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PERSPECTIVE

Joint Radar and Communications: Architectures, Use Cases, Aspects of Radio Access, Signal Processing, and Hardware

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ABSTRACT Joint Radar and Communications (JRC) can satisfy the apparent demand for applications based on object detection, tracking, ranging, and positioning. JRC is, therefore, often seen as candidate technology for 6G mobile systems. Implementing JRC will require novel approaches in many research and engineering fields, including protocol design, digital and analog signal processing, and hardware development. The ongoing debates on JRC already include many white papers and research articles ranging in content from very specific technical problems to comprehensive bird's eye-level reviews. This paper represents the work within the Open6GHub research project in Germany, which aims to investigate and implement potential end-to-end solutions for 6G. In this framework, we propose a consolidated vision for potential JRC architectural approaches. The subsequent discussion on integrating radar sensing with communications highlights this technology's state-of-the-art and presents relevant opportunities and challenges.

INDEX TERMS 6G, joint communications and sensing (JCAS), joint radar and communications (JRC), integrated sensing and communications (ISAC), radar-communications (RadCom), radio access network (RAN) architecture.

I. INTRODUCTION

Among other emerging technologies, joint radar and communications (JRC) is widely accepted as one of the promising

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for 6G [1], [2], [3], attracting significant attention from the research community all over the globe. This trend is supported by interest from major networking and telecommunications players such as Nokia [4] and Ericsson [5]; moreover, 3rd Generation Partnership Project (3GPP) recently included a study on JRC into its work plan for Release 19 [6]. JRC facilitates various scenarios such as remote sensing, environmental monitoring, automotive industry, smart home, and human-machine interaction [1]. Within these scenarios, the scope of possible JRC applications includes everything from the drone swarm synthetic aperture radar (SAR) imaging and weather monitoring to gesture detection and fall detection [7].

Many projects these days examine different aspects of the future communications standard generation. The authors of this paper represent the Open6GHub project, launched in 2021, which brings together more than a hundred researchers from 17 German universities and research institutes. The project's ultimate goal is to develop a holistic 6G architecture, including experimental demonstrators, by the middle of 2025, when the 3GPP standardization process for 6G will likely begin. The topic of integrating sensing capabilities into the future generation of wireless networks dwells mainly within the framework of research on adaptive radio access network (RAN) technologies for 6G. In this context, we investigate different approaches to integrate sensing functionalities into 6G, making a significant effort in many relevant areas ranging from research on different 6G architectural concepts to design a real-world implementation of a scalable JRC 6G testbed that operates in sub-6 GHz and millimeter wave (mmWave) frequency ranges [8].

Integration of sensing capabilities with communications has different names, often used interchangeably (e.g., joint communication and sensing (JCAS) and integrated sensing and communication (ISAC)). Here, the term JRC is used to represent the class of concepts, narrowing the term 'sensing' exclusively to radar functionality.

A. RELATED WORKS AND STATE-OF-THE-ART

There is already a significant number of research papers discussing JRC; this research varies in level of detail and highlights different JRC aspects. Some prominent examples include [9], [10], [11], [12], [13], [14], [15], [16]. Merging the radar functionality into future networks and providing new use cases already in the 6G requires addressing multiple technological dimensions, ranging from defining novel architectural concepts to practical implementation issues.

Answering the question of which network agent(s) performs new functions of target illumination and subsequent echo collection and radar signal processing influences individual network components and the whole end-to-end framework. However, there is still very little research considering possible radar feature addition in 6G from the architectural point of view. One possible solution is to rely exclusively on available static communications infrastructure (e.g., to equip base stations (BSs) with additional mono- and/or multistatic radar capability [17]). Another option assumes involving the user equipments (UEs) for target illumination and/or radar signal processing. Potential integration of mobile JRC-capable intelligent transportation systems (ITSs) and non-terrestrial networks (NTNs) components into the 6G ecosystem [18], [19] can significantly scale not only the coverage but also environmental understanding within the future generation networks. Thus, system requirements linked to the use of radar-equipped vehicles, drones and satellites in 6G deserve more careful study. The ongoing discussion on architectural innovation for the 6G network mainly revolves around topics of network slicing [20] and Open RAN [21] and almost neglects specific JRC-related challenges.

The high connectivity planned for 6G networks and the advanced artificial intelligence (AI) technologies that will be core in their design can be exploited in the lower layers of the stack and enable new JRC functionalities. For instance, 3D reconstruction of the local environment by utilizing information collected from the surrounding network [22], [23] as well as the characterization of materials and surfaces based on the scattered and/or reflected signals properties. Consequently, the choice of an apt JRC waveform that could be employed for both the radar and communications [24] is essential, in addition to the support of real-time spectrum sharing and sensing capabilities that ensures meeting both the radar and communications key performance indicator (KPI) requirements from the physical layer (PHY) and medium access control (MAC) layers perspectives [25].

Next, the signal processing in a JRC system must be compatible with the orthogonal frequency-division multiple access (OFDMA)-based communications system. Existing approaches already demonstrate the general feasibility for radar sensing with orthogonal frequency-division multiplexing (OFDM) (see [26]), but are not suitable for use with the multi-user communication systems used for JRC, as described in [27]. Specific features, such as multi-user resource allocation in time-, frequency-, and space, create challenges for JRC signal processing and must be re-designed to cooperatively balance the needs of the communications and sensing system simultaneously [28]. As resource allocation also impacts target detection, estimation, and tracking, JRC algorithms require a joint optimization thereof, but can also leverage the communications system to their advantage to improve the overall sensing and communications performance [27].

Last but not least, the feasibility of the designed concept heavily depends on reachable hardware capabilities. The baseband and frontend equipment of current 5G BSs already provides a good basis for JRC applications, which are currently under discussion for 6G [29]. However, they do not meet all requirements [30], especially when it comes to monostatic sensing, where full-duplex (FDX) operation with good suppression of the coupled signal is required [31]. This can, for instance, be achieved with analog self-interference cancellation stages that replicate the paths of the transmitter

(TX)-receiver (RX) coupling and the reflections from strong or close static targets in the surrounding of the antennas [32]. Another solution to circumvent this is multistatic sensing. However, in this case, good synchronization between the BSs and methods for exchanging the radar data and fusing them are required [33].

B. CONTRIBUTIONS AND STRUCTURE OF THE PAPER

The main objective of this article is to present a holistic overview of various JRC aspects and open research and implementation problems, providing pointers towards 6G wireless systems. The key contributions of this paper can be summarized as follows:

- Recognizing the different capabilities of the network nodes and the relationship between them, we come up with a classification of the possible JRC architectures, which, to the best of authors' knowledge, has not been proposed yet. More specifically, we first categorize JRC architectures into infrastructure-based, infrastructure-less, and heterogeneous JRC networks, and then highlight and define a few sub-categories;
- We provide an overview of integration levels which facilitate the simultaneous operation of both sensing and communication functions in JRC systems despite their conflicting requirements. Based on the application requirements, we have divided the integration levels into three types: radar-centric, communication-centric, and full integration;
- We discuss the PHY and MAC layers' aspects that are relevant to the design of future JRC systems and the associated challenges that need to be considered;
- We present a review of signal processing stages for JRC. In this context, we show that the signal processing in JRC systems is strongly intertwined with the communication system, raising new opportunities and challenges related to detection, estimation, resource allocation, data fusion, and tracking;
- Based on practical experience, we review various JRC-relevant hardware aspects from both analog and digital domains. We show that the hardware of current BSs already provides a good basis for JRC applications and outline the requirements which have not been met yet.

The paper is structured as follows. Chapter II classifies JRC architectures based on components' structure and functionality, illustrating each architecture by a relevant use case. In addition, this chapter provides insights into what kind of spatial information is really useful and needs to be sensed, keeping in mind limitations in the amount of data to process and move through the network. Chapter III overviews different levels of integrating communications and radar functionalities into a whole. Chapter IV scrutinizes PHY and MAC layers, additionally providing an overview of the ongoing discussion regarding suitable JRC waveforms. Finally, Chapters V and VI shed light on signal processing and hardware-related topics for JRC, highlighting current work in these fields and challenges to be overcome.

II. SYSTEM ARCHITECTURAL ASPECTS AND USE CASES

Initial attempts to describe JRC architectures can be traced back to [34], which discusses topologies for two users. Then, the authors of [35] consider the collaborative approach involving more than two JRC-capable users. Thomä et al. in [36] address a network consisting of several JRC nodes in the framework of cellular technology, developing this idea later in [17]. Our paper summarizes previous efforts and extends the architectural classification concerning different possible infrastructures.

Depending on the structure and functionality of the involved components, JRC architectures can be classified as infrastructure-based, infrastructure-less, and mixed heterogeneous type. Below, we provide a description of these categories and discuss relevant technologies, challenges, features, and potential applications. We illustrate each architecture with a figure showing an abstract high-level structure, additionally providing a picture of a corresponding 'real-life' use case.

A. INFRASTRUCTURE-BASED JRC

The first JRC architecture assumes the use of the dedicated infrastructure at fixed and known locations, e.g., cellular BSs or Wi-Fi access points, that are capable to perform both communications and radar. Based on the type of nodes, sensing methods, and access, we further classify infrastructure-based JRC into three subcategories.

1) NETWORK-ONLY SENSING

In network-only sensing, all the radar components belong to the infrastructure, which is used to illuminate targets and collect echoes. For example, in the case of cellular networks, sensing is performed by BSs, consisting of remote radio units (RRUs) connected to a baseband unit (BBU). In addition to the standard task of processing uplink (UL) and downlink (DL) data traffic and controlling RRU functionality, a JRC-capable BBU has to be able to perform radar signal processing. In general, the network-only approach allows the JRC-capable infrastructure nodes to be mobile as well (e.g., see NTN access with the help of satellites or drones).

Depending on the spatial configuration of the transmitters and receivers, radar sensing can be performed in a monostatic or multistatic mode.

- In a monostatic mode, the BS works as a stand-alone active radar (see Fig. 1). The antenna array is required to obtain an accurate direction of arrival (DoA) estimation. Besides, a FDX air interface is also necessary since the BS needs to receive the backscattered signal while transmitting the communications signal.
- In a multistatic infrastructure-based JRC, the localization is performed by a network of BSs (see Fig. 2). The networked BSs are spatially distributed and, in addition,

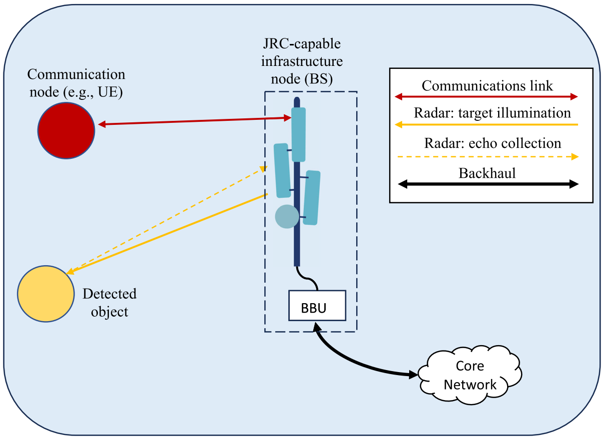

FIGURE 1. Network-only JRC architecture: monostatic case.

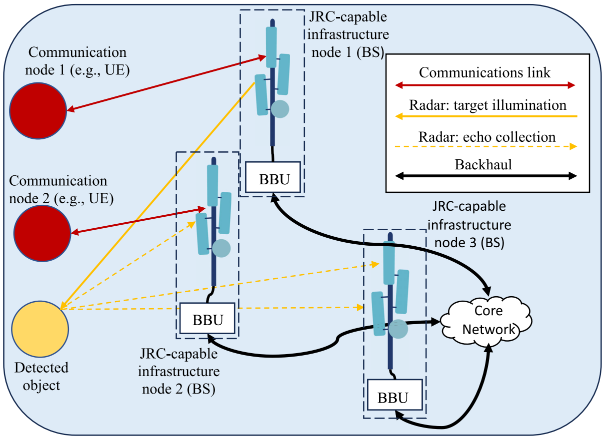

FIGURE 2. Network-only JRC architecture: multistatic case.

can be connected via synchronized links, e.g., fiber optic cables. Involved BSs and RRUs receive the direct line of sight (LOS), static clutter, and reflections from the targets. With the known reference signals (either via the backhaul or signal reconstruction), the RX-nodes can estimate the target signal parameters required for the localization.

