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Joint Communications & Sensing

Common Radio-Communications and sensor technology
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1 Background

The first two generations of mobile network, 1G and 2G, brought voice communication with universal availability. 1G mainly addressing business telephones, while the real breakthrough for end users came with the advent of 2G. The next two mobile network generations, 3G and 4G, enabled universal data communication. In the early days of 3G, the focus was on business smartphones (e.g. Blackberry and Nokia Communicator). It was the introduction of 4G that saw the start of this technology being widely used among end consumers.

Now, with the mobile network standard 5G, real and virtual objects can be controlled remotely via the network – either on their own, in interactive groups, or in a swarm. This is referred to as the 'Tactile Internet'.[1] As a new application for mobile networking, remote control and augmented/virtual reality (XR) is currently mainly being used on campus networks, primarily in industrial and commercial contexts. With the advent of 6G, this way of using remote control is now also set to be made widely available to end consumers. Application scenarios include controlling robots that take care of day-to-day tasks; coordinating drones; coordinated autonomous driving; and affordable, universally accessible augmented and virtual reality (AR/VR). This raises two questions: firstly, what exactly is missing from 5G that is needed to achieve this vision with no more than one new generation of mobile network standard? And secondly, how can industrial applications benefit from this technology too?

A core capability introduced by 6G will be the symbiosis between mobile communication and mobile sensing.[2] Mobile robots and XR must record their surroundings in 3D using sensors (e.g. radar, spectroscopy and localisation), and they must communicate with one another over mobile networks. However, today's radar system cannot cope with the demands that would be placed on it by the future density of mobile robots (including drones, autonomous cars and so on), especially when it comes to 3D radar and spectroscopy. The spectral efficiency of radar, and of mobile sensing in general, could nonetheless be improved significantly beyond the state of the art if particular radar applications were also to be coordinated with radio access. The mobile spectrum itself is unable to support the data transfer rates of up to 100 Gb/s that are to be expected in future. However, significant mobile resources for broadband communication are rarely needed at the same time for mobile sensing. This gives rise to the idea of operating both communication and sensing together in one system and frequency spectrum – this concept is referred to as 'Joint Communication and Sensing' (JC&S).

Developing JC&S requires expertise in mobile sensing and communication technology. The use of JC&S in 6G and other mobile networks, paired with robotics expertise, will revolutionise entire branches of industry and bring about entirely novel end-user applications. Germany and Europe have a strong presence in (consumer) markets that are to be revolutionized by JC&S and the 6G revolution, such as leisure, sport and fitness, kitchen equipment and white goods, mobility, logistics, garden equipment, and tools. When it comes to researching and developing JC&S, both Germany and Europe are in an excellent starting position. This, paired with the existing expertise in robotics and automation technology, as well as resource-efficient life-cycle management, results in having a pole position for the upcoming product revolution in these markets. If we proactively seize the opportunities offered by JC&S, this prime positioning of Germany and Europe will make it possible to ring in a new era of rapid technological expansion.

In this position paper, we aim to present the concept of JC&S and the enormous potential it offers for the future. We will explain various application scenarios, such as mobile robotics and coordinated autonomous driving, and take a look at the benefits of a shared spectrum and shared hardware. In addition to outlining the opportunities presented by JC&S, we will also describe some of the scientific, technical, regulatory, societal, resource-related and economic challenges associated with it. We will also recommend practical actions that can be taken to overcome these challenges.

1 G. Fettweis et al., „Taktiles Internet", VDE-Positionspapier, 2014, [Online] https://shop.vde.com/de/vde-positionspapier-taktiles-internet-8

2 T. Wild, V. Braun and H. Viswanathan, „Joint Design of Communication and Sensing for Beyond 5G and 6G Systems," in *IEEE Access*, vol. 9, pp. 30845-30857, 2021

2 Requirements

2.1 Basic concept and state of the art

Mobile robots (this also includes autonomous vehicles, drones, etc.) must have precise geolocalisation capabilities as well as accurate situation recognition abilities. However, cameras cannot be used in most cases since this could be an infringement of privacy, while LiDAR has certain limitations when it comes to sensing larger areas, especially in poor weather such as rain, snow and fog. As a result, there is an urgent need for radar technology. In order to enable material detection, spectroscopy must also be possible. However, today's radar spectrum is not equipped to deal with the density of mobile robots anticipated in future, nor does it offer spectroscopy functions. At the same time, the mobile spectrum is insufficient for the data transfer rates of the future. As mentioned above, an efficient solution to the problem would be to operate both, communication and radio based sensing, together in one system and spectrum so that the spectrum can be exchanged between the sensor system and communication functions. This would be of particular benefit to applications involving large ranges, such as autonomous driving, traffic monitoring, robotics and drone control.

Today already there are some examples of JC&S in operations in the real world. Going beyond the traditional scope of communications services, LTE and 5G are already offering some opportunities for geolocalisation. However, 4G and 5G have so far been subject to certain limitations in that only active localisation is supported. This means that a device must be connected to the network and able to send or receive pilot signals to enable localisation. The benefits are particularly pronounced in areas where there is weak or no reception of global navigation satellite systems (GNSS), for instance in buildings. 5G localisation is especially interesting for transitions between indoor and outdoor areas; for example, this enables forklift trucks or pallets to be tracked on an industrial site without any interruptions.

One use case involving active localisation which has already been successfully demonstrated with 5G is the protection of vulnerable road users.[3] Pedestrians and vehicles with 5G devices can be localised with up to one metre accuracy via the 5G wireless interface. Trajectories can be predicted and potential collisions detected, so that drivers can be warned, for example, that a child hidden from view behind an obstacle is about to run across the road.

But there is more to the vision of JC&S than just the current state of the technology (making use of active localisation). In future, it should be possible to use communication networks to detect and localise objects that are not connected to the mobile network.

One way in which JC&S is being used at present is in the ultra-wideband (UWB) impulse radio system (IEEE802.15.4z), see Figure 1. Under the umbrella of the Car Connectivity Consortium[4], mobile phone, automotive and semiconductor manufacturers have come together to standardise this UWB impulse radio system for distance measurement as a vehicle access system within the Digital Key 3.0 specification[5]. The first few products to make use of the 802.15.4z mobile technology have been available from Apple and Samsung since 2019.

