Joint Communication and Sensing: Models and Potentials of Using MIMO

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Abstract—The sixth-generation (6G) network is envisioned to integrate communication and sensing functions, so as to improve the spectrum efficiency (SE) and support explosive novel applications. Although the similarities of wireless communication and radio sensing lay the foundation for their combinations, their different requirements for electromagnetic signals make the joint system design a hard task. To simultaneously guarantee sensing accuracy and communication capacity, the multiple-input and multiple-output (MIMO) technique plays an important role, due to its unique capability of spatial beamforming and waveform shaping. However, the configuration of MIMO also brings high hardware cost, high power consumption, and high signal processing complexity. How to efficiently apply MIMO in the joint communication and sensing (JCAS) system is still open. In this survey, we discuss JCAS in the context of MIMO configurations. We first outline the roles of MIMO in the progress of communication and radar sensing. Then, we review current advances in both communication and sensing coexistence and integration in detail. Three novel JCAS MIMO models are subsequently discussed by introducing the promising 6G enablers, i.e., the unmanned aerial vehicle (UAV) and the reconfigurable intelligent surface (RIS). With the aim of building a compatible dual-function system, the benefits and challenges of MIMO in JCAS are summarized in each subsection. Promising solutions are also discussed from the system perspective with simple, intelligent and robust principles. In the end, open issues are outlined to envisage a comprehensive JCAS network in the near future.

Index Terms—Coexistence, integration, joint communication and sensing (JCAS), multiple-input and multiple-output (MIMO).

I. INTRODUCTION

Combining communication and sensing in wireless networks has recently attracted great interests. It not only allows for more efficient spectrum usage but also efficiently provides dual communication and sensing services for many applications, i.e., intelligent transportation [1], smart factories [2] and the Internet of Things (IoT) [3]. This has made joint communication and sensing (JCAS) a promising candidate for future networks.

The early motivation of JCAS comes from the scarcity of spectrum resources [4]. With the increasing requirements of high-resolution sensing and high-rate communication, communication and sensing networks have been constantly expanding and merging their frequency bands. For example, it has been reported by [5] that the global system for mobile communication shares the same spectrum with high UHF radars and that the long term evolution (LTE) and the WiMax system partially occupy the spectrum of S-band radars. In addition, as the technique of millimeter wave (mmWave) matures, spectrum sharing is also required between communication and sensing for the shake of efficient usage of the wideband [6]. To avoid serious mutual interference, it is necessary for communication and sensing systems to cooperate.

Since communication and sensing both use radio signals to carry information, the idea of integrating them into one platform naturally arises. Such an integrated communication and sensing (ICAS) system has incomparable benefits of low cost, low power consumption and compact volume [5], [7]–[14]. These are useful to those applications that require both communication and sensing services, but their platforms only have limited capabilities to support both. To achieve this kind of JCAS, the literature has made many attempts. The ideas that communication and sensing are physically combined and do not share any modules, share the same antennas but fed with separate radio frequency (RF) chains and totally share the same components have been evaluated. For the dual-function waveform, different schemes of embedding information into sensing waveform [9], [10], using the communication signal for target detection [11] and creating new communication and sensing waveforms have been proposed.

Despite these fruitful results, there is still a long way to go for practical JCAS deployments. Inherent differences between communication and sensing lead to many challenges to the dual-function system. Looking back to the development of wireless communication and radio sensing, the multiple-input and multiple-output (MIMO) technique both plays an important role in their progress. MIMO extends resource utilization into the spatial domain and greatly improves the communication rate and sensing resolution. In this sense, MIMO would also be a strong supporter for JCAS. However, MIMO inherently has high complexity and high cost. How to efficiently use MIMO to build a satisfying JCAS system has not yet been fully discussed.

Different from surveys [5], [7], [8], [12]–[14], which reviewed the JCAS in a comprehensive manner but did not detail the JCAS MIMO issue. In this paper, we discuss JCAS specialized in the MIMO context. We present recent advances on both communication and sensing coexistence and
The key issue of the cooperative MIMO is to achieve rate was able to exploit the spatial degrees of freedom (DoFs) to obtain the processing gains as the single link, MU-MIMO further considered the spatial sharing among different user channels. A series of practical strategies, including channel-aware precoding, channel estimation and feedback and multi-user receivers were devised. Combined with effective scheduling schemes, the achieve rate was able to approach the theoretical limit of MU-MIMO. Moving forward, people extended MU-MIMO into the cooperative MIMO, which cooperates the transceivers located in different positions, such as cellular BSs, to further exploit the spatial efficiency. The key issue of the cooperative MIMO is to tackle the co-channel interference. A creative idea named interference alignment was further proposed, which achieves $K/2 \log(1 + \text{SNR})$ rate when serving $K$ users. The gap between the sum capacity of SU-MIMO and the sum rate of cooperative MIMO network was greatly shortened. In the last fifteen years, massive MIMO (mMIMO) has come to the history stage. Compared with MIMO, mMIMO uses a much larger array, and this quantitative change brings amazing qualitative changes. The literature found that if the transmitter uses infinite antennas to serve only several users, the random fast fading would vanish, and channels tend to be orthogonal. This enables MIMO to be a scalable technique and greatly improves the spectrum efficiency (SE). Moreover, the large antenna gains of mMIMO could combat the high path loss of mmWave communication. Based on the sparsity of mmWave channels, the techniques of hybrid digital-analog precoding and compressed sensing were ingeniously applied to overcome the high cost of mMIMO. The combination of mMIMO and mmWave communication greatly promoted the progress of wireless communication. Just when mMIMO is still under development, a brand new MIMO technique, named RIS, or passive MIMO, has come into the research vision. In essence, the RIS is a surface that consists of many low-cost and energy-efficient adjustable units. By adjusting these units, RIS could reform the incident signal into a desired pattern. Since the RIS unit is nearly passive and low-cost, the RIS usually has massive units. The great DoFs allow RISs to enhance the communication link in an energy-efficient way. Due to the outstanding merits of low cost and high DoFs, the RIS is a popular candidate for future 6G networks.

In regard to radars, the usage of the antenna array could date back to the 1950s. At that time, people invented the first phased array radar, which overcomes the drawback of low scanning frequency and limited scanning range of mechanical scanning radars. Subsequently, with the progress of digitization, a plethora of processing algorithms, i.e., Capon, MUSIC and ESPRIT, have emerged and improved the sensing resolution of phased array radars. To further increase the sensing performance, the large array consisting of hundreds of antenna elements has been widely used. Moving forward, the MIMO concept was gradually introduced into the sensing field as it strongly promoted the development of communication. The MIMO radar was devised, and researchers found that MIMO could improve the estimation resolution compared with the phased array thanks to the great DoFs. Subsequently, the statistical MIMO radar was developed, which uses widely spaced transmitter and receiver (T&R) antennas to observe targets from different perspectives. In contrast, the literature found that MIMO radar with collocated antennas, which allows the correlation among different antennas, is also excellent. By exploiting waveform diversity, this MIMO radar demonstrates super resolution, super parameter identifiability and great flexibility to shape the waveform. To exploit both the coherent gains of phased array radars and spatial diversity of MIMO radars, the concept of hybrid phased-MIMO radars was proposed, which coincides with the idea of hybrid digital-analog beamforming in the communication field. More recently, people also extended MIMO radars into the mMIMO to pursue better sensing performance.
B. Merits of MIMO in Communication Systems

a) Spatial diversity: Spatial diversity is used to combat fading, which averages the deep fading probability from one path to multiple independent paths to increase the reliability. Theories have proven that if the antenna space is more than ten wavelengths, the transmit or receive signals experience independent fading. This means that MIMO is able to provide a maximum of $M_t \times N_r$ independent T&R paths. Using this property, if transmit antennas emit the same signal, the receiver thus obtains $M_t \times N_r$ independent replicas. The probability that these replicas all go through deep fading is the $M_t \times N_r$th power of the probability of one path so that the outage probability is largely reduced \[32\].

b) Spatial multiplexing: Spatial multiplexing is an effective way to increase SE. In contrast to spatial diversity, which aims to combat fading, spatial multiplexing utilizes DoFs brought by fading to improve the system rate \[32\]. If T&R pairs experience independent fading, the corresponding channel matrix is more likely to be well conditioned and full rank, which means it could be decomposed into multiple parallel paths. Using this property, multiple streams are allowed to transmit concurrently using overlapped time and frequency resources so that the SE is largely improved.

c) Flexible beamforming: With multiple choices to exploit spatial diversity and spatial multiplexing, MIMO supports different beamforming strategies for different scenarios \[33\]. Take transmit beamforming as an example. When serving one user, the high directional beam is used to focus power on the user to improve the received signal-to-noise ratio (SNR). When serving multiple users, spatially separable beams could be applied to the target different users to support multi-user communications. Zero-forcing precoding provides interference-free channels for different users. When considering a multi-cell environment, the pencil beam limits power leakage to adjacent cells, and thus, the background noise is controlled. In essence, different beamforming schemes are achieved by the flexible utilization of spatial diversity and multiplexing.