2) DEVICE-TO-NETWORK JRC

Similarly to the previous architecture, here, radar signal processing is performed fully by the infrastructure nodes; however, both DL and UL signals can be used for target illumination (see Fig. 3). This architecture can be seen as the multistatic radar approach involving the UEs as potential radar signal transmitters. Due to the mobility of the UEs, the radar network is spatially dynamic and may constantly change. The architecture can also follow the passive sensing principle, where radar receivers exploit cooperative and potentially non-cooperative communications transmitters in the environment.

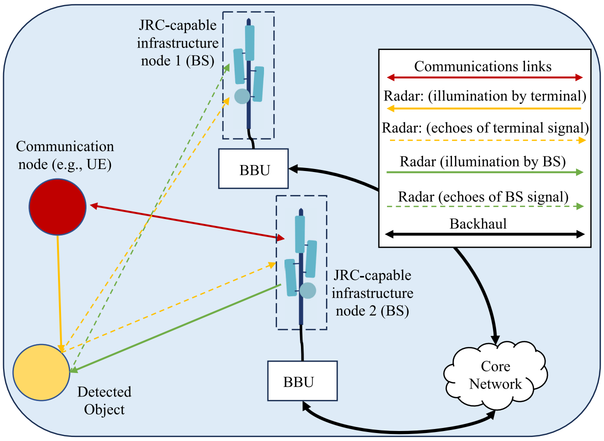

FIGURE 3. Device-to-network infrastructure-based JRC architecture.

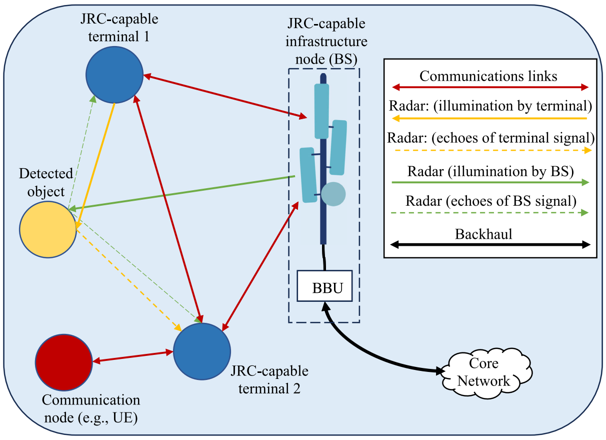

FIGURE 4. Network-assisted JRC architecture.

An example of device-to-network JRC is shown in Fig. 5 (in the upper-left part). Here, one of the unmanned aerial vehicles (UAVs) serves as a mobile node capable of communications that simultaneously illuminates and another UAV, non-collaborative and potentially malicious. The reflections from the non-collaborative UAVs are then used by the JRC-capable BS to detect it as a passive object.

3) NETWORK-ASSISTED JRC

In contrast with the approaches introduced above, where radar receivers are co-located with the infrastructure nodes, it is also possible for the radar receiver functionality to be integrated into the end-user communications devices. The role of the infrastructure in sensing can either remain the same or be reduced to the assistive.

In network-assisted JRC, the side links will also be available in addition to the communications links between UEs and BSs (see Fig. 4). The sensing network may combine several access methods, e.g., cellular and vehicle-to-vehicle (V2V) communications networks. The effective utilization of side links requires infrastructures to provide an improved control strategy for sharing information between

FIGURE 5. **Use case for network-only JRC sensing: UAV detection and object tracking for critical infrastructure (here, an airport). Yellow lines correspond to illumination (solid) and echo (dashed) signals. Objects' and lines' colors have the same meaning as in the abstract architectural figures. Pale yellow beams depict target illumination by infrastructure nodes, capable of both communications and radar functionalities. Illuminated targets are shown in yellow colour. Notice two types of drones: one (blue) belongs to the infrastructure, acting as a mobile node capable of communications and target illumination, and another one, non-collaborative and potentially malicious, detected by the BS as a passive object. This procedure belongs to the subcategory of infrastructure-assisted JRC.**

sensors, including synchronization issues. Here, the BS could orchestrate the whole process.

Use case: As a simple example for JRC use case definition, we describe a scenario that leverages synergies between communications and wireless sensors in an unprecedented way. The JRC architecture (also called ICAS [17]) emphasizes the seamless integration of sensing functionality into a distributed BS architecture. The application scenario is about upcoming commercial drone traffic. While hobby drones have already proven to be a safety threat to airports [37], [38], [39], [40], commercial drone traffic will present completely new and far-reaching challenges in ensuring safe air traffic to support legal drone activity and commercial success of drone business. For the purpose of using the low-altitude airspace by drones (also UAVs, or UAS, Unmanned Aircraft Systems), a special airspace has been established called "U-Space", in which rules for safe traffic are defined (see also EU Drone policy 2.0). In this context, 5G/6G is envisaged as a reliable and ubiquitous communications platform for controlling drones over longer distances. However, the uncrewed aircraft system traffic management (UTM) systems planned on this basis alone are not sufficient to ensure safe flight operations, as they do not provide sufficient security against intentional or unintentional misuse or incorrect use of U-space or prevent possible collisions with other flying objects (birds, hobby drones, paragliders, etc.).

In conventional air traffic control, dedicated systems are used for this purpose. These surveillance systems perform radar localization and tracking of passive objects. They can also detect flying objects by their actively emitted radio waves. Following the "trust but verify" principle, these dedicated systems allow independent verification and confirmation of the information provided by the primary cooperative surveillance system and reported via ADS-B [41], as well as timely detection of intruders and threat situations. However, the existing air traffic control systems cannot be used for the U-space because they are neither technically designed for this purpose nor can they be operated on an area-wide basis in order to economically secure the U-space level. We would need a scaled-down system that would be available to public and commercial drone operators everywhere.

In contrast, a mobile radio network with JRC capability for radar sensing and radiolocation could provide a ubiquitous (area-wide) solution for the detection of rule violations and unauthorized use of the U-Space at comparatively low effort. Reusing the existing mobile communications infrastructure ensures low installation costs and ubiquitous coverage. Unlike the established localization services already included in the 3GPP standard, JRC/ICAS surveillance would be able to detect, locate, and track UAVs based on their plain radio emissions. It would not rely on specific pilot signals and protocols (as 3GPP does). Therefore, UAVs not participating in the cooperative UTM system can also be identified. Positions reported by cooperative UAVs can be independently verified. At the next level, the JRC radar function also enables the detection of flying objects that do not actively emit radio signals. Based on the flight dynamics and the shape of the radar reflection, which may include the micro-Doppler signature, the purpose and type of drone or flying object can be identified. The system would be adaptive and self-learning, since the verified UAVs that act in accordance with rules and regulations (which outnumber the violators) can be used as a reference database.

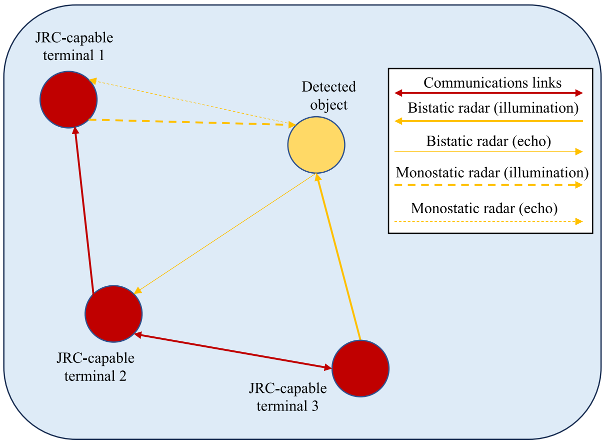

FIGURE 6. **JRC architecture without the support from a base station.**

The benefit of JRC is to provide an economically efficient surveillance system for lower airspace with low capital expenditures (CAPEX) and operational expenditures (OPEX) when integrated into an existing mobile RAN. It not only reuses the available radio access resources but also takes advantage from data transport and computational capabilities of network for data fusion. In addition, JRC can be integrated to upcoming UTM systems by mobile network operators (MNOs) as an administrated radar service with controlled quality of service (perhaps complemented by radio surveillance) for public and proprietary environments (such as campus networks). With this, JRC can support a variety of application, e.g., enhancing safety, reliability, and effectivity of transport and logistics, to support public safety and law enforcement to protect critical infrastructure.

B. INFRASTRUCTURE-LESS JRC

Next to the aforementioned architectures, ad hoc networks, like vehicular ad hoc networks (VANETs), are getting more and more in the focus. In this context, the traditional infrastructure-based architectures are getting replaced or at least expanded by sidelink communications capabilities (see Fig. 6).

Although the following points are taken up in the automotive context in particular, they should also be transferred in general to ad hoc networks as in the context of UAV-to-UAV communications.

An exemplary architecture is indicated in Fig. 7, where the communications link between agent nodes is established using sidelink. The communications signal, however, also gets scattered back by the communications partner as well as the surroundings. In consequence, a transceiver in FDX mode can extract sensing information out of its transmitted communications signal, acting as a monostatic radar. A fully connected architecture even extends this by the fact that the receiving communications partner is aware of the originally sent communications signal. As a result, bi- or more advanced multistatic architectures can be built up, which help to improve the overall sensing, organized in so-called radar networks. These radar networks are still under research, however, promising benefits, especially in scenes where several perspectives of various JRC-capable nodes can be fused together to extend the limited or even impaired view of a single node.

Therefore, a distinction must be made between fully networked JRC-capable nodes, which exchange their communications and radar detection data, and ego nodes, which rely only on their self recorded sensor data or on generally available information (like prior knowledge of the environment). This is the case when there are no other JRC-capable nodes nearby or when an ego node is surrounded by passive objects or only not JRC-capable nodes that do not have a high technical standard. Since the average lifespan of cars is about twelve years, penetration of the technology in the automotive sector will not occur until 6G is introduced in 2030. Moreover, there will always be nodes like old-timers or in more general outdated nodes that will never enter the 6G networks, however are operated due to economic or nostalgic reasons.

1) EGO-PERSPECTIVE

This architecture relies only on its own perspective (hence the name), including its own sensor data and its own plan for future actions (such as intended trajectories or accelerations). In consequence, the system does not rely on data sharing between nodes/objects. An argument for such an architecture can be found especially in scenes where no other JRC-capable nodes (e.g., vehicles) are around or only nodes that do not have the technological standard to share information. It can be predicted that this will be quite common in the near future, in particular as automation levels are still in their infancy and the transition to being fully automated in the context of industrial and automotive environments is still not available.

The JRC-capable node perceives its surroundings by means of the internal sensor systems, as shown in Fig. 7. In addition to radar, also other sensor data available at the node such as camera, light detection and ranging (LiDAR), infrared or ultrasound-based data can be taken into account or even fused together to further improve the internal representation of the surrounding. The obtained sensing information is then available to plan future actions of the ego node. Future actions can be understood as both mechanical actions, such as steering the node, and actions, such as the optimized alignment of the antennas with a possible communication partner. Established understanding of the environment helps to find an optimized alignment, like avoiding potential obstacles and non-light-of-sight (NLOS) connections or, if necessary, mitigating them by targeted amplification of the multipath. Inter alia, the resilience of safety-critical communications can be increased as a direct consequence.

