

A Multi-Scale Spatiotemporal Perspective of Connected and Automated Vehicles: Applications and Wireless Networking

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Abstract—Wireless communication is a basis of the vision of connected and automated vehicles (CAVs). Given the heterogeneity of both wireless communication technologies and CAV applications, one question that is critical to technology road-mapping and policy making is which communication technology is more suitable for a specific CAV application. Focusing on the technical aspect of this question, we present a multi-scale spatiotemporal perspective of wireless communication technologies as well as canonical CAV applications in active safety, fuel economy and emission control, vehicle automation, and vehicular infotainment. Our analysis shows that CAV applications in the regime of small spatiotemporal scale communication requirements are best supported by V2V communications, applications in the regime of large spatiotemporal scale communication requirements are better supported by cellular communications, and applications in the regime of small spatial scale but medium-to-large temporal scale can be supported by both V2V and cellular communications and provide the opportunity of leveraging heterogeneous communication resources.

I. INTRODUCTION

Transforming the traditional paradigm of single-vehicle-oriented optimization and operation, next-generation vehicles are expected to coordinate with one another, transportation infrastructures, Internet clouds, and people in maximizing the safety, sustainability, and comfort of road transportation. One basic enabler of this vision of connected and automated vehicle (CAV) operation is for vehicles to wirelessly communicate with one another, transportation infrastructures, Internet clouds, and people. Given the wide spectrum of available wireless communication technologies (e.g., cellular and DSRC) and the heterogeneity of CAV applications envisioned, there has been heated debate on the exact wireless communication technologies to be used for CAVs, and complex factors such as market penetration of new technologies have complicated this debate. Towards a thorough technical examination of the debate and for enabling strategic planning of technology roadmap, we analyze different categories of CAV applications by examining their

spatiotemporal scales of communication requirements, and we analyze capacity limits of different wireless communication alternatives. Based on this analysis, we make recommendations on technology planning.

The rest of this article is organized as follows. In Section II, we review representative CAV applications and their communication requirements. In Section III, we comparatively analyze cellular communication and V2V communication in supporting CAV applications. We make concluding remarks in Section IV.

II. CONNECTED AND AUTOMATED VEHICLE APPLICATIONS

Through wireless communication with one another, transportation infrastructures, Internet clouds, and people, connected and automated vehicles (CAVs) will optimize their operations for safety, sustainability, and user comfort by treating themselves as integral parts of the transportation ecosystem, and they will also serve as enablers and active participants in new paradigms of road transportation. For instance, wireless communication enables non-line-of-sight sensing among vehicles and transportation infrastructures, thus effectively extending the sensing range of what traditional radars and cameras can enable. Wireless communication enables vehicles to share in real-time their internal operation state (e.g., hard brake) that were infeasible before [1]. Wireless communication enables vehicles to exchange their knowledge about traffic condition, road condition, and the environment, thus enabling real-time, extended sensing of driving conditions as well as data-driven transportation planning. Wireless communication also connects vehicles and people in a seamless manner, thus enabling transformative user experience.

In what follows, we review representative CAV applications in the broad areas of active safety, fuel economy and emission control, automation, and infotainment. When presenting the type of communication required by a CAV application (e.g., in Tables I-IV), we use “V”, “I”, “C”, and “M” to denote “Vehicle”, “Infrastructure”, “Internet cloud”, and “Mobile device” respectively.

