Invited Paper

Resource management in THz-based system: background, modelling and challenges

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(Received June 2024)

Abstract: Terahertz (THz) technology, with its ultra-wide bandwidth, is poised to play a significant role in the future of 6G wireless communications and sensing systems. This leap in technology, however, raises the bar for channel modelling, data transmission, structure of transceivers' design, and signal processing. This paper delves into the propagation characteristics of communications within the THz band, outlines the architecture of THz transceivers, and explores the intricacies of managing wireless resources when THz communication intersects with other critical communication technologies. Furthermore, prevalent resource management issues within THz communications, together with strategies for addressing these challenges in model-based and machine learning (ML)-based methods are discussed, and concludes with a discussion on the future hurdles in managing resources within THz communication systems with integrated sensing and communication (ISAC) functionalities. As we navigate the convergence of varied communication technologies and escalating business demands, there's a pressing need to merge traditional model-based optimization techniques with ML approaches to achieve effective and robust resource management.

Keywords: Terahertz communication, ISAC, Resource management, Machine learning

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1. Introduction

The wireless communication landscape is undergoing rapid expansion, with an ever-increasing user base. As reported by the Ericsson Mobility Report in November 2023 [1], it is projected that by the close of 2029, the global average monthly data consumption per smartphone will soar to 56*GB*, and 5G subscriptions will surpass the 5.3 billion marks. This surge in user numbers and the diverse demands of various services in complex environments challenge the current communication technologies to meet the stringent requirements for latency and throughput. Despite advancements in modulation techniques and signal processing that enhance spectral efficiency, the communication rates are still hampered by the narrow bandwidth of existing operational bands, struggling to achieve the coveted 100 *GBits/s* mark. A promising solution lies in the elevation of carrier frequencies to broaden channel bandwidths, which has sparked significant interest in the research community.

The millimeter-wave and THz frequency bands are the frontrunners for high-frequency communication. While millimeter waves have found their application in the FR2 band of 5G, the THz band promises a bandwidth an order of magnitude greater, supporting data rates at the terabit-per-second scale. The THz band boasts higher directionality due to smaller antenna apertures, reducing the likelihood of free-space diffraction compared to millimeter waves. This makes THz communication a strong candidate for achieving terabit-per-second rates, with potential applications in extend/virtual reality (XR/VR), small-scale communication, and short-range ultra-high-speed transmission [2]. Moreover, the demand for precise target positioning and high-resolution sensing imaging by smart terminals and application further propels the demand for ultra-wide bandwidth, carving out new avenues for THz communication.

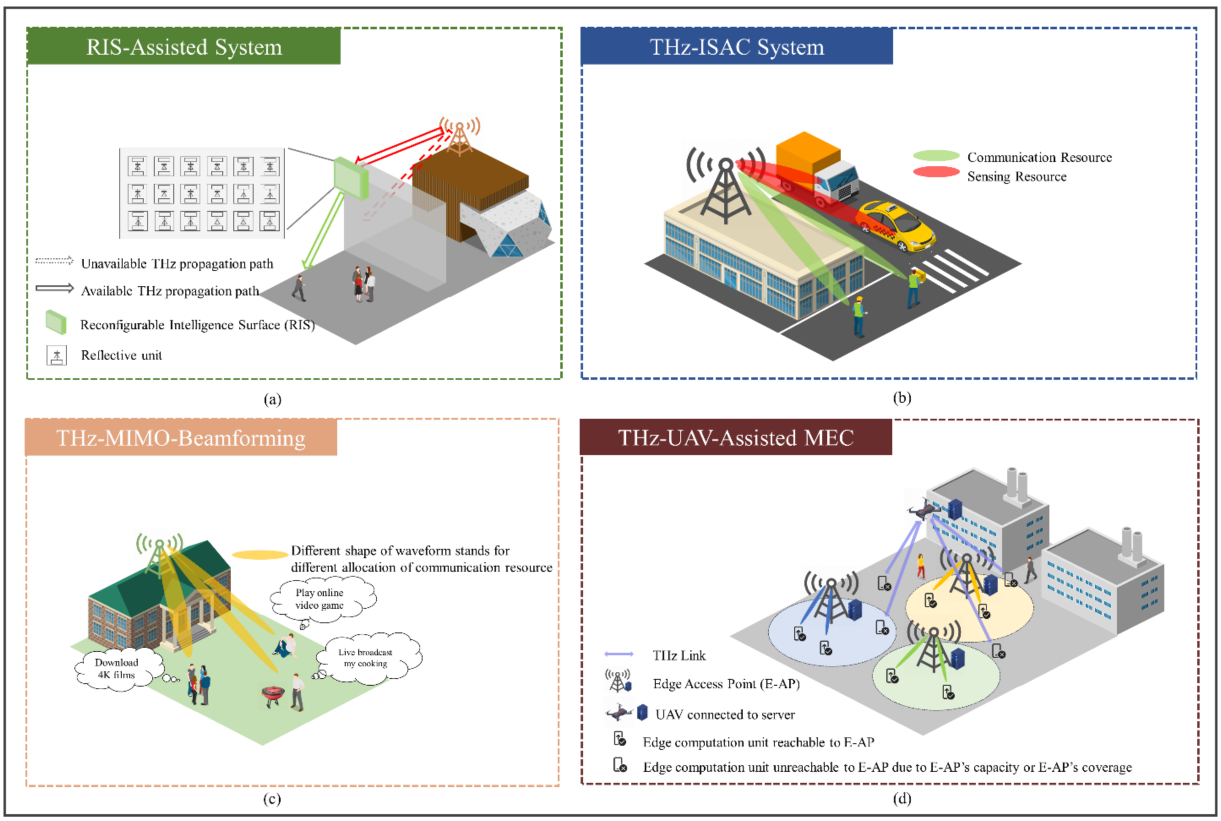

Fig. 1 Classic resource management scenarios in THz system. (a) A RIS-assisted THz communication system which enlarge system coverage; (b) A THz-ISAC system deployed at crossroad to detect incoming vehicles while providing communication service by allocating limited radio resource; (c) A THz-multi-input multi-output (MIMO)-beamforming communication system that satisfy various users' service requirement; (d) A THz-unmanned aerial vehicles (UAV)-assisted mobile edge computing system, where UAV provides THz-link service for edge computation units.

