Terahertz Wireless Communications for 2030 and Beyond: A Cutting-Edge Frontier

Zhi Chen, Chong Han, Yongzhi Wu, Lingxiang Li, Chongwen Huang, Zhaoyang Zhang, Guangjian Wang, and Wen Tong

***Abstract*—For 6G in 2030 and beyond, key performance metrics long for Terabit-per-second, one-tenth of millisecond latency with zero jitter, millimeter-precision sensing and positioning, and seamless connectivity, among others. To meet these demands, the Terahertz (0.1-10 THz) band comes into the horizon, with ultra-broad bandwidth and sub-millimeter wavelength, which however suffers from distance limitation and power consumption concern. In this paper, four interdisciplinary directions to address the above challenges and unleash the full potential of THz communications are investigated, namely, integrated sensing and communication, ultra-massive MIMO and dynamic hybrid beamforming, intelligent surfaces, and machine/deep learning. Furthermore, open problems as well as integration of these solutions are elaborated. Qualitative and quantitative studies demonstrate the benefits and performance of the proposed solutions.**

I. Introduction

With the rapid development of 5G, not only humans will be better connected, but also more and more intelligent things such as industrial equipment, cars, sensors, and home devices will all be connected. This trend will continue beyond 2030, leading to *intelligent connection of everything, anywhere, all-time*. Accompanying the exponential boost of the number of interconnected devices, 6G in 2030 and beyond foresees the key performance indicators (KPI) including: i) hundreds of Giga-bit-per-second and even Terabit-per-second (Tbps) rates, ii) lower latency of around one-tenth of millisecond, and close to zero jitter performance, iii) higher positioning and sensing resolution and accuracy at millimeter level, iv) reduced energy consumption and 100$\times$ improved energy efficiency, v) 99.99999% improved reliability, security, and scalability [1]–[3].

To support these demands for future wireless communications, National Institute of Standards and Technology (NIST) on Future Generation Wireless Research and Development Gap states that *"future generation networks will need to leverage higher frequencies (above 6 GHz and up to THz) in conjunction with existing technologies (below 6 GHz) in order to meet the performance expectations of seamless user connectivity, improved speed, and ultra-reliability."* To this end, *Terahertz (THz) band (0.1-10 THz) communication* is a promising pillar technology to fulfill the demands of 6G for 2030 and beyond [4].

The use of the THz frequency band will open up new applications for future ultra-high data rate communication and high resolution sensing scenarios, including Tbps indoor wireless links (e.g., for virtual and augmented reality, holographic communication, etc.), and wireless backhaul and access in small cell networks, and also the interconnection among micro/nanoscale machines or nanomachines. In addition to the communication applications, the THz band will also enable high resolution and accuracy sensing scenarios, including the millimeter-resolution wireless positioning and tracking, gesture and motion recognition high-accuracy imaging and mapping, augmented human sense, among others [5].

While owing ultra-broad bandwidth to support Tbps wireless transmission, two major challenges for THz communications are to overcome coverage distance limitation and improve energy efficiency, in light of the following THz features. On one hand, with the increase of carrier frequencies and ultra-short wavelength, THz wave propagation suffers from higher spreading loss, as well as stronger non-line-of-sight (NLoS) propagation losses caused by diffuse scattering and specular reflection, diffraction and shadowing. In addition, it is further attenuated by the weather influences due to atmospheric effects in the propagation medium. On the other hand, the lack of THz transceivers with high transmission power results in lower transmit power than in the microwave band. Although it is possible to boost the transmit power using phased-array architecture, it comes at the expense of having highly directive radiation beams. Meanwhile, the noise power increases proportionally with the used bandwidth and the receiver noise figure becomes about 10 dB higher compared to the microwave band [6].

