5G-ACIA White Paper

Use Cases and Requirements for Integrated Sensing and Communication (ISAC) in Connected Industries and Automation

5G Alliance for Connected Industries and Automation

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1 Executive Summary

This document explores industrial use cases and requirements of currently emerging integrated sensing and communication (ISAC) technologies for future mobile networks. It begins by providing an overview of ISAC technologies and use cases that have been proposed in connection with standardization and research activities, and then describes ten potential industrial applications. Five specific industrial use cases are presented, including details of their functional and performance requirements. Key proposals for defining performance requirements are also presented while emphasizing the importance of having clear indices and a good understanding of sensing error distribution for ensuring reliable data.

About 5G-ACIA

The **5G Alliance for Connected Industries and Automation** (5G-ACIA) was established to serve as the main global forum for addressing, discussing and evaluating relevant technical, regulatory and business aspects of 5G for the industrial domain. It embraces the entire ecosystem and all relevant stakeholders, which include but are not limited to the operational technology industry (industrial automation companies, engineering companies, production system manufacturers, end users etc.), the information and communication technology industry (chip manufacturers, network infrastructure vendors, mobile network operators etc.), universities, government agencies, research facilities and industry associations. 5G-ACIA's overarching goal is to promote the best possible use of industrial 5G while maximizing the usefulness of 5G technology and 5G networks in the industrial domain. This includes ensuring that ongoing 5G standardization and regulatory activities adequately consider relevant interests and requirements and that new developments in 5G are effectively communicated to and understood by manufacturers.

2 Introduction

Cellular network technologies are evolving beyond conventional wireless communications toward multifunctional networks. For example, they now also include positioning services for user equipment (UE). Emerging Integrated Sensing and Communication (ISAC) technologies have recently been attracting considerable attention. Numerous research projects are already addressing aspects of them, although actual product development has not yet begun. Various standardization bodies are also formulating specifications, foremost among them the 3rd Generation Partnership Project (3GPP). 3GPP's Service & System Aspects working group 1 (3GPP SA1) initiated a stage-one study of ISAC Release 19 in August 2023, leading to the publication of technical report TR22.837 on over 30 ISAC use cases and technical specification TS22.137, which addresses the service requirements of ISAC. In late 2023, the 3GPP Radio Access Network Working Group 1 (RAN1) also began studying channel modeling of ISAC for 5G NR. The Radiocommunication Sector of the International Telecommunication Union (ITU-R) has included ISAC as one of the six usage scenarios of the International Mobile Telecommunications – 2030 (IMT-2030) framework, which defines the objectives for the sixth generation of cellular networks (6G).

Since the advent of 5G, industrial automation has been one of the main verticals addressed by the mobile telecommunications industry. ISAC could significantly benefit industrial automation use cases, even going beyond the possibilities identified by 3GPP SA1. By leveraging communications infrastructure in factories and plants with suitable spectra, ISAC can provide augmented sensory data for a host of industrial processes. This sensory data can be used for dynamically capturing the environment, including both active and passive persons and objects, to augment or improve automation processes.

To ensure ISAC's practicability in industrial automation contexts, it is necessary to comprehensively and thoroughly study and analyze the requirements. 5G-ACIA, as a leading global organization, should also closely monitor the development of ISAC and endeavor to ensure that associated innovations and developments meet the requirements of industrial automation.

This report sheds light on how ISAC could support and strengthen the industrial automation sector. It begins by reviewing existing ISAC technologies, use cases proposed by standards development organizations such as 3GPP, IEEE and ETSI ISG THz and research carried out by the IMT-2030 (6G) Promotion Group, the one6G association and the Hexa-X and Hexa-X-II projects. A number of industrial ISAC use cases are grouped based on their principal applications and analyzed. The findings are then used to identify potential industrial uses for ISAC . Several specific industrial use cases are proposed and described in detail, also covering their functional and performance requirements. Finally, observations and proposals for identifying performance requirements are presented.

3 Survey of Integrated Sensing and Communication

3.1 Overview of ISAC Technologies

In addition to providing conventional wireless data communication services, the next-generation mobile radio network will also have wireless sensing capabilities. Sensing and communication have traditionally been provided by distinct entities over different frequency bands. More recently, the mobile network has been hugely successful, providing most people and businesses with data connections via its ubiquitous radio frequency (RF) signal. As the existing mobile network technologies and infrastructure continue evolving, it will also become possible to use the RF signal for a wide range of sensing applications. This will yield novel use cases and new business opportunities. The idea has also spawned the new concept of ISAC, which has attracted major interest and led to numerous research projects including Hexa-X and Hexa-X-II and others now being carried out by the one6G association and the IMT-2030 (6G) promotion group. Standardization bodies such as 3GPP [18][19], the IEEE 802.11bf task group and ETSI ISAC ISG are also working on it. Three levels can be distinguished for integrating sensing and communication functionality in the mobile network of the future [16]:

- **Level 1 (application level):** Sensing and communication systems are separate; sensing information from outside the wireless communication system is exchanged on this level.
- **Level 2 (spectrum level):** Sensing and communications signals are multiplexed in time, frequency and space, which lets them share the same spectrum and, to some extent, also hardware resources.
- **Level 3 (full integration):** Here sensing and communication systems are fully integrated and share information across layers, modules and nodes. This approach is also known as joint communication and sensing (JCAS). In it, sensing takes place using waveforms transmitted across a network. In order to fully integrate sensing and communication, wireless systems will be designed that use the same spectral resources and hardware to support both. This will reduce costs, power consumption, latency and size.

Signal transmission, reception and processing in ISAC can take place at both ends of mobile networks and UE. MIMO technology and array processing have improved significantly since the emergence of 5G, resulting in much better data throughput and link reliability while unleashing the potential of accurate positioning and sensing. The next-generation

Table 1: Comparison of communication, radar and positioning systems

	Input	System	Output
Communications	Communication signal/message sequence	Communication channel, direct path/multipath	Received signal
Radar	Radar waveform	Objects in environment	Received echo
Positioning	Communication or radar signal	Communication channel and targets in environment	Angle and/or time of arrival

Source: 5G-ACIA / ZVEI e. V.

mobile network will continue to use the millimeter wave (mmWave) spectrum band while possibly also adding the sub-terahertz (THz) range, which would improve sensing applications to an even greater extent:

- The available signal bandwidth is getting broader, and the ranging resolution for sensing will be scaled up as a result.
- Smaller wavelengths will make it possible to achieve higher angular resolution using compact antenna systems.

Compared to conventional optical sensing methods such as LiDAR and cameras, RF-based sensing in ISAC may be able to detect objects at greater distances, also under non-line-of-sight (NLOS) conditions. It can also quickly and accurately capture rapid movements and changes in velocity using straightforward Doppler shift measurements. When implemented in a mobile network, ISAC can use views from multiple nodes, including base stations and UE, to create a holistic sensing network. Having a large number of radio nodes significantly increases sensing accuracy while reducing blind spots. Integrating both sensing and communication in the same spectrum also makes scheduling more efficient and improves coordination.

In addition to leveraging RF signals transmitted and received by the RAN and UE for sensing purposes, the ISAC framework also incorporates other sensor types (e.g., camera, LiDAR, radar, sonar and so on) for supporting sensing applications. 3GPP has taken non-3GPP sensors into account for ISAC, which is specified in [19]; several example use cases are presented in [18].

3.1.1 Goals and Fundamentals of Communication and Radar Systems

ISAC is essentially driving the evolution of cellular communication networks by introducing a radio sensing function that is similar to RAdio Detection And Ranging (radar). An understanding of the goals and fundamental design aspects of communication and radar technologies is therefore important for designing and analyzing ISAC systems.

The overarching goal of communication systems is to convey information from a source to an intended receiver. In contrast, radar systems detect the presence of objects of interest, distinguish them from clutter, estimate their parameters and track their movements in space and time. Unlike positioning systems, which are designed to determine the positions of connected (active) UE, radar systems are designed to detect and track unconnected or passive objects in the surrounding environment. While the input and output of a communication system are modulated communication signals, distorted and noisy versions of which arrive at the receiver, radar systems transmit waveforms and process scattered and noisy versions to extract information on potential passive objects [1]. In the case of positioning systems, the desired output is the angle or time of arrival of transmitted signals at one or more receiver nodes, which use this information to derive the positions of connected devices [2].

Communication and radar systems have quite different basic building blocks, corresponding to their purposes. Specifically, a communication system typically uses channel sounding or channel estimation to derive channel state information (CSI) at its transmitter and receiver nodes. CSI makes it possible for nodes to use transceiver methods to compensate for deterioration of message sequences that is caused by communication channels. For example, a receiver node can estimate the correct message sequence if it has acquired accurate information on how the channel responds to predesigned inputs [3].

In the case of radar systems, the channel between the radar transmitter and radar receiver (which can be either separate or combined in a single physical node) and its characteristics are mainly important for determining the presence, locations or velocities of passive objects. For this purpose, radar systems emit predefined waveforms and, by observing the scattered and echoed signals that return, attempt to characterize the surrounding environment [1][4].

3.1.2 From Coexisting to Integrated Sensing and Communication Systems

Radar and communication systems, including cellular systems, have traditionally been designed to operate in separate spectrum bands. This lets them be individually optimized, which is helpful for enabling them to perform with high spectral efficiency as intended. However, this design approach incurs high overall costs. It also makes it necessary to allocate guard bands and minimize out-of-band emissions in order to prevent intersystem interference. It is essential to carefully design and deploy them in order to prevent unwanted out-of-band emissions in the forms of harmonics, intermodulation spurs and spectrum regrowth [5].

An alternative approach is to design coexisting systems that share some parts of frequency bands and use spectrum sharing techniques, such as spectrum shaping, power control and directional communication with beamforming and spectrum sensing. In fact, 5G utilizes shared spectrum in the sub-6 GHz and mmWave frequencies, where devices must coexist with other wireless systems; examples include those used for airport surveillance (2700-3000 MHz, 3100-3500 MHz) and military radar (3450-3550 MHz). Similar to the use of separate spectrum bands, a coexistence-based design approach lets these services be operated relatively independently of one another and also individually optimized, but at the expense of potentially large intersystem interference that can only be mitigated with complex solutions. Since separate hardware and sites are required for deployment, this approach is also costly [6].

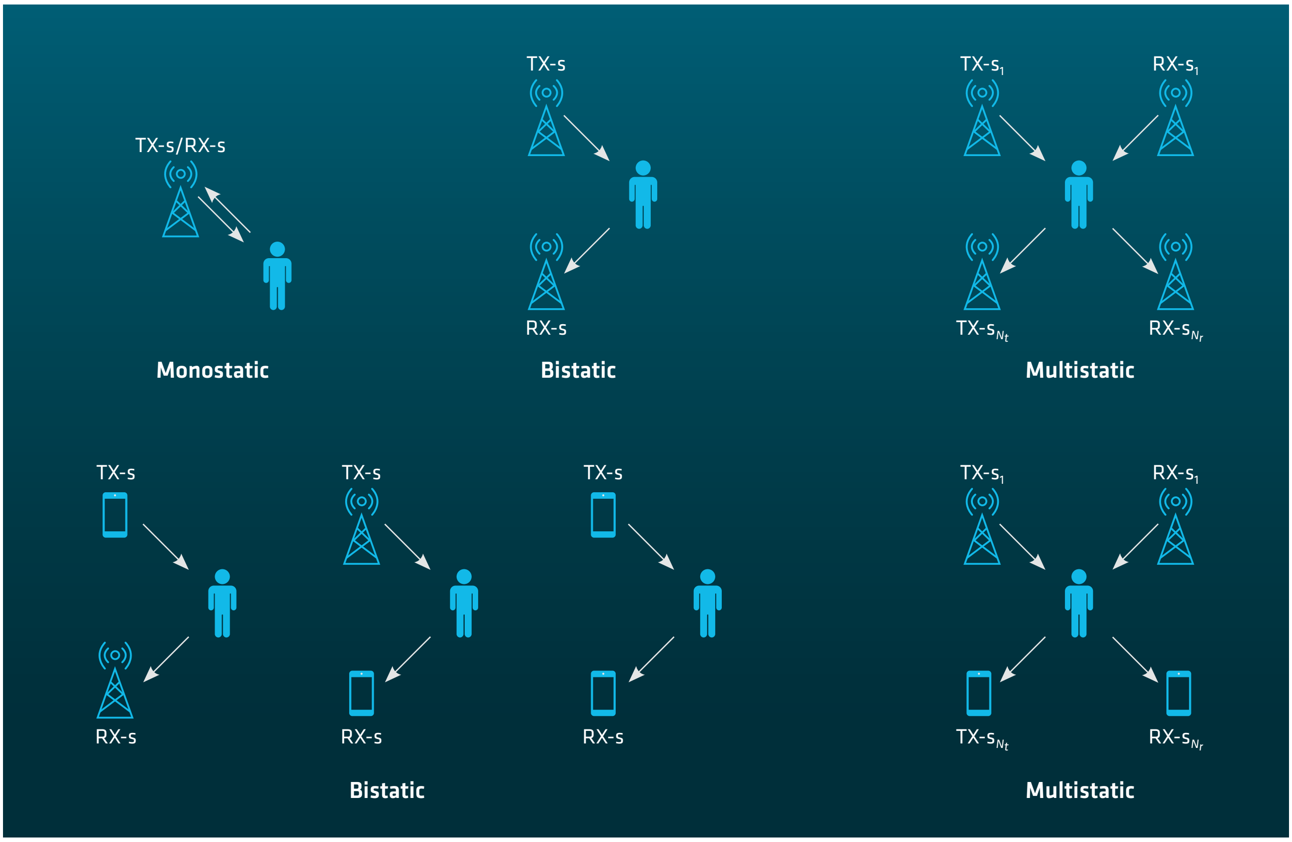
The described disadvantages of separately designing and deploying communication and radar systems have given rise to solutions involving loosely integrated sensing and communication systems that share the same deployment sites and, to some extent, also the same hardware and spectrum. In this approach, each of the two systems separately transmits signals in time, frequency, code, space and/or polarization domains. This makes it possible to design individual signals and waveforms while greatly reducing intersystem interference. Reusing sites and some hardware can make the associated deployment and operating costs lower than with the other mentioned designs. However, this scheme has the drawback of lower spectral efficiency as a result of partitioning resources, as well as unused resources in some of the mentioned domains [6][7].