These mobile phone manufacturers have been using the UWB impulse radio technology in the latest generations of their devices to localise other mobile phones and objects that are market with beacons or tags. Meanwhile, the FiRaTM Consortium[6] has been investigating a wealth of other possible applications. These include hands-free access systems, ticketing for public transport, social distancing, point and trigger applications, indoor navigation and smartphone payment systems[7]. UWB can also be used to precisely localise sensor nodes in challenging non-line-of-sight (NLOS) environments, such as aeroplane cabins.[8]

[3] S. Saur et al., „5GCAR Demonstration: Vulnerable Road User Protection through Positioning with Synchronized Antenna Signal Processing," International ITG Workshop on Smart Antennas, Hamburg, Deutschland, Februar, 2020
[4] https://carconnectivity.org/
[5] https://global-carconnectivity.org/wp-content/uploads/2020/04/CCC_Digital_Key_2.0.pdf - Chapter 4-Outlook
[6] https://www.firaconsortium.org/
[7] https://www.firaconsortium.org/discover/use-cases
[8] G. Karadeniz, F. Geyer, T. Multerer, D. Schupke „Precise UWB-Based Localization for Aircraft Sensor Nodes," AIAA/IEEE Digital Avionics Systems Conference, Virtual Conference, Oktober, 2020

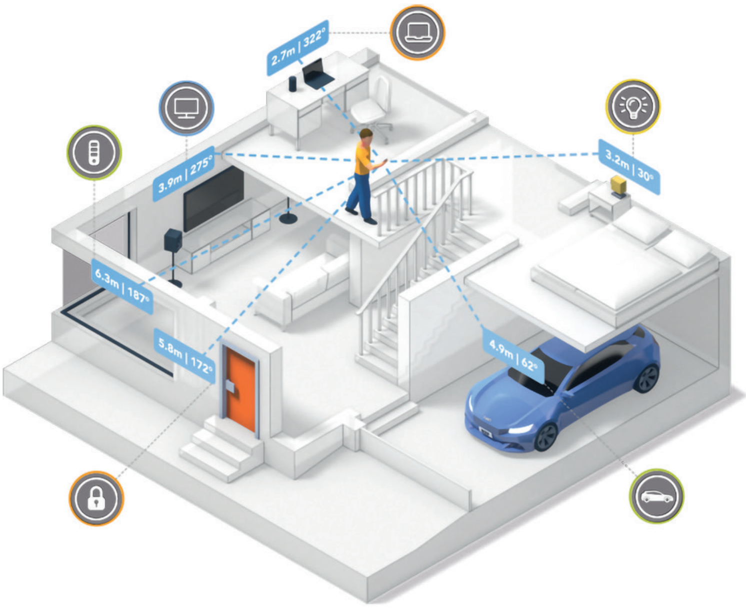

Figure 1: NXP Trimension™ - Use of UWB radio technology as a distance and direction sensor in a smartphone, a vehicle and the Internet of Things

The IEEE 802.15.4z uses a sequence of pulses for data transmission. The MAC layer has various configuration options that enable repeat distance measurement of a number of other devices at a fixed repetition frequency. Conventional data transfer is also possible. During the distance measurement, check and control signals are transmitted in data packages or integrated into the distance measurement packages. Therefore, UWB is already bringing about a convergence of data transfer, secure distance measurement, 3D incident angle measurement (with two or more parallel receivers) and radar (e.g. presence detection) over short distances. The aim now is to take this convergence between communication and sensing that has already been achieved with UWB, and turn it into a foundation block of the new 6G standard. Other notable JC&S initiatives include the omlox[9] standard for establishing interoperability between various mobile localisation technologies, the IEEE 802.11bf project for WLAN sensing, and the Integrated Sensing and Communication Emerging Technology Initiative[10] from the IEEE Communications Society for supporting research and standardisation projects.

2.2 Sensor data fusion through communication

JC&S is a tool that enables cooperative collection, transmission and processing of sensor data. These networked sensors make it possible to compile data from spatially distributed platforms, in a procedure that is called sensor fusion. In general terms, this means that incomplete and imprecise information from multiple sensors is combined to improve the overall perception of the environment. This sensed information can include information about the current position and dynamics of both active participants (equipped with sensors) and passive ones. Depending on the type and quantity of sensors, it may also be possible to obtain additional information, such as target classification and movement predictions. With JC&S, it is also possible to distribute the sensor information among network users, including the users that do not contribute to the overall result with their own sensor observations.

One example of sensor fusion with JC&S is networked and automatic driving and flying (see Figure 2). This has helped to bring about a revolution in private transport that requires many new types of technology in order to succeed. The introduction of 5G saw the advent of real-time data communication between vehicles, as well as between vehicles and road infrastructure components. However, this is not sufficient to meet many of the new demands, such as precise and reliable vehicle localisation within the road infrastructure, as well as the localisation of other road users such as pedestrians or cyclists. JC&S is not limited to road traffic alone – drones could also be integrated into the network.