As overviewed in Fig. 1, in this paper we investigate four interdisciplinary technologies for 6G THz communications, to overcome distance limitation and enhance the energy efficiency. First, we analyze the THz *integrated sensing and communication (ISAC)*, which enables sharing of spectrum, hardware, signal processing and mutually enhanced performance. Second, we design *ultra-massive MIMO (UM-MIMO)* and propose hybrid beamforming, for which dynamic array-of-subarray to enhance energy efficiency and fixed true-time-delay (FTTD) to mitigate beam squint are developed, respectively. Third, we delineate the design of *intelligent surfaces (IS)* to realize reconfigurable wireless environments. With smart placement of IS and holographic MIMO, THz IS can efficiently address line-of-sight (LoS) blockage and enhance the signal coverage and physical-layer security. Finally, we study *machine/deep learning (ML/DL)* to address high dimension, vulnerable transmission, model-free, among other features of THz communications. For each of the above four technologies, new research directions and key ideas are elaborated in our paper. Meanwhile, interdisciplinary studies on the above four technologies are investigated in terms of open problems and

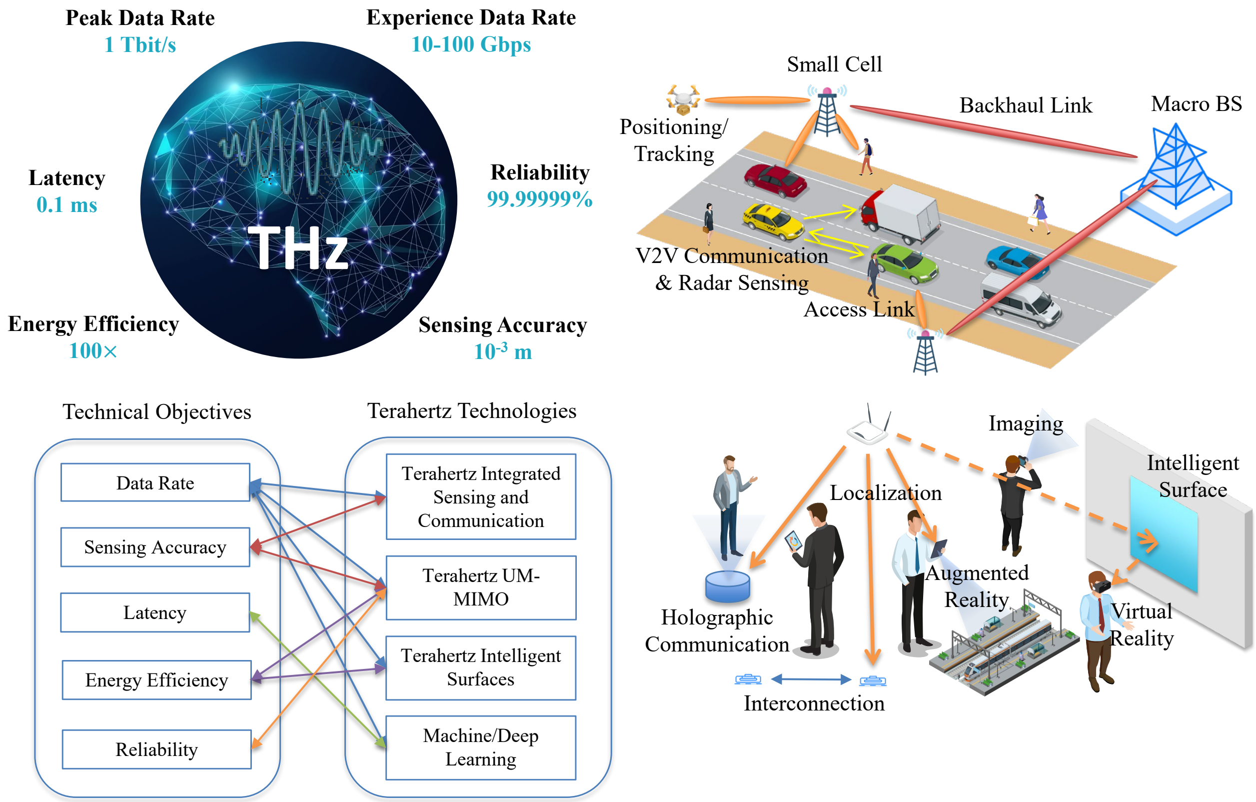

Fig. 1. 6G requirements and applications driven by four Terahertz technologies.

possible solutions for the joint design of these technologies. Few existing papers discuss the integration of these four technologies to unleash the full potential of THz wireless communications and meet the KPIs of 2030 and beyond, while addressing the challenges of distance limitation and power consumption concern. In addition to the key ideas and open problems, numerical evaluations of these THz interdisciplinary technologies are presented.