A fully integrated sensing and communication system (ISAC) can potentially achieve the greatest overall spectral efficiency by concurrently using communication and radar signals with no or only minimal mutual interference. ISAC systems entirely share transmitter hardware and, to a considerable extent, also receiver hardware. It is therefore necessary to design and optimize dual-purpose signals and signal processing algorithms for them [8][9][15]. Considerable challenges also need to be met to enable full-duplex transmission or ensure high-precision synchronization among infrastructure nodes and/or UE while managing shared use of resources over control and user data channels for communication and sensing purposes [10][15].

In radar systems, as already mentioned, channels connecting a radar transmitter (TX-s, see Figure 1) to one or more radar receivers (RX-s) and their characteristics are the basis for detecting and tracking objects of interest. Depending on how the TX-s and RX-s nodes are arranged, it is possible to perform monostatic, bistatic and/or multistatic sensing as illustrated above. With monostatic sensing, TX-s and RX-s functionalities are implemented in the same physical entity, such as a cellular base station. To prevent the separate signal transmission and reception periods around the base station from causing blind spots, the base station must continuously transmit signals and analyze the echoes that arrive back, which calls for in-band full-duplex capabilities. Implementing full-duplex transceivers in large-scale systems is very challenging, however. This is due on the one hand to the demanding requirements that must be met to provide large (>110 dB) self-interference cancellation capabilities, and on the other to significant levels of interference between sectors and base stations [10].

Bistatic and multistatic ISAC architectures and algorithms are attractive because of their ability to capture and analyze scattered and reflected sensing signals at multiple RX-s nodes, resulting in improved detection and tracking. In addition to exploiting spatial diversity and improving sensing performance, bistatic and multistatic ISAC may also be easier to implement because no full-duplex hardware is needed: the transmitter TX-s and receiver RX-s nodes are physically separated from one another. On the other hand, deploying bistatic and multistatic ISAC does pose some challenges, such as for synchronizing and orchestrating the sensing nodes. When UE is employed as Tx or Rx nodes in bistatic or multistatic radar, it is essential to accurately determine the positions of these devices; this may be challenging in some use cases. In addition, if UE is employed as RX-s nodes then communication

Figure 1: Examples of monostatic, bistatic and multistatic sensing in a cellular system (Tx: transmitter, Rx: receiver; the "s" indicates sensing functionality, so TX-s transmits a sensing signal while RX-s receives one)



Source: 5G-ACIA / ZVEI e. V.

resources are needed for localizing and tracking objects and combining RX-s measurements in a central processing unit [11].

3.1.3 ISAC and Perceptive Cellular Networks

As already discussed, ISAC systems are now attracting considerable interest in the academic and industrial research communities. This is because of the benefits of fully integrated radar and communication systems, which are now being enabled by advanced antenna systems and the ubiquitous coverage of 5G systems. Perceptive cellular networks are a natural next step in the evolution of point-to-point ISAC toward future cellular networks [6]. Depending on the sensing mechanisms used, base stations and/or UE can be deployed in a perceptive cellular network to implement effective self-interference cancellation techniques that facilitate full-duplex communication. Alternatively, sensing can be implemented with bistatic signals, with the radar transmission and reception nodes as physically distinct entities.

In many of these use cases, ISAC can deliver two types of benefits as opposed to relying on purpose-built sensors:

- Supplementary sensing over the cellular network: in this case, deploying ISAC in the ubiquitous cellular infrastructure can help detect objects that are not picked up by existing sensors. A good example is when a vulnerable road user driving behind another vehicle fails to be spotted by sensors installed on other vehicles [12].
- Cost savings: ISAC can save significant costs in scenarios in which a cellular network eliminates the need to deploy purpose-built sensors. Examples include geofencing, sensing of parking spaces, counting and classification of vehicles, detection of unauthorized drones and detection and localization of automated guided vehicles and robots in factories.

Adding radar functionality to existing mobile networks makes it possible to cooperatively capture, transmit and fuse sensor data. Depending on the use case, sensor types and quantity of captured data, ISAC will open up opportunities to capture additional information on the environment, for example for classifying and kinematically predicting multiple targets.

3.1.4 Resource Sharing Approaches in ISAC systems

A basic consideration with ISAC is that – since the positions of objects are unknown – time-variable directional beam sweeping is typically required for sensing. This contrasts with communication with active objects, which require stable, accurately pointed beams to achieve beamforming gains and are able to use CSI to achieve a high signal-to-noise ratio with, for example, maximum ratio transmission or zero-forcing transmission [13][14].

A multibeam is a suitable beamforming waveform that has more than one main lobe and can be steered using, for example, a single analog antenna array. The main lobe is used to transmit toward a target receiver, while forming and sweeping lateral lobes sense in the angular domain. Multiple concurrent transmission beams utilizing CSI can support efficient beamformed communication, and additional sweeping beams or lobes can be used to sense the environment around the TX-s node (for example, a base station)[8][13][14]. When multiple RF chains are available at the transmitter, the Tx-s node can separate the communication and sensing beams using spatial multiplexing, and potentially also create subbeams [8][15].

3.1.5 Sensing for Enhancing Communication Performance

In addition to providing a new service to end users, ISAC can also improve communication [29][30] in the Industrial Internet of Things (IIoT). While using the same RF spectrum resources, ISAC technologies integrates environmental sensing with data transmission. Besides improving network capacity, this dual functionality may also improve QoS by enabling more intelligent and responsive network management. Here are some key areas in which ISAC can improve wireless communication:

1. **Sensing-assisted resource allocation**
   a. Optimized allocation: ISAC uses sensing to capture data on locations and line-of-sight conditions, which can then be used to intelligently allocate beamwidth, power and time slots. This in turn improves link reliability, reduces latency and increases spectrum reuse.
   b. Predictive resource preparation: ISAC can be used to anticipate the trajectories of moving users or devices. Resources can then be prepared in advance to enable seamless handovers and uninterrupted service, which in turn minimizes link outages and maintains a strict QoS.
2. **Sensing-assisted beam management**
   a. Fast beam training and robust tracking: ISAC systems enable rapid beam training to quickly establish optimal communication paths and perform robust tracking to maintain stable links, even if devices change their orientation or position.
   b. Precise beam prediction: Predictive algorithms use sensed data to anticipate future device positions and orientations, proactively adjusting beams to ensure uninterrupted, robust communication links and improving network efficiency.
3. **Sensing-assisted channel estimation**
   By continuously sensing and correlating the CSI with the user's location and environmental conditions, ISAC can significantly reduce the need to frequently transmit reference signals. The diminished overhead frees up network resources.

Table 1: ISAC use cases from 3GPP TR22.837 [18]

Application area	Use cases
Security/safety	Intruder detection in smart homes; pedestrian/animal intrusion detection on highways; sensing of flooding in smart cities; intruder detection around smart homes; sensing for railway intrusion detection; sensing for UAV intrusion detection; public safety search and rescue or apprehend; UAVs/vehicles/pedestrians detection near smart grid equipment; sensing for traffic management at tourist spots
Smart transportation	UAV flight trajectory tracing; network-assisted sensing for preventing UAV collisions; sensing to determine whether parking spaces are occupied; vehicle sensing for ADAS; accurate automotive sensing systems for navigating and maneuvering when there is no RAN service; sensing at crossroads with/without obstacles; detection of blind spots
Factories	AGV detection and tracking; prevention of AMR collisions; integrated sensing and positioning
Health	Contactless sleep monitoring service; health monitoring at home; service continuity of unobtrusive health monitoring; roaming for sensing of sports monitoring
XR/immersive interactions	Seamless XR streaming; sensing-based immersive experiences; coarse gesture recognition for application navigation and interaction
Agriculture etc.	Rainfall monitoring
General	Transparent sensing use cases; protection of sensing information; sensor groups

Source: 5G-ACIA / ZVEI e. V.

3.2 Overview of ISAC Use Cases

Numerous use cases have been proposed within the scope of activities to study and standardize ISAC. This section provides an overview of the proposals advanced by major standardization organizations such as 3GPP, IEEE and ETSI ISG THz as well as representative research initiatives such as the IMT-2030 6G Promotion Group, the one6G association Hexa-X and Hexa-X-II projects. The use cases are categorized based on their core applications, thus laying the groundwork for identifying more potential industrial applications and use cases for ISAC.

3.2.1 ISAC Use Cases in 3GPP

The 3GPP SA1 working group released its "Study on Integrated Sensing and Communication (FS_Sensing)" in September 2023. A technical report (TR22.837 [18]) was subsequently compiled on the basis of that study. It contains an overview of over 30 ISAC use cases, which are listed in Table 1 below.

3.2.2 Sensing Use Cases of IEEE Task Group 802.11bf

The IEEE Task Group 802.11bf (WLAN Sensing) is working to add radio sensing capabilities to the WLAN standard. The use cases it has proposed [20] are summarized in the following table.

3.2.3 ISAC Use Cases in one6G

one6G is a global research association devoted to studying next-generation (6G) mobile network technologies. Its members are companies, research institutes and universities. Its declared aims are to evolve, test and promote next-generation cellular and wireless technology-based communication solutions. By supporting global 6G research and standardization efforts, it is working to accelerate their adoption and overall market penetration while addressing societal and industry-driven needs for enhanced connected mobility, with the ambition of speeding up the development of new services and applications in domains such as advanced autonomous driving, advanced manufacturing, advanced wireless e-health, remote education etc.

one6G has released a series of white papers and position papers [21][22][23] on various use cases and the enabling technologies of 6G. The ISAC-related use cases among them are listed in the following table.

3.2.4 ISAC Use Cases from IMT-2030 6G Promotion Group

The Chinese Ministry of Industry and Information Technology (MIIT) established the IMT-2030 (6G) promotion group in June 2019. Its organizational structure is based on that of the original IMT-2020 (5G) promotion group. Its members include major Chinese operators, vendors, universities and research institutions. The group is the main platform for bringing together China's industry- and university-based forces, promoting China's sixth-generation mobile communications technology research and fostering cooperation and international exchanges of views. The 6G Promotion Group has released a research report [24] on the requirements and application scenarios of 6G ISAC, proposing more than 20 different ISAC application scenarios across eight sectors: transportation, industry, agriculture, logistics, medical, entertainment, social services and smart homes. Of these, the following are relevant to industry:

3.2.5 ISAC Use Cases in the Hexa-X and Hexa-X-II Projects

The EU-funded Hexa-X project is a significant initiative aimed at shaping the future of 6G technology. It brings together leading industry players, research institutions and experts to explore and define the possibilities of 6G wireless communication technology. While focusing on developing a holistic vision for 6G, Hexa-X is aimed at addressing the evolving needs of society and industries and setting the stage for the next generation of wireless networks and connectivity.

Table 2: IEEE P802.11bf Task Group (WLAN sensing) use cases

Categories	Use Cases	Description
Room *sensing*	Room sensing	Presence detection, person count
	Smart meeting room	Presence detection, person count, localization of active people
	Motion detection in a room	Motion detection (of humans)
	Home security	Intruder detection in a home
	Audio with user tracking	Tracking persons in a room and pointing the sound of an audio system at them
	Store sensing	Number of persons, their locations and speeds of movement; accuracy is less important
	Home appliance control	Tracking persons and motions; gesture detection
Gesture *recognition*	Gesture recognition – short range (finger movements)	Identification of a gesture from a set of gestures within a range < 0.5 m
	Gesture recognition – medium range (hand movements)	Identification of a gesture from a set of gestures within a range > 0.5 m
	Gesture recognition – large range (full body movements)	Identification of a gesture from a set of gestures within a range > 2 m
	Aliveness detection	Determination of whether a nearby object is alive or not
	Face/body recognition	Selection of a person's identity from a set of known persons
	Proximity detection	Detection of object in close proximity of device
	Home appliance control	Gesture detection
Health *care*	Health care/fall detection	Fall detection, abnormal position detection
	Health case/remote diagnostics	Measurements of breathing rate, heart rate etc.
	Surveillance/monitoring of older people and/or children	Tracking person and presence detection
	Sneeze sensing	Detecting and localizing a target human and sneezing droplet volume
3D vision	3D vision	Building a 3D picture of an environment using multiple stations
In car sensing	In-car sensing/detection	Detection of humans in a car
	In-car sensing	Driver sleepiness detection/detection aid

Source: 5G-ACIA / ZVEI e. V.

