Integrated Sensing and Communications: Background and Applications

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Abstract In this chapter, we present the basic principles and recent advances in integrated sensing and communications (ISAC), which is identified to be one of the most promising technologies of the next-generation wireless networks. The subject of ISAC involves many aspects of wireless communications, signal processing, and mobile computing technologies, ranging from fundamental limits, advanced beamforming and precoding methods, new networking architectures and protocols, novel platforms, and more powerful computing and recognition algorithms, which will be elaborated one by one in the rest of this book. Prior to that, of particular importance in the development of ISAC is to identify "*what is ISAC?*", "*what are the underlying driving forces in ISAC?*", and "*where ISAC may be applied?*". In this chapter, we aim to answer the above questions by overviewing the definition, driving forces, applications, as well as the standardization progress of ISAC.

1 Introduction

Driving a gradual integration of the physical and digital worlds is perceived to become a reality in the 6G era, from vehicles to drones, from surveillance facilities in cities to agricultural tools in the countryside. To this end, the wireless industry suggests that the future network should be able to "see" the physical world, which is identified

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as one of the unique capabilities of next-generation networks, rather than traditional communication-only functionalities. This idea has been driving researchers to rethink the designs of current communication infrastructures and terminals, which has triggered the recent research area of “integrated sensing and communications (ISAC)”. In this paradigm, sensing and communication (S&C) functionalities are possibly jointly designed, optimized, and dispatched to share resources or assist in each other, via the same hardware platform, common spectrum, joint signal processing strategy, and even a unified control framework.

The rationale of the “integration” operation was raised from the basic propagation characteristics of electromagnetic waves: *a radio emission could simultaneously convey communication data from the transmitter to the receiver, and extract environmental information from scattered echoes*. However, the distinct viewpoints on the to-be-processed information between S&C raise a number of fundamental challenges in ISAC, particularly for signal processing and waveform design.

Consider a monostatic ISAC system as an example, in which S&C shares the same resource such as hardware, location, spectrum, and waveform by designing a proper dual-functional transmitter. On the one hand, the sensing receiver collects and extracts environmental information from noisy observations of the received waveform, which is usually designed as a reference-type signal like a typical radar system. On the other hand, the communication receiver focuses on transferring information by treating the wireless signal as the carrier and then, recovering information from its noisy reception. The wireless signal is then expected to be *as random as possible* to achieve the communication channel capacity [1]. Nevertheless, to realize better sensing performance, the wireless signal should be *deterministic* to a certain degree. It is clear that both S&C functionalities can be simultaneously implemented in the above ISAC system, yet there is a fundamental tradeoff determining the S&C performance any signaling strategy may achieve. The above random-deterministic tradeoff is just one among many conflicts of interest when integrating S&C into a single system. These challenges and tradeoffs are precisely what makes the research of ISAC attractive.

ISAC [2] refers to a design paradigm in which (radio) S&C systems are integrated to efficiently utilize scarse resources and even to pursue mutual benefits, as well as to the corresponding enabling technologies for realizing this paradigm. We define “integration” as any combined use of two or more S&C systems in whole or in part. For example, a wireless sensor network relies on hardware integration between sensing modules and communication modules in a distributed manner, a secondary surveillance radar system involves signaling integration between a surveillance radar and a communication transponder, and a cognitive radar operating in the communication band requires spectrum integration. Although ISAC has the potential to improve systems’ hardware, spectral, temporal, signaling, and energy efficiencies, the specific aspects in which integration is applied determine which resources can be re-used between S&C.

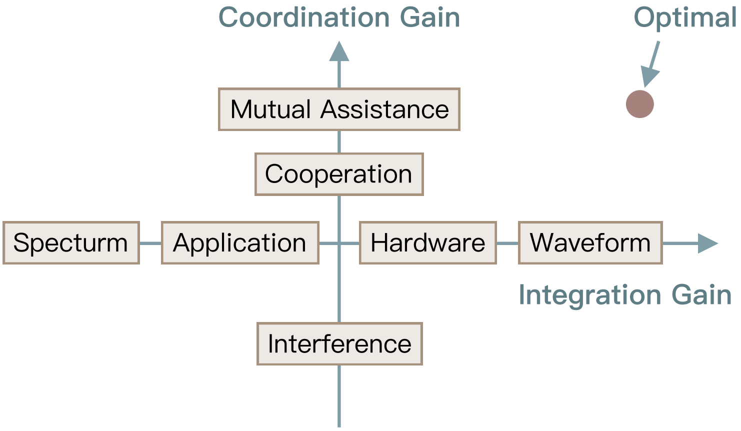

Fig. 1 The integration and coordination gains in ISAC

Several terms have been used to describe the related research output, such as joint radar communications/joint communications radar (JRC/JCR) [3], joint communication and radar/radio sensing (JCAS) [4], dual-functional radar communications (DFRC) [5, 6], radio-frequency (RF) convergence, and radar-communication (RadCom) [7]. From our perspective, the aim of DFRC is to design novel waveforms to enable both radar and communication functionalities. RF convergence refers to broader radio integration, including communication, positioning, navigation, and timing systems. RadCom mainly focuses on endowing radar equipment with communication capabilities. JCAS is more concerned with the incorporation of sensing functionalities into the communication infrastructures' side, particularly in cellular networks. In this chapter, we use ISAC as a unified term to refer to all the joint designs of radio S&C (Fig. 1).

