INVITED PAPER

Next-Generation Multiple Access for Integrated Sensing and Communications

This article discusses the development of integrated sensing and communications (ISAC) from the multiple-access viewpoint, i.e., from orthogonal transmission strategies to nonorthogonal ones over different resource domains.

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ABSTRACT | Integrated sensing and communications (ISAC) has received considerable attention from both industry and academia. By sharing the spectrum and hardware platform, ISAC significantly reduces costs and improves spectral, energy, and hardware efficiencies. To support the large number of communication users (CUs) and sensing targets (STs), the design of multiple access (MA) is a fundamental issue in ISAC. MA techniques in ISAC are expected to avoid mutual interference between sensing and communicating functions under the critical constraints of both functions. In this article, we present an overview on approaches of MA for ISAC, from orthogonal transmission strategies to nonorthogonal ones, realized in time, frequency, code, spatial, delay–Doppler, power, and/or multiple domains. We discuss their individual implementation schemes and corresponding resource allocation strategies, as well as highlight future research opportunities.

KEYWORDS | Integrated sensing and communications (ISAC); interference control; multiple access (MA); next generation; resource allocation; sixth generation (6G).

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I. INTRODUCTION

A. Background

Integrated sensing and communications (ISAC) enables the shared use of wireless resources, physical infrastructures, and devices between sensing and communication functionalities to reduce costs and improve the efficiency of spectrum, energy, and hardware. ISAC is also known as radar communication (RadCom), joint communication and radar (JCR), joint radar and communication (JRC), and dual-functional radar-communications (DFRC), which further drives various use cases including but not limited to sensing as a service, in-cabin sensing in smart home, vehicle to everything, smart manufacturing and the industrial Internet of Things (IoT), and environmental monitoring [1], [2], [3].

Due to its ability to provide numerous benefits and facilitate a spectrum of burgeoning applications, it has attracted the interest of researchers and has prompted active involvement from standardization organizations [4], [5], [6], [7], [8]. In 2023, ISAC has been recognized as one of the six key usage scenarios in international mobile telecommunications (IMT)-2030 by international telecommunication union radiocommunication sector (ITU-R) for the future sixth-generation (6G) wireless systems [4]. A proposal "New SID on Integrated Sensing and Communication" was submitted with the potential target of Release 19, in November 2021 by Third-Generation Partnership Project (3GPP) work group 1 where the purpose of ISAC and typical scenarios are listed [5], [6]. In 2020, Institute of Electrical and Electronics Engineers (IEEE) initiated a project to develop the IEEE 802.11bf standard for Wi-Fi or wireless local area network (WLAN) sensing [7]. The European Telecommunications Standards Institute (ETSI) has launched the ETSI industry specification group (ISG) ISAC to develop a roadmap of prioritized ISAC 6G use cases and sensing types [8]. The above standardization process provides essential guidance for the deployment of ISAC, ensuring its potential revolutionary role in the future 6G era and beyond.

In conventional communication networks, the multiple access (MA) technique, one of the most fundamental enabling wireless technologies, supports simultaneous communication for multicommunication users (CUs) by efficiently utilizing various resources to manage interference. This dramatically improves the connectivity, capacity, reliability, and energy efficiency of the network toward the higher demands in fifth-generation (5G) wireless systems [9], [10], including massive machine type communications, enhanced mobile broadband, ultrareliable and low-latency communications, and enhanced low-power communication [11], [12]. In future ISAC networks, the MA technique is also envisioned as an essential element to enhance the performance of both sensing and communication toward future 6G and beyond, including Seventh-generation (7G) wireless systems.

From the perspective of resource allocation, MA techniques help appropriately allocate different types of resources to achieve optimal performance of dual-functionalities. There exist classical tradeoffs between communication and sensing, comprising those regarding the information-theoretical limits [13], [14], [15], physical layer performance [16], [17], [18], propagation channels [19], and cross-layer metrics [20], which reflect an intuitive vision that communication and sensing compete with each other for resources [1]. Hence, it is necessary to reasonably and flexibly schedule multidimensional resources to improve the efficiency of both communication and sensing services. This has led to the development of various MA technologies.

From the perspective of interference control, MA techniques may cancel the interference among MA points to achieve better dual-functional performance. Except for the interuser interference in conventional communication-only networks, the sensing tasks also introduce additional interference that needs to be eliminated in ISAC [21]. In downlink ISAC, when the downlink CU recovers its intended information, the interuser interference and newly introduced sensing-to-communication interference coexist and impede communication performance, as depicted in Fig. 1(a) [21], [22], [23]. In uplink ISAC, the

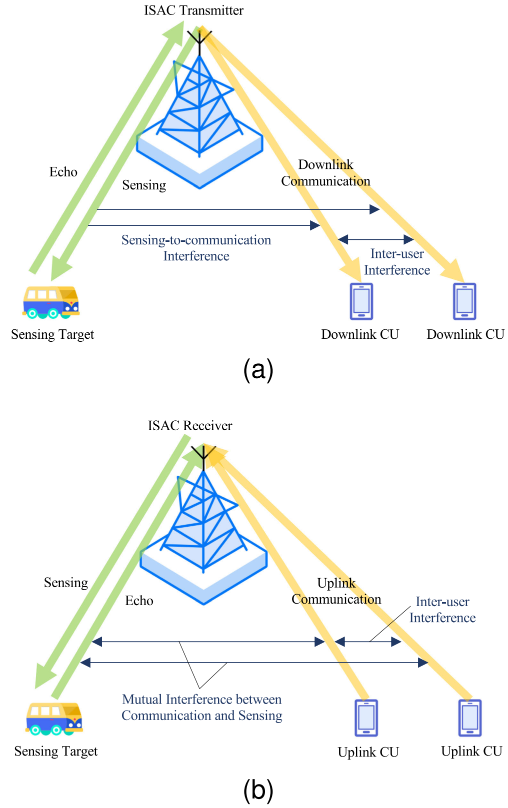


Fig. 1. ***Various interference types in downlink and uplink ISAC. (a) Downlink ISAC. (b) Uplink ISAC.***

transmission for communication and probing signaling for sensing simultaneously proceed, resulting in sensing-to-communication interference for data recovery and communication-to-sensing interference for target detection at the ISAC receiver, also accompanied by interuser interference similar to that in communication-only networks, as depicted in Fig. 1(b) [21], [24]. Since the cancellation of mutual interference between communication and sensing is similar to that of interuser interference in communication-only networks, MA techniques can also be applied to further eliminate or alleviate the newly introduced interference in ISAC. Consequently, how to establish new MA schemes in ISAC toward the next-generation 6G and beyond becomes an essential problem.

In summary, the MA technology is an essential component in ISAC networks. It faces new challenges due to the distinct resource allocation and interference control strategies compared with communication-only MA, which necessitates completely new design methodologies.

B. Brief Review of the State-of-the-Art MA Techniques

In wireless networks, MA techniques have significantly evolved over consecutive generations, ranging from first-generation (1G) wireless systems to 5G [10], [25], [26]. The frequency-division MA was combined with an analog frequency-modulation-based technology in 1G for analog

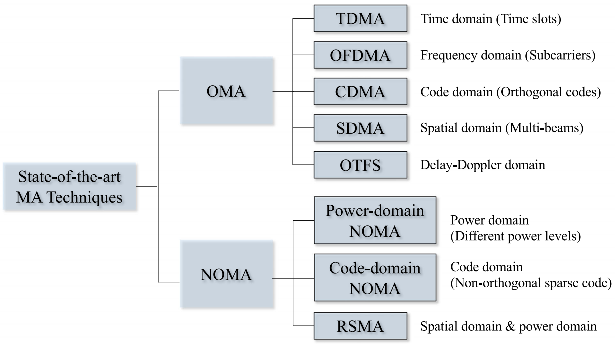


Fig. 2. ***Existing state-of-the-art MA techniques.***

voice call service [10]. Afterward, time-division multiple access (TDMA) was adopted in second-generation (2G) wireless systems global system for mobile communications and 2.5G generation packet radio service to support digital voice calls [27], [28]. Code-domain multiple access (CDMA) became the dominant MA technique applied in third-generation (3G) wireless systems standards, such as wideband code-division MA and CDMA 2000 [10]. Subsequently, orthogonal frequency-division multiple access (OFDMA) was utilized for fourth-generation (4G) wireless systems long-term evolution to further improve the spectrum efficiency [10]. To improve data rates and connectivity, additional MA techniques are implemented in 5G, including spatial-division multiple access (SDMA), nonorthogonal multiple access (NOMA), some emerging orthogonal time frequency space (OTFS), and rate-splitting multiple access (RSMA).

Existing works primarily revolve around mature MA techniques; hence, this article mainly discusses advanced MA methods applied in ISAC networks across the generations of communication networks from 1G to 5G. Therefore, the classification of MA techniques in ISAC is similar to that in communication-only networks, which can be categorized into orthogonal multiple access (OMA) and NOMA [29], as illustrated in Fig. 2.

The former OMA allocates orthogonal resources to different CUs in time, frequency, code, or other domains and can be further divided into TDMA, OFDMA, CDMA, SDMA, and OTFS according to their resource domains [29]. TDMA partitions temporal resources into small slots in the time domain, which are then allocated to different CUs to avoid transmission collision [30]. OFDMA modulates symbols of different CUs on orthogonal subcarriers in the frequency domain and transmits them in parallel to support simultaneous multiuser communications [31]. CDMA assigns a unique orthogonal/quasi-orthogonal codes to each CU in code domain [32]. SDMA transmits multiple beams toward different CUs where the resources in the spatial domain are fully exploited to achieve noninteracting transmission, also referred to as multiple-input mulitple-output (MIMO) technology [17]. Finally, OTFS is an uprising modulation technique that exploits the resources in the new concept of 2-D delay–Doppler domain to support simultaneous transmission [33].

NOMA technologies allow multiple CUs to share the same above orthogonal resources via power domain and code domain multiplexing, roughly including power-domain NOMA, code-domain NOMA, and RSMA [29]. Power-domain NOMA utilizes superposition coding (SC) at the transmitter to allocate different levels of power to CUs and then adopts successive interference cancellation (SIC) at the receiver for differentiating signals in the power domain [10]. Although code-domain NOMA techniques also utilize the code resources to differentiate CUs in the code domain, the used codes are sparse and nonorthogonal rather than the orthogonal codes in OMA CDMA. Such techniques allocate user-specific nonorthogonal sparse codes to CUs and detect their signals based on the message passing algorithm, mainly including low-density spreading code-domain multiple access (LDS-CDMA), low-density spreading orthogonal frequency-division multiplexing (LDS-OFDM), and sparse code multiple access (SCMA) [34]. The uprising RSMA is a unified framework that combines OMA SDMA and power-domain NOMA. Here, RSMA is also viewed as a NOMA technique for the sake of clarity [35].

C. Motivation and Contributions

Although the aforementioned MA technologies have been extensively studied and applied in communication-only scenarios, their application in ISAC still remains widely unexplored, as can be seen in Table 1. Although Mu et al. [21] introduce the MA techniques referring to ISAC, they mainly focused on power-domain NOMA. The main reason is that the performance metrics for sensing are different from those of communication, and thus, they utilize wireless resources in different manners. Commonly used performance metrics for evaluating communication consist of spectral efficiency, energy efficiency, bit error rate, and achievable rate [36], [37], [38], while those for measuring the sensing performance are typically determined based on specific sensing tasks, e.g., detection probability and false-alarm probability for detection [39], mean square error and Cramér–Rao lower bound (CRB) for estimation [40], and recognition accuracy [41]. Different design criteria between communication and sensing systems lead to performance tradeoffs when they share and compete for the same wireless resources. As a result, MA techniques should be elaborately designed to optimally balance their performance. In addition, the newly introduced interference, i.e., the sensing-to-communication interference in downlink ISAC and the mutual interference in uplink ISAC, needs to be canceled or mitigated by MA techniques.

Here, we investigate existing MA techniques in ISAC toward 5G and future 6G. Our contributions mainly lie in the following aspects.

Table 1 Comparison of Existing Magazine Articles and Surveys of MA Techniques in ISAC

Contents	Dai et al. [29]	Ding et al. [9]	Liu et al. [10]	Cai et al. [42]	Clerckx et al. [35]	Mu et al. [21]	This work
Towards **ISAC**						✓	✓
Time-domain OMA							✓
Frequency-domain OMA				✓			✓
Code-domain OMA							✓
Spatial-domain OMA	✓	✓	✓				✓
OTFS				✓			✓
power-domain NOMA	✓	✓	✓	✓		✓	✓
code-domain NOMA	✓	✓	✓	✓			✓
RSMA					✓		✓

1) We introduce the background of ISAC and its application scenarios. Then, we highlight the importance of MA in ISAC, particularly with respect to resource allocation and interference control. In addition, we briefly review existing state-of-the-art MA techniques and summarize their general principles.
2) We investigate well-known OMA techniques in ISAC, including TDMA in time domain, OFDMA in frequency domain, CDMA in code domain, SDMA in spatial domain, and OTFS in delay–Doppler domain. In TDMA, the ISAC frame structure, time scheduling schemes, and 5G new radio (NR) frame structure are described. In OFDMA, the orthogonal subcarriers, their allocation scheme, and the corresponding signal parameter optimization are explained. In CDMA, the orthogonal codes for spectrum spreading are introduced, and different codes used for communication and sensing in ISAC are described. In SDMA, we formulate the existing MIMO beamforming problems under two signaling strategies and provide their solutions. In OTFS, the transmit waveform and delay-Doppler resource block (DDRB) allocation are illustrated.
3) We demonstrate the prominent NOMA techniques in ISAC, including power domain NOMA, code domain NOMA, and RSMA. In power-domain NOMA, SC at the transmitter, SIC at the receiver, and power allocation are described. In code-domain NOMA, nonorthogonal sparse codes used in three primary methods, i.e., LDS-CDMA, LDS-OFDM, and SCMA, and their corresponding multiuser detection methods are explained. In RSMA, the division of the common stream and private stream and its linear precoding are illustrated. The literature review related to these techniques primarily focuses on the upcoming 5G and 6G networks.
4) We identify key issues and challenges of each MA technique derived by the coexistence between communication and sensing. Finally, we identify a number of future research opportunities related to the cancellation of other interference caused by more complex implementations, the selection of techniques toward different application scenarios, and the multidomain fusion of MA methods. The challenges and opportunities of specific MA approaches for future research are geared toward future 6G and 7G.

For the sake of clarity, we depict existing MA techniques and their general principles in ISAC in Fig. 3.

The remainder of this article is structured as follows. OMA technologies in ISAC are stated in Sections II–VI, where MA in the time domain, frequency domain, code domain, spatial domain, and delay–Doppler domain are discussed, respectively. NOMA technologies in ISAC are described in Sections VII and VIII, where power-domain NOMA and code-domain NOMA are introduced in Section VII, and RSMA is discussed in Section VIII. Finally, Section IX concludes this article and considers future research directions.

