Terahertz-Band Integrated Sensing and Communications: Challenges and Opportunities

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***Abstract*—The sixth generation (6G) wireless networks aim to achieve ultra-high data transmission rates, very low latency and enhanced energy-efficiency. To this end, terahertz (THz) band is one of the key enablers of 6G to meet such requirements. The THz-band systems are also quickly emerging as high-resolution sensing devices because of their ultra-wide bandwidth and very narrow beamwidth. As a means to efficiently utilize spectrum and thereby save cost and power, THz *integrated sensing and communications* (ISAC) paradigm envisages a single integrated hardware platform with common signaling mechanism. However, ISAC at THz-band entails several design challenges such as beam split, range-dependent bandwidth, near-field beamforming, and distinct channel model. This article examines the technologies that have the potential to bring forth ISAC and THz transmission together. In particular, it provides an overview of antenna and array design, hybrid beamforming, integration with reflecting surfaces and data-driven techniques such as machine learning. These systems also provide research opportunities in developing novel methodologies for channel estimation, near-field beam split, waveform design and beam misalignment.**

I. INTRODUCTION

Lately, the millimeter-wave (mm-Wave) spectrum has been extensively investigated for the fifth-generation (5G) wireless networks to address the demand for high data rates. While the mm-Wave band provides tens of GHz bandwidth, the future sixth-generation (6G) wireless networks are expected to achieve substantial enhancement of data transmission rates ($>$ 100Gb/s), low latency ($<$ 1ms), and ultra-reliability ($>$ 99.999%). In this context, the terahertz (THz) band ($0.1 - 10$ THz) is expected to be an essential enabling technology in 6G for 2030 and beyond [1]. To this end, the US Federal Communications Commission (FCC) has already invited new experimental licenses at 95 GHz and 3 THz [2].

In addition to the improvement of existing communications technologies in 6G, an unprecedented paradigm shift is envisioned on the integration of ultra-reliable communications with high-resolution sensing [3]. Further, to save hardware cost and improve resource management, *THz integrated sensing and communications* (ISAC) has been recently suggested to jointly harness the key benefits of THz-band, e.g., ultra-wide bandwidth and enhanced pencil beamforming [3]. Combining THz communications with THz sensing functionalities finds applications in vehicle-to-everything (V2X), indoor localization, radio-frequency (RF) tagging, and extended/virtual reality.

Initial ISAC systems had sensing and communications (S&C) systems operating separate hardware in the same frequency bands and using techniques to avoid interference from each other. However, with increasing convergence between S&C operations, joint hardware is required. The ISAC systems, therefore, are broadly classified into radar-communications coexistence (RCC) and dual-functional radar-communications (DFRC) [3]. Herein, RCC aims to provide interference mitigation and resource management so that both systems can operate without unduly interfering with each other, whereas DFRC focuses on performing S&C tasks on the same infrastructure. The evolution from RCC to ISAC requires the usage of common waveforms, integrated transmit/receive hardware design, and joint processing techniques. While existing mm-Wave communications protocols/waveforms, e.g., the IEEE 802.11ad standard wi-fi protocol, have been proposed for communications-aided vehicular sensing, recent studies have employed similar signaling methods for low THz ($0.06 - 4$ THz) vehicle-to-vehicle (V2V) ISAC [4]. The Third-Generation Partnership Project (3GPP) Release-16 specifies 5G localization and sensing in monostatic mode through time difference-of-arrival (TDoA) [3]. Currently, there exists a work item S1-220144 on ISAC in the 3GPP targeting Release-19.

Certain characteristics of mm-Wave become more aggravated at THz such as high path loss, short transmission range, extreme channel sparsity, and beam squint (Fig. 1). To overcome these challenges, new signal processing techniques and hardware are required for THz-ISAC design. For instance, analogous to their massive multiple-input multiple-output (MIMO) counterpart in mm-Wave, the ultra-massive (UM) MIMO configurations are developed to compensate for high path loss in THz [2]. Further, novel approaches are needed for reliable S&C performance in terms of channel modeling and wideband signal processing because of THz-specific peculiarities such as beam split, distance-dependent bandwidth, and severe Doppler-induced interference.

