THz ISAC: A Physical-Layer Perspective of Terahertz Integrated Sensing and Communication

Chong Han, Yongzhi Wu, Zhi Chen, Yi Chen, and Guangjian Wang

ABSTRACT

The terahertz (0.1–10 THz) band holds enormous potential for supporting unprecedented data rates and millimeter-level accurate sensing thanks to its ultra-broad bandwidth. Terahertz integrated sensing and communication (ISAC) is viewed as a game-changing technology to realize connected intelligence in 6G and beyond systems. In this article, challenges from the THz channel and transceiver perspectives, as well as difficulties of ISAC, are elaborated. Motivated by these challenges, THz ISAC channels are studied in terms of channel types, measurement, and models. Moreover, four key signal processing techniques to unleash the full potential of THz ISAC are investigated, namely, waveform design, receiver processing, narrowbeam management, and localization. Quantitative studies demonstrate the benefits and performance of the state-of-the-art signal processing methods. Finally, open problems and potential solutions are discussed.

INTRODUCTION

With the revolutionary enhancement of wireless data rates and the increasing demand for highly accurate sensing capability, a promising blueprint is expected to be realized: all things are sensing, connected, and intelligent [1]. The terahertz (THz) band, and integrated sensing and communication are two descriptive technologies for achieving such a vision for sixth generation (6G) and beyond wireless systems, by exploring the new spectrum as well as the new function of sensing, respectively. Two forces drive together to motivate the study of integration of these two technologies. On one hand, wireless links with terabits per second will become reality in the future intelligent information society. On the other hand, the ultra-broad bandwidth in the band also provides huge potential to realize ultra-accurate sensing (e.g., millimeter-level and millidegree-level accuracy).

Thanks to the abundant continuous bandwidth in the THz band [2], the integration of THz sensing and communication (THz ISAC) can enable simultaneously transmitting billions of data streams and ultra-accurate sensing by sharing the spectrum, hardware, and signal processing modules. In addition to enhancing the performance and functionality, THz ISAC is able to effectively reduce the hardware cost, and improve the spectral and energy efficiency [3]. In light of these, THz ISAC is envisioned to provide high quality of experience (QoE) for various future services and applications demanding ultra-high data rates and ultra-high-resolution sensing. As shown in Fig. 1, we envision the applications driven by THz ISAC technologies including smart urban and rural areas, smart transportation, smart home, smart health, smart web 3.0, and smart industry, among many other emerging ones to appear.

With an increasing level of integration, THz ISAC systems can be divided into the following four categories [4].

- At the bottom level, communication and sensing coexistence improves the spectral efficiency by encouraging frequency reuse for these two functionalities.
- At the second level, transmitting separate signals with partially or fully shared system hardware is helpful to reduce the cost, size, and weight of the system.
- To reach a higher level of integration, signal processing can be shared to jointly design and optimize the transmit waveform used for both communication and sensing.
- With full-fledged integration, THz ISAC systems evolve more successfully when the protocol and network design is shared beyond the physical layer design.

In this article, we investigate channel modeling and signal processing of THz ISAC from the physical layer perspective. First, we analyze the challenges of THz ISAC and difficulties of integration due to the peculiarities of THz channels and transceivers. Next, we analyze four signal processing techniques for THz ISAC systems, including transmit waveform, receiver processing, narrowbeam management, and localization. For each of them, problems and possible solutions are delineated, respectively. To assess the performance, numerical evaluations of THz ISAC channel, waveform, and receiver signal processing methods are elaborated. Finally, some open problems and potential research directions of THz ISAC are presented.

CHALLENGES OF THz ISAC

Despite the wonderful vision of the THz spectrum, challenges are still encountered from two
perspectives of THz propagation and devices. On one hand, the signal processing methods for THz ISAC, including the transmitter and receiver design, should be tailored for specific THz communication and sensing channels to make the best of the available spectrum. On the other hand, since the transceiver impairments increase drastically at higher frequencies, the signal processing strategy is more affected by the transceiver features when it comes to the THz band.

Challenges from THz Channel Perspectives

Propagation Delay: Since the reflection and scattering losses at THz frequencies depend on the angle of incidence and may result in strong power loss of a non-line-of-sight (NLoS) path and decreasing number of dominant rays, the delay spread of THz communication channel is reduced. Since cyclic prefix (CP) duration is usually set longer than the maximum delay spread, the CP length in the THz band can be reduced to improve spectral efficiency. Nevertheless, for classical orthogonal frequency-division multiplexing (OFDM) sensing systems, the round-trip delay of the maximum sensing distance should be smaller than CP duration. With the decrease of communication delay spread, the CP duration is reduced in THz ISAC systems and limits the sensing distance even when the link budget is sufficient [5].