II. MA ISAC IN TIME DOMAIN

TDMA utilizes time resources to support CUs and sensing target (ST) access.

A. ISAC Frame Structure

In TDMA, time is divided into several periodic ISAC frames, and each ISAC frame is further divided into several time slots [30]. Like TDMA for communication-only networks, different CUs are assigned one or more different time slots, i.e., different communication channels, within an ISAC frame for information transmission to avoid interuser interference [43], [44], [45]. In ISAC, partial time slots are allocated to sensing tasks to prevent sensing-over-communication interference from dedicated sensing signals [46], [47]. For example, in [1], the target recognition and communication are split into the sensing phases and communication phases, and in [48], the transmission duration is divided into radar cycles and radio cycles. The TDMA ISAC frame structure is shown in Fig. 4. Generally, each time slot in a frame contains not only the information message or probing signal but also some extra bits for synchronization, adaptation, control, and guard time [3], [43]. In addition, the TDMA protocols can be categorized into centralized, distributed, and hybrid protocols [49]. The frame structure of TDMA is applicable to both uplink and downlink ISAC, with uplink and downlink transmission and sensing conducted in separate orthogonal time resource blocks.

B. Scheduling Scheme

TDMA scheduling scheme, also referred to as time allocation strategy [47], [50], aims to assign time slots to

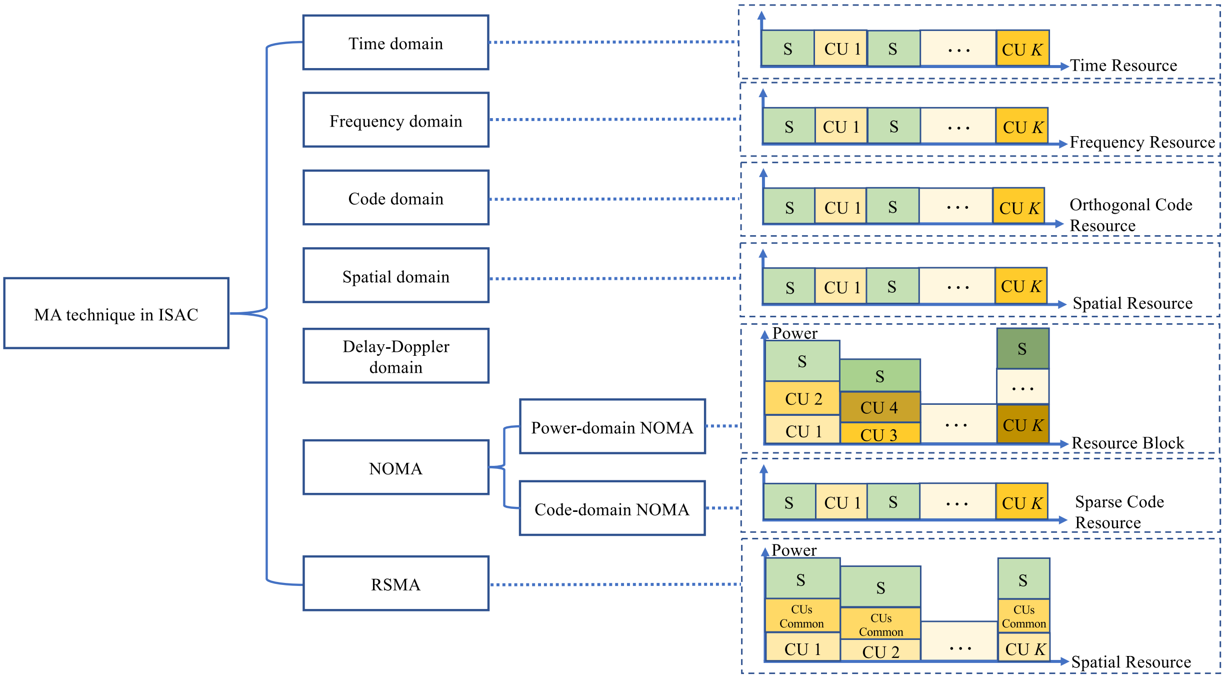


Fig. 3. ***Existing MA techniques and their general principles in ISAC.***

the competing nodes, say CUs and STs, in the network to avoid collision interference and balance the performance between data transmission and target detection [30], [51], [52], [53]. The optimization goal can be binary states that represent whether a CU or an ST is served in a certain time slot [47], [52], [53], [54], [55], [56], or can be start times or time durations for communication and sensing tasks, respectively [53], [54], [55], [57], [58]. Accordingly, the ratio of the time slot allocation between communication and sensing or among CUs may be changed dynamically based on different service requirements [46]. Common metrics involved in communication service requirements include throughput [53], [54], [55], achievable rate [56], [58], signal-to-interference-plus-noise ratio (SINR) [57], and those involved in sensing requirements include radar detection probability [53], [54], [57], CRB [55], and beam pattern gain [58]. Other integrated system performance metrics, such as the queue stability that reflects the waiting time [53], [54] and age of information [55], [57] that characterizes freshness of data after sensing and transmission, are also optimized as objectives in some works. Furthermore, the scheduling scheme is sometimes jointly designed with other system parameters, e.g., the transmit power [55], [56], the beamforming matrix [58], or the trajectory of UAV [55], [56], [57], [58]. These optimization problems are usually complicated nonconvex forms and thus difficult to solve. Approaches to solve them may be converting them into convex problems by, e.g., Lyapunov function [53], [54], successive convex approximation iterative algorithm [55], [56], extremum principles [57], dynamic programming algorithm [57], and semidefinite relaxation [58].

C. 5G New Radio Frame Structure

In 5G NR, a frame lasts for 10 ms and contains ten subframes. Each subframe is split into $2^{\mu}, \mu = 0, 1, \ldots, 4$ slots, and each slot further includes 14 orthogonal frequency-division multiplexing (OFDM) symbols [59], as depicted

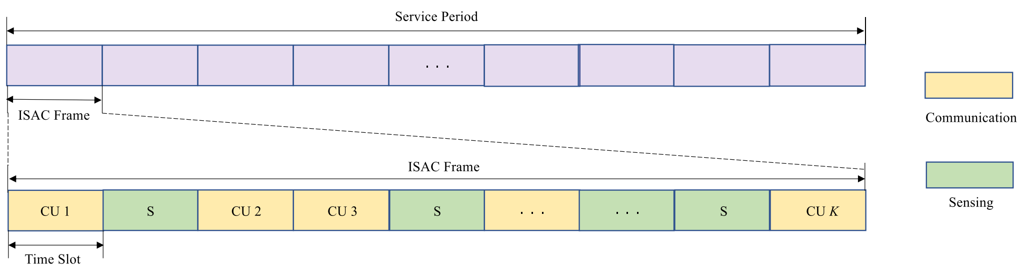


Fig. 4. ***Illustration of TDMA ISAC frame structure.***

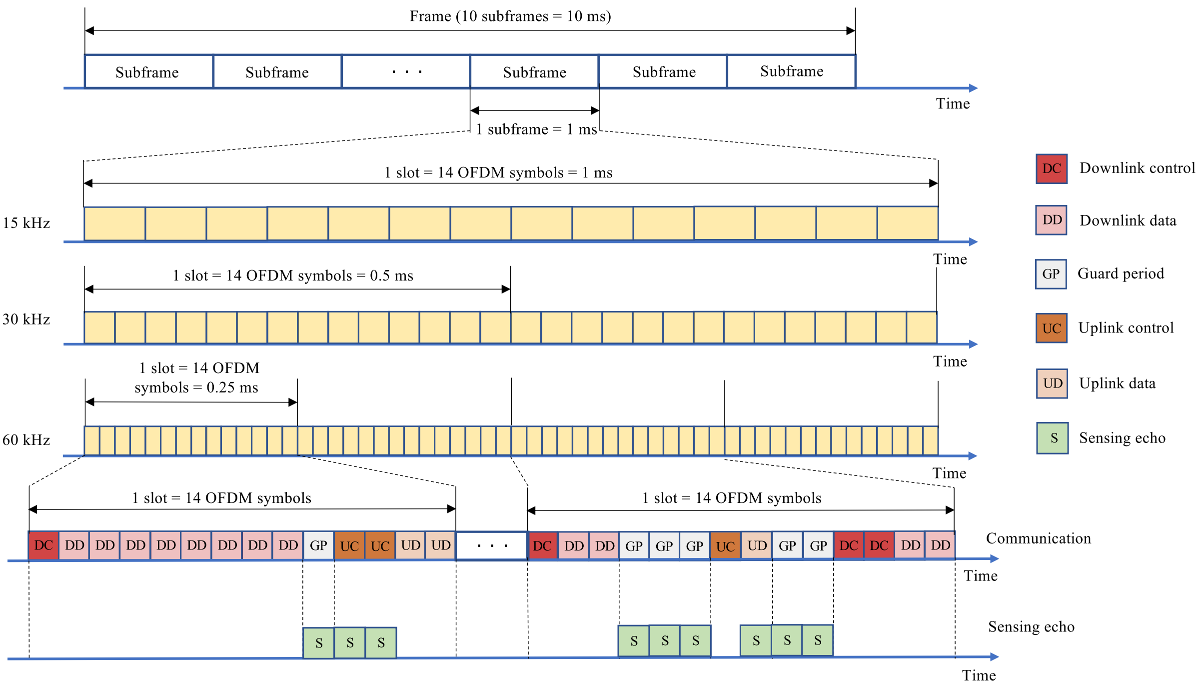


Fig. 5. ***Illustrations of 5G NR frame structure and time slots for sensing.***

in Fig. 5. For example, when the subcarrier spacings are 15, 30, and 60 kHz, one slot lasts for 1, 0.5, and 0.25 ms, respectively. OFDM symbols in a slot can be designed for only downlink, only uplink, or combined mode [60]. The guard period in each slot can carry the control signals or channels at the beginning or the ending of the OFDM symbols for downlink or uplink [60]. It is worth noting that different subcarrier spacings can be multiplexed within one subframe [60]. To simultaneously support communication transmission and sensing detection/tracking in ISAC, the dedicated sensing signals are also transmitted during the downlink stage in "Downlink control" or "Downlink data" in Fig. 5 [3]. Besides, the radar echo signals are received and processed during the guard period or the uplink stage in "Guard period," "Uplink control," or "Uplink data" in Fig. 5 [3]. Particularly, if the uplink communication signals are superposed with the radar echo, communication and sensing will interfere with each other; otherwise, there is no mutual interference due to the time division.

D. Discussion on Some Key Issues and Challenges

Despite that TDMA is readily implementable for ISAC transmission, there are yet a number of unique challenges to be addressed, particularly due to the inherent randomness of both communication signaling and radar targets.

1) Nonuniform PRI: Over the past decades, the feasibility of TDMA-ISAC has been investigated in various commercial wireless standards, such as 5G NR, IEEE 802.11p, and IEEE 802.11ad [1], [61], [62], where the channel estimation field (CEF) or pilot signals in the frame structure, originally conceived for communication channel estimation, may also be employed for radar target sensing. In typical communication frames, however, the CEF may not appear in a strictly periodic manner, as the specific temporal resource scheduling scheme has to be adaptive to a variety of practical conditions including user equipments (UE's) movement, uplink/downlink switching, and indoor–outdoor switching. For instance, the Wi-Fi access point (AP)/cellular base station may need to transmit pilots more frequently for high-mobility users, whereas less pilots are required for serving slowly moving users. This, in contrast to conventional pulsed radar systems transmitting uniform pulses at a fixed duty cycle, results in a nonuniform distribution of exploitable sensing time slots in the communication frame, also known as pulse repetition interval (PRI) staggering in radar signal processing [63]. Illustrations of uniform PRI and random PRI are depicted in Fig. 6.

The emission of nonuniform pulses, needless to say, leads to a series of signal processing challenges for moving target sensing in terms of Doppler estimation, among which an essential problem would be pulse association. More precisely, determining the one-to-one mapping between the transmitted and returned echo pulses becomes complex given the fact that the PRI is randomly varying. Note that in conventional pulsed radar systems, one may uniquely correspond the returned echo to a transmitted pulse, as long as the target's round-trip

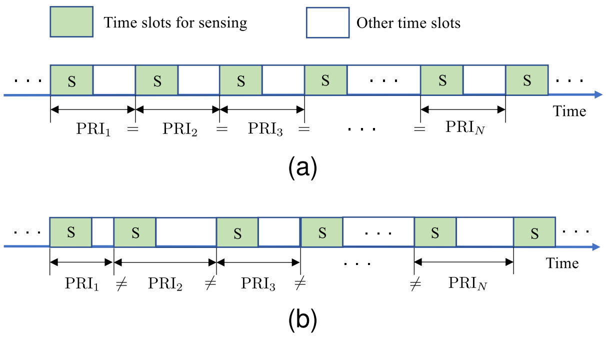


Fig. 6. *Illustrations of PRI. (a) Uniform PRI. (b) Random PRI.*

delay is within a single PRI. In TDMA-ISAC systems with varying PRIs, the pulse association has to be performed over a random pulse train, which incurs significant processing complexity. Coherent combination over multiple pulses, which aligns the phases of pulses through fast Fourier transform (FFT) so as to improve the echo signal-plus-noise ratio (SNR), now becomes quite challenging due to randomly staggered PRIs. A viable approach in such a situation would be to leverage compressive sensing by exploiting the sparse nature of targets over the Doppler domain [64].

Although computationally expensive, PRI staggering in TDMA-ISAC is favorable for resolving the Doppler ambiguity. This is because uniform pulsed radar may be treated as Nyquist sampling of the Doppler shift over the slow-time domain, where the maximum unambiguous Doppler frequency is restricted to half of the pulse repetition frequency (PRF $=$ 1/PRI). By adding variability into the PRI/PRF, the Doppler ambiguity may be unwrapped through well-established methods, e.g., the Chinese remainder theorem [65]. More interestingly, by appropriately designing the slow-time coding strategy, PRI staggering can flatten the Doppler sidelobes, which facilitates improved detection probability for high-speed targets, such as vehicles and drones.

2) Target Echo as an Outlier in TDMA Scheduling: In a TDMA-ISAC network, wireless resources have to be efficiently scheduled so as to improve both the sensing accuracy and communication throughput performance. In conventional communication-only TDMA, scheduling is designed to minimize the transmission latency or to avoid mutual interference among users, which relies on a centralized control plane of the network by fully controlling the transmission and reception activities of communication devices. Nevertheless, in an ISAC network, the target echo tends to be an outlier, as it may randomly appear in the time domain, which could be highly unpredictable and thereby uncontrollable. Accordingly, target echo signals possess much higher uncertainty compared to conventional communication packets, leading to higher probabilities of collisions [1], [66]. Illustration of random arrival of target echo in TDMA scheduling is depicted in Fig. 7. This is particularly pronounced in high-mobility or time-sensitive target detection events where sudden status changes are likely to happen, which necessitates a complete redesign of the scheduling schemes in TDMA-ISAC networks [66]. While sensor scheduling approaches have been extensively studied over the past few decades in the area of distributed estimation for sensor networks, they generally assume that the sensing observations are readily attainable at each sensor, with an aim to minimize the sensing errors by selecting a given number of sensors out of the entire network [67]. In general, TDMA-ISAC scheduling could be much more challenging than simply selecting the optimal subset of sensing devices, as one needs to simultaneously take the randomness of target echoes, communication efficiency, and sensing quality of service into consideration.

