Intelligent Transportation Systems in the Context of 5G-Beyond and 6G Networks

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***Abstract*—The role of wireless communications in guaranteeing safe and resource-efficient intelligent transportation systems (ITS) is of great significance. With the advent of a new technological epoch in cellular network development, various novel technical solutions are being considered as key enablers for future 5G-beyond and 6G networks. In this position paper, we identify and discuss three key pillars in the wireless network evolution that we suppose to be the foundation for the practical deployment of mass ITS. We first show how edge-located solutions may help in data delivery, next we present the role of the integrated communications and sensing paradigm (ICAS) in vehicular communications, and finally, we concentrate on advances in cellular-based sidelink communications.**

***Index Terms*—ITS, V2X communications, ICAS, short-range communications, content caching, 6G.**

I. INTRODUCTION

It is widely agreed that the improvement of driving performance reduces the impact of mass transport on the natural environment leading to more sustainable and safe transportation system. Various advanced solutions have been widely implemented leading to an increase of driving comfort and overall safety, such as Anti Slip Regulation (ASR), or Electronic Stability Program (ESP), just to mention a few. From the perspective of collision avoidance, Adaptive Cruise Control (ACC) systems, or its cooperative version, Cooperative ACC (CACC) have been widely investigated. Effective cooperation between vehicles, pedestrians and infrastructure elements entails however the need for fast and reliable wireless data exchange. Accurate and safe wireless communication between road users and other elements, known as vehicle-to-everything (V2X), is a fundamental requirement to guarantee safe driving and increase the efficiency of road infrastructure usage.

Nowadays, there are two dominating approaches in V2X communications, mainly dedicated short-range communications (DSRC) or Cellular V2X (C-V2X). The former relies on the IEEE 802.11p standard and the latter - on the Long Term Evolution (LTE) or New Radio (NR) standards [1]. From the beginning of research towards 5G systems, automotive applications have been treated as one of the key vertical sectors, where new technological solutions within a cellular network would play a central role. As 5G is on its road towards mass deployment all over the world, research is concentrating on new directions that could be applicable in future 5G-beyond and 6G wireless networks, including applications for automotive sectors.

In this position paper, we identify three key research domains that will play an important role in the process of making mass transportation safer, more efficient, and more sustainable from an environmental perspective. The first pillar is the application of edge solutions for V2X communications, the second is related to the application of integrated communication and sensing (ICAS) for automotive purposes, and the third deals with advances in short-range communications in lower (sub-6G) and higher frequency bands (mmWaves) for efficient data delivery between closely located network nodes.

In the next three sections, we present the above-identified technologies and illustrate our motivation for classifying them

The work by A.Kliks has been realized within the project no. 2018/29/B/ST7/01241 funded by the National Science Centre in Poland

as key technological enablers for future transportation systems.

II. Network Edge Solutions Towards Better V2X Communications

As discussed above, we foresee that edge-located solutions will play a dominant role in practical implementations of intelligent transportation systems. As the traffic increases, the amount of data that has to be transmitted wirelessly between numerous road users will grow. Such exchanged V2X delay-constrained content needs to be leveraged for traffic management, road safety, environment monitoring and infotainment of passengers. The need for efficient manipulation of voluminous content is addressed by the Vehicular Edge Computing (VEC) paradigm as shown in Fig. 1, mainly handling content with efficient offloading (task computation, content delivery) and storage.

6G emerging technologies for delivery of delay-constrained content are mostly based on connected intelligence. Big data techniques and Machine Learning (ML) enable emerging technologies in dynamic environments of multi-modal and time-varying data being produced for high-definition maps, material for infotainment, dynamic planning information, etc., as they can efficiently and without explicitly given programmed rules extract knowledge from noisy data with non-stationary features. ML-based approaches, including either optimization or inference of latent variables for data-driven models, are supported by the rapid increase of data sources, advances in network softwarization, and the massive low-cost storage and computing resources in the cloud.

