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Integrated Sensing and Communications (ISAC) for Vehicular Communication Networks (VCN)

Xiang Cheng, *Fellow, IEEE*, Dongliang Duan, *Senior Member, IEEE*, Shijian Gao, *Graduate Student Member, IEEE*, and Liuqing Yang, *Fellow, IEEE*

Abstract*—With the unprecedented development of smart vehicles and road side units equipped with wireless connectivity, the transportation system is undergoing revolutionary changes in the past decade or two. Bearing safety and efficiency as the utmost objectives, the vehicular environments are witnessing explosive increase of various sensors onboard vehicles and equipped at transportation infrastructures. On the one hand, these sensors are destined to be wirelessly connected to provide more comprehensive situational awareness for transportation purposes. On the other hand, the abundance of sensor data of the environment can potentially shed light on the channel propagation characteristics that lie at the core of any communications system design. The integrated sensing and communications (ISAC) is henceforth both necessary and natural in vehicular communications networks (VCN). Different from existing ISAC works that target generic environments but are limited to dual-function radar-communications (DFRC), in this paper we focus on transportation scenarios and applications but take a wholistic view of ISAC possibilities. First, we argue that, even though many sensors in transportation settings are non-RF-based, functional ISAC (fISAC) is feasible and necessary, in both communication-centric (CC) or sensing-centric (SC) modes. To facilitate this, the concept of synesthesia is introduced to ISAC to accommodate "machine senses" in the RF and non-RF formats. We then zoom in to RF-based sensors and propose the so-termed signaling ISAC (sISAC), with either unified-hardware (UH) or separate-hardware (SH) platforms, and delineate the unique issues arising in transportation settings. Several transportation-specific case studies are included to demonstrate these various ISAC regimes. Towards the end, the relationships of these ISAC (su-)categories are discussed with a roadmap laid out.

Keywords: integrated sensing and communications, intelligent transportation, vehicular communication networks

I. INTRODUCTION

Recent years have witnessed the leaping advance of transportation technology, with growing intelligence permeating the design of both individual vehicles and the transportation infrastructure. It is expected that, in the near future, a significant number of vehicles on the road will be equipped with aggressive driving assistance and autonomous driving at various levels. Consequently, more and more drivers will be relieved from the tedious driving tasks, and even enjoy the freedom of working or entertainment during daily commutes or long road trips (see, e.g., [1], [2]).

This exciting vision is not without challenges. From the transportation perspective, numerous accidents, including the very recent Tesla Model Y crushing under a semi-truck in Detroit, keep reminding us of the risk of relying on the intelligence of a single vehicle when it comes to safety. Also critical to the transportation system is the efficiency in terms of both the passenger/commodity travel time and fuel/energy economy. This, again, is a matter that inevitably depends upon the interactions of multiple vehicles and the infrastructure. To this end, vehicular communication networks (VCNs) come to rescue. Consisting of vehicles, infrastructures, passengers, pedestrians, clouds, and other devices with communication modules, VCNs include vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), vehicle-to-infrastructure (V2I), and vehicle-to-network (V2N) communication modes [3], [4]. With VCNs, safe and efficient transportation can be facilitated from multiple aspects [5], [6]. First, VCNs make it possible for vehicles to access local and global transportation information with significantly increased information redundancy that can enhance driving safety. Secondly, VCNs also imply better informed transportation management and the possibility of personalized real-time traffic control. Last but not least, VCNs also bring the hope towards transforming vehicles to offices or entertainment spaces on the move [5], [7].

In recent years, mainly driven by the spectrum scarcity, there is a growing interest in the so-termed integrated sensing & communications (ISAC) [8]. The main idea is to let communications and radar sensing share the radio spectrum, with the design challenge of being able to separate the transmitted signal for each purpose or to reuse the same signal for both purposes, while striking for acceptable performance tradeoffs. In the vehicular setup, as the autonomous driving assistance system (ADAS) is becoming standard and the dawn of fully autonomous lvehicles is at the horizon, the automotive radar is getting to a point that it is almost indispensable. As a

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Xiang Cheng is with the State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronics, School of Electronics Engineering and Computer Science, Peking University, China, and also with Department of Broadband Communication, Peng Cheng Laboratory, 518055 (Email: xiangcheng@pku.edu.cn).

Dongliang Duan is with the Department of Electrical and Computer Engineering, University of Wyoming, WY, USA (Email: dduan@uwyo.edu).

Shijian Gao is with the Department of Electrical and Computer Engineering, University of Minnesota, MN, USA (Email: gao00379@umn.edu).

Liuqing Yang is with the Internet of Things Thrust & Intelligent Transportation Thrust, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China, and also with the Department of Electronic and Computer Engineering, The Hong Kong University of Science and Technology, Hong Kong SAR, China (Email: lqyang@ust.hk).

result, bearing the goal of improving spectrum utilization while reducing the number of antennas, system size, weight, and power consumption, the ISAC research in transportation environments has been focused on dual-function radar-communications (DFRC) designs, which accommodate the vehicular radar and communications functionalities as a single system [9]–[11]. In view of the extensive and explosive deployment of both sensing and communications in transportation, DFRC is clearly just one very special and focused use case where it solely replies on radio-frequency (RF) components for dual-functionalities and requires communications and sensing to take place in the same spectrum and hardware.

In practical VCNs, sensing is frequently carried out by non-RF components. That sensed information is typically in an abstract format, rendering unique challenges in its integration with communications. On top of that, the dual-functionalities might be realized across multiple platforms and through various resource domains. Therefore merely relying on DFRC is incapable of unleashing the utmost potential of ISAC in VCNs. In light of the current deficiencies, this paper has made the following efforts on ISAC dedicated to VCNs, in anticipation of garnering more research endeavors invested in this field:

- Exploration of the unique features of vehicular environment to argue the necessity and readiness of ISAC in vehicular scenarios.
- Establishment of a more general and diverse ISAC framework encompassing multi-layer, multi-format, and multi-objective integration.
- Introduction of the concept of synesthesia to ISAC to accommodate "machine senses" in the RF and non-RF formats, which could also be dynamic in space, time, and frequency.
- Demonstrations via preliminary studies in order to validate the benefits of ISAC in VCNs, and showcase a broad spectrum of research opportunities and challenges therein.