1.1 Integration and Coordination Gains

In general, the ultimate goal of ISAC is to unify S&C and to pursue direct tradeoffs between them as well as mutual assistance. Hence, one may group the potential gains into two categories: *the integration gain* acquired by improving resource efficiency, and *the coordination gain* to perform co-design for balancing performance or achieving mutual benefits. Indeed, defining and quantifying these two gains could improve our understanding of a given ISAC strategy.

Boosting the performance of S&C rely upon exploiting the wireless resources, including spectral, temporal, spatial, and power resources. Larger bandwidth improves the transmission data rate for communications and yields finer range resolution for radar sensing. In the meantime, the scale-up of the antenna array brings more spatial DoFs to both S&C, and also improves the angular resolution. Hence, by

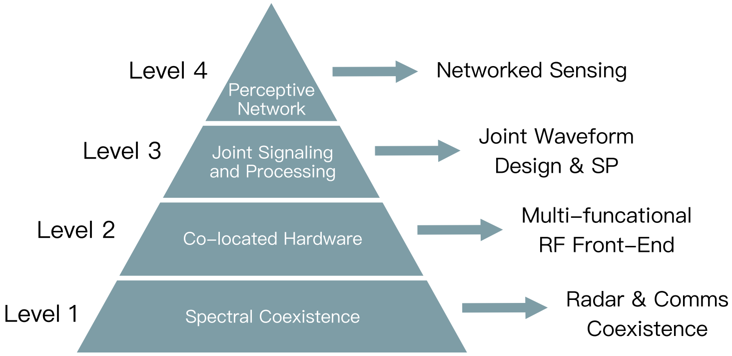

Fig. 2 Level of integration

characterizing the *integration gain*, one may evaluate the superiority of ISAC over dedicated S&C systems by considering how tightly the components or resources for S&C are integrated. Meanwhile, depending on the degree of coupling of each component between S&C, various benefits may be obtained, including improved size, hardware, spectral, and energy efficiency as well as lower latency and signaling costs. Such looser configurations have also drawn numerous attention from both industry and academia.

Depending on the level of integration, various types of information can be conveniently shared in a cross-function or cross-user manner, e.g., in shared memory or in the same processor, to provide a basis for co-designing S&C processing strategies for balancing performance or achieving mutual assistance. Therefore, characterizing the *coordination gain* may provide a way to evaluate the performance improvement from the joint S&C strategies.

The level of integration of ISAC systems impacts integration and coordination gains in direct and indirect manners.In Fig. 2 we attempt to divide the integration level into four categories.

- **Level 1**: Sharing the spectral resources between two individual S&C systems without unduly interfering with each other [8, 9].
- **Level 2**: Deploying S&C functionalities on the same hardware platform in addition to sharing the spectrum only.
- **Level 3**: Realizing S&C functionalities via a common waveform and a unified signal processing framework.
- **Level 4**: Constructing a *perceptive network* by integrating radar sensing functionality into the current wireless network, which is capable of supporting a large number of emerging IoT, 5G-Advanced (5G-A), and 6G applications that require high-quality communication, sensing, and localization services [10, 11].

1.2 Design Philosophy

Though combining and jointly designing the S&C functions may take place over various integration levels, their main focuses may always be on the following design philosophies, namely sensing-centric design, communication-centric design, and unified joint design [12]:

- **Sensing-Centric Design**: The priority of sensing functionality is higher than the communication functionality, e.g., endowing wireless communication capability into a radar sensor by embedding communication symbols in the emitted waveform. In such cases, ISAC design strategies may focus on maximizing sensing performance or implementing basic communication capabilities on existing sensing waveforms or infrastructures [13].
- **Communication-Centric Design**: Exploiting the minimum modification for endowing wireless sensing into existing communication system/infrastructures. Since the standardized communication waveform is not always tailored for radar, sophisticated processing techniques are necessary to improve its sensing performance. In such cases, the priority of communication functionality is higher than sensing functionality.
- **Joint Design**: The priorities of S&C functions are required to be smoothly adjusted [14]. As a consequence, the design strategies are tailored for pursuing a favorable performance tradeoff, e.g. a more flexible resource allocation framework, between S&C functions [15, 16].