Popular content can be proactively fetched on the edge level and the vehicle can broadcast among peer vehicles. The decision about which content needs to be cached can be taken collectively, e.g., Qin et al. [2] propose a hierarchical edge-to-edge approach based on collaboration among data communication, computation offloading and content caching and find a sub-optimal solution with a deep deterministic policy gradient-based resource allocation scheme. Wu et al. [3] leverage multiple radio access technologies (multi-RATs) to distribute task-offloading and suggest an offloading decision mechanism based on a fronthaul-aware upper confidence bound algorithm. Kuo et al. [4] jointly optimize caching, computing and communication among vehicles and roadside units (RSUs) of the vehicular network to ensure video quality, and observe that the application of a cache replacement scheme can significantly improve the quality.

Challenges associated with edge caching in 6G V2X content distribution are associated with supporting massive connectivity in a highly dynamic environment. They include the high dimensionality of raw data collected, incomplete data collection and impediments while harvesting data and preserving privacy of the users, the dynamic nature of parameters of various operators and vendor-proprietary data as well as unrealistic bandwidth demands for training.

A possible approach to manage such complexity is *virtualized edge computing* [5], as introduced above, which leverages the flexibility enabled by Network Function Virtualization and the softwarization of the network to deliver smooth service provisioning and operations. This is achieved by the opportunistic and dynamic integration of communication, computing and storage resources locally available at the edge, typically characterized by a high degree of heterogeneity. The ultimate aim of this approach is to cater for a large variety of requirements, e.g. coming from Smart City and ITS verticals. The key idea underlying virtualized edge computing is to aggregate and coordinate static, infrastructure-based components (such as static base stations and collocated edge servers) and logical functions abstracting those resources made available by mobile users. The resulting aggregate is made available for the implementation of any virtualized function required by applications. These aggregate resources are organized into clusters, and managed by an orchestrator, which coordinates multiple clusters by balancing load among them in real time, by managing their composition over time (as required by the resource churn induced by mobility) as well as the interaction among them. The orchestrator acts by continuously checking and optimizing the location of microservices within the clusters, migrating them according to spatio-temporal patterns of demand and of resource availability in a QoS and context-aware manner.

Some of the state-of-the-art current solutions include Federated Learning (FL)-based crowd-sourcing of devices with various QoS requirements, mostly supported by clustering of network devices and device-to-device communication to reduce network communication, reinforcement learning-based comprehensive edge-to-edge AI, consideration of critical time in order to update outdated ML models, calculate pre-trained weights. etc., post-quantum cryptography techniques, e.g. multivariate polynomial cryptography, that could be incorporated in the 6G network hardware and software, and privacy-preserving learning-based offloading mechanisms.

III. The Role of ICAS for V2X

The design of beyond 5G networks has increased the interest in ICAS for different reasons: first, new applications require not only high-performance communications, but also improved sensing and, second, the use of higher frequencies and wider bands allow higher-resolutions in time and space [6]. Since connected vehicles act as mobile sensor nodes, they can provide new sensing capabilities, helpful to create a detailed map of the environment or even digital twins of the surrounding physical scenario, able to perform joint communication and sensing, essential for an authentic digital representation of the physical world, clearly highlighting the ICAS role in future 6G vehicular networks [7].

To date, communication and sensing functions are typically performed separately through different devices operating in different frequency bands and supplied by different industries, but, as the level of connectivity and automation of vehicles increases, the implementation of new applications will imply a strong convergence of automation and connectivity on-board. Hence, beside radars, cameras and lidars, beyond 5G-V2X communication signals can be exploited for radar sensing.

VEC_Section1.pdf

Fig. 1. Vehicular Edge Computing (VEC) architecture, mainly handling content with efficient offloading (task computation, content delivery) and storage.

Figures/v2x_picture.pdf

Fig. 2. General architecture of a virtualized edge computing system. Resources from static infrastructure and from mobile users are organized in clusters. An orchestrator manages in real time load distribution among clusters and cluster composition, migrating microservices among them based on resource availability and spatio-temporal patterns of service demand.

The integration of sensing functionalities into communication devices requires challenging modifications, such as the use of full duplex radios to allow simultaneous transmissions and receptions and complex mechanisms for self-interference cancellation. Specifically, ICAS allows to share signal processing algorithms, hardware architectures and frequency spectrum between communication and sensing systems, providing radar functionalities for free, exploiting the communication signal already used for V2X communication between vehicles or between vehicles and other road users [8].