[9] https://omlox.com/home
[10] https://isac.committees.comsoc.org/

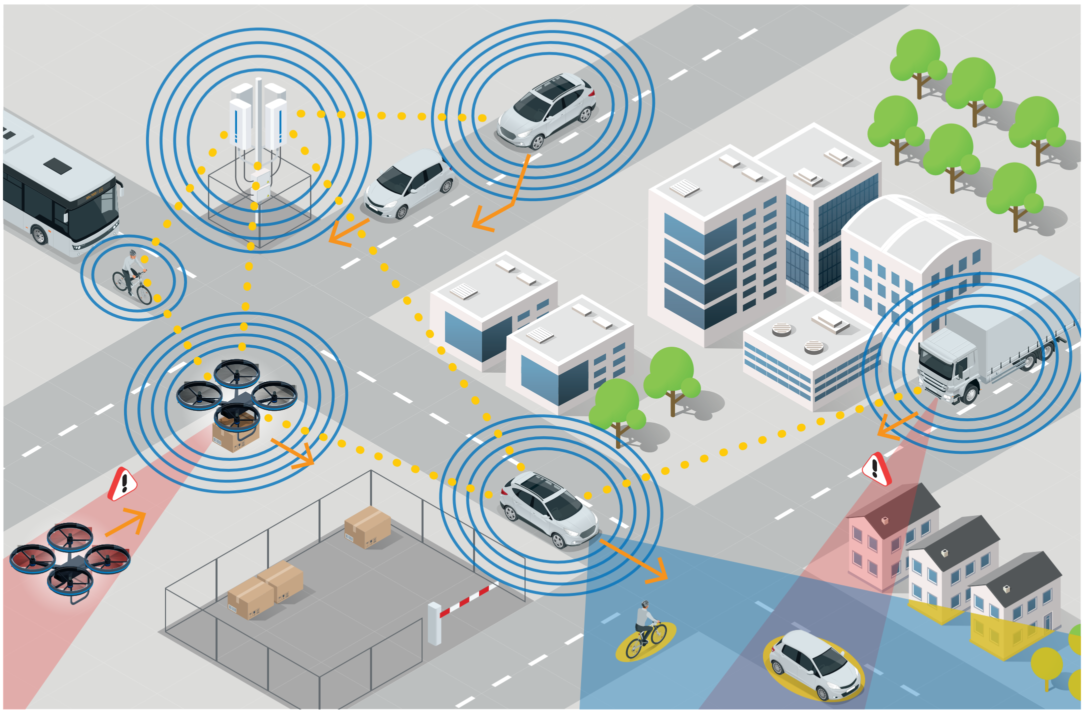

Figure 2: Sensor fusion in road and air traffic using JC&S.

Figure 3 provides an overview of possible architectures for JC&S systems. The illustration shows the example of road traffic as discussed above. However, the concepts can also be applied to other use cases (e.g. production halls), which will be discussed later on in this publication.

Figure 3-A) depicts a case in which orthogonal waveforms are used for radar and communication. Both waveforms use the same physical mobile interface and are multiplexed in the frequency, time or code range. Since the base station sends and receives the radar signal at the same location, full-duplex operation (monostatic arrangement in radar terminology) is required. In this case, the base station acts as a standalone radar and thus requires an antenna array.

An alternative setup is shown in Figure 3-B), in which the same waveform is used for radar and communication. In this case, the base station sends the communication data to the mobile device, which simultaneously acts as a mobile sensor. A single signal is therefore used twice – for data communication and for radar sensing. In this system, the base station and device can operate in half-duplex mode. In this case, the base station does not require an antenna array, since the spatially distributed end devices – and potentially also other base stations – are used as radar sensors. This system is also referred to as distributed or multistatic multiple-input multiple-output (MIMO) radar. In this system, the accuracy and geographical coverage depend on the spatial distribution of the mobile devices. Compared with the monostatic radar arrangement shown in Figure 3-A), a significant increase in the target diversity can be seen here. This significantly increases the likelihood of detecting a target if multiple bistatic (i.e. multistatic) measurements are available. This is a known advantage of distributed MIMO radar.

A third possibility is an ad hoc network, which is illustrated in Figure 3-C). The same signal that is transmitted from node 1 to node 2 is scattered back by the target (the cyclist). If full-duplex mode is available, this makes it possible to use a monostatic radar. At the same time, node 2 also receives the signal from node 1, meaning that an additional bistatic echo can be obtained. Depending on the particular use case, it is likely that hybrid approaches that combine the ideas of the system architectures discussed here will become prevalent in practice.

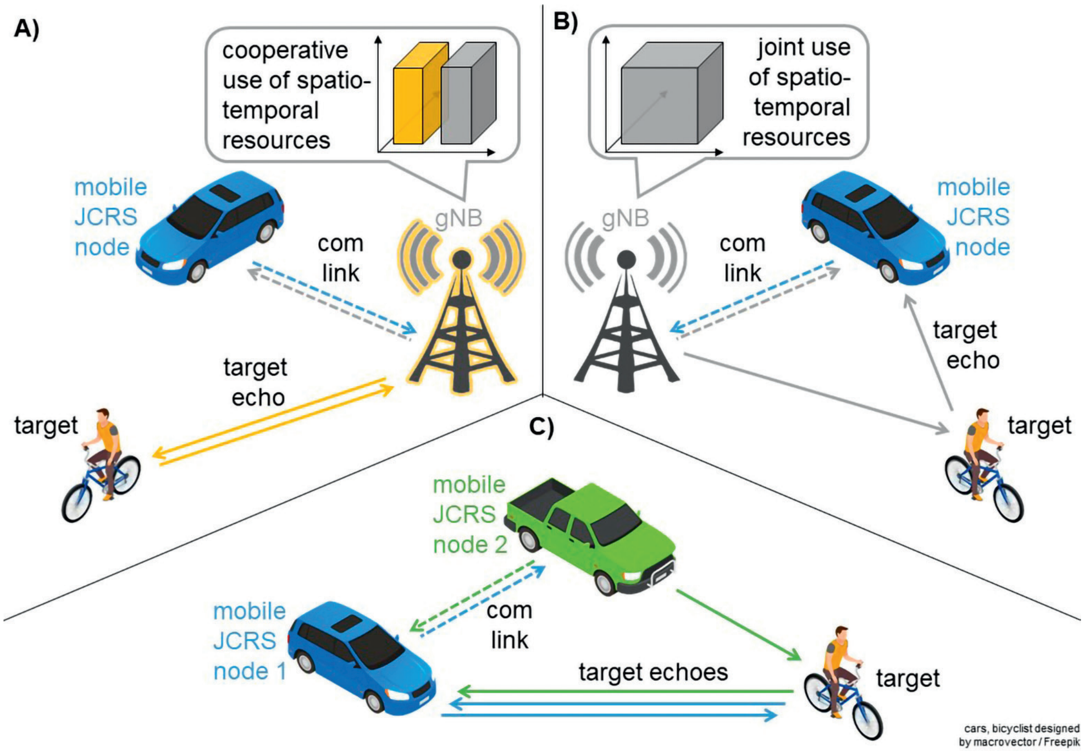

Figure 3: JC&S system architectures. A) Monostatic sensing of a base station and mobile nodes with orthogonal waveforms. B) Bistatic sensing of mobile nodes with JC&S waveforms emitted from a base station. C) V2V-based monostatic and bistatic sensing of mobile nodes without support from a base station.[11]