Nonetheless, THz communication faces several challenges. The high frequency and short wavelength contribute to significant free-space losses during transmission, limited diffraction capabilities, and sensitivity to obstacle attenuation, resulting in poor penetration and high reflection losses. These factors lead to non-line of sight (NLoS) transmission paths experiencing more severe losses compared to line of sight (LoS) paths, thus constraining the transmission range of THz frequencies. Consequently, one of the most viable applications for THz communication is within indoor settings. Even in indoor environments, challenges persist, such as the amplified path loss with increased communication distance, limited range for ultra-high-speed transmission, and the existence of spectral windows due to molecular absorption that render certain frequencies unusable. These distinct characteristics and channel attributes of THz communication systems introduce novel opportunities and challenges in managing THz communication resources.

Fig. 1 shows some classic examples of THz resource management scenarios. In comparison to conventional resource management challenges, communication systems operating within the THz frequency band leverage advanced technologies to enhance system performance. This includes achieving broader communication coverage (as illustrated in Fig. 1(a), where reconfigurable intelligent surfaces are employed to relay THz signals around obstacles to the intended target) and improving spectrum efficiency (demonstrated in Fig. 1(b) through the application of MIMO-beamforming for optimal utilization of wireless resources to cater to diverse user demands). Furthermore, a portion of the wireless resources might be allocated for environmental sensing, as depicted in Fig. 1(c), facilitating the convergence of ISAC. This approach introduces novel benefits and imposes additional constraints during the modeling of such systems. In mobile edge computing scenario, UAV connected to a server can offer supplementary THz-connectivity services to edge computation units unable to connect to an edge-access point (E-AP), thereby ensuring the uninterrupted and stable functioning of edge computing operations, shown in Fig. 1(d).

2. Overview of THz-based communication system

A. Key technologies

1) NOMA: The core concept of non-orthogonal multiple access (NOMA) lies in its unique approach of non-orthogonal transmission at the sender's side. It purposely incorporates interference information, which is then correctly demodulated via serial interference cancellation (SIC) at the receiver's side. Although this increases the complexity of the SIC-equipped receivers, it considerably boosts spectral efficiency. Contrarily, orthogonal multiple access technique only permits the allocation of a single wireless resource to each user, either by time or frequency division. In contrast, NOMA facilitates resource assignment to numerous users simultaneously, Fig. 2 shows how multiple UEs data stream is allocated in time, frequency and power domain and at receivers' side, the signal can be distinguished with each other by signal power, therefore multiple users' data stream could be transmitted at the same resource block (RB). This results in diverse signal power for each user once the signals reach the receiver end. The SIC receiver, in response, cancels out the interference in a specific sequence, based on the varying signal power levels, guaranteeing correct demodulation and user differentiation.

Current hardware constraints prevent the stable generation of THz signals across the entire THz spectrum, and the limited THz bandwidth is available. Maximizing spectral efficiency becomes crucial in THz-based system, and by integrating NOMA with THz communications, it becomes feasible to accommodate a larger number of users within the available spectral bandwidth. This approach significantly boosts the system's throughput and spectral efficiency, showcasing the potential of NOMA technology to overcome the inherent limitations of THz communications and enhance network performance. For instance, NOMA is introduced and resource allocation problem is formulated considering NOMA constraints in research [3-5], and the simulation results shows the potential of NOMA when facing multi-user access scenario.

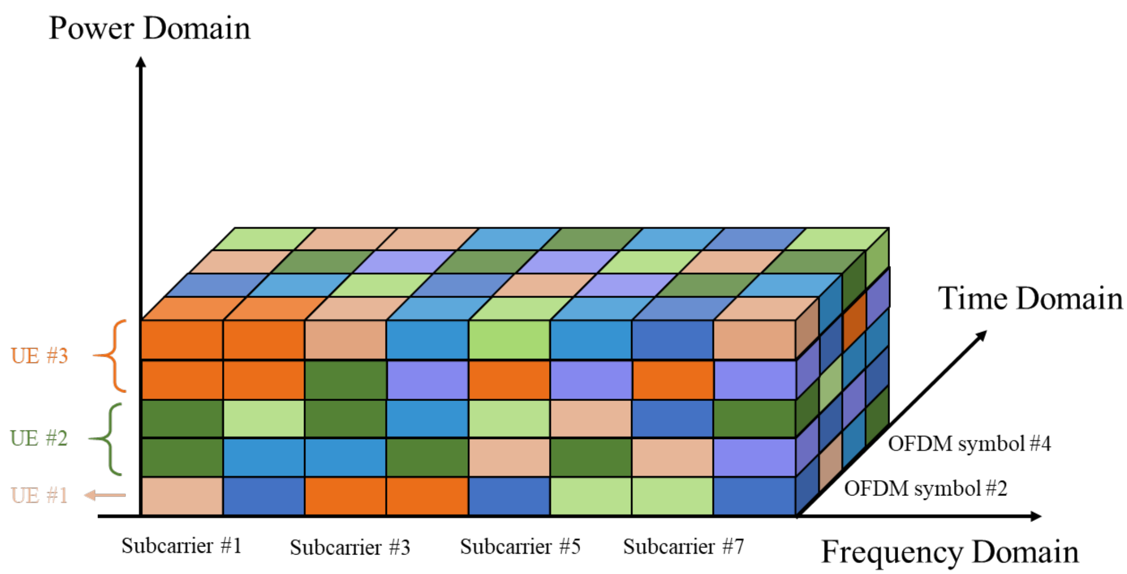

Fig. 2 Resource mapping in time, frequency and power domain using NOMA, same RB at the first subcarrier and the first OFDM symbol is used within different users, distinguished by power (value denoted by color).