It might be observed that, in spite the fact that future automated vehicles will be equipped with advanced on board sensors for sensing and localization, they work in line-of-sight (LOS) conditions only. Each vehicle mounts a different sensor, working at difference frequency bands, without sharing standardisation rules as instead it happens for communication. It is then easy to understand that, the signals used for V2X communications, which are standard for all vehicles, can be exploited to also sense the environment, thus detecting the presence of objects or even their shape, location, and speed, without any additional spectral occupation, just processing the backscattered responce from the environment due to V2X signals [9].

There has been an increasing interest in ICAS in vehicular scenarios in the recent literature, but the main limitation is represented by the fact that most works do not deal with vehicular wireless access technologies, but with generic radar sensing at different frequencies. A breakthrough in ICAS research in vehicular scenarios could be, instead, represented by the use of dedicated technologies, such as 5G-V2X and beyond, that will allow wider bandwidth (hence, higher resolutions) also in sub-6 GHz bands. To date, most works consider millimeter waves (mmWaves) in the range of $20-80$ GHz, discussing the use of new waveforms [7] or of the same signal and hardware for both sensing and communication [10]. Few works investigate the sensing performance of technologies specifically dedicated to vehicular scenarios and they all consider IEEE 802.11p or ITS-G5, but not C-V2X [11]. Hence, we here discuss the main challenges and potentialities of C-V2X in ICAS scenarios.

A. The Impact of 5G-V2X Parameters on ICAS

As far as the pillar of the ICAS paradigm is concerned, to discuss the impact and the challenges of communication on sensing we here focus on the sidelink of 5G-V2X, hence we consider direct communication between vehicles; we also assume full-duplex radios with the radar receiver co-located with the V2X transmitter, thus having perfect knowledge of the transmitted data symbols, that can be exploited for parameter estimation. An example scenario is shown in Fig. 3: Vehicles broadcast messages that are also used to estimate the distance between the transmitting vehicle and the target by computing the delay from the target and to estimate the relative speed of the target by estimating the Doppler shift. The accuracy of these estimations depends on the maximum bandwidth and on the signal duration. In the following, we discuss the potential impact of physical and radio access parameters on the speed and range estimation.

- Two frequency ranges are foreseen for 5G-V2X: frequency range 1 (FR1) from 410 MHz to 7.125 GHz (sub-6 GHz) and frequency range 2 (FR2), from 24.25 GHz to 52.6 GHz (mmWave). FR2 allows larger bandwidth and could allow higher accuracy in the estimation, but it suffers of shorter coverage ranges.
- A V2X sidelink transmission is composed of a slot in the time domain and a number of subchannels in the frequency domain, depending on the message dimension. Increasing the subcarrier spacing (SCS), the slot duration decreases, providing lower latency and higher resistance against Doppler effect or carrier frequency offset and the bandwidth occupied by a physical resource block (PRB) increases. This implies that the available resources decrease; hence, higher modulation and coding schemes (MCSs) could be adopted to accommodate the message.
- The vehicular density impacts on the generated interference when vehicles share the medium. Hence, medium access and resource allocation policies imply different levels of interference that each vehicle can experience. In particular, 5G-V2X allows two sidelink modes, named Mode 1 and Mode 2, that correspond to controlled (the base station allocate the resources) and autonomous (vehicles autonomously select the resources without the support of the base station) operation modes. In Mode 2, the same pool of resources can be shared among different vehicles due to the distributed allocation mechanism, generating interference that, inevitably, has an impact on the sensing performance.