2.3 Technical requirements

The application scenarios for sensor fusion discussed above in section 2.2 require picture of the situation to be built up from the sensor data. This makes it possible to continuously record the area and depth of the corresponding traffic zones and thereby create 3D pictures of the situation in real time. In order to create these situation pictures, the information obtained via the sensors passes through multiple processing levels, from the acquisition of raw data through to describing the position of the detected road users on the basis of coordinates. Here it is possible to use radars that actively emit a signal in order to detect objects, as well as passive radars that use signals emitted by other transmitter systems in order to localise an object in 3D. The raw data obtained from the radars must first be resolved along distance, azimuth and elevation angles. In addition, it is possible to determine the radial speed, in other words the speed in the viewing direction of the radar (in the radial direction) by considering the Doppler shift. Signal components that are unambiguously caused by reflections are then identified. In the subsequent processing steps, reflections that are close to one another can be combined into objects and classified, and the movement of these objects can be tracked or the trajectories of moving objects predicted. This means that information about the location, type, and speed and direction of movement of the objects (or road users) is available when creating the situation picture.

In scenarios with a high density of road users, such as inner-city environments, it must be possible to differentiate between these road users and predict their direction of movement. Otherwise, multiple objects that are close together (e.g. a cyclist next to a car) would be fused together in the situation picture as a single participant. Faulty interpretations of this sort carry with them a high risk of accidents. The ideal solution is therefore to obtain the highest resolution possible based on the Doppler displacement, distance, azimuth and elevation of an object. Imaging radars are commonly mentioned in this connection. They are capable of producing highly detailed situation pictures. For instance, these radars can use long measuring times to achieve high Doppler resolutions, making it possible to detect very small and diverse movements of individual elements of a road user (e.g. the limbs of a pedestrian). These micro-Doppler signatures enable more reliable separation and classification of the participants based on different speed profiles.

[11] R. Thomä, T. Dallmann, S. Jovanovska, P. Knott, A. Schmeink, „Joint Communication and Radar Sensing: An Overview", in *Proc. European Conference on Antennas and Propagation*, Düsseldorf, Deutschland, März 2021

However, a high distance resolution is also required in order for these radars to separate objects from one another spatially. This in turn requires a signal with the widest possible frequency bandwidth, which is a particular challenge due to the fact that the electromagnetic spectrum is already heavily used.

Nonetheless, there are two different functional principles that imaging radars can use for additional spatial differentiation of objects perpendicular to the distance resolution. One option is to use large antenna arrays to generate a large number of virtual antennas so that the highest possible angular resolution can be obtained. Depending on the angular resolution, this yields a highly detailed description of the environment that is comparable to an optical depiction. Another option is to move the sensors through the space along a particular trajectory, recording measurement data at each position and putting it together to create a quasi-optical image (synthetic-aperture radar, SAR). Here, too, the result is a highly detailed description of the environment.

The JC&S technology described in this publication offers a low-resource method of creating imaging radar networks, which could also be expanded to spectroscopy, for instance. The technologies described above could be integrated as follows for this purpose:

- The distance resolution can be increased by using multiple frequency bands simultaneously (aggregation). It is also possible to integrate mobile radio bands here, since JC&S technology enables communication via these bands at the same time.

- Multiple sensor nodes can be synchronised via data exchange and thus joined together to form a sensor network (cooperative radar). Together, the nodes act as a widely distributed and accordingly large antenna system (along the lines of the distributed MIMO systems described in section 2.2. and shown in Figure 3-B), which previously impossible angular resolutions can be achieved.

- This arrangement also allows for the integration of transmitter systems that do not permit synchronisation. This is done by means of passive radar functions at each sensor node. The additional information that is thereby obtained about the environment increases the likelihood of all relevant road users being detected and traffic situations being assessed more realistically.

- Furthermore, by merging the radial speed profiles and Doppler signatures via the sensor network, it is possible to precisely reconstruct movement vectors along all directions and to classify the road users regardless of their direction of movement.

- Finally, the movement along a trajectory of sensors installed on road users makes it possible to generate quasi-optical images that are transmitted via the communication interface in the sensor network and can be merged using suitable fusion methods.

This makes JC&S-based sensor networks the ideal tool for creating an accurate and detailed 3D situation picture of an environment, thus offering greater safety to all road users in a partially or fully automated traffic scenario.

Increasing automation also requires suitable communication systems that take into account the particular characteristics of industrial environments that differentiate them from urban or rural spaces. Small, often metal structures in machines, production cells and storage racks generate reflections and shadows. It is also crucial to protect against malicious attacks and faults. Consistently reliable and predictable communication with robots, sensors or other industrial trucks must be ensured. The simultaneous use of mobile devices as spectrum sensing nodes for spectral analysis can support reliable operation by means of automated coexistence and fault management[12]. The corresponding radio nodes on the mobile robots can be used together with a suitable radar function to detect obstacles, including people. Overall, this approach can make a significant contribution to improving functional safety. To date, there has not been a satisfactory solution for areas outside factory buildings, or for ports, since the varying weather conditions make it difficult to use the optical solutions that are favoured in indoor environments, such as LiDAR.

Here, too, JC&S can help to optimise functionality and costs while ensuring resource efficiency.

[12] VDI/VDE Richtlinie 2185, Blatt 2: Koexistenzmanagement von Funklösungen

The reliability requirements that are placed on communications and sensor systems depend heavily on the specific use case or the particular usage domain. For radar sensors used in distance measuring, this can range from resolutions on the sub-centimetre scale in order to detect fine gestures at small distances from the sensor, all the way up to the kilometre scale in the case of flight radars. There is a similar picture when it comes to data transfer. Closed control loops in industrial settings often require latency times on the order of 1 ms in conjunction with 99.9999% availability of the communication service. By contrast, many other applications, such as using a mobile operating panel to configure a machine, do not differ too significantly from conventional consumer applications. When specifying and configuring a JC&S system, it is therefore imperative that the area of application be defined clearly and analysed in detail. Potential solutions must also be adapted flexibly to accommodate JC&S applications and the specific conditions on site, as well as taking application-specific limit cases and exceptions into consideration from the outset. As well as being highly reliable and secure, the network infrastructure must also have the capacity to permit demanding application scenarios. This is absolutely vital for industrial use.