II. Terahertz Integrated Sensing and Communication

A. Key Concepts and Ideas

Following the trend of sensing and connecting all things in 6G communications, THz wireless systems are expected to simultaneously transmit billions of data streams and sense the environment or human activity, namely, *THz integrated sensing and communication (ISAC)*. On one hand, by sharing the frequency bands, hardware, and signal processing modules, the integration of THz communication and sensing can enhance spectrum efficiency, and reduce the hardware cost and computational complexity. On the other hand, by extracting features and information from THz signals, THz ISAC is able to prompt communication and sensing to assist each other and further realize Tbps links and millimeter-level sensing accuracy [7].

THz ISAC systems can be divided into the following five classes with an increasing level of integration. At the bottom level, communication and sensing coexistence encourages sharing the same spectrum for these two functionalities and improves the spectrum efficiency. A typical scenario is a communication system sharing the same frequency band with a co-located radar system, where interference is a major issue. While narrow beams can weaken such interference in the THz band, the high density of 6G networks might result in non-negligible interference. Thus, efficient interference management techniques are required to avoid the conflict of communication and sensing signals [8]. At the second level, the system hardware is partially or fully shared, such as using radio frequency (RF) front-end in common. In particular, the floor-plan for the single-chip integration of the mmWave radar and 5G communication transceiver is proposed in [9] by adopting sub-harmonic injection locking. In this case, an integrated system can share the hardware, although using separately transmitted signals, which could reduce the cost, size and weight of the system [10]. To reach a higher level of integration, a common transmitted waveform is required to be jointly designed and optimized for both communication and sensing [8]. When processing a single transmitted waveform, sensing and communication can fully share the transmitter in terms of the hardware and signal processing modules and thus, reduce power consumption and signal processing complexity [10]. Beyond the physical layer design, THz ISAC systems evolve more effectively when an interface is provided to share information across different layers, functionalities, and nodes. For instance, beam alignment and tracking can be implemented by employing sensing feedback, and wireless devices can be localized based on the features of THz communication signals.

Ideally, at the top level, communication and sensing interact with each other to realize mutually enhanced performance.

B. THz ISAC Technologies

1) Waveform design for THz ISAC: With multiple objectives including sensing targets and information transmission, when a THz ISAC system transmits a common designed signal, there exists different requirements on the shared waveform in terms of modulation schemes, transmit power, bandwidth, among others. Based on communication waveforms, including single-carrier, orthogonal frequency division multiplexing (OFDM), orthogonal time frequency space (OTFS), a number of ISAC systems are proposed with corresponding sensing algorithms and display promising communication and sensing abilities. When it comes to the THz band, single-carrier family, containing DFT-s-OFDM and its variants, is regarded as more potential candidate waveforms for THz ISAC due to the following two aspects. First, with limited multi-path and high antenna directivity, the coherence bandwidth of the THz channel is increased and thus its frequency-selectivity characteristic is weakened. Second, single-carrier waveforms are able to achieve lower peak-to-average power ratio (PAPR) than multi-carrier modulations and thus decrease the power backoff of power amplifiers (PAs). As a result, the average transmit power is improved and the efficiency of THz communication and sensing is promoted.

2) Beamforming design for THz ISAC: With the usage of directional beams to compensate for severe path loss in the THz band, conflict may occur among communication and sensing due to the distinction of their objectives, i.e., sensing prefers scanning beams to search targets as much as possible, while communication requires stable beams towards receivers. To harmonize communication and sensing, a feasible approach is to generate and update multiple beams, namely, integrating a fixed sub-beam for point-to-point communications and several time-varying sub-beams for sensing purposes. Nevertheless, sharing of spatial resources sacrifices the beamforming gain of wireless links, since the energy of transmit signals is not concentrated on the direction toward the desired user. Thus, flexible scheduling of spatial resources while satisfying the sensing requirements contributes to achieving a good tradeoff between the high data rate and high-resolution sensing ability.

3) Deep learning powered THz ISAC: Driven by a huge amount of data streams in the THz networks, deep learning techniques that relate to Sec. V can empower THz ISAC to gain more potential, specifically, in the following three aspects. First, deep learning is able to address the imperfections of THz systems better than classical signal processing methods when recovering transmission data. Second, it paves the way to design an integrated detector for communication and sensing. As an example, THz ISAC can be viewed as a multi-task learning problem, i.e., signal recovery and sensing parameter estimation. With the received data symbols as input features, we are able to train a deep neural network that performs well for both communication and sensing functionalities. Third, a lot of information about the environment and human activity can be mined from THz signals by using learning based techniques, such as THz indoor localization based on channel state information (CSI) features.