Doppler Effects: Being proportional to the carrier frequency, the Doppler spread effect becomes even stricter in the THz band, especially in high-mobility scenarios. Doubly selective channels with high Doppler spreads may break orthogonality of subcarriers and cause inter-carrier interference. Increasing the subcarrier spacing can mitigate the Doppler effect, but it may sacrifice the velocity estimation accuracy.

Blockage Problem: Due to the strong penetration loss, the blockage effect needs to be considered in THz ISAC. THz waves nearly lose the ability to go through common blockages such as walls and human bodies. In an environment encountering various blockages, the line-of-sight (LoS) path between an access point and a user equipment might be blocked, and thus, the coverage distance of the access point would be reduced. Meanwhile, blockages may affect the accuracy of THz localization and map construction in realistic environments, since they can block some THz rays and reduce the number of channel features.

Near- and Far-field Propagation: In the THz band, when transmission distance is shorter than the Rayleigh distance of the antenna array, we need to consider near-field propagation. In this case, the planar-wave propagation, which is an approximation of spherical-wave propagation, becomes invalid and causes difficulties in beamforming.

Challenges from THz Transceiver Perspectives

Power Amplifier Efficiency: Noticeably, the saturated output power of power amplifiers (PAs)
Channel measurement is to obtain the channel response of the channel between the transmitter and receiver. The channel response contains information about the gain and delay of the multipaths.

THz ISAC Channel

Channel Measurement and Modeling

Channel measurement is done to obtain the channel response of the channel between the Tx and Rx. The channel response contains information about the gain and delay of the multipaths. The angular information of the multipaths draws much interest in ISAC channels. Therefore, the focus of channel measurement is to extend the ability of ISAC systems for positioning, e.g., time of arrival (ToA) to the angle of arrival and angle of departure. There are three categories of channel sounding methods for the wideband channel measurement. First, a vector network analyzer is leveraged to provide high beamforming gain. Herein, a beam squint effect arises in wideband ultra-massive multiple-input multiple-output (UM-MIMO) with analog or hybrid beamforming. Without full freedom of beam weighting, hybrid or passive structures utilize phase shifters that tune the same weights for all frequencies, and thus the beam directions may deviate away from the central one and off target. As a result, the array gain is substantially reduced, which affects the performance of sensing and communication.

Implementation Complexity: To support wireless links with ultra-fast data rates, THz transceivers must be well designed in terms of the implementation complexity. Since complex transceivers with terabit-per-second digital processors are still challenging, low-complexity signal processing methods are preferred, especially receiver processing, including channel parameter estimation and data detection. The algorithms should be designed with logarithmic or linear time complexity.

Challenges of Integration of Sensing and Communication

Integrating sensing function with communication encounters several challenges due to different requirements and objectives of signal processing and separate channels. First, when sensing and communication are scheduled on non-overlapped wireless resources in time, frequency, spatial, and code domains, resource allocation schemes need to be coordinated and optimized [3]. Second, if sensing and communication are integrated with a unified ISAC waveform, these two functionalities have different requirements on the waveform and modulations. Specifically, sensing demands good autocorrelation properties to realize high resolution, while communication prefers high efficiency and reliability. Third, the separation and intersection of sensing and communication channels are influenced by types of sensing services (e.g., active or passive sensing), which apply different designs for sensing receivers with or without knowledge of transmit signal. Fourth, since sensing aims to estimate target parameters while communication needs to recover transmit data, signal processing for sensing and communication is generally hard to integrate, which motivates novel multi-task receiver design.

In this section, the influence of some unique features of THz ISAC are described, such as propagation delay and spherical wave propagation. In addition, compared to the millimeter-wave (mmWave) band, many effects become more severe and cause stricter requirements on signal processing of THz ISAC (e.g., stronger Doppler effect, decreased saturated output power of PAs, and worsening beam squint effect). Considering these, innovative studies are presented in terms of THz ISAC channel, transmitter, and receiver signal processing.

