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Research Article

Integrated Sensing And Communication In 6g: Applications And Key Performance Indicators

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ABSTRACT

As the evolution of wireless communication progresses towards 6G networks, the integration of sensing and communication functionalities emerges as a fundamental paradigm shift. This paper explores the concept of Integrated Sensing and Communication (ISAC) in the context of 6G, where both sensing and communication functions are seamlessly unified within a single system. The envisioned ISAC framework entails the coexistence and integration of sensing and communication tasks, leveraging shared resources across time, frequency, and spatial domains. Key elements such as waveform design, signal processing algorithms, and hardware architecture are intricately interwoven to support this integration. This study delineates four distinct categories of ISAC use cases that are anticipated to define the landscape of new services in 6G networks. Each category is accompanied by a detailed examination of the corresponding performance requirements.

Keywords: Integrated Sensing and Communication (ISAC); 6G; signal processing algorithms; waveform design

Introduction

Since the 1980s, cellular mobile communication systems have evolved, culminating in the commercialization of 5G, which offers enhanced connectivity and integration of diverse devices. Looking ahead to 6G, there's a shift towards connected intelligence, where mobile networks seamlessly integrate intelligent devices capable of sensing and communicating. This fusion, augmented by Artificial Intelligence (AI), bridges physical and cyber realms, endowing networks with human-like cognition.
6G's higher frequency bands and denser antenna arrays enable the integration of wireless sensing & communication, enhancing both functions. Communication systems act as sensors, leveraging radio waves to understand the physical environment, while sensing capabilities improve communication performance through precise localization and imaging. Integration can occur at various levels, from shared spectrum to fully integrated systems, fostering seamless cross-module information sharing.
Integrated Sensing and Communication (ISAC) in 6G facilitates scenarios like autonomous driving in challenging conditions, eliminating the need for separate radar and lidar systems. In light of these advancements and possibilities, this paper delves into the exploration of novel applications, key performance metrics, and requirements for ISAC design in the context of 6G networks.

Overview of ISAC use cases and new performance indicators

In 6G, ISAC systems will revolutionize networked sensing, providing high-resolution capabilities for localization, imaging, and activity recognition. These capabilities enable a wide range of new services categorized into:

1. High-accuracy localization and tracking
2. Simultaneous imaging, mapping, and localization
3. Augmented human senses
4. Gesture and activity recognition

For instance, ISAC facilitates automatic drone docking and complex robot collaboration through high-accuracy localization. Simultaneous imaging and mapping enable 3D non-line-of-sight imaging and mapping indoors and outdoors. Augmented human senses in smart hospitals can monitor vital signs beyond human capabilities. Gesture and activity recognition promote contactless interfaces and patient supervision.
New key performance indicators (KPIs) introduced for ISAC include high-resolution sensing, non-line-of-sight imaging, and machine learning-based activity recognition, all vital for advancing sensing capabilities in 6G networks.

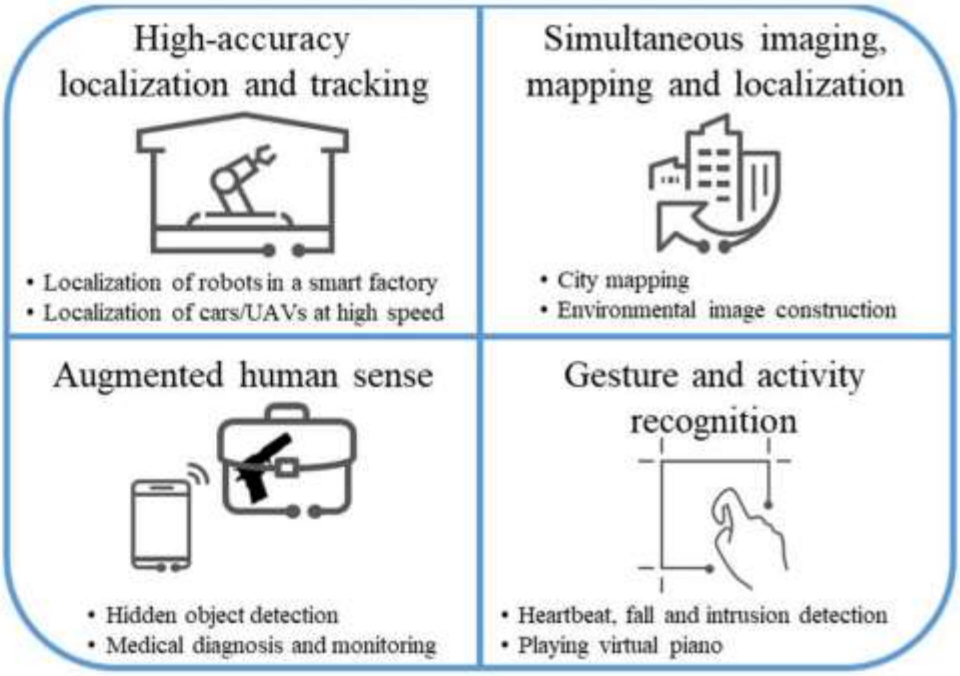

Fig. 1. Four categories of ISAC use cases as the new services in 6G (Dong, et al 2022).