2) Beamforming and massive MIMO: Beamforming in communication system means focusing the majority of signals produced by the transmitting antenna array towards a desired angular direction, subsequently centralizing the signal energy in that specific direction. In practice, it involves broadcasting the same signal across multiple transmission antennas but with varying weights, and on the reception end, coherently combining received signals of different weights to maximize the signal-to-noise ratio and hence, achieve directional communication. A beamforming radio frequency (RF) frontend can be described as antenna-arrays with a controller, which dynamically adjusts parameters of antennas so as to adjust transmit signal to the desired direction. During THz transmission, signals experience significant path attenuation, necessitating the adoption of beamforming techniques that utilize ultra-large scale antenna arrays to mitigate this loss, which is critical in ensuring the effective propagation of THz signals across distances. As opposed to omnipresent communication, directional communication not only minimizes disruptions to non-target receivers but also curtails energy wastage related to signal transmission. Furthermore, beamforming is capable of addressing time delay disparities associated with antenna arrays and, the formation of high-gain beams can diminish signal interference amid user devices, thereby enhancing the efficacy of wireless communication.

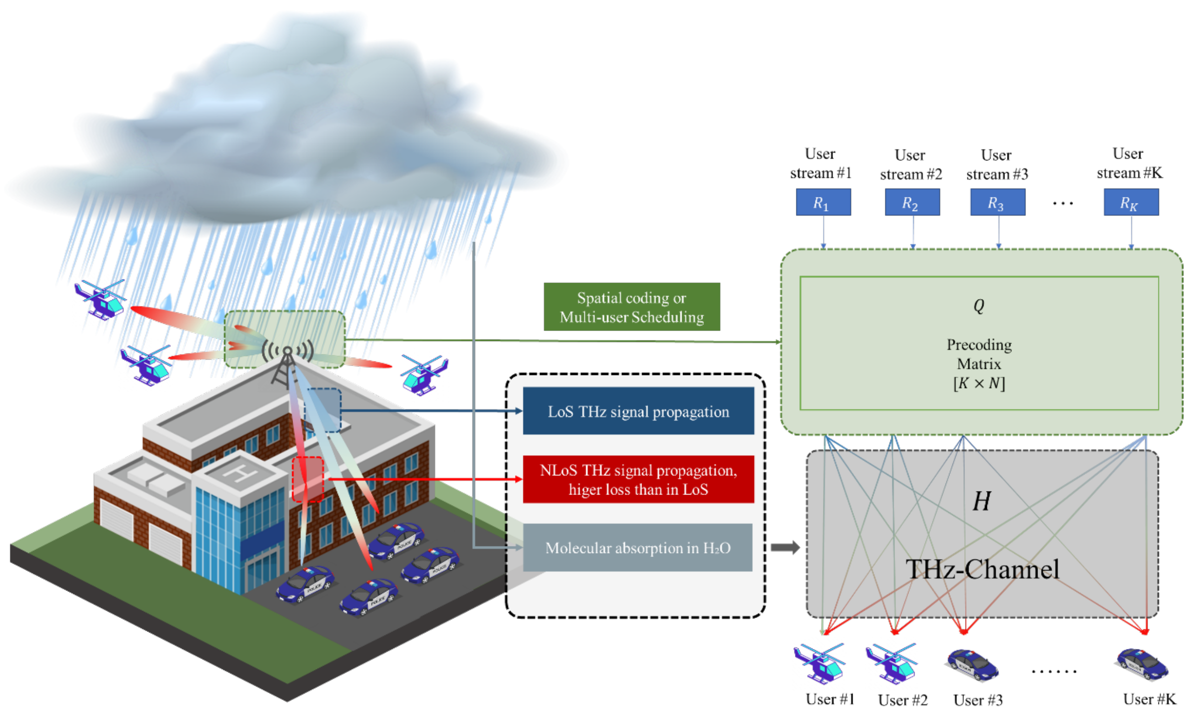

Fig. 3 Mitigating water molecule absorption and path loss in rainy weather at a police station scenario by using massive MIMO.

MIMO is a communication technique involving the use of multiple antennas at both the transmitter and receiver ends, and can be treated as an approach to realize beamforming. Before data streams with different transmission targets are sent, a precoding matrix Q is then multiplied to the data streams. Matrix Q is to designed to introduce characteristic of maximizing difference between each stream, so the receivers can decode the required data with less interference while making more use of the bandwidth resource. As the number of antennas increases, the channels between users tend towards orthogonality, thereby yielding superior channel characteristics, and MIMO becomes massive MIMO. The adoption of massive MIMO outperforms conventional MIMO by offering increased throughput and energy efficiency, as well as higher spectral efficiency. In THz communication, this efficiency stems from coherent superposition of wavefront antennas, enabling focused transmission power within a smaller range, which in turn enhances energy efficiency, so antenna design plays a crucial role in implementing MIMO technology within THz band. Efforts to develop two-element MIMO antenna systems capable of supporting the bandwidth requirements for super wideband operation have been documented in [6, 7]. Yet, these systems typically grapple with substantial physical dimensions. In contrast, a more recent proposal has introduced a more compact two-element MIMO antenna system, designed to efficiently facilitate super wideband operations in THz MIMO settings, showcasing progress towards overcoming size constraints in [8].

In summary, MIMO has the capability to merge numerous THz signals mid-air, minimizing fading and delay, and this makes it ideal for counterbalancing the fading effects commonly observed in THz channels. Furthermore, through spatial multiplexing, each array antenna can simultaneously transmit independently-coded data streams to different users. Fig. 3 depicts a scenario at a police station equipped with a THz communication system where massive MIMO is used to mitigate the impact of water molecule absorption and transmission losses in THz link.