C. Open Problems

1) RF front-end impairments mitigation and compensation: Strong RF impairments appear at the THz transceivers, including phase noise at the local oscillator (LO), non-linear distortion of PA, the imbalance between in-phase/quadrature (IQ) branches, and may influence the link performance seriously. THz ISAC systems need to be well designed to mitigate or compensate these hardware imperfectness.

2) Sensing parameter estimation and pattern recognition: The goal of sensing is to estimate the physical parameters, including target range and speed, as well as to monitor the state or pattern of the environment and human. Regarded as non-linear problems, efficient design of the sensing estimators and pattern analysis techniques, such as using deep learning powered detectors, for THz ISAC is required.

3) Cooperative beamforming and resource allocation: Benefiting from the sensing feedback, wireless access points can conduct cooperative beamforming to track the location with reduced pilot overhead and latency. Furthermore, the allocation schemes of communication resources can be optimized according to dynamic environments and user information served by sensing to provide enhanced quality-of-experience of user association.

III. Terahertz Ultra-Massive MIMO and Dynamic Hybrid Beamforming

A. Concepts and Challenges

To overcome the distance limitation of THz communications, THz UM-MIMO that equips with hundreds and thousands of antennas is coming into the play in the first place. In the THz band, hybrid beamforming utilizes the ultra-massive antenna array by combining digital and analog domain signal processing, and substantially reduces the number of RF chains compared to the fully digital beamforming, while achieving a comparable performance. Many challenges arise for THz hybrid beamforming, in light of the following THz peculiarities. First, as a result of blockage and huge reflection and scattering losses, the THz channel has high sparsity and the resulting spatial degree-of-freedom is limited below 5, which strictly limits the potential of spatial multiplexing. Second, the energy efficiency of the very large array is stringent, by considering the power consumption of 1024 or more antennas, phase shifters (PSs), switches, etc. Third, planar-wave approximation becomes inaccurate as the antenna spacing could extend to tens of wavelength. Fourth, beam squint effect could cause over 5 dB array gain loss due to the multi-GHz bandwidth.

B. THz Dynamic Hybrid Beamforming

1) THz DAoSA architecture: With the aim of reducing power consumption while maintaining enticing spectral efficiency, the dynamic array-of-subarray (DAoSA) architecture with flexible hardware connection is envisioned [11]. In this design, the antennas are divided into multiple subarrays, and switches are inserted between each RF chain and each subarray. The state of switches, i.e., open and closed, are intelligently determined to control the connection between the RF chains and the subarrays.

2) THz dynamic subarray FTTD-based architecture: With wideband communications in the THz band, e.g., 30 GHz bandwidth at the center frequency of 300 GHz, a severe beam squint problem appears, mainly due to frequency-independent adjustment of PSs. Over the very large antenna array and ultra-broad bandwidth, the generated beams are deviated from the pointing direction, which causes reduction of the array gains. To this end, true-time-delay (TTD) architecture that substitutes PSs is promising, which is frequency-dependent across the frequency spectrum. As a result, the PS adjusted by TTD is designed to be proportional to the carrier frequency, which thereby well compensates the beam squint effect in the wideband THz hybrid beamforming system. To further reduce the hardware complexity, the design of fixed TTD with pre-defined delay parameters is promising. Combining with a low-complexity switch network, the resulting dynamic subarray fixed TTD can achieve satisfactory spectral efficiency while largely reducing the power consumption and hardware complexity.

C. Open Problems

1) Hardware-efficient design: When it comes to the THz band, the hardware challenges increase drastically, e.g., high-resolution PS, TTD, and DAC/ADC are still difficult to produce. Therefore, THz hybrid beamforming architectures and algorithms used for low-resolution PS, TTD, and DAC/ADC are urgently needed when implementing practical systems with satisfactory energy efficiency. To realize THz hybrid beamforming, one alternative direction is to investigate lens array. With a matching antenna array placed on the focal surface of an electromagnetic lens, it can focus the THz wave.