II. SENSING IN VEHICULAR ENVIRONMENTS

With the leaping development of intelligence in transportation, sensing units are densely deployed in transportation scenarios [12], [13]. Applications such as augmented sensing to support intelligent vehicles, safety of vulnerable road users, and data collection for city government, have motivated the enhancement of situational awareness and intelligence of the transportation infrastructure. The modernized infrastructure is rich in various types of sensors including cameras, radio frequency identification (RFID) devices, pressure detectors, inductive loop detectors, magnetic detectors, ultrasonic detectors, microwave detectors, and infrared detectors. In the mean time, newer vehicles are usually also equipped with one or more of the following sensing devices (see, e.g., [12], [14]–[23]):

- Global positioning system (GPS) to acquire the absolute position of the vehicle.
- Light detection and ranging (LiDAR) devices use narrow laser beams to generate high resolution three-dimensional (3D) digital images, where pixels are also associated with depth, to detect fixed and moving objects.
- Various types of cameras to detect and track lanes, other vehicles, pedestrians/cyclists, traffic signs and signals, etc.
- Sonars to detect and measure the distance and position information of obstacles surrounding a vehicle.
- Long-range radars to detect vehicles and measure velocity and facilitate adaptive cruise control.
- Medium-range radars to support cross-traffic alerts, lane change assistance, and blind spot detection.
- Short-range radars to detect objects around the vehicle and provide parking and pre-crash assistance.
- Articulating radars to detect moving vehicles at a long range over a wide field of view.

In fact, if one also includes the on-board diagnostic OBD-based vehicle sensors such as those for vehicle speed, revolutions per minute (RPM), battery voltage, coolant temperature, coordinates, direction, distance travelled, diagnostic trouble codes (DTC), fuel consumption etc., then the average number of sensors on a vehicle today is reportedly well around 200 [12].

All these sensors are meant to improve the situational awareness of both the vehicles and the infrastructure, and in turn enhance the reliability and efficiency of both the individual vehicles and the overall transportation system. However, the autonomous driving related accidents reported in recent years have raised deep concerns to designs that are dependent on individual vehicle sensing. Such a "solo" sensing mode is lacking in both redundancy and diversity, and thereby causing negligence and failure in the area of interest and in turn compromised reliability.

Leveraging the widely deployed VCNs that provide V2V and V2I connectivity, researchers start to combine sensing with communications from the transportation automation perspective (see, e.g., [13], [24], [25]). In particular, the concept of societal intelligence empowered by a hierarchical information fusion framework has been proposed in [14], [26], in which the VCN is the key enabler for fusing multi-modal multi-view sensing data. The vision is to facilitate inter-vehicle sensing information exchange, as well as infrastructure assisted transportation scene construction, situational interpretation, and decision making. Next, we will present two case studies in more detail to illustrate this envisioned aspect of sensing-communications integration.

Case Study 1: Multi-Vehicle Multi-Sensor Cooperative Tracking

One example is the multi-vehicle multi-sensor cooperative tracking framework proposed in [27]. In this framework, vehicles share data via the VCN from not only traditional sensors such as the inertia measurement units (IMU) and the GPS, but also the modern ones including camera, mmWave radar, and LiDAR, to conduct cooperative tracking. The cooperative tracking is composed of local and global filtering processes. At local filtering of individual vehicles, from the traditional sensors including IMU and GPS, vehicles conduct self tracking of their respective position and speed measurements; from other sensors, vehicles take observations on their neighbor

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vehicles and obtain their relative motion against themselves to infer the tracking of those neighbor vehicles by combining with their self-tracking information. Then, the local filtering results will be collected and combined at a global fusion center.

Although the framework appears to be quite intuitive, its implementation is facing various challenges. The first challenge is the heterogeneity in the sensor data. A unified model is needed to incorporate all kinds of sensor data. Furthermore, the dynamic model needs to capture both the self and relative motion of vehicles. As a result, the correlation among the models needs to be handled well at the global filter. Secondly, it should be noted that the communication range for each vehicle is limited and the number of vehicles that can be sensed by a vehicle is also limited. However, it is desirable that the vehicles could cooperate and benefit from each other via indirect V2V/V2X links even though they cannot directly communicate with each other. Hence, the global filtering process should be designed in a manner that can cope with missing measurements. Thirdly, it is possible that some vehicles are malicious and could purposely send fake information to other vehicles to mislead their tracking process. Therefore, it is crucial to include a malicious user detection module for the framework (see [28]). Other practical issues, such as the communication delays in the VCN, should also be considered and compensated for via the dynamic model of vehicle motion.

With this framework, the localization and tracking accuracy needed for autonomous driving can be achieved with a lower cost in the cooperative mode compared with the "solo"-mode solution. Furthermore, road side units (RSUs) could also participate in the cooperation. Due to the preciseness in the self location information of RSUs, the introduction of RSUs into this cooperative tracking framework could significantly improve the tracking performance. In addition, the communications among vehicles supported by VCN could greatly extend the service range of RSUs. As a result, the cost of RSU installation in the transportation infrastructure could be greatly reduced. An exemplary simulation result is shown in Fig. 1. The accuracy of GPS and sensors in the simulations are set to be the typical values for most commercial products. From this result, we can see that first of all, the accuracy improves when the number of cooperative vehicles increases. Secondly, the RSU can greatly improve the tracking performance. Even with only one vehicle, one RSU can reduce the root mean squared error (RMSE) by more than 60% (from 0.27 to 0.1) and even more with two RSUs. The tracking precision is well at the level of centi-meter that is required for autonomous driving.

As a matter of fact, while traditional tracking schemes are all quite sensitive to the environment since they heavily rely on GPS as the core tracking device, the proposed cooperative tracking strategy is much more robust against adverse environment factors thanks to the diversity of sensors involved in the cooperation. Another example is shown in Fig. 2, in which only two vehicles are involved in the cooperative tracking process. It can be seen that, when the vehicle enters a tunnel, the positioning error of GPS increases significantly. However, the cooperative tracking error stays at the same level thanks to the cooperation.