This article examines potential technologies to bring forth these two 6G enablers — THz transmission and ISAC — along with system characteristics/requirements, challenges, and potential solution paths. While there exist extensive surveys separately on both THz communications [1, 2] and ISAC [3],

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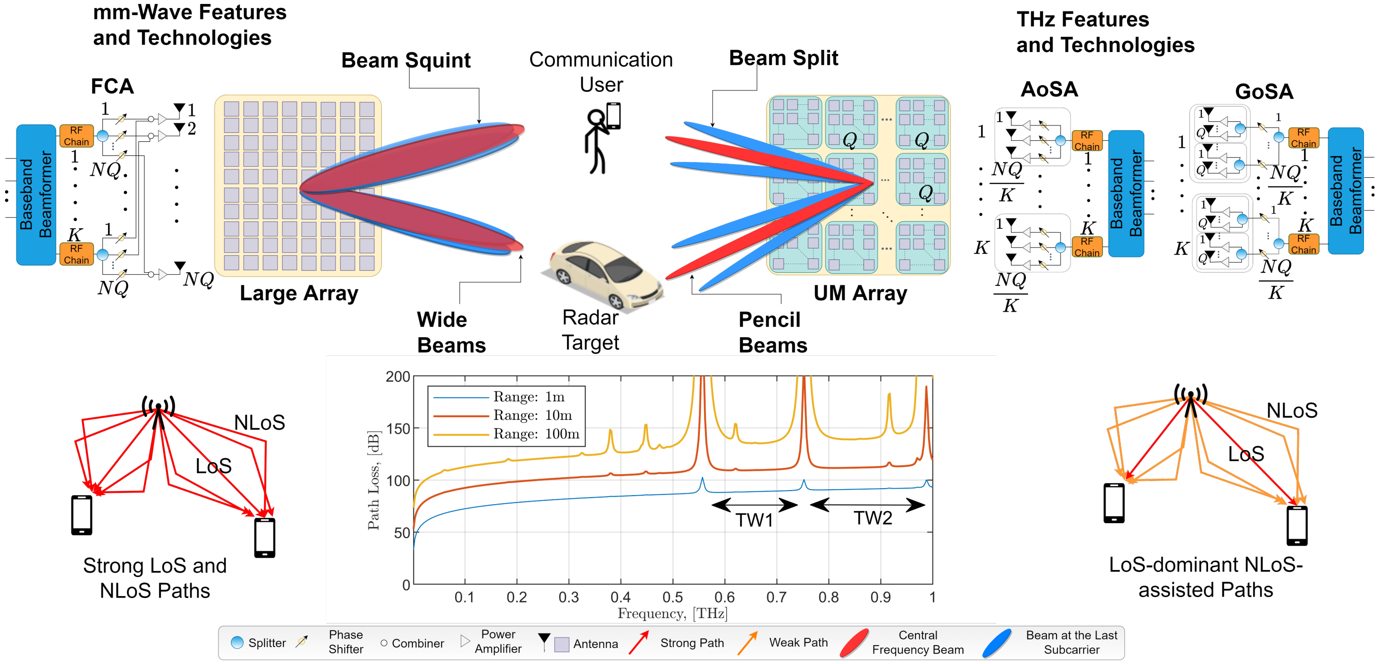

Fig. 1. Comparison of mm-Wave and THz-band characteristics for ISAC design including distance-dependent path loss, multipath components, beam alignment, and antenna array structures.

the THz-ISAC remains relatively overlooked. In the next section, we introduce the unique features of THz-band and their implications, related requirements, and trade-offs for THz-ISAC design. Next, we discuss antenna/array design, hybrid beamforming, integration with intelligent reflecting surfaces (IRSs), and machine learning (ML) to meet THz-ISAC challenges. Finally, we provide a synopsis of research opportunities in THz channel acquisition, near-field beam split, waveform design, beam misalignment, and interference management.

II. THZ-BAND CHARACTERISTICS FOR ISAC DESIGN

Compared to the mm-Wave channel, the THz channel exhibits certain unique characteristics (Fig. 1). In what follows, we investigate them along with their implications, requirements and trade-offs for reliable THz-ISAC design.

