Integrated Communication and Sensing for B5G/6G—Part 1: Key Drivers and Applications

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Abstract:
In the existing wireless communication systems, it has been studied about how quickly and how many packets could be delivered in time to how many devices. Beyond fifth generation (B5G) or sixth generation (6G) wireless communication systems can operate as a sensor for recognizing surrounding environments or objects as well as for delivering packets. If two different systems; the communication system and the sensing system are integrated, new opportunities and new design issues can arise. This article explores integrated communication and sensing (ICS) technologies for B5G or 6G wireless communication systems. New applications, key technology enablers, their underlying challenges, and design issues for ICS systems are summarized. Contents of this article are divided into two parts. This is the first part which summarizes key drivers and relevant applications of ICS. The second part will summarize technical challenges and system design for ICS.

Introduction
Recognizing or sensing the surrounding environment in mobile communication systems is attracting more and more people's attention. Several applications have been discussed, for example, positioning from 911 emergency call to through-the-wall intruder detection, self-driving vehicle navigation system, robot and drone tracking, social networking, and motion detection for seniors to healthcare services. In addition to sensory information of surrounding environment, data communication with neighboring wireless devices may also be beneficial. In an example, self-driving cars need to constantly monitor and sense their surroundings to navigate efficiently and safely. Data communicated from neighboring vehicles and roadside units are essential to avoid obstacles, select the best routes, detect hazards, and comply with traffic regulations. The recognizing or the sensing is not just limited in physical location, movement or behavior detection, but also extended to detecting gas emission, metal, humidity, and even human emotion (seems like psychological phenomenon) which can also be recognized based on wireless signals [1]. These new applications will enhance user experience and create new business opportunities. For example, it may bring more profits to device manufacturers that provides various sensing functions or may provide a new service from the operator's point of view. In other words, the B5G or 6G network will not only be used for data communication, but will act as a sensor, and this change will create new opportunities.

Wireless sensing, positioning, and recognizing various aspects for emerging applications are under study in many academic and industrial communities. A wireless device may determine a wide range of functions, such as determining the distance, angle, and velocity of objects. The wireless device may further cover advanced functions such as imaging, mapping, or computing. Nowadays, proprietary sensors such as camera, Lidar, and Radar, have been developed and widely used to provide such functionalities. However, the proprietary sensors may require additional complexity and battery consumption. They also require dedicated spectrum. For a more efficient evolution and brining more benefit to users, it is desirable to integrate such sensing technologies into wireless communication systems. Integrated communication and sensing (ICS) may reuse and extend the existing technologies. Sensing performance may be enhanced by utilizing data communication. Also, conversely, sensing information can help to improve communication performance. For example, sensing the location of a wireless device can help reduce the number of beam sweeps, estimate CSI, or simplify complex handover processes. In the first part of this article, it summarizes key drivers and applications of the ICS.

Key drivers of ICS

For ICS in B5G/6G, there are several key drivers as follows,

- **Limitation on existing sensing systems:** Video-based sensing systems have limitations in Non-Line-Of-Sight (NLOS) environments, in the dark, through smoke or walls. Lidar-based sensing can be used in the dark but still have limitation on detecting non-line-of-sight (LOS) objects. Those sensing systems may not detect NLOS objects. They are also computationally intensive and have lower localization accuracy. RF (radio frequency)-based sensing mechanisms using wireless signals can have less limitations for better sensing accuracy in those harsh (e.g., dark, smoke, or NLOS) environments.

- **Spectrum utilization:** Currently, radar system operates in the spectrum between 19 MHz to 300 GHz. The range of frequencies have different usage. Radar frequencies from 30 to 300 MHz (VHF band) are used to very-long-range surveillance. Frequency range from 4 to 8 GHz (C band) is used for long-range tracking of airborne weather detection. 27 to 40 GHz frequency range (Ka band) is used for very-high-resolution mapping for airport surveillance. Radar has many uses and has a long history of functional applications. Beside technical restrictions regarding the utilized bandwidth of a radar system, special frequency bands in the 6 GHz range (C-band), 10 GHz range (X-band), 24 GHz range (K-band), and 80 GHz range (W-band) have been designated to industrial radar systems. However, spectrum is a scarce resource and using it for both sensing and communication simultaneously is more efficient than dedicated spectrum usage. Referring [2], fig. 1 illustrates a market penetration forecast in 2022 of automotive radar and mobile phone users. Of the population on earth of about 8 billion, about 19% of the population uses automotive radar, whereas about 91% of the population uses cellular phones. However, since it is an ISM (industrial, scientific, and medical) band to use the automotive radar, there is no need to pay fee using the automotive radar, but billions of cost may be required to support cellular phone users. Therefore, the current dedicated spectrum for sensing system such as radar is somewhat unfair. If a single modem supports both sensing and communication, spectrum can be reused much more efficiently, and users can use a much wider bandwidth, benefiting everyone.