Primarily, beamforming technologies are classified into digital, analog and hybrid beamforming. In digital beamforming, adjustments to the phase and amplitude are made at the baseband level, enabling the highest degree of flexibility and the greatest shaping gain. However, the practical deployment of digital beamforming in the millimeter-wave bands is limited by high power consumption and costs, which means in THz band a higher power consumption may occur due to the high frequency of THz signals. In contrast, analog beamforming, by adjusting the phase and amplitude at the RF or intermediate frequency stages, minimizes the reliance on numerous conversion devices. This approach significantly reduces costs and power consumption, proving more practical for millimeter-wave applications. However, limitation of analog beamforming lies in its lack of adjustment flexibility, allowing for the formation of only a single beam across the full bandwidth, which restricts the reuse of resources among users and complicates the support for spatial multiplexing. Employing analog beamforming in THz communication can lead to significant inefficiencies in the use of the already scarce spectrum resources. This inefficiency hinders the ability to maximize the capabilities and performance of THz communication systems, suggesting a need for alternative approaches to manage spectrum usage more effectively. Hybrid beamforming merges the benefits of digital and analog methods, offering a balance between flexibility and efficiency in terms of cost and power. In hybrid beamforming, the origin digital beamforming is segmented into two components: one facilitated by low-dimensional digital beamforming techniques and the other by high-dimensional analog beamforming methods. This strategic division significantly lowers the demand for RF chains' quantities. Consequently, hybrid beamforming is essential for THz frequencies, as number of antennas and RF chains increases to resist high loss in THz propagation, hardware cost should be balanced.

Based on these previous studies in millimeter-wave, research in THz communication is considerably nascent, with the majority of studies focusing on subarray configurations. Addressing multi-user systems, a hybrid beamforming approach based on a codebook with minimal complexity. conducted a comparative analysis of these antenna frameworks is crafted in [9], noting that in millimeter-wave and sub-THz frequencies, the throughput achievable with subarray configurations typically surpasses that of fully-connected setups, offering enhanced spectral and energy efficiencies. Consequently, antenna designs for THz frequencies might favor subarray configurations. In crafting hybrid beamformers for THz communications, due to the predominantly digital control of phase shifters at millimeter-wave and THz frequencies and the limitation to quantized angles, analog beamforming is tasked with selecting beamforming angles from a finite-sized codebook. This process of analog beamforming design is effectively a search within a beam control codebook, executed atop the RF chain framework. Digital beamforming can be architected employing techniques such as zero-forcing, singular value decomposition (SVD), and block diagonalization, which involves a series of design decisions related to resource allocation to facilitate improved communication performance [10-12].

3) RIS: RIS are passive reflectors that adapt their transmission characteristics in response to the needs of communication systems. They offer a cost-effective and scalable solution to meet varying communication requirements in complex environments. The first layer of the RIS features a dielectric substrate onto which multiple reflecting elements are printed. These units, upon receiving a signal, adjust their phase as per the communication requirements to reflect the signal, thereby enhancing system performance. The second layer comprises a copper or other metal plate, forming an anti-attenuation barrier that prevents signal penetration and reduces attenuation. The third layer includes a control circuit system, composed of circuit boards that independently regulate the capacitance, inductance, and resistance of all RIS reflective units, facilitating adjustments in signal amplitude and phase. The RIS controller is typically realized by Field-programmable Gate Arrays (FPGA), enables precise control over each reflecting element.

In a typical THz communication setting, during signal transmission, THz signals face obstacles that influence their path, causing reflections, refractions, and molecular absorption. These result in the creation of different multipath components of the original signal, each reaching the receiver with unique amplitudes, phases, and delays. These components, when arriving at the receiver, can augment or interfere with the original signal, a phenomenon termed multipath fading, which significantly impacts wireless communication performance. RIS, through the smart governance of a multitude of economical electromagnetic units, manipulates the reflective properties of these wireless signals. This allows for the redesign of the wireless propagation environment, rendering the radio environment "controllable". By modulating the reflection phase shift of RIS's electromagnetic units, both the reflected signals traversing RIS and the signals channeling through alternative pathways can uniformly superimpose at the receiver end, enhancing the quality of the acquired signal. In contrast to traditional active phased arrays that rely on built-in transceivers for intricate signal processing tasks, RIS operate without such components, thereby avoiding the introduction of additional noise into the system. It is this absence of noise-inducing elements and the ability to influence signal behavior that distinguishes RIS from its conventional counterparts. RIS typically serves as a go-between for transmitters and receivers, facilitating communication by acting as a reflective surface that can be adjusted to optimize signal paths. The strategic placement of RIS in the environment between the transmitting and receiving devices allows for real-time manipulation of the wireless propagation channel, offering a novel means to enhance connectivity in complex wireless networks. By combining RIS with THz communication system, [13, 14] explore how the RIS improve performance of the system and formulate related resource management problem including optimizing energy consumption, RIS design and minimizing signal to interference and noise ratio (SINR).