Path Loss: The THz channel faces severe path loss (~ 120 dB$/100$ m at 0.6 THz [5]) governed by both the spreading loss and molecular absorption, which is more significant than the mm-Wave [2]. In THz-ISAC systems, the radar echo signals experiencing high path loss may still cause stronger interference to the communications system. The high path loss is compensated by beamforming gain through UM antennas that generate multiple beams toward both communications users and radar targets [6].

Transmission Range: A THz-ISAC system has the trade-off that the transmission distance should be long, e.g., up to 200 m [3], for sensing, while communications tasks may require shorter ranges, e.g., 20 m, to achieve 100 Gbps data rate [2].

Multipath: The THz channel is characterized as line-of-sight (LoS)-dominant and non-LoS (NLoS)-assisted models [3]. While a THz-ISAC system can benefit from NLoS paths to improve spatial diversity, especially for communications with low-resolution beamformers, the highly attenuated NLoS links imply fewer secondary echoes in THz sensing/radar applications. Furthermore, UM arrays that generate ultra-narrow beams also reduce the effect of clutter caused by multipath propagation [7].

Wideband Beam Split: The subcarrier-independent analog beamformers largely used in the wideband systems may lead to *beam split* effect in THz channels: the generated beams split into different physical directions at each subcarrier due to ultra-wide bandwidth [5, 12]. This phenomenon has also been called *beam squint* in mm-Wave works [1, 3]. While both beam squint and beam split pertain to a similar phenomenon, the latter has a more severe achievable rate of degradation in communications. In particular, the main lobes of the array gain corresponding to the lowest and highest subcarrier frequencies do not overlap at THz at all while there is a relatively small deviation in the mm-Wave band (Fig. 1). For sensing, the beam split is approximately 4° (1.4°) for 0.3 THz with 30 GHz (60 GHz with 2 GHz) bandwidth, respectively for a broadside target direction-of-arrival (DoA) [3, 12]. The compensation of beam split in the THz-ISAC systems requires a hardware trade-off: additional devices (e.g., time-delayer networks) are required for beam split-corrected analog beamformer but they are inessential for digital processing tasks like DoA estimation and channel estimation [3, 13].

Near-field Effect: Due to shorter transmission distance, the THz wave emitted from the transmitter impinging on the receive array may be no longer plane-wave. Hence, the spherical-wave propagation model should be considered for near-field transmission, i.e., when the distance is shorter than

TABLE I
STATE-OF-THE-ART IN THZ-ISAC DESIGN

Application	Signal Processing Techniques	Advantages	Drawbacks
Hybrid beamforming [3]	Joint manifold optimization for the single-user multi-target case	Energy-efficient and corrects beam split without additional hardware	SE degradation due to fewer DoF
IRS-assisted hybrid beamforming [8]	Beampattern generation via Proximal policy optimization	Joint design of transmit and IRS beamformers with enhanced capacity	Only narrowband THz scenario is considered
OTFS-based waveform design [9]	DFT-spread OTFS design with superimposed pilot signals	Robustness against the Doppler shift and reduced PAPR compared to OFDM	High receiver cost and complexity
OFDM-based waveform design [10]	Non-uniform multi-wideband OFDM signaling	Low receiver complexity	Subcarrier spacing depends on Doppler shift
Beam alignment [11]	Sensing assisted SSB burst transmission	Reduces beam misalignment by 70%	Performance depends on sensing capability

the Rayleigh distance, which is proportional to the square of the array aperture. While this distance is 4 m for an array size of 0.1 m in mm-Wave (60 GHz), it becomes approximately 40 m at 0.6 THz [2, 14]. This manifests as another degree-of-freedom (DoF) in the range dimension in THz-ISAC design, unlike its mm-Wave counterpart. It may be used to mitigate interference in both angle and distance domains via beam-focusing rather than beam-steering for both sensing targets and communications users. Near-field effects may introduce complex objective functions such as bi-quadratic matrices to the waveform design problem that also necessitates developing low-complexity algorithms [15].

Distance-dependent Bandwidth: As the transmission distance increases, the THz-specific molecular absorption becomes significant in varying THz-bands, which defines multiple usable transmission windows, each of which is tens of hundreds of GHz wide, and they are separated with absorption peaks, a phenomenon called *broadening of the absorption lines* [2]. Furthermore, the bandwidth of each of these transmission windows shrinks with the distance. For instance, the transmission window $0.55 - 0.75$ THz (i.e., TW1 in Fig.1) may be used entirely for 1 m range while only $0.6 - 0.7$ THz of the same band is available for 10 m range [6]. In THz-ISAC design, distance-aware and bandwidth-adaptive modulations/receivers must include the effects of this phenomenon to their advantage.