The aforementioned aspects are, however, also conceivable for BSs if they are equipped with sensors. In this case, the JRC-capable BS performs detection and can address

FIGURE 7. Use case for infrastructure-less JRC architecture: platooning in a city scenario with no infrastructure involved. Cars grouped together sense the environment (including group members and relevant surroundings) and share obtained information with each other, thus extending their ego view. Here, radar sensing can be performed in both mono- and bistatic modes. Passive objects to be sensed are colored in yellow. Yellow arrows represent the propagation paths of a signal used for radar purposes. Communications links are shown in red.

communications partners individually based on the environment drawn from the sensing data, resulting in more efficient resource management by an individual addressing of UEs in the sense of adapted beamforming or an avoidance of interferers by spectrum sensing.

Use case: This approach can be transferred to non-public networks (NPNs) in the industrial sector, as autonomous intralogistics faces similar challenges. It enables features like platooning, which is discussed in the automotive sector (see Fig. 7), however also is supposed to increase efficiency in intralogistics. In the field of intralogistics, the underlying assumptions regarding speed and acceleration are drastically reduced compared to those of autonomous driving. As a result, time requirements for safety-critical functions and for the sensing itself are reduced. Therefore multisensory equipment of autonomous vehicles in intralogistics can be lowered to a few or individual sensor devices in order to meet the safety requirements. In a fully automated environment, the requirements are reduced even further due to the predictability of the entire environment. By introducing a solution that serves as a communications interface on the one hand and a sensor on the other, both the energy consumption and the computational complexity of the JRC-capable nodes are minimized.

2) COLLABORATIVE JRC

An additional approach to resolve scenarios, where no infrastructure is available, is the so-called collaborative JRC architecture. It operates independently by direct interaction over the sidelink via the radio interface, similar to dedicated short-range communication (DSRC) implemented in C-V2X sidelink mode 4 [42]. Thus, it is organized in a decentralized manner without depending on central cellular network connections and can be considered as an extension of the previously discussed ego-perspective.

If a FDX mode is available, a monostatic radar can be used. In addition to expanding the monostatic approach to a distributed bi- or multistatic approach, fully connected JRC technology offers the possibility for nearby JRC-capable nodes to exchange sensor data directly. This, for example, includes the exchange of target lists resulting from the radar processed in each JRC-node (e.g. UAV or vehicle) and can be extended to all different kind of sensor data of different type available at the node. Possible incorrect or unknown target classifications and clusterings can be corrected or retraced. In summary, two main advantages are identified: Multiple distributed sensors can be synchronized via the sidelink to form a sensor network (cooperative radar). Consequently, it enables multilateration estimation and cooperative multiangular estimation. Furthermore, radar detections are improved by fusing the target lists created by individual radars of the network.

The combined sensor data can also be used for adaptive beamforming to align the antennas to an inaccurately detected target and thus, improve the communications link to this object. Consider an intersection as an example: A JRC-capable node, in this case a vehicle, wants to connect with another UE, but does not see it in time before it reaches the intersection. However, thanks to the shared sensor data of a better-positioned vehicle, its antennas are aligned during the turn to establish an optimal connection to this object.

Moreover, information can also be drawn from future heterogeneous networks, where the network is not limited to one technology but can be built, for example, by non-terrestrial communications in addition to traditional cellular communications. With the help of spectrum sensing, the

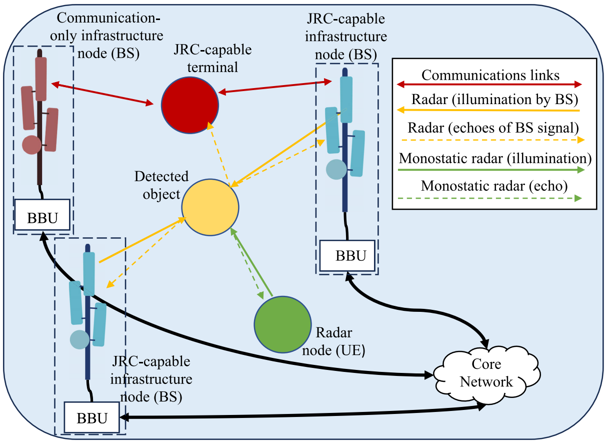

FIGURE 8. **Heterogenous JRC architecture.**

best technology can be selected and communications can be secured.

Bringing the collaborative approach back to the previously mentioned intralogistics use case, there are further optimizations to be expected. With a fleet that is completely under the control of a factory owner, these same collaborative approaches can be rolled out to all equipment or vehicles. This can lead to an optimization of fleet control through a common perception of the environment, which can take into account much more aspects than an ego perspective-based control. With the help of environmental perception, planning for logistics can be derived, as, e.g., temporarily highly loaded areas can be detected and avoided. In addition, the sensing information can be used to obtain a more detailed, up-to-date overview of the status of the intralogistics system on the basis of which optimal decisions can be made regarding incoming requests from the ERP.

C. HETEROGENOUS JRC NETWORKS

Given the technological trend towards the integration of radar and communications technologies into systems and devices, the current wireless networks may evolve into heterogeneous joint radar and communications network (HJRCN) in the near future. An HJRCN consists of co-located radars, communications nodes, and JRC nodes with dual functionality (see Fig. 8).

HJRCN provides an exciting opportunity to collaborate with heterogeneous nodes, and it also has the potential for deeper integration of sensing and communications functionalities inside a network to create a digital representation of the physical world and deliver location- or context-aware services. However, to reap the benefits of HJRCN, several challenges need to be addressed, ranging from the issue of coexistence between heterogeneous nodes to cross-technology interference and effective wireless resource allocation inside the network. Since both radar and communications nodes require higher bandwidth for sensing and data transmission, efficient sharing of spectrum between them for achieving peaceful coexistence is not trivial. There has been a number of works [25], [43], [44] in recent years which analyze the issue of coexistence between heterogeneous nodes. Munari et al. in [43], studied the coexistence between radar and communications nodes operating in the mmWave frequency band. Authors in [25] analyzed the fundamental tradeoffs of radar and communications coexistence in a JRC network. Additionally, the disparate transmit power and receiver sensitivity in the case of radar and communications nodes make the issue of coexistence more difficult. Furthermore, attaining fairness in HJRCN through optimal resource allocation and existing multiple access schemes may not be possible due to different radar dwell time and communications throughput requirements [45]. Therefore, there is a need for a proactive mechanism to alleviate the issue of coexistence in HJRCN. This can be mainly accomplished by employing a centralized resource management entity, which enables inter-network coordination for heterogeneous node coexistence. Authors in [46] proposed a cloud radio access network (C-RAN) architecture for flexible resource allocation between radar and communications nodes. Another approach is to opt for distributed architecture with a proactive signaling scheme as proposed in [45], where nodes coordinate among each other to share the resources and maximize their joint performances.

Use case: It is anticipated that the HJRCN will play an increasingly important role in every aspect of future civilization, including smart city surveillance, smart house monitoring, and autonomous vehicle platooning, among others. Fig. 9 illustrates an example of a future smart city, where devices of communications, radar, and JRC capabilities are integrated into a wireless network. The advantage of leveraging both radar and communications functionalities collectively in a coordinated fashion makes heterogeneous JRC networks usable for dynamic scenarios. For example, multivehicle collaboration is essential for autonomous vehicle platooning to enable cooperative adaptive cruise control and platoon-based driving. Each autonomous vehicle is analogous to a heterogeneous JRC node comprised of multiple radar, LiDAR, and communications units. Investigating what the ideal sensing and communications protocol for this highly dynamic environment should be to extend the sensing capabilities of collaborative vehicles and improve data sharing between them. Similarly, in the case of indoor and outdoor surveillance and monitoring, where a heterogeneous mix of radar and communications nodes are installed, initiating a coordinated response among them in a potentially uncoordinated manner and sharing the available network resources cooperatively will enable innovative services and solutions with a higher degree of accuracy.

Another use case can be access control for restricted areas, if both the gate and the passing object are connected via 6G, communications and sensing can be combined and authentication can be done based on the data from the 6G system.

FIGURE 9. A heterogeneous JRC networks architecture consists of JRC-capable infrastructure nodes, JRC-capable UE nodes, communications-only BSs, and radar nodes. In this figure, we present a smart city scenario where nodes with different capabilities, such as JRC, communications, and sensing would coexist. JRC-capable BSs can communicate with their users (shown by the red lines) while also performing radar-based sensing operations (represented by the yellow lines). In some cases, two BSs can synchronize to conduct bistatic sensing for passive object identification, where one BS transmits its sensing signal (shown as a yellow solid line) and the other BS detects the sensing echo signal (yellow dashed line). Further, the radar-only nodes can perform their monostatic sensing operation (represented by a green beam) for passive target detection. Since all the sensing and communications operations are performed independently, all nodes can collaborate and synchronize to fuse their individual information to achieve complete and accurate sensing of the complex environment.

Summarizing our view of the potential JRC architectures, we envision increased interest in the multistatic approach. Distributed multisensor JRC, also known as multi-sensor (MS) multiple input multiple output (MIMO) ISAC [17], [47], is the most promising direction for the convergence of mobile communication and distributed sensing networks due to its many advantages. First, the cross-linked structure of mobile radio networks offers great potential for cooperative radar sensing, as it fits MS JRC. The ubiquitous availability of mobile radio access provides a distributed network of radar sensors, with the underlying rules for service quality equivalent to communications. Furthermore, the multi-access edge computing (MEC) provides the computational resources required for machine learning and artificial intelligence for adaptive resource allocation, target parameter estimation, and scene recognition. This way, MS JRC will become a ubiquitous and cognitive radar-sensing network. Lastly, a distributed JRC system takes advantage of the inherent target-related diversity gain, well known from distributed MIMO radar [48]. Due to the variety of directions from which the target is illuminated and observed (including multi-bounce interactions with the environment), the spatial diversity increases detection probability and mitigates Doppler blind spots. The latter is important for estimating the full 3D dynamic target state vector that contains the target's 3D position, orientation, and speed [49].

D. ADDITIONAL REMARKS ON WHAT NEEDS TO BE SENSED

Despite significant technological progress and a fair assumption that transmission rates of TBit/s will be typical in future networks, implementation efforts and limitations imposed by system design must be considered. Antenna, network density, needed bandwidth, and other system parameters can vary depending on performance requirements. For example, the requirements for object detection (object present or not present) differ from those of precise localization, where the object's full 3D state vector is required (e.g., in position, orientation, speed, and acceleration). Based on this assumption, we want to highlight the importance of which kind of information needs to be derived from radar sensing. For example, information about moving objects and environmental changes is obviously valuable, whereas detecting buildings or trees constantly present at a known location can be redundant. This specific knowledge of the fluctuating environmental behavior acquired from sensing can be roughly expressed as a ratio of the new useful information (unknown a priori) and the total amount of data that can be transmitted and processed. The difference between the two types of passive objects is shown in Figs. 5, 7, and 9, where moving objects illuminated by radar signals are colored in yellow, and invariable surroundings are in the background. Knowledge about environmental dynamics may be used to reduce radar bandwidth and the number of transmissions, resulting in more efficient spectrum use, improved latency, less interference, simplified MAC layer design, and lower requirements regarding a JRC device's hardware and computational capabilities.

III. INTEGRATION LEVELS

Integration in JRC can be categorized into two distinct types. The first is the integration of sensing and communications

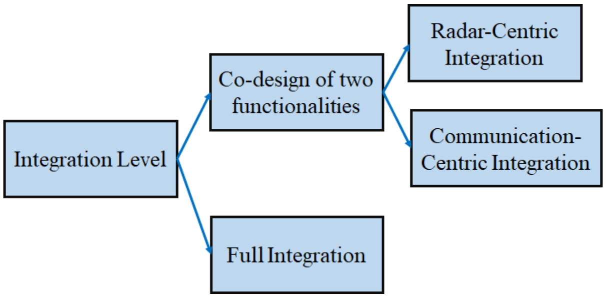

FIGURE 10. **A classification of integration levels in JRC systems.**

functions into a single system, with the two functions operating in tandem or a layered fashion using either identical or different signals. Second, both functionalities are integrated by sharing hardware components and jointly optimizing the same signal to improve both sensing and communications capabilities. The former one can be divided into two types based on the priority assigned to the functionality, such as radar-centric integration and communications-centric integration. The main issue in this type of integration is to mitigate mutual interference while guaranteeing satisfactory performance from both functions [50]. The latter type of JRC integration, on the other hand, is full integration, in which both functionalities share and reuse resources with different quality of service (QoS) priorities. Several unique challenges, however, need to be addressed to realize the benefits of total integration in JRC fully. In particular, from a systemic perspective, the main emphasis is on the design and optimization of signal waveforms, beamforming vectors, suitable medium access protocol designs, and dynamic scheduling mechanisms to manage interference between the sensing and communications functions, as well as guarantee performance without biasing either function. The classification of integration levels in JRC systems is presented in Fig. 10.