- **Larger bandwidth in 5G/6G:** New bands for B5G/6G are expected to have higher bandwidths on the order of 1 GHz or more, which will provide high-resolution sensing possibilities.

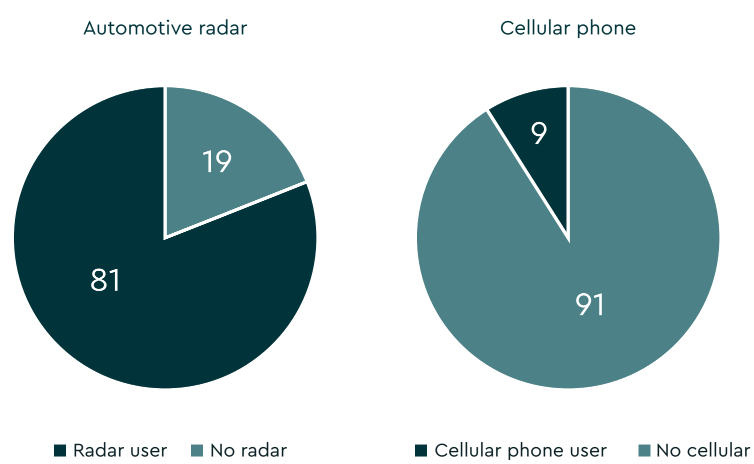

FIG. 1: Market penetration of automotive radar and cellular phone

The higher frequency can have the more direct relation between the propagation paths and the propagation environment. The Larger bandwidths lead to the more resolvable multi-path in time domain. Shorter wavelengths imply smaller antennas, so that small devices can be packed with tens or hundreds of antennas, which will be beneficial for angle or direction estimation. Beamforming technologies may suppress multiple path components and enhance a dominant path's time delay estimation accuracy.

- **Privacy issue for sensing:** Recently, we are being monitored by surveillance cameras or personal smartphone cameras everywhere. Camera may not be allowed to be installed everywhere. However, RF signals intrude less on privacy than cameras. In addition, although the camera directly records the external appearance of an individual's face and clothing, the RF signal-based sensing system only detects the approximate appearance of the face or clothing, so there is less privacy problem.

- **Densification of reference nodes:** Cellular systems are becoming ubiquitous with increasing density, and are also moving inside vertical industries, e.g., factories. This denser deployment provides the opportunity to enable RF sensing over a wide area with common infrastructure and spectrum reuse. Most sensing methods show better performance when there are more reference nodes.

- **AI/ML evolutions:** AI/ML evolutions leverage the unprecedented availability of data and computing resources to tackle the hardest problems in wireless communication systems. Inclusion of AI/ML may enable further possibilities for data fusion at both base stations and UEs. For example, AI/ML processing could provide benefits for example for object detection algorithms, clutter removal etc. that could be based on advanced deep learning techniques with neural networks. Also, AI-enabled Air interface in B5G or 6G can be reused or shard with Ai/ML processing for sensing. This could reduce computational complexity of ICS systems.

ICS applications

Sensing using wireless signals has been extensively studied and covers a large number of use cases. In the ICS system, wireless RF signals can be used for sensing, and in this section, it is summarized that how the existing RF signals or measurements are used for sensing. See [3] for the extensive list. Some applications and descriptions are summarized as below. Note that these applications have been mainly developed for Wi-Fi systems, but many solutions can be extended in B5G or 6G systems and some use cases developed in indoor scenario can be used in outdoor scenarios.