III. MA ISAC IN FREQUENCY DOMAIN

OFDMA modulates the communication symbols to be transmitted to different CUs or dedicated sensing waveforms onto several orthogonal subcarriers and then transmits these subcarriers in parallel to support simultaneous transmission and detection [31]. From a physical layer perspective, the downlink OFDMA system is basically identical to an OFDM system extended to multiuser communication scenarios [31].

A. OFDM and Orthogonal Subcarrier

At the mth OFDM block, the OFDM-modulated signal can be represented by [2], [42], [68], [69], [70]

$$s_m(t) = \underbrace{\sum_{k=1}^{N_\mathrm{C}} c_{m,k} e^{j2\pi k \triangle f t}}_{\text{Communication Subcarriers}} + \underbrace{\sum_{k=N_\mathrm{C}+1}^{N_\mathrm{C}+N_\mathrm{S}} s_{m,k} e^{j2\pi k \triangle f t}}_{\text{Sensing Subcarriers}} \quad 0 \le t \le T_\mathrm{s} \tag{1}$$

where $c_{m,k}$ and $s_{m,k}$ represent the transmit complex symbols for communication or sensing; N_C and N_S represent the numbers of communication subcarriers and sensing subcarriers, respectively; and T_s and $\triangle f$ represent the symbol duration and subcarrier space, respectively [68].

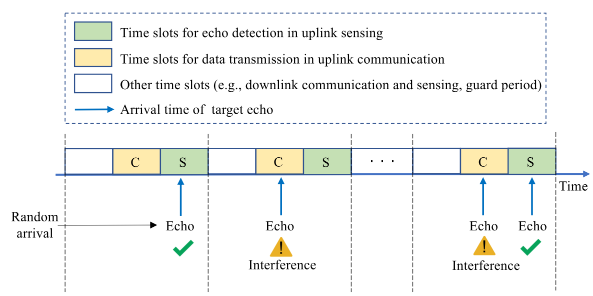


Fig. 7. *Illustration of random arrival of target echo.*

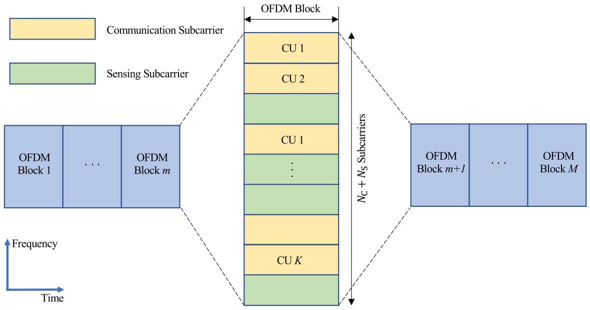


Fig. 8. ***OFDM blocks and subcarriers.***

Like OFDMA in communication-only networks, different CUs occupy different orthogonal communication subcarriers to avoid interuser interference [31], [45]. In ISAC, the sensing tasks are performed with the help of both communication and sensing subcarriers where the sensing subcarriers are exploited to transmit dedicated sensing signals to avoid sensing-over-communication interference [69]. The orthogonal condition $T_s \triangle f = 1$ should be satisfied to make $e^{-j2\pi k \triangle f t}$ orthogonal to each other for different k [42]. Illustration of OFDM blocks and orthogonal subcarriers is depicted in Fig. 8.

More generally, at the OFDMA transmitter, the carrier assignment scheme should be conducted first to determine which subcarriers the CUs can use to deliver information and then followed up with the inverse discrete Fourier transform to modulate signals and cyclic prefix insertion to avoid interference between adjacent blocks [31]. In addition, OFDM is usually coupled with other modulation methods to further improve the sensing performance in ISAC [71], e.g., linear frequency modulation [72], phase coding [73], and spread spectrum [74].

By utilizing the orthogonality among subcarriers, the transmitted symbol $c_{m,k}$ at the receiver can be detected by

$$c_{m,k} = \frac{1}{T_s} \int_0^{T_s} s_m(t)\, e^{-j2\pi k \triangle f t} dt. \tag{2}$$

More generally, the frequency/timing estimation and correction, the cyclic prefix discarding, the discrete Fourier transform, and the channel estimation and equalization are executed in turn to help accurate decoding of the desired data at the receiver [31]. The 2-D FFT method is used extensively for processing most OFDM-based ISAC signals [71].

B. Subcarrier Allocation

Subcarrier allocation determines which subcarrier is assigned to CUs or STs for mitigating interference. Although the distinguishing between the communication data and sensing echo is conducted in uplink ISAC networks, OFDMA allocates different orthogonal subcarriers for communication and sensing when the base station transmits mixed signals in downlink ISAC network. Therefore, even though OFDMA is applicable in both downlink ISAC and uplink ISAC, we discuss the subcarrier allocation in OFDMA in downlink ISAC. When there are dedicated sensing signals, the subcarrier allocation concerns the designation between communication and sensing in ISAC to avoid sensing-over-communication interference, where the goal is usually to optimize the binary assignment indicator $a_k \in \{0, 1\}$ that characterizes the kth subcarrier being assigned to communication or sensing [75], [76], [77], [78]. Conversely, if the communication signals support both communication and sensing, subcarrier allocation mainly focuses on the designation among CUs to avoid interuser interference like OFDMA for communication-only networks, where the goal is usually to optimize the binary assignment indicator $a_{k,r} \in \{0, 1\}$ that indicates whether the kth subcarrier is assigned to the rth CU [79], [80]. Subcarrier allocation aims to optimize these assignment indicators to fulfill the requirements of both communication and sensing while balancing the intricate tradeoffs between them. For communication purposes, commonly used performance metrics include throughput [77], data rate [75], [78], [80], and mutual information [79], while for sensing, they include SINR [77] and mutual information [75], [76], [78], [79], [80].

Since the feasible domain is discrete and large, subcarrier allocation typically involves solving a mixed integer nonlinear programming problem, which is generally nondeterministic polynomial-time (NP)-hard [75], [77], [80]. In addition, subcarrier allocation is usually jointly designed with power allocation, which is also regarded as a portion of signal parameter optimization [75], [77], [78], [79], [80], and thus, the coupling between the metrics and polymorphic variables is complicated. Some methods such as a branch and bound algorithm [77], penalized sequential convex programming [77], greedy strategy [75], and Karush–Kuhn–Tuckers condition [76], [78], [79] have been adopted to seek the suboptima or even optima solutions for subcarrier allocation after appropriate relaxation, approximation, and problem partitioning.

C. Signal Parameter Optimization

Signal parameter optimization aims to optimize the transmitted complex symbols $\{c_{m,k}, s_{m,k}\} \forall m, k$ with limited transmit power to achieve the satisfying performance of both communication and sensing tasks [69], [70], [81], [82], [83], sometimes along with the joint optimization of precoders in MIMO [84], [85], [86], [87]. To evaluate the performance, commonly used communication metrics include data information rate [70], [81], [83], channel capacity [82], and multiuser interference [84], [85], [86]. Commonly used sensing metrics include CRB [69], [82], [87], mutual information [70], [81], [83], beam pattern [84], [85], [86], ambiguity function [84], and detection probability [85], [86]. The peak-to-average power ratio (PAPR), indicating the ratio between the peak power and the average power of the transmitted signal [71], is often considered as a constraint during the optimization [69], [70], [84], [85], [86]. The optimization problems are usually nonconvex due to the complicated performance metrics. Various techniques have been considered to obtain the optima or suboptima of these nonconvex problems, including problem partitioning [70], greedy algorithm [81], nondominated sorting genetic algorithm II [82], Broyden–Fletcher–Goldfarb–Shanno algorithm [84], and semidefinite relaxation [85], [86], [87].

D. Discussion on Some Key Issues and Challenges

Being compatible with the state-of-the-art 5G NR standards, sensing and communication signals may be simply scheduled over different subcarriers in an OFDMA system. Nonetheless, several implementation issues and challenges need particular attention, as we elaborate in the following.

1) Preference Discrepancies of Sensing and Communications Over Frequency Subspaces: The optimal power allocation strategy in communication systems is the celebrated water-filling criterion, which has been widely applied to various scenarios including point-to-point and multiuser MIMO systems, and of course OFDMA communications, in an effort to maximize the sum rate or throughput. The basic rationale of water filling is to determine the allocated power at each subcarrier based on the signaling quality of each subchannel, namely, the SNR, which is expressed as [19]

$$p_i = \left(\gamma - \mathrm{SNR}_i^{-1}\right)^+ \quad \forall i \tag{3}$$

where SNR_i is the receive SNR at the ith subcarrier, γ is the "water level" chosen to meet the total power constraint, and $(x)^+ = \max\{x, 0\}$. It can be readily observed that the higher the SNR_i is, the more the power is allocated to the ith channel. If the SNR is so small that SNR_i^{-1} is above the water level, zero power will be assigned.

With the above understanding, a natural question is: what is a general criterion for sensing subcarrier allocation? Does the optimality of water filling still hold for wireless sensing? The answer depends on what kind of sensing performance metric is adopted. For instance, let us consider a simplistic ranging problem, where the receiver observes a noisy signal

$$y(t) = \alpha s(t-\tau) + n(t). \tag{4}$$

Here, α is the complex channel gain, $s(t)$ is the transmitted ranging waveform, $n(t)$ is the additive white Gaussian noise with variance σ^2, and $\tau = d/c$ is the propagation delay, with d and c being the distance of the target and speed of light, respectively. Let $\hat{d}$ be an estimate of d based on $y(t)$. The CRB of estimating d is given in the form of [88]

$$\mathbb{E}\left\{\left(d-\hat{d}\right)^2\right\} \geq c^2\left(8\pi^2\beta^2\,\mathrm{SNR}\right)^{-1} \tag{5}$$

where $\beta = \int_{-\infty}^{\infty} f^2|S(f)|^2\, df / \int_{-\infty}^{\infty}|S(f)|^2\, df$ is the root-mean-squared (rms) bandwidth, with $S(f)$ being the Fourier transform of $s(t)$, and the SNR is defined as $\mathrm{SNR} = (1/\sigma^2)\int_{-\infty}^{\infty} s^2(t)dt$. To minimize the CRB, one needs to maximize the rms bandwidth β, which leads to completely different subcarrier allocation strategies compared to water filling. In fact, the spectrum shaping scheme that possesses the maximum rms bandwidth is the so-called two-tone signal, i.e., allocating the total power evenly to the first and last subcarriers, respectively.

Despite being CRB-optimal, using two-tone signals for ranging may rarely meet the practical performance requirement due to the integer ambiguity issue, which may only be resolved in a high-SNR regime. It is, therefore, desirable to conceive a more reliable power allocation strategy dedicated to sensing, potentially oriented from a more comprehensive sensing metric. To that aim, one may employ the Ziv–Zakai bound (ZZB), which is known as a global lower bound that works well for both low- and high-SNR regimes [89]. By receiving $y(t)$, the ZZB for estimating d reads [90]

$$\mathbb{E}\left\{\left(d-\hat{d}\right)^2\right\} \geq \zeta_{\mathrm{SNR}}\left[\widetilde{R}\right] := \int_0^{\epsilon_{\max}} xQ\left(\sqrt{2^{-1}\,\mathrm{SNR}\left(1-\widetilde{R}(x)\right)}\right)dx \tag{6}$$

where $\epsilon_{\max}$ is the maximum possible ranging error, namely, $\epsilon_{\max} = c(\tau_{\max}-\tau_{\min})/2$, $Q(\cdot)$ denotes the function of $Q(z) = \int_z^{\infty}(1/(2\pi)^{1/2})e^{-(1/2)x^2}dx$, and $\widetilde{R}(x)$ denotes the normalized autocorrelation function (ACF) defined as

$$\widetilde{R}(x) = R(x/c)/R(0) \tag{7}$$

with $R(\tau)$ being the ACF of $s(t)$ given by $R(\tau) = \int_{-\infty}^{\infty} s(t-\tau)s(t)dt$, while SNR is the signal-to-noise rate given by $\mathrm{SNR} = (1/N_0)\int_{-\infty}^{\infty} s^2(t)dt$.

It is noteworthy that the ZZB is related to the SNR in quite a nonlinear manner, whereas the CRB-optimal waveform is independent of the SNR value. This implies that the ZZB-optimal waveform should be SNR-adaptive. Indeed, minimizing (6) yields a ranging waveform whose spectrum shape varies at different SNR levels [91]. In particular, more power should be allocated to higher frequency subcarriers in the high-SNR regime and low-frequency counterparts in the low-SNR regime. The intuition behind this strategy is that the frequency spectrum shaping determines the geometry of the ambiguity function. When the

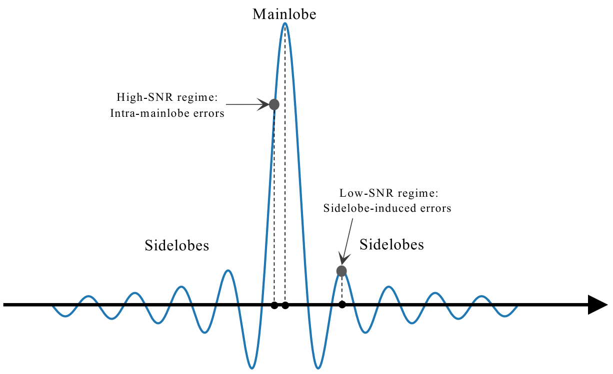


Fig. 9. ***Mainlobe and sidelobes in a signal ACF.***

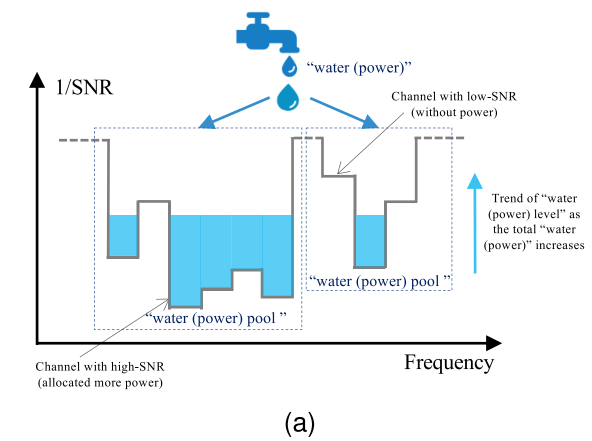
SNR is high, the estimation performance is mainly determined by the curvature of the mainlobe of the ambiguity function, as well as the likelihood function, which becomes sharper if the high frequencies dominate. Otherwise, when the SNR is low, the estimation performance depends on the sidelobe levels, where allocating more power to the low-frequency side will incorporate the nearby sidelobes into the mainlobe, thereby improving estimation accuracy. Illustrations of mainlobe and sidelobes in a signal ACF are depicted in Fig. 9.