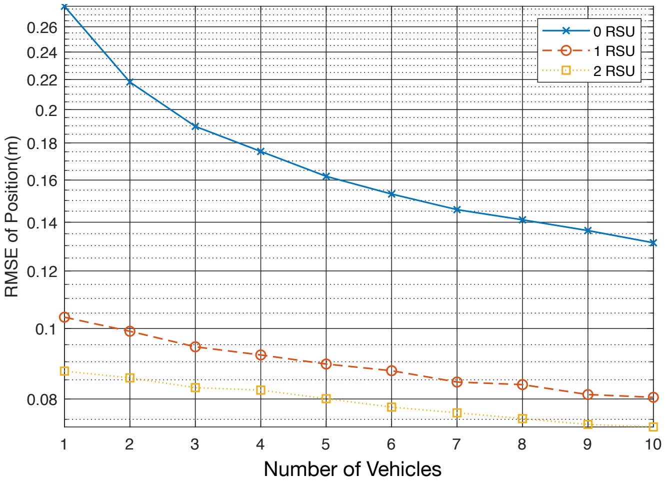

Fig. 1. Cooperative Tracking RMSE.

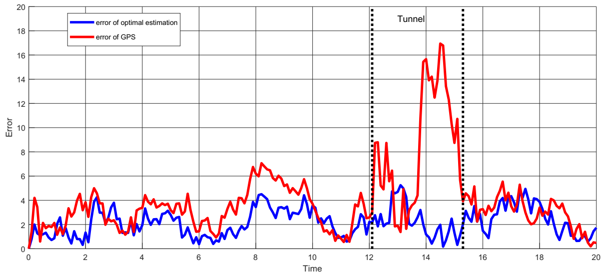

Fig. 2. An outstanding tracking mismatch when a vehicle goes through a tunnel.

Case Study 2: Multi-Vehicle Trajectory Prediction

Another good example for the VCN to support intelligent driving is the multi-vehicle trajectory prediction proposed in [29]. For single-vehicle trajectory prediction, the impact of the traffic context would be largely ignored and hence the beneficial environment information would not be taken into consideration when analyzing and interpreting the vehicle driving behavior. However, with the support of VCN, collaborations among multiple vehicles would be possible in trajectory prediction and driving behavior analyses. As a result, a multi-vehicle collaborative learning with spatial-temporal tensor fusion model can be established to facilitate vehicle trajectory prediction. To accommodate interactions among multiple vehicles, a novel auto-encoder social convolution module and a recurrent social mechanism are developed. With the support of VCN, the proposed convolution module and the social mechanism can fuse multi-agent information by manipulating the spatial and temporal structures, respectively, in the form of tensor fusion. Consequently, the relations of multiple time series are captured and modeled. At the same time, a generative adversarial network is also integrated into the model to generate possible socially-acceptable trajectories

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TABLE I
PREDICTION MSE WITH VS-GAN AND TS-GAN FOR DIFFERENT PREDICTION TIME.

Model	1s	2s	3s	4s	5s
VS-GAN (single-vehicle)	0.67	1.6	2.82	4.34	6.11
TS-GAN (multi-vehicle)	0.60	1.23	1.98	2.86	3.93

to deal with the inherent multi-modal characteristics of the vehicle driving motion.

The architecture is shown in Fig. 3. The proposed tensor fusion Generative Adversarial Network (TS-GAN) consists of a generator network and a discriminator network. Specifically, the former takes random noises as input and then produces plausible samples, and the latter plays the role of distinguishing the actual samples from the false ones of the generator's output. In general, the generator and discriminator play a two-player zero-sum game. A conditional adversarial network (cGAN) is employed in the model to deal with the multi-modal phenomenon of future trajectories. In particular, the generator G, which is formulated in a sequence-to-sequence form, captures the future trajectory distribution of the predicted vehicle under the condition of joint encoding of all vehicles' historical trajectories in the scene. Simultaneously, the discriminator D is employed to distinguish the actual trajectory from the false ones.

Part of the experimental results on NGSIM US-101 data are presented in Table I. Evidently, the single-vehicle trajectory prediction, termed as the vanilla sequence-to-sequence GAN (VS-GAN), fails to consider the interactions among multiple vehicles. On the contrary, the proposed TS-GAN captures the multi-vehicle spatio-temporal interaction information by introducing not only an auto-encoder social convolution mechanism but also a recurrent social module. The prediction error for TS-GAN is significantly smaller than VS-GAN and the advantage is even more obvious when the time window is wider. This is because the interactions among vehicles would be more important for vehicle trajectories over a longer time period. In this example, with the VCN, vehicles receive rich driving information voluntarily shared from adjacent vehicles over time, and reasonable planning of future trajectories could be inferred from the proposed model. The subtle and sophisticated interactions among multiple vehicles are captured efficiently by the proposed auto-encoder social convolution and recurrent social mechanism.

Clearly, the extensive sensing data and information exchanges as needed in these case studies set very stringent requirements for the VCN operation both in terms of the data rate and the latency. On the one hand, the overall VCN design has to be enhanced for high-mobility scenarios in order to better meet the data-hungry and latency-sensitive requirements of the idealized cooperative sensing framework. On the other hand, remedies and robustified modes of the cooperative sensing framework under imperfect or even partially compromised communications conditions also need to be investigated. Although no spectrum sharing considerations are involved, such intertwined interactions between sensing and communications should certainly be counted as a form of ISAC.

III. FUNCTIONAL ISAC (FISAC)

From the previous section, we observe that vehicular environments are distinctly rich with sensing devices. The automation and intelligence of the transportation system towards reliability and efficiency necessitate powerful communications to support the cooperative operation of the sensing devices therein, while the design of the latter is subject to the limitations and imperfections of the former. This naturally leads to ISAC in a broader sense, which relies on the inevitable co-existence and integration of sensing and communications. From the sensing-centered perspective in this section, this mode of ISAC is a *functional* integration that may or may not involve spectrum sharing between communications and radars for sensing. In the sequel, we will refer to this as the sensing-centric functional ISAC (SC-fISAC). It is also worth noting that this is both unique and inevitable in VCNs.

Let us now move to the communications side. To support the aforementioned applications in the vehicular environments that are either transportation-centered or traveler-centered, several potential solutions have been proposed for VCNs. These include the WLAN-based IEEE 802.11p, the long-term evolution-vehicle to everything (LTE-V2X) and the new radio (NR)-based V2X [6], [7], [30]. The 802.11p standard was initialized to realize dedicated short-range communications (DSRC) for V2V connections, and also developed the V2I mode to form a nationwide network through RSU access points. From industrial perspective, wide deployment of IEEE 802.11p requires huge investments on network infrastructure. In the mean time, new efforts have been devoted to the research and development of LTE-V2X with LTE 4G as a potential wireless access technology [6], [31]. In China, a 20MHz band (5905–5925 MHz) has been officially allocated for the validation of LTE-V2X, providing data rates of 30Mbps and ensuring a latency of no more than 10ms, which believed to be sufficient for basic road safety services. However, neither DSRC nor LTE-V2X can support use cases that require higher data rates and lower latency. Therefore, new radio (NR-)V2X has also been proposed with 5G NR, which employs higher frequency bands and even millimeter-wave bands to facilitate Gbps data rates and ensure <1ms latency [32]. NR-V2X shall complement LTE-V2X and support interoperability with LTE-V2X for advanced V2X services, such as vehicle platooning, autonomous driving, remote driving, and extended sensors etc. [30].