Doppler Shift: In wideband THz systems, the Doppler spread may cause significant inter-carrier-interference (ICI), especially in high mobility scenario [2]. For instance, the Doppler shift becomes 10 times larger at 0.3 THz than that of 30 GHz. The severe Doppler effect seriously damages the orthogonality among the subcarriers due to ICI, which makes the orthogonal frequency division multiplexing (OFDM) challenging [9]. The Doppler shift becomes more dominant because of high carrier frequency thereby worsening the false alarms caused by the range sidelobes [7].

III. ENABLING TECHNOLOGIES FOR THZ-ISAC

The design of THz-ISAC faces several challenging issues. To combat these challenges, herein, we discuss the key enabling technologies from hardware design and implementation perspectives along with an extensive discussion on the existing state-of-the-art signal processing techniques (see, e.g., Table I).

A. *Antenna and Array Design*

To tackle the severe path loss in THz, extremely dense antenna arrays (e.g., 5×5 cm^2) composed of thousands of antenna elements are employed [1, 6]. Hence, tunable graphene-based plasmonic nano-antennas or metamaterials are employed to provide dynamic THz beamforming capability [1, 2]. The graphene-based structure provides steering in the main-lobe direction by changing the energy levels of the graphene layer. In addition, leaky-wave antennas are also actively investigated for THz sensing and tracking applications [2].

Since the number of antennas in THz systems is huge, signal processing with a dedicated radio-frequency (RF) chain is not efficient even if hybrid analog/digital processing is used. Therefore, subarrayed architectures, e.g., AoSA and GoSA, as shown in Fig. 1, have been proposed for THz S&C systems as a promising solution against the fully-connected array (FCA) by exploiting the extreme-sparsity of the received THz signal [3, 6]. Consider a THz system with K RF chains and an antenna array with $M = QN$ antennas. Then, the FCA needs KM PSs, whereas AoSA and GoSA employ QN and N PSs, respectively. The main advantage of subarrayed architectures is that they connect a part of the antennas to the same RF chain, thereby reducing the power consumption due to the usage of PSs. Fig. 2 compares these arrays in terms of the number of PSs and power consumption, which is approximately $5\mathrm{mW}$ ($40\mathrm{mW}$) at 60 GHz (0.3 THz), respectively [5]. Here, AoSA and GoSA exhibit approximately 80 and 200 times less consumption compared to FCA. The superiority of GoSA is due to an extra grouping level connecting Q antennas to the RF chain as shown in Fig. 1. While the subarrayed connection in AoSA and GoSA enjoys low hardware and energy cost, it yields lower S&C performance in terms of spectral efficiency (SE) and localization due to fewer DoF than FCA. To address this, overlapped subarrays (OS) are used without additional hardware components. Each of these array setups leads to different S&C performance as illustrated in Fig. 3) [3]. Antenna selection techniques for UM arrays may also be used to yield the best subarray in terms of different communication/sensing performance metrics, e.g., SE, bit-error-rate (BER), and the Cramér-Rao lower bound (CRLB) of the target DoAs.

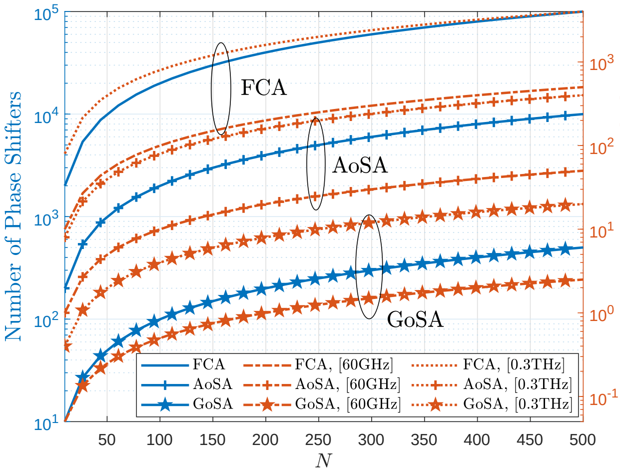

Fig. 2. (Left) Number of PSs and (Right) power consumption in FCA, AoSA and GoSA architectures, which employ the same number of antennas $M = NQ$. The number of RF chains is $K = 10$ and $Q = 10$.