The above discussion clearly indicates the preference discrepancies of sensing and communication for resource allocation over their respective frequency subspaces. While the communication-optimal water-filling strategy is only concerned with the SNR of each subchannel, regardless of its specific frequency, the sensing-optimal power allocation depends both on the SNR levels and the frequency indices of each subcarrier. This necessitates novel resource allocation and spectrum shaping methodologies when scheduling sensing and communication over different carrier frequencies. An illustration of optimal power allocation criteria for communication and sensing in the frequency domain is depicted in Fig. 10.

2) Multiband Sensing: Bandwidth plays a vital role in sensing, especially for range estimation. This may be evidently noted from the ranging CRB in (5), which is proportional to the rms bandwidth β. Moreover, the range resolution, another important ingredient in the wireless sensing performance evaluation framework, is known to be $c/2B$, where B is the nominal bandwidth. However, attaining sufficient bandwidth for sensing may not be an easy task in FDMA-ISAC systems. The 5G NR frequency range (FR) defined by the 3GPP includes FR 1 from 450 MHz to 6 GHz and FR 2 from 24.25 to 52.6 GHz. Accordingly, the channel bandwidth is up to 100 MHz for FR 1 and 400 MHz for FR 2, translating to range resolutions of 1.5 and 0.375 m, respectively, which are, in general, unable to support high-precision sensing applications, e.g., intelligent connected vehicles requiring a resolution of $\sim$0.1 m [1].

A straightforward solution to tackle the above challenge is to leverage multiple frequency bands for sensing through the carrier aggregation (CA) technique. As an example, if 16 subbands are aggregated, each of which occupies 100-MHz bandwidth, a range resolution of 0.094 m may be achieved. In practical FDMA-ISAC systems built upon commercial wireless standards and protocols; however, it is highly unlikely to have multiple contiguous subbands for sensing, due to the fact that the spectrum resources have to be primarily allocated to the communication functionality, which may be scheduled at random based on users' requirement and channel conditions. As a consequence, one has to rely on vacant subbands for sensing, which could be noncontiguous. Such a technique is known as multiband sensing in the area of wireless localization, which has been recently investigated for WLAN and LTE systems.

We show an exemplary system setting of multiband sensing in Fig. 11. It is not surprising to see that the frequency band aperture could be larger than the actual total



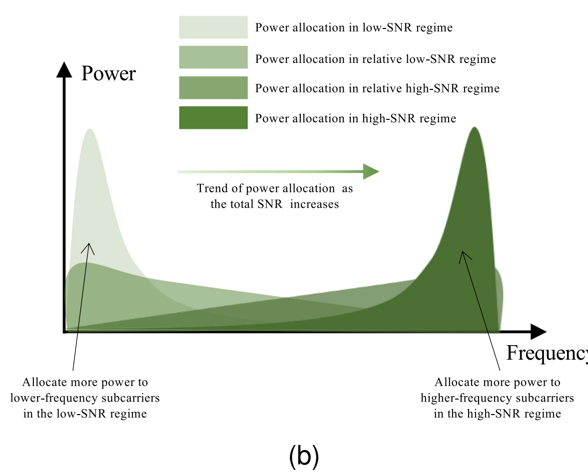


Fig. 10. ***Optimal power allocation criteria in the frequency domain. (a) Water-filling criterion for communication. (b) SNR-adaptive criterion for sensing.***

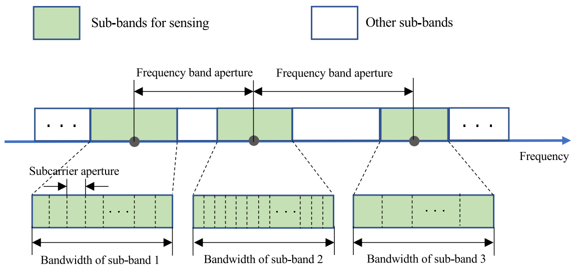


Fig. 11. *Exemplary system setting of multiband sensing.*

bandwidth occupied by the multiple subbands, leading to a greater rms bandwidth. Therefore, the achievable CRB may be improved compared to a contiguous bandwidth using the same amount of subbands. In [92], the ranging performance of multiband sensing has been examined through the maximum a priori (MAP) estimator. It turns out that the ranging root-mean-squared error (RMSE) tends to be nonmonotonic with an increasing gap between two subbands, i.e., the RMSE first decreases and then grows larger. Despite being counter-intuitive, such a behavior may be well-understood as the inherent ambiguity of the likelihood function for delay estimation. With the increase of the frequency band aperture, the mainlobe of the likelihood function tends to be sharper, which could facilitate range estimation if the estimated value falls into the mainlobe. In the meantime, the sidelobe level is also on the rise, causing ambiguity and multiple local optimum in solving the MAP problem. When the sidelobe effect dominates the sharpness of the mainlobe, the RMSE performance becomes worse. Again, since the CRB is merely a local bound reflecting the curvature of the mainlobe, it fails to characterize the ambiguity effect caused by the rising sidelobes. In such a case, the ZZB could be a more useful tool for analyzing the performance limits of multiband sensing in FDMA-ISAC systems. This is also consistent with our analysis of the abovementioned CRB-optimal two-tone signal, which may be viewed as an extreme case of the multiband sensing system.

IV. MA ISAC IN CODE DOMAIN

CDMA assigns a unique orthogonal/quasi-orthogonal code/sequence, also referred to as code channel, to each CU or sensing task for decoding the information-bearing signals and distinguishing dedicated sensing signals from communication [1], [32], [93], [94]. Three classical types of CDMA have been extensively investigated: 1) direct sequence CDMA; 2) frequency hopping CDMA; and 3) time hopping CDMA [32], [34], [95]. Among them, direct sequence CDMA is the most popular so that this section mainly focuses on this technique [96].

A. CDMA for Ommunication-Only Networks

For downlink communication, each CU is assigned a unique signature sequence for transmission, and the transmit signal of K CUs at time t can be expressed as [97], [98]

$$s(t) = \sum_{k=1}^{K} b_k(t)\, c_k(t) \tag{8}$$

where $b_k(t)$ and $c_k(t)$ represent the binary data signal of kth CU and its corresponding signature sequence, respectively. The encoding process spreads the spectrum of the information signal, which enables the share of the available bandwidth among CUs, and thus, CDMA is also known as spread spectrum MA [32], [94], [96], [99], [100], [101]. Assume that there exists no multipath interference, and the received signal at k-CU is [97]

$$r_k(t) = h_k s(t) + n(t) \tag{9}$$

where $r_k(t)$ and h_k represent the received signal of kth CU and its corresponding channel response, respectively.

To recover the information-bearing signal of the kth CU, a synchronously generated replica of signature/spreading sequence known by the receiver previously is correlated with the received signal [32], [98], and then, the output of the kth CU's correlator is given by [96], [102], [103]

$$\begin{aligned} y_k &= \frac{1}{T}\int_{t=0}^{T} r_k(t)\, c_k(t)\, dt \\ &= \underbrace{h_k b_k}_{\text{Recovered Data}} + \underbrace{\sum_{\hat{k}=1,\hat{k}\neq k}^{K} \rho_{k,\hat{k}} h_k b_{\hat{k}}}_{\text{Multiple Access Interference}} + \underbrace{z_k}_{\text{Noise}}. \end{aligned} \tag{10}$$

Here, T represents the signaling interval; $\rho_{k,\hat{k}} = (1/T) \int_{t=0}^{T} c_k(t)c_{\hat{k}}(t)dt$ denotes the cross correlation between codes $c_k(t)$ and $c_{\hat{k}}(t)$; and $z_k = (1/T)\int_{t=0}^{T} n(t)c_k(t)dt$ denotes the noise term. A block diagram of direct sequence CDMA is depicted in Fig. 12.

Mitigation of MA interference highly depends on the code waveform design [96]. Ideally, the codes should be orthogonal, i.e., $\rho_{k,\hat{k}} = 0, k \neq \hat{k} \forall k, \hat{k}$ and $y_k = h_k b_k + z_k$ [96], [104]. Whereas, since there exists a certain degree of asynchronism that causes delays in most channels, it is impossible to maintain perfect orthogonality of codes in practice [96], [105]. Therefore, designing nearly orthogonal spreading codes/sequences with sufficiently low cross-correlation is key to differentiating CUs in CDMA, in which communication scientists and mathematicians have widely studied in the past several decades [32], [95], [96], [104]. The commonly used codes/sequences in CDMA include Gold codes, Kasami codes, m-sequences, Walsh–Hadamard sequences, and orthogonal variable spreading factor codes [95].

Except for the code waveform design, there are other fundamental elements in direct sequence CDMA to help mitigate MA interference and multipath

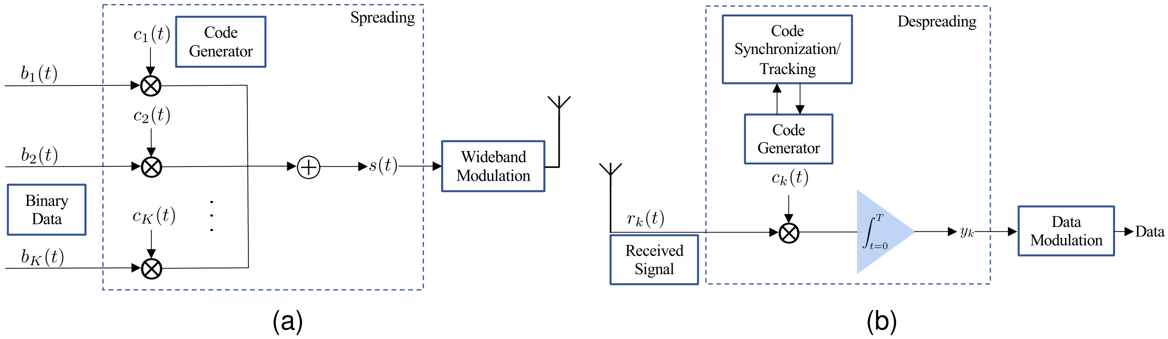


Fig. 12. *Block diagram of direct sequence CDMA. (a) Transmitter. (b) Receiver.*

interference [32], [96], [100], including RAKE receiver [106], power control [107], soft handover [108], and multiuser detection [96], [102], [103], [105], [109]. Multicarrier CDMA based on the combination of code division and OFDM has been widely studied, in which the chips of the spread data signal are transmitted in parallel over different subcarriers, rather than the serial transmission in direct sequence CDMA [110], [111]. In other words, the spreading operation is realized in the frequency domain in multicarrier CDMA, in contrast to the time domain in direct sequence CDMA [112]. At the receiver, commonly used detection strategies primarily include maximum ratio combining, minimum mean square error combining, equal gain combining, maximum likelihood multiuser detection, orthogonality restoring combining, and controlled equalization [111].

B. CDMA in ISAC

ISAC CDMA utilizes different orthogonal/quasi-orthogonal codes for spreading the spectrum of both communication and dedicated sensing signals to avoid mutual interference [1], [94], [113]. Similar to OFDMA, since different orthogonal codes can only be allocated to communication and sensing in the downlink ISAC networks, we only discuss CDMA in downlink ISAC. A typical integrated transmit signal at time t can be expressed as [93], [94], [113], [114]

$$s(t) = b_{\mathrm{c}}(t)\, c_{\mathrm{c}}(t) + b_{\mathrm{s}}(t)\, c_{\mathrm{s}}(t) \tag{11}$$

where $b_{\mathrm{c}}(t)$ and $b_{\mathrm{s}}(t)$ represent the communication symbol and dedicated sensing waveform, respectively, and $c_{\mathrm{c}}(t)$ and $c_{\mathrm{s}}(t)$ are their corresponding spreading codes. At the receiver, the communication information can be extracted from the mixed received signal by utilizing the orthogonality between communication and sensing signals [94]. In addition, the cancellation of the interuser interference in ISAC CDMA is the same as that in CDMA for communication-only networks [45], [115]. Furthermore, some well-performed codes/sequences are studied and exploited in ISAC CDMA, including m-sequence [115], Walsh–Hadamard code [93], [114], Zadoff–Chu sequence [116], Oppermann sequence [117], and Doppler-resilient sequence [118].

C. Discussion on Some Key Issues and Challenges

CDMA for ISAC treats the radar application as one of the users in traditional CDMA communications. In comparison with the OFDMA and TDMA-based ISAC systems, CDMA-based ISAC offers greater flexibility in spectrum and time utilization. This is because CDMA enables radar and communication to share all the spectrum and time resources. These characteristics allow CDMA-based approaches to overcome the range ambiguity issue caused by OFDMA and the velocity ambiguity problem caused by TDMA. Moreover, the CDMA-based ISAC approaches enable to design the code sequences with specific correlation characteristics based on the performance requirements of radar and communication. For instance, spreading sequences are designed to reduce the sidelobes in specific range and Doppler regions based on the requirements of the radar in [118].

Although CDMA ISAC approaches offer the aforementioned advantages, they also face some new challenges. In practical implementation, CDMA cannot guarantee ideal orthogonality among the transmitted waveforms of different users. This is because the cross-correlation of spreading codes is often not exactly zero. Additionally, even for the spreading codes that are mutually orthogonal, such as the Walsh–Hadamard code, the orthogonality between different codes is compromised when synchronization errors exist among different users. To minimize the interference among multiple users, traditional CDMA communications employ multiuser synchronization mechanisms to ensure that the reception signals from different users are received nearly simultaneously at the receiver. In addition, power control techniques are utilized to reduce interference by ensuring that the received powers of different users are approximately equal. However, as radar needs to detect the targets in a certain range region and the return time of target echoes is not known, it is not possible to effectively reduce the interference among multiple users through time coordination and power control. Furthermore, CDMA

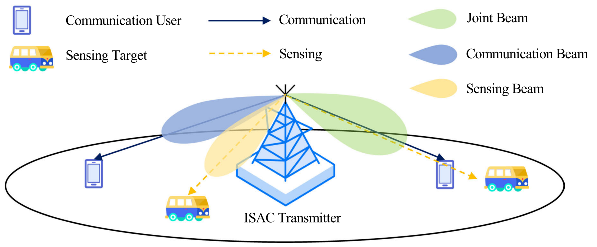


Fig. 13. *Illustration of SDMA in ISAC.*

systems are interference-limited, which means that the interference between the CUs and radar is severe when the number of CUs is large. Therefore, for CDMA-based ISAC systems, performance tradeoff between radar and communications should be considered.