Alongside the challenges faced by ubiquitous high-data-rate low-latency communications, the vehicular environment is also bringing unique opportunities for VCN capability enhancement. These opportunities, once again, are situated at the abundance of sensing devices. As noted before, sensing devices are a must for both the vehicles and the transportation infrastructure. While the acquired and aggregated physical environment information is intended to establish situational awareness that facilitates transportation automation and intelligence, it can also be exploited to assist and enhance communications. At the foundation of wireless communications

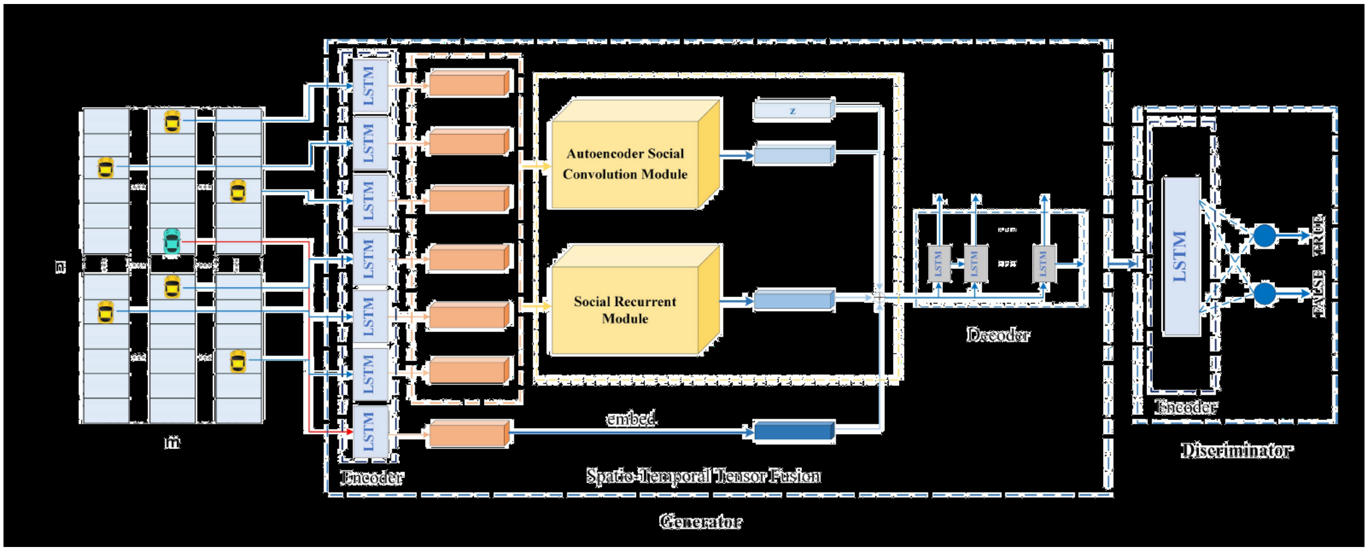

Fig. 3. Multi-vehicle collaborative learning model with spatio-temporal tensor fusion (TS-GAN) for vehicle trajectory prediction.

lies the channel that amounts to the electromagnetic propagation environment. Clearly, the channel is closely related to the physical environment, in which the communications take place.

However, this is not as straightforward as it appears to be, since a finite spatial-temporal span does not guarantee a bijection between the physical environments and the communication channel parameters. Hence, from the communications system design perspective, the research issue is to determine how to extract and exploit the sensing information; whereas from the sensing side, one needs to consider how the sensing direction, range, frequency, and processing could be modified to make the sensing information more useful for communications. Again, we see the emergence of intertwined considerations of both systems, which give rise to the communication-centric functional ISAC (CC-fISAC).

The channel information needed for the communications system is the electromagnetic wave propagation response from the transmitter to the receiver, at the corresponding frequency and bandwidth. However, depending on how the environment information is acquired, CC-fISAC can be categorized as follows:

- Trans-Domain: In this category, the environment information is obtained via GPS, LiDAR, cameras, or sonars, instead of using electromagnetic waves. Such information needs to be transferred into specific formats that are decipherable to the communication system.
- Trans-Spectrum: In this category, the environment information is obtained via radar that relies on electromagnetic waves. However, the signals being used may have different carrier frequency or bandwidth. As a result, the acquired environment features captured by the sensing signal will be different from the actual ones encountered by the signals used in the communications system.
- Trans-View: For both of the above cases, the sensing devices are likely to be placed at different locations on the vehicle body or different places at the transportation infrastructure. The views of the sensing and communication devices will also be different. Even if the sensing devices are co-located with the communications devices, view differences will still arise if their operations are not perfectly synchronized, due to the high mobility of the transportation environment. If not properly accounted for, this mismatch could significantly impact the usefulness of the sensing information for communications purposes. Instead of enhancing communications, such information may even harm the quality of the communications.

In recent years, this mode of the functional ISAC has attracted increasing research interests. Such efforts include the reduction of the beam training overhead with vehicle positioning [33]–[35], channel state detection [36] and channel estimation [25]. Millimeter-wave radar could provide the accurate position of a vehicle to significantly reduce the training overhead of beam alignment [33]–[35]. LiDAR data can be used for line-of-sight detection to reduce the overhead in mmWave beam-selection [36]. As the millimeter-wave communication channels and the radar received signals stem from the same environments, the spatial covariance of the received radar signals could be exploited for mmWave link configuration [25].

Despite all these efforts, some fundamental questions remain to be answered. For example, is it feasible to develop systematic mapping of the acquired environment information into channel characterizing parameters, based on which novel channel modeling mechanisms may be possible. Such endeavors are also expected to lead to individually unique solutions when covering the trans-domain, trans-spectrum and trans-view challenges. In addition, the acquired environment information will inevitably be subject to errors. From the existing research, it is not yet clear under what conditions will sensing help communications, and especially when the sensing and communication devices are under some resource (e.g., power) constraints.