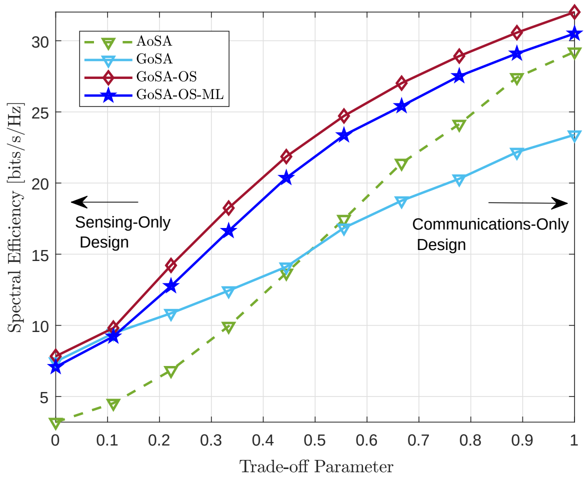

Fig. 3. SE trade-off in THz-ISAC with respect to hybrid beamformer tuning parameter for AoSA, GoSA and GoSA-OS as well as ML-aided GoSA-OS.

B. *Hybrid Beamforming for THz-ISAC*

Hybrid beamforming is an enabling technology for THz-ISAC, although it has been mainly introduced for mm-Wave communications systems to reduce the system cost while providing satisfactory SE. The hybrid architecture consists of a few digital beamformers and a large number of analog PSs. In ISAC, the main aim of hybrid beamforming is to realize a beampattern toward both communications users and radar targets effectively [3]. The THz-ISAC hybrid beamforming problem faces the following challenges:

- Compared to its mm-Wave counterpart, the THz hybrid beamforming is more challenging due to the UM number of antennas for the solution of the optimization problem, which is highly non-linear and non-convex due to the coupling between analog/digital beamformers, and the constant-modulus constraint for realizing PSs.
- THz-ISAC hybrid beamforming design should consider THz-specific peculiarities such as the beam split phenomenon and beam misalignment due to the generation of very narrow beams in THz. Furthermore, the path loss in THz is distance-dependent for which the THz-ISAC system should employ multiple transmission windows for long- and short-distance targets/users.

Considering the aforementioned challenges, the design of THz-ISAC hybrid beamforming also requires the combination of different performance metrics of sensing (mean-squared-error (MSE) of DoA estimation) and communications (SE). One possible approach is the optimization of the hybrid beamforming weights jointly with radar- and communications-only beamformers with a tuning parameter [3, 13]. Herein, the radar beamformer consists of the steering vectors corresponding to the target DoAs whereas the communications beamformer is constructed from the singular value decomposition (SVD) of the channel matrix. The tuning parameter controls the trade-off between the accuracy/prominence of S&C tasks. For instance, as illustrated in Fig. 3, this tuning parameter is usually selected between 0 (sensing-only design) and 1 (communications-only design) to optimize the balance over the performance metrics related to both radar and communications.

Fig. 4 shows the orthogonal matching pursuit (OMP)-based THz-ISAC hybrid beamforming performance, wherein the targets and the users are in the near-field of the BS. We observe that the near-field ISAC beamformer performs close to fully digital (FD) ISAC and communications-only beamformers with the trade-off parameters of 0.5 and 1, respectively. Fig. 4 also demonstrates poor SE performance when a far-field assumption is imposed while designing the OMP dictionary.

Due to the usage of subcarrier-independent analog beamformers, the generated beams at central and low-/high-end subcarrier frequencies face a severe array gain loss causing beams to split into different directions (Fig. 1). One approach to mitigate beam split in THz transmission is realizing the analog beamformer with PSs and time delayers, hence called delay-phase precoding (DPP) [5]. This approach first generates a subcarrier-independent beamformer, then constructs virtual subcarrier-dependent beams with beam split compensation by using time delayers. The additional time delayer network is expensive because each PS should connect multiple time delayers, each of which consumes approximately 100 mW, which is more than that of a PS (40 mW) in THz [5].