Sensing applications and key performance requirements

High-accuracy Localization and Tracking

In future 6G networks, ISAC capabilities will revolutionize high-accuracy localization and tracking, crucial for diverse applications like intelligent factories and autonomous systems. Existing techniques in 4G and 5G offer meter-level accuracy but fall short for advanced scenarios requiring centimetre-level precision. With ISAC, "6G systems can achieve such accuracy using the same wireless communication infrastructure, offering cost-effectiveness and resilience in harsh conditions where traditional methods like cameras or lidars may fail (**Wei, et al 2022).**
Sub-centimetre accuracy (e.g., 5 mm) is essential for proximity-based tasks in smart manufacturing, such as drone landing on moving carriers or refill operations by delivery robots. These tasks may involve asymmetric radio systems, ranging from simple RFID tags to sophisticated RF arrays, depending on communication requirements and cost considerations **(Costa, et al 2022)**
Moreover, future localization tasks may incorporate semantic destinations, requiring AI or communication technologies to interpret and navigate. ISAC systems must learn and understand both physical coordinates and semantic meanings, mirroring human-like common sense in interpreting geometric environments.

Simultaneous Imaging, Mapping and Localization

In addition to high-accuracy localization, the integration of mapping and localization in 6G networks facilitates the development of robots and machines with human-like senses. For example, With the help of artificial intelligence, a robot may map out its position in relation to the room's furniture and then use that information to plot out and carry out a path to deliver a target to a person. The SLAM method improves positioning accuracy by reconstructing 2D pictures and 3D models of the environment using channel multipath information. **(Aladsani, Alkhateeb, & Trichopoulos, 2019).**
Due to the finite number of physical transceivers (PT), traditional localization systems rely on them as anchors, which limits their performance. Virtual transmitters can be located by devices using environment sensing, such as reflections of physical transmitters off surrounding walls, serving as reliable virtual anchors to improve localization accuracy.
In Figure 1.2, SLAM-based localization achieves a 10 cm accuracy with accurately learned VT locations, traditional approaches to localization that use raw multipath components can only achieve a 60 cm accuracy

(or 60%). This proves an accuracy boost of six times. The constant presence of VTs during SLAM can help determine the location of walls, and the estimation of VT locations can be revised incrementally over time.
It is noteworthy that mapping accuracy for autonomous vehicles in outdoor scenarios may be lower due to higher speeds, compared to indoor scenarios with low-mobility devices. However, for specific applications such as 3D building/environment reconstruction, mapping accuracy can reach 1 cm when the mapping device moves at low speed with stable orientation.

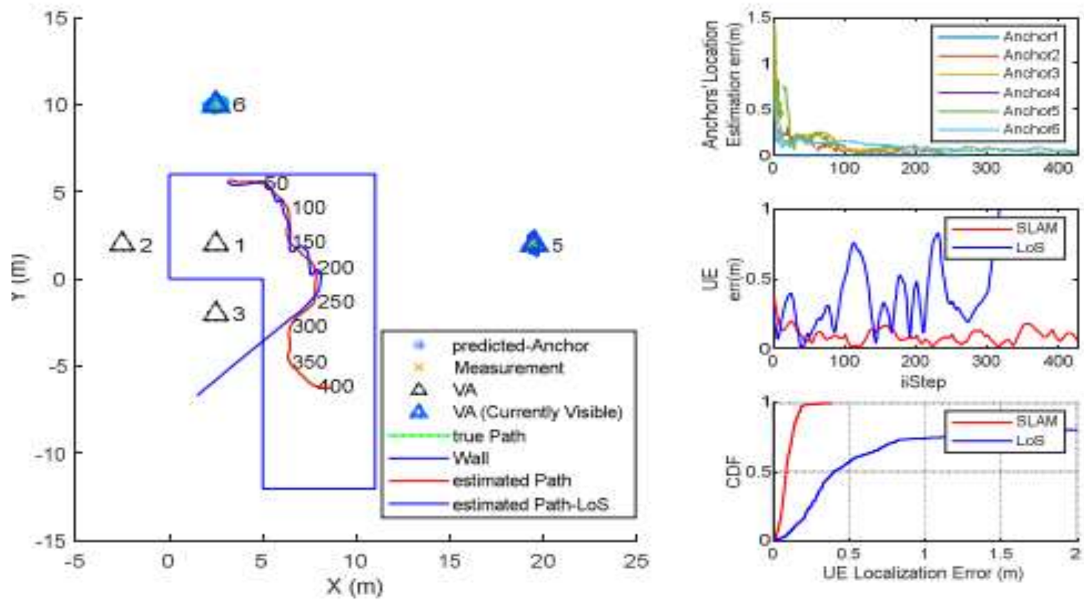

Fig. 1.2. SLAM ensures precise UE and VT localization. Predictions of where VTs are located tend to converge over time. The UE localization error is significantly reduced when using the VT location learned from the NLOS routes compared to circumstances when the LOS-path only was used. (**Dong, et al 2022).**

Augmented Human Sense

RF sensing techniques, leveraging the capabilities of 6G networks, promise a myriad of applications, including remote surgery, product defect detection, and leak detection. SLAM ensures precise UE and VT localization. Predictions of where VTs are located tend to converge over time. The UE localization error is significantly reduced when using the VT location learned from the NLOS routes compared to circumstances when the LOS-path only was used.