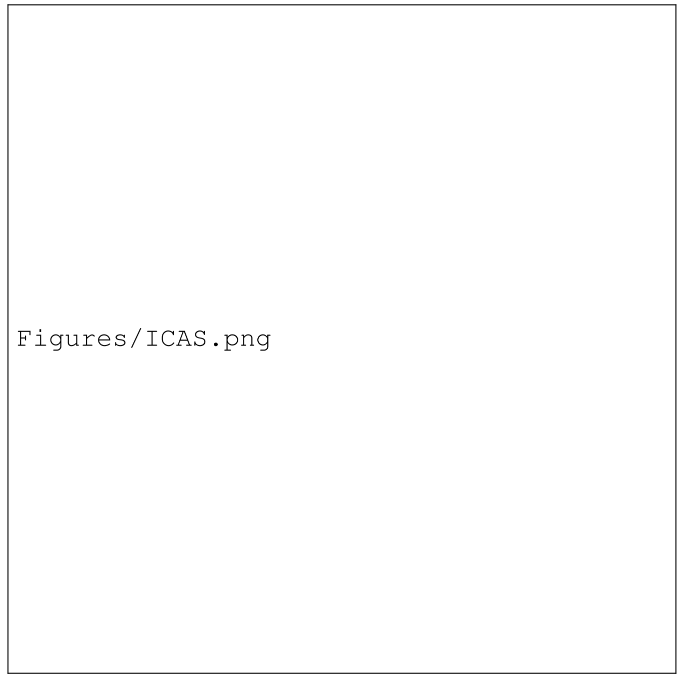

Fig. 3. Example of ICAS in vehicular scenarios: vehicles transmit broadcast messages and are equipped with a full-duplex radio capable of listening to the backscattered response from the environment while transmitting, thus detecting the presence of a target, such as other non-connected vehicles or pedestrians.

New important research directions could be devoted to the evaluation of the mentioned parameters on the sensing performance, also including discussions on the use of beamforming to achieve not only target detection but also its localization.

Hence, ICAS can be considered as one of the key technologies on the way to 6G. Significantly adding value in many vehicular applications, from safety to sustainability and comfort. It is more cost-efficient than having two separate systems and it allows for more efficient and flexible usage of spectrum, also reducing energy consumption. ICAS could also make it easier for automotive industries to come up with a positive return and to justify investments in 5G and 6G.

B. Security and Privacy in ICAS

V2X communications can greatly benefit from having ICAS as a core feature of the network, thus allowing traffic environment perception that enables advanced applications that rely on the estimation of the number of vehicles and their velocities. However, in V2X applications, sensible information is transmitted in sensing signals, thus ICAS rises unique security and privacy issues once the radiation power is concentrated toward the direction of targets of interest, which can potentially act maliciously by trying to leak the confidential information. Therefore, there is a trade-off between sensing performance and security [12].

Besides the application of widely-known crytographic solutions, that may face limitations in V2X scenarios due to the challenges for management and exchange of secret keys in highly mobility scenarios and introduction of delays, physical layer security (PLS) techniques may render an interesting complementary approach [13]. These techniques rely on exploiting wireless channels to provide information-theoretic security guarantees; however, the majority of solutions rely on impractical assumptions regarding the knowledge about eavesdroppers.

Nonetheless, with ICAS, the position of a target can be inferred from the echo signal reflected from the target, thus the channel of the eavesdropper can be estimated, which can potentially be used to enable many PLS approaches, such as beamforming or cooperative jamming. Initial works have shown that secure transmissions can be attained, in scenarios with malicious targets, by proper design of beamformers and exploitation of artificial noise [14], and by designing waveform and receive beamformer to exploit constructive interference from multi-user interference in order to disrupt the eavesdroppers [15]. All in all, there are still open issues for the design of robust secure ICAS systems that can effectively explore the sensing information, for instance, at a network-level approach by taking advantage of heterogeneity, mobility and high density of nodes in vehicular networks. Moreover, the sensing capabilities also rises privacy concerns as sensitive information, such as location or identity of users and vehicles of the network, can be inferred and tracked through communication links, so that adversaries can launch attacks or steal private information. Therefore, the design of privacy-preserving waveforms and beamformers that allow to hinder the location information, thus preventing localization from unauthorized parties [16], will be critical for V2X applications.

IV. Short-Range Access Technologies for Reliable V2X

When looking at safety applications, the adoption of short range wireless communications is expected to represent the turning point in the future of ITS. Following several decades of research and on-field experiments, its deployment has finally begun. In Europe, in fact, on-board units (OBUs) have started to be introduced as standard features in some car models and road side units (RSUs) are being installed in several countries to provide safety-related cooperative-intelligent transport systems (C-ITS) services. The technology currently adopted in Europe is ITS-G5, which is based on IEEE 802.11p, and the frequency band is the so-called ITS band around $5.9\,\mathrm{GHz}$, which is similarly allocated also in many other countries worldwide for the same scope.