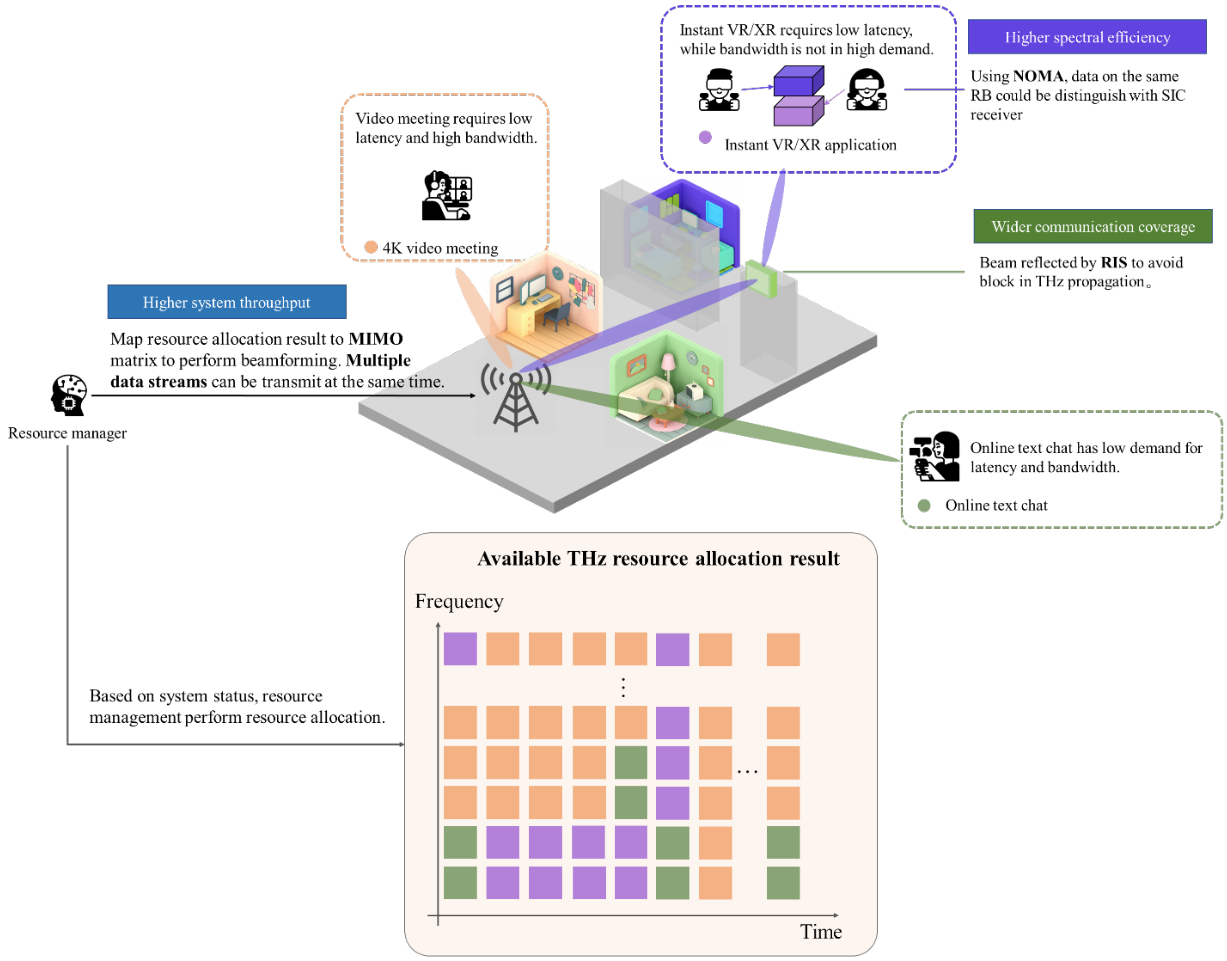

Fig. 4 Key technologies used in THz indoor communication scenario.

Summary outlines the integration of key technologies with THz communication systems, as depicted in Fig. 4. It is important to recognize that these technologies are not unique to THz communications, and application across various frequency bands can be utilized in tandem. The adoption of these technologies within THz communications aims to enhance coverage, energy, and spectrum efficiencies, thereby optimizing service delivery in scenarios where resources are constrained. NOMA, for instance, enables the shared use of identical frequency resources by multiple users concurrently, thereby boosting spectrum utilization. MIMO-Beamforming leverages multiple antennas at both the transmitter and receiver ends to facilitate the independent and simultaneous transmission of several data streams. This technique not only enhances throughput and channel capacity on individual links but, when integrated with NOMA, further augments system throughput and mitigates multipath interference effects. Additionally, employing RIS for signal link control expands the communication service coverage. It allows for adaptive link management based on specific service requirements, such as prioritizing shorter transmission paths for latency-sensitive services or choosing channels with minimal attenuation and interference for services demanding high reliability. Consequently, these strategies collectively contribute to the realization of efficient THz communications, while resource management in power, radio frequency, link control should be considered.

B. THz-based transceiver structure

To date, the evolution of THz systems has diverged into three distinct technological routes: electronic, photonic, and plasmonic methodologies Fig. 5 illustrates the primary components of these approaches, with a detailed examination of each to follow.

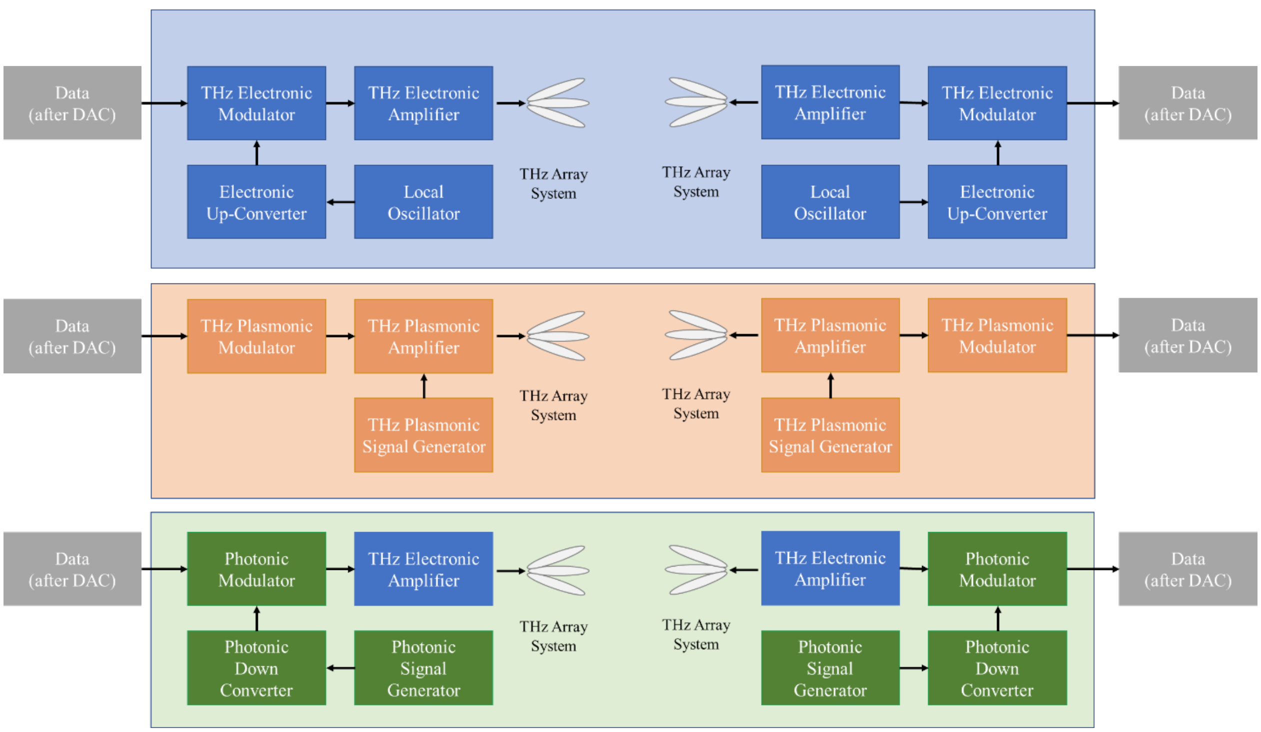

Fig. 5 Main components of different types of THz transceivers.