The effect of beam split can also be mitigated via signal processing techniques without additional hardware. For instance, [3] devises a beam split correction technique, wherein the corruptions in subcarrier-independent analog beamformer due to beam split are computed and passed into subcarrier-dependent digital beamformers which are then corrected to realize beam split-free beampattern. As a result, the high power consumption of time delayer networks requires better signal processing approaches for beam split mitigation. Another possible research direction may include the THz-ISAC hybrid beamformer design in low earth orbit (LEO)

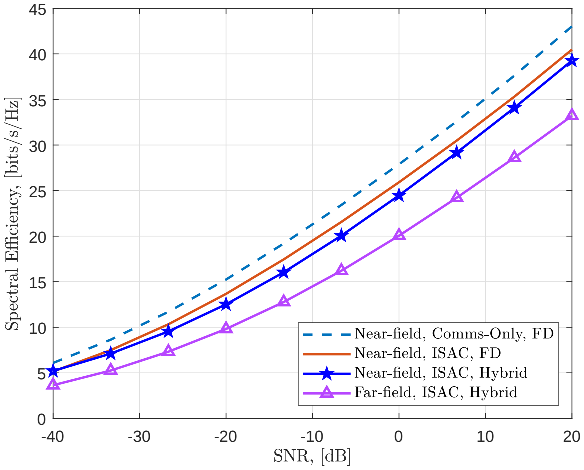

Fig. 4. Near-field THz-ISAC beamforming performance in terms of SE for FD and hybrid beamforming in communications-only and ISAC scenario.

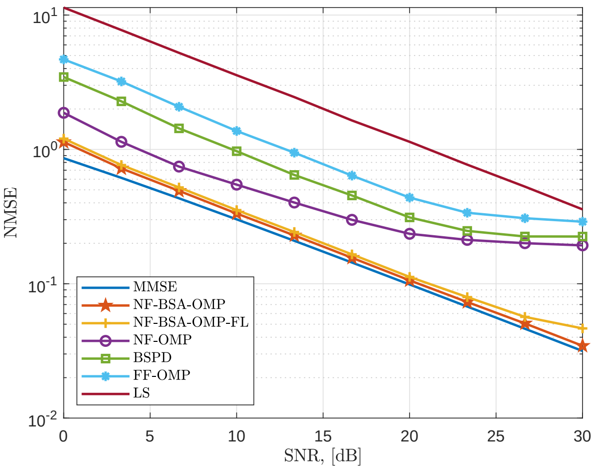

Fig. 5. Near-field THz channel estimation performance in terms of NMSE for signal processing (BSA-OMP, BSPD, and LS) as well as ML-empowered (BSA-OMP-FL) approaches.

satellites, for which the THz channel does not face significant attenuation. In addition, developing a common performance metric for S&C to better represent the system requirements can improve the performance and lower the hardware cost.

C. IRS-assisted systems

An IRS is a two-dimensional (2D) surface composed of a large number of meta-material elements, reflecting the incoming signal toward the intended direction by introducing a pre-determined phase shift. Thus, the IRS provides improved energy and spectral efficiency in wireless networks. The usage of IRS can be especially advantageous in THz-ISAC in compensating for the high path loss and improving the sensing coverage and communications performance. Compared to conventional ISAC, the IRS-assisted case is more challenging since it involves the joint design of transmitter beamformers and IRS phase shifts. For this purpose, a proximal policy optimization (PPO) approach with reinforcement learning (RL) is proposed in [8], wherein the transmitter and IRS parameters are jointly optimized for THz-ISAC, wherein the users are also designated as radar targets. However, [8] considers only narrowband scenarios without exploiting the key advantage of ultra-wide bandwidths in THz.

In fact, the IRS-assisted ISAC design is a new paradigm even for the mm-Wave band as it is envisioned for 6G wireless networks. Therefore, several design challenges in IRS-assisted ISAC are unexamined such as wideband processing and waveform design, clutter/multi-user interference suppression, and physical layer security. Besides the conventional IRS, the simultaneously transmitting and reflecting intelligent surface (STARS)-assisted ISAC provides full-space coverage and more DoF, hence, opening new research opportunities.