To fully realize the promise of ISAC technology, advanced signal processing techniques are indispensable. Therefore, in this book, we will review recent research progress on the fundamental limits and signal processing problems that arises from the ISAC framework. We will also discuss recent advances in waveform designs, networked sensing, and several important applications.

2 The Interplay Between S&C

2.1 ISAC: From Resource Competition to Co-design

The ubiquitous deployment of S&C systems leads to severe competition over various resource domains. A variety of S&C systems have to cohabitate within multiple frequency bands, which, inevitably, incurs significant mutual interference between the two functionalities. To ensure harmonic coexistence between S&C, orthogonal resource allocation based on cognitive radio mechanism became a viable approach [17]. That is, radar or communication system periodically senses their common operational spectrum to detect the existence of interfering signals, and transmits over unoccupied TF resource blocks. Nevertheless, orthogonal allocation results in low resource efficiency for both S&C. Aiming for fully excavating the potential of the limited wireless resources, and to enable the co-design of the S&C functionalities, ISAC was proposed as a key technology for both the next-generation wireless networks and radar systems.

From a historical viewpoint, during the past three decades, the development of ISAC has been supported by a number of governmental projects worldwide, among which the most influential ones are the "Advanced Multifunction Radio Frequency Concept (AMRFC)" program initiated by the Office of Naval Research (ONR) of the US in the 1990s [18], and the "Shared Spectrum Access for Radar and Communications (SSPARC)" project funded by the Defense Advanced Research Projects Agency (DARPA) of the US in the 2010s [19]. While both projects were motivated by the need of sharing resources between S&C, the AMRFC mainly focused on colocating multi-functional modules (radar, communications, and electronic warfare) on the same RF front-ends, and the SSPARC aimed for releasing part of the sub-6 GHz spectrum from the radar bands for shared use between S&C. Most of the technical outcome of these projects formulating the Level-1 to Level-3 ISAC approaches. In the 2020s, networked sensing (Level-4 ISAC) was recognized by major enterprises in the communications industry (Huawei, Ericsson, ZTE, Intel, and Nokia) as one of the core air interface technologies for WiFi-7, 5G-Advanced and 6G. In 2020, IEEE 802.11 formed the 802.11bf task group to realize WLAN sensing in WiFi-7, which is expected to be finalized in 2024 [20]. In 2022, 3GPP established the first study item on ISAC towards its Rel-19 for 5G-Advanced standards [10].

2.2 *The Driving Forces*

Although the emergence of the ISAC concept can be traced back to the early work [21], where coded pulses were employed to convey information in a radar for missile range instrumentation, there was a paucity of further developments in the following decades. We tend to attribute this observed stagnation to the use of dedicatedly designed RF circuits at the time, meaning that previous RF devices tended to be specific to the domain of either radio (radar) sensing or communications.

Hardware. With recent advances in solid-state circuits and microwave technology, the hardware feasibility of leveraging radio sensing in tiny IoT products tends to no longer be a barrier. For example, a multiple-input multiple-output (MIMO) radar system-on-a-chip (SoC) constructed from 192 virtual receivers has been reported to achieve a ±1° angular resolution and a 0.099 km/h Doppler resolution, within silicon areas of only 14 mm^2 for 12 mmWave transceivers and 71 mm^2 for the overall SoC [22].

Signal Processing. The combined use of mmWave frequencies and massive MIMO technology results in striking similarities between communication and radio sensing systems in terms of the hardware architecture[1], channel characteristics, and

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[1] To reduce the cost of RF chains in MIMO configurations, existing commercial mmWave RF front-ends are implemented with phase shifters together with variable gain amplifiers. This has

information processing pipeline. Moreover, with the development of mmWave technology and beam-domain signal processing strategies, it has become possible to straightforwardly extend several radar missions, e.g., angle of arrival (AoA) estimation, angle of departure (AoD) estimation, and moving target tracking, to address emerging communication challenges, e.g., beam management. It is reasonable to envision that the reuse of signaling strategies between the S&C functionalities can lead to mutual benefits.

Mobile Computing. Current Wi-Fi sensing applications require the extraction of multipath channel information from the raw channel state information (CSI) measurements, since this multipath information is the principal component that captures how the surrounding environment changes. In general, the raw CSI measurements have been compensated in Wi-Fi baseband processors, e.g., by means of the sampling time offset (STO), to synchronize the oscillator clocks of the transmitter and receiver. However, such offsets are hidden in a communication black box and are thereby unknown to the sensing modules. Consequently, time and frequency offsets create ambiguity when a sensing module calculates range/velocity estimates and increases the false alarm probability when recognizing human activities. To address this issue, an additional processing procedure of fitting and then removing the clock/frequency offsets is employed. However, these offsets can instead be straightforwardly removed by breaking the cross-system isolation and exchanging the necessary information between the S&C functionalities in the baseband processor.