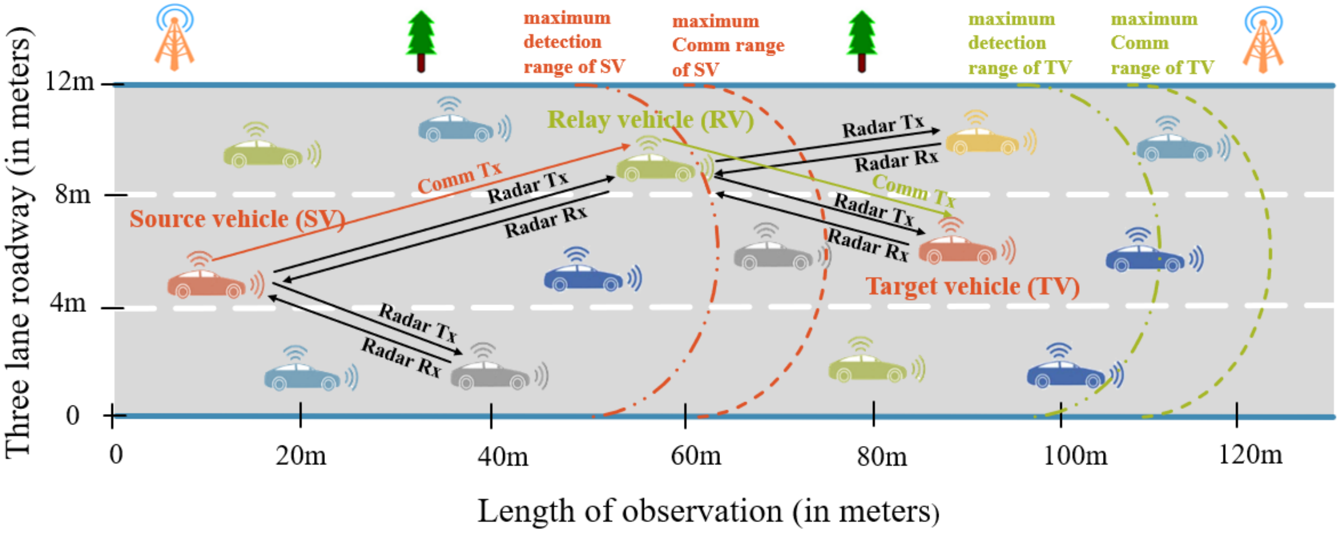

Fig. 4. Schematic of a vehicular network where each vehicle can serve sensing and communications simultaneously.

TABLE II
VEHICULAR NETWORKING SYSTEM PARAMETERS USED FOR THE SIMULATION.

Parameters	**Radar**	**Comm**
Transmit power limit to a single antenna	1.5W	0.5W
Number of transmit antennas	8	8
Number of receive antennas	8	8
Receiver SNR threshold	5dB	5dB
Radar's sensitivity factor	$\beta = 0.2$	\
Variance of GPS positioning error	\	$\sigma_c^2 = 0.1$
Carrier frequency	24G	28G
Bandwidth	B_r=500M	B_c=100M
Noise power	174dBm/Hz+10$\log_{10} B_r$ +4.5dB	174dBm/Hz+10$\log_{10} B_c$ +10dB
Transmit antenna gain	8dB	\
Receive antenna gain	8dB	\
Target RCS	$100m^2$	\
Detection angular range	$[-\pi/3, \pi/3]$	\

A Feasibility Study

To gain some insight, we consider a case where the sensing and communication devices are subject to some total *transmission power* constraint and investigate into a CC-fISAC application within a vehicular network. All the relevant simulation parameters are listed in Table II for the readers' reference. As shown in Fig. 4, each vehicle is equipped with communication and radar devices. The latter is used to detect the surrounding cars' range and position within its detectable limit. Those detected vehicles can form a multi-hop network to help relay the information from a source vehicle to its destination. The goal is to minimize the overall power consumption under a preset quality-of-service (QoS) objective, hereby referred to as the end-to-end outage probability in this context. In the absence of radar's involvement, all power goes to the communication side (corresponding to the "Comm-only" in simulations). In this case, the source vehicle will randomly establish a link and apply beamforming to forward information based on available position information from GPS. With radar coming into play, part of the power will be allocated to sensing tasks to facilitate information delivery. Despite having to activate both wireless communications and wireless sensing operations, ISAC is remarkably more power-efficient than communication only with proper power allocation, as depicted in Fig. 5. From one-hop to two-hop, the power reduction is nearly 50% within a reasonable outage probability region. The promising result in this feasibility study is of no surprise and can be explained as follows:

- Radar sensing helps to depict a fine-grid network topology to guide link establishment.
- The sensed angular information significantly augments the precision in beam steering.
- Fusing the positioning information from multiple sources further boosts the beamforming gain.

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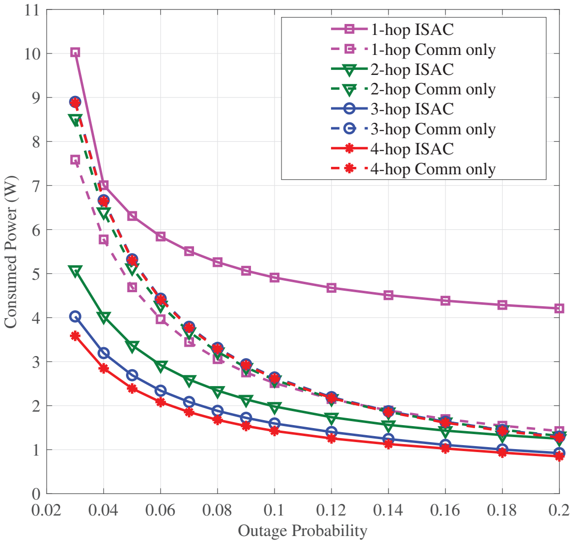

Fig. 5. Power consumption of ISAC and Communication only under different networking hops ($\beta = 0.2, \sigma_c^2 = 0.1$).