Table 3: ISAC use cases from one6G

Use case	Short description
ISAC for V2X in ultradense networks [21]	Improvement of V2X network efficiency in crowded areas by sensing and responding to dynamic environments and objects
ISAC for V2V communication [21]	Ensuring consistent V2V communication by sensing nearby objects, adapting to dynamic environments, controlling power and aligning beams
ISAC for motion control in dynamic factory environments [21]	Environment sensing (e.g. proximity of obstacles, humans or objects of interest), capability of collaborative robots (cobots) to execute precise, low-latency motions, improvement of human-robot cooperation in modern factories
ISAC for cooperative carrying of unknown objects by mobile robots [21]	Coordination of multiple mobile robots based on sensed object characteristics to ensure effective handling in factories
RF or optical wireless communication enhanced by optical sensing [21]	Improvement of RF and optical networks with high-resolution optical sensors for improved beam searches, tracking precision, speed and reliability
Multimodal sensing and communication [22]	Improvement of environmental awareness and efficient data transfer and fusion, which are crucial for beam training and localization
ISAC at THz frequencies [22]	Use of THz bands in 6G networks for unique sensing applications, improved security, precise localization and 3D mapping, with the prospect of improved communication and spectrum use
Cooperative carrying with robots [23]	Use of mobile robots in factories for precise coordination and environmental sensing for handling diverse objects and ensuring effective cooperation
Robots in inventory management [23]	Automation of inventory tasks in supply chains with high-accuracy sensing and positioning systems to improve productivity, increase accuracy and reduce costs
Collaborative robots in industrial environments [23]	Improvement of industrial flexibility with cobots sensing human movements for dynamic assembly lines and safe coexistence with humans
Service robots for healthcare assistance at home [23]	Use of companion robots with high-precision sensors to detect human behaviors, emotional cues and physical states for providing emotional support
Flexible robots for healthcare services [23]	Performance of healthcare tasks such as delivery of medications and cleanliness management with accurate sensing for safe navigation and situational awareness

Source: 5G-ACIA / ZVEI e. V.

Table 4: ISAC application scenarios for industries (source: IMT-2030 6G Promotion Group)

Application scenario	Description
Campus management	6G sensing technology can improve industrial campus management in several ways: 1. Intelligent security: sensing systems for detecting unauthorized entries 24/7 to ensure safety without impacting human health. 2. Intelligent patrolling: smart devices for performing unstaffed inspections to check fire equipment, emergency services and environmental conditions and automatically report anomalies. 3. Vehicle management: imaging and visual perception technologies to read vehicles' license plates and types, followed by navigation and tracking using positioning technology. 4. Personnel management: advanced sensing to improve attendance tracking, detect absences or sleeping on duty, recognize gatherings and monitor the use of safety helmets with high resolution and accuracy.
Production in factories	6G sensing technology can improve factory production in two main areas: 1. Internal logistics: this involves handling materials, packaging and storage with intelligent sorting, asset inventories, AGV scheduling, smart avoidance of obstacles, automatic driving and calculation of optimal paths. Sensing technologies identify and count materials and products during packaging and storage. 2. Smart manufacturing: this involves automation with 6G sensing and positioning technologies; future smart factories will rely on robots with high-precision 3D positioning and flexible arms controlled by wireless signals. Real-time sensing of robot positions and movements enables precise performance of tasks using active and passive positioning technologies such as radio frequency identification (RFID) to ensure efficient and low-power operation.
Quality inspection	ISAC technologies can improve product quality inspection in the industrial sector using terahertz (THz) waves for nondestructive testing. High-resolution THz imaging safely and quickly detects surface and internal defects in materials without emitting any harmful radiation. Product data captured with THz imaging is transmitted over 6G networks to MEC, where AI algorithms analyze it in real time to ensure adherence to quality standards. This process enables real-time detection of defects, automatic alarm activation, quality traceability and model sharing across production lines.
Conveyance of goods	In intelligent logistics systems, conveyor belts require high-accuracy sensors for detecting the presence, height and position of items and checking for belt alignment. ISAC technologies with radio waves can improve reliability and accuracy in dusty environments, ensure precise identification and prevent blockages and damage.
Sorting of goods	In logistical sorting systems, it is crucial to accurately measure the distance to sorting equipment, as well as the placement, volume and weight of and logistical information on goods. Sorting machines handle 2,500 to 3,500 items per hour, which calls for high precision and sensor responsiveness. Current systems use pressure sensors, image sensors and RFID readers for detection, since 6G ISAC cannot yet detect weight, barcodes or IDs, making it challenging to replace existing methods with 6G-based solutions.
Handling of goods	In logistics, goods handling involves moving items within factories or warehouses and between facilities and vehicles, which requires high stability, precise navigation, accurate loading and avoidance of obstacles to prevent damage or loss. AGVs have replaced manual handling but require real-time sensory capabilities in order to navigate accurately. Although millimeter-wave ISAC is a potential alternative to current sensors, currently it only meets general performance requirements and is not suitable for high-value cargo scenarios that require high precision such as 0.2 mm distance resolution.
Stacking of goods	For stacking goods, stacker cranes in automated warehouses store and retrieve items, which requires precise distance sensing to prevent imbalances and avoid scattering or toppling containers. Accurate distance measurements are crucial for preventing collisions with walls, ceilings, columns and lights and ensuring safe, efficient handling and storage.
Warehouse management	Warehouse management involves three crucial aspects: 1. Temperature and humidity monitoring to ensure the quality of perishable and fragile goods by continually monitoring environmental conditions. 2. Security monitoring and surveillance to detect fire hazards and unauthorized access, with prompt detection and alarms. 3. Use of RFID tags to speed up identification, localization and retrieval of goods for dispatch. This integrated approach ensures safe, high-quality and efficient storage and handling of goods.

Source: 5G-ACIA / ZVEI e. V.

Hexa-X's deliverable D1.2 [25] proposes 23 use cases grouped into five categories. Deliverable D3.1 [26] covers localization and sensing use cases with specific KPIs and gap analyses, which are listed in Table 5.

Of the Hexa-X project's proposed sensing use cases, the following are particularly relevant to industrial automation:

- Small-coverage, low-power micro-networks in production and manufacturing networks
- Digital twins for manufacturing
- Gesture recognition for human-machine interfaces
- Sensing and mapping of the environment
- Sensing of objects on which robots/cobots execute certain tasks
- Autonomous supply chains

The Hexa-X-II project follows in the tracks of the Hexa-X project, which established a foundation for the global communication network of the 2030s by developing the 6G vision and basic concepts, including candidate key technology enablers. The ongoing work on Hexa-X-II is progressing from research to systemization analysis, early validation and proof of con-

Table 5: ISAC use cases from the Hexa-X project

Use case families	
Sustainable development	E-health for all
	Earth monitor
	Institutional coverage
	Autonomous supply chain
Immersive telepresence for enhanced interactions	Gesture recognition for human-machine interfaces
	Augmented reality
Local trust zones for human and machine	Precision healthcare
	Sensor infrastructure web
	Infrastructure-less network extensions and embedded networks
	Automatic public security
	Local coverage for temporary use
	Small-coverage, low-power micro-networks in networks for production and manufacturing
Massive twinning	Digital twins for manufacturing
	Immersive smart cities
	Digital twins for sustainable food production
Robots to cobots	Environmental sensing and mapping
	Sensing of objects on which robots/cobots execute certain tasks

Source: 5G-ACIA / ZVEI e. V.

cept. Based on the 6G key enablers connecting the human, physical and digital worlds, it is proceeding to advanced technology readiness – validated technology – that includes the key aspects of modules, protocols and interfaces, and data. The Hexa-X-II deliverable D1.2 [27] proposes six families of use cases:

- Collaborative robots
- Physical awareness
- Immersive experience
- Digital twins
- Trusted environments
- Fully connected world

Sensing-related capabilities are regarded as relevant to five of these (all but the last family). Where industries and automation are concerned, the following use cases proposed in Hexa-X-II D1.2 are particularly relevant:

- Cooperating mobile robots
- Autonomous embodied agents within flexible manufacturing
- Industrial sensors network for safe production and manufacturing
- Immersive interactive experience with VR, AR and MR
- Smart maintenance

3.2.6 ISAC Use Cases from ETSI ISG THz

In January 2024, the ETSI Industry Specification Group (ISG) Terahertz (THz) released a report [28] proposing several ISAC use cases for THz communication systems.

3.2.7 Categorization of ISAC Use Cases

1. **Object detection and tracking**
   This involves identifying and monitoring the positions and movements of physical objects in real time using wireless signals. The objects include AGVs (automated guided vehicles), AMRs (autonomous mobile robots), automotive vehicles, drones and various kinds of goods.
2. **Human detection and tracking**
   Similar to detection and tracking of objects, this activity specifically focuses on monitoring the position and movements of humans, which is crucial for applications such as workplace safety, intruder detection, smart homes and care of the elderly. The sensing function must also be able to differentiate between humans and inanimate objects.
3. **Human gesture sensing**
   ISAC can detect human gestures and translate them into control data for machines in both the real world and virtual environments, such as XR applications. This capability enables touchless interactions among humans and machines in both real and virtual environments.
4. **Human vital sign sensing**
   ISAC can remotely monitor vital signs such as heartbeat and respiration rates by analyzing Doppler frequency changes in radio signals or by using photoplethysmography (PPG). It is useful in healthcare for monitoring patients without the need for wearable devices that require body contact. It can also be used to distinguish humans from inanimate objects.
5. **2D/3D environment reconstruction**
   ISAC can analyze wireless signals to create two-dimensional or three-dimensional models of environments, which are valuable for mapping, XR and improving communication and localization.
6. **Material sensing**
   ISAC can identify materials based on how they interact with wireless signals within a defined frequency range. This can be used for quality control in manufacturing or for detecting hazardous substances.

7 **Micro-Doppler sensing**
   ISAC captures the Doppler shifts caused by fine movements and provides detailed information on the motion characteristics of objects. It is useful for detecting gestures, vital signs, deformations and vibrations.

8. **Object size measurement**
   ISAC can estimate objects' dimensions by analyzing how wireless signals interact with their surfaces; this is useful in logistics for making the best possible use of space.

9. **Sensing for improving communication**
   Sensing of environmental parameters can be used to improve communication by adjusting the parameters of wireless networks for greater efficiency and reliability.
10. **Sensing for improved localization**
    The localization function of the cellular system, which relies on active transmission of signals by the target, can be improved by incorporating passive sensing capabilities for greater accuracy.
11. **Integration of non-3GPP sensors**
    This involves integrating sensors – such as cameras, LiDAR, radar, sonar, Wi-Fi, Bluetooth or RFID devices and other media not covered by the 3GPP standards – to expand the capabilities of ISAC systems beyond passive sensing with radio waves.
12. **Imaging**
    By interpreting wireless signal reflections, ISAC can be used similarly to radar and sonar to generate images. This can be useful for through-wall imaging and other applications.
13. **Ensuring the security of sensing information**
    Ensuring that data obtained by sensing is secure from interception and unauthorized access is a key aspect of ISAC, especially for sensitive applications.

Table 6: ISAC use cases from ETSI ISG THz

Use Case	Description
Remote surgery	The use of THz technologies on the remote site extends human sensory capacities through the use of imaging, spectroscopy and high-sensitivity temperature detection.
Cooperative mobile robots	Cooperative mobile robots require high-precision sensing and localization in the THz spectrum to interact effectively with their environment, other robots and moving objects for tasks such as assembly and logistics.
Work with hazardous materials	Robots designed for handling chemicals and hazardous materials protect human workers by operating in dangerous or inaccessible environments, and provide enhanced sensing and precision that exceed human capabilities.
Remote education	THz-based sensing can capture the environment, including the weather, landscape, flora and fauna. It can enable precise characterization of on-site conditions and a teacher's motions and gestures, as well as the required low-latency data transfers.
Interactive immersive XR	THz-based sensing enables precise characterization of environments, including the weather, landscape and living organisms, and uses low-latency data transfer for capturing movements and gestures.
Mission-critical XR	Mission-critical XR, prioritized for scenarios such as public safety, calls for high reliability and low latency; in such setups, the commanding vehicle uses THz sensing complemented by additional data from robots and drones.
Real-time industrial control	THz signal sensing enhances industrial monitoring by supervising machine operations and supporting process control.
Simultaneous imaging, mapping and localization	Next-generation communication devices will integrate environmental sensing, imaging, mapping and localization, utilizing features such as large-scale antenna arrays operated at above 100 GHz for precise localization and high-resolution imaging, supported by computer vision data to streamline RF sensing.
Local area collaboration for vehicular applications	For V2X applications in which low latency and ultra-high reliability are crucial, the THz spectrum facilitates superior communication and precise sensing.

Source: 5G-ACIA / ZVEI e. V.

4 Potential Industrial Applications of ISAC

Based on the overview of the ISAC use cases related to standardization and research activities in the previous chapter, the potential industrial applications of ISAC are identified and illustrated in the following.

4.1 Detection and Tracking of Ground and Aerial Vehicles

In today's dynamic industrial environments, including factories and chemical processing plants, autonomously guided vehicles (AGVs) and various other kinds of ground transportation have ushered in major increases in operational efficiency. They are indispensable for transporting materials, tools and products, among other reasons because of their ability to quickly adapt to meet the needs of highly customizable production processes. It is also increasingly vital to integrate mobile robots, which are able to precisely and flexibly navigate a wide variety of manufacturing settings.