C. Merits of MIMO in Sensing Systems

a) Spatial diversity: Similar to communication, one of the outstanding merits of MIMO radar is the spatial diversity \[34\]. Using properly-spaced configurations, $M_t \times N_r$ independent observations could be obtained at the receiver. This reduces the probability of missing targets due to scintillation and makes the detection robust to cluttering effects. From another perspective, the collocated MIMO, which allows for correlations among different T&R paths, demonstrates great parameter identifiability and high resolution \[35\]. Compared with the phased array radar, the parameter identifiability of MIMO radars has at most $M_t \times N_r$-fold improvement.

Indices:
- $M_t$ and $N_r$ are the numbers of transmit and receive antennas of the communication transceiver.
- $M_t$ and $N_r$ are the numbers of transmit and receive antennas of the radar.
b) Adaptive waveform manipulation: Another unique feature of MIMO radar is the capability of adaptive waveform designs [35]. To improve the reliability of target detection, the probing beam could emit high power toward the target while nulling surrounding clutters. To improve the multi-target identifiability, the transmit covariance matrix could be devised to have low correlations among different sub-beams. To detect the high-speed target, which is likely to be missed by single-beam scanning, multiple directional beams could be simultaneously generated to probe the whole area. In regard to target tracking, the dynamic beam is used to follow this target. Similar to communication, great flexibility is achieved by choosing different combinations of coherent processing and spatial separation.

D. Summary

We summarize the main role of MIMO and its incurred incompatibilities between two functions in Tab. I. As we can see, the exploitation of spatial resources and supporting flexible adaptations are the main merits of MIMO. Its functions in communication and sensing are similar in many aspects, i.e., using spatial diversity to improve reliability. Despite this, communication and sensing have their own particular emphasis on the role of MIMO. Communication mainly uses MIMO to make adaptations to channels, with the emphasis on directional beamforming, so as to focus on different users and control interference. Radars mainly use MIMO to make adaptations to targets, with the emphasis on the waveform, so as to facilitate signal processing to extract target information. Due to different emphases, the JCAS designs are required to balance their fundamental requirements. In the next section, we overview current advancements on JCAS MIMO to detail this issue.

III. STATE-OF-THE-ART OF MIMO-EMPOWERED JCAS

In the literature, the combination of communication and sensing is a gradual process. At first, spectrum scarcity motivates the two to coexist. Further advances in fabrication and signal processing promote the coexistence of communication and sensing to the ICAS. In the following, we first review the coexistence of communication and sensing and then present the integration of communication and sensing. We put our focus on the communication and sensing balance using the MIMO technique. The main roles that MIMO plays for the compatible dual-function design are summarized, and promising solutions are outlined.

A. Communication and Sensing Coexistence

Spectrum sharing is the main issue addressed by communication and sensing when they do not share the hardware. The mutual interference motivates originally separate systems to cooperate. The term “coexistence” is used to depict the relationship of communication and sensing in this situation. Spectrum sharing between communication and sensing is different from that in traditional communication systems. First, the radio sensing system referring to radars is usually characterized by high-power transmitters [3]. If the communication transceiver is directly interfered by radar signals, corresponding communication signals are inevitable to experience the fatal outage. As for radar sensing, besides SNR, particular requirements of the waveform, i.e., the constant envelope and correlation properties [36], are also of great importance. To achieve peaceful coexistence, the dual-function system requires at least one participant to make adaptations. In the following, current studies are divided into communication adaptation schemes, radar adaptation schemes, and joint adaptation schemes and are reviewed.

1) Communication Adaptation Schemes: Communication adaptation schemes refer to the scheme in which only communication systems make adaptations while radar systems remain unchanged. Ebithal H. G. et al. considered a one-user and one-target scenario and applied linear constraint variance minimization (LCVM) beamforming at the BS so that the user is allowed to reuse the radar spectrum [37]. In regard to multi-user scenarios, both inter-user and inter-system interference were considered in [38]–[40]. Liu et al. first proposed a robust beamforming scheme to maximize the radar detection performance under the constraint of the user rate [38]. Then, in [39], the authors found it is not power-efficient to totally eliminate the inter-user interference, which could be constructive if it helps align the received symbols in the right discrimination region. A power minimization precoding scheme was proposed to utilize inter-user interference as the constructive green power rather than harmful noises. Keshav et al. designed DL beamforming and uplink (UL) power allocation for a full duplex (FD) BS [40]. In this study, the two-tier spectrum sharing of uplink and downlink (UL&DL) and communication and sensing greatly improves the spectrum utilization but complicates practical implementations. More recently, Wang et al. proved the effectiveness of the RIS for interference mitigation using a joint BS transmit precoding and RIS passive precoding scheme. In this design, the RIS impact on radars was modeled the same as clutters, but since the adjustment of RIS would change radar echo patterns, such impacts should be further considered [41].

2) Radar Adaptation Schemes: Schemes focused on radar systems paid great attention to the radar waveform, for that the a good waveform is the key to high-quality sensing. To control the interference to the communication system, Alireza et al. designed a zero-forcing precoding that projects radar interference into the null space of the effective interfering channels. However, this leads the radar waveform far away from the desired shapes. The authors further relaxed the condition of null-space projection to give more DoFs for the waveform shaping [42]. Mahal et al. further applied this scheme to the coexistence of a radar and a coordinated multi-point cellular system [43]. Dan et al. divided radar antennas into several subarrays to exploit the high directivity of phased array radars and waveform diversity of MIMO radars. The radar SNR is maximized under the user-rate constraint [44]. Hai et al. devised a radar receiving scheme that combines target focusing and interference mitigation into the beamforming design [45]. In addition to spatial beamforming, Kang et al. proposed a precoding scheme that not only considers the spatial shape but
TABLE I
MIMO ENABLED COMMUNICATION AND SENSING SYSTEM

| System     | Metric                     | The Role of MIMO                  | Function                                           | Incompatibility                                  |
|------------|----------------------------|-----------------------------------|----------------------------------------------------|--------------------------------------------------|
| communication | single-user rate          | coherent beamforming              | improve the directionality and SNR                | may cause high PAPR, high sidelobe and destroy the correlation properties |
|            | outage probability        | space-time coding                 | combat multi-path fading; improve the reliability |                                                  |
|            | system capacity            | spatial precoding                 | construct spatial independent channels; lower down the interference |                                                  |
| sensing    | detection probability      | coherent beamforming              | improve the SNR                                   | influence the spatial separability, may cause symbol distortion and influence the data carrying capability |
|            | detection reliability      | waveform diversity                | lower down the target missing probability        |                                                  |
|            | estimation resolution      | waveform shaping                  | lower down the sidelobe; ensure correlation properties; constant envelop, etc. |                                                  |

Also the spectrum shape of the radar waveform. A spectrum constraint was imposed to limit radar power in the band that communication users occupy [46]. Moreover, Kilani et al. investigated a placement scheme of distributed radars. Different from previous studies that directly regard communication signals as interference, the author applied the successive interference cancellation (SIC) technique, which first decodes the message of communication users and then removes it from received signals. The placement design hence considered the proper position to both detect targets and decode messages [47].