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Nevertheless, the PAPR of OTFS is still not satisfactory considering THz PAs, and the receiver processing complexity of OTFS remains a pivotal issue. Recently, a discrete Fourier transform (DFT) spread OTFS (DFT-s-OTFS) waveform was proposed in [11] to reduce the PAPR of OTFS by developing a DFT precoding operation on the information symbols along the Doppler axis. In Table 1, the aforementioned THz ISAC waveforms are compared in terms of PAPR, guard interval design, pilot overhead, out-of-band emission, and detection complexity.

**RECOMMENDED METHODS FOR THZ ISAC**

**WAVEFORM DESIGN**

Sensing and communication can fully share the hardware and signal processing modules when jointly designing the ISAC transmit waveform, thereby reducing power consumption and signal processing complexity. OFDM is a potential ISAC waveform, since it has good compatibility with 4G and 5G standards. However, OFDM waveforms inherently suffer from a high PAPR and might induce undesirable clipping distortions in THz PAs [9]. Meanwhile, the Doppler shifts are difficult to handle in the time-frequency domain, while Doppler effects become stronger at THz frequencies.

When it comes to the single-carrier counterpart, DFT-s-OFDM and its variants are regarded as more potential candidate waveforms for THz ISAC, thanks to their low PAPR compared to multi-carrier waveforms. DFT-s-OFDM data signals present Gaussian randomness in the frequency domain, which causes severe noise amplification in point-wise division of OFDM sensing [5]. Thus, constant-enveloped pilot signals can be employed to conduct sensing parameter estimation.

In contrast, orthogonal frequency time space (OTFS) modulation can deal with Doppler effects and conveniently accommodate the channel dynamics in the delay-Doppler domain [10]. Nevertheless, the PAPR of OTFS is still not satisfactory considering THz PAs, and the receiver processing complexity of OTFS remains a pivotal issue. Recently, a discrete Fourier transform (DFT) spread OTFS (DFT-s-OTFS) waveform was proposed in [11] to reduce the PAPR of OTFS by developing a DFT precoding operation on the information symbols along the Doppler axis. In Table 1, the aforementioned THz ISAC waveforms are compared in terms of PAPR, guard interval design, pilot overhead, out-of-band emission, and detection complexity.

**RECEIVER SIGNAL PROCESSING**

Despite the promising sensing and communication abilities of THz ISAC waveforms, it is crucial to design signal processing methods at the receiver side due to the following challenges. For OFDM and DFT-s-OFDM systems, the link performance might be seriously deteriorated by severe nonlinear distortion effects at the THz transceivers, such as phase noise effects and Doppler effects in high-mobility scenarios (as discussed earlier). In this case, deep-learning-based methods are developed to improve the sensing and communication performance, thanks to the stronger robustness against non-ideal conditions in contrast to conventional methods.

While OTFS is proposed to deal with the Doppler effects, the implementation complexity of an OTFS Rx is a significant challenge. To be specific, channel parameter estimation and data detection of OTFS have high complexity. To realize high-speed baseband digital processing in the THz band, the computational efficiency of OTFS systems by using iterative least squares (LS) algorithms is designed in [11], since the derived channel matrix with fractional delay and Doppler inherent shifts are difficult to handle in the time-frequency domain, while Doppler effects become stronger at THz frequencies.

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| Methods                                      | Functionality                                                                 |
|---------------------------------------------|-------------------------------------------------------------------------------|
| Sensing                                    | Channel estimation               | Equalization/ data detection       | Applicable waveform                  | Complexity                              | Remarks                      |
| 2D FFT                                     | ✓                               |                                   | OFDM, DFT-s-OFDM                     | $O(MN \log(MN))$                       | Low resolution               |
| MUSIC                                       | ✓                               |                                   | OFDM, DFT-s-OFDM                     | $O(MN^2)$                             | High accuracy with high complexity |
| Sensing neural network                      | ✓                               |                                   | OFDM, DFT-s-OFDM                     | $O(MN)$                               | Reducing complexity order     |
| LS estimation and channel interpolation     | ✓                               |                                   | OFDM, DFT-s-OFDM                     | $O(MN)$                               | Estimating channel frequency response |
| MMSE                                        | ✓                               |                                   | OFDM, DFT-s-OFDM; OTFS, DFT-s-OTFS   | $O(MN)$; $O(MN^2)$                    | High complexity for OTFS      |
| Communication neural network                | ✓                               |                                   | OFDM, DFT-s-OFDM                     | $O(MN)$                               | Improving robustness against phase noise and Doppler effects |
| Multi-task neural network                   | ✓                               | ✓                                 | OFDM, DFT-s-OFDM                     | $O(MN)$                               | Integrated signal processing for ISAC receivers |
| Message passing based detector              | ✓                               |                                   | OTFS                                | $O(n_{iter} M N)$                      | Inapplicable to DFT-s-OTFS   |
| On-grid search + off-grid search            | ✓                               | ✓                                 | OTFS, DFT-s-OTFS                     | $O(MN \log(MN))$                      | Modest complexity compared to exhaustive search |
| Iterative LS algorithms exploiting FFT      | ✓                               |                                   | OTFS, DFT-s-OTFS                     | $O(MN \log(MN))$                      | Reducing complexity compared to MMSE |