V. MA ISAC IN SPATIAL DOMAIN

SDMA partitions different spatial channels to exclusively transmit the communication/sensing signals with designed power while avoiding interuser interference and sensing-over-communication interference at the communication receiver. As depicted in Fig. 13, SDMA is realized based on transmitting multiple beams, i.e., spatial channels, toward CUs and/or STs in the spatial domain. Like SDMA for communication-only networks, different beams for CUs in ISAC are also carefully designed to avoid interference between beams. In ISAC, for closely located CUs and STs, joint beam is realized to share transmit energy between communication and probing functionalities. SDMA is only applicable to downlink ISAC networks, benefiting from the distinct locations of users and targets. Therefore, we discuss the SDMA in downlink ISAC in this section.

A. Typical Approaches of SDMA

These directional beams are generated by transmitting precoded signals with an antenna array. In ISAC, there are two main categories of signaling strategies. Both strategies formulate the precoding approaches as any optimization problem and seek efficient solutions.

1) Signaling Strategies: Precoding strategies include: 1) precoding the communication-only symbols [16], [119], [120], [121], [122], [123], [124], [125] and 2) precoding both communication symbols and dedicated radar waveform [17], [126], [127], [128]. Illustrations of these two precoding strategies are depicted in Fig. 14.

To demonstrate this, consider an antenna array with M elements and K CUs in the scenario. Let $\mathbf{c}[n] = [c_1, c_2, \ldots, c_K]^{\mathrm{T}} \in \mathbb{C}^K$ be K communication symbols intended to the K CUs, respectively at the nth time slot. The former precoding strategy uses communication-only signals. Particularly, the transmit signal of the antenna array at nth time slot is represented by

$$\mathbf{x}[n] = \mathbf{W}_{\mathrm{C}}\mathbf{c}[n] \in \mathbb{C}^M \quad (12)$$

where $\mathbf{W}_{\mathrm{C}} \in \mathbb{C}^{M\times K}$ represents the communication precoder to be designed. In the latter scheme, the transmit signal is

$$\mathbf{x}[n] = \mathbf{W}_{\mathrm{C}}\mathbf{c}[n] + \mathbf{W}_{\mathrm{S}}\mathbf{s}[n] \quad (13)$$

where $\mathbf{s}[n] \in \mathbb{C}^M$ represents the dedicated sensing waveforms and $\mathbf{W}_{\mathrm{S}} \in \mathbb{C}^{M\times M}$ is the corresponding precoder to design.

We compare these two strategies below. By setting $\mathbf{s}[n] = 0$, we reduce the scheme with dedicated radar waveform into the former scheme that precoders communication-only symbols. Therefore, the latter is always expected to have better performance by jointly optimizing $\mathbf{W}_{\mathrm{C}}$ and $\mathbf{W}_{\mathrm{S}}$. Simulation results verify that jointly optimizing $\mathbf{W}_{\mathrm{C}}$ and $\mathbf{W}_{\mathrm{S}}$ can achieve better performance than only optimizing $\mathbf{W}_{\mathrm{C}}$, depicted in Fig. 15. It is apparent from practical experience that the benefit comes from the increase of degrees of freedom (DoF): Under the former communication-only strategy, the available DoF of MIMO radar equals K, the number of CUs, while the latter which incorporates dedicated radar waveforms extends the DoF to its maximum, i.e., the number of transmit antennas, M. The DoF affects the radar beam pattern and especially the ability to form multiple main beams for different radar targets.

2) Problem Formulation: The precoding matrices $\{\mathbf{W}_{\mathrm{C}}, \mathbf{W}_{\mathrm{S}}\}$ are optimized to satisfy the requirements of both communication and sensing tasks. There are generally three kinds of optimization models, with $O_{\mathrm{C}}(\mathbf{W}_{\mathrm{C}}, \mathbf{W}_{\mathrm{S}})$ and $O_{\mathrm{S}}(\mathbf{W}_{\mathrm{C}}, \mathbf{W}_{\mathrm{S}})$ denoting the objective

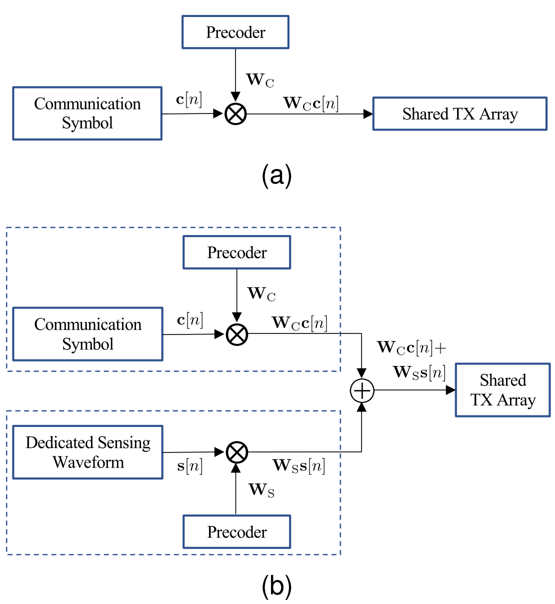


Fig. 14. *Precoding strategies. (a) Precoding the communication-only symbols. (b) Precoding both communication symbols and dedicated radar waveform.*

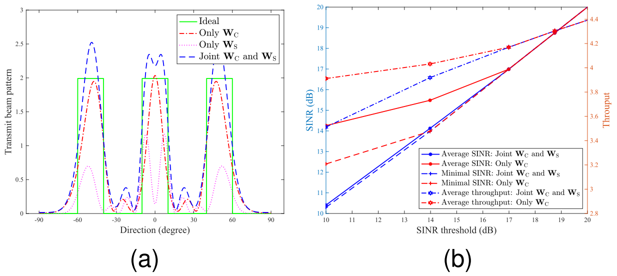


Fig. 15. ***Comparison performance of joint W_C and W_S with only W_C. Such an optimization problem aims to find the optimal precoders to minimize the mismatch between achieved and desired waveforms for sensing under the constraints of required SINR for communication [17]. (a) Transmit beam pattern for sensing performance. (b) SINR and throughput for communication performance.***

functions which measure the communication and sensing performance, respectively.

1) Communication-optimized or sensing-constrained tasks: Maximizing O_C preferentially under the minimum requirements for O_S. For an extreme case, Liu et al. [128] maximized the communication performance while fixing the radar performance.
2) Sensing-optimized or communication-constrained tasks: Maximizing O_S with lower bounded O_C; see [17] as an example.
3) Balanced tasks: Jointly maximizing the weighted sum of O_C and O_S where the weight is determined by some practical demand, such as [119].

The design of the objectives $\{O_C, O_S\}$ essentially affects the ISAC system performance. For the communication functionality, the objective should quantify the quality of service for CU. Particularly in an ISAC system with MA, interuser interference and sensing-over-communication interference at the CUs are key issues in service quality. Therefore, commonly used metrics include multiuser interference [119], [120], [121], sum rate [122], and SINR [16], [17], [124], [125], [126], [127], [128] at CUs. It is worth noting that applying some nonlinear precoding techniques, such as dirty paper coding, can also reduce the interference between CUs [129]. The basic idea is to encode the communication signals to adapt to the interference and is shown to achieve the capacity region of an MIMO Gaussian broadcast channel [130].

Regarding the sensing task, one aims to improve the detection and estimation of the target, which can be assessed using a variety of quantitative metrics, such as the mismatch between achieved and desired waveform [119], [123], the signal-clutter-noise ratio [121], [122], the CRB on the estimation accuracy of the target parameters [16], and beam pattern shape [17], [120], [124], [125], [126], [127].

3) Solutions to These Optimization Problems: Due to the complexity of the objective functions, the precoding optimization problems in ISAC are typically nonconvex and thus are difficult to solve. However, by using semidefinite relaxation, some nonconvex problems can be recast to convex ones. Such relaxation is often tight as the solution to the solvable relaxed problem is proved to be the global optimizer of the original nonconvex problem [17].

Zero-forcing is a suboptimal approach, by restricting the interuser interference and radar interference by zero. Zero-forcing methods usually further reduce the computational burden and are sometimes to approach optimal performance in setups requiring high SINR between multiuser communications.

Table 2 summarizes research contributions on SDMA in downlink ISAC. Illustrations of sensing rate versus SNR for sensing-centric MIMO ISAC, communication-centric MIMO ISAC, and frequency-division ISAC are depicted in Fig. 16 [131]. It is observed that MIMO ISAC achieves better performance than frequency-division ISAC, especially in high-SNR regime. It is mainly caused by additional DoF provided by MIMO ISAC. Furthermore, Ouyang et al. [131] verify that the MIMO ISAC achieves a broader rate region, i.e., sensing rate versus communication rate, than frequency-division ISAC.

B. Discussion on Some Key Issues and Challenges

With the advancement of multiantenna technology, MIMO provides additional spatial DoF for user access, and SDMA, by focusing beams toward users and targets, has become one of the key MA techniques for enhancing spectral efficiency. There are new challenges and opportunities when SDMA is applied in ISAC networks.

1) Mutual Benefits Between Communication and Sensing: SDMA for ISAC generalizes the counterpart for a communication-only system. The conventional precoding technique applied in the communication-only system also works for an ISAC system by regarding the target to probe as a CU, which is, however, a suboptimal approach. An advantage of the ISAC precoding scheme over the communication-only SDMA precoding scheme lies in the fact that the transmit signal designed for CU

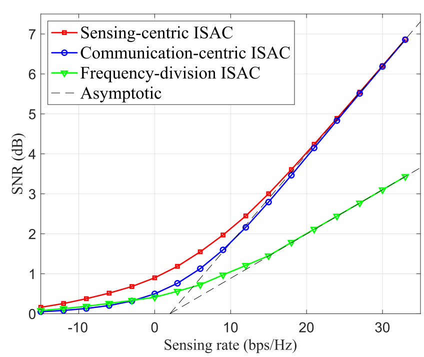


Fig. 16. ***Sensing rate versus SNR for sensing-centric MIMO ISAC, communication-centric MIMO ISAC, and frequency-division ISAC. The sensing rate is defined as the sensing mutual information per unit time, and sensing mutual information characterizes the sensing theory limit on how much environmental data can be observed.***

Table 2 Contributions on SDMA in Downlink ISAC

Ref.	Signalling strategies	Optimization model	Communication metrics	Sensing metrics	Method
[119]	Strategy 1)	Model 3)	Multi-user interference	Mismatch	Semidefinite relaxation
[120]	Strategy 1)	Model 1)	Multi-user interference	Beam pattern shape	Choesky decomposition
[121]	Strategy 1)	Model 2)	Multi-user interference	Signal-clutter-noise ratio	Relaxation
[122]	Strategy 1)	Model 1) & 2)	Sum rate	Signal-clutter-noise ratio	Successive convex approximation
[123]	Strategy 1)	Model 3)	—	Mismatch	Relaxation
[16]	Strategy 1)	Model 2)	SINR	CRB	Semi-definite relaxation
[124]	Strategy 1)	Model 2)	SINR	Beam pattern shape	Semi-definite relaxation
[125]	Strategy 1)	Model 2)	SINR	Beam pattern shape	Semi-definite relaxation
[126]	Strategy 2)	Model 1) & 2)	SINR	Beam pattern shape	Zero-forcing
[127]	Strategy 2)	Model 2)	SINR	Beam pattern shape	Semi-definite relaxation
[17]	Strategy 2)	Model 2)	SINR	Beam pattern shape	Zero-forcing
[128]	Strategy 2)	Model 1)	SINR	—	Lagrange & Duality

can also be used for probing, other than being regarded as communication-over-sensing interference. This can be illustrated by a simple but special case where the ST is located the same as a CU: the transmit power allocated to this CU can be simultaneously shared by the sensing task without further cost. For more general cases where the channels of the ST and CU are neither the same nor orthogonal, part of the communication signal can be exploited for target probing, the ratio of which depends on the correlation between the channels [132].

2) Tradeoff Between Communication and Sensing: Despite the energy sharing between the communicating and sensing functionalities in such a SDMA ISAC system, there is an inherent tradeoff between these two functions. The performance tradeoff has not only been verified by numerical experiments in many precoding schemes [16], [17], [119], [120], [121], [122], [123], [124], [125], [126], [127], [128], but also addressed by theoretical analyses, which derive the communication capacity under radar performance constraint [126], [129]. Results show that tighter radar constraints reduce communication capacity. Particularly, in a toy example with a single CU and ST, one obtains analytical solutions of the optimal transmit signal, indicating that the signal design is actually power allocation between the radar target and CU. Whether or how much of the communication energy simultaneously benefits the probing function depends on the correlation between the channels of ST and CU [132].

3) Imperfect Channel State Information: In practical applications, the channel is usually not perfectly known at the transmitter, with a certain degree of channel estimation error. For future work, the precoder design with a partially known channel should be considered, where the prior knowledge about the difference between the real channel and the estimated one can be fully excavated for guidance. Channel with frequency selection should also be studied.

4) Reconfigurable Holographic Surface for Overcoming Implementation Difficulties of Subwavelength Antennas: MIMO systems enhance ISAC performance by steering multiple beams, but the antenna spacing is limited due to the manufacturing difficulties of the subwavelength size antenna and mutual coupling effect [133]. As a promising solution, metamaterial antennas, such as the reconfigurable holographic surface (RHS), overcome the half-wavelength antenna spacing limitation, enabling better beam-steering and integrated design for reduced system complexity and cost [134], [135]. RHS enables ultramassive MIMO by developing a holographic beamforming optimization based on the hardware design and full-wave analyses [136].

Holographic beamforming with such metamaterials has been widely studied in various scenarios, including radar systems [137], [138], wireless communication networks [139], [140], satellite communications [141], and ISAC networks [133], [142]. It provides a potential paradigm for communication and sensing given different hardware implementations. In [133], holographic beamforming is executed by a base station equipped with an RHS, where the base station implements digital beamforming, and the RHS carries out analog beamforming by adjusting the radiated amplitude of each metamaterial unit. The optimal digital and analog precoders are finely tuned by maximizing the beam pattern gain toward STs under the constraints of communication SINR requirements. Main challenges and future research directions for RHS-based ISAC mainly focus on the fundamental designs of the RHS, including the RHS size design and the scaling to higher frequencies. Furthermore, a novel boundary analysis needs to be developed [142].

5) Near-Field ISAC With Higher DoF: Benefiting from extremely large-scale antenna arrays, tremendously high frequencies, and innovative antenna types, a new paradigm is emerging that shifts the focus of electromagnetic characteristics from far-field to near-field communication, offering novel propagation properties [143], [144], [145], [146]. Near-field communication exhibits spherical wavefronts, which enables a new function, referred to as beam focusing, which concentrates the beam energy in a specific location/region [147]. Specifically, far-field beamforming can be compared to a "flashlight," which allows for beam steering, whereas near-field beamforming resembles a "spotlight," enabling precise beam focusing [148]. It indicates that except for the angle, the distance in the spatial domain can also be regarded as a new dimension of resources to support more access [149], [150]. Xie et al. [151] verify that near-field MIMO systems achieve higher effective DoF than free-space far-field ones, and the capability of discrete MIMO converges to that of continuous aperture MIMO. However, the beam split effect introduced by analog beamforming and extremely large-scale antenna arrays will deteriorate the performance in wideband systems [143], and the true time delayers are exploited to mitigate such effects [152].