ISAC applications have already gone far beyond academic studies, particularly in regard to Wi-Fi sensing applications.

Commercial Progress. The CSI measured in Wi-Fi networks has been widely analyzed to support various short-range sensing tasks in a device-free[2] manner. For example, Wi-Fi devices can detect the presence of humans in a conference room (with an accuracy of $97-100\%$); recognize human activities (with an accuracy of $73-100\%$, depending on the set of activities considered) such as walking, running, and exercising; and even imaging surrounding objects (with an imaging error of $< 4.5\ cm/\pm 1^\circ$). Furthermore, according to Intel, WLAN sensing is recognized as a key direction of development toward Wi-Fi 7 [23].

Spectrum Regulatory Aspect. Another strong force driving ISAC forward is exerted by the vast commercial requirements on radio sensing. Unfortunately, novel civilian radio sensors bear a disproportionate regulatory burden. For instance, the Federal Communications Commission (FCC) granted the spectrum allocation request of the Soli project only after a year-long discussion, and at present, Soli is still not allowed to operate in many major countries, such as Japan, India, and China. Moreover, S&C functionalities in large IoT devices tend to operate in shared and often congested or even contested spectra, e.g., 5G-based IoT devices versus military radar in the 3.5 GHz band and mmWave automotive radar versus mmWave 5G

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led to the emergence of phased-MIMO radar and hybrid beamforming techniques in the radar and communication literature, respectively.

[2] Here, 'device-free' means without relying on a connection with user's devices or requiring them to carry any device.

communication in the 60 GHz band. To help overcome these conflicts, ISAC can conveniently enable communication devices to sense the environment while sharing the same spectrum [24].

3 Use Cases

When the concept '*Internet of Things (IoT)*' first emerged, its additional sensing capabilities were identified as a critical paradigm shift from computer networks. From then on, S&C, these two fundamental functionalities have been recognized to be indispensable in the design and implementation of ubiquitous IoT devices, ranging from autonomous vehicles, wearable electronics, and Wi-Fi to drones and satellites. In the current hardened-into-fixed IoT data processing pipelines, S&C are individually accomplished by black-box-like modules, which do not necessarily share any external knowledge of their internal workings. This modularized IoT architecture encourages S&C driving on two parallel layers (i.e., the sensing layer and the communication layer) with limited hardware intersection, little mutual assistance, and, therefore, rare integration.

Meanwhile, an unprecedented proliferation of new IoT services, e.g. extended reality (XR), digital twins, autonomous systems, and flying vehicles expresses a huge desire for novel sensing solutions. Wireless sensing capability enabled by analyzing received RF signal patterns and characteristics has the potential to become an essential component of the sensing solution. On the other hand, the combined use of high frequencies and large antenna array results in striking similarities between communication and radio sensing systems, in terms of the hardware architecture, channel characteristics, and information processing pipeline. Consequently, S&C systems can be jointly designed, optimized, and dispatched to assist in each other or transmitted via the same hardware platform, common spectrum, joint signal processing strategy, and unified control framework (Fig. 3).

With the various influences exerted from the technical and commercial perspectives, the sensing layer and communication layer are moving from separation to integration, which results in a paradigm shift in the IoT architecture. As a consequence, a new *signaling layer* enabled by ISAC is emerging, with the advantages of low hardware cost, power consumption, and signaling latency as well as a small product size and improved spectral efficiency. Moreover, ISAC technology can provably endow current communication infrastructures with sensing functionalities while requiring minimal standard modifications, allowing existing communication networks to provide civilian sensing and surveillance services. As a result, many new use cases can be made available in the contexts of autonomous vehicles, smart cities, smart homes, and cellular networks for 5G-Advanced and 6G.