2.4 Data analysis and processing

An important aspect of JC&S is determining where and how the collected sensor data is to be processed. Owing to the real-time capability, the data needs to be processed as close as possible to the user or the executing processes (e.g. self-driving car, drone, environment detection device). This is referred to as edge computing. If the end device has sufficient computing resources available, the data processing can happen right there. If this is not the case, it is recommended to use base stations or multi-access edge computing (MEC) locations. Power consumption is an aspect that must be taken into consideration here. The use of these remote locations also increases data security in the event of a physical theft or break-in.

It is not advisable to use a central network for data processing, since this imposes a high latency time on many applications. In principle, additional data that does not support so many real-time-relevant actions can of course be transposed to the central network. This makes it possible to conduct higher-level evaluations of situations between different or adjacent MEC locations across a wider action radius, thereby obtaining an overall assessment of a more comprehensive situation picture.

Another question relating to the processing of sensor data is how to make it usable for machine learning (ML). With ML, it is possible to extract highly useful information from mobile signals that can support a wide variety of sensing applications, such as object detection, localisation and tracking. For this reason, ML must be an integral part of an overall JC&S system. The issue here is how to integrate ML into this overall system, since it is often impossible to collect all the raw data at a central point where ML algorithms can also be applied in order to extract useful information, or where deep learning models can be trained and subsequently distributed. One promising approach for resource-efficient machine learning based on data distributed within the network is federated learning. This is a collaborative form of machine learning that solves a particular problem associated with ML without the need to transmit all information to a central point. The training process is distributed across multiple learning partners and coordinated by a central controller. The challenge here lies in developing monitored and semi-monitored learning algorithms that can overcome the various challenges in mobile networks, such as unreliable connections or correlated random samples.

A problem associated with the use of ML is that of adversarial attacks and retaining GDPR-compliant privacy. Research into finding ways to prevent these attacks is currently ongoing. Adversarial attacks use false data in an attempt to overload ML networks or train them incorrectly, with the aim of disrupting the network and reducing its efficiency. If ML is to be used safely in JC&S systems, it must be resilient to attacks of this kind.

In addition to machine learning, another current area of research is the fusion of the processed sensor information, as discussed in section 2.2. Here it will be necessary to reach a consensus so that fusion can be used to increase the resolution and/or the coverage offered by sensor-based target evaluation.

2.5 Shared KPIs

The performance of communications and sensing systems is measured at the application level by means of various key performance indicators (KPIs). For communications systems, KPIs such as achievable data rate and short latency time at high spectral efficiency are of primary importance. The quality of a sensing system is primarily determined on the basis of its positioning accuracy and resolution, as well as the number of correct predictions when classifying detected objects. Other KPIs that are relevant to communications and sensing alike include costs, installation size, and energy efficiency. Generally speaking, KPIs often contradict one another. For instance, minimising latency or maximising energy efficiency is usually only possible at the expense of spectral efficiency. This leads to complex Pareto optimisation problems which must be solved in order to achieve an adequate operating point in relation to the underlying application in a particular environment and at a particular time.

Although it is difficult to define in quantitative terms, resilience is another important KPI for today's sensor and communications systems. In this context, its scope extends beyond the conventional approaches to reliability and security. Another required function is reconfigurability. This is necessary for optimal navigation towards a compromise between reliability, performance, energy efficiency and latency in critical applications[13].

[13] G. Fettweis et al., „Resiliente Netze mit Funkzugang“ VDE-Positionspapier, 2017, [Online] https://shop.vde.com/en/vde-positionspapier-resiliente-netze-mit-funkzugang

3 Opportunities

In this section we will outline some of the opportunities for the future that are presented by the technical possibilities of JC&S.

3.1 A shared spectrum

Radar is traditionally used in the military sphere, remote sensing, aviation, shipping and the automotive industry. All of these applications use specific frequency bands that are assigned to them exclusively. Most of these applications only use these bands infrequently and to a limited geographical extent, i.e. locally. However, vehicle radars are increasingly becoming mass-market applications that must also meet high safety requirements and quality standards. The rise of autonomous vehicles will also bring about extreme growth in the density of radar applications. This is down to the sharply rising number of vehicles equipped with radar, as well as the fact that ultimately all vehicles will be fitted with multiple radar sensors and systems that use various frequency bands. However, mass radar deployment has not yet been optimised for bandwidth efficiency, while coordinated multi-user (multi-sensor) access is also lacking. Since the individual radar requires a large signal-to-interference power and product of bandwidth and measurement-time in order to achieve the required spatial resolution, access coordination is needed. Furthermore, there is a growing number of radar applications that are not subject to the extreme safety requirements of collision avoidance.

If frequency bands for radar and communication are to overlap, flexible use and coordinated access would be useful. This would enable the mobile network operators (MNOs) to offer a common communications and radar service, as well as working out a fair way of allocating the frequency bands. Use of the frequency spectrum as a resource is at its most efficient if the same signal can be used for both communications and sensing. Another important point to note is that large, contiguous frequency blocks are not essential for achieving a high distance resolution. It is often sufficient to use smaller, more separated frequency blocks that are combined, as is the case for example with carrier aggregation in 4G and 5G. This requires flexible frequency band access. The distributed mobile radio bands should therefore be seen as an opportunity, since they enable highly diverse applications with variable use.

3.2 Shared hardware

The fusion of communications and sensing applications on a shared hardware platform makes it possible to use existing infrastructure without draining resources. In particular, existing antenna and base station areas can be used for additional services, offering functional added value to citizens. Conserving resources has a major impact on the resulting investment needs, since it avoids the duplicated costs that would be associated with a parallel installation for different services. Furthermore, combining radar and mobile network systems in one type of hardware could, through the use of a communication link between the sensors, solve the interference problems that occur when there are a large number of (uncoordinated) radar systems in a small space. This would make it possible to create cooperative sensor networks with improved performance capabilities.