Near-field communication holds potential in numerous application scenarios, with near-field ISAC standing out as a typical example [147], [153], [154], [155], [156], [157]. On the one hand, the effect of beam focusing and the incorporation of distance dimension enhance the SINR of both transmission and echo signals, which contributed to dual-functional performance [147], [153]. On the other hand, near-field sensing achieves a more accurate positioning function with the additional knowledge of distance that helps improve spatial resolution [154], [155], [156]. Li et al. [154] verify that one single base station with limited bandwidths can locate a target in both angle and distance domains. In addition, Wang et al. [155] verify that a closer distance results in more accurate sensing. Furthermore, in near-field ISAC beamforming, the hybrid-analog-and-digital precoder scheme usually outperforms the fully digital one where CRB related to both angle and distance is minimized while ensuring the minimum communication rate [154], [155].

VI. MA ISAC IN DELAY–DOPPLER DOMAIN

OTFS is an uprising 2-D modulation technique where the signal processing is conducted in the delay–Doppler domain rather than the time–frequency domain of classic OFDM modulation. This is particularly adapted to high-mobility channels [33], [158], [159]. It is worth noting that OTFS is an extension of OFDM, which can be compatible with OFDM by adding a precoding module [71].

A. OTFS Waveform

At the ISAC transmitter, the information symbols $x[l,k]$, $l \in \{1,\ldots,M\}, k \in \{1,\ldots,N\}$ in the delay–Doppler domain are first mapped into symbols $X[m,n], m \in \{1,\ldots,M\}, n \in \{1,\ldots,N\}$ in the time–frequency domain through a combination of the inverse symplectic Fourier transform and windowing, also called OTFS transform [159], [160], [161], given by

$$X[m,n] = \frac{1}{\sqrt{MN}} \sum_{k=1}^{N-1} \sum_{l=1}^{M-1} x[l,k]\, e^{j2\pi\left(\frac{nk}{N}-\frac{ml}{M}\right)}. \quad (14)$$

Then, the modulated signal $X[n,m]$ is converted to a time-domain signal $s(t)$ based on the Heisenberg transform for transmission [159], [160], [161], represented as

$$s(t) = \sum_{n=1}^{N-1} \sum_{m=1}^{M-1} X[m,n]\, g_{\text{tx}}(t-nT)\, e^{j2\pi m \Delta f (t-nT)} \quad (15)$$

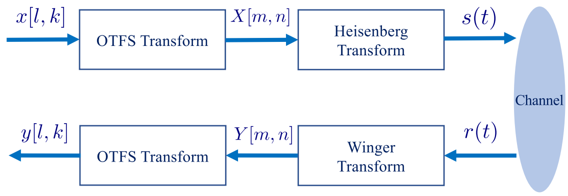


Fig. 17. *Transmitter and receiver diagrams of OTFS transmission.*

where $g_{\text{tx}}(t)$ represents the pulse waveform, and Δf, T are the grid intervals in the time–frequency domain. At the receiver, the reverse operations are executed where the received time signal $r(t)$ is first mapped to the time–frequency domain based on the Wigner transform, i.e., the inverse of the Heisenberg transform, and then to the delay–Doppler domain [160], [161]. The transmitter and receiver diagrams of OTFS transmission are depicted in Fig. 17.

B. DDRB Allocation

In downlink ISAC, communication signals in existing OTFS are mainly exploited for sensing without dedicated sensing signals [158], [162], [163], [164], [165], [166], where the sensing-over-communication interference is neglected. Hence, OTFS MA techniques for ISAC in existing works are basically identical to those for communication-only networks among CUs to eliminate interuser interference [166]. The OTFS MA designs the information symbol matrix $\mathbf{x} = [x[l,k]] \in \mathbb{C}^{M\times N}$ to allocate different DDRBs $x[l,k]$ to different CUs where the orthogonality in delay–Doppler domain guarantees the user differentiation in downlink ISAC, called DDRB allocation, which is usually optimized with power $|x[l,k]|^2$ [166]. Wei et al. [33] regard that carefully designed user scheduling and guard spaces in the delay–Doppler domain should be employed, which has the potential to avoid interuser interference. Cui et al. [167] use the pilot signals for radar sensing, in which the pilot signals and communication symbols occupy different DDRBs.

The works on DDRB allocation are mainly concentrated in uplink but less in downlink, and mostly focus on communication-only networks but less on ISAC. The DDRB allocation for uplink communication-only networks can be categorized into three schemes [168]: orthogonality in delay domain [168], [169], orthogonality in Doppler domain [168], [169], and orthogonality both in delay–Doppler domain and in time–frequency domain [168], [170], [171]. The DDRB allocations are depicted in Fig. 18. In DDRB for uplink communication-only networks, the performance metrics involve bit error rate [168], [171], achievable rate [169], spectral efficiency [170], and PAPR [171].

C. Discussion on Some Key Issues and Challenges

OTFS is an uprising modulation technique that designs modulation symbols under the new concept of delay–Doppler domain rather than the conventional time,

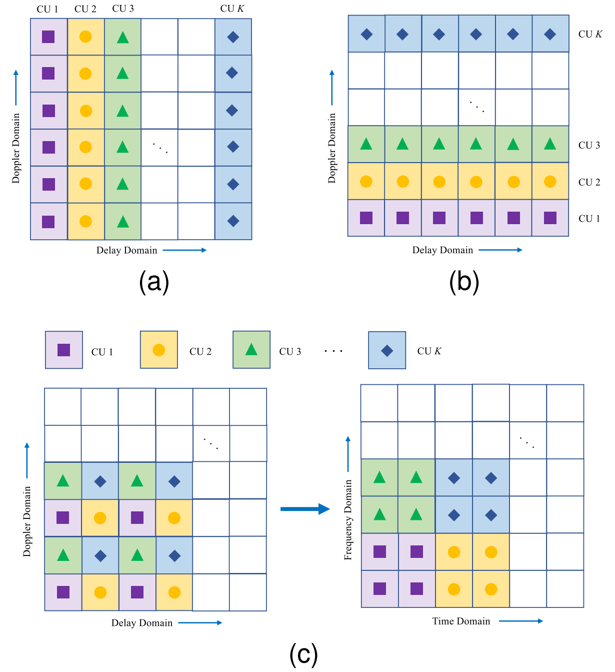


Fig. 18. ***DDRB allocation in three schemes. (a) Orthogonality in delay domain. (b) Orthogonality in Doppler domain. (c) Orthogonality both in delay–Doppler domain and in time–frequency domain.***

frequency, code, or spatial domains. This approach allows OTFS to counteract the Doppler effects in high-mobility environments more effectively, as the channel characteristics are relatively stable in the delay–Doppler domain, making it easier to recover the signal. Hence, OTFS has strong delay-resilience and Doppler-resilience [33]. MA referring to OTFS, called OTFS MA for simplicity, utilizes the orthogonal resource blocks in the delay–Doppler domain to cancel interference in uplink communication-only networks. Similar to the relationship between OFDM and OFDMA, the OTFS MA is basically identical to an OTFS system extended to multiuser scenarios. Existing works on OTFS MA in ISAC are still in a very fundamental stage where the cancellation of dedicated sensing signal is rarely considered. Inspired by the three DDRB schemes used in uplink communication-only networks, new OTFS MA techniques can be explored to occupy the orthogonal resource blocks in the delay domain, the Doppler domain, or both in the delay–Doppler domain for dedicated sensing signals to alleviate the sensing-to-communication interference in ISAC.

In addition, OTFS waveform design in ISAC is a promising research topic, and some initial progress has been made. Li et al. [159] conclude that OTFS modulation and demodulation can be characterized by the inverse discrete Zak transform and discrete Zak transform that guides the derivations on the OTFS system model. Besides, the authors show that the calculation of the range-Doppler matrix for radar sensing is essentially the application of the discrete Zak transform, or more precisely, OTFS demodulation. However, the corresponding research is still in its infancy, which leads to some interesting future research directions as follows.

1) Theoretical connections between ISAC and OTFS waveform: These connections can further guide better OTFS waveform toward ISAC. For instance, the Zak transform has a direct relationship with the ambiguity function [172], an essential performance metric for sensing. The design of OTFS waveform with improved ambiguity function can be explored.
2) Fundamental performance limits: Li et al. [159] conclude that OTFS waveforms outperform the OFDM waveforms considering several performance metrics, including achievable rate, error rate, and range-Doppler matrix. As the next step, the achievable region of OTFS in ISAC compared with other waveforms should be explored.
3) Sensing-assisted communication applications: The delay–Doppler domain channel can be easily obtained from radar sensing [159], which may also guide the transmitted signal design for OTFS. For example, in [173], a roadside unit formulates transmit precoders to combat the predicted channel impairments based on the estimated parameters calculated by radar echoes before the transmission of OTFS signals.

VII. NOMA FOR ISAC

NOMA allows multiple CUs and STs to share the same orthogonal resource block to concurrently operate transmission and detection in ISAC, e.g., the same time slot, the same subcarrier, the same spreading code, or the same spatial channel [9], [174]. Existing NOMA schemes in communication-only networks primarily include power-domain NOMA and code-domain NOMA [29], [42].

A. Power-Domain NOMA

Power-domain NOMA utilizes the SC at the transmitter to superimpose communication and sensing signals with different power levels and then adopts SIC techniques to cancel interference and distinguish signals at the receiver [10], [175], [176].

1) SC and SIC: SC: At nth time slot, the ISAC base station exploits SC and then broadcasts the following signal:

$$\mathbf{x}[n] = \sum_{k=1}^{K} \sqrt{p_k} c_k [n] + \sum_{m=1}^{M} \sqrt{p_m} s_m [n] \tag{16}$$

where $c_k[n]$ and $s_m[n]$ represent the kth communication symbol and mth sensing waveform, respectively, and p_k, p_m represent their corresponding transmit power.

SIC: After receiving the superimposed signals, each user exploits SIC to cancel the interference and recover its desired signal. In ISAC, the SIC decodes the sensing signals first and cancels part or all of them from the received signal for CUs by regarding it as virtual CUs that convey

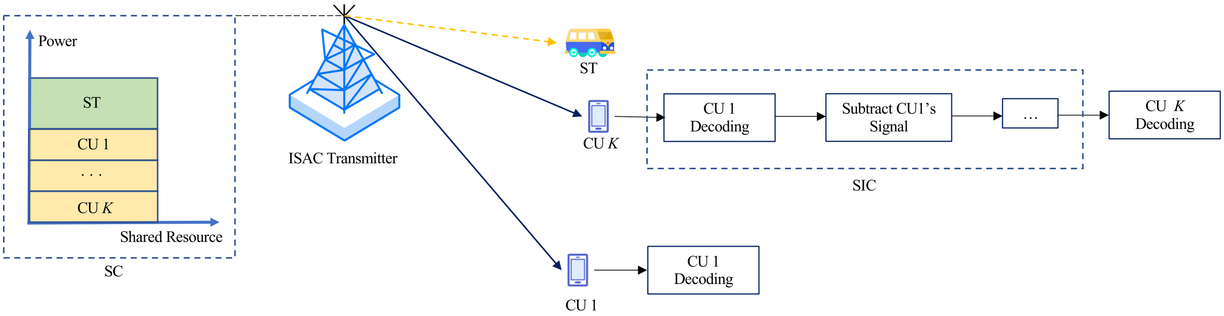


Fig. 19. *Illustration of SC and SIC in power-domain NOMA.*

information bits [21]. Then, the remaining signal is a communication-only signal that can be further decoded according to the SIC scheme in the communication-only networks, where the signals with higher power are successively decoded and canceled until the desired signal is decoded. Illustrations of SC and SIC are depicted in Fig. 19. Usually, an NOMA protocol allocates higher power to weaker users with poor channel conditions, which ensures the optimal decoding order where the weaker users can be decoded preferentially [9], [10], [175], [177]. For example, let h_k denote the channel gain of the kth CU and suppose that $h_1 \leq h_2 \leq \cdots \leq h_K$ [175]. Then, the NOMA protocol ensures that $p_1 \geq p_2 \geq \cdots \geq p_K$ and $p_1|h_1|^2 \geq p_2|h_2|^2 \geq \cdots \geq p_K|h_K|^2$. Therefore, the kth CU can decode the signals of the lth CUs for $l < k$ and remove them from the received signal, which enables the cancellation of partial interuser interference. The achievable rate of kth CU is then given by [178], [179]

$$R_k = \log\left(1 + \frac{p_k|h_k|^2}{\sum_{\hat{k}=k+1}^{K} p_{\hat{k}}|h_k|^2 + \sigma^2}\right). \quad (17)$$

Note that if sensing interference is not fully canceled, it needs to be taken into consideration by the interference term in the denominator.

2) Power Allocation in Downlink ISAC: The goal of power domain NOMA is to search the optimal transmit power $p_k, p_m \forall k \forall m$ to satisfy requirements of both communication and sensing tasks with specific decoding sequences, also called power allocation [177], [178]. For communication functionality, commonly used performance metrics mainly include achievable rate [22], [180], [181], [182], [183], [184], [185], [186], [187], SINR [186], [187], [188], and throughput [23], [189]. For sensing functionality, performance metrics include beam pattern shape [22], [23], [180], [181], [182], [183], [184], [189], mutual information [185], signal-clutter-noise ratio [185], and echo SNR [186], [187]. Power allocation is usually jointly designed with the complex beamforming matrix where the amplitude exactly represents the corresponding transmit power [22], [23], [180], [181], [182], [183], [184], [185], [186], [187], [188], [189]. Since the objectives and the constraints are complex, power allocation problems in ISAC are basically nonconvex, which is difficult to solve. Various techniques have been suggested to convert the nonconvex forms into convex ones, e.g., semidefinite relaxation [22], [23], [180], [181], [182], [188], successive convex approximation [181], [182], [185], [186], [187], penalty function method [183], [184], [185], fractional programming [188], and the first-order Taylor expansion [189].

Table 3 summarizes some of the existing contributions on power-domain NOMA in downlink ISAC where "Sensing signal" represents whether the transmit signals comprise dedicated sensing signal; "MA model": "Mode 1" represents the MA among CUs, "Mode 2" represents the MA between communication and sensing, and "Optimization model" is in accordance with that in SDMA. Optimization convergence and achieved beam pattern for NOMA ISAC are depicted in Fig. 20, which indicates that the power-domain NOMA is valid in ISAC networks [22]. In addition, Wang et al. [22] illustrate the tradeoffs between communication throughput and effective sensing power by NOMA and OMA, and the numerical results verify that the power domain NOMA outperforms the conventional OMA in the underloaded regime experiencing highly correlated channels and in the overloaded regime for ISAC networks.