A. Active safety

Enabling vehicles and transportation infrastructures to sense and coordinate with one another, wireless communication can

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help prevent up to 80% of today’s accidents [2]. In particular, eight high-priority active safety applications identified by NHTSA and VSC are as follows [2], [3]:

- *Pre-crash sensing (PCS)*: it is used to prepare for imminent, unavoidable collisions.
- *Emergency brake lights (EBL)*: When a vehicle brakes hard, it sends a message to other vehicles following behind.
- *Collaborative collision warning (CCW)*: it collects surrounding vehicle locations and dynamics and warns the driver when a collision is likely.
- *Left turn assistant (LTA)*: it provides information to drivers about oncoming traffic to help them make a left turn at a signalized intersection without a phasing left turn arrow.
- *Lane change warning (LCW)*: it provides a warning to the driver if an intended lane change may cause a crash with a nearby vehicle.
- *Traffic signal violation warning (TSV)*: it uses infrastructure-to-vehicle communication to warn the driver to stop at the legally prescribed location if the traffic signal indicates a stop and it is predicted that the driver will be in violation.
- *Stop sign violation warning (SSV)*: it uses infrastructure-to-vehicle communication to warn the driver if the distance to the legally prescribed stopping location and the speed of the vehicle indicate that a relatively high level of braking is required for a complete stop.
- *Curve speed warning (CSW)*: it aids the driver in negotiating curves at appropriate speeds.

Table I summarizes the communication requirements for these active safety applications.

Application	Comm. type	Range	Frequency	Tolerable latency
PCS	V2V	50m	50Hz	20msec
EBL	V2V	200m	10Hz	100msec
CCW	V2V	150m	10Hz	100msec
LTA	I2V, V2I	300m	10Hz	100msec
LCW	V2V	150m	10Hz	100msec
TSV	I2V	250m	10Hz	100msec
SSV	I2V, V2I	300m	10Hz	100msec
CSW	I2V	200m	1Hz	1000msec

TABLE I
COMMUNICATION REQUIREMENTS OF ACTIVE SAFETY APPLICATIONS [2]

B. Fuel economy and emission control

By enabling sensing of traffic, road, infrastructure, and environmental conditions at different spatiotemporal scales, wireless communication enables the paradigm shift from single-vehicle-centered fuel economy and emission control to networked control. A few canonical examples are as follows:

- *Low emission zone (LEZ)*: it lets a hybrid electrical vehicle (HEV) operate in the minimal-greenhouse-gas-emission mode in certain geographical zones (i.e., low emission zones) specified by GPS data [4]. The low emission zones can be specified by governments, organizations, and/or individuals.

- *Fuel-economy-oriented trip planning (FEP)*: it performs trip-wide, global energy usage optimization based on trip previewing and profiling. It includes both mode control and continuous control (e.g., torque control, torque allocation to different actuators such as the mechanical and the electrical motors), and the control considers optimization over a spatial scale ranging from hundreds of feet to tens of miles [5], [6].
- *Preview-based fuel economy optimization (PFO)*: it optimizes hybrid electrical vehicle (HEV) powertrain based on previewed road information, and it focuses on instantaneous mode and continuous control [7], [8], [9], [10], [11], [12]. (Note: unlike PFO, FEP is for PHEV with additional/more battery than HEV.)
- *Stop-start*: to save fuel, it stops/starts traditional engines based on surrounding vehicle state and immediate traffic regulation state, for instance, temporarily stopping an engine in front of red light [13], [14], [15].
- *Platoon*: it organizes vehicles into platoons to reduce the air drag for the lead and following vehicles so as to save fuel/energy while ensuring safety [6], [16], [17], [18], [1].

Based on typical operating scenarios of these fuel economy and emission control applications, Table II summarizes their communication requirements.

Application	Comm. type	Range	Frequency	Tolerable latency
LEZ	C2V,V2C	$\geq 1\text{km}$	$\leq 1\text{Hz}$, e.g., 0.1Hz	$\geq 10\text{sec}$
FEP	C/I/V2V, V2V/I/C	$\geq 300\text{m}$	$\geq 1\text{Hz}$	$\sim 1\text{sec}$
PFO	C/I/V2V, V2V/I/C	300m-13km	$\geq 1\text{Hz}$	distance- dependent
Stop-start	V2V,V2I,I2V	$\sim 50\text{m}$	$\geq 1\text{Hz}$	$\sim 100\text{msec}$
Platoon	V2V	50m-300m	$\geq 10\text{Hz}$	$\sim 100\text{msec}$