D. ML Solutions for THz-ISAC Design

Compared to model-based techniques relying on accurate mathematical expressions, ML-based approaches exhibit three main advantages: robustness against imperfections in the data, environment-adaptivity via retraining with new data and post-training computational complexity. As a result, ML has been regarded as one of the key enabling technologies for 6G wireless networks [2, 14].

With the aforementioned benefits, ML-based techniques gained much interest separately for sensing (DoA estimation, localization) and communications (channel estimation, beamforming, resource management) applications. For ML-based THz-ISAC design, one should consider jointly solving multiple problems related to S&C based on the available training data. For instance, [8] devises a reinforcement learning (RL) approach for joint beamformer design at the DFRC and IRS. Also, ML-based THz-ISAC hybrid beamforming is proposed in [3], wherein two different learning models (one for DoA estimation and another for beamforming) are designed. This approach achieves approximately 200 times lower computation time while providing satisfactory SE compared to fully-digital beamforming (see Fig. 3).

Most of the ML algorithms rely on collecting the data from the edge devices, e.g., mobile phones, to a central server, wherein the learning model is trained. The size of the datasets usually scales with the number of antennas in the array. Hence, dataset transmission entails huge communications overhead (CO) in centralized learning (CL) schemes. To reduce the high CO in CL, federated learning (FL) approach is introduced for near-field THz channel estimation problem [14] where approximately 12 times lower CO is obtained while providing satisfactory NMSE performance (see Fig. 5). In order to achieve more communications-efficient learning capability, the sparsity of THz channels can be exploited to reduce the size of learning models, thereby developing quantized or compressed neural networks.

IV. OPEN PROBLEMS AND RESEARCH OPPORTUNITIES

The vision of THz-ISAC faces several design challenges, to name some, THz channel characteristics due to shorter S&C range, waveform design providing a joint signaling as well as beam misalignment and link failures due to pencil beamforming. In the following, we provide an extensive discussion and highlight the related research opportunities.

A. THz Channel Acquisition

Compared to its mm-Wave counterpart, THz channel estimation is more challenging due to the involvement of additional error sources to be modeled, e.g., beam split effect, near-/far-field channel modeling, etc.

1) Beam Split: True-time-delay (TTD) processing is conventionally used for THz channel estimation in the presence of beam split, wherein a time delayer network is used to realize analog beamformers similar to the DPP approach in [5]. While this approach necessitates additional time delayer network, signal processing-based approaches, e.g., beam split pattern detection (BPSD) [12] and beam split aware (BSA) OMP [14] can also be used for accurate THz channel estimation.

2) Near-field Beam Split: In contrast to far-field, wideband THz transmission in near-field causes beams to split in different directions as well as different distances. This leads to a new phenomenon called *near-field beam split* which is range-dependent and not easily mitigated by direct application of the far-field beam split correction techniques [14]. The near-field beam split leads to serious problems in both S&C. In this case, the transmitted signal fails to focus on the desired user/target location, at which only the beams generated at the central frequency can arrive. Furthermore, the radar receiver should take into account designing the matched filters with the impulse response of the range-dependent propagation channel as well as beam split. Fig. 5 shows the NMSE performance for near-field wideband THz channel estimation at 300 GHz with 30 GHz bandwidth [14]. Fig. 5 indicates that BSA-OMP attains close to minimum mean-squared-error (MMSE) estimation performance. We observe that the direct application of the far-field model (FF-OMP and BSPD) as well as the techniques that do not take into account the impact of beam split (NF-OMP and least-squares (LS)) yield poor NMSE performance. The BSA-OMP approach also involves FL which leads to performance loss arising from decentralized model training.

B. Waveform Design

The ISAC receiver is responsible for accurately demodulating the received communications signal while recovering the echo signal from the targets. When S&C signals do not overlap, conventional signal processing techniques can be employed. On the other hand, ISAC aims to improve the *integration gain* via joint processing of S&C signals, thereby reducing the hardware requirements [3].

For waveform design, the ISAC resource allocation can be performed in either communications-centric (CC), sensing-centric (SC), or unified design schemes. The former techniques may be easier at the cost of low efficiency; while the latter has improved accuracy in both S&C with high signal processing and computational complexity.