The hardware used must meet the demands of the various services and applications proficiently and cost-effectively. One important contributor to this is microtechnological integration with modern, integrated semiconductor components. These components offer a way to select a suitable form of technology to achieve multiple functionalities with varying technical requirements with virtually no additional construction volume needed.

3.3 New services and applications

In addition to the road traffic coordination functions discussed in section 2.2, another possible application of JC&S is in safeguarding the lower airspace. This became necessary as soon as drones started to be sold commercially, a situation for which conventional flight monitoring systems are ill-equipped. These conventional systems would be far too expensive and cannot be scaled to this problem: the objects to be monitored are becoming ever smaller, moving around in new ways and constantly growing in number. The JC&S concept proposed here offers an efficient approach to solving this problem.

Beyond drones and autonomous vehicles, the future is also set to bring a variety of other mobile personal robots, the use of which will be facilitated and coordinated by JC&S. Examples include robots for cleaning the home and other everyday assistants such as kitchen robots, care robots for private use or in hospitals, assistants for fitness activities or sports, exoskeletons for supporting people with limited mobility, and many others that even today we cannot yet possibly imagine. Another use case involving networked robotics that is made possible by JC&S is self-organised production in industrial environments, also referred to as 'Industry 4.0'. In this concept, humans, machines, systems, mobile robots, logistics and products all communicate and cooperate with one another directly. The agricultural sector calls this smart farming, or 'Agriculture 4.0'. An illustration of this concept is shown in Figure 4.

Figure 4: Smart farming made possible by JC&S. Humans, mobile robots, drones and systems communicate and cooperate with one another.[14]

[14] AndSus / stock.adobe.com

Thanks to the comprehensive network availability and good localisation ability of networked devices, many other application scenarios will be possible in future. One example which we will discuss here relates to major events, where arrivals, parking spaces, seating and departures all need to be managed. There is a high degree of inefficiency here, because behaviour is coordinated individually by the attendees and the overall information that is available or can be collected cannot be used. Routes could be optimised here according to price categories, while waiting times could be reduced through smart merging with friends or acquaintances who also happen to be there. Meanwhile, if an attendee's starting location and the type of transport they have chosen for their journey to the event indicate that they will not be able to reach the venue on time, resale of their ticket could be initiated automatically, in much the same way as a person switching on their heating 15 minutes before they arrive home in the winter.

Generally speaking, it is of growing interest to society to move people and goods around in the most resource-friendly way possible, which in turn also brings greater coordination. The concept of JC&S creates the technological basis necessary for this. Other fields of application that would benefit from an efficient combination of communications and sensing include the intelligent management of other resources, such as increasingly scarce drinking water, food production (smart farming, shown in Figure 4), energy distribution and general space and land usage. These could all be made more demand-oriented and better optimised for the prevailing climate and weather, which is of vital interest to society in light of the climate crisis and a growing global population.

4 Challenges

In this section, we will discuss some of the challenges that must be overcome on the way to making JC&S a reality with the introduction of 6G. These challenges not just technical, but also political and social in nature.

4.1 Channel models and information theory

Suitable channel models are required in order to successfully build JC&S systems. The geometry-based stochastic channel models (GBSCMs) commonly used at present in mobile networks are poorly suited to localisation and entirely unsuitable for radar, gesture detection, and spectroscopy. This is because these channel models are drop-based, which means they are resolved as static scenarios but do not permit a varying of the parameters that is consistent in space and time, as would result from the movement of the radar sensors or the targets along specific trajectories. Furthermore, GBSCMs are not correctly mapped in geometric terms in relation to the environment. In contrast, ray tracing (RT) does reflect the structure of the environment in geometrically correct terms. However, it too generally does not permit consistent modelling of the target parameters along defined trajectories. Consequently, there is a need for GBSCM and RT that are consistent in space and time for the statistical and deterministic modelling of multi-target scenarios that change rapidly in spatio-temporal terms. This also includes adequate reproduction of the multi-path interaction with the environment.

Another key area of research is information theory. In communications technology, a good understanding of information theory has already been developed that specifically includes multi-user and network scenarios. By contrast, sensor information theory (radar/spectroscopy/localisation) is still in its infancy. Here, too, a mathematical theory that is based on probability theory and statistics is needed in order to determine the performance limits of sensor systems, define suitable quality parameters and indicate how they will be achieved. This is the only way to attain the goal of adaptive and efficient allocation of sensor system resources.

A particularly under-developed area of information theory is in radar networks with multiple sensors, which is equivalent to multi-user or network information theory in communications technology. To date, JC&S remains untouched by information theory. The joint optimisation of such systems will require an overarching theoretical level that brings together the potentially competing influencing factors of radar and communications. The findings of this theory will be reflected in the concepts for estimation procedures and resource allocation in JC&S networks.

4.2 Sensor system standardisation

Standardisation in 3GPP was a major element in the success of mobile network systems, enabling a global ecosystem to take shape. In today's sensor systems, this high degree of standardisation has not yet been reached. The market is fragmented and dominated by proprietary solutions. As the number of proprietary sensor applications increases, the resulting heavy interference will make it all but impossible to use the available spectrum efficiently.

In order to realise the vision of JC&S, it will be necessary to expand future communication systems to include characteristics that permit coordinated and thus efficient use for sensor-based tasks. It is therefore necessary to integrate the associated requirements into the 3GPP standardisation, as well as IEEE 802.11 and IEEE 802.15, and to expand the design of the physical layer and the media access protocols to meet these new requirements. It would also be beneficial to standardise suitable management protocols and functions. Standardisation makes it possible to implement harmonised procedures globally, which in turn leads to more efficient use of the spectrum.

4.3 Media access challenges

The efficient allocation of mobile resources has always been one of the most important tasks in cellular communication systems, since the frequency spectra are a rare commodity. Existing requirements imposed on resource allocation in mobile networks include the use of favourable channel states; modulation and coding methods that are adapted to the situation at hand; selecting antenna configurations; considering the priorities and requirements of individual services; and avoiding interference. The use cases discussed here will give rise to new requirements on top of all these, which must be given due consideration. To prevent or minimise mutual interference one of the first challenges to overcome is that, in addition to the traditional influencing variables that apply to decisions of the scheduler, it will now also be necessary to consider the spatial correlation of objects being detected, directions being recorded and potential data recipients. It will also be necessary to develop resource structures in the dimensions of time, space and frequency that permit efficient parallel use of pilot signals for channel estimation, suitable sensing signals and data transfer itself. Another challenge lies in coordinating the efficient allocation of resources at neighbouring base stations in order to minimise interference. By coordinating nearby base stations, it is also possible to conduct network sensing in which the transmitter and receiver of sensing signals can be different base stations, which helps to improve accuracy. Suitable media access protocols must be developed that satisfy these requirements.