Note: $M$ and $N$ denote the number of used subcarriers and symbols, respectively. $n_{iter}$ refers to the iteration times.

**TABLE 2.** Receiver signal processing methods for THz ISAC waveform.

**Narrowbeam Management**

When using directional beams to overcome severe path loss in the THz band, communication and sensing have different objectives, which may cause conflict on the beam directions. On one hand, sensing prefers scanning beams in the search phase and accurately directing beams toward targets in the estimation phase. On the other hand, communication requires several stable beams toward multiple users. When THz channels are shared between sensing and communication, the angle of departure and angle of arrival information of communication beams can be exploited to assist sensing and localization in beam-based THz ISAC systems. Thus, effective narrowbeam management schemes are important to realize ISAC in THz UM-MIMO systems, including beamforming design, beam scanning, beam tracking, and cooperative beamforming.

To manage multiple narrowbeams for THz ISAC systems, two stages, target searching and target estimation, can be established. In the first stage, scanning beams are generated to search for possible targets in the surrounding environment. The beam squint effect causes beam misalignment from the central direction at non-central frequencies, which can be exploited to widen the scanning sensing beams and accelerate seeking a target of interest. At the second stage, when estimating parameters of the sensing target, the beam squint effect needs to be mitigated to focus the sensing beam in the target direction. A promising solution to solve this problem is to use THz dynamic subarray with fixed-truetime-delay (DS-FTTD) hybrid beamforming architecture [6]. For array of subarrays (AoSA) or fully connected hybrid beamforming structures, the subspace-based methods, including MUSIC and ESPRIT, can achieve super-resolution angle estimation by exploiting the subspace conducted from eigenvalue decomposition. To further address the problems of super-precision AoA estimation and tracking in THz dynamic array of subarray (DAoSA) systems, the DL-based methods can be designed to capture the angle variation with reduced computational complexity and beamforming training overhead.

**Localization and Map Reconstruction**

As popular sensing services, high-accuracy localization and map reconstruction have gained increasing attention. Thanks to the ultra-broad bandwidth, centimeter-level and even millimeter-level localization can be realized by employing the channel state information (CSI) of THz signals, including angle of arrival, received power, and propagation delay [14]. While geometry-based and learning-based algorithms for THz localization systems are investigated in [15] based on these input features, we can use the aforementioned receiver processing methods to extract them from the THz ISAC signals, as elaborated earlier.

It is a significant problem to realize high-precision localization based on CSI. A DL-based solution can be developed to solve the 3D THz indoor localization problem with an offline stage and an online stage [14]. In the offline stage, based on multiple THz access points (APs), we first extract the CSI features from the received signals at the user equipment (UE) to build the dataset and train a neural network model. Then in the online stage, we deploy the trained DL model at the UE, which is employed to predict 3D UE coordinates and realize ultra-accurate real-time localization.
Performance Evaluations

In this section, we provide numerical results to quantitatively illustrate the channel properties and the performance of the state-of-the-art signal processing methods for THz ISAC.

THz ISAC Channel

Monostatic and bistatic channel measurement in the low THz band has been conducted in indoor meeting room, office room, and outdoor scenarios. In particular, a monostatic channel measurement campaign at 140 GHz from [8] has been conducted for sensing an office room. As shown in Fig. 2, the transmitter/receiver (Trx) is surrounded by cubicles, and the power of the received THz echoes from the scanned directions are represented by different colors. The transmitter scans the surrounding environment in the azimuth domain from 0° to 360° with a spatial rotation step of 1°. The receiver extracts the round-trip delay from the channel impulse response, and identifies the locations of the cubicles and the walls of the office room. To assess the accuracy of reconstruction, the error between the reconstructed geometry and the measured office room is calculated to follow an exponential distribution, with the mean value of 0.39 m.