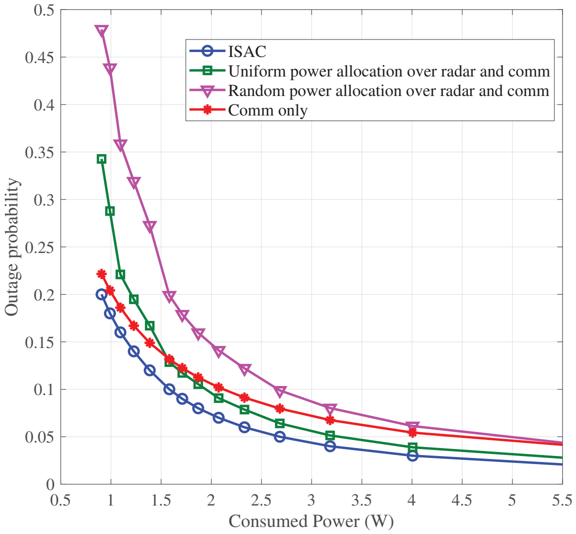

Fig. 6. Outage probability under various power allocation schemes in a 3-hop vehicular network ($\beta = 0.2, \sigma_c^2 = 0.1$).

Note that the remarkable advantage of ISAC over non-sensing aided communication is not always there with arbitrary resource allocation. On the contrary, such advantage is primarily attributed to a judiciously designed resource (power in the context of this case study) allocation scheme. To support this argument, in the following, we will restrict our attention to a 3-hop vehicular network configuration and compare the resultant outage probability under various power allocation schemes. As shown in Fig. 6, randomly allocating power between communication and sensing generally leads to a much higher outage probability than that via communication only. Although through uniform power allocation, ISAC can gradually surpass the situation in the absence of sensing as the transmitter increases power, it still largely underperforms the comm-only case in the region of low transmission power. As can be seen, only through an optimized power allocation scheme will ISAC fulfill its utmost potential and consistently outperform the condition where all power goes to communications.

So far, we have seen that the sensing devices in transportation can be categorized into two major types, namely radars that utilize radio-frequency (RF) electromagnetic waves that is also used by the wireless communications, and non-RF-based sensors such as cameras, LiDARs etc. It is worth noting that the integration of communications and sensing under CC-fISAC is not limited to RF-based sensors. Of course, as one starts to jointly consider the design and optimization of communications and the RF-based sensors, more interesting research issues will arise, as we will discuss in the next section.

IV. SIGNALING ISAC (sISAC)

Both wireless communications and radars are technologies that hinge upon the emission and reception of electromagnetic waves. They also both consist of three common components, namely the transmitter, the propagation channel, and the receiver. Traditionally, communications and radars have been investigated independently due to several fundamental distinctions:

- The communications system intends to recover the *unknown* transmitted signal from the received signal, in which the environment information (channel) is often assumed known; whereas the radar system intends to extract the environment information (target) from the received signal, in which the transmitted signal is often assumed *known*.
- For communications systems, the transmitted signal is often designed to be *insensitive* to the environment change such that the channel does not need to be frequently estimated. For radar systems, the transmitted signal is often designed to be *sensitive* to the environment change since the latter may be precisely what carries features of the target.

However, in recent years, as the operation frequency of wireless communications moves towards the mmWave spectrum, and as automotive radars become standard for vehicles, there is an increasing interest in the interactions of the two when they do share the same spectrum. We henceforth will term such interactions as signaling ISAC (sISAC). The DFRC designs that we mentioned in the introduction consist of a subset of sISAC, in that they require the communications and radars to share not only the same spectrum, but also the same hardware. In practice, the communication and radar systems involved in sISAC may or may not share one hardware platform. We will term the two cases as unified-hardware (UH)-sISAC and separate-hardware (SH)-sISAC, respectively, with the former corresponding to DFRC in the literature.

A. Spectrum Sharing via Waveform Design

So long as the same spectrum is shared by the communication and radar systems, both categories are subject to the same issue of how the spectrum and power are shared between the two, regardless of whether unified or separate hardware is deployed. The spectrum co-existence between communications and radar is usually resolved via judicious

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waveform design. This has also been one main focus of the current ISAC research. Next, we will briefly discuss the three major ways of the communications/radar waveform design. Interested readers can find further details by referring to the references embedded in the discussions.

Orthogonal Signaling

The radar and communication devices use waveforms that are orthogonal in some domains (usually frequency and/or time) to create interference-free operations of the two, such that the sensing and communications can be carried out independently. To facilitate such orthogonality, there are two prevalent solutions.

One is a deterministic approach, in which the radar and communication devices operate in a time-division or frequency-division manner. Then the design objective would be to optimize the frequency and/or time allocation between sensing and communications such that certain performance requirements could be achieved (see, e.g., [37], [38]).

The other is a cognitive approach, in which the communication (or sensing) device first gains cognition of the frequency or time occupancy of the sensing (or communication) device, and then utilizes the blank space in frequency or time (see, e.g., [39], [40]).

Non-orthogonal Signaling

Different from orthogonal signaling, here interference is permitted between radar and communications. This leads to much higher flexibility at the price of inevitable interference, which usually manifests either to performance degradation or high complexity. In addition to frequency and time, space is frequently used as another domain where the sharing occurs between sensing and communications. Conceptually, the same deterministic and cognitive approaches under orthogonal signaling could be adopted here, by simply replacing the orthogonality constraints with desired interference limitations (see, e.g., [41], [42]). As space is often considered, some research has been devoted to issues such as antenna isolation, antenna cancellation, etc. [43].

Opportunistic Signaling

Here, all resources are designated to either radar or communications, while the other can only attempt to extract information opportunistically from the waveforms that are designated to the other. In other words, a communication system may occupy the entire frequency band at all times. However, in addition to carrying communication information, the transmitted waveforms will undergo the environment and thus the received waveforms will carry useful information for sensing. The radar system can then attempt to extract and distill the desired environment information, such as the direction, distance, or even type, of the target. For sensing purposes, waveforms with distinct and sharp peaks in the corresponding autocorrelation functions tend to be favorable in accurate time, and in turn distance, estimation. Hence, one natural approach is to use waveforms with good auto-correlation properties for communications. These information-carrying waveforms could then be exploited for radar sensing purposes, and thus improving the spectrum utilization efficiency. In the literature, both orthogonal frequency division multiplexing (OFDM) and spread-spectrum signals have been explored (see, e.g., [9], [44]).

Of course, this setting could also be reversed, with the communications system opportunistically using the radar sensing waveforms to carry information symbols. To this end, it was proposed in [45], [46] to apply the concept of index modulation to a given library of sensing waveforms. Specifically, the radar system has the flexibility of using one or more of the waveforms in this library for sensing. However, the very *index* of the active waveforms is what carries the information to be transmitted to the communications receiver.