4.4 Integrated frontend

When it comes to the high-frequency frontend, JC&S poses a number of challenges that affect the production technology of the integrated circuits, the high-frequency circuit technology, baseband processing and the media access processor.

The overarching issue here is that, at present, the transceivers in base stations and user terminals are tailored to the functions and signal forms required for communication so that the various requirements. To meet cost-efficiency topics to be addressed are such as energy efficiency and linearity in the transmitter, and the noise figure in the receiver. In some cases, this runs counter to the specifications required for localisation. For this reason, reconfigurable circuitry is gaining an increasing profile. Meanwhile, at critical points such as the final stages of transmitters, semiconductor technology with improved technical performance may be required. In order to achieve a high spatial resolution, it will also be necessary to use phased array antennas that have a large number of individual elements at the highest possible bandwidths, and thus also at high carrier frequencies.

The resulting challenges on the path to creating an integrated frontend as an alternative to separate transceivers for communication and localisation can be summarised as follows:

1) Sufficient linearity and performance capability of the transmitter, so that the diverse requirements of both applications can be met;

2) high bandwidth and sufficiently high signal-to-noise ratio (SNR) for communication and radar detection;

3) the integration of antenna/antenna arrays in small form factors, especially for use on mobile devices;

4) the use of duplex operation, which requires special techniques to suppress the transmit signal in the radar and communications receiver;

5) high sampling rates in baseband processing and for the A/D converter in order to support the high channel bandwidths required for high distance estimation accuracy and high data rates; and

6) the combination of the diverse requirements relating to digital processing for radar and communications systems at the physical layer.

In order to achieve these functions, beyond the individual semiconductor technologies themselves, a vital role will also be played in future by high-performance and cost-effective hetero-integration and construction technologies.

4.5 Regulatory challenges

As already discussed, JC&S has a wide variety of possible applications, ranging from transport (automotive, rail travel, aviation) to hospitals to industrial settings. All of these areas have their own regulations and regulatory authorities (e.g. the Federal Institute for Drugs and Medical Devices [BfARM], the Federal Railway Authority). These authorities must be involved from an early stage so that possible ways to integrate their regulations can be determined. An example not to follow is the missing regulatory coordination of the use of 5G frequency bands in hospitals and their potential coexistence with medical devices. Meanwhile, the introduction of 5G campus networks has shown that a more intensive process of familiarisation with the communications industry and Industry 4.0 is required. Since Germany is an industry leader in the automotive, railway and medical technology sectors, the opportunity should be seized to make these industries aware of the possibilities and general framework offered by JC&S and seek their involvement in its definition.

From the perspective of frequency regulation, action will be needed as soon as services and applications are intended to be used in frequency bands for which there are no suitable assignments, designations in the frequency plan or spectrum allocations (e.g. radar applications in mobile radio bands). This problem will then have to be addressed at the European or international level. In particular, assigning frequency bands to new mobile services at the level of the International Telecommunication Union (ITU) requires a multi-year lead time that involves compatibility tests, the outcome of which is not guaranteed.

4.6 Data protection

It is without question that new sensor capabilities, integrated into future mobile networks as a basic service, offer a wealth of potential. However, they also enable far-reaching surveillance of the public sphere. Recorded sensor data can be combined with machine learning to predict properties that go far beyond simple object detection. This affects not just the users of these new functions, but also uninvolved third parties who are detected by the sensors. Since MNOs are conscious of their data protection responsibilities, and consumers or (cyber) criminals may be interested in sensor data for many reasons, JC&S systems must be designed such that misuse of the sensor data is ruled out at the technical level. New solutions must be developed for this that go far beyond the current state of the art. They must enable trustworthy acquisition and pre-processing of sensor data directly at the sensor in such a way that misuse is impossible and the desired user functionality can be provided at the same time. Further research and development efforts are required here. Substantive technical and regulatory solutions are vital foundations for a large-scale rollout of JC&S.

4.7 Sustainability

JC&S has direct and indirect impacts on the power consumption of sectors that are highly critical to sustainability, such as transport and industry (e.g. energy regulation and heat supply). The quantity of sensors and 6G communications systems, and in particular the associated material consumption during production and the recyclability at the end of their life, will result in energy and resources being used in higher quantities than they are at present. When integrating sensing and communications concepts, there is therefore a high potential to improve resource efficiency and thereby increase sustainability. Also, the capability of a device to network to the sensors of the surrounding devices or the infrastructure can dramatically reduce the number of sensor needed in total. A key goal will be to save more resources than the 6G network will consume on top of those already in use. This means that the concepts developed must be evaluated and ranked on a comparative basis, e.g. based on the life-cycle analysis or a comparison of the energy used by the JC&S network compared to the energy saved by optimising traffic flows. This will ensure the sustainability of JC&S developments as well as supporting society's overarching climate goals.

4.8 Business models

The networking of sensors and the resulting possibility for exchanging the pre-processed sensor data give rise to three new application possibilities at the broadest level:

1) Exchange of raw sensor data and aggregation at a base station or MEC location;

2) Exchange of pre-processed sensor data and generation of 3D situation pictures of the environment, or of material maps based on 3D spectroscopy (e.g. to track pollution in the soil/water/air). In this case, 'on-demand probing' of the mobile network infrastructure or the terminals to improve the resolution is also conceivable as a service.

3) Exchange of cognitively pre-processed sensor data, in particular for detected moving gesture input and/or objects such as people, bicycles, cars, birds and autonomous robotic systems.