In the following, we discuss the three integration types in JRC, accentuating their advantages and disadvantages.

A. RADAR-CENTRIC INTEGRATION

The main idea in radar-centric integration is to merge the communications function into a radar system. The communications service can thus be interpreted as an on-top service on a radar service. In other words, the radar service would be seen as a primary service, whereas communications can be seen as a secondary service. This type of integration can be done at the signal level, i.e., modulating the messages to be wirelessly communicated into a radar waveform. A classical approach is to go for pulse interval modulation, where the communications symbols are embedded between two radar pulses. Furthermore, advanced information embedding is made possible by modern radar systems like MIMO-OFDM radar and frequency-hopping radar, which uses index modulation [51] for signal integration. Another design approach is to use orthogonal beamforming for sensing and communications operation [52]. The main lobe of the beam can be utilized to illuminate the target, and the side lobes are used for communications purposes [53]. The primary goal of radar-centric integrated systems is to design radar pulses to achieve a high signal-to-interference-and-noise ratio (SINR) at the radar receiver while keeping interference from the coexisting communications function within a predetermined limit.

One of the main advantages of radar-centric integration is its capability for operating long-range transmission [46]. This could be utilized for covering a large geographical region for communication. However, the main disadvantage of this integration is that the system's data rate is limited due to an inherent limitation in the radar waveform [9]. It restricts the potential of acceptance of this approach for infrastructure-based JRC in 6G and beyond; however, it can be used in HJRCN or such infrastructure-less architectural approaches, where the high data rate is not critical. In addition to low data rates, designing a suitable communications protocol, particularly a MAC protocol and frame structure, that can be implemented on the radar system is quite tedious. Although optimizing radar waveforms is a well-established strategy in theory, in practice, it is not always feasible because governments and military are hesitant to make significant changes to their radar deployments, which may cause additional CAPEX and OPEX [54].

B. COMMUNICATIONS-CENTRIC INTEGRATION

Communications-centric integration aims to incorporate sensing capabilities into existing communications devices by adapting or modifying the existing communications protocol for sensing purposes. There are two ways to do it in terms of design. First, it can be done at the frame level, which means changing the frame or protocol of existing standards (e.g., Wi-Fi and 5G NR) to integrate the sensing functionalities into the default communications structure. Second, integration can be done at the network level, where sensing functions are used by all devices in the network and managed by an edge device, and go for distributed or networked sensing. This can be achieved by utilizing advanced cellular infrastructure such as C-RAN [55], in which the densely distributed RRUs perform both communications and sensing operations and forward these data to the central cloud for further processing. This system integration provides additional dimensions to the communications systems. The information obtained about the surrounding environment through the sensing signals would benefit the communications systems in terms of dynamically adapting their network resources. Communications-centric JRC that can add radar functionality to the cellular infrastructure nodes without compromising data rates is an attractive choice for 6G and beyond. Further, the networked sensing functionality provides a digital map of the surroundings and is helpful for advanced applications such as digital twins, augmented reality (AR), and extended reality (XR).

Nonetheless, this integration approach has the drawback of limited sensing capabilities. This is because in existing communications devices, communications is the primary function, and sensing is an add-on feature with lower priority. To obtain reliable sensing results, more resources (e.g., additional pilot symbols, subcarriers, antennas, power, or bandwidth) are required, which cannot be made available exclusively for sensing. Furthermore, from a hardware perspective, integrating radar into traditional communications systems requires FDX transceivers, which are still in their infancy. In the case of networked sensing, multiple nodes simultaneously perform the sensing and communications operations at the same frequency band, posing several challenges. This uncoordinated transmission of either sensing or communications signals from devices causes significant mutual interference, affecting both the communications and sensing functionalities, and its effect is severe in the case of dense deployment scenarios [9]. Therefore, the communications-centric JRC system design requires significant modifications of existing protocols to achieve optimal performance.

C. FULL INTEGRATION

Full integration can be viewed as a state of mutually beneficial coexistence between sensing and communications functionalities, devoid of any potential for inter-functional interference and offering full potential for exploiting performance improvements on both sides [34]. This approach is suitable for any JRC architecture described in Chapter II. To realize this multi-objective, fully integrated JRC system relies on an FDX transceiver co-located with an advanced signal processing unit, leveraging the benefits of self-interference cancellation algorithms for successful reception of both communications and sensing information. It will further rely on designing a dual-functional waveform (e.g., by exploiting existing 5G numerology), capable of both sensing and communications while realizing the trade-off between two performances.

The following are some of the benefits offered by JRC systems that are based on total integration. The first benefit is an increase in spectral efficiency, which is a direct result of the spectrum being fully shared between the communications and radar functions. The second type of gain is coordination gain. This type of gain refers to the additional benefit achieved by the communications systems due to their exploitation of the channel characteristic results obtained from the sensing unit. For example, a JRC system operating in a harsh environment can exploit the sensing data for efficient beam training and beam steering. Similarly, the communications links offer an additional connectedness to numerous sensing nodes within a distributed network. Finally, integrating both sensing and communications units into a single platform reduces the system's overall cost, weight, and size of the system [9].

The main challenge in realizing a fully integrated JRC system is its high design complexity in signal level and hardware systems. For example, the aforementioned dual-functional waveform must balance the communications requirements (e.g., data rate, latency) and sensing demands while considering their dynamic behavior and QoS demands. This task is difficult and challenging to implement in real-time setups [34]. 5G systems provide a tool to solve the problem by various waveform design options (to a certain degree) via 5G numerology and resource scheduling. However, the dynamic mixture of sensing and communication requirements (which can conflict or align, depending on the current application scenario) makes it challenging to solve the joint optimization under real-time constraints.

IV. PHYSICAL LAYER, RADIO ACCESS, AND WAVEFORMS FOR JRC

This section discusses JRC from the perspective of the radio access layer, which is mainly aspects of the PHY layer, MAC layer, and the processing of the sensing information. First, we start with an overview of the information available in the PHY layer. This brief reminder serves as a basis for a discussion about the physical possibilities and limitations.

A. PHYSICAL LAYER

1) PHYSICAL LAYER CHARACTERISTICS

All radar-based sensing information, regardless of the type of radar or the waveform, is essentially a reflection of a transmitted signal by an object. This reflected signal contains the following information:

- Delay
- DoA
- Doppler shift
- Amplitude
- Phase

Typically, the delay is translated into a distance, which gives – together with the DoA – the location of the target. For monostatic radar, this location is given directly in spherical coordinates. In case of bistatic radar, the DoA is separated into the angle of departure and the angle of arrival and the delay defines an ellipsoid of possible locations. The received signal as a function of transmit (bistatic: and receive) angle is a convolution of the reflection characteristics of the target and the antenna pattern(s), which can make the detected image of the object blurry in case of a wide main lobe. To reconstruct the accurate shape of the object, a deconvolution process has to be performed.

The recognition of an object requires a reflected signal from the target. Objects can be invisible to radar due to several reasons:

- The target exhibits a large absorption or transmission coefficient in the frequency range of the radar. Although this might not play a significant role in case of classical radar systems it becomes of increasing importance for high frequencies up to the THz range as targeted in 6G.
- The target is located in a large distance and it is scattering in all directions so the backscattered signal vanishes within the noise level.

- The target has such a smooth surface in comparison to the wavelength that it is not scattering but reflecting like a mirror and the reflection condition of the incident angle being equal to the reflecting angle is not fulfilled.

For monostatic as well as for bistatic radar, the image resulting from a single radar system is always two-dimensional. To reconstruct the three-dimensional information of an object, the target has to move relative to the radar system or the information of a whole network observing the object from different directions needs to be processed jointly. Thus, the dynamic and highly connected ecosystem envisioned by 6G facilitates the 3D reconstruction of the local environment surrounding the network.

In settings with strong scattering and/or reflecting surfaces, e.g., in industrial scenarios with metallic interior, multiple reflections can be expected. While first order reflections can be evaluated analytically, second and higher order reflections do not offer unambiguous solutions. Any algorithm for room reconstruction that is at least partially analytical has to distinguish between first and higher order reflections. Second and higher order reflections could be only associated with probabilities to certain reflection areas. Here, an artificial intelligence with a site or object-specific training might be of help to reconstruct the most likely scenario.

2) SURFACE AND MATERIAL CHARACTERIZATION FROM A PHYSICAL LAYER PERSPECTIVE

Observing an object from different angles allows for a three-dimensional reconstruction of the shape of the object. Further information about the object's surface structure and its material characteristics can be extracted from the amplitude of the received signal as a function of the observation angle and the spectral response of the object.

The following example, depicted in Fig. 11, illustrates the options for surface characterization: A radar system moves along a rough concrete wall and along a mirror (see Fig. 11**b**). Here, the concrete wall serves as an example of an idealized scattering surface. The complete wall is visible in radar from all angles and its reflection characteristics are independent of the incident angle for the wall in the example. A radar system on a vehicle driving by sees the complete wall already from a large distance, always convoluted with the antenna pattern as shown in Fig. 11**b**. In case the whole wall is covered in mirrors, the wall is only visible from angles, where the reflection condition is fulfilled, i.e. only, if the vehicle is directly in front of the mirror and also then, it sees only that part of the mirror, where the condition is fulfilled. A complete view of the wall is only possible, if the vehicle is driving by the complete wall as depicted in Fig. 11**b**. Thus, from the angle-resolved signal as a function of the vehicle's trajectory, the scattering characteristic of the surface can be derived.

6G will provide communication with multiple technologies in different frequency bands reaching up to the THz range. The scattering characteristics of an object depend on the size of the surface structure in comparison to the wavelength. Hence, from scanning an object by multiple frequencies, one can derive the size of the surface structure. In addition, the material of the target can be characterized by its reflection characteristics, determined by the refractive index of the material. This will play an increasing role for higher frequencies. E.g., the humidity of the air already leads to absorptions in the THz range. Thus, by comparing the spectral response of the scattered or reflected signal, one gets at least a rough impression of the material.

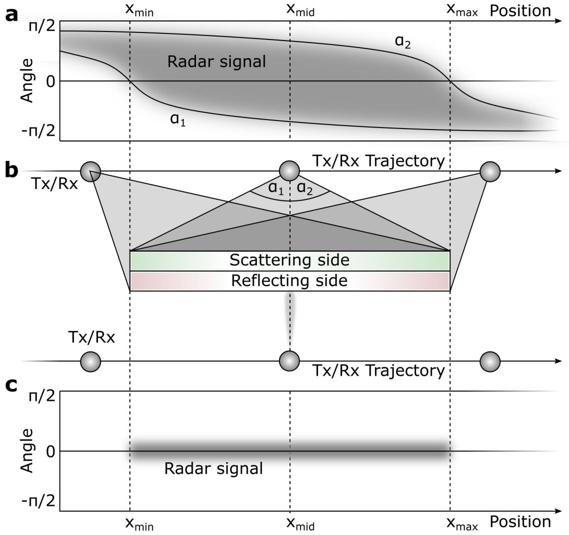

FIGURE 11. Surface characterization using radar. a: Radar signal (grey area) as a function of angle and trajectory for a scattering wall. b, top: Radar system on a trajectory along a scattering wall. Bottom: Radar system on a trajectory along a reflecting wall. c: Radar signal (grey line) as a function of angle and trajectory for a reflecting wall.