- **Health (for elderly people) Monitoring:** The population of people aged 65 years or older is increasing, and their ratio to the population of people aged 20–64 will approach 35% in 2030. Every year 33% of elderly people over the age of 65 will fall, and the percentage increases for the elderlies living in care institutions. The fall could cause injuries and reduction of the quality of life. Unfortunately, fall represents one of the main reasons of the death of elderly people. Most of the time, the elderly at high risk of falling need to move to institutionalized care, which can approximately cost US$3,500 per month. Authors in [4] proposed a Wi-Fi based fall detection system WiFall, by taking advantage of the CSI measurements. The basic idea is to analyze the change in CSI when human activities affect the environment. Authors in [5] reported that they were able to detect the breathing rate of a person by analyzing the fluctuation of received signal strength indicator (RSSI) in the received packets from 20 nodes around the person. Human breathing, breathing rate, or falling are detected.

- **Activity Classification:** The growing concern about law enforcement and public safety has resulted in a large increase in the number of surveillance cameras. There is a growing interest in both the research community and in the industry to automate the analysis of human activities and behaviors. The main approach of these techniques is to model normal behaviors, and then detecting the abnormal behavior by comparing the observed behavior and the normal behavior. Then the variation is labelled as abnormal. Abnormal behavior detection has gained increasing interest in surveillance applications recently. Authors of [6] classified simple activities by capturing features from the variation of the signal between two wireless communication devices. Authors in [7] proposed the use of the wireless channel, where they monitored the fluctuation in the RSSI, which is calculated for each packet at the receiver, they attempted to recognize activities performed in front of a mobile phone.

- **Gesture Recognition:** Nowadays, computers are used everywhere. There is an increasing need for novel ways to interact with the computers. The Xbox Kinect [8] is a recent example of a sensor that enables interaction based on gesture using computer vision and depth sensing. The success of these devices has increased the interest in building novel user interfaces that decrease the dependence on traditional interfaces such as the mouse and the keyboard. Gestures can be used as a new interaction technique for computing that is embedded in the environment [9]. Authors in [10] presented a Wi-Fi based gesture recognition system by using variation in RSSI resulting from hand gestures. Authors in [11] used the electromagnetic noise resulted from electronic devices to recognize different gestures. They presented accurate gesture recognition with an accuracy of 93% for 12 gestures. Authors in [9] proposed WISEE, a gesture recognition system that uses Wi-Fi signals to recognize human gesture. Authors in [12] presented WiHear, which investigated the potential of using Wi-Fi signals to hear the talk of people. The proposed system locates the mouth of the user and then recognizes his speech by analyzing the signals reflected from his mouth.

- **People Counting:** Crowd counting is increasingly becoming important in a number of applications, such as crowd control and guided tour [13]. However, crowd behaviors are usually unpredictable which pose many challenges for crowd counting and estimation. Other challenges include object occlusions and real-time processing requirement. There are many applications that can benefit from people counting. Smart building management is one example, where the heating can be optimized based on the number of people, which can result in a large energy saving. There are many other similar applications that can be also optimized based on the number of people. Crowd estimation may also play an important role in emergency situations where a crowd needs to be evacuated from an area. Mostofi et al. [13] proposed a Wi-Fi based system that counts the number of walking people in an area using only RSS measurements between a pair of transmitter and receiver antennas. In [14], multiple Wi-Fi nodes and RSS measurements were used to count the number of up to 4 persons. They reported an accuracy within an error of 1 person 84% of the time approximately. In [15] a similar approach was used but with fewer nodes, they were able to count up to three people. In [16], a transmitter-receiver pair was used to estimate the number of people based on RSS measurements. An extensive training data was used to develop the underlying model, an error up to 6 persons were reported in experiments limited to 9 persons. Authors in [17] proposed a people counting system based on CSI measurements. The basic idea of the proposed approach is that the number of people can be accurately estimated by analyzing the changes in the CSI.