TABLE II
COMMUNICATION REQUIREMENTS OF FUEL ECONOMY AND EMISSION CONTROL APPLICATIONS

C. Networked vehicle automation

Besides networked fuel economy and emission control as discussed in Section II-B, other advanced vehicle automation features include the following:

- *Adaptive vehicle tuning (AVT)*: it adjusts the operation state (e.g., refining vehicle suspension and driveline parameters and pre-boosting brake and electronic stability control) of a following vehicle based on real-time information about the operation state of leading vehicles as well as the ensuing road conditions (e.g., speed bumps and potholes) [19], [20], [21], [22], [23].
- *Collaborative failure-mode-effect-management (CFEM)*: In the event of sensor failures on autonomous vehicles, wireless communication enables functioning vehicles to share sensing results with vehicles of mal-functioning sensors [19], [20], [6].
- *Traffic jam assist (TJA)*: it enables automated driving in traffic jam with stop-and-go and lane keeping [24], [25].

- *Supercruise with opportunistic lane change (SCLC)*: it enables automated driving on highways while allowing for lane changes [24], [26].
- *Automated valet/street parking (AP)*: it enables automated valet or street parking without involving drivers [27], [28].

Based on typical operating scenarios of these vehicle automation applications, Table III summarizes their communication requirements.

Application	Comm. type	Range	Frequency	Tolerable latency
AVT	V2V,V2C2V	~100m or context (e.g. speed, inter-vehicle gaps) dependent	~10Hz	~100msec
CFEM	V2V,V2I,I2V	~300m	~10Hz	~100msec
TJA	V2V	10m-300m	~10Hz	~100msec
SCLC	V2V	10m-300m	~10Hz	~100msec
AP	V2V,V2C2V, V2Sensor	10m-1km+	≤1Hz	≥1sec

TABLE III
COMMUNICATION REQUIREMENTS OF VEHICLE AUTOMATION APPLICATIONS

D. Vehicular infotainment

By interconnecting vehicles with one another, the transportation infrastructures, the Internet, and people, wireless communication enables networked infotainment services that significantly enhance user experience and vehicle operation. Six canonical examples of user-centric infotainment applications are as follows:

- *Remote vehicle status (RVS)*: a mobile device (e.g., smartphone, tablet, or smartwatch) application is used to check status of certain vehicle parameters such as its state of charging and location. This is particularly useful for electric vehicles to know the current state of charging, for instance, when parked in a location without being plugged in (e.g., in shopping malls and airports) or plugged in (e.g., at work or other charging facilities) [29].
- *Remote vehicle command (RVC)*: a mobile device application is used to send commands to a vehicle to perform functions such as door lock/unlock, remote-start, climate-control, and vehicle charging policy update [30], [31].
- *Real-time cloud services to vehicle (RTCS)*: it enables HMI or powertrain information (e.g., fuel economy) to be served from the cloud in a context-aware manner [32].
- *Crowd-sourced sensing (CSS)*: it enables Waze-like applications for sensing traffic, air-quality, noise, parking, fuel consumption, camera feeds, etc [33].
- *Delay-insensitive downloads (DID)*: it enables downloading multimedia content (e.g., audio, video, movies) requested by users [6].
- *Geographic proximity applications (GPA)*: it includes, among others, bringing real-time location-specific information (e.g., business ads, coupons, free parking slots)

to users and enabling caravanning for group-travelers (e.g., follow-me, group chat) [34].