At the same time, the concurrent presence of mobile machinery and human workers in the same space poses significant safety challenges and especially the risk of collisions. In order to use these vehicles and robots to improve production processes, it is therefore essential to precisely know their locations and trajectories at all times. Aerial vehicles, and especially unpiloted aerial vehicles (UAVs), also pose security risks in the form of unauthorized intrusions, which can jeopardize the safety and integrity of sensitive industrial operations.

Leveraging the capabilities of ISAC in cellular systems can provide a transformative solution to these challenges. ISAC enables real-time tracking of both ground and aerial vehicles without requiring the latter to actively transmit beacon signals. In addition to improving safety by supporting dynamic path planning and advanced collision avoidance mechanisms, this technology also increases operational efficiency by providing critical data on vehicle positions and movement patterns.

ISAC's sophisticated sensing capabilities also include detecting unauthorized UAVs and ground vehicles and facilitating immediate and effective responses. The dual functions of communication and sensing ensure consistently high levels of security and operational continuity in industrial environments, which is crucial for modern high-stakes manufacturing and processing industries.

In summary, deploying ISAC in industrial settings not only mitigates risks associated with vehicle movements and potential intrusions, but also propels the industry toward a future in which technological integration and improved safety combine to enable more resilient and efficient operations.

4.2 Detection and Tracking of Humans

To ensure safety and efficiency, in a wide variety of industrial environments it is vital to reliably detect and track human workers. ISAC makes it possible to monitor their presence and movements in real time. This capability is vital for preventing accidents, since it ensures compliance with safety protocols by, for example, designating danger zones around hazardous machinery and autonomous systems, automatically halting operations when required and preventing collisions.

In addition to ensuring greater safety, it is also possible to significantly improve efficiency across a wide range of industrial settings by detecting and tracking humans. Real-time data can be used to optimally allocate tasks while assigning the closest available worker to handle a manual intervention, thus minimizing downtime and improving the workflow. Analysis of workers' movement patterns also helps identify inefficiencies and bottlenecks, resulting in improved processes and streamlining operations. These technologies foster a safer, more productive industrial environment while benefiting workers and improving overall operational performance.

4.3 Tracking and Size Measurement of Goods

In logistics, ISAC facilitates real-time tracking of goods throughout the supply chain. This includes monitoring the location, condition and movement of products, which is crucial for managing inventory, optimizing logistics operations and ensuring timely delivery.

In warehouse environments, it is vital to measure and efficiently sort, handle, stack and monitor goods. ISAC can be used to track them in real time and ensure that they are accurately identified and categorized as they advance along the supply chain from receipt and storage to picking and dispatch.

Determining the size of items is essential in order to optimally utilize storage space and ensure safe handling and stacking. Automated warehouse systems can measure arriving goods and determine where they can be most efficiently stored while maximizing space use and ensuring stable stacks. This reduces the risk of damage to goods and improves overall warehouse safety. Size data can also be used to control automated handling equipment such as robotic arms and conveyor systems for sorting and moving items more efficiently. This reduces the need for manual labor and accelerates processes.

Real-time tracking and size data is also important for warehouse monitoring and management. It lets warehouse managers track inventory levels and storage locations, resulting in better planning and decision-making. Among other things, knowing the exact dimensions and locations of items helps optimize picking routes, reduce the time that workers take to get between two points and speed up order fulfillment. It also helps keep accurate inventory records, prevents discrepancies and ensures that goods are available and readily accessible when needed. The use of tracking and size measurement technologies in industrial environments improves overall efficiency, reduces costs and improves the quality of service.

4.4 Quality Inspection

A 6G ISAC system with high-frequency radio signals (and especially a THz signal) is well-suited for quality inspections. This is because of these signals' short wavelengths, highly available bandwidth, high-resolution imaging capabilities and ability to penetrate a variety of nonconducting materials such as plastics and ceramics. Penetrative imaging (the use of imaging technologies to photograph internal structures) can be used to nondestructively examine composite materials for internal defects such as delamination and cracking. THz imaging can also be used to measure the thickness and uniformity of coatings and paints to ensure consistent application and prevent corrosion and wear.

THz imaging is also invaluable for inspecting electronic components and semiconductor devices, since it reveals hidden defects and impurities that traditional optical methods might miss. Integrating THz imaging into production lines enables real-time monitoring and immediate correction of defects, thus reducing waste and increasing the overall efficiency of production. By using terahertz signals, industries can achieve superior quality control, improve the reliability of products and reduce operating costs.

4.5 Safety and Health at Work

In industrial environments, ISAC can be very helpful for monitoring workers' health and safety by checking vital signs and recording accidents. It can use high-frequency radio in the mmWave and sub-THz ranges to continuously monitor workers' physiological parameters, such as heart rate and respiration, in real time. This enables early detection of health issues to ensure that workers receive prompt medical attention when required. For instance, if a worker's vital signs indicate distress or an abnormal condition, the system can automatically alert medical personnel and supervisors.

The use of ISAC technologies can also make industrial environments safer for workers. For example, ISAC systems can improve workplace safety by detecting falls and other accidents. If one is detected, the ISAC system can instantly notify emergency responders and communicate the exact location, thus permitting significantly faster responses. This capability is crucial for minimizing the repercussions of injuries and improving overall safety.

4.6 Environmental Mapping

High-resolution maps are essential in order for automated and semiautomated systems to efficiently find and follow paths while avoiding obstacles. ISAC can continually update them in real time to reflect changes in the environment, thus ensuring that AGVs and AMRs can navigate safely and efficiently. This capability reduces the risk of collisions and improves the overall efficiency of operations, since machines can dynamically adjust their routes based on up-to-the-minute data.

Knowledge of environments collected from ISAC systems can also be used to improve wireless communication and positioning in industrial settings. Detailed maps are an important prerequisite for planning and improving communication networks, since they help identify potential signal blockages and optimally place wireless nodes. This in turn means improved network coverage, reliability and capacity. Accurate environmental data also improves positioning accuracy, which is critical for coordinating the movements of multiple automated systems and performing tasks that require precise tracking of locations, such as inventory management and equipment monitoring.

4.7 Predictive Maintenance

In industrial settings, ISAC can monitor the condition of machinery and facilities by sensing vibrations and capturing other important metrics. By continuously collecting and analyzing data on equipment performance, ISAC systems are enabled to detect anomalies and signs of wear and tear that may indicate an impending failure. This real-time monitoring enables a proactive approach to maintenance (known as predictive maintenance) in which issues are identified and addressed before they can lead to equipment breakdowns.

ISAC-enabled predictive maintenance significantly reduces downtimes and costs. The ability to anticipate failures makes it possible to schedule maintenance work during off-peak times to reduce disruptions. Addressing problems before they can escalate also prevents costly repairs and prolongs the useful life of machinery. Besides enabling smoother, more efficient operation, this approach increases the overall reliability and productivity of industrial facilities.

4.8 Human-Machine Collaboration

In industrial environments, ISAC can employ intuitive control mechanisms such as gesture recognition to improve interactions between humans and machines. ISAC systems can accurately interpret human gestures and movements, a capability that can be taken advantage by workers for seamlessly controlling machinery and equipment. Such natural, intuitive interactions minimize the need for physical interfaces and manual controls, simplify complex tasks and flatten the learning curve for operating advanced machinery. In addition to increasing efficiency, gesture recognition by ISAC ensures safer working conditions: workers can operate machinery from a safe distance, which reduces their exposure to potential hazards. For instance, a worker can use a simple hand gesture to instruct a robotic arm to halt or adjust its operation, thus avoiding the need for direct contact with moving parts. This capability is particularly valuable in environments in which quick responses are crucial for preventing accidents. Overall, ISAC's ability to facilitate intuitive human-machine interaction results in a safer, more efficient industrial workspace in which technology adapts to human needs instead of the other way around.

4.9 Machine-Machine Collaboration

In industrial environments, ISAC can use precise relative positioning and reliable communication to allow machines to collaborate with one another more effectively. In the first case, ISAC enables machines to accurately sense their relative positions and navigate and operate very precisely in close proximity to one another. Accurate positioning is crucial for tasks that require coordinated movements, like for assembling parts or performing intricate maneuvers within a limited space. By constantly monitoring their surroundings and the positions of other machines, these systems can avoid collisions and optimize their paths to efficiently execute tasks. Second, machines can continuously share information on their states and movements and on environmental conditions in real time. This enables all collaborating machines to remain synchronized while dynamically adjusting their actions in response to input from their peers. For cooperative carrying tasks, for example, robots can coordinate their movements to evenly distribute a load, navigate around obstacles and deliver items to precise locations without the need for human intervention. This combination of accurate relative positioning and real-time communication enables ISAC-equipped machines to work together safely and efficiently, thus significantly increasing productivity and operational effectiveness in industrial settings.

4.10 Sensing for Improved Localization in Industrial Environment

Mobile machines or goods can be localized much more accurately and reliably if ISAC is integrated with a conventional localization service. 3GPP TR22.837 [18] Section 5.32 proposes augmenting the positioning and sensing capabilities of cellular systems to achieve more accurate tracking by autonomous mobile robots (AMRs) and automated guided vehicles (AGVs) in smart factories, especially in high-traffic areas where there is a need for this. They can obtain data from the physical AMR/AGV body via reflections of the sensing signal.

5 Industrial Use Cases and Requirements

This is the core part of this document. The aim is to compile a set of ISAC use cases across all industrial and automation applications such as factory and process automation, logistics, digital twins, flexible manufacturing, Industrial 4.0 and so on. Conventional (e.g. camera-based) sensing may not be sufficiently effective in factories with typical layouts, equipment and processes. Barriers such as walls, furniture, large machines, smoke and liquids can block the line of sight, making it necessary to install sensors extremely densely.

Wireless sensing is more robust and able to detect movements and the presence of other phenomena. In addition to the constraining factors mentioned above, some conventional sensing technologies can also raise privacy issues. Cameras, microphones and wearables can capture data to which privacy concerns apply, while the risk of this is less with wireless sensing.

Despite this, ISAC can be designed to collaborate with conventional sensing modes. Especially in scenarios with campus networks installed in factories, sensors are already in place and it can therefore be more cost-effective to add features.

5.1 Gesture Recognition in Industrial Environments

5.1.1 Description

Interaction of robots and humans in factory environments is a dynamically evolving aspect of modern manufacturing. This collaboration involves various levels of cooperation, communication and coordination between robotic systems and human operators. Robot-robot interactions are also a possibility.

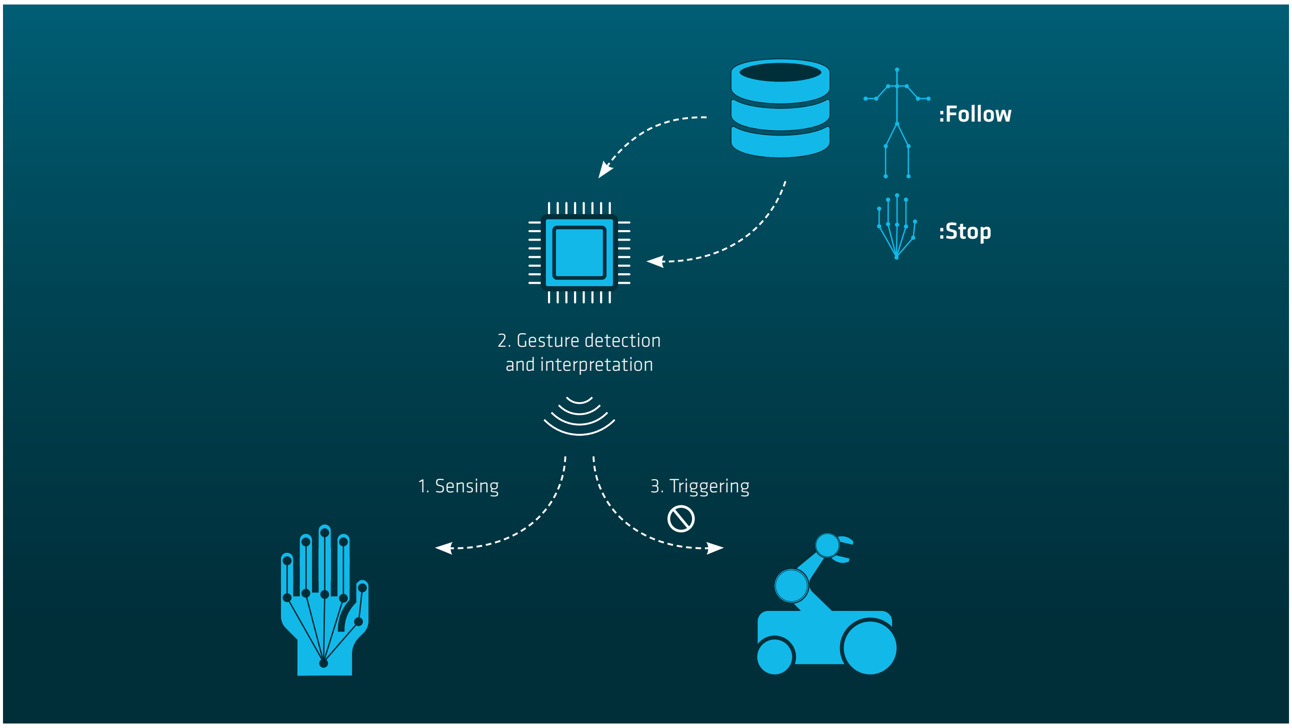
Cobots (collaborative robots) are designed to directly and collaboratively interact with humans, often in close proximity. They complement human capabilities, especially for performing tasks that are repetitive or physically demanding or require a high degree of precision. Efficient interaction ensures that cobots and humans can work together seamlessly, leveraging each other's strengths to maximize the overall productivity of manufacturing processes.