- **Through the Wall Sensing:** Through the wall sensing is a new research area that was introduced to address the increasing need to see through the walls for many applications, such as recognizing and classifying objects in the building. It could be also used in emergency situations such as earthquakes to check whether a person exists under the rubble. Through the wall sensing is highly desirable by emergency workers and the police. Accurate through the wall sensing and imaging can help the police forces to get a precise description of the person movement inside a building, it can also help firefighters to locate people who are trapped inside a burning building. Through the wall imaging has attracted much interest recently particularly for security applications [18]. Through the wall imaging uses radio frequency sensors to penetrate walls that obscure objects of interest and to map the building interior behind the walls. These features make through the wall systems more suitable for search and rescue, and covert surveillance. Through the wall sensing systems utilize signal attenuation caused by the walls, where the attenuation is lower at low frequencies. It must also consider the need for large bandwidths to get a high range resolution. The majority of through the wall sensors are UWB radars, which have many advantages over classical narrow band sensors. In [19] and [20] a series of experiments were conducted to investigate the effectiveness of using Wi-Fi signals as an illuminator of opportunity for through the wall people localization. In [20] an indoor events detection system was proposed by using the time reversal technique to detect changes in indoor multipath environments. The proposed system enables a single antenna device that operates in the ISM band to capture indoor activities through the walls. The system uses the time reversal technique to detect changes in the environment and to compress high-dimensional features by mapping the multipath profile to the time reversal space, which will enable the implementation of fast and simple detection algorithms. Furthermore, a real prototype was built to evaluate the feasibility and the performance of the system. The experimental results showed that the system achieved a detection rate of 96.92% with a false alarm rate of less than 3.08% in both LOS and NLOS environments. However, when the person is close to the transmitter or the receiver, the miss detection rate increased significantly. In [21] a new method for localization and motion tracking through walls was presented. The method takes advantage of variations in received signal strength measurements caused by people motions. By using a model for the multipath channel, they showed that the signal strength of a wireless link is highly dependent on the multipath components that contain moving objects. A mathematical model relating the locations of movement to the RSSI variance was used to estimate the motion. From that motion, the Kalman filter is then used to track the positions of the moving objects. The experimental results were presented for 34 nodes that perform through the wall tracking over an area that covers a 780 square foot. The system was able to track a moving object through the walls with a 3ft average error approximately. An object that moves in place can be localized with 1.5ft average error approximately.

- **Emotion Recognition:** Emotion recognition is an active research area that has drawn growing interest recently from the research community [22]. It seeks to answer a simple question: can we build a device that senses our emotions. Such a device will enable smart homes to react according to our emotions and adjust the music or the television accordingly. Movie makers will have interesting new tools to evaluate people experience. Advertisers will get people reaction immediately. Computers will automatically diagnose symptoms of anxiety, depression, and bipolar disorder, allowing early detection and response to such problems. More broadly, computers will no longer be limited to usual commands, it will interact with the users in a way similar to the way we interact with each other. Emotions can be recognized from body gesture, Bull [23] indicated that dynamic configurations of the human body hold a large amount of information about emotions. He showed that body motions and positions could be used as an indicator of the human state such as boredom or interest along with other 14 emotions. Wi-Fi could play an interesting role to detect body pose and gesture, and to use this information to recognize human emotions. Authors in [24] presented a new system that can recognize user emotions using RF signals that are reflected off his body. The system transmits a wireless signal and analyses the reflections from the user body to recognize his emotions such as happiness, sadness, etc. The key building block of the system is a new algorithm that extracts the heartbeats from the wireless signal at an accuracy close to Electrocardiogram (ECG) monitors. The extracted heartbeats are then used to extract features related to emotions, then these features are used in a machine learning emotion classifier. The researchers demonstrated that the emotion recognition accuracy is comparable with the state-of-the-art emotion recognition systems based on ECG monitors.

- **Keystrokes Recognition:** In [25], it was shown that Wi-Fi signals could be used to recognize keystrokes. Wi-Fi signals are now everywhere, at offices, home, and shopping centers. The basic idea is that while typing a specific key, the fingers and hands of the person move in a unique formation, and therefore produce a unique time-series pattern of CSI values, which can be called the CSI waveform of that key. The keystrokes of the keys produce relatively different multipath variations in Wi-Fi signals, which can be used to recognize keystrokes. Due to the high data rates of recent Wi-Fi devices, Wi-Fi devices produce enough CSI values within the duration of a keystroke, which will help in building more accurate keystrokes recognition systems. In [26], a keystroke database of 10 human subjects was built. The keystroke detection rate of the proposed system was 97.5% and the recognition accuracy for classifying a single key was 96.4%. The proposed system can recognize keystrokes in a continuously typing situation with an accuracy of 93.5%. However, the system works well only in controlled environments. The accuracy of the system is affected by many factors such as changes in distance and orientation of transceivers, human motions in surrounding areas, typing speed, and keyboard size and layout.