1) Electronic-based: Electronic-based THz communication systems grounded in electronics, the transmitter is fundamentally divided into two components: the baseband and the RF front-end. The processing of signals within the baseband domain is typically executed on a FPGA, renowned for its capacity for rapid computations. This entails the transformation of the signal from a randomly generated sequence into a baseband signal through a series of steps including scrambling, encoding, and modulation. The front-end apparatus comprises several elements such as the baseband system, frequency multipliers, mixers, inherent signal generators, power amplifiers, and antennas. The digital signals originating from the baseband undergo conversion by a Digital to Analog Converter(DAC)into intermediate-frequency analog signals. For the RF segment, the low-frequency signals from the local oscillator are first refined through a phase-locked dielectric resonator oscillator and frequency multipliers, elevating them to a higher frequency range. Following this, the mixer employs harmonics derived from the frequency-multiplied signal to blend the intermediate-frequency analog signal into the targeted THz frequency band. This THz signal, after amplification by a power amplifier, is ultimately broadcasted via the antenna. It is worth noting that experiments have successfully demonstrated transceiver arrays equipped with eight parallel channels, operating at a frequency of $140GHz$, as referenced in [15, 16]. These channels are capable of independently operating on-chip antennas through a fully digital MIMO strategy. Alternatively, they can collaborate with analog antenna arrays to facilitate the development of hybrid beamforming systems.

2) Photonic-assisted: The photonic method, also referred to as the opto-electronic heterodyne approach, relies on opto-electronic conversion to produce THz signals. The objective of this method is to extend the capabilities of photonic technologies in optical wireless communications (OWC) to encompass the THz frequency band. This technique exploits the ultra-high frequencies of light and the extensive bandwidth capabilities of optical devices to bypass the bandwidth constraints of electronic components, making it as a prevalent strategy in high-capacity THz communication systems. The uni-traveling carrier photodiode (UTC-PD) is notably favored in these systems for its broad bandwidth, rapid response, high sensitivity, and integration ease, serving as the primary opto-electronic conversion device at the transmitter's end [17]. A transmitter in a UTC-PD-based photon-assisted THz communication system typically includes components such as external cavity lasers (ECL), a Mach-Zehnder modulator (MZM), an optical coupler, an optical amplifier, a variable optical attenuator, and the UTC-PD itself.

Two ECLs are used to produce optical signals at specific frequencies. One of these signals undergoes digital modulation via an I/Q modulator, which includes an MZM and a phase shifter, while the other signal, serving as the local oscillator, remains unmodulated and is fed directly into the optical coupler. The frequency down-converted signals from these systems are characterized by higher spectral purity and reduced amplitude and phase noise. Furthermore, the utilization of available wide-bandwidth optical modulators enables the generation of THz signals with extensive bandwidths. In practice, photonic transmitters are paired with electronic receivers, which typically rely on frequency-multiplying chains in heterodyne setups, as outlined in the preceding section. The absence of an optical device capable of up-converting THz signals carrying information to the optical domain for processing with existing optical technologies presents a significant challenge.

3) Plasmonic-based: The generation of THz signals using fully electronic or photon-assisted techniques typically does not yield frequencies beyond 1 THz. To achieve signals with frequencies over 1 *THz*, the quantum cascade approach, also known as direct modulation laser technology, is often employed. This method predominantly utilizes the THz quantum cascade laser (THz-QCL) for rapid modulation. However, the THz-QCL demands specific environmental conditions, particularly low temperatures [18], which substantially restricts its use in practical THz communication systems. Plasmonic THz devices typically operate at frequencies ranging from several hundred GHz to a few THz, boasting bandwidths that exceed 10% of their carrier frequency. Moreover, these devices are remarkably compact, specifically ranging from hundreds of nanometers to a few micrometers in size. It's important to note that their diminutive size, significantly smaller than the wavelength of THz, is attributed to the plasmonic confinement effect. The diminutive size of THz communication devices serves a dual purpose within THz communication systems.

To conclude, the plasmonic-based approach to THz communications represents a less established and more adventurous path compared to the electronic-based and photonic-assisted approaches. It carries a higher risk but also the potential for substantial rewards, which include genuine THz operation, exceptionally wide bandwidths, and enhanced capabilities for reconfiguration and tuning. Though hardware realization in THz communication system seems to play no important role higher-level resource management, yet we need to realize that the development in hardware exerts significant influence on performance upper limits, which means performance in PHY-layer or Hardware layer may determine how the resource management in THz communication system is performed and formulated.

3. Resource management in THz-based communication system

A. Attenuation in THz propagation

Different from the existing frequency communication technologies, signal propagation in the THz band experiences not only free-space attenuation but also significant effects of molecular absorption. Additionally, reflected objects present in the NLoS path can lead to extra reflection losses. The noise existing within the THz band includes thermal noise from multipliers and mixers, phase noise originating from oscillators, as well as noise due to molecular absorption.

Specifically, for LoS path transmission, a higher frequency f leads to greater transmission losses. In NLoS context, where path from transmitter to reflection point and from the reflection point to the receiver should be considered, while reflection coefficient and Fresnel equation are also account for channel modelling.