Various (industrial) robot types already exist. They include AGVs, which typically travel on well-defined tracks within factories, and AMRs that are equipped with sensors and able to make real-time decisions for avoiding obstacles etc. There are also humanoids, AMRs with human-like capabilities and conventional robotic arms that emulate human arm movements in automated processes like those for picking items, lifting heavy parts or packaging products. Different types of robots types can also be combined to perform specific tasks; this is typically done to automate processes and factories, mostly within separate areas or cages without interacting with humans. Cobots, in contrast, are robots designed to work collaboratively alongside or attached to humans. It is always important for them to include interactive modes, for example for reparametrization or maintenance. With cobots, easy, ongoing and intuitive interaction is key for success.

In some environments and scenarios, (touch) panels and other handheld devices for interacting with robots are impractical – for example, if a worker is wearing heavy protective gloves or needs their hands to perform a concurrent task. In other scenarios, for example when performing certain dangerous tasks, nonstop visual monitoring of the cobot by the human is required. Factory environments can also be too noisy to use a voice interface. In scenarios of this kind, it would be helpful to have an easy and intuitive way of interacting, for example with gestures; this could be described as a touchless interface. Two main functions are required for reading gestures: object detection and pattern recognition.

In contrast to continuous gesture recognition (for example, by moving a mouse pointer on a screen), discrete gesture detection is more appropriate for scenarios involving interactions with a cobot. Typically, a predefined set of gestures is employed, with each of them corresponding to a specific action. Interactions can be additionally enhanced by visual acknowledgements etc. to assist communication between humans and cobots.

Figure 2: ISAC for gesture recognition in an industrial environment.



Source: 5G-ACIA / ZVEI e. V.

Gesture-based interfaces are likely to become more sophisticated and permit the use of a wider range of gestures for more nuanced communication between humans and cobots. Human gestures can be categorized as follows:

- Hand and arm gestures: hand gestures, arm positions and movements, finger positions and pointing directions
- Body gestures: full body actions, motions or poses
- Head gestures: nodding, shaking or pointing with the head
- Facial gestures: winking or closing one or both eyes

When cobots work alongside humans instead of in separate, gated areas, steps must be taken to prevent incorrectly used gesture commands from provoking dangerous situations. Many security concepts for ICT systems focus on encrypting application-to-application data flows. It is also important to ensure that only authorized persons can access and work with sensing data.

Data integrity is generally crucial in connection with sensing in industrial environments and must be seamlessly ensured. Depending on how sensing data is generated and used, physical layer mechanisms (like that described in 802.11.15z with physical layer data integrity for UWB ranging) can additionally support security.

The performance requirements for sensing objects and detecting gesture patterns can vary depending on the gesture set and scenario.

5.1.2 Service Flows

A factory in which such a scenario is implemented requires a mobile network and wireless coverage in the relevant areas. A cellular system with ISAC capabilities requires standardized interfaces for accessing information. The provided information should include a detailed estimate of the margin of error of the provided measurement data.

The steps in the service flow are the following:

Step 1: A worker wishing to take an autonomous mobile robot (AMR) with integrated UE somewhere else to perform a task walks toward it and stands in front of it.

Step 2: The worker laterally raises their arms, which is a predefined gesture for telling the robot to follow.

Step 3: The cellular system uses specialized radio signals from the infrastructure and/or nearby UE to sense the environment.

Step 4: The cellular system processes the sensor data and interprets the gesture.

Step 5: The cellular system forwards the recognized request to the AMR.

Step 6: The AMR follows the worker while the system continually interprets any new gestures.

Here the worker has used gesture detection to deliberately control a nearby machine. This is done intuitively without the need to touch the machine or use a device to issue commands or otherwise control it. This increases the worker's efficiency and productivity.

Machines can also monitor workers to detect any anomalies in their behavior that could require the machines to stop operating. This can help ensure safe factory operations.

5.1.3 Functional Requirements

For recognizing relevant body language in industrial environments, the ISAC system is required to have the following abilities:

1. Monitoring and recognition of a worker's hand gestures.
2. Monitoring and recognition of a worker's limb positions.
3. Monitoring and recognition of a worker's facial expressions.
4. Monitoring and recognition of a worker's body positions.

Table 7: Performance requirements of ISAC for gesture recognition in industrial environments

Scenario		Gesture recognition in industrial environments
Sensing service area		Indoor
Confidence level [%]		99%
Sensing resolution (hand gestures) [32][33]	Horizontal resolution [m]	≤0.02
	Vertical resolution [m]	≤0.02
Sensing resolution (facial gestures) [35]	Horizontal resolution [m]	≤0.002
	Vertical resolution [m]	≤0.002
Sensing resolution (head gestures) [35]	Horizontal resolution [m]	≤0.05
	Vertical resolution [m]	≤0.05
Sensing resolution (body gestures) [36][37]	Horizontal resolution [m]	≤ 0.1
	Vertical resolution [m]	≤ 0.1
Max. sensing service latency [ms]		≤20
Refresh rate [s]		≤0.02
Missed detection [%]		Application-dependent
False alarm [%]		Application-dependent

Source: 5G-ACIA / ZVEI e. V.

5.1.4 Performance Requirements

A sensor's resolution is proportional to the accuracy of recognition. The following figures have been calculated for currently available camera-based recognition systems. No angular resolution for the sensor is given, since it depends on the distance from the subject. A combination of different sensors could be implemented to meet these requirements.

5.2 Vibration Monitoring in Industrial Environment

5.2.1 Description

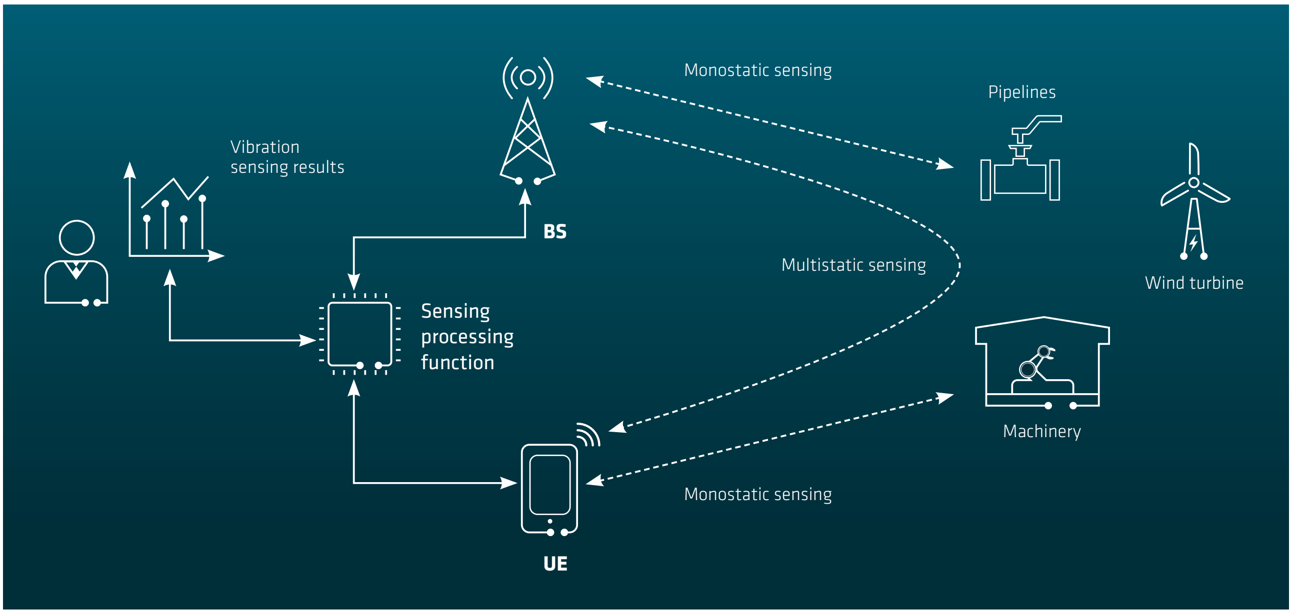
Vibration monitoring in industrial environments, and especially in factory and process automation, plays a crucial role in ensuring the health and operational efficiency of machinery [17]. Vibrations in industrial settings are typically caused by imbalances in rotating parts, misalignments, gear problems, bearing failures and/or loose components. External factors such as nearby machinery or environmental conditions can also contribute. Vibrations have the following negative effects:

- Factory automation: In factory settings, excessive vibrations can cause wear and tear of machines and equipment and reduce their lifespans. It can also cause misalignment of machine parts, resulting in poor product quality or even halting production.
- Process automation: In process industries such as those that produce chemicals or food, vibrations can disturb sensitive processes and reduce product consistency. It can also cause seals to fail in pumps or compressors, resulting in leaks or hazardous conditions.

The ISAC capability of the future mobile network enables an attractive solution for monitoring vibrations in industrial settings, with the following benefits:

1. The use of wireless RF signals can enable contactless measurement. In some challenging environmental conditions, such as high temperatures, hazards or difficult access, it is not feasible to attach vibration sensors.
2. Installing a large number of vibration sensors (such as accelerometers) at different points can pose logistical challenges and increase costs, also for maintenance and replacing batteries. Deploying a single ISAC network is a more flexible solution, making it possible to measure vibrations across multiple and even dynamically shifting locations without these drawbacks.
3. Use of an RF signal makes it straightforward to calculate vibration frequencies by taking advantage of the micro-Doppler effect in the RF signal, provided that it is possible to point the latter at the object of interest.
4. The ISAC enables concurrent measurements by multiple network nodes, which can increase accuracy and prevent blind spots.
5. RF signals can penetrate some materials, such as thin nonmetallic covers, to measure vibrations in components behind them.
6. An ISAC network can cover a wider area and improve responsiveness compared to conventional vibration sensors. This makes it suitable for large-scale industrial environments in which multiple points need to be concurrently monitored.
7. Sensing vibration with ISAC has significant advantages over optical/laser approaches. Radio sensors are robust,

Figure 3: ISAC for monitoring vibrations in an industrial environment.



Source: 5G-ACIA / ZVEI e. V.

provide broad coverage from a single point and require less maintenance. They can also can detect vibrations through nonconductive materials and operate safely without a direct line of sight, which makes them a versatile and cost-effective solution for continuous monitoring.

8. The ISAC network can capture all vibration data and deliver it to the user, and even help analyze it to pinpoint existing failures and predict potential future ones.

In this use case, we consider a factory equipped with a mobile network with ISAC capabilities. The network can provide data connectivity among machines, controllers, sensors and human operators. In addition, RF signals of the mobile network propagate in the factory environment and communicate vibration impacts from multiple sources. They are transmitted and received by base stations and UE that are able to measure the locations of vibrations and vibration frequencies, either independently or jointly.

5.2.2 Service Flows

In this use case, a mobile network that is capable of both data communication and environment sensing is deployed in a factory. The mobile network comprises one or more base stations as well as multiple user devices for providing mobile data connections for communication in the factory. Some or all of the base stations and UE are able to sense vibrations in their surroundings.

The base station and user devices wirelessly exchange data and control messages via both downlink and uplink. If there are vibration sources in the environment, this can induce micro-Doppler frequency changes in in both downlink and uplink wireless signals.

The steps of the service flow are as follows**:**

1. For assessing the health of production facilities, the factory operator needs to measure vibration frequencies and identify the locations of potential vibration sources such as rotating machine components, pipes carrying gas or liquid in parts of the building and so on. The factory operator therefore requests the mobile network to provide vibration sensing information, possibly while indicating the positions of potential vibration sources.
2. The base stations and UE are able to measure micro-Doppler frequency changes in communication signals and measure vibration frequencies from one or more sources.
3. The base stations and UE are also able to capture information on vibration sources, such as which direction they are coming from or even their exact locations. The base stations and UEs can collaborate for measurement and detection purposes.
4. In another case, the base station or UE can transmit dedicated sensing signals for the purpose of detecting the frequency and position of vibration sources. The signal can be monostatically received and processed by the sender itself or bistatically and/or multistatically by other UE or base stations.
5. The mobile network provides information on the captured frequencies and positions of vibrations to the factory operator.
6. For very precisely sensing an object's vibrations, the base station and UE used for this purpose should not be installed on anything that could also vibrate.

The factory operator uses vibration sensing information provided by the mobile network to optimize the production equipment in the factory. Here are three examples of how this can be useful:

1. For detecting vibrations that could indicate that facilities are malfunctioning and need to be immediately repaired.
2. To detect vibrations that indicate that certain machinery may start malfunctioning at some time and should therefore be scheduled for maintenance.
3. To detect potentially harmful resonance of the building structure induced by nearby machinery or vehicles to prevent damage.