However, other solutions are available, such as the LTE-V2X sidelink and the NR-V2X sidelink, and the debate on the best option [17], [18] and their coexistence [19] is still on-going. Additionally, whereas current solutions appear suitable for the services defined as *Day 1* (where each vehicle informs about its status and movements), enhancements are required to enable advanced applications like, e.g., automated driving features. Among these, particular emphasis is being devoted to the use of mmWaves, which promise wide bandwidth but, at the same time, require highly directive antennas and suffer of heavy path-loss and signal blockage from obstacles.

In this section, we aim at discussing the main open issues and research trends first focusing on the solutions in the ITS band or lower frequencies, sometimes named sub-$6\,\mathrm{GHz}$, and then looking at the mmWave domain.

A. Technologies in the sub-$6\,GHz$ bands

Indeed, recently the NR-V2X sidelink has been defined, which is similar but not inter-operable with LTE-V2X. It introduces the flexible numerology of NR at the physical layer, the implications of which have been studied in a few works, e.g. [20], and a number of modifications compared to the predecessor at the medium access control (MAC) layer. In NR-V2X, the controlled resource allocation is called Mode 1 and the autonomous one is called Mode 2. When looking at the controlled mode, one issue is the need to optimize the trade-off between signaling overhead and accuracy of the information in the network; another relevant open issue, is how to manage situations where a node moves from the network from one operator to another one from a different operator, which may be especially relevant when the vehicle is moving from one country to another.

Also regarding NR-V2X, such as for LTE-V2X, most of the work has been done so far looking at the autonomous mode, where early works mainly focused on the impact of the modifications to the sensing based semi-persistent scheduling (SB-SPS). In particular, the main one is that the relevance of sensing the past use of resources is reduced and the decisions rely more on what indicated by the control information associated to each transmission [21], [22].

Congestion control and the management of traffic with non-periodic and variable-size messages [23] also appear to be challenging issues that are still under investigated. Additionally, still focusing on the autonomous mode, there are new features that represent new opportunities, such as the possibility to use unicast and groupcast transmissions, which may be very relevant for some use cases, or the inter-user coordination, where nodes share their view of resource reservation, thus allowing improved knowledge of the distributed allocation process at the cost of increased signalling load.

In addition to the several open issues related to the available or almost completed wireless standards, a number of specific aspects and new technologies are also being considered on the path towards 6G. Among them, possibly disruptive solutions are in-band full-duplex (FD), non-orthogonal multiple access (NOMA), and reconfigurable intelligent surface (RIS). The use of self-interference cancellation (i.e., FD) can be used to receive while transmitting; this ability can not only be used to increase the number of received messages, but also and mainly in order to allow concurrent sensing with collision detection [24]. With NOMA, multiple signals can use the same resource, which promises a significant increase of the spectral efficiency and may lead to a redesign of the resource allocation algorithms [25]. Finally, in the future, RISs may be installed on road infrastructure or vehicle body panels; their use can greatly increase the performance but opens complex challenges as remarked for example in [26].

B. Massive Multiple-Input Multiple-Ouput (MIMO) for Reliable V2I Communications

Low-latency and high reliability, i.e., low frame error rates, are of increasing importance for V2I applications in advanced uses cases for connected, cooperative, and automated mobility (CCAM) [27]. The physical layer of wireless communication systems is affected by multi-path propagation, resulting in delay and Doppler dispersion. This causes a random fluctuation of the signal to noise ratio (SNR) at the receive antenna, due to either constructive or destructive superposition of all propagation paths (fading). To overcome random SNR fluctuations due to fading, diversity in space, time and frequency must be utilized by the PHY layer of 5G and 6G systems to the utmost extent possible. 5G systems utilize spatial diversity by means of massive MIMO systems. Massive MIMO uses much more transmit antenna elements (e.g., 64) than there are active users within a cell (e.g., 30). By proper beam-forming, it is ensured that signal contributions from all propagation paths add up constructively at the Rx antenna, thus maximizing the obtained SNR while minimizing random fluctuations. This effect is called channel hardening and depends on the propagation conditions [28]. The beam forming in massive MIMO relies on channel state information (CSI), which is acquired in a time-division duplex (TDD) setup during the up-link transmission and used in the following down-link phase.