Signal Processing for THz ISAC

While comparisons between OFDM and OTFS have been studied in the literature, we introduce two candidate waveforms for THz ISAC, DFT-s-OFDM and DFT-s-OTFS, to compare their PAPR performance and sensing accuracy. To list the key simulation parameters, the carrier frequency equals 0.3 THz. The subcarrier spacing is set as 1.92 MHz. A 4-QAM (quadrature amplitude modulation) scheme is employed. The PAPR of these waveforms is evaluated by conducting 4× oversampling on the discrete-time baseband signal. As shown in Fig. 4, we learn that all of these waveforms can achieve millimeter-level range estimation accuracy. Moreover, the range estimation error can be reduced by increasing the subcarrier number from 64 to 128 and the symbol number from 16 to 32.

In summary, in low-mobility channels, OFDM is still an excellent candidate for THz ISAC, and achieves good sensing and communication performance since it enables good compatibility with UM-MIMO, and flexible multi-user scheduling and resource allocation. In high-mobility scenarios, DFT-s-OTFS provides stronger robustness to severe Doppler spread by exploiting the channel sparsity of delay-Doppler domain, while it comes at the price of increased detection complexity. For energy-constrained links, DFT-s-OFDM and DFT-s-OTFS are shown to realize high energy efficiency due to their low PAPR characteristics.

Open Problems and Potential Research Directions

THz ISAC Transmission

Despite the PAPR issue, OFDM is still a potential candidate waveform for THz ISAC. Without inter-symbol interference, OFDM enables flexible multiple access (i.e., allowing multiple users to select their own subset of time-frequency resource blocks). In addition, sensing-centric waveform with embedded information data may improve the sensing resolution while sacrificing the spectral efficiency.
schemes of THz ISAC systems, including half-du-
plex, full-duplex, and hybrid-duplex (i.e., commu-
nication is half-duplex while radar is full-duplex). When using half-duplex schemes, the sensing dis-
tance is limited by the switching time between trans-
mitter and receiver mode at both the base sta-
tion (BS) and UE. In addition, it is still an open
issue whether the functionality of THz sensing
should be supported at BS, UE, or both.

**THz ISAC with UM-MIMO**

While THz ISAC systems are usually enabled with
UM-MIMO, the compatibility between UM-MI-
MO and transmit waveform needs to be consid-
ered. Moreover, with narrow beams generated
by UM-MIMO, interference management is still
a significant issue, such as intra-cell and inter-cell
interference management when performing THz
sensing. In this case, unique sensing sequences
in UM-MIMO systems must be interference-resis-
tant, in which their length and amount need to be
optimized for different scenarios, including vehic-
ular networks, and outdoor and indoor wearable/
handheld applications.

In THz ISAC systems with UM-MIMO, shar-
ing of spatial resources is indispensable. To some
extent, the beamforming gain of wireless links
needs to be controlled, since the energy might
leak in other angles apart from the direction
toward the desired user. Thus, to achieve a sat-
isfying trade-off between high communication
capacity and high-resolution sensing ability, spatial
resources need to be flexibly scheduled while sat-
isfying the sensing requirements.

**Immersive Resource Allocation**

Besides the spatial resource allocation, frequen-
cy-division, time-division, and mixed schemes for
resource allocation among communication and
sensing need to be investigated. In a communi-
cation framework, several types of signals can be
employed for sensing, such as data payload signals,
signal synchronization blocks (SSBs), and demod-
ulation reference signals (DMRS). However, it is
still not determined which type and how much
resource of these signals should be used for THz
sensing. Moreover, sharing such resources results
in performance trade-off between sensing accuracy
and communication capacity.

In addition to the above allocation problems, it is
an open issue to intelligently allocate the associ-
ated access points for users and sensing functionality
in the presence of blockages. Artificial intelligence tec-
niques can be leveraged to optimize the resource
allocation schemes in such scenarios.

**Conclusion**

THz ISAC is a key promising enabler to meet
demands for next-generation wireless systems. In
this article, channel modeling and signal process-
ing techniques are investigated to overcome the
challenges and improve the performance of THz
ISAC. Channel modeling and measurement meth-
ods of THz ISAC are summarized. Four signal pro-
cessing technologies, including waveform design,
receiver signal processing, narrowbeam manage-
ment, and localization, are thoroughly analyzed
and evaluated. Finally, open problems and poten-
tial research directions are stated.

**Acknowledgment**

The work of Chong Han was supported in part by
the National Key Research and Development Pro-
gram of China under Project 2020YFB1805700.

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