2) Influence of imperfect channel state information: It is challenging to obtain perfect channel state information (CSI) of the THz UM-MIMO channel due to its high-dimensional feature. In addition, with ultra-sharp beam generated by THz UM-MIMO systems, imperfect CSI and beam misalignment will significantly degrade the performance. As a result, on one hand, millidegree-precision angle and reliable channel estimation methods need to be developed. On the other hand, THz hybrid beamforming algorithms, which are immune to imperfect CSI, are required to be investigated.

IV. Terahertz Intelligent Surfaces

A. Concepts and Ideas

Intelligent Surface (IS) refers to a low-cost smart thin composite material sheet, which is comprised of metallic or dielectric scattering particles and can be realized by different technologies. When the IS is made of discrete tiny antenna elements, the inter-distance of particles is often equal to half of the wavelength of the radio waves, while when the IS is made of meta-surfaces, the inter-distance is usually 5-10 times smaller than the wavelength. These elements are usually controlled by a central processor, which manipulates the reflecting amplitude and phase shift of each element and thereby, leading wireless environment into a transformable EM space [12].

In the reconfigurable wireless environments, IS can be a transmitter, receiver, or reflector. At the transceiver, the IS is active for which energy-intensive RF circuits and signal processing units are embedded in the surface. By contrast, when aiding as a reflector, the IS is passive and becomes a passive metal mirror or “wave collector”, which usually consists of passive elements with no power consumption.

B. THz IS Technologies

1) Placement of IS: While IS-based systems are capable of reconfiguring the EM propagation, it is natural to expect that IS-based wireless communication systems exhibit unique features. For example, when the LoS path is blocked by obstacles, the capacity performance without IS sharply drops. Instead, by adjusting the beam direction toward IS and maximizing the reflected signal strength of the receiver, the IS-aided communication system is able to maintain good link performance. Another example is the multi-hop IS-assisted THz communication networks, where the IS-aided THz communication system can noticeably improve the capacity performance and provide a better coverage capability than the one without IS [13].

2) Holographic MIMO: With the help of metasurfaces comprised of sub-wavelength metallic structures, it is possible to integrate a massive, possibly infinite, number of antennas in a compact space. For example, for an IS of size 3cm*3cm and working at 1 THz, 1000*1000 meta-atoms can be accommodated, with spacing between meta-atoms at one-tenth-wavelength. This type of planar structure is referred to as holographic MIMO Surfaces, which can realize extreme spatial resolution and unprecedented spectral efficiency. Different from UM-MIMO in Sec. III, holographic MIMO can realize the continuous receive and transmit aperture, and its transmission mechanism is transformative difference by leveraging the interference and diffraction principle. The unprecedented abilities of holographic MIMO makes IS an emerging candidate for building connections, enhanced in-building coverage, energy-efficient beamforming, physical-layer security, and high accurate indoor positioning.

C. Open Problems

1) Environment-aware channel estimation: Environment-aware beamforming is on the premise of accurate channel estimation. For passive IS, it does not possess any active components and thus has no ability to implement signal processing required by channel estimation. To this end, a binary-reflection controlled channel estimation scheme can be utilized, with further reduced network latency. For active IS, due to the very large UM-MIMO channels, it requires extremely intensive pilot overhead. To further consider user mobility, it is more challenging to design efficient time-varying channel estimation schemes with low latency for the IS-enabled THz communication scenarios. Furthermore, fundamental limits including the mathematically tractable and numerically reproducible channel models that characterizes holographic MIMO are still yet to be conclusively established.

2) Near-field communications: In some application scenarios, e.g., indoor environments, IS may operate in the near-field regime. In this case, the use of geometrically large IS opens the possibility of building new wireless networks. A consequence of using extremely large IS is that the aperture can resolve not only the AoA/AoD of a wave but also the channel gain differences to the meta-atoms. This makes channel modelling and beam management harder than the one for far-field communications. Due to the sub-wavelength spacing between elements, realistic models by taking coupling into account for the propagation of the signals scattered by metasurfaces are also needed, making the channel modelling more challenging.

3) Joint active and passive beamforming: To mitigate the LoS blockage and extend the coverage of THz communications, joint active and passive beamforming that employs IS at the transceiver as well as in the propagation environment needs to be analyzed [6]. The hybrid beamforming architecture performs active beamforming at the transmitter and receiver to improve the strength of the signal and the data rate. Meanwhile, IS embedded in the environment can provide passive beamforming to adjust the phase of the incident signal and control the direction of the reflected signal, to further increase the signal strength. Hence, new signal processing algorithms and networking protocols for the joint design of UM-MIMO and IS technologies are needed for capacity optimization and smart placement of IS.