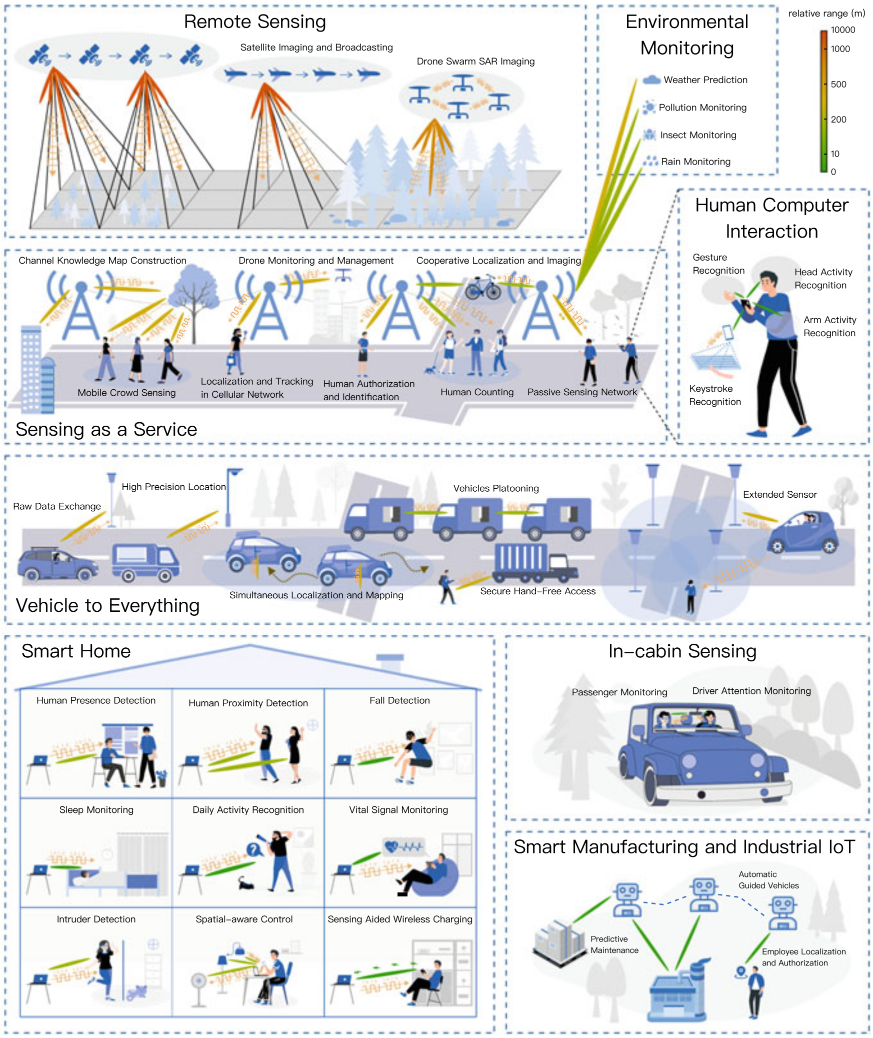

Fig. 3 Representative use cases for the ISAC technology

3.1 *Sensing as a Service*

The recent deployment of dense cellular networks as part of 5G provides unique opportunities for sensing [25]. Current communication infrastructures can be reused for sensing with only small modifications in hardware, signaling strategy, and communication standards. In such a setting, integrating sensing into current IoT devices and cellular networks will be performed rapidly and cheaply, by reusing reference or synchronization signals as sensing waveforms. As a step forward, S&C functionalities can be fully integrated into all radio emissions [5], where both pilot and payload signals can be exploited for sensing.

With the use of ISAC technologies, the role of existing cellular networks will turn to a ubiquitously deployed large-scale sensor network, namely a perceptive network [24], which triggers a variety of applications for the current communication industry [11]. We provide some examples below:

Enhanced Localization and Tracking: Localization has been a key feature in the standardization, implementation, and exploitation of existing cellular networks, from 1G to the future 6G [26]. Due to the low range and angle resolutions that are respectively caused by bandwidth and antenna limitations, most of current cellular networks (e.g., 4G and 5G) only provide measurement data with meter-level accuracy to assist in global navigation satellite systems (GNSS). According to the key parameter indicators (KPIs) of 5G New Radio (NR) Release 17 [27], the highest required localization accuracies are 0.2 m/1 m horizontally/vertically in industrial IoT applications, which are unable to meet the requirement of future applications. Particularly, location resolution requirements to pinpoint the position of users are higher in indoor environments than that in outdoor, e.g., indoor human activity recognition [28] ($\sim$1 cm), autonomous robot and manufacturing [29] ($\sim$5 mm). On the other hand, current wireless localization technologies are mostly implemented in a device-based manner, where a wireless equipment (e.g., a smartphone) is attached to the locating object by computing its location through signal interactions and geometrical relationships with other deployed wireless equipments (e.g. a Wi-Fi access point or a base station (BS)). However, the device-based approach limits the choice of locating objects and does not generalize to diverse scenarios.

Benefiting from additional Doppler processing and by exploiting useful information from multi-path components, ISAC enabled cellular networks are able to improve localization accuracy compared to current localization technologies. On top of that, a cellular network with sensing functionality is not limited to just pinpointing the location of a certain object with a smartphone, but also suits broader scenarios that extract spectroscopic and geometric information from the surrounding environment.