Two canonical examples of vehicle-centric infotainment applications are as follows:

- *Extended surrounding sensing (ESS)*: it collects surrounding environment and road conditions by integrating the sensing views of multiple vehicles. The extended surrounding sensing information can be used for both driver assistance (e.g., providing 360-degree views) and vehicle control [35].
- *Cloud-based diagnostics/prognostics/analytics (CDPA)*: Data is collected in the cloud regarding certain interesting events or periodic parameters pertaining to vehicle state such as powertrain parameters, fuel economy, diagnostics trouble code, HMI usage statistics, and vehicle dynamic state (e.g., location, heading, velocity, and acceleration) [33].

Based on typical operating scenarios of these vehicular infotainment applications, Table IV summarizes their communication requirements.

Application	Comm. type	Range	Frequency	Tolerable latency
RVS	V2C,C2V, C2M	cellular radius, vehicle-user distance	≤0.1Hz	best-effort
RVC	M2C,C2V, V2C,C2M	cellular radius, vehicle-user distance	event-driven	≤5sec
RTCS	C2V	cellular radius	≤10Hz	100ms-10sec
CSS	V2V,V2C, C/I2V	cellular radius, inter-vehicle gaps	event-driven, periodic at ≤1Hz	1sec-1min
DID	C2V,V2C	cellular radius	event-driven	best-effort
GPA	V2V,V2C/I, C/I2V	inter-vehicle gaps, V2I distance, cellular radius	event-driven, periodic at ≤1Hz	100msec+, best-effort
ESS	V2V,V2I,I2V	100m-300m	~10Hz	~100msec
CDPA	V2C	cellular radius	event-driven, periodic at ≥10Hz	best-effort, 5-10mins for powertrain fault report

TABLE IV
COMMUNICATION REQUIREMENTS OF VEHICULAR INFOTAINMENT APPLICATIONS

E. A multi-scale spatiotemporal perspective

From the discussions above, we observe that different CAV applications have different spatiotemporal requirements on information exchange. For reasoning about the communication requirements of different CAV applications, it is informative to organize the different application along their spatiotemporal

scales. We summarize this multi-scale spatiotemporal perspective in Figure 1.¹ We see that, for active safety, fuel economy

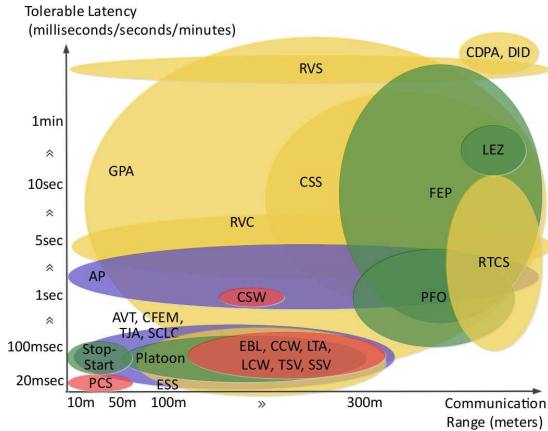


Fig. 1. A multi-scale spatiotemporal perspective of CAV applications

and emission control, and networked vehicle automation, the spatial and temporal scales of communication requirements are correlated in general.

III. ANALYSIS OF VEHICULAR WIRELESS NETWORKING

Two basic paradigms of vehicular wireless communication are vehicle-to-vehicle (V2V) communication and cellular communication, and one basic question is which paradigm is more suitable for the different connected and automated vehicle (CAV) applications. In what follows, we first qualitatively compare the V2V and cellular paradigms, and then we quantitatively analyze the capacity of V2V networks, based on which we make recommendations on reasoning about the paradigm-choice problem from a multi-scale spatiotemporal perspective.