3) Joint Adaptation Schemes: In terms of joint optimization, Li et al. considered a clutter environment and optimized the communication and radar transmit precoding to maximize the signal-to-interference-plus-noise ratio (SINR) of the radar. To avoid the high complexity of semidefinite programming (SDP), an efficient second-order cone programming (SOCP) algorithm was devised for the radar precoding [48]. In [49], the authors proposed a robust precoding scheme considering the unknown radar cross section variances and delays. Qian et al. paid attention to the effect of multiple clutters and proposed two spectrum sharing schemes, respectively maximizing the radar SINR and user rate. Considering the imperfection of the channel state information (CSI), the author pointed out that the proposed scheme lacks robustness, and perhaps some optimality should be given up for better resilience [50]. Recently, Qian et al. further studied a multi-target scenario and did a joint communication code book and radar precoding design, and the effective interference of the radar was minimized [51]. Similar to [40], Biswas et al. considered the coexistence of an FD communication system and a radar. Instead of joint designs, separate precoding schemes were devised for communication and sensing on account of imperfect CSI and hardware distortions [52]. In this study, users are also equipped with multiple antennas to further reduce the received interference. However, the algorithm suffers from intractable complexity. More than $1 \times e^{10}$ complex multiplications are required in each optimization iteration, only for a two-UL-users and two-DL-users setting. In [53] and [54], Li et al. investigated the spectrum sharing between a matrix completion (MC)-based MIMO radar and the MIMO communication transmitter. The MC-based radar refers to the radar that only forwards sub-sampled data to the processing center, and MC is used to reconstruct the original matrix. Such a sub-sampling process provides additional flexibility to change the interfering channel space from the BS to the radar so that a larger null space could be constructed for BS precoding. He et al. paid particular attention to the radar waveform in the joint optimization design. Practical constraints of the similarity to the desired waveform and the constant modulus were taken into account. With the additional constant-modulus constraint, the optimized waveform takes on the low peak-to-average power ratio (PAPR) and low sidelobe, but the optimization complexity is largely increased [36]. Instead of using SINR as the radar metric, Cheng et al. minimized the Cramér–Rao bound (CRB) of the direction-of-arrival angle under the user SINR and waveform similarity constraints with imperfect CSI. The alternating direction method of multipliers (ADMM) and SDP algorithm were applied for optimizing the radar and BS precoding [55]. Considering both inter-user interference and inter-system interference, Rihan et al. [56] and Hong et al. [57] investigated the scheme of the interference alignment, the core idea of which is to align different interference vectors into a small space at receivers, and thus the complementary space is interference-free for data transmissions and target detection. In addition, Crossi et al. optimized communication transmit variance, radar transmit power, and radar linear filters to maximize the EE of the communication system while satisfying a predefined SINR of the radar in all range resolution bins [58].

4) Discussion: We summarize these studies in Table. II, by comparing their settings, applied schemes and model assumptions. It is obvious that MIMO mainly undertakes the task of spatial separation to make the two functions coexist in a spectrum-sharing system. Transmit beamforming was the most addressed issue to direct communication and sensing signals into spatially separable spaces at receivers. Multi-antenna receivers could further support spatial filters to exclude residue interference. As for sensing functions, MIMO enables the phase and amplitude adjustment for a good waveform. However, this dual-function system suffers from high burdens under MIMO configurations. The overheads of channel estimation and feedback are linear growth with the antenna numbers. Much more power is required to use the large array and execute the multi-stream processing, whose complexity is polynomial and even index growth with antenna numbers.

We may find that current JCAS MIMO schemes heavily rely on the tight cooperation of communication and sensing
TABLE II
MIMO ENABLED COMMUNICATION AND SENSING COEXISTENCE

| Settings¹ | Tackled Interference² | Applied Schemes² | Channel Models | Perfect CSI | Same Sampling Rate | Programming Schemes |
|-----------|-----------------------|------------------|----------------|-------------|-------------------|------------------|
| ST-MIMO, MISO | C to S | BS precoding | unspecific | yes | no | LCVM [37] |
| ST-MIMO, MU-MISO | C&S, inter-user | BS precoding | flat Rayleigh fading | yes/no | yes | SDP [38] |
| ST-MIMO, MU-MISO | C&S, inter-user | BS precoding | flat Rayleigh fading | yes/no | yes | 39 |
| ST-MIMO, FD MU-MISO | C&S, inter-user, UL&DL | joint BS DL precoding and UL power allocation | flat Rayleigh fading | yes/no | yes | SOCP [40] |
| ST-MIMO, MU-MISO | C&S, inter-user | joint BS and RIS precoding | block fading and quasi-static | yes | unspecific | SDP [41] |
| ST-MIMO, MU-MIMO | S to C | radar precoding | flat Rayleigh fading | yes | no | singular value decomposition (SVD) [42] |
| ST-MIMO, multiple MU-MIMO | S to C | radar precoding | block fading and quasi-static | yes | yes | SVD [43] |
| MT-MIMO, MU-MIMO | S to C | radar precoding | block fading | yes | yes | SDP [44] |
| MIMO, unspecific | S to C | radar waveform | unspecific | no | no | quadratic programming [46] |
| ST-MIMO, SU-MIMO | C&S | joint radar and BS precoding | block fading | yes | yes | SOCP [48] |
| ST-MIMO, SU-MIMO | C&S | joint radar and BS precoding | block fading | yes | no | alternating optimization and sequential convex programming [49] |
| ST-MIMO, SU-MIMO | C&S | S: waveform, receive filter, C: space-time code matrix | flat fading | yes | yes | SOCP [50] |
| MT-MIMO, SU-MIMO | C&S | joint radar waveform and communication code book | unspecified | yes | yes | SDP [51] |
| ST-MIMO, FD MU-MIMO | C&S, inter-user, UL&DL | S: precoding, C:UL&DL, T&R precoding | composite channel model | no | no | SVD,SDP [52] |
| MT-MIMO, SU-MIMO | C&S | S: subsampling matrix, C: transmit covariance matrix | flat Rayleigh fading | yes | yes/no | lagrangian dual decomposition [53] |
| MT-MIMO, SU-MIMO | C&S | S: transmit covariance matrix, subsampling matrix, C: transmit covariance matrix | flat and block fading | yes | yes | SDP [54] |
| MT-MIMO, MU-MIMO | C&S, inter-user | joint radar and BS, T&R precoding | unspecific | yes | yes | SDP [56] |
| ST-MIMO, multiple SU-MISO | C&S, inter-cell | joint radar waveform and BS precoding | flat fading | no | yes | ADMM,SDP [55] |
| MT-MIMO, MU-MIMO | C&S, inter-user | joint radar and BS, T&R precoding | block fading and quasi-static | yes | yes | alternating optimization [50] |
| ST-MIMO, MU-MIMO | C&S, inter-user | joint radar and BS transmit precoding | time varying and frequency selective | yes | yes | linear equations [57] |
| ST-MIMO, SU-MIMO | C&S | joint radar transmit power, receive filter and communication transmit covariance | unspecified | yes | yes | block coordinate ascent method [58] |

¹ C&S: communication and sensing, ST-MIMO: single-target MIMO, MT-MIMO: multi-target MIMO, SU-MISO: single-user multi-input and single-output (MISO), MU-MISO: multi-user MISO.
² C to S: communication to sensing, C: communication, S: sensing.