The classification of the information about the surface characteristics, e.g., concrete, wood, metal, could be a task for artificial intelligence, trained by measurements of the respective materials and objects.

Despite the possibilities for 3D reconstruction including deconvolution and surface and material characterization, the hope to get the complete knowledge about the surrounding might be a bit far-fetched due to the limited visibility of certain objects. In addition, the complete surrounding has to be covered by the radar network. Assuming that the environment is dynamic, which holds true for most use cases, this coverage has to be guaranteed at any time. So far, we discussed the possibilities and limitations of radar on the physical layer, which already have a long history. Combining these options with communications creates new challenges also on the physical layer.

3) THE TRADE-OFF BETWEEN COMMUNICATION AND SENSING

There is an inherent trade-off in joint communication and sensing which is illustrated in Fig. 12 for a bistatic JRC system. In the following, this trade-off and ways, how to deal with it are discussed.

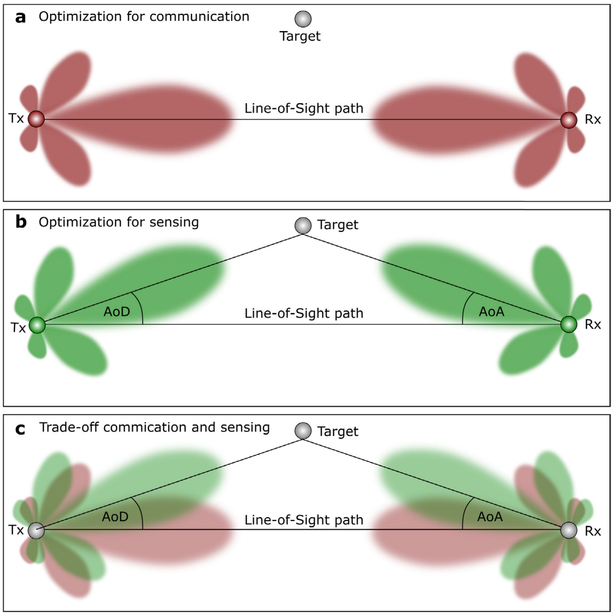

FIGURE 12. **Trade-off between communication and sensing. a: System optimized for communication. b: System optimized for sensing. c: System in a trade-off between communication and sensing. The decreased color intensity indicates a reduction of power in both beams, which is necessary in order to keep the overall transmit power constant.**

Wireless communication performs optimally if all the available transmission power is directed as a pencil beam from the transmitter in the direction of the receiver, which steers its listening direction towards the transmitter (cf. Fig. 12**a**). This can be implemented via phase shift in large antenna arrays. In such a situation, the available transmit power is optimally used for communication, but sensing is impossible since only the line-of sight-component of the channel impulse response is existing. No signal reaches the objects in the surrounding to be reflected. Sensing requires scattering from the local surrounding which is best achieved by omnidirectional transmission or by scanning the surrounding in all available angles. Fig. 12**b** shows a system optimized for the detection of a target. Note, that the possible scanning range is a limitation for any rigid system using antenna arrays since the beam steering angles usually vary in-between maximally ±60°. Everything significantly outside of this range remains invisible. However, the optimization criteria for communication and sensing are opposing: Both cannot be optimized simultaneously, although the same waveforms can be applied and the same signal can be used for both, sensing and communication.

Options to deal with this trade-off have to be in some way always a compromise on both sides, communication and sensing. The goal is to find the sweet spot in this trade-off, the best compromise possible. Possibilities could be reusing as much signal power as possible and dynamically optimizing the system for the current requirements.

Reusing the signals is possible, e.g., by utilizing the information acquired during the beam search procedure of two beam steering capable devices finding each other. This process is basically a scanning of the surrounding in all angular directions, which is exactly what is needed for sensing. This beam search would have to be repeated regularly to keep track of the dynamics of the surroundings, e.g., moving objects. For point-to-point communication, tracking the communication partner would be sufficient. Another option to use signal power for both, communication and sensing would be to generate separate beams for communication and sensing as in Fig. 12**c**, both fed with the same waveform data input. The ''sensing beam'' could be either back reflected to the transmitter (in full-duplex function) and utilized for monostatic radar imaging or it could be reflected to the receiver, where it can be employed for bistatic radar or reused as a multipath component of the channel impulse response of the communication signal. This is a very energy-efficient solution for JRC with the drawback, that the sensing component of the channel impulse response increases the requirements for equalization. This concept of using multiple beams for communication and sensing could be dynamically adaptable in terms of the power of the respective beams. An additional degree of freedom is the design of the wave front that generates the radiation pattern beyond just generating two or more beams: With large antenna arrays and access to the phase and amplitude of the individual antenna elements, the waveform can be customized to control the beam width of the main lobe and the magnitude and position of the sidelobes.

4) WAVEFORMS FOR JRC

For systems that use the same signal for communication and sensing, a major decision is the choice of the waveform. Like for the overall JRC system design, there are radar-centric and communication-centric waveforms. However, this section will focus on communication-centric waveforms like OFDM and orthogonal time frequency space (OTFS) modulation which could enable a high throughput in 6G. For a more detailed overview, we would like to refer the reader to [24], [56], [57], [58], [59], [60], [61], [62], [63], and [64].

On the one hand, the objective of communication systems is to transmit information reliably while being efficient in terms of energy consumption and spectrum usage. Therefore, performance metrics for communication systems include, but are not limited to, throughput, bit error rate (BER), achievable information rate and spectral efficiency. On the other hand, the objective of sensing is to detect targets and estimate their corresponding parameters like, e.g., distance and velocity. Hence, a sensing system aims to estimate the parameters of the sensing channel

$$h(t) = \sum_{i=1}^{P} h_i \delta(t - \tau_i) e^{j2\pi \nu_i t}, \tag{1}$$

where P denotes the number of targets, and h_i, τ_i and ν_i represent the reflection coefficient, time delay and Doppler shift induced by the ith target, respectively. The time delay

$\tau_i = 2\frac{r_i}{c_0}$ and Doppler shift $\nu_i = \frac{2v_i f_c}{c_0}$ are given by the target distance r_i and its velocity v_i, where f_c and c_0 denote the carrier frequency and the speed of light, respectively. Performance metrics for sensing include the image signal-to-noise ratio (SNR), the detection probability and the Cramér-Rao (lower) Bound (CRB) for the parameter estimation. While the range resolution $\Delta R = \frac{c_0}{2B}$ and velocity resolution $\Delta v = c_0\,(2T_{\text{frame}}f_c)^{-1}$ are usually given by the occupied bandwidth B and duration T_{frame} of the JRC signal, the waveforms differ, e.g., in their processing complexity, robustness against hardware impairments or frequency offsets.

We start our discussion by reviewing OFDM, which is currently state-of-the-art in mobile communication systems like 5G. In OFDM, the constellation symbols are modulated onto sub-carriers in the frequency domain and are transformed to the time-domain using the inverse fast Fourier transform (IFFT). The resulting orthogonal sub-carriers can be used to transmit to different users. At the receiver, the received signal is transformed back to the frequency domain using the fast Fourier transform (FFT) and the signal can be equalized efficiently using a one-tap equalizer. For sensing, the instantaneous approximated channel transfer function $H(f)$ can be obtained by a point-wise division of the received symbols Y by the transmitted symbols X, i.e., $H = Y/X$. Finally, the range Doppler matrix (RDM) can be obtained by applying an FFT along the OFDM symbols and the IFFT along the sub-carriers [65]. Hence, communication signals can be used to carry out sensing. However, a major drawback of OFDM is its high peak-to-average power ratio (PAPR), which reduces the average transmit power and consequently the image SNR. Constant-envelope waveforms are preferred for sensing because these allow us to operate the power amplifier in saturation and to maximize the image SNR. Additionally, the communication and sensing performance of OFDM degrades in high-mobility scenarios in which the resulting Doppler shift is in the order of the sub-carrier spacing.

Another interesting waveform candidate for JRC systems is OTFS, which modulates the constellation symbols directly in the delay Doppler (DD) domain. OTFS can be viewed from different angles [66]. Firstly, OTFS can be interpreted as an extension of OFDM where a pre-processing and post-processing step are added at the transmitter and receiver, respectively. This eases the backwards compatibility to current OFDM systems. The symbols in the DD domain $X_{\text{dd}}[k,l]$ and the symbols in the time-frequency domain $X_{\text{tf}}[n,m]$ are related via the inverse symplectic finite Fourier transform (SFFT)

$$X_{\text{tf}}[n,m] = \frac{1}{\sqrt{NM}} \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} X_{\text{dd}}[k,l] \mathrm{e}^{-\mathrm{j}2\pi\left(\frac{mk}{M}-\frac{nl}{N}\right)}. \tag{2}$$

Hence, OTFS can be interpreted as a spreading scheme in the time-frequency domain with maximally spread-out orthogonal basis functions. Therefore, OTFS achieves full diversity on linear time invariant channels and enables a reliable communication also in high-mobility scenarios which is an important advantage over OFDM. Since doubly dispersive channels are both time invariant and (usually) sparse in the DD domain, OTFS enables an efficient equalization of doubly dispersive channels [66]. Secondly, OTFS can be interpreted using the Zak transform

$$X_{\text{dd}}[k,l] = \frac{1}{\sqrt{L}} \sum_{m=0}^{L-1} x[k+mK] \mathrm{e}^{-\mathrm{j}2\pi\frac{l}{L}m} \tag{3}$$

which transforms the periodic time domain signal $x[k]$ with a period KL directly to constellation symbols in the DD domain and is closely related to the signal processing in a pulse Doppler radar [67]. The symbols are arranged in a two-dimensional grid and the FFT is taken along the so called slow axis to transform the received signal in the DD domain [67]. A two-dimensional correlation between the transmitted and received symbols is carried out in the DD domain to obtain the RDM of the sensing channel [68, Ch. 10]. It has been shown that OTFS and OFDM have a similar CRB and yield similar sensing performance [69]. However, one drawback of OTFS is the increased receiver complexity compared to a classical OFDM system.

Finally, we want to highlight that most publications investigating JRC waveforms assume hardware without imperfections. This assumption might not always be fulfilled in real world applications. For example, the local oscillator and transceiver amplifiers induce a frequency offset, phase noise and non-linearities. While the various waveforms transport the same information in general, the hardware impairments impact signal representations in various domains to a different extend. Additionally, an isolated, omnidirectionally reflecting target, as often used in simulations, is an idealized model. Real world objects have complex scattering characteristics, which often show at least a mild angular dependency. In indoor scenarios, the floor, the ceiling, and the side walls are among other object, also contributing to multipath components. Hence, the choice of the waveform depends on both the scenario and the hardware impairments.

5) INTERFERENCE MANAGEMENT

Interference management is essential to the JRC system's radar and communications performance. In contrast to conventional communications systems, where interference is primarily caused by transmissions of communications signals, JRC is primarily affected by cross-interference from both radar pulses and communications signals. We broadly divide the types of interference into the following categories.

- *Self-interference*: This mainly occurs in the case of a monostatic case due to the transmit signal leaking to the receiver element. In infrastructure-based JRC, where the base station is used simultaneously as a communications TX and a radar transceiver, the transmit waveform will create interference at the receiver end.

- *Interference between uplink communications signal and echos*: This is mainly the interference from the radar pulses to the uplink communications signal.

6) POWER CONTROL AND SPECTRUM SHARING MECHANISMS

A joint design for the coexistence of the sensing and communications functionalities in JRC systems necessitates cooperation between the communications and radar features. This holds particularly true when operating in a shared spectrum mode, i.e., using the same frequencies for both the communications and sensing resources. Spectrum sharing schemes encourage efficient utilization of the spectrum by multiple users as opposed to static configurations. The spectrum sharing problem is not unique to JRC systems nor it is novel due to the ever overcrowding of radio frequencies; however, for JRC systems it is mainly linked to the system's ability to manage self- and mutual-interference between the radar and communications signals [70]. Real-time spectrum sensing capabilities and intelligent beamforming techniques are some of the key-enablers supporting a shared spectrum JRC operation.