A. Cellular vs. V2V networks

In what follows, we qualitatively analyze the strengths of cellular and V2V networks in supporting different CAV applications. Focusing on the technical aspect of the topic and with a goal of shedding light on longer-term science and technology strategy planning, our analysis is not confined by today's cellular and V2V technologies. Accordingly, we model cellular networks as those wireless networks where mobile stations (e.g., vehicles) communicate with one another, the transportation infrastructures, and the Internet through cellular base stations which were mostly statically deployed, and we model V2V networks as those networks where vehicles communicate with one another and the transportation infrastructures themselves without involving cellular base stations in data exchange. By this approach, the mode of cellular networks where mobile stations directly communicate with one another without involving base stations in data exchange (e.g., in the envisioned 5G cellular networks) is treated as a type of V2V network. Focusing on comparative capacity analysis of cellular

and V2V networks, we also assume that cellular and V2V networks have access to the same amount of wireless spectrum.

Compared with V2V networks, cellular networks have the following advantages:

- With cellular base stations connected to the rest of the Internet, cellular networks can enable easy access from vehicles to the cloud resources and vice versa. Therefore, cellular networks are suitable for CAV applications that need to involve the Internet cloud resources, including cloud-assisted vehicle control and infotainment applications.
- Cellular base stations are usually elevated above the ground, thus the channel conditions between cellular base stations and vehicles may be better than if the cellular base stations were put on ground. With the availability of multi-hop networking and relay-based collaborative communication, however, this advantage of cellular networks may become less important over time.

There have been arguments that cellular networks do not have the challenge that V2V networks have in terms of market penetration. This is only partially true. It is the case that today's deployed cellular networks can already support many CAV applications (e.g., low emission zone and remove vehicle status applications) in the regime of large spatiotemporal scales of communication requirements. Designed for traditional consumer electronics markets, however, today's cellular networks (including LTE) were not designed for mission-critical, real-time CAV control in the regime of small spatiotemporal scales of communication requirements, and they cannot ensure predictable reliability, timeliness, and throughput as required by many CAV control applications. For mission-critical, real-time vehicle control applications that are important for transportation safety, efficiency, and comfort, therefore, cellular networks also have to face the challenge of deploying new equipment and/or capabilities.

Compared with cellular networks and considering a spatial scale at the coverage of a cellular base station, V2V networks have the following strengths in supporting CAV applications:

- V2V enables smaller delay in inter-vehicle communication for the following reasons: 1) V2V networks enables direct communication between vehicles without having to go through a base station as in cellular networks, thus eliminating the delay introduced by the base station relay in terms of wireless transmission and reception delay as well as software, processing delay at the base station; 2) with the same transmission power, the shorter links in direct V2V communication enable higher signal-to-noise-ratios (SNRs) at receivers and thus higher success rate in packet delivery, which in turn reduces the number of retransmissions needed to deliver a packet and thus reduces delay; 3) when transmission power is controlled according to link length, the smaller contention region in direct V2V communication reduces channel access delay. In addition to helping reduce delay, the smaller contention region in V2V communication also enables higher throughput by reducing channel contention time and improving channel spatial reuse.

¹The figure is not drawn to scale.

For communication between vehicles along a linear/cross roads (as envisioned for active safety and platoon applications), in particular, the number of vehicles contending for channel access is proportional to the length of roads covered by V2V or cellular communication signals. Assuming that the ratio of interference range² to communication range is similar in V2V and cellular networks, the ratio of the timeliness³ and per-vehicle throughput in V2V networks to those in cellular networks is approximately twice the ratio of the radius of a base-station-covered cell to the communication range of direct V2V communication.

- The transmission power and thus the contention region of V2V communication can be adaptively tuned according to the required communication range (e.g., as determined by inter-vehicle distance), thus enabling further enhancement and adaptation of communication throughput and timeliness. This flexibility of capacity adaptation is also critical for the co-design of CAV control and wireless networking. In cellular networks, however, base stations are mostly fixed, and this fact confines the flexibility of communication range adaptation and thus hampers effective capacity utilization; for instance, even if two close-by vehicles need to communicate with each other, they have to transmit at a high-enough power to reach the cellular base station.
- Many inter-vehicle communication required by CAV applications is broadcast in nature (e.g., for active safety and extended surrounding sensing), and this matches well with the broadcast nature of V2V wireless communication. Existing cellular architecture, however, is designed around point-to-point communication, and it introduces unnecessary overhead in supporting broadcast.
- V2V communication does not rely on road-side infrastructures (e.g., base stations), and, for CAV applications in the regime of small spatiotemporal scale of communication requires, V2V networks provide the communication service whenever and wherever need be, even in areas (e.g., rural areas) of little or no cellular coverage.