B. Further Considerations

Aside from the spectrum issue, many additional considerations must be taken into account in order to lay out a holistic ISAC framework dedicated to VCNs. In the sequel, we categorize these design considerations into four major groups: hardware implementation, design orientation, mobility incorporation, and networking expansion.

Separate vs. Unified Hardware So long as the communications and radar modules are sharing the same spectrum, the issues discussed in the previous subsection will always arise, regardless of whether the two are based on separate hardware platforms or a single unified one. However, with separate hardware platforms, it may be possible for the two modules to use directional antennas so their respective transmitted waveforms will not interfere with each other; whereas this is not an option for the unified hardware design. In addition, the unified platform will also give rise to total power constraints. While being subject to more stringent design considerations, the unified platform possesses the benefit of largely avoiding the trans-view problem, since here the communication and sensing modules are co-located and synchronous in operation.

Sensing-Centered vs. Communications-Centered

As discussed before, fISAC leads to additional benefits to both sensing and communications by exploiting the functionality of each other. However, these benefits do not come for free, and instead require additional processing and/or resource utilization. Depending on whether the system operation is sensing-centered or communications-centered, different strategic and methodological tradeoffs could be desirable. At the foundation of this lies the quantification of the performance gain in terms of the extra cost entailed by the cooperation. Some may argue that the sensing information can often be exploited to enhance communications without any additional processing of resource utilization, and therefore more beneficial. However, this is not necessarily true since the trans-domain, trans-view and trans-spectrum challenges are almost always involved. On the other hand, similar could be the case if the channel estimation results from the communications module are used to enhance environmental sensing, of course with similar trans-domain, trans-view and trans-spectrum considerations. This second aspect may be of more interest to the vehicular environment, where sensing is critically important for safety and reliability concerns.

For sISAC, the tradeoff between sensing and communications is more prominent and direct, as the two will compete directly for the spectrum, time, beam space, and power. To this end, there is also a significant lack of quantitative study in terms of the performance, gain, as well as resource and computation cost. At the current stage, the research emphasis seems to be mainly on whether one can do something to simply let sensing and communications share the same spectrum, regardless of the corresponding gain and cost. The answer, however, is rather straightforward if no bar is set for their respective performance and the interference is not carefully accounted for. In addition, radar sensing is on its own a broad subject, for which the waveform design could differ significantly depending on the purpose of sensing. In the existing research, however, radar sensing appears to be a rather general term referring to the practice of transmitting some known waveform, but with unclear purposes and unclear performance requirements. Hence, it is urgent to switch such ad hoc efforts to more systematic ones, in which the radar sensing objective is specified and performance quantifiable. It is then possible to delineate the tradeoffs in different sISAC strategies and sensible to carry out meaningful optimization in the corresponding designs. This is particularly the case for vehicular applications, where sensing is not something nice-to-have, but life-critical.

Mobility Considerations

Almost all existing sISAC designs are based on static environments, while mobility is inevitable in transportation systems. In addition to bringing trans-view issues, especially for sISAC with separate hardware platforms, mobility can significantly impact the radar and communications waveform designs and how their respect waveforms will interfere each other. Communications waveforms tend to be designed to be robust against environment changes. For example, if the autocorrelation function of a communications waveform is flat over time, then this waveform is robust against timing errors and will in turn lead to improved communication performance. Such a methodology can be transcended to design superb waveforms from other domains, such as frequency or space. The more *invariant* such properties are, the more robust the communication performance is, with respect to the environment changes (such as Doppler) and imperfections in environment acquisition. Radar sensing signals tend to be the opposite, in that a waveform whose autocorrelation function exhibits a sharp peak will lead to timing and location estimates with high accuracy.

In addition, the (likely wideband) Doppler effects in mobile environments are expected to give rise to complicated and dynamic interferences between sensing and communications. Not only that such interference needs to be addressed in the design stage, but also dynamic adaptations will be needed based on predictive methods. In this aspect, the vehicular environment may bring some advantages with the abundant environmental information therein. This will render low-complexity high-accuracy prediction readily available, as demonstrated in [47] for vehicular V2V.

From P2P to Networked Operation

Resource management has traditionally been a challenging and crucial part of the vehicular network research. With radar sensing and communications sharing the same spectrum under sISAC, this task will be markedly more challenging. Not only that interference from multiple network participants needs to be managed, but also across both sensing and communication modules. In addition, the performance measures should account for both communications and sensing purposes. While posing challenges, such networked operation also provides the opportunity for the radar units to operate in cooperative modes as bistatic or even multistatic radar systems, jointly covering shared areas of interest. This is of particular interest to vehicular applications, especially autonomous driving, as this could largely overcome the limited sensing range and view of monostatic radar units equipped at individual vehicles. In terms of resource and interference management, the tasks should be jointly considered with the scheduling of radar sensing, which concerns about which units to be activated and whether they would operate in transmitting or receiving modes.

V. THE ROADMAP TOWARDS VEHICULAR ISAC

The (sub-)categories of our envisioned ISAC in vehicular environments are summarized in Fig. 7. Regardless of whether the sensing is RF-based or not, the functional ISAC can always take place, in the form of either communications-centered (CC) or sensing-centered (SC). For RF-based sensing devices, the signaling ISAC has to be considered, with the sensing and communications hardware being unified or separate. The design objective of the sISAC could also be either CC or SC in terms of the functionality.

Due to the diverse nature of the sensing devices in VCN, ISAC could be trans-domain, trans-spectrum, or trans-view, as detailed in Section III. Essentially, such integration implies synesthesia of "machine senses" in various RF and non-RF formats. Synesthesia is a neurological condition in which one sense stimulates senses of distinct categories. In the context of sensing in vehicular environments, by synesthesia, we are referring to the intrinsic connections among the sensed information from distinct domains via different sensing media. For example, the channel information in the wireless electromagnetic wave propagation domain, images and videos from cameras in the visible or infrared light spectra, and the point cloud obtained from LiDARs, all root upon the physical environment while capturing different physical properties of such environment. Regarding the variety of the sensing modality as the counterpart of different human senses for machines, or vehicles in transportation, ISAC in the general sense would necessitate the migration or stimulation of senses across categories, RF-based or not. In the context of human synesthesia, scientists are attempting to explain the synesthesia mechanism from the perspective of interconnected neural networks. In the generalized ISAC, the natural synesthesia mechanism could be potentially bonded with the artificial neural network technology to reveal the trans-domain mapping relationship under space-time-frequency dynamics. From this perspective, ISAC would be more precisely interpreted as integrated synesthesia and communications.