THz wavelengths can induce a molecular absorption phenomenon [17], which is determined by the resonance strength between electromagnetic waves of certain frequencies and the medium's molecules, resulting in a high degree of frequency selectivity in molecular absorption. At resonance frequencies, molecular absorption is locally at its peak, producing numerous absorption peaks in the THz range, hence defining THz spectral windows with broad, multi-GHz bandwidths. It is recommended to conduct wireless transmissions within these spectral windows to mitigate the impact of substantial molecular absorption losses. This results from the fact that THz wavelengths closely align with the size of dust, rain, snow, and gas molecules in the atmosphere. The atmospheric gases cause resonance that affects specific frequency bands due to molecular absorption. In high-frequency transmissions over long distances, the degradation caused by molecular absorption can even surpass path losses.

In short, molecular absorption loss, albeit initially negligible, accelerates dramatically as the propagation distance amplifies. This trait, if not accommodated within the transmission scheme, can severely curtail the coverage extent of THz communication. As a possible remedy, [19] presents a distance-adaptive communication method whereby the transmission band is dynamically tailored according to distance to circumvent absorption peaks correlating to the distance.

B. General metrics and examples

Resource management plays a pivotal role in the realm of wireless communications, involving crucial processes like access control, allocation of resources, balancing loads, and coordinating interference among others. Its primary aim is to optimize spectral, energy, and coverage efficiency and the overall capacity of the communication systems, ensuring a satisfactory level of service quality for users. To gauge the success of resource management strategies, several key performance metrics are typically employed:

Quality of Service (QoS): This is measured through various quantitative parameters such as the rate of data transfer or system capacity, throughput, the rate of data loss, delay times, and variations in delay (latency jitter). [20] explores the optimization of UAV placement, THz resource allocation, and computation offloading, taking into account QoS constraints, and to minimize the overall time delay experienced by all wireless user devices, while adhering to resource and energy constraints, A deep reinforcement learning (DRL) approach emerges as a promising solution to this complex, non-convex problem aimed at reducing latency. [10] jointly optimizes beamforming, power allocation and bandwidth allocation in the downlink NOMA system to meet the QoS requirements of each user and maximize the network throughput.

Spectral Efficiency (SE): This is defined as the average rate of data transfer per unit of bandwidth, measured in bits per second per Hertz (bits/s/Hz). Previous work [21, 22] formulate SE maximization problem in THz-based communication system, where MIMO technology is introduced, and a hybrid beamforming method of multi-carrier transmission with range awareness is proposed, which adaptively allocates power and gives the selection strategy of antenna subarrays with low complexity while also guaranteeing QoS Requirements. [23] examines the effects of key system parameters, including transmission distance, the power consumption and bandwidth of the system. Optimization of energy consumption and spectral efficiency are both considered, and an optimal balance between them that minimizes energy usage while adhering to the QoS requirements for sub-THz communications is identified.

Energy Efficiency (EE): This metric compares the total throughput of the network against its total energy expenditure, expressed in bits per Joule. Evaluating spectral and energy efficiencies together allows for a holistic view of performance, aiming for an optimal balance. In [5], a NOMA-THz downlink system is modeled, and the resource allocation problem is addressed using a Dinkelbach-style algorithm which decomposes the problem into subchannel assignment and power optimization issues. Utilizing the alternating direction method of multipliers (ADMM) algorithm, these two sub-problems are effectively solved and further developed to obtain a solution. The simulation results demonstrate a significantly enhanced EE compared to traditional approaches. The problem of optimizing energy efficiency in RIS-assisted multi-user rate-splitting multiple access (RSMA) systems under THz propagation conditions is investigated in [19], a sparrow search algorithm (SSA) method is used to prevent the results from becoming trapped in local optima while less computational time is required and significantly enhancing the overall performance of the system. An RIS assisted THz-MIMO downlink wireless network system is established which is formulated in [14], and the original EE problem is decomposed into a phase-shift matrix optimization and a power allocation problem. By transforming the original nonlinear problem into a convex optimization problem, the optimization is done. A model is developed for cache-enabled dense vehicular networks utilizing THz frequency links in [24]. The resource management challenge within these networks is addressed by formulating a joint optimization problem for sub-band and power allocation aimed at maximizing EE. This problem is subsequently transformed into a mean-field game framework. Within this framework, each cache access point can independently tackle its local EE optimization issue using the Dinkelbach method and the Lagrangian dual approach.

Coverage Range: Typically, this is the likelihood that the signal-to-noise ratio at a given point falls below a specified threshold $\mathrm{SINR}^{\mathrm{T}}$, reflecting the network's ability to serve random users with adequate throughput. [25] develops a mathematical framework and evaluation criteria to characterize the coverage probability of co-existed sensing and communication networks, starting preliminary discussions on the cost and benefit of sensing. Based on [25], time-frequency resource allocation for sensing signal mapping schemes that maximize the coverage probability of the multi-users ISAC-THz networks with reduced sensing costs is examined in [26]. In this study, total received power is calculated in consideration of THz-propagation pathloss and transceivers' antennas gain, and total noise power is divided into two parts: the average interference together with other users' signals, and the sum of the molecular absorption noise and transmission noise.

C. Typical solutions

In THz-based system, more technologies are involved so as to improve system performance, hence introducing more combinational constraints and optimization targets. The following sections will discuss two types of solutions in resource management problems, which can be formulated to optimization problems.

1) Model-based solutions: channel state information (CSI) and (or) the QoS are required in model-based resource management solution, which frame the resource management challenge as an optimization issue bounded by multiple constraints. This involves finding the extreme values of a multivariate function within a specified set. Typically, these optimization problems are non-convex; thus, they must be converted into convex optimization problems to be amenable to algorithmic solutions. This conversion paves the way for application of various theoretical and methodological tools, including optimization theory, graph theory, game theory, Markov decision processes, and queueing theory to find solutions.