Area Imaging: RF imaging technology generates high-resolution, day-and-night, and weather-independent images for a multitude of applications ranging from environmental monitoring, climate change research, and security-related applications [30]. Importantly, compared to camera based imaging, it is less intrusive and allows focusing on the intended information without revealing sensitive information in the surrounding environment. Due to the limited bandwidth used in past-generation cellular systems, the range resolution is roughly meter-level which does not support high-resolution services. Thanks to the deployment of mmWave and mMIMO technologies, future BSs could possibly pursue high range and angle resolutions by cooperatively sensing and imaging a specified area. Consequently, the future cellular network and user equipment (UE) could “see” the surrounding environment, which would further support high-layer applications such as digital twins, virtual reality, and more [31]. Furthermore, with significantly improved imaging resolutions due to higher frequencies, future cellular network would also support spectrogram-related and spatial/location-aware services. Finally, cellular BSs and user equipments (UEs) with imaging abilities could provide additional commercial values to traditional telecommunication carriers, as a new billing service for civilians.

Drone Monitoring and Management: In recent years, the enthusiasm for using UAVs in civilian and commercial applications has skyrocketed [32]. However, the civilization of drones is posing new regulatory and management headaches. As an aerial platform that could fly over various terrains, drones have the potential to be employed in non-fly zones and in illegal activities, e.g., unauthorized reconnaissance, surveillance of objects and individuals. With the merits of low altitude, small size and varying shape, such non-cooperative UAVs always operate below the line-of-sight (LoS) of current airborne radars, and are difficult to be detected by other surveillance technologies such as video or thermal sensors. The existing cellular network with sensing functionality would not only provide an affordable solution to monitor non-cooperative UAVs in low-altitude airspace, but also act as a RAN to manage and control cooperative UAVs with cellular connections, and assist their navigation in swarms. As a result, the ISAC cellular network could develop into the drone infrastructure that provides drone monitoring and management services to secure future low-altitude airspace applications.

3.2 Smart Home and In-Cabin Sensing

Currently, in most indoor applications, such as in-home and in-cabin scenarios, electronic devices are expected to be interactive and intelligent to fit out a comfortable, convenient and safe living condition. Aiming for this purpose, smart IoT devices should be able to understand the residents both physically and physiologically. With the merits of privacy-preserving, unobtrusive and ubiquitous, standardized wireless signals have been widely employed to figure out what is going on in the surrounding indoor scenario [33, 34].

Recently, ISAC enabled IoT has shown great potential in daily activity recognition, daily health care, home security, driver attention monitoring, etc., in which several of them have been implemented into household products [35]. To mention but a few:

Human Activity Recognition: Activity recognition is essential to both humanity and computer science, since it records people's behaviors with data that allows computing systems to monitor, analyze, and assist their daily life. Over-the-air signals are affected by both static or moving objects, as well as dynamic human activities [36]. Therefore, amplitude/phase variations of wireless signal could be employed to detect or to recognize human presence/proximity/fall/sleep/breathing/daily activities [37], by extracting the range, Doppler, or micro-Doppler features while moving indoor. Moreover, if the sensing resolution is high enough, fatigue driving could be recognized by identifying the driver's blink rate. By integrating sensing functionality into current commercial wireless devices, e.g., Wi-Fi devices, they are able to detect and recognize resident's activities to support a smart and human-centric living environment [38].

Spatial-aware Computing: Further exploitation of geometric relationship among massive IoT devices also potentially enhances residents' well-being as well as living comfort, which serves as the ultimate goal of spatial-aware computing techniques. The ubiquity of wireless signals with high spatial resolution represents an opportunity for gathering all spatial relationships between the indoor devices [39], which may be densely and temporarily deployed in a cramped space. For instance, a smartphone with centimeter-level sensing precision is able to pinpoint the location of any electronic devices with angle resolution reaching $\pm 3^\circ$. Therefore, once directing the smartphone towards a given device, they can connect and control each other automatically [40].

In addition, knowing where the devices are in space and time promises a deeper understanding of neighbors, networks, and the environment. By considering spatial relationships between moving devices and access points, initial access or cross-network handover operations may be expedited, rather than (signal-to-interference-plus-noise ratio) SINR-only considerations. Furthermore, spatial-aware computing promises to coordinate distributedly deployed household products to jointly analyze the movement, understand patterns of mobility, and eventually to support augmented virtual reality applications.

3.3 Vehicle to Everything (V2X)

Autonomous vehicles promise the possibility of fundamentally changing the transportation industry, with an increase in both highway capacity and traffic flow, less fuel consumption and pollution, and hopefully fewer accidents [41]. To achieve this, vehicles are equipped with communication transceivers as well as various sensors, aiming to simultaneously extract the environmental information and exchange information with road side units (RSUs), other vehicles, or even pedestrians [42]. The combination of S&C is provably a viable path, with reduced number of antennas, system size, weight and power consumption, as well as alleviate concerns for electromagnetic compatibility and spectrum congestion [41]. For example, ISAC-aided V2X communications could provide environmental information to support fast vehicle platooning, secure and seamless access, and simultaneous localization and mapping (SLAM). RSU networks can provide sensing services to extend the sensing range of a passing vehicle beyond its own LoS and field-of-view (FoV). We briefly discuss two representative use cases.