B. Per-vehicle transmission capacity and delay in V2V networks

To elaborate on the analysis of Section III-A, here we analyze the per-vehicle transmission capacity and delay in V2V networks.

To understand the impact of the road and traffic condition, we consider scenarios where the number of lanes (denoted by N) in a road segment ranges from 2 to 8, and the inter-vehicle gap (denoted by D) ranges from 6 meters to 300 meters representing different degrees of traffic congestion and speed [36]. For other network parameters, we consider the following typical settings:

- Transmission range: R meters (default 300 meters);
- Ratio of interference range to transmission range: I (default 2 as a typical value as shown by Zhang et. al [37]);

²The range within which the concurrent transmissions by two vehicles are regarded as interfering with each other.

³Timeliness is defined as the inverse of delay.

- Wireless channel capacity: C Mbps (default 27Mbps, i.e., the maximum rate of the current IEEE 802.11p-based DSRC technology);
- Overall capacity utilization ratio to account for protocol overhead: $U \in [0, 1]$ (default 0.9)
- Packet length: L bytes (default 400 bytes)

Given a specific value of N and D and considering a straight road, the number of vehicles interfering with the transmission by a vehicle is $(\frac{2RI}{D} + 1)N - 1$, and the effective overall capacity shared by a vehicle and its interfering vehicles is CU . Thus the average per-vehicle transmission capacity T (Mbps) is as follows:⁴

$$T = \frac{CU}{(\frac{2RI}{D} + 1)N}, \quad (1)$$

And the average per-packet transmission delay d (msec) is as follows:

$$d = \frac{8L}{1000T}. \quad (2)$$

With the default parameter settings, we have Tables V and VI for the average per-vehicle capacity and per-packet delay respectively. We see that the per-packet delay is less than

Inter-vehicle gap D (meters)	Number of lanes N			
	2	4	6	8
6	0.0604	0.0302	0.0201	0.0151
20	0.1992	0.0996	0.0664	0.0498
50	0.4860	0.2430	0.1620	0.1215
100	0.9346	0.4673	0.3115	0.2337
200	1.7357	0.8679	0.5786	0.4339
300	2.4300	1.2150	0.8100	0.6075

TABLE V
AVERAGE PER-VEHICLE TRANSMISSION CAPACITY (MBPS)

Inter-vehicle gap D (meters)	Number of lanes N			
	2	4	6	8
6	52.9383	105.8765	158.8148	211.7531
20	16.0658	32.1317	48.1975	64.2634
50	6.5844	13.1687	19.7531	26.3374
100	3.4239	6.8477	10.2716	13.6955
200	1.8436	3.6872	5.5309	7.3745
300	1.3169	2.6337	3.9506	5.2675

TABLE VI
AVERAGE PER-PACKET TRANSMISSION DELAY (MSEC)

100msec in most cases except for the very high-density settings of $D = 6m$ and $N \geq 4$. To further increase per-vehicle capacity and to reduce per-packet delay, we can use the following mechanisms:

- It is expected that, in settings of denser vehicle distributions, the vehicle speed will be lower and the required communication range can be reduced. Therefore, we can adaptively control the transmission range (e.g., through transmission power control) to reduce the number

⁴For simplicity, we do not consider intersections, and we assume all the vehicles are along a single road.

of interfering vehicles and thus increase the per-vehicle capacity. For the case of $D = 6m$ and $N = 8$, for instance, using a transmission range of 60 meters (i.e., 10 times the inter-vehicle distance) instead of 300 meters will increase the per-vehicle capacity and reduce the per-packet delay by a factor of about 5. Note that, since it is difficult/impossible to adaptively change the locations of cellular base stations on the fly, it is easy to implement adaptive transmission range control in V2V networks but not in cellular networks.