1) Physical Layer THz-ISAC Waveform Design: The wideband processing is critical in THz-bands, at which the Doppler spread causes ICI, which makes OFDM inapplicable, especially in high mobility cases. To this end, orthogonal time-frequency-space (OTFS) multiplexing techniques can provide robustness against the Doppler shift in THz-ISAC [9]. The OTFS is also advantageous in reducing the peak-to-average power ratio (PAPR), from which the OFDM systems suffer. Nevertheless, the OTFS-based waveform design comes with a non-negligible receiver cost and complexity. Instead, ML-based modulation classification techniques may be more efficient, wherein the 2D time-frequency frames can be used as input data. An efficient design is introduced in [10] by exploiting non-uniform multi-wideband (NU-MW) OFDM subcarriers. However, one should design the subcarrier spacing carefully in this technique since it needs to be less than the maximum Doppler shift, which may be application-dependent. In practice, adaptive methods may be helpful for controlling the subcarrier spacing.

The ISAC waveform design techniques should also take into account the THz transmission windows, which may shrink with the transmission range (see Fig. 1). By exploiting the transmission windows in THz, distance-aware approaches can be deployed for the THz-ISAC applications. That is, the central part of the bandwidth is dedicated to the long-distance users/targets while the S&C operations can benefit the whole bandwidth for the short-distance users/targets [6].

2) Higher Layer THz-ISAC Waveform Design: Most of the ISAC literature concentrates on physical layer design, while there are a few works on higher layer coordination of S&C with multiple access technologies. For instance, by utilizing the preamble sequence in IEEE 802.11ad frame, a radar-aware carrier-sense multiple access (RA-CSMA) is proposed in [4] for low-THz ($0.06 - 4$ THz) V2V ISAC. In particular, the sensing signals are treated as a packet in CSMA. Although this approach is advantageous in terms of SE, it may lead to a low sensing duty cycle in case of congestion of radars.

C. Beam Misalignment

Another challenging issue in THz-ISAC is beam misalignment due to pencil beamforming. In THz, the beamwidth is very narrow such that the beams at the transmitter and the users may not be aligned. While pencil beamforming with narrow beamwidth reduces the randomness of the path loss in the THz-band, it causes link failures, inter-cell handovers, and intra-cell beam switches. An ISAC-like approach (i.e., sensing-assisted communication) is developed in [11], wherein multiple synchronization signal blocks (SSBs) are transmitted to mitigate beam misalignment. It is reported in [11] that the sensing-aided approach reduces beam misalignment probability by up to 70%. On the other hand, the algorithm performance directly depends on the sensing accuracy.

D. Interference Management

The specific features of the THz-band, such as path loss and the Doppler shift, aggravate the ISAC interference management. The communications systems also suffer from multi-user interference. Similarly, suppression of clutter echoes (reflections from unwanted targets) is always a concern in radar processing. IRS-aided systems have shown encouraging results for clutter suppression by utilizing echoes from multiple NLoS paths [3, 8]. Advanced waveform design techniques may be employed such that the S&C systems ensure multiple access signaling via time, frequency, spatial, and code domains to prevent mutual interference. These non-overlapping resource allocation methods have a rich heritage of research and implementation. However, the objective of ISAC design is to integrate S&C seamlessly. To this end, recent overlapping resource management techniques have been shown to achieve a unified waveform design by maximizing the signal-to-interference-plus-noise ratio (SINR) of both systems with increased DoFs [9].

V. CONCLUSIONS

Despite the potential advantages of THz-band, several complex issues are yet to be addressed and present new research opportunities. This article provided a synopsis of state-of-the-art techniques for THz-ISAC design to combat these challenges using UM antenna array architectures, hybrid beamforming, and waveform design.

Each of these challenges should be taken into account together with THz-specific peculiarities for reliable THz-ISAC. For instance, one must consider the severe path loss and channel sparsity for array design in addition to new antenna design/fabrication techniques for extremely dense arrays. Both THz-ISAC hybrid beamforming and THz channel estimation techniques mandate the use of advanced signal processing for beam split correction because employing time delayer network approaches consumes more power.

Furthermore, distance-dependent bandwidth and Doppler shift should be considered for wideband THz S&C applications. Transmission range is also critical for accurately estimating the THz channel, which may necessitate a spherical propagation model.

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