They all assumed the timely CSI is available and that two systems could constantly make adaptations to keep pace with the varying CSI. In this way, communication and sensing systems have to spend considerable resources for CSI acquisition. Sometimes, the same sampling rate, same symbol duration, and accurate time, frequency, and phase synchronization are also required to exactly avoid the mutual interference. This brings huge overheads and also makes the whole system not robust to the out-sync of the communication and sensing parts. Therefore, we may think the loosely coordinated cooperation is more friendly in the practical implementation. In detail, we use the large-scale CSI rather than the full CSI to coordinate the two systems. The large-scale CSI is slowly varying and highly depends on the surroundings. Thanks to these properties, it could be estimated without inter-system interactions. To do so, a site-specific database, named the radio map, could be introduced to estimate the large-scale CSI [59]. The radio map records historical channel states and outputs the corresponding large-scale CSI according to the input T&R positions. On this basis, the large-scale CSI is used to instruct the coexistence design of two systems. Its contained position information is helpful to decouple the interference geographically [60]–[62]. Since the large-scale CSI is slowly varying, communication and sensing systems only need to keep low-frequency interactions and thus work in a loose coordinated manner. This inaccurate CSI inevitably leads to performance loss, but it also brings the benefits of reduced overhead and reduced system interactions, thus enabling the JCAS system to be simple and robust.
B. Communication and Sensing Integration

Unified hardware leaves out many troublesome problems compared with separate settings. The expenses of signaling, information exchange and accurate synchronization no longer exist. In the literature, we use the term “integration” to depict the relationship of communication and sensing. To effectively use one platform for two functions, the first mission is to balance the communication and sensing requirements in the waveform design. In the literature, there are three main ideas for the unified configuration. The first tries to adjust radar platforms for communication. Different information embedding schemes are proposed to enable radar waveforms to carry information. The second attempts to assign sensing tasks to the communication system. Different information extraction schemes are evaluated for communication signals. The last gives efforts to the dual-function waveform design, which achieves more balance of two functions.

1) Radar-Centric Designs: Using radar platforms for data transmissions was proposed early for the ICAS because communication signals could leverage the high power and large antenna arrays of radars. In the literature, how to embed information into radar waveforms without impairing the sensing function was the main issue investigated. An early idea was to embed information in radar sidelobes so that the mainlobe is unchanged to ensure the sensing performance. In [63], the authors used amplitude modulation (AM) to modulate the sidelobe and convey information. The waveform diversity is applied to transmit multiple symbols in parallel. However, this scheme has a fatal drawback of being powerless to serve the user in the mainlobe direction. Motivated by this, Hassanien et al. further devised phase-modulation-based solutions [64]–[66]. The phase modulation (PM) was implemented by a bank of weighted vectors, each of which constructs a certain phase offset in the radar waveform. Since only the phase is altered to convey information, the mainlobe is thus available for information embedding. Moving forward, Ferreira et al. proposed a robust dual modulation scheme in which the PM and AM are selectively applied according to the user in the mainlobe or not. In this study, both PM and AM vectors are expressed in closed-form, which not only gets rid of the troubling optimization but also improves the robustness to combat angular errors in case the radar has no exact user positions [67]. Moreover, Ji et al. proposed an embedding scheme to map the binary bits into positive or negative frequency increments using the frequency-diverse MIMO radar. This kind of radar is characterized by high resolution because its waveform is range- and angle-dependent [68]. Realizing this, Alselwii et al. divided the transmit platform into overlapped subarrays and applied incremental carrier frequencies to illuminate the target. A closed-loop architecture was devised by using the detection feedback as the indicator to choose transmit beamforming vectors and embedding schemes, where the phase shift key (PSK) and amplitude and phase shift key (APSK) were used for the user in the mainlobe or not [69].

In addition to traditional modulation schemes, the index modulation (IM) was investigated in [70]–[73], which uses the index of a candidate set to convey information. When the candidate set is the waveform, information is embedded by shuffling different waveforms across transmit antennas. This embedding scheme is transparent to radar operations for that the matched filtering at radar receivers undoes this shuffling, enabling the radar operation to proceed as if it is a radar-only platform [70], [71]. Wang et al. further applied the sparse array and combined antenna selections and permutations for IM [72]. When the candidate set turns to the transmit codes, information is thus embedded by pairing the codes with transmit antennas. In [73], the frequency-hopping (FH) radar was investigated to carry information by assigning different FH codes to different antennas. Under this design, the embedded waveform has a better spectrum profile than the PSK-based scheme, for which the phase discontinuity brings significant power variations among different spectra. Benefiting from multiple permutations and combinations, the communication rate under IM could achieve several Mbps.

In addition to [73], FH radars have also been investigated in [74]–[78]. This kind of radar divides one pulse into multiple sub-pulses, namely, hops, and uses different frequencies in different hops. Information bits are thus embedded in each hop rather than each pulse so that the communication rate is improved. The corresponding schemes of PSK [74]–[75], frequency shift keying (FSK) [76], differential phase shift keying (DPSK) [77], and continuous phase modulation (CPM) [78] were successively proposed. Similarly, the linear frequency modulation (LFM) waveform was applied in [79], where the sweep time was divided into multiple subunits for information embedding. However, these fast-time embedding schemes are sensitive to inaccurate factors. Corresponding issues of time offsetting [80], channel estimations [81], and engineering-friendly coding and decoding schemes have not been fully investigated [82]. This indicates that present schemes are still far from practical implementations. From another aspect, the embedding impacts on original sensing functions should be evaluated. Analysis found that after embedding, the waveform has reduced range sidelobe levels due to the randomness of embedded symbols, which lowers the correlation among radar pulses [83]. However, such randomness also causes pulse variations within the coherent processing interval and brings with the range sidelobe modulation (RSM), which would weaken the target visibility [84].

The above embedding schemes all use pulse radars as dual-function radar and communication (DFRC) platforms. Another kind of radar, named the continuous wave radar, has also been considered for the dual-function design. Different from pulse radars, continuous wave radars continuously emit probing signals and receive echoes. To reduce the signal leakage from transmitters to receivers, the continuous wave radar usually uses low-power signals and small antenna arrays and is small in volume. These traits make them friendly to civil applications. To ensure the accuracy of the parameter estimation, Dokhanchi et al. applied a multi-antenna frequency modulated continuous waveform (FMCM) radar and proposed a DPSK modulation scheme [85]. For vehicular applications, Ma et al. investigated a hybrid PM and IM scheme operating over the phase modulated continuous waveform (PMCW), which achieves better bit error rate (BER) than the PM-only
modulation. In this design, the complexity and cost are well controlled by using the sparse array and reduced RF modules [80].

Summary: We summarize the information embedding schemes in Table I by comparing their embedding methods, achievable communication rates, and incurred impacts on the sensing waveform. Since communication is the secondary function in these designs, it suffers from a quite low rate, high outage probability, and the weak serving ability, i.e., only supporting one user at a time. In these designs, the MIMO configuration provides more compatibility for communication functions. Supported by the waveform diversity, MIMO radar could simultaneously bear multiple symbols in the orthogonal waveform, and improve the communication rate to the Mbps level. Controlled by multiple RF chains, the transmit beam could flexibly carry different information toward different directions and concurrently serve several users. As for the primary sensing function, MIMO also improves its resistance to the waveform distortion. However, despite using MIMO, it is still far from the satisfying ICAS. First, information embedding brings more or less alterations to the radar waveform, most of which are negative. The non-constant envelopes, widening spectrum, RSMs, and grating ambiguity function (AF) patterns are all possible impacts [9], [10], [63]. Second, the communication function is far from practical requirements. Corresponding schemes merely realize this function. As for the most investigated DL information embedding, practical issues of inaccurate CSI, time/frequency/phase offset and detailed coding and decoding schemes have not been fully addressed [10], [82]. In terms of UL access, new mechanisms should be introduced to respond to random user requests. The most challenging issue is the differentiation of target echoes and user signals. Note that the target echo is much likely submerged in noises for it experiences two-fold attenuation. If users and targets are located in different directions, directional T&R beamforming works to divide communication and sensing signals, but when users and targets are rightly in the same direction, separating the mixed signals is not an easy task [10]. One possible solution is to use the SIC technique. But the cost is improved complexity, especially when multiple streams are simultaneously processed.