In terms of power control and depending on the integration level of the JRC system, coexistence could be achieved by applying multi-objective optimization techniques that define power constraints of minimum acceptable service for one feature while maximizing the performance of the other [71], [72]. For instance, the power constraint for a communications-centric system to maximize the radar's SINR while maintaining a minimum throughput for communications or vice versa for a radar-centric system [73]. For a fully integrated JRC system, joint optimization algorithms, codesign of waveforms, and precoding techniques that take into account both sensing and communications KPIs are needed [9].

B. MEDIUM ACCESS CONTROL LAYER

Despite being promising for next-generation wireless networks, achieving an optimal performance trade-off between sensing and communications functionalities is quite challenging in the design of JRC networks. The intrinsic reason is that the JRC network is susceptible to severe cross-functionalities interference due to its shared hardware architecture and spectrum sharing. For example, in the case of a heterogeneous JRC network, where different nodes (radar or communications nodes) are co-located and share the same wireless spectrum, experience excessive interference due to simultaneous transmissions. Therefore, an effective channel access mechanism is required for both radar and communications operations. In this section, we explore the core issues associated with access control and interference reduction in a coexistence scenario, as well as discuss existing MAC protocols and scheduling mechanisms for heterogeneous JRC networks.

1) MEDIUM ACCESS MECHANISM

The emerging heterogeneous JRC networks pose new interesting challenges in terms of medium access mechanisms. When a large number of radar and communications transceiver nodes share a common wireless channel and transmit in a possibly uncoordinated fashion, it triggers a natural question of how the channel should be shared. For communications nodes, e.g., radar pulses represent an additional source of interference, which may differ significantly from interference generated from another communications node. Typically, the spectrum usage pattern of radar nodes is very sporadic temporally, i.e., pulses are transmitted in the form of periodic short bursts, as opposed to long and aperiodic communications data transmission. Similarly, for the radar nodes, the sensing in the coexistence scenario is particularly challenging due to the presence of additional transmissions and their inability to mitigate the effect of mutual interference. This results in a higher false alarm rate and target detection inaccuracy. The purpose of the channel access mechanism is to regulate the access of different devices to the common wireless channel and ensure their overall performance.

In literature, few of the works studied the medium access techniques for the coexistence of radar and communications nodes. Authors in [34], studied the frequency division (FD)-based channel assignment approach in which the overall bandwidth is split into two sub-bands, one for radar and the other for communications alone. Data rate and estimation rate are regarded to be performance metrics for communications and radar, respectively, and the performance bound of both parameters is examined. In [44], authors model the channel access mechanism of radars as ALOHA protocol and analyze the radar-to-radar interference and radar detection performance in a large radar density scenario. Ishikawa et al. analyzed in [74] the performance of carrier sensing (CS)-based frequency-modulated continuous-wave (FMCW) radar performance and proposed two CS-based schemes to improve the narrowband interference in radar. Apart from this, channel access mechanisms for the coexistence of communications and radar nodes are given in [25], [43], and [75]. In [75], the authors proposed necessary changes for the communications system receiver to detect the radar pulses and analyzed the impact of modified communications systems on the radar performance. In [25] and [43], authors model the channel access mechanism of both communications and radar systems as ALOHA protocol and analyze the impact of uncoordinated transmission on the performances of the overall system. In [76], the authors study a JRC network, in which each node alternates between sensing and communications modes in an uncoordinated manner. During the communications mode, each node employs a CS-based medium access protocol to access the shared channel. Apart from all the above works, which follow orthogonal multiple access schemes, in [77], the authors propose the idea of non-orthogonal multiple access (NOMA)-based resource allocation for sensing and communications. Different types of NOMA-based interference mitigation schemes are proposed and analyzed for both uplink and downlink communications.

Nevertheless, designing an optimal channel access mechanism for heterogeneous JRC networks is quite challenging. First of all, the MAC protocols are typically designed for communications networks and may not capture the functioning of radar systems accurately. Second, there is no central coordinator to control the channel access of heterogeneous devices, and each device has no full information about its environment. In this case, advanced distributed machine learning-based methods with proper signalling methods may be useful. Finally, the fairness criterion should be considered that different system nodes have different performance objectives and may require different channel access duration.

2) SCHEDULING MECHANISM

In this subsection, we discuss the scheduling mechanism from two perspectives. First, from a JRC node perspective, where both radar and communications are codesigned into a single system, and the node has to decide the scheduling mechanism between sensing and communications. Second, in the case of JRC networks, where multiple JRC nodes simultaneously track targets and perform communications operations, how to schedule the radar and communications operation.

In a typical JRC node, both radar and communications functionalities are implemented using single hardware devices, and both functionalities share the system resources such as power, bandwidth, and antennas. Therefore, one of the major issues of a JRC node is how to schedule the radar and communications mode adaptively and optimize the resource sharing between them. For example, consider an autonomous vehicle as a JRC node which requires both radar and communications functionalities to navigate efficiently and safely in a complex environment [78]. The radar function in the vehicle detects the presence of pedestrians or other incoming vehicles under bad weather conditions. The communications function helps it to transmit the surrounding information to the nearby base station or vehicle. In case of bad weather conditions, the vehicle has to switch to radar mode frequently to detect the surrounding environment more accurately. However, in case of good weather conditions, it may assign lesser time to the radar mode. Since both radar and communications modes share the same frequency, there exists a tradeoff between the switching of radar and communications. Intuitively, assigning more time to radar mode to maximize detection accuracy decreases throughput. Similarly, improving the throughput by assigning more time to the communications mode may decrease the radar mode performance.

Developing an efficient medium access control mechanism for a fully-integrated JRC system, while balancing the competing needs of sensing and communication is still an open problem. Adaptive channel access methods and scheduling techniques must be designed in the future to handle ultra-dense JRC systems. Recently, there have been studies exploring the use of machine learning-based media access control systems to manage diverse communication traffic [79], [80]. Similar approaches can be followed to design adaptive medium access control schemes to support flexible, dynamic and application-oriented resource sharing and multiple access methods for JRC systems.

V. SIGNAL PROCESSING AND ESTIMATION

As outlined in the previous sections, the JRC signal processing must handle a variety of different use cases, scenarios, and applications. The focus of this section is the communications-centric case, where the constraints of the communications signal are decisive. To this end, we provide and overview of the necessary signal processing for a JRC system, and divide them into two different stages: the *detection and estimation* and *data fusion*.

A. DETECTION AND ESTIMATION

The *Detection and Estimation* is responsible for the detection and signal parameter estimation of the sensing targets. Figs. 5, 7, and 9 all illustrate how the received signals contain a mixture of propagation paths from clutter and sensing target(s). Hence, the task of this stage is to decompose that mixture, and obtain the sensing target parameters for the localization. The whole process is illustrated in Fig. 13.

Starting at the received signals in complex baseband, the first step is to estimate the wireless channel impulse response. As the JRC system described in this paper is mainly based on OFDMA, this can be efficiently done similar to the channel estimation in the wireless communications system such that both systems share this signal processing step. Using knowledge of the known subcarriers in the transmitted signal (pilots), a common approach is to perform the processing in the modulation-symbol domain [26]. In case not all subcarriers are known to the RX, a two step approach can be used by demodulating the received signal, performing error correction, and using the received bit-stream to reconstruct the unknown subcarrier modulation symbols [27].

From the channel estimate, the sensing targets are detected and their parameters (i.e., delay, Doppler, DoA, amplitude, and phase) are estimated. To this end, detection algorithms as constant false alarm rate (CFAR) and parameter estimation algorithms, such as multiple signal classification (MUSIC) [81], are often used, which can be loosely divided into four groups: subspace algorithms [81], iterative maximum likelihood (ML) [81], sparse signal recovery (SSR) [82], and newly also deep learning [83], [84]. However, when applied to a JRC system, these algorithms must be adopted to handle the unique challenges of JRC systems. The following overview elaborates on different aspects of these challenges and possible solutions.

1) RICH MULTIPATH ENVIRONMENTS

Due to the application scenarios, the signal processing in any JRC system faces a rich multipath environment. Such

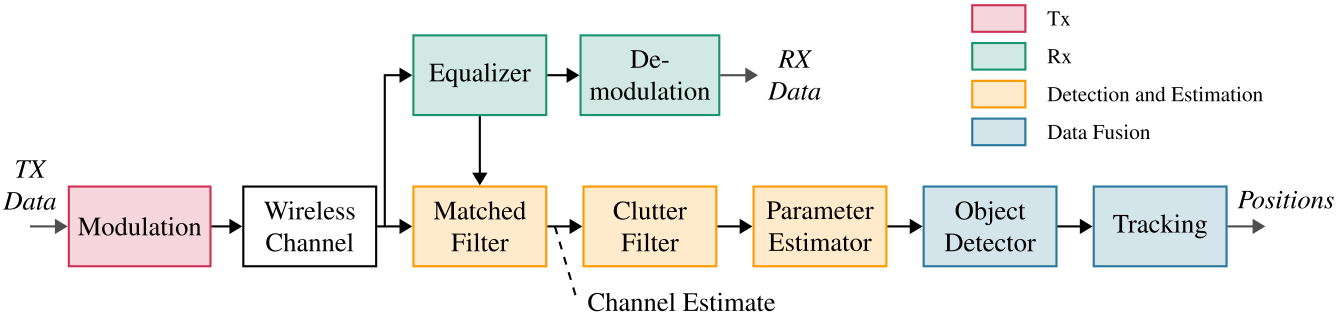

FIGURE 13. Signal processing stages. The sensing stage detects targets and estimates their parameters from channel measurements. In the second stage, the detected sensing targets from multiple RX are localized and tracked.

an environment is, e.g, shown in the application scenarios in Fig. 5. The number of sensing targets with the intense clutter of the propagation environments presents a significant algorithmic challenge, as the efficiency of the detection and estimation is limited by spectral resources of the sensing signal. An often noted limitation is with regards to bandwidth, which limits the range-resolution, and subsequently the systems ability to separate spatially close targets in range. However, targets can be separated in any signal dimension and with the availability of antenna arrays, JRC systems have at least four dimensions available for target separation: range (delay), relative velocity (Doppler-shift), and DoA (with azimuth and elevation). Current parameter estimation approaches used in radar sensing do not process all signal dimensions jointly, e.g., range finding is treated separately from direction finding [85], [86], [87]. This is due to the lack of algorithms and processing power necessary to utilize all dimensions while still performing under real-time constraints. To this end, one possible solution is to develop new algorithms, which can process all signal dimensions jointly under real-time constraints to achieve the required target and clutter separation for JRC. Recent results in deep learning-based parameter estimation show promising results in this regard [88], [89]. The presented methods demonstrate the possibility to obtain the parameter estimates from a forward-pass through the neural network which is constant in time. As a possible extension, the obtained estimates can be sufficiently close to global minimum of the non-convex likelihood function of the signal model, such that a smooth gradient iteration can converge [84]. It can therefore reduce computation times significantly for ML-based approaches, and enable the use of high resolution parameter estimation (HRPE)-methods for more accurate positioning results. Other results also demonstrate that deep learning can be combined with subspace methods, e.g., MUSIC [90] to condition the measured covariance matrices prior to running the algorithms itself.