- Using multiple wireless channels instead of a single channel will also enhance capacity and reduce delay.

Another observation from this analysis is that the capacity of V2V networks is only barely enough to support today's application requirements (especially in dense vehicle traffic scenarios) even with a high capacity utilization ratio of 0.9. Contention-based channel access control such as that in the IEEE 802.11p-based DSRC usually has a much lower capacity utilization ratio (e.g., less than 0.5), thus TDMA-based channel access control [38] is expected to be more suitable for CAV applications at the small spatiotemporal scale of communication requirements.

C. A multi-scale spatiotemporal perspective

From the above analysis, we see that, with direct inter-vehicle communication and flexible, adaptive control of transmission ranges and interference ranges, V2V networks are suitable for those CAV applications in the regime of small spatiotemporal scales of communication requirements; on the other hand, cellular networks are more suitable for those CAV applications in the regime of large spatiotemporal scales of communication requirements. We summarize this multi-scale spatiotemporal perspective in Figure 2.⁵ The fact that both V2V networks and

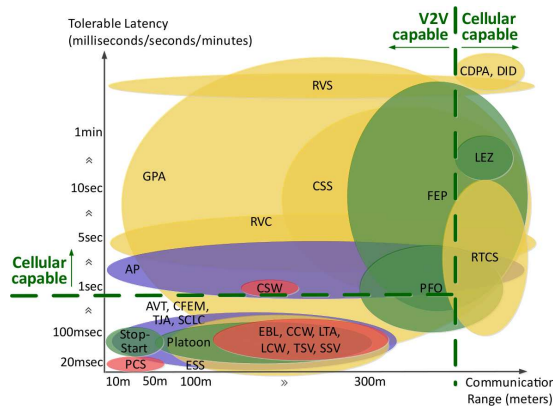


Fig. 2. A multi-scale spatiotemporal perspective of wireless networking for CAV applications

cellular networks are suitable for those CAV applications in the regime of small spatial scales but medium-to-large temporal scales of communication requirements implies the opportunity of jointly utilizing the capacity of V2V and cellular networks for those applications, for instance, for maximizing application utilities or minimizing cost [39].

⁵The figure is not drawn to scale.

IV. CONCLUDING REMARKS

We have examined the wireless communication requirements by canonical CAV applications in active safety, fuel economy and emission control, vehicle automation, and infotainment. We have observed that the spatiotemporal framework can serve as a good mechanism of reasoning about the wireless communication requirements of CAV applications.⁶ Using the spatiotemporal framework, we have shown that V2V networks are effective in supporting CAV applications in the regime of small spatiotemporal scales of communication requirements, and, in the small spatiotemporal scale regime, time-division-multiple-access (TDMA) [38] is expected to be more suitable than contention-based channel access control such as that in IEEE 802.11p. We have also observed the opportunity of jointly using the V2V and cellular networks in the small spatial scale but medium-to-large temporal scale regime. These findings suggest the benefits and need for effectively utilizing V2V networks in realizing the CAV vision, incorporating TDMA as a basic channel access control mechanism in V2V networks, and leveraging the heterogeneous wireless networks available to CAV.

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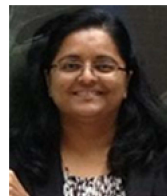
⁶Note that, even though spatiotemporal scales of CAV applications have been considered in some existing work [40], [41], no work has systematically examined the multi-scale spatiotemporal aspects of CAV applications and their implications for vehicular wireless networking.

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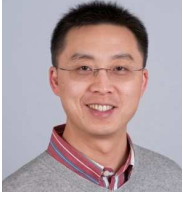
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