Vehicle Platooning: Autonomous vehicles in tightly spaced, computer-controlled platoons will lead to increased highway capacity and increased passenger comfort. Current vehicle platooning schemes are mostly based on cooperative adaptive cruise control (CACC) through a conventional leader-follower framework [43, 44], which requires multi-hop Vehicle-to-Vehicle (V2V) communications to transfer the state information of each vehicle over all the platooned vehicles. However, the high latency of multi-hop communications leads to the out-of-sync problem on situational information of the platooned vehicles, particularly when the platoon is very long and highly dynamic. In this case, platooned vehicles that are unaware of situational changes increase the control risk. RSU, as vehicle infrastructure, offers a more reliable approach to form and maintain the vehicle platoon, as it serves multiple vehicles simultaneously [45, 46]. More importantly, the wireless sensing functionality equipped on the RSU provides an alternative way to acquire vehicles' states in a fast and cheap manner, which in turn facilitates the V2I communications and platooning by significantly reducing the beam training overhead and latency [47, 48].

Simultaneous Localization and Mapping (SLAM): Joint localization and mapping can provide vehicles with situational awareness without the need for high-precision maps [49]. Based on the environment data extracted from various sensors, a vehicle could obtain its current location and the spatial relationship with the objects in a local area, and accordingly to perform navigation and path planning. Most of previous SLAM studies rely on camera or lidar sensors, which overlooked the fact that the channel propagation characteristics could be utilized to construct 2D or 3D maps of the surrounding environment. In this sense, ISAC-based radio sensing has the potential to become a key component to be integrated into current SLAM solutions, by endowing communication devices with sensing functionalities while requiring minimum hardware/software modification. The ISAC receive signal processing pipeline for SLAM poses a number of challenges, such as the separation of S&C signals, and the reconstruction of high-quality point clouds.

3.4 Smart Manufacturing and Industrial IoT

The penetration of wireless networks in the hard industries such as construction, car manufacturing, and product lines among others has given rise to the revolution of Industrial IoT [50], showing orders-of-magnitude increase in automation and production efficiency. Such scenarios often involve network nodes and robots that coordinate to carry out complex and often delicate tasks, that require connectivity in large numbers and with severe latency limitations.

ISAC offers paramount advantages in such smart factory scenarios, where in addition to ultra-fast, low-latency communications typical for such scenarios [51], the integration of the sensing functionality will enable the factory nodes and robots to seamlessly navigate, coordinate, map the environment and potentially cut signaling overheads dedicated to such functionalities. The desired technology here involves elements of the above cases such as swarm navigation, platooning, imaging, but under the important constraints of ultra reliability, ultra low latency and massive connectivity, often encountered in smart factory scenarios [50].

3.5 Remote Sensing and Geoscience

Radar carried by satellites or planes has been widely applied in geoscience and remote sensing to provide high-resolution all-weather day-and-night imaging. Today, more than 15 spaceborne radar systems are operated for innumerous applications, ranging from environmental and Earth system monitoring, change detection, 4D mapping (space and time), security-related applications to planetary exploration [30]. All these radars are operated in synthetic aperture radar (SAR) mode, mostly using chirp or OFDM waveforms. Communication data can be embedded into these waveform, enabling these radar infrastructures to broadcast low-speed data streams to its imaging area, or provide covert communication services in a battlefield.

Being able to rapidly deploy and loiter over a disaster area for hours, drones provide essential emergency response capability against many natural disasters. Such response tasks include damage assessment, search-and-rescue operation [52], and emergency communication for disaster areas. To accomplish these tasks, drones should carry various heavy and energy-consuming payloads, including airborne imaging radar, communication BS, and thermal sensors, which severely limits drones' endurance. Benefiting from ISAC, the radio sensing system and emergency communication system can be merged to achieve higher energy and hardware efficiency, via exploiting the integration gain.

More interestingly, a swarm of drones or satellites could exchange sensed information, and therefore cooperatively act as a mobile antenna array forming a large virtual aperture. In such a case, drone swarm based SAR algorithms may be exploited to implement a high-resolution low-attitude airborne imaging system.