For both CC-fISAC and sISAC, the existing research has been focused on the P2P mode in the sense that typically one

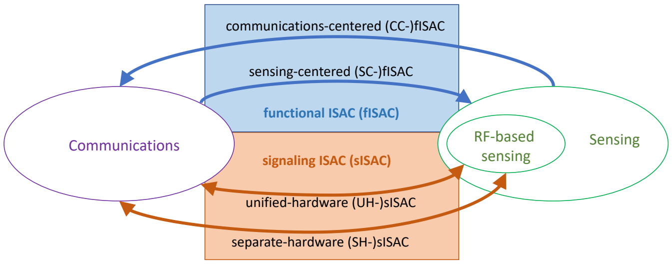

Fig. 7. ISAC (sub-)caterogies.

communications link is considered with one sensing device. Even in this scenario, the trans-domain, trans-view, and trans-spectrum considerations are rarely addressed. When multiple communications links and multiple sensing devices come in to play in a networked setup, even CC-fISAC involving only non-RF-based sensing will give rise to formidable challenges that will intertwine with the exchange and possibly fusion of sensing information, which will in turn rely on the SC-fISAC design and performance. Unfortunately, as of today, the latter are usually based on idealized assumptions on the communications capability, giving rise to a chicken-egg problem.

Hence, it makes sense to take a divide-and-conquer approach. On the one hand, the fISAC designs could be carried on and possibly moving from the P2P mode towards the networked mode, with the research emphasis on trans-domain and trans-view considerations. On the other hand, the sISAC designs may be better suited to focus more on the P2P mode, while addressing the trans-spectrum, mobility. and hardware issues. When the two directions are ready to merge, we will eventually be better equipped to tackle flexible networked communication and sensing operations that can benefit each other across multiple vehicles and the infrastructure.

VI. CONCLUSIONS

With ISAC being both natural and inevitable in VCNs, we take a wholistic view of ISAC possibilities and potentials specifically for the transportation scenarios and applications. This is to be contrasted with existing ISAC works that target generic environments but are mostly limited to DFRC, which leaves out majority of transportation sensors that are non-RF-based, such as cameras, LiDARs etc. Through several transportation-specific case studies, we demonstrated that it is feasible and beneficial to develop fISAC that can enhance sensing and/or communications, regardless of the sensor type. For the subset of RF-based transportation sensors, one could further push the integration to the RF signaling side of the design, with either unified-hardware (UH) or separate-hardware (SH) platforms. We then delineated the relationships of the ISAC (sub-)categories with a projected roadmap towards fully-networked fISAC and sISAC.

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Xiang Cheng (S'05-M'10-SM'13-F'22) received the Ph.D. degree jointly from Heriot-Watt University and the University of Edinburgh, Edinburgh, U.K., in 2009. He is currently a Boya Distinguished Professor of Peking University. His general research interests are in areas of channel modeling, wireless communications, and data analytics, subject on which he has published more than 280 journal and conference papers, 9 books, and holds 17 patents. Prof. Cheng is a Distinguished Young Investigator of China Frontiers of Engineering, a recipient of the IEEE Asia Pacific Outstanding Young Researcher Award in 2015, a Distinguished Lecturer of IEEE Vehicular Technology Society, and a Highly Cited Chinese Researcher in 2020. He was a co-recipient of the 2016 IEEE JSAC Best Paper Award: Leonard G. Abraham Prize, and IET Communications Best Paper Award: Premium Award. He has also received the Best Paper Awards at IEEE ITST'12, ICCC'13, ITSC'14, ICC'16, ICNC'17, GLOBECOM'18, ICCS'18, and ICC'19. He has served as the symposium lead chair, co-chair, and member of the Technical Program Committee for several international conferences. He is currently a Subject Editor of IET Communications and an Associate Editor of the IEEE Transactions on Wireless Communications, IEEE Transactions on Intelligent Transportation Systems, IEEE Wireless Communications Letters, and the Journal of Communications and Information Networks. In 2021, he was selected into two world scientist lists, including World's Top 2% Scientists released by Stanford University and Top Computer Science Scientists released by Guide2Research.

Dongliang Duan (S'07-M'12-SM'21) received the B.S. degree from Huazhong University of Science and Technology, Wuhan, China in 2006, the M.S. degree from the University of Florida, Gainesville, FL in 2009, and the Ph.D. degree from the Colorado State University, Fort Collins, CO in 2012, all in electrical engineering. Since graduation, he joined the department of Electrical and Computer Engineering at the University of Wyoming and is now an associate professor. He is currently a subject editor for IET Communications, and a guest editor for the special issue on the IoT for Power Grid on IEEE Internet of Things Journal. His current research interests are signal processing and data analytics for power and intelligent transportation systems.

Shijian Gao received Ph.D. degree in Electrical Engineering from the University of Minnesota, in 2022. His research interests are in the areas of wireless communications and related fields.

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Liuqing Yang (S'02-M'04-SM'06-F'15) received her Ph.D. degree in Electrical and Computer Engineering from the University of Minnesota, Minneapolis, in 2004. She has been a faculty member with the Department of Electrical and Computer Engineering, at University of Florida, Colorado State University, and University of Minnesota, and is presently a Chair Professor with Hong Kong University of Science and Technology (GZ). Her general interests are in communications, sensing, and connected intelligence – subjects on which she has published more than 380 journal and conference papers, 4 book chapters and 6 books. Dr. Yang became an IEEE Fellow in 2015. She was the recipient of the ONR Young Investigator Program (YIP) award in 2007, and the NSF Faculty Early Career Development (CAREER) award in 2009, the Best Paper Award at IEEE ICUWB'06, ICCC'13, ITSC'14, GLOBECOM'14, ICC'16, WCSP'16, GLOBECOM'18, ICCS'18 and ICC'19. She is the Editor in Chief for IET Communications, Executive Editorial Committee (EEC) member for IEEE Transactions on Wireless Communications, and Senior Editor for IEEE Transactions on Signal Processing. She has also served as editor for IEEE Transactions on Communications, IEEE Transactions on Intelligent Transportation Systems, IEEE Intelligent Systems, and PHYCOM: Physical Communication, and as program chair, track/symposium or TPC chair for many conferences.