2) Communication-Centric Designs: Using communication signals for sensing is another way to achieve the ICAS. We put our focus on DL sensing because BSs are more likely to equip with massive antennas and have strong signal processing ability. As for DL sensing, the most straightforward way is to directly use standard communication signals and extract information from their echoes. In [87], the preamble of the single-carrier frame of IEEE 802.11ad was exploited to conduct target detection and parameter estimation. Based on the perfect auto-correlation property of the Golay complementary sequences in the preamble, it achieves cm-level range accuracy and cm/s-level velocity accuracy. In [88], Kumari et al. devised sparse analog beamforming for IEEE 802.11ad-based JCAS. For each transmission, a subarray is randomly activated, and the receiver obtains the target information from randomness incurred grading lobes. In [89], Pucci et al. evaluated the sensing performance of the 5G new radio. Instead of directly using communication signals, communication and sensing beams are spatially separated and the power of orthogonal frequency division multiplexing (OFDM) signals is split for these two functions. Through a series of evaluations, the results show that tens of targets could be detected with sub-meter level accuracy, which shows the great potential to endow the communication system with sensing functions. In [90], the OFDM physical layer convergence protocol preamble of IEEE 802.11a was used for passive sensing, which means there is no cooperation between communication transmitters and sensing receivers. By exploiting the prior knowledge of the preamble, the detection performance was largely improved compared with the blind estimation. Using the 5G new radio demodulation reference signal, Kanhere et al. estimated location parameters under the bi-/multi-static configurations. The estimation error was analyzed under different geometrical

### Summary of Information Embedding Schemes

| Radar Waveform | Embedding Schemes | Directional/Broadcast Communication | Achievable Rate | Impacts on Sensing |
|----------------|-------------------|------------------------------------|----------------|-------------------|
| optimized waveform | AM | directional | \(f_{PRF} \times N_{sym} \times M_f\) | sidelobe variations [63] |
| | PM | directional | \(f_{PRF} \times N_{sym}\) | RSM [64] |
| | PM | directional, broadcast | \(f_{PRF} \times N_{sym} \times M_f\) | RSM [65], [66] |
| | PMKAM | directional | \(f_{PRF} \times N_{sym}\) | sidelobe variations [67] |
| frequency diverse | FM | directional | \(f_{PRF} \times N_{sym} \times (M_f - 1)\) | unspecific [68] |
| unspecified | IM | directional | \(f_{PRF} \times \log(M_f)\) | RSM [70], [71] |
| | IM | broadcast | \(f_{PRF} \times \log(K \times C_{M_f}^{N_{sym}})\) | peak ripples of the main beam [72] |
| | FH | IM | broadcast | \(f_{PRF} \times Q \times \log(C_{M_f}^{N_{sym}})\) | RSM [73] |
| | FH | PSK,DPSK,CPM | broadcast | \(f_{PRF} \times Q \times M_f \times N_{sym}\) | spectrum widening, RSM [74], [75], [76] |
| | FH | FSK | broadcast | \(f_{PRF} \times Q \times M_f \times N_{sym}\) | frequency shift [77] |
| | LF | PSK | broadcast | \(f_{PRF} \times N_{sym}\) or \(f_{PRF} \times M_f \times N_{sym}\) | grating lobe of the AF [78] |
| | PMCW | PAM | broadcast | \(f_{SW} \times N_{sym} \times \log(K \times C_{M_f}^{N_{sym}})\) | unspecific [85] |
| | PMCW | IM & PM | broadcast | \(f_{SW} \times N_{sym} \times \log(K \times C_{M_f}^{N_{sym}})\) | unspecific [86] |

\(f_{PRF}\) is the pulse repetition frequency, \(N_{sym}\) is the bits carried by one symbol, \(M_f\) is the number of radar transmit antennas, \(K\) is the number of selected antennas for one transmission, \(Q\) is the hop number of one pulse, \(f_{SW}\) is the sweep frequency, \(M_e\) is the code number and \(M_f\) is the carrier frequency number.
T&R settings [91].

Directly using standard communication signals for sensing is not the optimal choice. Due to the randomness of carried symbols, communication echoes present high-range sidelobes after correlation-based processing, which motivates to make the adaptations of current communication signals. Liu et al. used the modified OFDM waveform and devised a high-resolution range estimation algorithm by effectively using the whole array aperture and the available bandwidth [92]. Systematic parameters to meet both communication and sensing requirements were further discussed in [93]. Ni et al. added a separate receiving antenna to BSs to bypass the FD problem and proposed a waveform optimization scheme to maximize the relaxed communication SINR with constrained radar metrics of mutual information and CRB [94]. However, to avoid information loss, it is more desirable to use large arrays at receivers. The proposed one-antenna scheme deserves further refinement.

Summary: We summarize these studies in Table. IV by comparing their sensing settings, used signals, and achieved sensing performances. In these designs, MIMO enables the communication transceivers more spatial “receptive filed” to sense the surroundings. In current 5G networks, cellular BSs are densely deployed, and these infrastructures offer ubiquitous platforms for ICAS. If corresponding schemes become mature, the pipe-only network would upgrade to the perceptive network and better support massive applications. However, before practical deployments, several technical obstacles must be overcome. First, the impact of imperfect CSI and out-of-sync should be fully evaluated. As for OFDM waveform, it is sensitive to carrier offset. The introduced inter-carrier interference would largely degrade the sensing accuracy [95]. The second one is the FD problem. If BSs turn into ICAS platforms, the UL&DL separate working regime is not applicable. They have to simultaneously transmit signals and receive echoes. It still lacks practical schemes to effectively isolate the signal leakage from transmitters to receivers, the impact of which is especially serious when large T&R arrays are compacted in a tiny space [12]. Similar to radar-centric designs, the discrimination of echoes and user signals is not an easy task. More advanced signal processing is needed. Promisingly, the UL user signal also carries target information and can be further utilized [96]. Another aspect is bi-static and passive sensing, in which sensing receivers are not collocated with transmitters. Problems mainly lie in two aspects: interference and synchronization. If T&R do not cooperate, the received signal is more likely to be a mixed one of many signals from adjacent transmitters [12]. It is difficult to extract information from this noise-like mixture. But even if a clear signal is obtained, imperfect synchronization can lead to sensing ambiguity due to the failure of preamble location caused by inter-symbol and inter-carrier interference [5]. Perfect time/frequency/phase synchronization is a challenging issue if there is no wired link to connect T&R devices.

3) Novel Waveform Designs: Designing the novel waveform moves a further step for ICAS. In the literature, there are three different hardware configurations. The first uses separate modules to bypass the incompatible problems of communication and sensing. In this situation, the mutual interference of the two signals was the most addressed problems. Temiz et al. applied a novel communication transmit precoder that effectively exploits radar interference. The radar signal was optimized to approximate the communication signal so as to reduce the communication precoding cost of eliminating radar interference [97]. On this basis, two optimal power allocation schemes were devised in [98], with the objective of sum-rate and EE. Recently, the authors further detailed the UL receiving procedure, where the user messages and target echoes are successively processed using the SIC. Analytical works were conducted under the consideration of imperfect CSI and self-interference and the trade-off relationship of the achievable rate and radar detection performance was revealed [99]. Liu et al. proposed two precoding schemes to compare the performance of separate and shared deployments. The former divides antennas into two groups, and they are connected to independent communication and sensing modules, while the latter unifies all the components. The results show that the shared deployment achieves better performance due to more available DoFs [100]. In [101], Dong et al. investigated the same separate setting as [100] and further proposed a low complexity algorithm.

The second configuration uses separate RF chains but the same antenna array. In this situation, it is the synthetic waveform that impinges the targets and determines the sensing

| Communication Waveform | Sensing Settings | Used Signals | Achievable Sensing Performance | Required Adaptations |
|------------------------|------------------|-------------|-------------------------------|----------------------|
| single-carrier waveform | T&R collocated   | IEEE 802.11ad frame | cm-level range resolution, cm/s-level velocity resolution using 1.76GHz bandwidth | FD designs [94] |
| OFDM                   | T&R collocated   | 5G new radio signals | tens of targets, sub-meter level location resolution at 28GHz | FD designs [89] |
| OFDM                   | T&R separate, passive sensing | preamble of IEEE 802.11a frame | Improved detection performance compared with blind estimation | not required [90] |
| unspecific             | T&R separate     | demodulation reference signal | 0.1m location error of the bi-static setting using 400MHz bandwidth | time synchronization [91] |
| OFDM                   | T&R collocated   | varied version of the OFDM frame | 15m range resolution of 0.25MHz subcarrier bandwidth | FD designs [92] |
| OFDM                   | T&R separate     | the whole frame | unspecific | An additional separate receiving antenna [94] |