In order to guarantee the success of JC&S as a mass product, there is a need for evaluation methods and business models for the Mobile Network Operators. Examples of these include saving energy on the basis of detailed processes in a location pattern (on-demand resource provision), measuring the customer experience and an index for the customer experience in location grids, and GDPR-compliant data provision for various applications and the sale of data to third parties. Data is provided flexibly depending on the priority and needs, e.g. event-based, at pre-defined intervals or on demand. Another option would be for MNOs to offer the sensing function as a value-added service (e.g. 'radar as a service').

5 Recommendations for action

In addition to higher data transfer rates, energy efficiency and security, JC&S is poised to be one of the most important aspects of the development and standardisation of 6G mobile networks. In this way, the foundations are being laid for the future of personal mobile robotics. In particular this thanks to the fusion of networking, sensing and robotics. 6G will pave the way for personal mobile robotics on the consumer market, in applications ranging from games to everyday assistants and from care to delivery drones, or as autonomous cars in coordinated road traffic. The fantasy promised by numerous science fiction novels over the last century is becoming reality. The revolution will sweep through virtually all end user sectors, from sport and exercise to house and garden work, from assistance systems to kitchen aids, shopping and personal mobility. Today, we can already see a glimpse of this vision in action, in the form of vacuum cleaner robots and the first level 2 autonomous vehicles. In all the market sectors listed above, Germany is a leader when it comes to products but has been put under pressure by innovations springing up elsewhere. Just as the Tesla shock swept through the European automotive industry and continues to do so, all other sectors of the German consumer industry will face similar challenges from around 2030, especially as a result of 6G.

Germany has a huge opportunity to take on a leading role in 6G and JC&S. In technology terms, Germany is in a prime position when it comes to expertise in communications technology, sensor systems and robotics. In many of the end user sectors that are set to be revolutionised by robotics, Germany also holds a globally dominant position and is able to market, maintain and recycle products over and beyond their entire life span.

Over the next five years, Germany's solid positioning in the product and technology spheres can be used to assert leadership in the development of 6G and to bring about the transformation in these end user sectors. This gives rise to the following recommended actions for the research and development of JC&S:

1. Promotion of research

   - Promotion of research partnerships between manufacturers of JC&S hardware, commercial operators (MNOs), authorities (due to the relevance to public safety and security), research institutes and universities.
   - Joint research on the physical layer and on radio access for the integration of sensors and data transfer in a radio access network.
   - Research into achieving data agglomeration (using federated/consensus-based AI) of distributed data information.
   - Research into AI-assisted cartography of sensor data in the network, less so in terms of the raw sensor data but instead focusing more on

     i. the sensor imaging maps (e.g. geolocalisation data, radar imaging maps, spectroscopy imaging maps) using fusion AI and federated AI, and

     ii. the object imaging maps (e.g. object localisation, object detection and placement maps, material detection and location).
   - Research into algorithms for object detection and classification based on the fusion of data from distributed sensor nodes.
   - Research into cost-efficient hardware for implementing JC&S (e.g. antenna systems, transceivers and digital signal processing).
   - Research into GDPR-compliant system solutions for sensing data access.
   - Research in the areas of sustainability, resource consumption and circular economy.

2. Integration of JC&S into existing test fields, and expanding test fields:

    - For autonous driving.
    - At traffic hotspots for traffic monitoring and control.
    - In campus networks on public industrial sites.
    - Experimental environments for consumer products, e.g. drones.

3. Standardisation and regulation

    - Stimulation of a coordinated 3GPP standardisation initiative for JC&S systems.
    - Support for activities already under way, such as IEEE 802.11bf (WLAN sensing).
    - Developing regulations for frequency band usage and data protection.
    - Prompt execution of the studies required into the effects of exposure.
    - Prompt execution of studies to derive recommendations for improving sustainability.

4. Transition from research to the development of specific products and business models

    - Development of a system architecture that accommodates all three levels of new business models without monopolisation.
    - Promotion of German industry in order to expand the end user device market through the use of 6G.
    - Production of core components in Germany and Europe.
    - Supporting the development of JC&S-compatible hardware components and algorithms in Germany and Europe.
    - Promotion of the relevant semiconductor technology in order to ensure technological sovereignty in Germany and Europe (not necessarily highly scaled CMOS) and of technologies for hetero-integration at chip level.
    - Promotion of construction and connection technology for highly integrated hybrid systems.
    - Development of seamless design flows across and beyond various technology borders in order to develop complex multi-technology systems.
    - Development of GDPR-compliant business models for MNOs.

About VDE

VDE, one of the largest technology organisations in Europe, has stood for innovation and technological progress for more than 125 years VDE is the only organisation in the world that unites science, standardisation, testing, certification and application consulting under one roof. The VDE mark has been synonymous with the highest safety standards and consumer protection for 100 years.

We advocate for the promotion of research and young talent and life-long learning with on-the-job continuing education offers. 2,000 employees at more than 60 locations worldwide, more than 100,000 volunteer experts and around 1,500 companies in the VDE network are creating a future worth living: networked, digital, electric. We are creating the e-digital future.

The VDE (Verband der Elektrotechnik Elektronik und Informationstechnik e. V. - Association for Electrical, Electronic and Information Technologies) is headquartered in Frankfurt am Main. More information at www.vde.com.

About VDE ITG

VDE ITG was founded in 1954 and is integrated into VDE's interdisciplinary network as an interdisciplinary speciality research association. It acts as an interface for information technology (IT) experts in the economy, administration, teaching and research. Its members represent the bundled German competence in the field of IT in close international cooperation.

VDE ITG promotes the research and application of this key technology and its efficient use in the fields of data and communication technology and systems, environmental protection, medicine and traffic.

With its huge international network, VDE ITG is a platform for innovations and the transfer of knowledge for the successful collaboration of industrial partners and research institutions. To this end, VDE ITG conducts a number of symposia, discussion sessions and workshops. With its studies and recommendations, VDE ITG contributes its expertise towards policy and society and participates in promotion programs.

Another focus of VDE ITG's activities is the intensive promotion of young talent in science and research and the education and continuing training of the engineers, scientists and researchers active in the field of information technology.

VDE ITG (The Information Technology Society) currently has approx. 7,200 members and 1,200 volunteer employees. The technical work is done in 7 subject areas with 34 technical committees and 32 technical groups as well as several focussed projects.

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