2) RESOURCE ALLOCATION

A new unique challenge to JRC systems stems from the multiplexing schemes used in modern communications systems. These systems apply multiplexing in time-, frequency-, space-, and code-domain to the OFDMA signal to simultaneously serve multiple users with low-latency, and high data rates. In a JRC system, it means the detection and estimation algorithms must be able to handle the effects of time-varying, sparse resource allocations, such as fast-changing effective signal bandwidths, missing or unallocated symbols, and switching beam patterns. Foremost, the sparse resource allocations reduce the achievable SNR processing gain, and hence detection probability of the sensing system. Furthermore, simple discrete Fourier transform (DFT) interpolation approaches for estimation are not suitable, due to the irregular distortions and rotations of the mainlobe and even sidelobe levels created by the allocation patterns.

A further aspect is added to the problem in case of a fully-integrated JRC system. In such a system, the requirements of the sensing tasks must also be considered in the resource allocation algorithm. When a new resource allocation is compiled, it must consider the QoS demands of the communications *and* sensing system [91]. But, as explained in the previous section, the global (or general) goals of the two systems lead to contradictory resource requirements. However, local optimality (in a specific scenario) strongly depends on the current QoS demands created by the user requirements. Meaning, it is not always necessary (nor desired) for the communications system to transmit, e.g., at full bandwidth, nor does the sensing system require constant sensing resources. It is hence possible to optimize the resource allocation patterns such that the required QoS can be satisfied for both systems. In addition, further constraints, such as reducing power consumption, can also still be considered.

3) HARDWARE IMPERFECTIONS

Another challenge is the difference between the noisy measured data and the signal model in the algorithms. Nonlinearities in the TX and RX transceiver hardware, e.g., from the antennas, power amplifiers, and analog-to-digital converters (ADCs), create distortions in the data [92]. For model-based parameter estimation algorithms, it translates into a model mismatch and leads to false detections and ghost targets. Calibration procedures can alleviate the adverse effects to a certain degree but require costly measurements and are inevitably specific to the hardware used in the measurement.

As shown in [90] for simulated distortions, the use of deep learning-based or -assisted methods can help alleviate these issues. However, it still remains a subject for future research to quantify, how well the deep learning solutions can generalize under the large set of possible hardware configurations or what suitable re-training strategies for different configurations exist.

4) INTERFERENCE

Two different types of interference are relevant to the detection and estimation in a JRC system: self-interference and interference from other BSs or RRUs in the same coverage area.

The self-interference strongly impacts monostatic JRC deployments, as the TX and RX are either in identical positions or in a quasi monostatic configuration. Due to the time duration of OFDM symbols, switching of the TX and RX paths is not sufficient and further measures are required for self-interference. Comparably, in bi- and multistatic setups the TX and RX explicitly require the TX-RX signal path to create the reference for the localization.

Other sources of interference in a layered JRC stem from the other communications systems. The aforementioned multiplexing techniques enable efficient reuse of time-, frequency-, and spatial resources. Adverse effects of such interference are well-known in conventional radar systems and have been shown to cause ghost targets and increase false detection rates [93], [94]. However, in a full-integration JRC system these interferences can be mitigated by using the joint scheduling and interference mitigation techniques already available in the communications system [27]. This also highlights how existing communications system techniques (scheduling, interference management) can solve issues of layered JRC systems by extending them to a fully integrated JRC system.

B. DATA FUSION

The task of the *Data Fusion* stage is to collect and jointly process the estimated parameters to localize and track multiple sensing targets. In case of a single RX deployment, the estimated parameters stem only from a location and the localization is straightforward to compute, e.g., by combining the range measurement with the measured DoA. However, due to the measurement accuracy of the DoA, the localization accuracy deteriorates with increasing range. Note, that this holds true regardless of whether a mono- or bistatic system is used.

Comparably, using multiple RX in a JRC system [27], [36] circumvents this issue completely by creating a fully meshed JRC network. In such a network, the data fusion combines results from multiple RX sites to create a joint localization results. While such a network can be build using only monostatic RX links, it would disregard many of the benefits available to a full multistatic setup. First, the multistatic sensor network is truly a superset of the monostatic sensor network, as it utilizes all available target responses (reflections) to localize the target. The most advanced version of such a distributed multisensor JRC system combines measurements from all available links to create the full distributed MIMO matrix [17], [47]. To this end, a multistatic sensor network can operate in a resource efficient *broadcast* mode, where one TX illuminates the sensing targets for multiple RX. If the TX has full-duplex capabilities, the monostatic reflection can also be utilized.

Depending of the operation mode of the *data fusion* stage, different signal processing steps are required. In the following we introduce two steps, namely the data association and multi-target tracking, and discuss JRC specific issues and possible solutions.

1) DATA ASSOCIATION

When the data fusion stage receives the parameter estimates from multiple RX, each report can contain a varying number of targets. Having multiple sources for measurements introduces a problem known as unknown data association, which refers to the problem of correctly associating measurements with the objects being tracked. This problem can be addressed using multi-hypothesis tracking (MHT) methods, which involve maintaining multiple hypotheses about the object associations and updating them with new measurements. A big challenge in MHT is that the number of possible hypotheses grows very quickly over time and is intractable even for a few numbers of objects [95].

Another important aspect of tracking is modeling the uncertainties in the data. One popular approach for this is using random-finite sets (RFS), which provides a framework for representing and manipulating sets of uncertain objects. In these terms, both the existing objects in the field of view and the measurements acquired from the objects are modeled as distinct sets [96].

There are several methods for state estimation such as Kalman filters and particle filters, which can often be deployed to address the Multi-Object Tracking (MOT) problem using MHT techniques. However, the performance of MHT methods depends on both, how the state of each object is tracked and how the exploding number of hypotheses are managed. These methods are based on a recursive estimation framework, where the current state estimate and hypotheses are updated based on the measurements and the dynamics of the objects. Some of the state-of-the-art MHT methods are Poisson multiple target multi-Bernoulli filters (e.g., see [97]) and Generalized Labeled Multi-Bernoulli filters (e.g., see [98]).

Recently, machine learning techniques have seen increasing interest to improve the performance of the algorithms. These techniques are used for state estimation and resolving the hypotheses. Transformer models, in particular, have shown great promise in this regard, with their ability to learn complex data associations between the measurements and objects, e.g., in [99].

2) MULTI-TARGET TRACKING

As the final processing stage of the sensing target locations, target tracking enables more stable and accurate predictions. This excess accuracy is the consequence of having more observation, e.g., from more sensing nodes, and exploiting the tracks of the objects that are associated with the measurements. The tracking results in a lower false-alarm-rate and more accurate object locations.

Hence, the main goal of tracking is to maintain a consistent and accurate estimate of the objects' states, despite the presence of measurement noise, occlusions, and false detections [100]. In the context of JRC, the acquired measurements refer to the estimated sensing target parameters, while the state of the objects refers to the location and orientation. These measurements are acquired from sensor nodes that observe a field of view, which can contain one or more objects of interest.

To address the tracking problem, multi-object models are used in the tracking task due to their ability to handle multiple objects simultaneously, as well as clutters in the environment. Clutters mainly consist of false detections and are defined as any measurement that should not be assigned to a target of interest. This category of tracking problems is often referred to as MOT [101].

In summary, the presented signal processing in JRC requires a combination of existing and novel approaches to facilitate the diverse set of JRC use cases. In the future, additional computational resources, such as MEC close to the core network, can even support the flexible implementation and optimization of application-specific signal processing algorithms.

VI. JRC HARDWARE ASPECTS

The realization of sensing applications in 6G not only depends on reasonable use cases but also on the availability of suitable hardware, e.g., large enough bandwidths for a good range resolution or the multi-user allocation scheme that determines how the available bandwidth is split between the BS and the UEs. In the end, all hardware components, ranging from the antennas to the analog frontends, the BBUs and the storage have to fulfill the requirements of the sensing application.

A. ANALOG FRONTEND

1) FREQUENCY BANDS AND AVAILABLE BANDWIDTHS

The usable frequency bands for 5G which could also be reused in 6G are mainly divided in the two frequency ranges (FR) 1 and 2. FR1 is ranging from 410 MHz to 7.125 GHz and FR2 form 24.25 GHz to 52.6 GHz [102]. Below 1 GHz the only duplexing scheme allowed is frequency division duplex (FDD) which is of very limited use for JRC. Above, also time division duplex (TDD), which is more suitable for JRC under certain circumstances (see Section VI-A4), is specified for some bands. However, in FR1 the available bandwidth is only in the range between 5 MHz and 100 MHz which results in range resolutions between 30 m and 1.5 m for the sensing, which is for most applications too inaccurate for a precise localization or detailed environment surveillance. In FR2, due to the higher carrier frequencies, channel bandwidths up to 400 MHz are usable in 5G resulting in a range resolution of 37.5 cm which is much more suitable for the sensing part. Going even higher to 60 GHz or the currently discussed frequency region around 140 GHz signal bandwidths of 2 GHz and more are imaginable which could drastically improve the image quality and localization accuracy of the sensing. However, no frequency bands have been assigned yet around 140 GHz for 5G or 6G and there are also competing interests, e.g., by automotive radar suppliers.

2) BEAMFORMING

In particular, at the higher carrier frequencies in FR2, some kind of TX and RX beamforming is required for communications to compensate for the higher free space losses and maintain the SNR at least in outdoor scenarios. In this case, most of the TX power is received at the RX due to the focusing of the beam. However, this tilting of the communications beams towards specific UEs is contrary to most sensing applications where the positions of the targets are not known a priory and thus, the whole environment has to be sensed. Thus, DoA estimation would not be possible anymore. One possibility two cover both interests is to do the sensing for example in time slots where the BS is looking for new UEs, and thus it has to broaden the beams or switch the beams between different directions.

3) PERMISSIBLE EIRP

The Federal Communications Commission (FCC) has defined a very high effective isotropically radiated power (EIRP) limit of 75 dBm/100 MHz for the FR2 bands [103]. In particular, in case of low antenna gain which is preferable for the sensing task, this limit is challenging to reach with reasonable hardware costs, size and weight. The limit is only reachable with high antenna gains, e.g., by massive MIMO setups, where the beams are pointed directly to the UEs with known positions.

4) DUPLEXING

- FDD is not suitable for monostatic or quasi-monostatic sensing with a single BS since the receiver operates at another frequency as depicted in Fig. 14(a) and consequently cannot receive the reflected signals from the targets and the environment. However, if at least two BSs work together to form a radar network as shown in Fig. 2, and the second one can receive at the same frequency as the first one transmits, FDD would be usable. In this case, a precise time and frequency synchronization, e.g., via a LOS link between the collaborating base stations, would be necessary.

- TDD would only be suitable in monostatic or quasi-monostatic setups if the hardware allows to receive signals during the transmission as indicated in Fig. 14(b) and no switches block the connection between the receive chain and the antennas. However, in most of the currently available TDD chip sets this is not the case.
- FDX is best suited for a monostatic operation in terms of the hardware since the BS simultaneously transmits and receives at the same frequency and consequently can receive the reflected signals from the targets. However, the BS also receives the coupled TX signal from the BS as well as the TX signals from the UEs as shown in Fig. 14(c). Their receive power level is probably much higher than the one from the target reflections who suffers from an attenuation which is proportional to R^4. In case of the TX signals from the UEs, this effect can partly be compensated by the processing gain of the radar if the TX signal of the BS and the RX signals from the UEs are uncorrelated which can be assumed in most cases. In addition, the radar image can be improved by successive interference cancellation where the signals of the UEs are reconstructed and then subtracted from the overall RX signal.
- Cross-division duplex (XDD) is an extension of the FDX mode where the available frame is split into time-frequency parts which are dynamically allocated to the BS and the UEs [104] as can be seen in Fig. 14(d). XDD is in principle suitable for sensing, but the quality depends strongly on the percentage shares between the DL and UL and the distribution of the allocated parts. Since in most cases the allocated parts for the BS are not equally distributed within the time-frequency frame, simple FFT algorithms to estimate the range and velocity of the targets can no longer be used. Instead, more complex algorithms such as compressed sensing or AI-based approaches would be necessary. On the other hand, the interference level would be less compared to the FDX mode since BS and UEs use orthogonal time and frequency slots.