V. Machine/Deep Learning Powered THz Communications

A. Concepts and Ideas

As we all know, current wireless communications intemperately rely on mathematical models that define the wireless signal transmission over the air. However, such mathematical models usually are inaccurate to characterize the physical systems. Moreover, in some typical communication scenarios, we usually do not obtain their mathematical equations, for example, in the dense building blocks of wireless networks, indoor THz Communications, etc. On the other hand, the ML/DL-enable method as an extraordinarily remarkable technology has been introduced in recent years for addressing the high-dimension, complex electromagnetic environment, model-free, and intractable non-linear issues. In light of inherent challenges of THz communications, like high dimension, vulnerable transmission, model-free, etc., overwhelming research interests are poured into ML/DL technology for the future 6G THz Communications systems for dealing with the non-trivial problems [14], [15], such as channel estimation, beamforming design, beam tracking and blockage predication, interference mitigating, etc.

B. ML/DL-empowered THz Technologies

1) Channel estimation: Due to the very high operating frequency and a limited number of RF chains in THz Communications systems, channel estimation is a very critical and challenging problem. To solve this challenge, some ML/DL-empowered solutions are proposed in the existing works. On one hand, it is to formulate the channel estimation of THz communications as the sparse recovery problem by exploiting the sparsity, then, a general neural network can be proposed to obtain the sensing matrix and achieve the signal reconstruction simultaneously. On the other hand, channel estimation along with other modules, e.g., coding, modulation, demodulation, etc., can be realized in an end-to-end autoencoder.

2) Beamforming design: Intelligent beamforming and smart antenna steering solutions can significantly improve the performance of the throughput, spectral efficiency and energy efficiency, mitigate interferences, increase coverage, and enable highly mobile applications. The intelligent beamforming solution is already an integral part of current 5G communications and will be promoted further for THz 6G communications leveraging the advantages of ML/DL, where digital beamforming and analog beamforming of the communication chains will be characterized by some levels of intelligence or at least capacity to operate in an optimal way following some degrees of training.

3) Beam tracking and blockage predication: Intelligent beam tracking and blockage predication technologies are also critical techniques to enhance the robust communication links and overcome the path loss. Usually, tracking the user's mobility is the foundation for beam tracking in highly mobile THz systems, however, traditional methods, like Kalman filtering-based method, have a high computation complexity. ML/DL-enable techniques to learn the mobility of users and blockage open a new era of user-trajectory-based beam tracking and blockage prediction methods for future mobile THz communication systems. Intelligent blockage prediction and agile scheduling in relay networks can be inspired by deep learning to address the LoS blockage problem, which aligns with the motivation of THz IS design in Sec. IV.

4) Interference mitigating: In the dense Terahertz networks, a large number of users access the transmissions will cause substantial interference due to the uncoordinated directional transmissions, while such interference is usually received randomly in a short time interval, and the received power is also strong. To solve the challenge, ML/DL-based methods, such as reinforcement learning is leveraged to efficiently detect and intelligent cancel the intermittent interference from uncoordinated directions, but with much less computation time, which lays the foundation for intelligently supporting massive connectivities and diverse services.

C. Open Problems

1) Scalability for global intelligence: ML/DL-based methods consist of many different models, of which the scalability and efficiency are challenging. Furthermore, the THz communications usually are vulnerable to the environment and changes, which result in the considered ML/DL methods that are difficult to adopt for the many different dynamic scenarios.

2) High computation overhead: The wider bandwidth and higher throughput in the THz communications pose a higher demand for training and running the machine learning models.

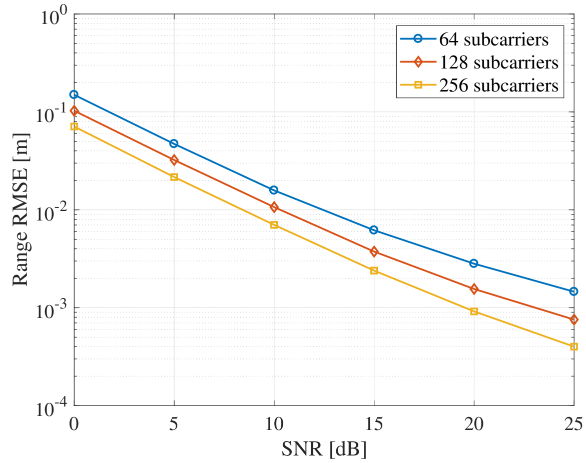

Fig. 2. Range estimation accuracy of THz sensing versus SNR using different numbers of subcarriers.