For mobile users such as vehicles, the channel state information (CSI) available at the base station will get outdated depending on the speed of the vehicle, the carrier frequency, and the pilot scheme in use. Hence, channel prediction is an important tool to combat channel aging [29] in V2I use cases. The utilization of time- and frequency diversity can be maximized by using orthogonal precoding (OP) by means of an unitary matrix transform. OP became popular under the term orthogonal space, time frequency (OTFS) [30]. However, it was shown in [31] that all unitary matrices with constant modulus elements achieve the same diversity gain in terms of channel hardening. The beneficial combination of massive MIMO with OP for 6G V2X system is investigated and discussed in [32].

Recently, cell free massive MIMO systems became of great interest as potential technology for future 6G systems. Here, the antenna elements are not placed in an array at the location of the base station but the antenna elements are distributed over a large geographical area [33] and their received signal is processed coherently at a central processing unit. This setup enables strong gains in terms of throughput, electromagnetic field reduction as well as improved reliability. First measurements from an V2I scenario are reported by the authors of [34] using a software defined radio test bed.

For all above described PHY layer concepts, energy and computational efficient signal processing algorithms are required, both in the domain of channel estimation as well as for data detection. Especially for cell free systems, large scale trials in all relevant scenarios are needed to obtain the empirical foundation for numerical geometry based channel models, energy efficient implementations, scalable front haul architectures and low-latency operation.

C. Technologies in the mmWave Frequency Band

Innovative solutions for beyond 5G and 6G V2X networks are being developed as a result of the advancement of connected and automated cars (CAVs) technology. A critical aspect that characterizes propagation at mmWaves is the high attenuation that makes beam-based communication necessary. Therefore, precise beam targeting is required to ensure a reliable communication link, especially in high mobility scenario. This can be achieved through sub-6GHz networks that provide control of mmWaves for implementing beam-based communications [35]. One of the biggest challenges is represented by the selection of the best beam to set up the communication among a variety of alternatives. 5G NR uses periodic spatial synchronization signals for the initial access (IA), beam failure recovery, and beam tracking mode depending on channel status data to achieve this. Multiple beam directions are used to disseminate these signals selectively.

Using an effective 6G architecture, various IA strategies can be adopted to speed up the existing 5G NR standard. Proactive methods represent the most promising future research direction to choose the best beam and allow for a quick IA [36]. Probabilistic codebook (PCB) approaches have been proposed based on the idea of prioritized beams that exploit the non-uniform distribution of the communication directions induced by road topological constraints. Conventional IA approaches based only on the communication protocols are characterized by high training times and frequent link interruptions. To overcome these issues side information coming from sensors at both vehicular UE, e.g., Global Position System (GPS), and Base Station (BS), e.g., radar, side can be integrated in the IA procedures. In [37] pros and cons are shown of the two approaches and a joint radar- and GPS-aided IA procedure is proposed that allows to reduce training time in typical urban scenario.

Another challenge in V2X at mmWaves is the blockage of the LOS propagation by both, static and moving obstacles, which result in an excessive path loss. To address this issue the most promising research direction among those under investigation is based on the use of relays [38]. Traditional relay techniques, on the other hand, react to link failure and use instantaneous information, which makes it difficult to choose an effective relay in highly dynamic and complicated networks, as those found in vehicular settings. In this regard, proactive relaying methods that make use of CAV collaboration and environmental data to forecast the dynamic LOS-map can be adopted. A dynamic LOS-map can be used by proactive relaying techniques to maximize network connectivity. A novel framework integrating actual mobility patterns and geometric channel propagation models is proposed in [39].

V. Conclusions

In this position paper, we have discussed three technological pillars, that we suppose will be the foundation for future wireless systems supporting ITS. We have discussed the need of advanced solutions for edge-computing and edge-intelligence technologies, as well as the importance of ICAS-based algorithms. Finally, we have presented the advances in cellular-based sidelink communications, focusing on both low- and high-frequency applications. We stand at the position that these three pillars build the foundation for safe and reliable communications required for future ITS deployment.

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