TABLE IV
MIMO ENABLED COMMUNICATION-CENTRIC DESIGN FOR ICAS
Performance. McCormick et al. investigated a spatial separate beamforming scheme and considered the high PAPR problem of the synthetic waveform. A constant-envelope constraint was imposed in the beamforming design [102]. In [103], the authors further conducted practical experiments to verify the effectiveness of the proposed spatial beamforming scheme. Similarly, Jiang et al. used the linear superposition to combine spatially separate communication and sensing beams. The constant-modulus constraint was imposed to overcome the high PAPR problem of the synthetic waveform [104]. Liu et al. put the cross correlation into account and proposed a joint communication and sensing precoding scheme to optimize the combined waveform close to the desired one [105]. Taking the detailed waveform metric into account, Liu et al. further used the CRB as the sensing objective and optimized the precoding matrix. Particularly, the optimal closed-form solution is derived for the single-user case [106]. Buzzi et al. investigated the configuration of mMIMO and applied zero-forcing beamforming for communication signals and channel matched beamforming for sensing signals [107]. Qi et al. proposed a hybrid beamforming scheme to detect multiple targets and communicate with multiple users. The detection pattern is optimized with the constraint of the user SINR [108]. In reality, the detected targets are likely to be malicious eavesdroppers, especially in the military. By taking this into account, Chalise et al. used the secure rate as the communication metric and put up a joint optimization scheme, including the radar waveform, radar precoding, and communication transmit covariance [109]. Moreover, Ding et al. further combined the MIMO ICAS design with the computation resource allocation. In the proposed network, multiple dual-function user terminals perform communication and sensing tasks simultaneously. Then, their sensing data are required to be further processed locally or offloaded to the

| Integration Degree | Settings | Applied Schemes | Sensing Metrics | Communication Metrics | Programming Schemes |
|-------------------|----------|----------------|----------------|----------------------|---------------------|
| separate RF chains and separate antennas | MT-MIMO, MU-MISO | radar waveform and power, BS transmit precoding and power | waveform similarity | sum rate and EE | unspecific [98] |
| | MT-MIMO, MU-MISO | radar transmit covariance matrix, BS precoding | waveform similarity | SINR | SDP [100] |
| | ST-MIMO, SU-MISO | joint radar and BS precoding | desired radar signal, constant envelope | desired communication signal | error reduction algorithm [102] |
| | MT-MIMO, MU-MISO | joint radar and BS precoding | waveform similarity, cross correlation | SINR | QSDP [105] |
| | ST-MIMO, MU-MISO | joint precoding | waveform similarity | SINR | SDP [106] |
| | MT-MIMO, MU-MISO | hybrid beamforming | waveform similarity | SINR | second order cone programming [108] |
| | ST-MIMO, SU-MISO | radar transmit signals and precoding, communication transmit covariance | desired radar pattern | transmission delay | fractional programming, Taylor expansion [110] |
| | Multiple ST-MIMO, MU-MIMO | transmit covariance matrix of radar and BS, computation resource | desired radar pattern | transmission delay | fractional programming, Taylor expansion [110] |
| | ST-MIMO, MU-MISO | waveform matrix | range sidelobe and waveform similarity | multi-user interference | Riemannian gradient conjugate algorithm [112] |
| | MT-MIMO, MU-MISO | waveform matrix | waveform similarity | multi-user interference | Riemannian gradient conjugate algorithm [113] |
| | ST-MIMO, MU-MISO | transmit baseband and RF precoding, receive RF precoding | radar power | gain of each user | unspecific [114] |
| | MT-MIMO, SU-MIMO | transmit covariance matrix | CRLB of locations | capacity | SDP and sequential parameter metric convex approximation [115] |
| | ST-MIMO, SU-MISO | joint T&R precoding | Kullback-Leibler divergence, PAPR | word error probability | alternating direction sequential relaxation programming [116] |
| | ST-MIMO, SU-MISO | transmit and receive vectors | SINR, PAPR and constant modulus | constructive interference instructed constructive region requirement | majorization-minimization, ADMM [118] |
| | MT-MIMO, MU-MISO | transmit and receive vectors | a broad family of radar metrics | user error rate | alternating optimization [120] |
| | MT-MIMO, MU-MISO | transmit vector | effective receiving power and cross correlation of targets | sum rate | successive convex approximation [121] |
| | MT-MIMO, SU-MISO | transmit signal and distortion | SINR | secrecy rate | Taylor series approximation [122] |

1 ST-MIMO: single-target MIMO, MT-MIMO: multi-target MIMO, SU-MISO: signle-user multi-input and single-output (MISO), MU-MISO: multi-user MISO.
to mitigate the impact of self-interference [114]. To exploit the high-resolution merit of frequency diverse waveform, Zhou et al. investigated the phase-modulated frequency diverse waveform to perform both communication and sensing tasks. The sensing metric of the Cramér–Rao lower bound (CRLB) of locations and the communication metrics of capacity and BER were analytically derived, and the transmit precoding vector was optimized [115]. Recently, Wang et al. considered the waveform design for the joint synthetic aperture radar imaging and communication. Two novel waveforms of modified OFDM and space-time coding were devised to complete high-resolution imaging and data transmissions at the same time [116]. The author pointed out that the multidimensional waveform optimization is the way to mitigate the conflicts of communication and sensing. Tian et al. followed the sidelobe control idea in [63] and refined this scheme by joint T&R beamforming. Simulations showed that the new optimized waveform achieves better communication and sensing performance than the radar embedding scheme [117].

More recently, Liu et al. jointly optimized the transmit and receive vectors by using constructive interference based processing and space-time adaptive processing for the communication and sensing functions. The proposed scheme is robust to the strong clutter environment but has the problem of intractable computation burdens [118]. Zhang et al. devised a novel waveform characterized by the low sidelobe and ultra-reliability. The main idea of this design is to map the information bits into a high-dimensional sparse vector and thus obtains great spatial diversity to ensure the reliability [119]. Johnston et al. gave consideration to a DFRC using the OFDM signals. The radiated waveform and receive filters are jointly optimized with a general objective of radar sensing under the constraints of user error rate and transmit beampatterns [120]. In addition, Wang et al. used non-orthogonal multiple access (NOMA) to provide extra DoFs for communication improvements. The authors optimized the transmit precoding to maximize the weighted sum rate and effective receiving power of sensing targets [121]. Regarding the physical security, Deligiannis et al. employed the artificial noise to control the SINR received by the malicious target [122]. Su et al. applied this scheme in a multi-user scenario. A joint precoding and artificial noise optimization scheme was devised to minimize the target SINR while guaranteeing the SINR of legal users. Instead of ideal assumptions, the uncertainty of the target was considered using imperfect and statistical CSI [123].

**Summary:** We summarize these studies in Table. V by comparing their settings, applied schemes and used communication and sensing metrics. Compared with radar-centric and communication-centric methods, novel waveform designs are not restricted by the primary function so that full DoFs could be exploited. In terms of using one platform with totally separate modules, the communication and sensing beams are spatially separated to lower the mutual impact, which is similar to the case of coexistence. Since different RF chains and antenna arrays are applied, the separate configuration could achieve comparable performance with the communication and sensing standalone configuration while enjoying the convenience of joint communication and sensing optimization. When communication and sensing signals are generated independently but radiated from the same antennas, considerable attention has been given to the combined waveform whose properties would directly determine the sensing performance. To protect communication signals from being submerged in high-power sensing signals, the spatial beamforming is also needed. The totally unified setting is the most cost-friendly, and the corresponding MIMO schemes mainly focus on waveform designs. In three these settings, the communication and sensing trade-off mainly converts to the balance of waveform shaping and directional beamforming. The former guarantees sensing functions, and the latter ensures communication performance. With restricted DoFs, the ICAS MIMO sorts to find a balance between the incompatible requirements.