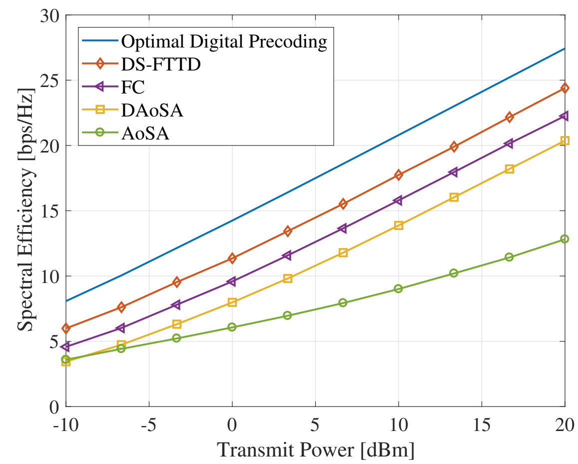

Fig. 3. Spectral efficiency versus transmit power with various THz hybrid beamforming architectures.

Furthermore, THz communications are usually integrated the current mobile networks by heterogeneous ways with a great number of connected devices. As a result, it is also not realistic to replace all current communication infrastructure with the newest developed computation facilities. These challenges inevitably arise to higher computation overhead.

3) Communication-efficient ML/DL: Efficient training and inference are foundation for the perfect integration of ML/DL and THz communication systems. However, it is also challenging for ML/DL, i.e., federated learning, to achieve efficient model training and inference in a super massive and heterogeneous network, which is because the communicating over the volatile THz channels and allocating the resource of the neural networks to the computing devices with limited computational capacity in the heterogeneous networks inevitably consume more resources and time.

VI. Performance Evaluation

In this section, we provide numerical results to quantitatively illustrate the benefits of the aforementioned four interdisciplinary technologies, which act as four pillars to support extended coverage and low power consumption THz communications.

1) THz Integrated Sensing and Communication: In THz communication systems, we can exploit both the pilot signals used for channel estimation and data payload signals to conduct THz sensing. We hereby consider range estimation accuracy using reference pilot signals in THz ISAC systems. The carrier frequency is set as 0.3 THz. The used subcarrier spacing equals to 15 MHz. We evaluate the root mean square error (RMSE) of range estimation for one target versus signal-to-noise ratio (SNR). In Fig. 2, it is indicated that the RMSE of range estimation can achieve at least centimeter-level and below 1 millimeter at high SNR regimes. In addition, THz sensing accuracy can be further improved by employing more subcarriers thanks to the increase of used bandwidth.

2) THz UM-MIMO and Dynamic Hybrid Beamforming: As shown in Fig. 3 in an outdoor multipath environment with LoS

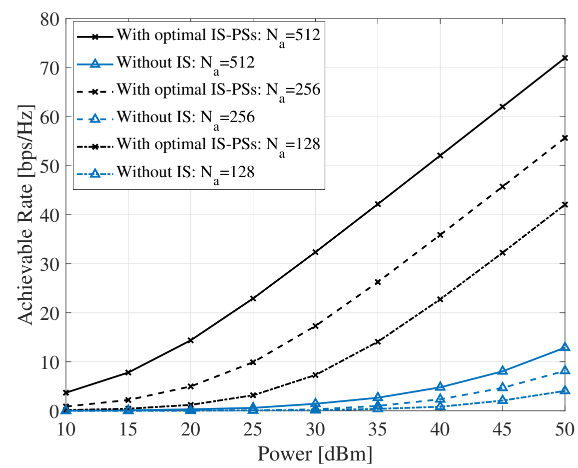

Fig. 4. Achievable rate of IS-assisted communications versus power.