3) SIC and Power Allocation in Uplink ISAC: Different from the decoding order in downlink ISAC, the communication signal is decoded first when the signal is superimposed in the same orthogonal resource block in uplink ISAC. In downlink ISAC, the dedicated sensing signal can be regarded as virtual users that convey information, and thus, power-domain NOMA can decode the sensing signals first in SIC. However, in uplink ISAC, since only the communication signals contain information bits, they have to be decoded first in the presence of the sensing interference [21]. Such a decoding order results in the communication performance always being constrained by the sensing interference. A semi-NOMA-based uplink ISAC scheme is designed where parts of the communication signals are allowed to occupy exclusive orthogonal resources that can be recovered without sensing interference to ensure the communication requirements [24],

Table 3 Important Contributions on Power-Domain NOMA in Downlink ISAC

Ref.	Sensing signal	MA model	Optimization model	Communication metrics	Sensing metrics	Method
[22]	✗	Mode 1	Model 3)	Achievable rate	Beam pattern shape	Semi-definite relaxation
[180]	✓	Mode 1 & 2	Model 2)	Achievable rate	Beam pattern shape	Semi-definite relaxation
[23]	✓	Mode 1 & 2	Model 3)	SINR	Beam pattern shape	Semi-definite relaxation
[183]	✗	Mode 1	Model 1)	Achievable rate	Beam pattern shape	Penalty-based Iteration
[184]	✗	Mode 1	Model 1)	Achievable rate	Beam pattern shape	Penalty-based Iteration
[181]	✗	Mode 1	Model 2)	Achievable rate	Beam pattern shape	Semi-definite relaxation
[182]	✗	Mode 1	Model 2)	Achievable rate	Beam pattern shape	Semi-definite relaxation
[187]	✓	Mode 1 & 2	Other	Achievable rate & SINR	Echo SNR	Semi-definite relaxation

[190], [191]. This scheme allows at least a portion of the communication signal to be recovered without sensing interference, but the proportion of additional orthogonal resources used needs to be determined based on the communication requirements. Zhang et al. [24], [190] verify that the channel capacity of semi-NOMA-based uplink ISAC scheme outperforms the conventional one, which enhances communication performance. In addition, since SDMA is only applicable to downlink ISAC, power allocation is typically jointly optimized with beamforming in downlink ISAC networks. However, in uplink ISAC networks, power allocation needs to be conducted separately or can be jointly optimized with subcarrier allocation [192].

B. Code-Domain NOMA

1) Code-Domain NOMA for Communication-Only Networks: Inspired by CDMA, code-domain NOMA also utilizes user-specific spreading sequences to distinguish CUs, while the sequences are either sparse or nonorthogonal with low correlation coefficient rather than dense and orthogonal in CDMA [29], [176], [178]. Existing code-domain NOMA mainly include LDS-CDMA, LDS-OFDM, and SCMA [42], [178], as detailed in the following.

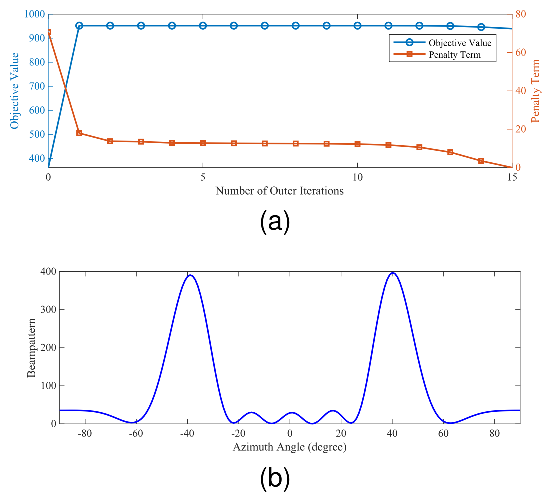


Fig. 20. ***Performance of power-domain NOMA in ISAC networks. (a) Optimization convergence. (b) Achieved beam pattern when communication rate = 15.63 b/s/Hz. Such an optimization for power allocation maximizes the weighted sum of the communication throughput and the effective sensing power where the rank-one constraints are transformed to a penalty term, which is then effectively solved by successive convex approximation [22]. Here, the dedicated sensing signal is not considered.***

LDS-CDMA adopts low-density signatures for transmission based on low-density parity check codes, which enables each code chip to contain only a few users instead of all users [193]. Let $\mathbf{F}_{K\times J}$ denote the spreading matrix, where $f_{k,j} \in \{0,1\}$ represents whether the jth CU contributes its data at the kth code chip [193], [194]. For example, if the numbers of CUs and code chips are $J = 6$ and $K = 4$, respectively, the spreading matrix is given by [194]

$$\mathbf{F}_{4\times 6} = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix}. \tag{18}$$

At the receiver, a low-complexity near-optimal multiuser detection based on message passing is applied [29], [42], [174].

LDS-OFDM can be regarded as a combination of LDS-CDMA and OFDM where the low-density spreading (LDS) is carried out in the frequency domain rather than the time domain [29], [42], [194]. First, the data symbols are spread to certain LDS sequences with corresponding LDS codes, and then, each code chip in these sequences is transmitted over a subcarrier of the OFDM system [29], [194]. Due to the low-density signature structure, each data symbol is spread over a small subset of subcarriers, and each subcarrier is occupied by only a small subset of data symbols corresponding to different CUs [195], [196]. Furthermore, the flexible subcarrier allocation can also be utilized to help improve system performance [194], such as sum rate [197], [198] and PAPR [199]. At the receiver, the message passing algorithm used in LDS-CDMA can also realize multiuser detection in LDS-OFDM [29], [196]. Specifically, LDS-CDMA may regarded as an improved form of multicarrier CDMA that uses LDS sequences instead of dense ones [29].

SCMA can be regarded as an enhanced version of LDS-CDMA where different bitstreams of CUs are directly mapped to different sparse codewords selected from user-specific codebooks based on the labeling of the bit sequence instead of the spreading of modulated symbols using low-density signatures in LDS-CDMA [29], [200],

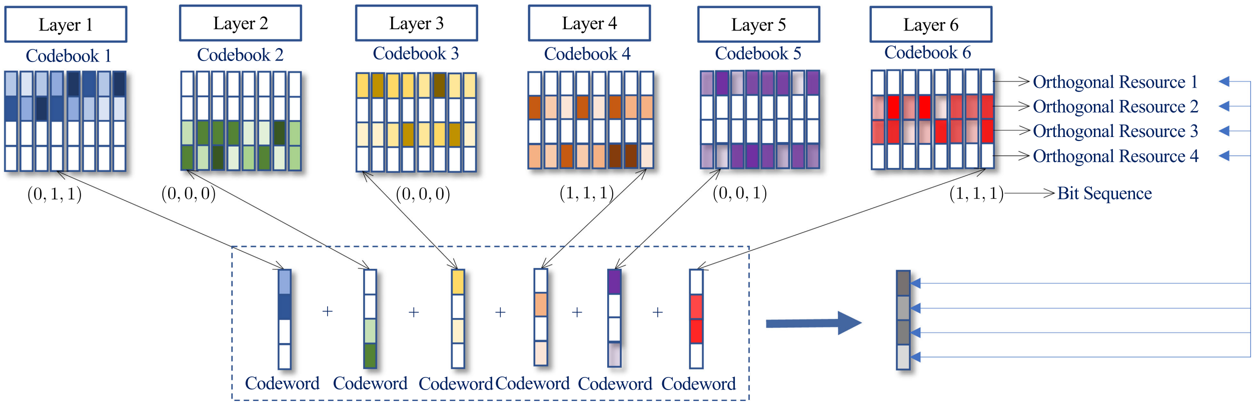


Fig. 21. *Example of SCMA encoding and multiplexing.*

[201]. Then, the mapped codewords are multiplexed over shared orthogonal resources, e.g., time slots, OFDM tones, and DDRBs [200], [202], [203]. Assume that there are J SCMA (CUs) layers to be multiplexed over K orthogonal resources, and each layer intends to transmit $\log_2(M)$ bits [200], [202]. Each layer has a predefined codebook that contains M codewords [29], [200]. These codewords in the same codebook are K-dimensional sparse complex vectors with $N < K$ nonzero entries, and they contain zero values in the same $K - N$ dimensions [200], [202]. An example of SCMA encoding and multiplexing ($J = 6$, $M = 8$, $K = 4$, and $N = 2$) is depicted in Fig. 21.

In SCMA, the codebook design is a complicated problem, which is usually realized based on multidimensional constellation design [202], [204], [205], [206], [207]. Generally, a base constellation is first designed, being formed by quadrature amplitude modulation [202], [204], [206], binary phase-shift keying [205], quadrature phase-shift keying [205], or star quadrature amplitude modulation [207], Then, some typical operations are applied on the base constellation to generate the mother constellation, such as phase rotation [202], [204], [205], [206], [207], shuffling in real and imaginary axes [202], [206], dimensional permutation [202], and interleaving [206]. Finally, the optimization of layer-specific operators (e.g., phase rotation and layer power offset [202]) is conducted based on the mother constellation. Particularly, in phase rotation, the rotation factors are optimized according to some specific design criteria, involving maximizing the minimum product distance or Euclidean distance between the codewords [202], [205], [206], [207], and maximizing the cutoff rate [204], which indicates lower bit error rate.

At the receiver, the message passing algorithm is also applied in the multiuser detection [208], [209]. In addition, SCMA supports the grouping of CUs based on channel conditions [42], [201], [210], [211] and the associated power allocation with the goal of optimizing sum capacity [210] or sum rate [201], [212], involving three categories: power allocation among subcarriers for single CU [210], [212], power allocation among intragroup CUs [201], [210], [213], and power allocation among CU groups [210], [211]. Similar to power-domain NOMA, the signals of different groups can be detected with the help of SIC when their transmit powers vary, and within each group, the signals of CUs are also distinguished by the message passing algorithm [42], [211].

2) Code-Domain NOMA in ISAC: There are few works of code-domain NOMA in ISAC. In [214], the data symbols of multiple CUs are transmitted to the AP using SCMA protocol for uplink communication, and those are also employed to sense the environmental information after reflection and scattering. An iterative and incremental scheme is proposed to recover the communication data based on the message-passing algorithm and estimate environmental information based on compressed sensing techniques at the AP.

C. Discussion on Some Key Issues and Challenges

Compared with existing OMA techniques, NOMA achieves separation of user signals by performing an SIC technique at the matrices' receiver, in which the signals of the CUs are successively estimated and interference is partially or fully eliminated. This provides a new vision for more access without the occupation of extra resources. As the studies on NOMA for ISAC are still in a very early stage, some newly brought issues and challenges deserve to be discussed.

1) Decoding Order in SIC: In downlink ISAC, the dedicated sensing signals can be decoded first, while in uplink ISAC, the communication signals are always preferentially canceled. In other words, the communication performance is always affected by sensing interference. This is very unfriendly for information recovery in communication-prior tasks due to the unavoidable interference. However, the pure sensing signal can be obtained without communication interference, and thus, this decoding order is particularly suitable for sensing-prior tasks. Some researchers have proposed allocating orthogonal resources to a portion of communication signals to satisfy high communication requirements [24]. More importantly, a flexible decoding order should be considered to cope with different demands, say communication-prior, radar-prior, and tradeoff tasks. In uplink ISAC systems, when two decoding orders are applied at the receiver, the performance of the achievable rate region is significantly improved compared to the scenario where only the sensing signal is decoded first [215], [216], [217]. Therefore, the issues on how to achieve flexible decoding order in practical implementation under incomplete channel state information still remain.

2) Nonuniform Analytical Framework: At present, the analytical framework and its corresponding performance metrics are still nonuniform. In conventional communication-only networks, the performance metrics in the Shannon theory, such as the diversity order and high SNR slopes, provide valuable insights. Whereas in ISAC, the performance metrics are less clear. In [131], mutual information is developed to define the information-theoretic limits of sensing and communication, which enables computational and analytical traceability. It is important to establish a unified performance evaluation framework for communication and sensing.

3) Error Propagation in SIC: Most of the existing works are based on the assumption that the signal can be correctly decoded by an SIC technique [176]. However, this assumption generally cannot be achieved in practice due to the imperfect power allocation, channel decoding, and hardware limitation, and thus, there exists a discount factor characterizing the degree of elimination in SIC [24]. If poor decoding occurs in the early stage of SIC, for example, in sensing signal decoding or weak user signal decoding, this error will propagate backward, and thus, its accumulation becomes increasingly severe [10]. On the one hand, several studies have investigated the effect of the error propagation in SIC based on multiple NOMA applied scenarios where the residual interference is modeled as a linear function of the received signal power, including two-way relay systems [218], single-cell multiantenna NOMA [219], and multicell uplink NOMA systems [220]. Furthermore, sophisticated mathematical models are employed to characterize this effect based on data collected by field tests. On the other hand, some works are proposed to improve SIC accuracy at the expense of the complexity, i.e., multistage channel estimation [221] and iterative SIC-aided receivers [222].

4) Imperfect Channel State Information: In power-domain NOMA, the decoding order adjusted by power allocation usually depends on the channel condition, where the signals for weak users with poor channel conditions tend to be decoded first. While in sensing tasks, channel state information is usually unknown to the transmitter and is exactly the information to be estimated, which increases the difficulty in power allocation between CUs and sensing tasks, especially for uplink ISAC. In addition, although the channel state information of CUs is known previously by the transmitter, imperfect channel estimation in practice causes errors in power allocation among CUs, which further affects the performance of SIC. For communication-only networks, imperfect channel state information can be usually classified into three categories, i.e., channel estimation errors [223], partial channel state information [224], and limited channel feedback [225], and their corresponding effects and solutions have been widely studied. In existing works for uplink ISAC, the communication signals are decoded in turn in the presence of unavoidable sensing interference in SIC, partially due to the lack of channel state information. Therefore, the channel state information in ISAC is a key issue for achieving better performance and supporting more flexible decoding orders, which requires further research.

5) Modulation and Detection Design: Efficient modulation and detection design is a key issue in ISAC NOMA to ensure that the theoretically achievable rates can be reached in practice [176]. In OMA, the modulation and detection of communication symbols for different CUs is carried out via orthogonal resource blocks without the interuser and sensing interference. While in NOMA for communication-only networks, the intended user symbols are demodulated in the presence of all left superimposed signals where the intended information and interference from other CUs are mixed [176]. In uplink ISAC, this effect will aggravate due to the unavoidable sensing interference. Hence, the elaborate modulation and power allocation design can improve the performance of demodulation [226], [227], [228]. Some new emerging modulation schemes have achieved initial advancements and show promise for application in ISAC MA for future research, such as spatial modulation [229] and index modulation [230]. Additionally, the receiver design in ISAC where the communication symbol detection and the state of ST estimation are both conducted is an interesting research topic. In [231], a target estimation scheme based on minimum mean squared error estimation is proposed, in which the structural information about communication constellations is exploited.

VIII. RATE-SPLITTING MA FOR ISAC

RSMA can be viewed as a general framework that unifies SDMA, NOMA, and OMA, where the message of each CU is split into a common submessage and a private submessage [35].