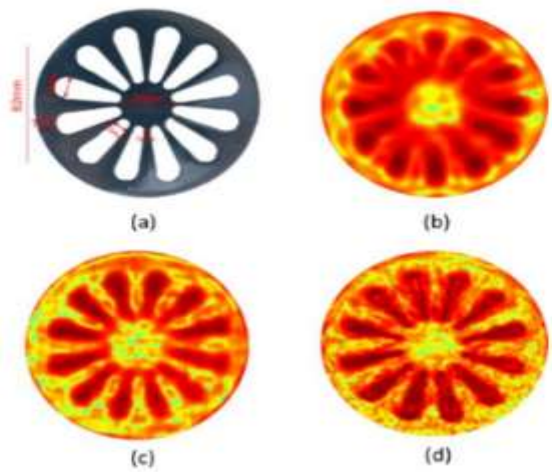

Fig. 1.3. A lemon core's imaging results at various frequencies: (a) the optical picture of the target; (b) imaging results at 73 GHz; (c) imaging results at 140 GHz; and (d) imaging results at 220 GHz. **Dong, et al 2022).**

Figure 1.3 shows an example of imaging resolution at the millimeter level. The optical picture of the target, a lemon core, is shown in Figure 1.3a. Wireless imaging results at 73 GHz, 140 GHz, and 220 GHz are shown in Figures 1.3b, 1.3c, and 1.3d, respectively. A half-wavelength-spaced virtual array scanning mechanism creates an equal 20 cm x 20 cm aperture. With an increase in frequency and bandwidth, the resolution goes from 8 mm to 4 mm and even farther to 1 mm. An all-day solution is provided by RF sensing, thanks to the propagation characteristics of radio waves, as opposed to human eyesight, which is dependent on optics. With 6G, all sorts of sensing devices will be possible, from mobile phones and wearables to medical implants.

Augmented human sensing, facilitated by scientific and technological advancements, enables information collection in various conditions, including darkness, confined spaces, and beneath the skin. In the medical field, 6G sensing aids in diagnosis, monitoring, and treatment of chronic diseases like asthma, arrhythmia, and hypoglycemia through wearable devices, providing real-time information such as heartbeats and blood stream images.

Moreover, higher frequencies enable spectrogram applications, allowing for material identification based on electromagnetic or photonic characteristics. Spectrogram sensing, feasible in THz and NIR frequencies, aids in distinguishing materials based on absorption, reflectivity, and permittivity parameters. For instance, the PM2.5 transmission spectrum exhibits distinct absorption bands between 2.5 and 7.5 THz, indicating the potential for spectral analysis to discern material compositions.

Gesture and Activity Recognition

In 6G, the higher frequency bands will facilitate finer resolution and accuracy for capturing activities and gestures, while the widespread adoption of artificial intelligence (AI) techniques with powerful computing capabilities will revolutionize activity and gesture recognition. In the near future, intelligent device-free systems for activity recognition and gesture capturing will extend beyond single homes to large-scale, complex indoor environments. Indoor cellular transmission points (TP) or base stations (BS) will serve as additional sensors alongside user equipment (UE), enhancing sensing performance through joint utilization. Moreover, these indoor cellular points enable sensing over remarkably extended ranges not reachable by UEs, with the fused sensing information being communicated with cloud-based services or among adjacent buildings **(Cui, et al 2021).**

With high classification accuracy, various functionalities such as gesture recognition, heartbeat detection, fall detection, and intrusion detection can be implemented in smart hospitals. As a novel use case, the medical rehabilitation system in smart hospitals enables automatic supervision of patients during physiotherapy exercises, with automatic alerts on incorrect movements significantly enhancing patient rehabilitation.

Extremely high categorization accuracy and pinpoint capturing capabilities are necessary for sophisticated contactless features, such as virtual piano playing. Sensing services, like imaging and gesture detection, greatly benefit from AI-based learning methodologies. Cooperating ISAC situations also allow nodes to exchange their beliefs in both space and time, which improves sensing performance by allowing several nodes to work together in space and time. Data processing and fusion techniques are also crucial to the performance of RF sensing. techniques that incorporate learning-based approaches, such as belief propagation algorithms, are advantageous in this regard.

Conclusion

In conclusion, ISAC emerges as a promising direction for 6G networks, transforming them beyond mere communication systems. The integration of sensing functions within communication systems enables the creation of new services and enhances existing ones. This paper explored key applications and their performance requirements, highlighting the importance of high-accuracy localization and millimeter-level imaging resolution for various scenarios. Moreover, leveraging the communication network itself enhances sensing performance. Additionally, the study discussed how sensing capabilities can improve communication quality. Overall, ISAC holds immense potential to redefine the capabilities of future wireless networks, offering novel services and advancements in both sensing and communication domains.

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