5.2.3 Functional Requirements

For monitoring vibrations, the mobile network is required to have the following functionalities:

1. The cellular system used with ISAC must be able to process sensed data to ascertain the frequency of vibrations.
2. Optionally, the cellular system should be able to detect where vibrations are originating.
3. Optionally, the cellular system shall be able to measure the amplitude of vibrations.
4. The detected Doppler shift and, optionally, the amplitudes and location(s) shall be communicated to external applications.
5. Optionally, the raw data of the Doppler shift and frequency spectrum can be provided to external applications for further analysis.

Table 8: Performance requirements for ISAC vibration monitoring in an industrial environment

Scenario		**Detection of vibrations in an industrial environment**
Sensing service area		Outdoor / indoor
Confidence level [%]		95%
Accuracy with which vibration frequencies are estimated (for achieving a certain level of confidence)		1% of ground truth
Accuracy with which vibration amplitudes are estimated (for achieving a certain level of confidence)		10% of ground truth
Accuracy of positioning estimate by sensing (for a target confidence level)	Horizontal [m]	≤1
	Vertical [m]	≤1
Accuracy of velocity estimates by sensing (for a target confidence level)	Horizontal [m/s]	N/A
	Vertical [m/s]	N/A
Sensing resolution	Range resolution [m]	≤1
	Velocity resolution (horizontal/vertical)	N/A
Maximum sensing service latency [ms]		≤3000
Refresh rate [s]		≤3000
Missed detection [%]		N/A
False alarm [%]		N/A

Source: 5G-ACIA / ZVEI e. V.

5.3 Monitoring of Stockpiles

5.3.1 Description

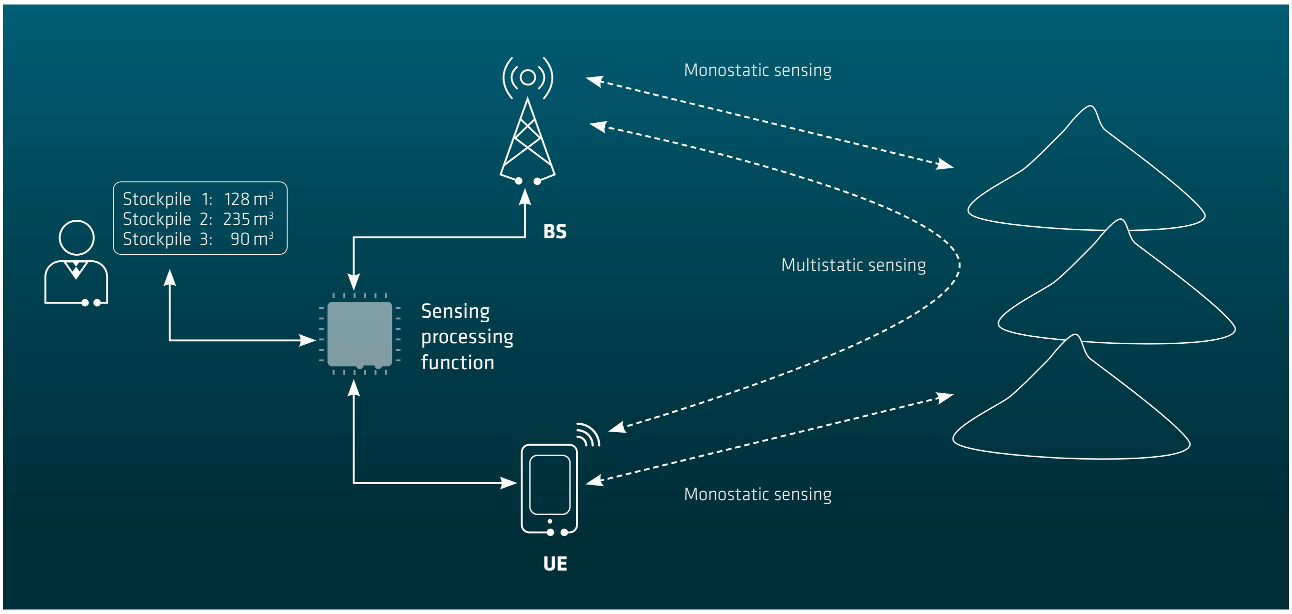
In industrial facilities, monitoring of stockpiles is an essential prerequisite for efficiently managing inventory, ensuring safety and optimizing operations.

- Accurate monitoring helps ensure the availability of materials, prevents overstocking and shortages and supports planning for procurement and production.
- In industrial environments, stockpile monitoring involves continually measuring and managing the quantity and quality of materials that are stored in large piles or stacks.
- Ensuring a consistent supply of raw materials and optimizing production processes are key parts of inventory management. They involve tracking how the quantities and composition of stockpiles change over time, which can be influenced by factors including utilization rates, environmental conditions and supply chain fluctuations.
- Effective monitoring helps predict demand, schedule deliveries and consistently ensure efficient operation.
- These steps are also essential for environmental compliance and workplace safety, since poor stockpile management can cause hazards such as dust emissions or unstable piles.

The use of ISAC technologies for monitoring stockpiles delivers the following benefits:

1. **Reliable operation under adverse conditions:** ISAC is able to operate reliably in challenging environmental conditions such as rain, fog, dust, smoke, hot gases and darkness. This ensures uninterrupted monitoring and precise data capture independently of external factors.
2. **Accurate measurements:** The technology enables precise measurements, which is crucial for effectively managing stockpiles. Accuracy is vital for maintaining required inventory levels, ensuring environmental compliance and preventing hazards, such as dust emissions or unstable formations, that could be caused by poorly managed stockpiles.

Figure 4: ISAC for stockpile monitoring



Source: 5G-ACIA / ZVEI e. V.

3. **Continuous monitoring of dynamic changes:** ISAC enables ongoing tracking of dynamic changes in stockpile conditions. Constant monitoring is essential for quickly adapting to changes in utilization rates, supply chains and environmental conditions.
4. **Integrated sensing and data transfer:** With ISAC, sensing and measurement data are transmitted over the same network. This integration simplifies and increases the efficiency of data management, thus reducing the likelihood of errors or data loss.

Overall, integrating ISAC in stockpile monitoring is a significant advance in industrial operations, enabling more accurate, reliable and efficient management of large volumes of materials under a wide range of conditions.

5.3.2 Service Flow

Mines can be equipped with ISAC-capable devices such as base stations and UE mounted on mining equipment and vehicles. These devices can sense the environment and communicate data. For monitoring purposes, the coordinates of designated areas for stockpiles are entered in the ISAC system. ISAC sensors are used to generate a detailed 3D map of the site, including an initial assessment of the terrain and stockpile locations. A reliable, secure communication network is installed to transmit data collected by ISAC sensors to a central monitoring system.

Steps of the service flow:

1. **Ongoing sensing and monitoring:** ISAC devices continuously monitor designated stockpile areas to detect changes in volume and composition. This data is captured in real time using the integrated sensing capabilities of ISAC technologies, which is also able to make accurate measurements in dusty environments and adverse weather conditions.
2. **Data analysis and processing:** The ISAC system's integrated communication capabilities are used to transmit captured data on stockpile areas to a central processing unit. There advanced algorithms analyze the data to calculate stockpile volumes, identify any anomalies and predict stockpile behavior on the basis of historical data patterns.
3. **Alerts and notifications:** If significant changes in stockpile volumes or potential safety hazards are detected, the system automatically generates alerts. These alerts are sent to the relevant personnel via the communication network, enabling swift action to manage the stockpile effectively.
4. **Operational adjustments:** Based on data received from the ISAC system, mining operations can be appropriately adjusted in real time. This includes optimizing the placement of material on stockpiles, scheduling transportation and efficiently deploying equipment.
5. **Report generation:** The system generates comprehensive reports on stockpiles, including changes in their volume, their material composition and trend analyses. These reports support strategic planning and operational decision-making.

Implementing ISAC technologies for stockpile monitoring in mining results in:

1. **Greater operational efficiency:** The mining operation benefits from optimized stockpile management, reduced waste and more efficient handling of materials.
2. **Greater safety:** Real-time monitoring and alerts contribute to a safer working environment by preventing stockpile-related accidents and enabling proactive management of situations to avert safety problems.
3. **Data-driven decisions:** Access to detailed and accurate data on stockpile volumes and material composition improves strategic planning and allocation of resources.
4. **Environmental compliance:** Improved stockpile management helps comply with environmental regulations and meet sustainability targets by minimizing dust and efficiently managing waste materials.

Using ISAC technologies to monitor stockpiles in mining not only increases operational efficiency and safety, but also supports data-driven decision-making and environmental compliance.

5.3.3 Functional Requirements

In order to monitor stockpiles, the mobile network must meet these requirements:

1. The ISAC-based cellular system must send ranging data to an external application for calculations, for example for ascertaining the heights of stockpiles.
2. Optionally, the cellular system must be able to send comprehensive sensing data, for example in the form of dot clouds, to an external application for calculating a stockpile's shape and volume.

5.3.4 Performance Requirements

Table 9: Performance requirements of ISAC for a stockpile monitoring use case

Scenario		Stockpile monitoring
Sensing service area		Outdoors/indoors
Confidence level [%]		95
Accuracy of positioning estimate by sensing (for a target confidence level)	Horizontal [m]	≤1
	Vertical [m]	≤1
Accuracy of velocity estimate by sensing (for a target confidence level)	Horizontal [m/s]	N/A
	Vertical [m/s]	N/A
Sensing resolution for shape measurement	Horizontal resolution [m]	≤0.2
	Vertical resolution [m]	≤0.2
	Velocity resolution (horizontal/vertical)	N/A
Maximum sensing service latency [ms]		≤1000
Refresh rate [s]		≤1000
Missed detection [%]		N/A
False alarm [%]		N/A

Source: 5G-ACIA / ZVEI e. V.

5.4 ISAC for Optimizing Flexible Production Flows

5.4.1 Description

In today's manufacturing industry, flexible production flows are essential for quickly and efficiently meeting customers' varying needs and expectations. The concept of Everything as a Service" (XaaS) in the context of smart factories [38], shown in Figure 5, is a modular approach in which various production activities and operations can be outsourced as services. They include production systems, transportation, intra- and extra-logistics and staff management, all of which are integrated in a digital infrastructure powered by a network and cloud platform. In this environment, ISAC can be used to increase efficiency and safety by continuously sensing and monitoring the movements of humans, carts and AGVs.

The use of ISAC technologies in environments of this kind can significantly improve safety and operational efficiency. The system is enabled to accurately track and communicate the positions and movements of humans and material transporters on the factory floor. This capability makes it possible to monitor and manage resources, improve safety protocols and optimize production flows, all in real time. The benefits include (a) improved overall productivity as a result of data-driven decision-making and optimization, (b) reduced downtimes by streamlining material movements and (c) prevention of accidents by consistently ensuring that machinery and personnel maintain safe distances from one another.

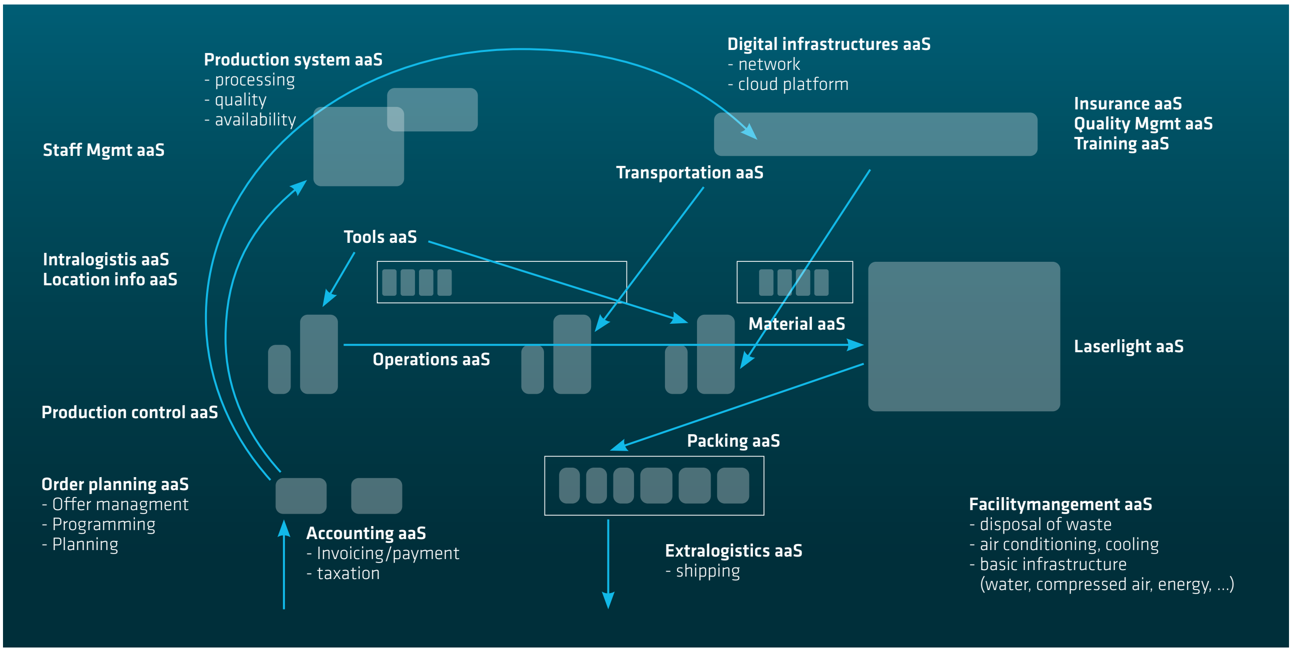
5.4.2 Service Flows

A factory is equipped with an ISAC-capable cellular system able to detect and track human workers and material transporters such as trolley carts and AGVs. Information captured by ISAC is provided to a flexible application for managing the production chain.