3.6 Environmental Monitoring

Environmental information such as humidity and particle concentration can be indicated by the propagation characteristics of transmitted wireless signals [53]. Wireless signals operating on different frequencies are aware of different environmental changes. For instance, high-frequency mmWave signals are sensitive to humidity because they are closer to the water vapor absorption bands. By analyzing the pathloss data of city-wide mmWave links between BSs and smart phones, it is possible to monitor rainfall or other variations in the atmospheric environment such as water vapor, air pollutants, and insects. As such, a cellular network with a sensing function serves as a built-in real-time monitoring facility and therefore, can be utilized as a widely-distributed large-scale atmospheric observation network. Moreover, with the continuous exploitation of higher frequency, future urban cellular networks could also monitor locusts or other insects, serving as an insect observation network in urban areas.

In the scenario of environmental monitoring, one needs to solve problems such as low spatial resolution, poor continuity, poor accuracy, expensive equipment and low deployment density of equipment. When using wireless communication links for monitoring, it is also necessary to consider the performance, robustness and complexity of the algorithm, the range and distance of monitoring, the environmental monitoring problems in different occasions, such as cities or open areas, the processing of received signals and the setting of the network management system.

3.7 Human Computer Interaction (HCI)

An object's characteristics and dynamics could be captured from the time/frequency/Doppler variations of the reflected signal. Therefore, gesture interaction detection via wireless signals is a promising HCI technology. For instance, a virtual keyboard that projects onto a desk could be constructed by recognizing the keystroke gesture at the corresponding position. Another well-known example is the Soli project of Google [54], which demonstrated radio sensing in HCI. Based on advanced signal processing from a broad antenna beam, Soli delivers an extremely high temporal resolution instead of focusing on high spatial resolution, i.e., its frame rates range from 100 to 10,000 frames per second, such that high dynamic gesture recognition is feasible. Benefiting from integrating sensing capability into smartphone and other UEs' communication systems, gesture-based touchless interaction may serve as the harbinger of new HCI applications, which may play a key role in the post COVID-19 era. The main challenges are how to improve micro-Doppler recognition accuracy and how to design a signal processing strategy providing high temporal resolution.

4 Industry Progress and Standardization

As initial research efforts towards 6G are well-underway, ISAC has drawn significant attention from major industrial companies. Recently, Ericsson [55], NTT DOCOMO [56], ZTE [57], China Mobile, China Unicom [57], Intel [58], and Huawei [31] have all suggested that sensing will play an important role in their 6G white papers and Wi-Fi 7 visions. In particular, in November 2020 Huawei identified harmonized S&C as one of the three new scenarios in 5.5G (a.k.a. B5G) [59]. The main focus of this new technology is to exploit the sensing capability of the existing mMIMO BSs, and to support future UAVs and automotive vehicles. Six months later, Huawei further envisioned that 6G new air interface will support simultaneous wireless communication and sensing signaling [31]. This will allow ISAC enabled cellular networks to "see" the physical world, which is one of the unique capabilities of 6G. Nokia has also launched a unified mmWave system as a blueprint of future indoor ISAC technology [60].

The IEEE standardization association (SA) and the third-generation partnership project (3GPP) have also devoted substantial efforts to develop ISAC related specifications. In particular, IEEE 802.11 formed the WLAN Sensing Topic Interest Group and Study Group in 2019, and created a new official Task Group IEEE 802.11bf [23] in 2020,[3] intending to define the appropriate modifications to existing Wi-Fi standards to enhance sensing capabilities through 802.11-compliant waveforms. On the other hand, in the NR Release 16 specification, the redefined positioning reference signal (PRS) obtains a more regular signal structure and a much larger bandwidth, which allows for easier signal correlation and parameter estimation (e.g., by estimating the time of arrival, ToA). Moreover, the measurements for PRSs received from multiple distinct BSs could be shared and fused at either the BS side or the UE side, which further enhance the parameter estimation accuracy to support advanced sensing ability. To foster the research and innovation surrounding the study, design, and development of ISAC, IEEE Communications Society (ComSoc) established an Emerging Technology Initiative (ETI)[4] and IEEE Signal Processing Society (SPS) created a Technical Working Group (TWG),[5] all focusing on ISAC.

5 Conclusions

This chapter provided a brief overview on the background, basic principles, and use cases of the ISAC technology. We introduced the background, definition, and rationale of ISAC, followed by a discussion of potential ISAC gains, levels of integration, as well as design philosophies. We also considered the interplay between S&C by overviewing the historical development and the driving forces. Finally, we studied a number of important use cases, in which the ISAC technology may find extensive usage.

The rest of this book will focus on a variety of technical aspects of ISAC, including fundamental limits, signal processing, networking, hardware platform, and its application in other emerging technologies. We hope that this book may serve as a stepping stone and reference point for researchers working in this area. We firmly believe that ISAC will not only serve as the foundation of the new air interface for the 6G network, but will also act as a bridge the physical and cyber worlds, where *everything is sensed, everything is connected, and everything is intelligent.*

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