- **Drawing in the Air:** In [26], it was demonstrated that it is possible to use Wi-Fi signals to enable hands-free drawing in the air. They introduced WiDraw, a hand tracking system that uses Wi-Fi signals to track the positions of the user's hand in both LOS and NLOS environments, without requiring the user to hold any device. The prototype used a wireless card, less than 5 cm error on average was reported in tracking the user's hand. They also used the same system to develop an in-air handwriting app, a word recognition accuracy of 91% was reported. However, one limitation of the proposed system is that it requires at least a dozen transmitters in order to be able to track the hand with high accuracy. Furthermore, the 3D tracking error is higher than the 2D tracking error, the main cause for this is the difficulty in accurately tracking depth changes. The system achieved high tracking accuracy only when the hand is within two feet from the receiver. The error starts to increase at larger distances.

- **Imaging:** The advantages and limits of performing imaging based on Wi-Fi signals were investigated in [27]. They presented Wision, a system that enables imaging of objects using Wi-Fi signals. The system uses the Wi-Fi signals from the environment to enable imaging. The approach uses multipath propagation where the signals reflect from objects before they arrive at the system. These reflections "illuminate" the objects, which the system uses for imaging. However, the main challenge is that the system receives a combination of reflections from many objects in the environment. The evaluation demonstrated the system ability to localize and image relatively large objects such as desktops, and couches, or objects with high reflective properties such as metallic surfaces. Smaller objects with low reflective properties have smaller cross-sections and thus reflect a smaller fraction of the Wi-Fi signals, which make them harder to image. Moreover, when the size of the object becomes close to the wavelength of the Wi-Fi signal, which is 12 cm approximately at 2.4 GHz, the interaction of the object with the Wi-Fi signals decreases. This is a fundamental limitation of imaging based on Wi-Fi signals. This fundamental limitation could be addressed using higher Wi-Fi frequencies such as 5 GHz that has a smaller wavelength of 6 cm approximately. Using Wi-Fi signals in imaging still represents a significant opportunity with many potential applications. Imaging resolution with Wi- Fi signals also depends on the antenna array length. The imaging resolution can be increased by increasing the length of the antenna array. A resolution close to the optimal at 2.4 GHz was reported in [27] for the considered array lengths. They observed that the resolution does not depend on the number of antennas, but rather depends mainly on the length of the antenna array. Recent theoretical work has also shown that similar resolutions can be achieved with a smaller number of antennas given that the length of the antenna array is the same. The main constraint they observed with their implementation is that smooth metallic objects are acting like mirrors, where they could be oriented in such a way making them hidden from the view of some transmitter positions. To address this issue, one may use antennas with wider radiation patterns or optimizing the antenna position to maximize their reach. One could also use signals from multiple Wi-Fi devices, which are more likely to be at various positions. Another approach is leveraging the mobility of the device to create images as the user moves around.

- **Smoking Detection:** In [28], authors proposed Smokey, a device-free passive smoking detection system that leverages the CSI variation information of Wi-Fi signals to detect the rhythmic smoking activity. They design a foreground detection-based motion acquisition method to extract the meaningful information from multiple noisy subcarriers that are even influenced by the posture changes.

- **Metal Detection:** Regarding increasing interest in detection of concealed metallic weapons, there is a great need to have robust and non-obtrusive metal detection systems with large coverage areas. Conventional systems based on electromagnetic induction or X-rays are effective but have small coverage areas in addition to requiring costly infrastructure. In [29], authors explore the use of ubiquitously present Wi-Fi signals for non-obtrusive detection of concealed metal objects. For the purpose, they build a prototype system consisting of a single-antenna commodity Wi-Fi radio as a transmitter, and two multi-antenna radios as receivers placed in an indoor environment. Extensive experiments were performed with subjects walking through the setup with (or without) a sheet of metal placed around their chests. The channel state-information is collected from the receivers to train a deep convolutional neural network, and the proposed system can differentiate between the metal and non-metal cases with an average accuracy of 86.44%.