A. Common Stream and Private Stream

Let s_c, s_k, and s_r denote the jointly encoded common stream of all users, the private stream of the kth CU, $\forall k \in \mathcal{K}$, and the dedicated sensing sequence [232], respectively. Then, the baseband transmit signal after linearly precoding can be expressed as [232]

$$\mathbf{x} = \mathbf{p}_c s_c + \sum_{k \in \mathcal{K}} \mathbf{p}_k s_k + \mathbf{p}_r s_r \tag{19}$$

where $\mathbf{p}_c$, $\mathbf{p}_k$, and $\mathbf{p}_r$ represent the precoders of the common stream, kth CU's private stream, and sensing sequence, respectively. At the receiver, the sensing sequence is first decoded via SIC like in power-domain NOMA or can be directly treated as interference like in SDMA where elaborate precoding is designed to help mitigate it [232]. Like RSMA in communication-only networks, the common stream is then decoded from the remaining communication stream via SIC, and this is followed by decoding the private stream in the presence of the remaining interuser interference [233], which enables partially decode interference (like in power-domain NOMA) and partially treat the remaining interference as noise (like in SDMA) [35]. Since SDMA is only applicable to downlink ISAC, RSMA, as a hybrid mechanism combining power-domain NOMA and SDMA, is also only applicable to downlink ISAC networks.

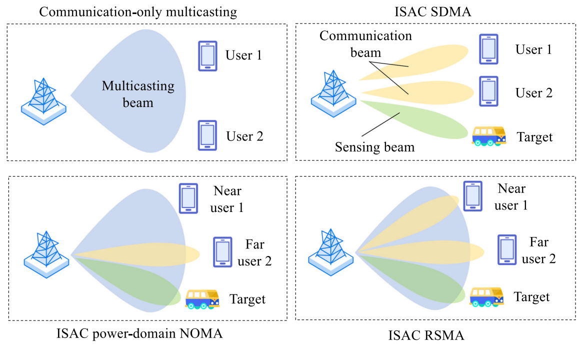


Fig. 22. ***Beam shapes of communication-only multicasting, SDMA, power-domain NOMA, and RSMA.***

B. Linear Precoding

In RSMA, similar to SDMA and power-domain NOMA, the precoders $\{\mathbf{p}_c, \mathbf{p}_1, \ldots, \mathbf{p}_K, \mathbf{p}_r\}$ are optimized to achieve satisfactory performance in both communication and sensing [232], [234], [235], [236], [237], [238], [239], [240]. The commonly used performance metrics for communication mainly involve weighted sum rate [232], [234], [235], [236], [237], minimum fairness rate [238], energy-efficiency [239], and user data rate [240], and those for sensing involve the beam pattern shape [232], [234], [235], [236], positioning error bound [237], CRB [238], [240], and mismatch between achieved and desired waveform [239]. These optimization problems are usually nonconvex and thus difficult to solve. Some techniques are used to tackle these problems, such as the alternating direction method of multipliers [232], [234], [235], [236], [239], semidefinite relaxation [234], [235], [236], [239], [240], and sequential convex approximation [237], [238], [239], [240].

C. Discussion on Some Key Issues and Challenges

RSMA is an uprising MA technique that combines the advantages of SDMA and power-domain NOMA to support a more flexible resource utilization pattern at the expense of higher complexity. To intuitively describe the benefits of RSMA, the beam shapes of communication-only multicasting, SDMA, power-domain NOMA, and RSMA are depicted in Fig. 22 [241]. Consequently, key issues and challenges in SDMA and power-domain NOMA are also applicable for RSMA to further improve its performance and practicability. In addition, as this technique is still in the early stage, some interesting research topics derived by RSMA are worthy of being discussed as follows.

1) Rate Splitting Ratio: RSMA splits the message into the common part and private part, where the former is canceled by SIC and the latter is designed to occupy the unique spatial resources. It is an essential issue to determine the proportion of common and private parts, called rate splitting ratio, to resist interuser interference and mutual interference between communication and sensing to the greatest extent. Specifically, the rate splitting ratio indicates how many signals can be eliminated through SIC or multiplexed in the spatial domain. In [237], the rate splitting ratio is considered as the optimization variable, as well as transmit precoders and scheduling policies, with the goal of maximizing both the sum rate and the positioning error bound. Moreover, different CU may have different rate splitting ratios to further support a more flexible adjustment on resource allocation, realizing an ideal scenario where some CUs are distinguished by only orthogonal spatial resources, some by only SIC, and the other by a mixed mode.

2) Power Allocation to Dedicated Sensing Signal: In downlink ISAC, how to allocate dedicated sensing signals is a relevant key issue. Most existing works do not consider dedicated sensing signals and directly utilize a superposition of common and private communication streams for sensing [234], [235], [236], [237], [238], [239], [240]. When power and spatial resources are sufficient to ensure the performance of both communication and sensing, or when CUs and STs are spatially close, it may only be necessary to allocate enough power to the common signal to satisfy sensing requirements, and dedicated sensing signals seem unnecessary. However, when resources are scarce and CUs are orthogonal to STs [132], dedicated sensing signals appear to be indispensable to sensing-oriented tasks. How to allocate power to sensing signals, or in other words, how to align dedicated sensing signals, remains unclear. Potential approaches include treating it as a separate item superimposed in the transmitted signal [232], integrating it within the common signal as the multicasting message [234], or adopting a hybrid method that combines these strategies. Like in SDMA, although the effectiveness of dedicated sensing signals has been proven in experiments, a theoretical explanation is still lacking. Besides, in uplink ISAC, although the interference from sensing echoes must be considered for communication signal recovery, RSMA degrades to power-domain NOMA due to the inapplicability of SDMA for uplink ISAC.

3) Extension to Multiple Domains: RSMA can be regarded as a unified framework that allows MA in both spatial and power domains. In the present implementation, each CU splits its signal into common and private parts and decodes partial signals by SIC, which means that for a specific CU, the interference from other CUs or sensing tasks can be partially alleviated either by spatial domain or by power domain. This enables a new vision to support the MA in multiple domains, i.e., the spatial domain and power domain, to collaboratively differentiate CUs. The cooperation of these two domains may bring some new challenges. On the one hand, SDMA and power-domain NOMA rely on channel state information for information recovery, and thus, imperfect channel state information becomes an essential issue to be solved for RSMA. On the other hand, when the location or channel is similar between CUs and STs or among CUs, neither SDMA nor power-domain NOMA can perfectly differentiate them. This is because SDMA relies on channel characteristics to couple with the designed precoders and the power-domain NOMA allocates power based on channel conditions at the ISAC transmitter. The union of other MA techniques may alleviate these difficulties.

IX. CONCLUSION AND FUTURE RESEARCH

ISAC is one of the most essential research orientations toward uprising usage scenarios of IMT-2030 for future 6G. Among several key methods in ISAC, the MA technique that supports a massive number of APs to avoid various mutual interference between communication and sensing or among CUs is one of the dominant components, which enhances the network capacity and spectrum effectiveness. In ISAC, MA techniques can be divided into OMA and NOMA. The former OMA uses orthogonal resources to distinguish CUs and STs, including TDMA in the time domain, OFDMA in the frequency domain, CDMA in the code domain, SDMA in the spatial domain, and OTFS MA in the delay–Doppler domain. The latter NOMA allows CUs and STs to share the same orthogonal resources, which can be further divided into power-domain NOMA, code-domain NOMA, and RSMA. In this article, we explicitly introduced the principles and their corresponding critical problems in existing works for the abovementioned MA approaches. We also discussed some key issues and future challenges of these techniques caused by the new performance evaluation system and wireless resource utilization in ISAC toward next-generation 6G and beyond. Several interesting research questions remain.

A. Correlations and Differences Between MA Techniques for ISAC and Those for Communication-Only Networks

They all concentrate on interference cancellation among CUs for transmission. In ISAC, simultaneous implementation of communication and sensing brings new mutual interference that deteriorates dual-functional performance. Therefore, MA techniques aim to not only cancel the interuser interference among CUs, but also cancel the mutual interference between CUs and STs. In ISAC OMA, extra unique orthogonal resources are allocated to dedicated sensing tasks rather than only to different CUs, including the resources in time, frequency, code, spatial, and delay–Doppler domains. In ISAC NOMA, the dedicated sensing signals are also considered to be distinguished by power allocation at the transmitter and SIC at the receiver in power-domain NOMA and RSMA or by nonorthogonal sparse spreading sequences in code-domain NOMA, not merely the power allocation or sequence assignment for CUs as communication-only NOMA. These differences may lead to some new issues and challenges for existing mature MA techniques in communication-only networks, which have been discussed in their corresponding sections.

B. Cancellation of Newly Introduced Interference in More Complex Emerging Scenarios

MA techniques can be regarded as interference cancellation methods to achieve better performance of both communication and sensing. This article mainly focuses on the cancellation of sensing-to-communication interference in downlink ISAC and partially mentions the cancellation of mutual interference between communication and sensing in uplink ISAC. In ISAC for future 6G and beyond, other sources of interference caused by more complex implementation may be joined to further impede performance. Mutual interference between downlink and uplink exists in the promising full-duplex implementation of 6G [242]. For example, the echoes from CUs can be considered as interference for sensing echoes at the receiver in uplink ISAC. Considering the popular reconfigurable intelligent surface [243], it may be beneficial for interference cancellation, in terms of accurately reflecting the signal to its intended CU, or harmful to interference cancellation, such as introducing more communication paths to impair the sensing performance. Therefore, how to design MA techniques to further eliminate the newly introduced interference is an essential topic for future work.

C. Selection of Appropriate MA Techniques Adapting to Different Application Scenarios

Different application scenarios arise with the thriving development of ISAC. Thus, appropriate MA techniques should be chosen and designed to cope with these scenarios with different communication and sensing demands. For communication-prior tasks, the assignable resources in ISAC OMA lean toward transmission, while for sensing-prior tasks, these resources lean toward target detection or tracking. Since the sensing interference cannot be decoded first in power-domain NOMA and RSMA for uplink ISAC, they may not be suitable for communication-prior tasks but suitable for sensing-prior tasks where pure sensing signals can be obtained. In addition, implementation complexity is another important factor in the selection of MA techniques. SDMA is primarily designed at the transmitter, while other MA approaches are designed at both the transmitter and receiver with different degrees of implementation complexities. Among them, TDMA and OFDMA are relatively simple and readily implementable for ISAC transmission. Furthermore, there are some scenarios with special demands, such as the inappropriate use of TDMA in low-delay scenarios or OTFS MA in high-mobility scenarios.

D. Fusion of Multiple-Domain MA Techniques

To achieve the demands of massive communication and ubiquitous connectivity in 6G [244], multiple MA techniques in ISAC can be utilized simultaneously to support more CU and ST within acceptable interference. Specifically, RSMA may be regarded as a combination of SDMA and power-domain NOMA, which utilizes the resources in both spatial and power domains. When power allocation and SIC are also performed, the SCMA can be viewed as a combination of code-domain NOMA and power-domain NOMA. Also, the popular multicarrier direct sequence CDMA could be a combination of CDMA and OFDMA. In [245], the multicarrier direct sequence CDMA is designed for joint RadCom systems where the interuser interference and sensing interference are canceled by orthogonal codes and unique subcarriers, respectively. Considering the MA in more domains, Xu et al. [246] utilize the resources in time, frequency, and power domains where the time allocation, subcarrier allocation, and power allocations are simultaneously conducted to avoid interference in half duplex cognitive systems. Therefore, it is a promising research topic to use a mix of existing MA techniques, in which some difficulties derived from this fusion should be explored.

E. Integration With Another 6G Candidate Technology RIS

ISAC is expected to be integrated into the network along with another candidate technology for 6G, namely, reconfigurable intelligent surface (RIS). RIS modifies the propagation direction of reflected signals by adjusting the phase of its surface units, thereby creating non-line-of-sight (NLoS) communication pathways and enabling focused and directive transmission [243], [247], [248], [249], [250]. This technology is considered a promising candidate for 6G, especially well-suited for high-frequency communications that encompass the terahertz (THz) spectrum [251]. It brings several benefits to ISAC networks. When line-of-sight (LoS) links are blocked by obstacles, RIS can establish an additional propagation link to support simultaneous communication and sensing [252], [253], [254]. In addition, RIS helps enhance the performance of both communication and sensing by adjusting phase shifts to maximize the gain of the reflected signal toward users or targets [181], [182]. However, the introduction of RIS also brings some challenges to the implementation of MA techniques in ISAC. RIS requires fine control to adjust the phase and amplitude of its elements, which makes joint resource allocation more difficult. Additionally, the dimension of the system's channel state information would increase, which affects the performance of MA techniques. Specifically, as mentioned above, RIS introduces some different types of interference, necessitating more complex MA mechanisms to handle them.

F. MA Techniques Applied in Other Typical ISAC Networks

We discuss the availability of various MA techniques in conventional ISAC networks. As a subsequent step, it is equally crucial to explore the implementations of MA techniques in other ISAC networks, including unmanned aerial vehicle (UAV) ISAC networks [255], IoT ISAC networks [7], vehicular ISAC networks [256], Wi-Fi ISAC systems, and satellite ISAC networks [257], [258], [259]. New challenges for specific scenarios will also emerge for MA techniques. In UAV ISAC networks, MA techniques need to adapt to highly dynamic environments to enable reliable communication and sensing capabilities even with significant signal attenuation [260]. In IoT ISAC networks, the energy constraints of IoT devices require MA techniques to be not only efficient but also capable of operating with low energy consumption to support massive device access. In vehicular ISAC networks, MA techniques need low latency due to the high requirement for real-time performance. In Wi-Fi ISAC systems, MA techniques need to utilize limited spectrum resources to provide accurate indoor positioning and communication service. In satellite ISAC networks, possible challenges include the large delays caused by long-distance transmission and the requirements for broad communication and sensing coverage.

G. New Protocols for Interference Cancellation From a Sensing Perspective

The concept of MA originates from the field of communications, referring to the technology that allows multiple users or communication devices to share the same communication resources. It can distinguish user signals by eliminating or mitigating interference among them. In the field of sensing technology, since the concept of "user" does not exist, the term MA may not be commonly used. Radio frequency sensing is a technology that uses radio waves to detect and identify objects or phenomena in the environment, mainly including multitarget detection. A key challenge in multitarget detection is to differentiate the echoes returned from different STs, typically employing techniques such as pulse-Doppler, signal processing, and pattern recognition. In ISAC, the individual purposes of sensing and communication tasks remain unchanged, but mutual interference appears due to the sharing of the same resources making it more difficult to distinguish CU signals and ST echoes. Existing works primarily develop MA techniques based on the perspective of communication, discussing how to eliminate or mitigate the mutual interference between communication and sensing. It is also a promising topic to eliminate such mutual interference from the perspective of sensing, such as utilizing mature multitarget detection technologies in sensing, for the future 6G and beyond ISAC networks. ■

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