The steps in the service flow are:

1. **Continuous sensing:** The ISAC system continuously monitors the locations and movements of humans and materials throughout the factory while distinguishing between living and nonliving entities.
2. **Data analysis for efficiency:** The system captures data on the movements and dwell times of workers and materials and identifies bottlenecks or inefficiencies in the production flow.
3. **Data processing for safety:** The system processes proximity data to identify potential safety hazards, such as when a human approaches an active machine, and

Figure 5: Flexible production flows in the XaaS approach



Source: 5G-ACIA / ZVEI e. V.

activates alarms or shuts down machines to prevent accidents.

4. **Optimization and feedback:** Based on analyzed data, the system proposes adjustments to the production schedule, machine settings or worker assignments to improve throughput and reduce idle times.
5. **Safety and efficiency adjustments:** The system implements recommended changes and continuously monitors their impacts while making adjustments as required.

The application of ISAC in the factory results in:

1. An optimized production process with reduced bottlenecks, shorter lead times and better resource utilization
2. A safer working environment in which the risk of accidents involving machinery is significantly reduced

5.4.3 Functional Requirements

The cellular system shall be able to provide sensing data to an external application to enable it to, for example, track human workers and material transporters such as trolley carts and AGVs or distinguish human workers from inanimate objects.

5.4.4 Performance Requirements

Table 10: ISAC performance requirements for optimizing a flexible production flow

Scenario		ISAC for optimizing the flexible production chain
Sensing service area		Outdoor / indoor
Confidence level [%]		99
Accuracy of position estimates by sensing (for a target confidence level)	Horizontal [m]	≤0.5
	Vertical [m]	N/A
Accuracy of velocity estimates by sensing (for a target confidence level)	Horizontal [m/s]	0.5
	Vertical [m/s]	N/A
Sensing resolution	Range resolution [m]	1
	Velocity resolution (horizontal/vertical)	0.5
Maximum sensing service latency [ms]		500
Refresh rate [s]		0.05
Missed detection [%]		N/A
False alarm [%]		N/A

Source: 5G-ACIA / ZVEI e. V.

5.5 ISAC for Preventing Hazards in Industrial Environments

5.5.1 Description

ISAC technologies can be adopted to prevent hazards and thus improve industrial safety. Protecting property and people has high priority in industrial facilities. Damaged property can be replaced or repaired, but accidents involving human workers can cause permanent harm or even death. It is therefore essential to protect them from suffering injuries and continually improve safety in work environments.

In order to take effective steps for preventing hazards in industrial environments, it is necessary to understand the types of safety risks that can arise in a factory. Factory workers can be injured, harmed or killed by various kinds of incidents:

- **Electrocution:** Suffering an electric shock as a result of accidentally touching an uninsulated wire
- **Collisions:** Being struck by a moving machine or vehicle
- **Falls:** Tripping on a uneven surface or over loose objects on the floor
- **Overexposure and other hazards in danger zones:** For example, from spending too much time in a freezer or being exposed to toxic gases from leaky pipes

ISAC can be especially useful for detecting the presence of the mentioned hazard scenarios and/or any unexpected changes in the environment or falling objects and alerting nearby human workers. It can also call for help if, for example, a worker falls or is trapped in a dangerous situation and needs immediate attention.

The best way to detect hazards is to combine a base station's ability of radio sensing with the information provided by other sensors (such as a camera or a gravity sensor) installed on UE in the area. In this scenario, it is assumed that only the base station has both sensing and communication capabilities. The UE's ability to receive radio signals is only a backup. Signals sent by the base station are reflected and refracted by obstacles, and the resulting scattered signals are then

Figure 6: Examples of hazardous scenarios in industrial environments (with AI-generated illustrations)

Source: 5G-ACIA / ZVEI e. V.

sensed and used to identify the location, size and shape of an obstacle or worker.

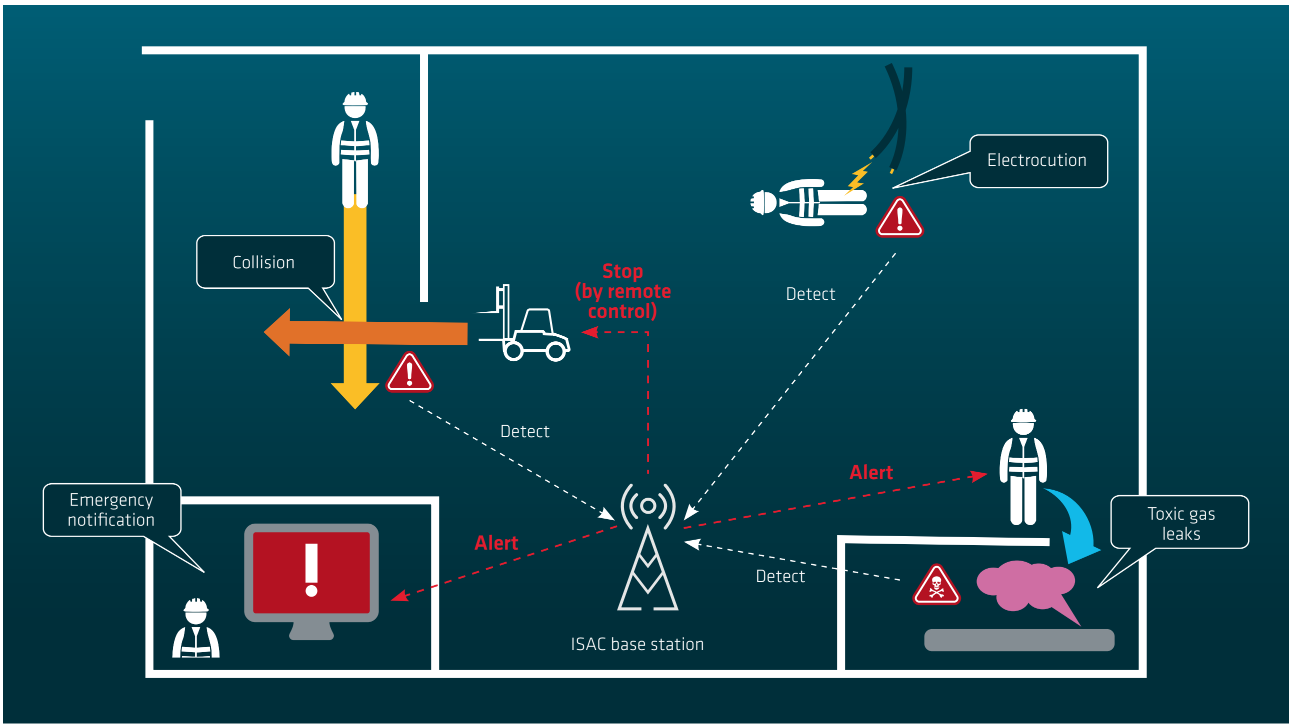
A baseline is normally established for information captured on a designated area at the outset or after a reset. The base station reports anomalies and objects identified in the monitored area to the application server, which analyzes this information to determine whether a hazardous situation exists. It is of limited value to use radio sensing by itself, because the base station is only able detect either an object's position and size or its velocity. By itself, the base station is unable to capture any additional information such as the identities of workers present in the area.

If a hazard detection system needs to be able to tell whether there is fire, smoke, a gas leak or water in or around a monitored area, it may be possible for it to receive this information via radio signals from sensors installed in the vicinity or from workers carrying communication devices. Depending on the installed sensing devices, it can receive detailed environmental information including positions (coordinates), images and/or video, voice and/or sound, temperature, the presence or absence of toxic gases, light and pressure.

For monitoring employees in a designated area, a worker-carried gravity sensor can trigger a "worker falling alarm" if a sudden change (defined as "falling" by the application server) coincides with detection of a falling object by the nearest base station. Specialized devices can significantly improve sensing accuracy, and this mechanism can be used for a variety of applications.

Although collaboration with UE can improve hazard detection, the most straightforward approach is to use information captured and communicated by one or more base stations. Base stations are primarily deployed in factories for communication purposes. Some of them may also include functionality for detecting hazards within a certain area. But

Figure 7: ISAC for preventing hazards in an industrial environment. The ISAC base station provides both communication and sensing functionality and can report environmental information in conjunction with other user devices.



Source: 5G-ACIA / ZVEI e. V.

there is no guarantee that any UE will be present, and even if it is, information may not always be available from them. There can also be other low-cost hazard detection options, such as using a video-based solution to survey a designated area, although this may not be feasible for privacy and confidentiality reasons. But despite the uncertainties, base stations supported by UE can be a baseline for hazard detection without the need for any additional resources. For simplicity's sake, it is therefore assumed that the UE mentioned here does not include radio sensing capabilities.

ISAC base stations and UE can jointly use their sensing capabilities to detect the surroundings and presence of workers. They provide the following functions:

- Detection of changes in order to identify obstacles near workers or along paths used by AGVs or AMRs
- Detection of the presence and movements of workers
- Prediction of human and machine actions to help coordinate them

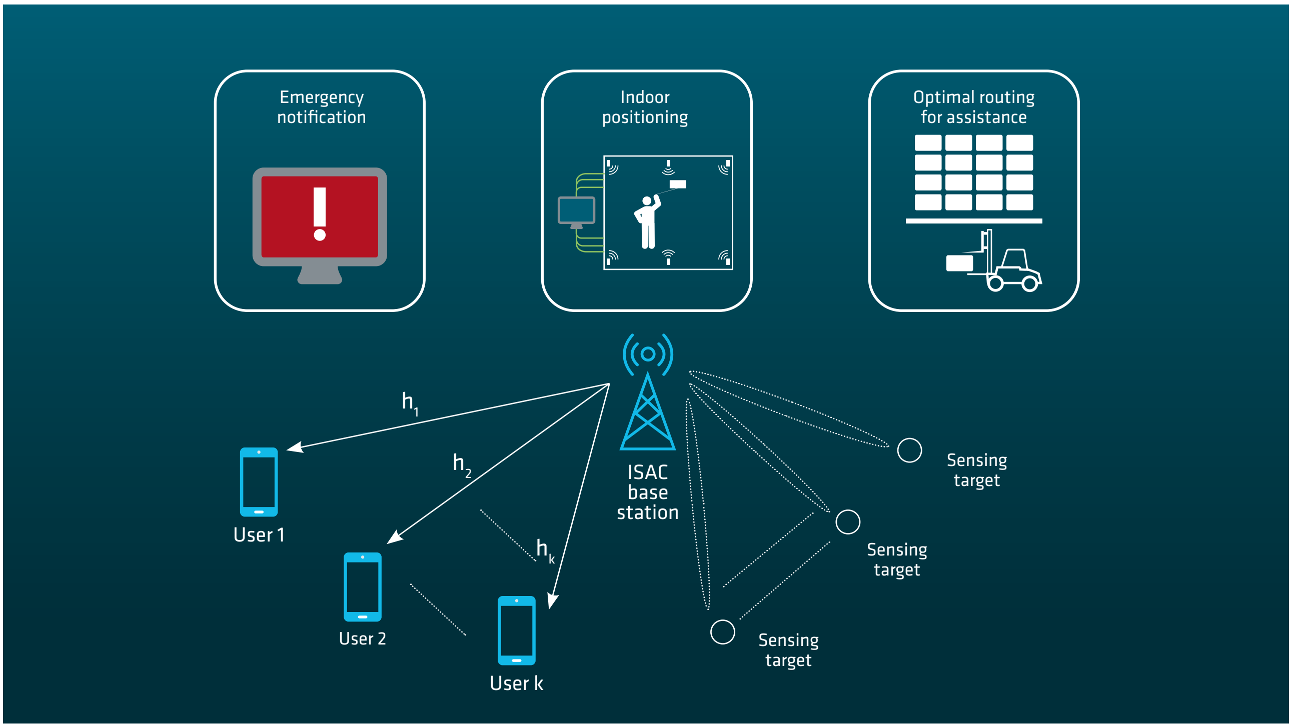
In each scenario, detected signals and information have to be communicated in real time to supervisors or the control room. To enable rapid responses in the event of an emergency, the ISAC system typically has to send the following information:

- Notification that there is an emergency
- The location of the emergency
- The optimal route for providing assistance

A potentially hazardous situation can be prevented, or at least the extent of damage reduced, if both human and inanimate actors are promptly warned when they are on a collision course. This makes it essential for the ISAC to anticipate the danger and communicate it to them in time.

When a hazardous situation is identified, base stations can promptly send an emergency notification to the involved players, use indoor positioning information to locate the

Figure 8: Transmission of information for quickly responding to emergency situations



Source: 5G-ACIA / ZVEI e. V.

worker and communicate the best possible routes for providing assistance, avoiding danger etc.

5.5.2 Service Flows

This section describes a simple hazard detection system consisting of a base station with radio frequency (RF) sensing and communication capabilities. Its accuracy can be improved by also considering information captured by UE or other local sensing equipment.

