get involved in an accident in the middle of an intersection, this can have a disruptive impact on all the traffic flow across a large area of the city. In that case, it is worth taking advantage of an LTE-A network to notify the fault across geographically larger areas. Whereas, the authorities via a mmWave communication infrastructure can gain access to the vehicle camcorders or LIDARs to assess the severity of the accident (see Fig. 1).

Generally, the proposed system paradigm is based on the idea of *data scalability*. This principle has originally been applied to video transmissions where a scalable video stream consists of a *base layer* and multiple *enhancement layers*. The base layer allows users to achieve a basic reconstruction quality, which is gradually improved as soon as the enhancement layers are successfully received. The same principle trespassed the natural boundaries of multimedia communications and is being applied to design systems capable of an analog-like service degradation [13].

The reminder of this section presents the key ITS agent components and their fundamental iterations.

A. Service Plane

As illustrated in Fig. 5a, the Service Plane is the place where all the next-generation ITS services and applications are developed regardless of how the data streams will be mapped onto multiple sublayers and regardless of which RAT will be used to transmit each sublayer. We consider the following key next-generation ITS services, which are expected to enhance the CAV-based MaaS paradigm:

- *Intelligent Traffic Planning*: Future ITS traffic planning services are needed to reroute autonomous vehicles in the event of traffic jams, to coordinate traffic lights to offload a congested road, or to provide drivers with essential up-to-date information.
- *Smart Emergency Vehicle Routing*: This service is a specialisation of the previous one and it assists emergency vehicles and provides the best route to reach the destination. Typical critical situations correspond to immediate medical assistance or disaster emergency management, such as fire alarms, where police vehicles need to promptly escort the fire trucks. Under these circumstances, the surrounding vehicles must be informed of the approaching emergency vehicles and rerouted to drastically reduce the traffic congestion. Furthermore, a traffic light synchronization system can minimize the overall journey time. A more complex use case scenario corresponds to the fully autonomous E-Ambulance system, where vehicles are equipped with health monitoring devices, such as wearable sensors, able to transmit the collected patience's data to the hospital or to a control centre before reaching the destination.
- *Multimodal Commuting*: This service aims to dynamically and adaptively plan the route of a road user, combining different transportation systems, depending on start and end points. For instance, an intelligent commuting system can notify drivers of available parking areas, where a shuttle bus service is offered to efficiently carry the employees to their workplace.

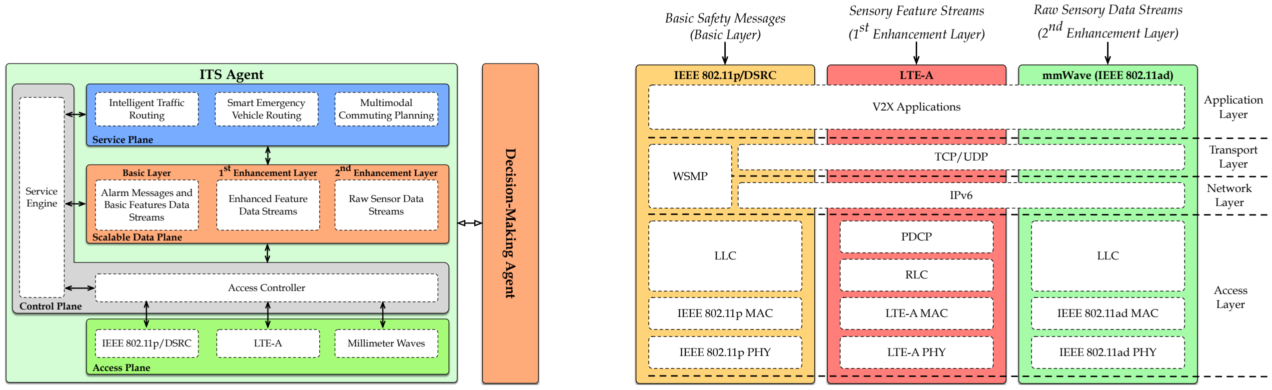
With regards to Section II, Table III summarizes the messages exchanged among the entities within a Decision-Making agent (see Section II), which are most relevant to the considered ITS services.

B. Scalable Data Plane

In the proposed system design, the Service Plane builds on to of the Scalable Data Plane, which is in charge of:

- Handling data streams from the lower system planes and dispatching them towards the Service Plane;
- Grouping data streams on the basis of their geographical relevance and QoS requirements.

The Scalable Data Plane assumes that each next-generation ITS service exchanges scalable data streams that comprise up to three independent data layers. The data streams mapped onto the base layer convey SAE J2735 messages for Road Safety Applications, in a V2X fashion. Among the fundamental SAE J2735 messages, it is worth mentioning the Basic Safety Messages (BSM), which are broadcast every 0.1 s and contain core vehicle information, such as vehicle size, GPS location, braking system status, etc. Along with the other SAE J2735 messages (for e.g., Intersection Collision Avoidance, Road Side Alert, etc.), BSMs allow the proposed ITS design to support basic safety/mission-critical ITS functionalities, such



(a) Structure of an ITS agent

(b) Detail of the Access Plane

Fig. 5. Proposed ITS agent architecture and detail of the proposed Access Plane incorporating the considered RATs.