- **Humidity Estimation:** Humidity is one of the most important environmental attributes for weather condition. It affects the economy of nature as well as human life. Many environmental processes are affected by this attribute. For example, rice has the most powerful photosynthesis when the atmospheric humidity is in between 50% and 60%. For most of the human being, the humidity in between 20% and 80% is good to have a healthy life. Consequently, accurate humidity measurement methods are important. Based on the accurate humidity estimation, a humidifier can adjust the spray amount indoor, for example. The existing methods are neither convenient for large scale deployment due to the high cost nor accurate enough to use. Researchers found that humidity has a direct effect on radio propagation. This observation is undoubtedly useful to measure humidity in the environment. However, the humidity estimation based on received signal strength indicator (RSSI) is easily affected by the temporal and spatial variance due to multipath effect. Meanwhile, the change of radio signals incurred by RSSI-based systems is not that much obvious when the transmitter and receiver are in close distance. As a result, it is challenging to measure humidity in indoor environments. In [30], authors provide a novel system, namely WiHumidity, to tackle this problem. The system utilizes the special diversity of CSI (CSI) to alleviate multipath effect at the receiver. Extensive experiments have been conducted to verify the effectiveness of WiHumidity.

- **Material sensing using THz:** Not long ago, the terahertz (THz or sub-THz) frequency range was considered the final frontier of the electromagnetic spectrum. The main reason was the difficulty in generating intense, directional terahertz radiation. During the past few years, optoelectronic approaches such as modern laser technologies, high-power electronic emitters, or beamforming technologies have helped to bridge the "terahertz gap". This has opened up a wealth of applications, taking advantage of the fact that materials like synthetics, textiles, paper and cardboard are transparent to terahertz waves. In addition, many gases and organic solids – including toxic or explosive substances – show absorption lines at frequencies between 0.1 and 5 THz. Many applications of THz radiation are thus related either to imaging or to terahertz spectroscopy. In [31], authors summarizes THz sensing applications. THz sensing technologies show a significant market potential, a finding that is confirmed by a number of recent market reports [32]. In the field of non-destructive, non-contact testing now successfully exploit the abilities of THz radiation, i.e., penetration of many opaque materials, depth resolution on the micrometer level, high spatial resolution as compared to microwaves. THz sensing can be used to material depth estimation, gas sensing, hydration monitoring, or security. THz sensing systems offer a unique combination of imaging and spectroscopic methods. THz waves penetrate materials like plastics, paper and – to some extent – textiles. They can thus reveal the presence of objects e.g., concealed in parcels, and identify the material in question by spectroscopic techniques. Prospective applications include the detection of drugs or explosives in mail envelopes, or the identification of liquids in suspicious bottles.

Concluding remarks

In summary, measuring a wireless signal such as RSSI or CSI can estimate little physical changes in motion, position, or gestures, and, it can be used to estimate degrees of humidity, gas, smoke, or motion, and detect materials. Advances in AI/ML technologies and signal processing technologies make this possible. If the new applications are supported in the wireless communication system, it is expected to provide numerous business opportunities. If these sensing applications are integrated into a single wireless communication modem, it is expected to reduce battery consumption and implementation complexity of device and access points. In part 2, it is summarized that what technical challenges there are for ICS system and what aspects should be considered in system design to solve them.

Acronym list

5G	Fifth Generation
B5G	Beyond Fifth Generation
6G	Sixth Generation
ICS	Integrated Communication and Sensing
NLOS	Non-Line-Of-Sight
LOS	Line-Of-Sight
RF	Radio Frequency
VHF	Very High Frequency
AI	Artificial Intelligence
ML	Machine Learning
RSSI	Received Signal Strength Indicator
CSI	Channel State Information
ECG	Electrocardiogram
THz	Tera Hertz

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About Ofinno:

Ofinno, LLC, is a research and development lab based in Northern Virginia, that specializes in inventing and patenting future technologies including 5G, IEEE, and video compression. Ofinno's researchers create technologies that address some of the most important issues faced by wireless device users and the carriers that serve them. Ofinno's research involves technologies such as 5G Radio and Core networks, IoT, V2X, and ultra-reliable low latency communications. Our innovators create the technologies and oversee the entire process from design to the time the technology is sold. For more information about Ofinno, please visit www.ofinno.com.