Facts:

- Many industrial safety accidents in factories involve collisions, falls, toxic gas leaks etc.
- Most of them are caused by human error and difficult to prevent and respond to immediately.

An ISAC hazard prevention system can detect dangers and immediately activate alarms and/or appropriately control machines (for example, by shutting them down) to reduce accidents. The following requirements apply:

1. Base stations must be installed and preconfigured to appropriately detect and identify areas and monitored objects within their range.
2. Additional sensing devices may be required to cover blind spots.
3. It is important to test installed radio connections within covered areas.

The service flow for using ISAC technologies to prevent hazards is described in the following. It may be necessary to add functions and capabilities that are supported by UE or servers in the network.

1. **Sensing and detection:** The prevention system described here takes advantage of ISAC's ability to monitor conditions within a designated area. Detected signals can either be continuously fed to the server or else locally buffered in a base station and only sent to the server if a change in the local environment is detected. Such an anomaly is also reported to the server, which can be located either on the premises or elsewhere in the network. In this use case, for simplicity's sake it is assumed that the base station monostatically performs the radio sensing part of the ISAC, although it is also possible for UE to have radio sensing capabilities that support more sophisticated multistatic sensing.
2. **Analysis:** When the base station senses or detects a change in the defined area, this information must be processed by an analyzer running on the application server. The analyzer processes the received information, compares it with a baseline and then zooms into the anomaly to determine if there is a hazard scenario such as a sudden fall by a worker. If that is the case, it triggers additional actions. The analyzer's effectiveness can be improved if additional information is provided via other detection equipment in the vicinity, for example UE.
3. **Prediction and monitoring:** An effective hazard prevention system should be able to make predictions based on captured data and monitor areas more closely in which there is a greater probability of hazards. Predictions can be made either in real time by monitoring the "current state", for example by calculating that a worker and an autonomous mobile robot (AMR) may be on a collision path, or by analyzing trends in historical data.

The successful use of ISAC technologies in a factory can prevent a number of hazard scenarios:

1. It can predict where the paths of workers and dangerous machines will intersect, so the workers can be alerted and machines halted to prevent hazards.
2. The ISAC base station and UE can immediately detect the presence of workers that enter a monitored hazard area.
3. The ISAC base station and UE can tell from workers' body positions if they are at risk (for example, of accidentally touching bare wires, being electrocuted and falling down) and inform the manager and safety team.
4. The ISAC base station and UE can monitor the number of workers in a restricted zone to ensure that no one remains behind in it.
5. The ISAC base station and UE can help analyze the factory environment in real time and advise the system

to take prompt action if there are sudden changes (such as falling items, a collapsed floor etc.).

5.5.3 Functional Requirements

In this hazard prevention use case, it is assumed that the ISAC system uses the base station for both communication and radio sensing, while UE only supports work with non-radio sensing. However, the functional requirements for ISAC system used for this purpose can be generalized independently of whether or not the UE is capable of radio sensing. The requirements include:

1. The ISAC system shall be able to distinguish between humans and machines.
2. The ISAC system shall be able to detect an object's location and velocity in an area of interest.
3. The ISAC system shall be able to monitor the environment in non-line-of-sight (NLOS) situations.
4. The ISAC system shall be able to recognize human body postures.

5.5.4 Performance Requirements

Table 11: ISAC performance requirements for preventing hazards in industrial environments

Type of application	Resolution	Update rate	Confidence level
Prediction of workers' and machines' actions	0.1 m	0.1 s	99.9%
Detection of workers' locations	1 m	1 s	99.9%
Detection of entry in dangerous areas	1 m	1 s	99.9%
Analysis of movements within an environment	0.1 m	1 s	99.9%

Source: 5G-ACIA / ZVEI e. V.

6 Sensing Performance Requirements – Observations and Proposals

6.1 Clarification of Performance Requirements

3GPP has defined the following performance requirements in Technical Specifications TS22.137 [19] and TR22.837 [18] (reproduced here verbatim without correcting the language, capitalization or punctuation):

- **Accuracy of positioning estimate** describes the closeness of the measured sensing result (i.e., position) of the target object to its true position value. It can be further derived into a horizontal sensing accuracy – referring to the sensing result error in a 2D reference or horizontal plane, and into a vertical sensing accuracy – referring to the sensing result error on the vertical axis or altitude.
- **Accuracy of velocity estimate** describes the closeness of the measured sensing result (i.e., velocity) of the target object to its true velocity.
- **Confidence level** describes the percentage of all the possible measured sensing results that can be expected to include the true sensing result considering the accuracy.
- **Sensing Resolution** describes the minimum difference in the measured magnitude of target objects (e.g., range, velocity) to be allowed to detect objects in different magnitudes.
- **Missed detection probability** describes the conditional probability of not detecting the presence of target object/environment when the target object/environment is present. This probability is denoted by the ratio of the number of events falsely identified as negative, over the total number of events with a positive state. It applies only to binary sensing results.
- **False alarm probability** describes the conditional probability of falsely detecting the presence of target object/environment when the target object/environment is not present. This probability is denoted by the ratio of the number of events falsely identified as being positive, over the total number of events with a negative state. It applies only to binary sensing results.
  NOTE 2: An event with a negative state refers to the non-presence of the characteristics of a target object or environment, including the event falsely identified as being positive and truly identified as being negative.
- **Max sensing service latency**: time elapsed between the event triggering the determination of the sensing result and the availability of the sensing result at the sensing system interface.
- **Refresh rate**: rate at which the sensing result is generated by the sensing system. It is the inverse of the time elapsed between two successive sensing results.
- **Rainfall estimation accuracy:** it describes the accuracy of rainfall monitoring in the unit of mm/h, which is according to a target confidence level. This is a performance requirement dedicated to the rainfall monitoring use case.

IMT-2030 PG's technical report "Research on 6G Sensing Requirements and Application Scenarios" [24] and the Hexa-X project's deliverable D3.1 [26] define some additional performance requirements, including the sensing distance and accuracy of range estimates as well as angular estimates and their resolutions.

Drawing on the performance requirements outlined in existing literature and the use cases presented in this document, the following is proposed:

1. The range resolution as outlined in 3GPP TS22.837 [18] appears to encompass not just the distance between the sensing target and the ISAC nodes, but also factors affecting the estimated resolution of location. This broader interpretation is necessitated by the bistatic and multistatic sensing approaches employed in ISAC, which use transmitting and receiving nodes situated

at varying locations. In addition, in the use case on UAV flight trajectory tracing described in section 5.10 of [18] , the specifications for range resolution extend to both horizontal and vertical dimensions, implying a requirement for precise location resolution within 3D space.
2. The requirements regarding the accuracy and resolution of sensing distance and angular estimates appear to apply exclusively to the monostatic sensing approach. The precision and resolution of position estimates on a 2D plane or in 3D space can be deduced from these distances and angular estimates. To ensure broader applicability, it is advised to utilize position estimate requirements instead of specific distance and angle estimates.
3. In imaging-based applications such as quality control and environmental mapping, additional performance metrics relating to image pixel resolution are regarded as necessary.
4. For sensing outcomes derived from micro-Doppler frequencies, like for human vital sign monitoring and vibration analysis, there is a need for novel performance metrics derived specifically from Doppler frequency measurements, such as the accuracy of heart rate, respiration rate, vibration frequency and vibration amplitude information.

6.2 Considerations Regarding Error Distribution

Specific use cases will have different requirements in terms of precision, accuracy and other aspects. A measurement system will usually be able to provide an estimation of errors, which can sometimes be intrinsic to the sensor itself and sometimes depend on a specific measurement. While it is common to have a known measurement error, an understanding of this error's distribution provides deeper insights into the sensor's reliability and limitations.

Error distribution is a mathematical representation of how measurement errors are distributed around the true value. One commonly encountered distribution is Gaussian (or normal) distribution, which is characterized by a symmetric bell-shaped curve. However, error distributions can also take other forms such as uniform, exponential or skewed. With more complex sensors, the error distribution can be a combination of other statistical distributions.

Here are a few reasons why it is important to know the error distribution:

- **For assessing accuracy:** The error distribution enables us to evaluate the accuracy of measurements. By understanding the spread and shape of the distribution, we can determine the likelihood of obtaining measurements within a certain range around the true value. This information is helpful for defining appropriate tolerances and determining the reliability of data.
- **Statistical analysis:** Knowledge of the error distribution enables us to apply statistical methods for analyzing the data. Statistical techniques such as hypothesis testing or confidence interval estimation rely on assumptions about the error distribution. By identifying the appropriate distribution, we can select the most suitable statistical tests and draw valid conclusions from the data or filter out inconsistent data.
- **Comparing sensors:** When multiple sensors are available for making the same measurement, knowledge of the error distribution lets them be fairly compared. A simple comparison of individual error figures can result in incorrect conclusions. By considering the distribution, we can assess the consistency, precision and bias of different sensors to help select the most suitable one for a specific application.

It is important for the sensor to provide information on the error distribution in the measured data.

7 Conclusions

ISAC is an emerging new capability that will introduce sensing beyond conventional mobile communications in future releases of cellular mobile networks. For industries and automation applications that cellular network technologies are now beginning to support and improve, ISAC can potentially become another enabler. The vision is that the cellular networks will deliver integrated sensing and communication capabilities for industries and automation, using a single network infrastructure that forms a unified, trusted service environment.

This white paper starts by providing an overview of ISAC technologies and a comprehensive presentation of ISAC use cases that are the focus of research and standardization activities; they include 3GPP, IEEE 802.11bf, one6G, IMT-2030 6G PG, Hexa-X/II projects and ETSI ISG THz, among others. Ten potential industrial applications for ISAC are identified, including detection and tracking of vehicles and humans, tracking and size measurement of goods, quality inspections, safety and health at work, environmental mapping, predictive maintenance, human-machine and machine-machine collaboration, and gas monitoring and sensing for improving localization in industrial environments.

In addition to the more generally described industrial applications of ISAC, five specific ISAC use cases have been proposed by 5G-ACIA members: gesture recognition, vibration monitoring, stockpile monitoring, optimization of flexible production flows and prevention of hazards. The specific functional and performance requirements for these use cases are described in detail.

Based on an investigation of industrial applications and use cases for ISAC, some proposals are made for achieving greater clarity for defining performance requirements. These include accuracy/resolution in space and new performance metrics for special sensing results such as those based on Doppler frequencies. It is also explained why an understanding of sensing error distributions is crucial for assessing accuracy, performing statistical analyses and comparing sensors to ensure the reliability of data.

ISAC is already attracting considerable interest as a new field in connection with cellular networks. It is still in an early stage and requires continued efforts with regard to research, standardization and the development of products and solutions. But it may have great potential for taking the connected industries and automation to the next level by serving as a unified communication and sensing infrastructure. Its principal benefits are the following:

1. Greater sensing accuracy and resolution as a result of reusing the communication spectrum for this purpose while coordinating inter-cell interference within networks.
2. Wireless and contactless sensing reduces the costs associated with dedicated sensors and can also be appropriate for use in harsh industrial environments.
3. Compared to sensors such as cameras, microphones and wearables, radio sensing has the advantage of minimal capture of privacy data.
4. A combination of multinode, multistatic and multimodality sensing results in better results by incorporating both 3GPP radio and authorized non-3GPP sensors.
5. A unified and trusted environment for collecting and transferring sensing data.

8 Definitions of Acronyms, Abbreviations and Key Terms

3GPP
The 3rd Generation Partnership Project (3GPP) is an umbrella term for a consortium embracing a number of standards organizations worldwide that are collaborating to develop globally accepted specifications for mobile telecommunications. As its name implies, it was originally created to establish specifications for the third generation (3G) of mobile communication systems. It has continued working on subsequent generations, including the fifth generation (5G), which is considered in this white paper.

5G-ACIA
The 5G Alliance for Connected Industries and Automation is the globally leading organization for shaping and promoting industrial 5G.

AGV
Automated guided vehicle.

AMR
Autonomous mobile robot.

AR
Augmented reality.

Cellular system
A cellular system is an integrated system comprising one or more user devices, a radio access network (RAN) and a core network to provide services to users. This definition is based on 5G (the Fifth Generation of Mobile Telephony, also known as 5G or the 5G System (5GS)), a technology for cellular networks that has been defined by 3GPP since Release 15, which was fully specified in 2019.

Cobot
Collaborative robot.

CSI
Channel state information.

ETSI ISG
European Telecommunications Standards Institute – Industry Specification Group.

ICT
Information and communication technologies.

IIoT
Industrial Internet of Things.

IMT-2030
International Mobile Telecommunications – 2030.

ISAC
Integrated sensing and communication.

ITU-R
Also known as the ITU Radiocommunication Sector, it is one of the three sectors of the International Telecommunication Union.

JCAS
Joint communication and sensing.

KPI
Key performance indicator.

LiDAR
Light detection and ranging.

MEC
Mobile edge computing.

mmWave
Millimeter wave.

MR
Mixed reality.

NLOS
Non-line-of-sight.

Radar
Radio detection and ranging.

RAN
Radio access network.

RF
Radio frequency.

RFID
Radio frequency identification.

SA
System aspect.

THz
Terahertz.

UE
User equipment.

V2V
Vehicle to vehicle.

V2X
Vehicle to everything.

VR
Virtual reality.

WLAN
Wireless local area network.

XaaS
Everything as a service.

XR
Extended reality.

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in Connected Industries and Automation

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