4) **Discussion:** At present, the ICAS is still preliminary. Making adaptations to radars or BSs is the first step. Since the radar-centric and communication-centric schemes are constrained by the pre-given function, it is difficult to balance communication and sensing. Open issues in terms of FD operations and imperfect synchronization and CSI need to be further considered. Moving a further step, devising a novel dual-function waveform is necessary for the long-term evolution of ICAS. But the roles that MIMO undertakes, waveform shaping and directional beamforming, are not compatible. Thus, communication and sensing parts inevitably have to compromise. In addition, the novel waveform optimization has the high complexity. Corresponding schemes mainly turn out to be high-dimension matrix optimization problems. In most cases, these non-convex problems are NP-hard. Even using the convex approximation to find a local optimum, has the polynomial-level complexity, making present schemes far from for engineering. To lower the problem-solving complexity, one possible solution is to use the intelligent method. The intelligent method through pre-training or constant interactions with the environment gradually accumulates “experience” and
establishes complex connections between inputs, i.e., the CSI and communication and sensing requirements, and outputs, i.e., the radio resource scheduling strategy. These complex connections are recorded in the network and could directly map the input information into the output design. Thus, the troublesome optimization is get rid of at each time. In particular, we emphasize the method of deep reinforcement learning (DRL). This method establishes a self-evolution loop by constantly interacting with the environment and adjusting its strategies. Based on this constant accumulation, the corresponding scheme is able to adapt to the environment in a timely manner while maintaining the low update complexity. Furthermore, instead of using limited DoFs to chase the communication and sensing balance, which regards them as competitors, the interdependence of communication and sensing could be exploited. On the one hand, sensing results provide effective side information for communication. Sensing-assisted channel estimation \cite{124} and sensing-assisted beam domain designs \cite{125} have been investigated and proven to be effective. From another perspective, communication also contributes to sensing. The sensing resolution could be greatly refined by the signal-level and data-level fusion. If we take this reciprocity into account, the dilemma of using limited DoFs to cater to incompatible communication and sensing requirements is largely mitigated. This communication and sensing symbiosis may form a self-evolution loop of communication-assisted sensing and sensing-assisted communication and finally achieve the ultimate performance of JCAS.

IV. INTERPLAY OF MIMO-EMPLOYED JCAS AND 6G ENABLERS

In this section, we discuss three novel JCAS MIMO structures that are promising in 6G. The first addresses the JCAS design with cooperative MIMO, which exploits not only the micro but also macro spatial DoFs. The second introduces UAVs into the communication and sensing network. They form a 3D MIMO structure. The last combines active MIMO and passive MIMO to enhance communication and sensing functions.

A. JCAS with Cooperative MIMO

Cooperative MIMO is promising to overcome the insufficient problem of using one single platform for two functions. It cooperatively uses distributed nodes to transmit or receive signals and these signals are jointly processed in a central unit. As for the communication side, a well-conditioned channel could be guaranteed by selectively activating and muting the transmit nodes to exploit the full multiplexing gains. The sensing function can also benefit from multi-perspective observations. In addition, we could assign different nodes with different communication or sensing tasks so that the insufficiency of using one beam to carry two functions is downplayed. In short, the newly brought macro diversity not only enhances the communication and sensing functions but also gives the system more choices to configure the two functions in a more compatible manner. In the literature, Ahmed et al. considered a distributed DFRC system and proposed a power allocation scheme. The sensing performance is largely improved since the receiver could obtain echoes from other DFRCs \cite{126}. Sanson et al. considered a vehicle network and devised a cascading information fusion method to improve the resolution of the multi-target detection. Results show that, enhanced by cooperative MIMO, the originally indistinguishable targets are distinguishable. Practical experiments have also been performed to verify this result \cite{127}.

In 5G network, an architecture named cloud random access network (C-RAN), is a kind of cooperative MIMO. It consists of distributed remote radio heads (RRHs), a base band unit (BBU) and a fronthaul network that connects RRHs to the BBU. The RRH charges for transmitting and receiving signals and the signal processing and resource allocation are performed by the BBU. This ready-made 5G platform provides a good basis to build the dual-function system. In Fig. 2 we illustrate a dual-function C-RAN used in the smart factory. In this setting, the sensing services are mainly applied to machines for monitoring their states while communication services are more provided for humans to meet their social and entertainment needs. Therefore, RRHs need to adopt different schemes to serve different objects. In the unmanned workshop, RRH1 and RRH2 are highly located and jointly take charge of the daily inspection. To improve the sensing ability, their received echoes are jointly processed in the BBU. In the manned workshop, the communication-only beam is used to connect different workers. Regarding moving devices, such as unmanned vehicles, they are scheduled and monitored by RRH3, using the dual-function MIMO beam. All of these signals are managed by the BBU. Promisingly, this dual-function network could further integrate the computing function to support smart manufacturing. In this way, sensing monitors the production progress, communication transmits data between the sensing and computation nodes and computing calculates the production decision. Different production processes could thus be automatically controlled without the human intervention. In the integrated network, the radio, power and computing resources are desired to be jointly scheduled. They are packaged into tailored slices and allocated to corresponding fabrication tasks. The integrated design not only guarantees
the performance of the fabrication process but also brings great flexibility to improve the resource efficiency.

B. JCAS with Dynamic 3D MIMO

The fact that antennas of terrestrial BSs pointing down to cover ground users brings the problem of limited view for sensing. Aerial platforms, such as UAVs, airships, and even balloons are necessary to provide complementary observations. In particular, by leveraging the maneuverability of UAVs, they could be flexibly deployed to provide on-demand communication and sensing services. When UAV flies high, the wide sensing beam could be used to illuminate the whole area, and when the UAV is close to the target or the user, the directional pencil beam may be used to refine the sensing resolution or improve the communication rate. Considering the whole trajectory of the UAV, the communication and sensing signals could be flexibly scheduled in different time slots. As shown in Fig. 3, we depict one execution process of a UAV on the sea. The UAV uses different communication and sensing schemes during its flight. The beam pattern is altered according to the UAV’s altitude.

In the literature, Meng et al. paid attention to the joint trajectory and radio scheduling issue for the UAV-enabled ICAS system, where the communication signal is constantly emitted and the detection task is only executed using a proportion of the signal frame. Through optimizing the transmit precoding, the UAV trajectory and the sensing start time in each frame, the user rate was maximized under the sensing beam pattern gain constraint [129]. Moreover, clustering different UAVs could further support multi-scale sensing and enhance the communication and sensing capability. In [130], the authors evaluated the performance of a cooperative sensing UAV network (CSUN), where UAVs emit orthogonal communication and sensing beams for downward sensing and horizontal communication. A novel metric named the cooperative sensing coverage area was proposed and evaluated. Using this metric, the JCAS CSUN demonstrates a 66.3% improvement compared with the communication and sensing separate CSUN. In general, the JCAS with dynamic MIMO exploits DoFs in both the spatial and temporal domains. The communication and sensing functions could be staggered on the timeline and jointly optimized with UAV’s deployment. This joint optimization brings great performance gains but also leads to high implementation complexity. The energy and hardware limitations of UAVs require the corresponding design to be simple. Compared to accurately mastering every DoF to chase the optimum, more robustness should be introduced to combat high dynamics.

C. JCAS with Hybrid Active and Passive MIMO

In the literature, Meng et al. paid attention to the joint trajectory and radio scheduling issue for the UAV-enabled ICAS system, where the communication signal is constantly emitted and the detection task is only executed using a proportion of the signal frame. Through optimizing the transmit precoding, the UAV trajectory and the sensing start time in each frame, the user rate was maximized under the sensing beam pattern gain constraint [129]. Moreover, clustering different UAVs could further support multi-scale sensing and enhance the communication and sensing capability. In [130], the authors evaluated the performance of a cooperative sensing UAV network (CSUN), where UAVs emit orthogonal communication and sensing beams for downward sensing and horizontal communication. A novel metric named the cooperative sensing coverage area was proposed and evaluated. Using this metric, the JCAS CSUN demonstrates a 66.3% improvement compared with the communication and sensing separate CSUN. In general, the JCAS with dynamic MIMO exploits DoFs in both the spatial and temporal domains. The communication and sensing functions could be staggered on the timeline and jointly optimized with UAV’s deployment. This joint optimization brings great performance gains but also leads to high implementation complexity. The energy and hardware limitations of UAVs require the corresponding design to be simple. Compared to accurately mastering every DoF to chase the optimum, more robustness should be introduced to combat high dynamics.