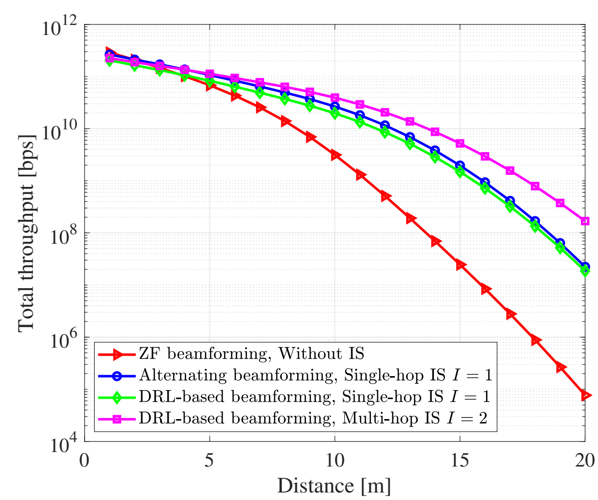

Fig. 5. Deep reinforcement learning (DRL)-based beamforming method for multi-hop IS-assisted wireless THz communication networks.

distance of 60m, when transmit power is 20 dBm and 1024 antennas are equipped, the fully-connected (FC) architecture achieves 2.3 bps/Hz and 9.2 bps/Hz higher spectral efficiency than the DAoSA and AoSA architectures. The power consumption of these three architectures grows accordingly, since the hardware connections between RF chains and antennas of them are fully-connected, dynamically-connected, and partially-connected, respectively. Consequently, the DAoSA architecture can achieve a trade-off between the spectral efficiency and power consumption of the FC and AoSA architectures. However, all these three architectures based on phase shifter can hardly tackle beam squint and still have large performance gap compared to optimal digital precoding. By contrast, the DS-FTTD architecture utilizes the frequency-proportional property of FTTD to combat the beam squint problem, and hence achieve significantly improved spectral efficiency.

3) THz Intelligent Surfaces: We evaluate the rate performance gain achieved by the IS-assisted communications, where IS is mounted on a wall of a room. With optimal IS-PSs, one applies the optimal IS phase shifters and the fully digital beamforming, while without IS, we treat IS as an indoor wall whose the first-order reflection losses are between 5.8 dB and 19.3 dB compared to the LoS. We observe that the performance gains of the IS-assisted schemes are significant compared to the scheme without IS, since the IS can provide aperture gains via their controllable reflection, so as to increase the received power at the user. Besides, as the number of antennas $\mathrm{N_a}$ increases from 128 to 512, the achievable rate by the IS-assisted scheme yields an increasing significant improvement.

4) Machine/Deep Learning for THz Communications: We evaluate the performance of the deep reinforcement learning (DRL)-based beamforming method in multi-hop IS-assisted wireless THz communication networks, and compare it with the well-known zero-forcing beamforming and alternating optimization beamforming methods [13], as shown in Fig. 5. We simulate a typical THz multi-hop system with the number of base station antenna as 8, the element number of IS as 128, and 32 users. Simulation results show that DRL-based method can offer the comparable with traditional optimization methods in one hop case. More importantly, it reveals that the DRL-empowered two-hop scheme can extend the transmission coverage by more than 50%, where the transmitted signal experiences two times reflecting by ISs to arrive at the receiver.

VII. Conclusion

The THz band is a promising enabler to meet the demands for 6G in 2030 and beyond. In this paper, four interdisciplinary directions are investigated to overcome the distance limitation and improve spectral as well as energy efficiency of THz communications, including integrated sensing and communication, ultra-massive MIMO and dynamic hybrid beamforming, IS, and machine/deep learning. In light of the THz spectrum features, key concepts and ideas, open problems and performance evaluation of these technologies are thoroughly analyzed.

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Biographies

Zhi Chen is a Professor with University of Electronic Science and Technology of China.

Chong Han is an Associate Professor with Shanghai Jiao Tong University, China.

Yongzhi Wu is currently pursuing a Ph.D. degree in the Terahertz Wireless Communication Laboratory, Shanghai Jiao Tong University, China.

Lingxiang Li is an Associate Professor with University of Electronic Science and Technology of China.

Chongwen Huang is an Assistant Professor with Zhejiang University, China.

Zhaoyang Zhang is a Distinguished Professor with Zhejiang University, China.

Guangjian Wang is a senior research scientist with Huawei Technologies, China.

Wen Tong is wireless CTO with Huawei Technologies, Canada.