TABLE III
RELEVANT MESSAGES FOR NEXT-GENERATION ITS SERVICES

ITS Services	Message Types and Impact on ITS Services
Intelligent Traffic Planning	*Environment:* City-wide map grids and road shape reports enabling the origin-to-destination long-term journey planning *Localisation:* City-wide knowledge of CAV positions for congestion prevention *Spatial Plans:* Low resolution on routes and destinations enabling congestion prediction and high level rerouting
Smart Emergency Vehicle Routing	*Exteroceptive Sensing:* Sensory raw data streams exchanged and processed in real-time for precise high-mobility manoeuvres *Objects:* Accurate representation of the nearby moving obstacles helping the decision making through accurate object tracking *Trajectories:* Enhanced cooperation between CAVs improving long-term manoeuvre smoothness
Multimodal Commuting	*Environment:* Awareness of available parking spaces, thus reducing the overall commuting time *Localisation:* Awareness of CAVs positions for continuous refinement of the expected arrival time *Proprioceptive Sensing:* Information on road disruptions (for e.g., accidents, adverse weather conditions) enabling CAVs rerouting

as: support to navigation, obstacle avoidance, traffic light status notification, etc. Given their low data rate, nearly *tactile*-like latency and local relevance, the V2X base layers are transmitted over IEEE 802.11/DSRC communication links.

The considered next-generation ITS applications (see Section IV-A) build on to of the aforementioned basic ITS functionalities and impact on potentially large areas of a city. These services are expected to deal with *feature streams* generated by each vehicle out of its on-board sensors, which correspond to the V2X first enhancement layer in the proposed ITS design. An example of this kind of data stream is given by the 3D bounding box representation of objects surrounding each vehicle. These highly refined information streams need to be shared among a large number of vehicles in order to allow them to take long-term decisions. In particular, the first enhancement layer requires a communication system providing large coverage and links capable of megabits-per-second, though there is no need for *tactile*-like latencies. Hence, we refer to LTE-A as RAT.

We observe that the first enhancement layer is the result of sensory data processing carried out by each vehicle independently. Considering the Smart Emergency Vehicle Routing application, in the case of large scale accidents, city-level emergency rooms may find it convenient to gather raw sensory data from multiple vehicles, combine them and then extract the required features. In fact, in the case of LIDAR data, combining raw data acquired from different locations can eliminate multiple blind spots and lead to a more accurate 3D bounding box object representation [14]. Streams of raw sensory data define the V2I second enhancement layer. Transmitting raw sensory data requires communication links capable of a gibabit-per-second, which implies the adoption of the mmWave infrastructure. However, due to the intermittent connectivity level associated with this technology, no reliability constraints should be associated to the second enhancement layer.

C. Access and Control Planes

To guarantee high system flexibility and adaptability, we propose to separate the Access Plane, encapsulating all the considered RATs, from the Control Plane, which is responsible for the data stream admission control and RAT selection. This approach is largely adopted in Software Defined Networking (SDN), where the decoupling of network control and forwarding devices enables system programmability and abstracts the network infrastructure from applications [15].

The Access Plane encompasses the three RAT solutions mentioned above, thus realizing a heterogeneous network capable of operating under various conditions and fulfilling diverse QoS profiles. As shown in Fig. 5b, each of the adopted standards is characterized by different protocol stacks. Besides the PHY and MAC layer described in Section III, IEEE 802.11p/DSRC and IEEE 802.11ad mmWave include the typical Logical Link Control (LLC) layer in charge of flow and error control, whereas LTE-A adopts the Radio Link Control (RLC), responsible for error detection and recovery, and the Packet Data Convergence Protocol (PDCP) for packet integrity protection and header compression. Moreover, in addition to the traditional TCP/IP suite located on top of the access layer, IEEE 802.11p/DSRC embraces the Wireless Access in Vehicular Environments (WAVE) Short Message Protocol (WSMP), supporting the one-hop broadcast transmission of high priority and time sensitive data messages.

In order to achieve the necessary level of abstraction, we consider a Control Plane consisting of two distinct system components: the *Service Engine* and the *Access Controller*. The former is responsible for classifying the incoming data streams based on the Scalable Data Plane configuration, while a decision algorithm determines which data stream must be processed. The *Access Controller* then chooses the appropriate RAT based on the decisions made by the *Service Engine* in accordance with the Scalable Data Plane, as discussed in Section IV-B, as well as taking into account the availability of the chosen technology.

V. Conclusions and Future Directions

This article proposed a new ITS design paradigm for CAVs, based on the concepts of multi-layer application data streaming and heterogeneous access networking. We discussed the main components of CAVs and the key role of wireless connectivity for message exchanging and cooperation, as well as the candidate RATs for V2X communications. Finally, we described the proposed ITS architecture and explored its main components.

Future research efforts will be targeted to evaluate the performance of the underlying heterogeneous access networks in actual city-wide scenarios, under diverse RAT availability and vehicle mobility conditions.

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