5) ANALOG SELF-INTERFERENCE CANCELLATION

In case of FDX or XDD the transmitter and receiver of the BS are simultaneously active at the same carrier frequency. Thus, coupling from the TX to the RX channels cannot be suppressed via filters as in FDD or by switches as in TDD. However, in particular for the sensing, the difference between the received power of the coupling or of intended communications on the one hand and the reflected signals from the targets on the other hand is extremely high due to the attenuation in the radar channel which is inversely proportional to R^4. And since the available dynamic range is mostly limited on the upper end by the TX-RX coupling and at the lower end by the quantization noise of the ADCs [105], weak targets could fall below the quantization noise level due to the limited bit resolution of the ADCs. An example for such weak targets that are of interest are drones as mentioned in Section II-A3. To prevent this effect, the coupling should be suppressed directly in the analog frontend by an active analog self-interference cancellation (SIC) circuit before the signal is sampled as exemplarily shown in Fig. 15. Therefore, a small part of the TX signal has to be fed internally to the RX, precisely attenuated and phase-shifted identically to the direct coupling and strong reflections from the surrounding, and finally subtracted from the RX signal coming from the antenna [32], [106]. In addition, this also prevents the LNA from possible saturation or necessary gain reduction in case of strong interference signals. Besides this, also the separation of TX and RX antennas helps to reduce the coupling.

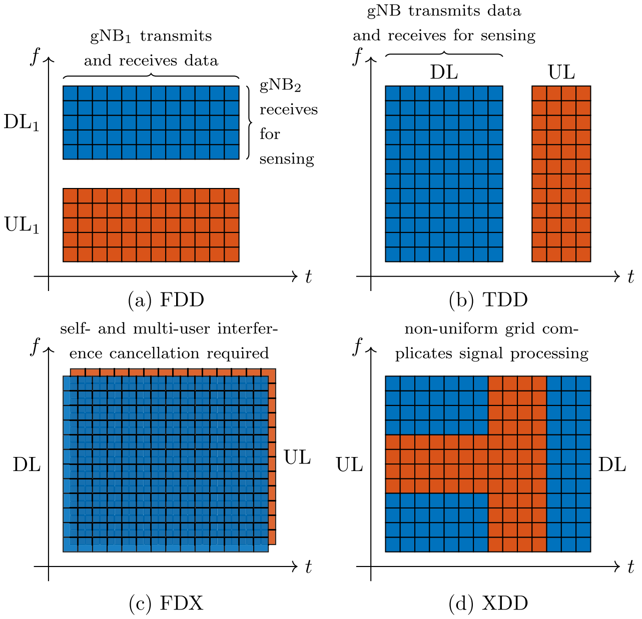

FIGURE 14. **Duplexing schemes and how they influence the sensing capabilities: (a) frequency-division duplex (FDD), (b) time-division duplex (TDD), (c) full-duplex (FDX), and (d) cross-division duplex (XDD).**

B. MIXED SIGNAL (DAC/ADC)

1) DIRECT VS. IF SAMPLING

The conversion from the digital to the analog domain and vice versa can be realized in two different modes, either via direct sampling of the baseband signal or with an additional digital frequency shift of the baseband signal to an intermediate frequency (IF) and the sampling of this IF signal. Both variants have advantages and disadvantages, both for communications and sensing. In case of direct sampling, the inphase (I) and quadrature (Q) channels of the complex-valued baseband signal are fed to two digital-to-analog converters (DACs) and afterwards directly upconverted to the RF with an IQ mixer. Thus, for each of the RF channels, two

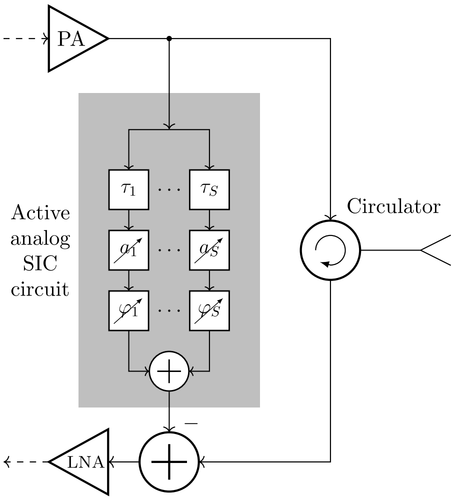

FIGURE 15. **Analog self-interference cancellation circuit to suppress the direct coupling as well as strong reflections from the static surrounding which are at the same frequency as the intended RX signal.**

DACs are required, but simultaneously also the RF bandwidth can be doubled without increasing their sampling rates. Since the baseband is directly upconverted, the carrier is in the center of the frequency spectrum. If the carrier feedthrough is poor or DC offsets occur the OFDM subcarriers at and around the center carrier can be distorted. The same occurs if DC blocks are used because they also block the subcarriers around DC. For communications, this is bearable since only a very small fraction of the usable subcarriers is distorted. For sensing, however, the effect is much more critical since the sidelobe levels of the targets dramatically increase resulting in weak targets that are masked by the sidelobes of stronger targets. On the other hand, no filters are needed to suppress images in the spectrum since this is automatically achieved with the IQ mixer. The contrary concept is IF sampling, where the complex-valued baseband signal is digitally upconverted and then fed to a single DAC. However, here, the sampling rate has to be at least two times the RF bandwidth according to the Nyquist theorem which can be challenging for large signal bandwidths in the range of GHz. On the other hand, for a fixed number of DACs, the total number of channels can be doubled compared to direct sampling where two DACs have to be spent for each RF channel. Another advantage is that DC offsets and carrier feedthrough do not influence the sensing quality since they lay outside of the frequency band used. Additionally, the DC offsets can easily be blocked with decoupling capacitors since no active subcarriers are affected. The drawback is that after the upconversion also the image spectrum appears at the output of the mixer which would occupy unnecessarily twice the wanted spectrum and could also cause distortions at the receiver when it overlays with the wanted band after the downconversion. To prevent this, either analog filters with a steep roll-off or image reject mixers each consisting of a quadrature hybrid coupler and an IQ mixer are needed. In particular to fulfill the required phase shift of 90° within the whole band can be challenging at a low IF.

2) SAMPLING RATES

The sampling rate f_s at the DACs and ADCs depends strongly on whether direct or IF sampling is used. In case of direct sampling in combination with IQ mixers f_s has to be slightly larger than the effective OFDM signal bandwidth B_eff. The small difference between B_eff and f_s is required for the roll-off of the analog low-pass filter which, on the one hand, suppresses image spectra that would cause out-of-band emissions and, on the other hand, avoids aliasing in the receiver. If IF sampling is used instead, f_s has to be increased significantly in most cases. However, the sampling rate does not necessarily have to be larger than twice the highest intended frequency, since also the second or higher Nyquist zones can be used if the analog RF bandwidth of the DACs and ADCs supports this. For example, the RFSoC from Xilinx offers an analog bandwidth of up to 6 GHz [107] in conjunction with digital mixers and filters which are explicitly intended for the usage in the second Nyquist zone to relax the sampling requirements for 5G and future 6G applications. In case of IF sampling, analog band-pass filters have to be used instead of low-pass filters and if the IF signal is for example further upconverted in the millimeter-wave range, additional filters or image-reject mixers are required to suppress the unwanted sidebands. To relax the demands on these hardware components, a high IF is advantageous.

C. DIGITAL BASEBAND AND BACKEND

1) DATA RATES

The data rates that have to be handled in the digital backend are related to the bandwidth of the OFDM signals. However, they are not necessarily directly proportional to the sampling rates of the DACs and ADCs, in particular, if IF sampling is used. In this case, the complex-valued baseband signal is normally interpolated in the transmitter and afterwards digitally upconverted directly before the DAC and vice versa in the ADC. The raw data rate is then the product of the sampling rate in the baseband and the bit width of the samples, mostly multiplied with the factor two due to IQ values.

2) MEMORY

In comparison to the processing of communications data where in most cases only a small buffering of the received data is required, for the sensing, a much larger amount of data has to be stored before the processing can be finalized. This is mainly due to the Doppler estimation that requires a certain measurement time to achieve a good velocity resolution. If OFDM is used, the range estimation can already start during the reception of the frame since it consists of an IFFT which is applied along the subcarriers of each sequentially received OFDM symbol. For the Doppler estimation, however, which is performed by an FFT along the OFDM symbols, the complete frame must be available. The required memory size is thus proportional to the number of subcarriers and OFDM symbols as well as the bit resolution during the processing. The data within the memory can be overwritten by the results of the range IFFT and Doppler FFT if the bit widths are adjusted by scaling and truncation. But not only for the velocity resolution a high measurement time is advantageous, it is also required to achieve a sufficiently high processing gain to compensate for the free space loss which is in the sensing case proportional to $1/R^4$, where R is the distance between the BS and the target.

3) STREAM PROCESSING

The high sampling rates that are anticipated for 6G often exceed the internal clock rates of field programmable gate arrays (FPGAs) that are currently widely used in research and development systems. Their big advantage is their reconfigurability which can, for example, be used for over-the-air protocol updates. However, the internal clock rates of FPGAs are often in the range of several hundreds of Megahertz, whereas the sampling rates at the data converters are in the range of Gigahertz. Thus, pipelined and parallel stream processing is required, which in turn fits well with FPGAs that can execute tasks in parallel in comparison to digital signal processors (DSPs) that work sequentially. In addition, handling parallel tasks is also well suited for MIMO streams that are a crucial part of 5G and in the future of 6G.

We envision, that the frontend architecture and hardware of BSs will be at least slightly adapted for 6G, e.g. through self-interference cancellation stages. The main drivers for these changes will likely be the increased and improved communication rates rather than JRC but as a side effect it will help to enable and improve mono-static sensing. In addition, future communication standards will likely allow higher channel bandwidths, which will further improve the resolution and accuracy of the sensing. These higher bandwidths will also be supported by advances in the development of powerful FPGAs and DSPs, which support high sampling rates and fast signal processing.

VII. CONCLUSION

In this work, we provided a comprehensive overview of JRC systems and their outlook within the context of future wireless networks. Fully-integrated JRC systems represent the epitome of joint design and operation of radar and communications systems; however, several challenges in terms of design complexity and functional optimization still impede the way to their realization.

An infrastructure-based JRC architecture allows, with different degrees of dynamics, the exploitation of the various network components for sensing functionalities. In turn, an infrastructure-less JRC paradigm offers the potential to build a radar network relying merely on UEs and terminal devices. For next-generation networks, a JRC network that employs both the radar and communications networks capabilities of its heterogeneous nodes and infrastructures is foreseen. The advantages distributed JRC architectures offer make it the most promising direction for the full convergence of communication and sensing networks, ultimately resulting in a flexible and ubiquitous system. However, questions on how to ensure co-existence, fairness in resource allocation, and cooperation between heterogeneous nodes operating one or both functionalities, remain to be addressed.

Future 6G networks offer several enabling technologies that could facilitate promising developments in JRC systems. From the radio access layer's perspective, these include: 3D reconstruction of environments through hyper-connectivity, surfaces and material characterization through multi-RAT, and simultaneous communications and sensing through leveraging beam-forming and -steering technologies as well as optimal scheduling of available resources. From the standpoint of signal processing methods, the use of deep learning-based algorithms could help immensely in the advancement of JRC systems in 6G. In the knowledge acquisition stage, deep learning techniques could help in real-time estimation and extraction of targets' parameters, which, in turn, is a necessary step for the data fusion stage, where the JRC systems use data from several sources for multiple targets tracking.

In terms of hardware supporting JRC implementations, several aspects need to be considered along the entire hardware chain; starting with the frontend, through the ADC/DAC stage, and finally the digital baseband and back-end. Frequencies within the range of FR2, are more reasonable and suitable for sensing applications. Upconversion of the baseband signal and higher sampling rates at the mixing stage, as well as larger memory and stream processing supporting-FPGA are favorable facets in the hardware design of future JRC systems.

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