The JCAS system could embrace passive MIMO devices, referred to as RISs, to offer better communication and sensing services. Recent studies show that RISs have great potential in both the communication and sensing fields [131] [132]. In the context of ICAS, the introduction of an RIS gives more a compatible solution to integrate the communication and sensing functions. As shown in Fig. 4, when the ICAS node could only emit a low-quality waveform, the RIS plays the role of refining it. It adjusts its elements to amplify the
mainlobe of each sub-beam and suppresses their sidelobes. The indistinguishable beam pattern is thus refined into the one like a hand with distinct sub-beams so that the target identifiability and user separability are improved.

In the literature, Wang et al. applied an RIS to assist with DL communication. A joint active and passive beamforming scheme was proposed to minimize the inter-user interference under the waveform similarity constraint [133]. In [135], the authors further proposed a joint constant-modulus waveform and passive phase shift design, with the aim of inter-user interference minimization under the CRB constraint. Sankar et al. adaptively divided RIS units into two parts: one group for communication and the other for localization. A multi-stage hierarchical codebook was designed to gradually refine location results while maintaining a good link to communication users [135]. Jiang et al. invoked an RIS to enhance target echoes with the user rate requirement as the constraint [59]. Different from the above studies, which focused on the JCAS, He et al. applied RISs to assist communication and sensing coexistence and two RISs were used. The former is placed close to the communication transmitter to surpress the interference from the transmitter to the radar and the later is placed closed to the communication receiver to surpress the radar interference. The active and passive precoding matrices are jointly optimized to maximize the communication SNR with the constraint of radar SNR [137]. The above studies all show that the JCAS with active and passive MIMO delivers more satisfying communication and sensing performance compared with the no RIS cases. However, the optimization task is not easy, especially when the RIS is large. Problems lie in the high computational burdens. One possible solution is to regard the RIS more as the environment but not a dedicated radio device in the dual-function system. They are not co-designed with active beamforming and only make changes in a coarse-grained manner. For example, we could set the RIS to alter its unit states according to a predefined pattern. In each time, the impinging beams are radiated to a certain direction. Only when the output beam directs to the target, are the received echoes obviously amplified. Based on the amplitude differences of the received echoes, the direction information is thus obtained.

D. Discussion

These extensions of JCAS MIMO bring great opportunities for the future 6G. But the scale increase, dimension increase and newly introduced dynamism complicate the JCAS schemes. As for JCAS with cooperative MIMO, the flexible orchestration of multiple nodes and their functions is the key issue, where the complex cooperation and competition relationships among different nodes should be well tackled. In terms of the JCAS with dynamic 3D MIMO, the corresponding design tends to be process-oriented and predictive. Radio scheduling should be jointly considered with UAV deployment. Joint active and passive MIMO brings great DoFs and also great complexity to the JCAS system. Regarding RIS as a part of environment may be more practical. In short, we could find these JCAS MIMO models all enlarge the optimization dimension to earn more flexibility so that the communication and sensing functions could be better supported. To make the system work efficiently, the JCAS schemes are expected to be simple and robust. In particular, we emphasize the loose cooperation regime for the JCAS with cooperative MIMO, which is similar to the case of communication and sensing coexistence. The radio map could be introduced to provide large-scale CSI and help geographically decouple the network [59]. What is more, if positions are known in advance, the radio map could further help estimate the future large-scale CSI and support the predictive and process-oriented JCAS design. Intelligent methods may be a good tool to bypass the theoretical obstacles and lower the complexity of high-dimensional optimization.

V. Open Issues and Future Directions

In this section, we briefly outline open issues and promising directions for JCAS. As the research on communication and sensing integration has just started recently, there is still great uncertainty on its future development. However, one can expect further works on intelligence, security and demand. One could also envision the interplay between JCAS and other cutting-edge technologies to take advantage of their mutual benefits.

A. JCAS in Integrated Space-Air-Terrestrial Network

To extend the coverage range of both communication and sensing, it is promising to design JCAS in the space-air-ground integrated network (SAGIN). In this scenario, the distinct rate, latency and reliability of satellite, aerial, and terrestrial links would render new challenges. Two kinds of integration, i.e., C&S integration and space-air-ground integration, could couple with each other. This consequently poses great challenges to the system design. One possible solution is to explore the hierarchical architecture of a hybrid system. As shown in [138], one may derive basic models for satellite-terrestrial cooperation and treat a complicated hybrid system as the combination of basic models. On that basis, basic JCAS-SAGIN models could be studied. Each basic model would contain both minimal space-air-ground infrastructures and minimal C&S functions. The agile orchestration of these basic models would lead to various large-scale JCAS-SAGINs. In this direction, both theoretical analysis and key technologies require research attentions.

B. JCAS Using Artificial Intelligence

The JCAS design may embrace artificial intelligence (AI) to overcome the high complexity of traditional methods. Data-driven deep learning could be used to learn the complex connections between the input raw data and output JCAS schemes. Reinforcement learning methods could be further used to interplay with the varying environment and learn the optimal JCAS policies in a gradual process. In this way, a well-trained network could directly map the input into the output without troubling optimization. In addition, although the intelligent method still acts as a black box without explicit explanations, the analysis of the output policies may be
heuristic for the theoretical breakthrough. However, it is not an easy task to extract high-level information from massive raw data. Perhaps the combination of model-based method and data-based method could be considered. For example, if we know the output results are sparse based on the prior knowledge of the physical JCAS system, a proper network structure could be chosen to simplify the training process.

C. Joint Communication, Computing, Control and Sensing

Future 6G networks are envisaged to shift from connecting things to connecting intelligence. In other words, we want to endow connected machines with human-like intelligence by ubiquitous connections. To do so, the network needs to be aware of device status and give instructions to control their actions. In this sense, JCAS that make wireless networks perceptive is the first step of connecting intelligence. A closed-loop of communication, computing, control and sensing (3CS) shall be further established to build the “nerve system” for machines. Under such closed-loops, these numb machines can adapt to the environment and accomplish different tasks automatically. In this way, the minimal unit of the wireless network is not a single link but a closed-loop. Optimization over these closed-loops covers information theory, control theory and machine learning theory. From this point of view, the 3CS design is still an open issue at present. A unified theoretical model shall be established first to figure out the basic relationships of 3CS.

D. Security Issues of JCAS

Security is one of the key issues for JCAS. The sensing function requires signals to fully interact with the environment so that the surrounding information could be greatly imprinted in the waveform. This increases the risk of eavesdropping. In addition, unlike communication users, who are authenticated before accessing the network, the sensing targets are not identified and are more likely to be malicious. How to ensure the target visibility while limiting the information leakage is still open. Furthermore, the JCAS would bring explosive data. The usage of data produces values but also increases risks. The balance of data security and data efficiency is challenging. We may combine JCAS with the blockchain technique to establish a distributed open network. The explosive data are stored in different nodes and exchanged, updated and cleared through the blockchain. In this way, the whole life of the data is recorded. But the information synchronization cost of the whole network is huge. How to balance efficiency and security is an interesting task for future investigations.

E. Combination of JCAS, Backscatter Communication and RIS

JCAS could combine other techniques, such as ambient backscatter communication [139] and RIS, to further exploit the new dimensional usage of the electromagnetic wave. Different from JCAS, which focuses on signal processing in T&R nodes, ambient backscatter communication and RIS change the signal in the process of the propagation. Thanks to the low-cost property of the RIS and backscatter tags, these devices could be deployed ubiquitously and control radio signals in the whole transmission process. In this way, not only more information could be conveyed by the radio signal but the uncertainty of the random environment could also be greatly reduced. The smart radio environment may be manually constructed to better support communication and sensing integration. However, the basic relationship of communication, sensing and the environment is unknown. Research on design of JCAS with smart radio environments is still in its infancy.

VI. Conclusions

In this paper, we have reviewed recent advances in JCAS MIMO. Detailed schemes of communication and sensing coexistence and communication and sensing integration have been presented. We have also investigated three novel JCAS models combined with promising 6G techniques. We have found that in proposed JCAS systems, MIMO mainly plays the role of directional beamforming for the communication function and waveform shaping for the sensing function. The main challenge thus lies in using restricted DoFs to balance these two incompatible requirements. Targeted at the problem of high complexity and high overhead of the JCAS MIMO design, we have discussed possible solutions based on simple, intelligent and robust principles. Open issues have been outlined in the end, with a great vision to embrace a comprehensive JCAS network in the upcoming 6G era.

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