For scenarios without constraints, solutions can be pursued through techniques such as the conjugate gradient, quasi-Newton, and simplex methods. When constraints are required, methods like feasible direction, sequential quadratic programming, and the use of Lagrange multipliers come into play. Additionally, algorithms such as the alternating direction method of multipliers and successive convex approximation can be employed to navigate these complex optimization landscapes. In the process of optimizing non-convex objective functions, a common approach involves transforming these non-convex goals into convex shapes using parametric methods [5, 20]. Alternatively, some constraints may be removed to shape a new feasible area that is convex and encompasses the original feasible area. This strategy aims to simplify the optimization process while striving to maintain the integrity of the solution space.

Graph theory describes structures made of vertices (or nodes) and edges. Vertices represent entities, and edges denote the relationships between them, embodying a logical connection. Each edge carries a specific weight, reflecting the strength or capacity of the connection. Graphs are categorized into directed and undirected types, differentiated by whether their edges have a directional attribute. When addressing resource allocation challenges, graph theory offers versatile modeling frameworks. For instance, an undirected bipartite graph $\mathcal{G} = (□, \mathcal{N}, □)$ can effectively represent such problems. In this model, □ and $\mathcal{N}$ are distinct sets of vertices representing, respectively, the entities receiving resources and the resources themselves. An edge(N_i, M_j), with its weight $w_{i,j}$, connects vertices N_i and M_j, forming a network of allocations within the edge set □. This setup simplifies the problem to finding optimal matches between resources and recipients, aiming to maximize or minimize the cumulative weight of these connections.

Strategies for solving THz resource management modeled in graph theory include algorithms like the Hungarian and Kuhn-Munkers, designed to find the most efficient allocation under given constraints [4, 27]. Additionally, resource allocation can be explored through directed graphs, employing edge or vertex coloring to ensure distinct assignments among adjacent entities. This approach seeks the minimal number of colors (or categories) necessary for effective allocation, with algorithms such as the greedy random allocation method offering solutions. Moreover, considerations of fairness can lead to modeling resource allocation as an optimal linear distribution problem in directed graphs, highlighting the adaptability of graph theory to diverse optimization objectives and constraints. A novel solution to solve graph-theory-based optimization model is by combining neural network with graph theory and use a graph neural network (GNN)-based method to improve resource management performance. By using GNN, the weighted mean rate of the digital twin network for the THz band is improved, and outperforms existing methods [28]. By leveraging different graph models and algorithms, resource management issues can be approached from multiple angles, each offering unique insights and solutions.

Game theory involves three key elements: participants, strategies, and utilities. In the dynamics of game theory, participants, or players, choose strategies from a predefined set in each round. The aggregate of these choices forms a strategy profile, which determines the utility or payoff each participant receives. This utility reflects the satisfaction or benefit derived from the chosen strategy, given the choices of others. The application of game theory spans various objectives, such as optimizing the utility of an individual or maximizing the collective utility of all participants. Equilibrium game-theory-based approaches are proposed in previous works [24, 29] to deal with resource allocation in their wireless networks. To address these diverse goals, several game theory methods are employed, including Stackelberg games, non-cooperative games, and auctions and pricing models. At the heart of many game theory models is the pursuit of Nash equilibrium, a state where no participant can gain by unilaterally changing their strategy, assuming other participants' strategies remain constant. This concept is crucial for designing solutions to resource allocation problems, as it represents a stable outcome where all players' strategies are optimized given the strategies of others. By leveraging these methods, game theory provides a robust framework for analyzing and solving complex decision-making and resource allocation challenges.

2) ML-based solutions: Algorithms powered by ML thrive highly on data. They harness the power of extensive data gathering combined with precise optimization techniques to refine model parameters. This process enables the extraction of insights from the amassed data, which in turn, equips these algorithms to tackle new challenges effectively. The core methodologies underpinning these algorithms encompass supervised learning, where models learn from labeled data; unsupervised learning, which deals with unlabeled data; and reinforcement learning, which focuses on making sequences of decisions to achieve a goal. Deep neural networks (DNNs) are at the forefront of ML, simulating the human brain's inter-connectedness with multiple layers of nodes. Each node processes inputs using weights and biases to produce an output, and when this output surpasses a certain threshold, the node is activated by activation function and forwards the data to the network's subsequent layer. Neural networks adopt this mapping function through training, fine-tuning themselves via the gradient descent method based on the loss function. For instance, in tasks like resource allocation in THz communication, DNNs have been applied, as documented in [18, 27] to address these challenges effectively. In the process of using deep neural networks for resource management problem modeling, several critical steps are involved:

Network Input: This consists of various known conditions and a subset of system parameters (X) within the communication system, which must be closely related to the problem at hand to avoid difficulties in neural network training convergence.

Network Structure Design: A deep neural network $F(X;\Theta)$ involves the strategic arrangement of matrix computations and nonlinear operations. The design of the network structure enables the extraction of hidden features from input data across time and space dimensions, thus enhancing the optimization task. When its inner parameters Θ is set and when comes the input X_i the network will output the result $\widehat{Y_i} = F(X_i;\Theta)$.

Network Output: This represents the solution format of the problem. In classification tasks, it identifies the option with the highest probability from a set of possibilities. For regression tasks, it predicts the value with the smallest deviation from the current input.

Loss Function and Optimization Method: The loss function indicates the direction for problem optimization and is crucial during the training phase. A well-designed loss function $L(\widehat{Y},Y)$ allows the network to target specific optimization goals while adhering to various constraints, where Y here is the true label in the collected dataset corresponding to the input X. The optimization method involves updating the network parameters through gradient descent techniques like SGD [30] and ADAM [31], among others.

Supervised learning leverages a collected training dataset to "guide" the model on generating the intended outputs, comprising both inputs and their corresponding correct outputs to facilitate the model's sustained learning. This approach uses a loss function to measure and refine its accuracy, aiming to minimize errors significantly. It tends to perform well when the data is uniformly distributed and voluminous. Supervised learning encompasses two primary problem types: classification and regression. Classification tasks involve assigning test data into predefined categories, such as identifying service types in communication traffic. In THz communication system, supervised learning could be used to identify kinds of service requested by user, by classifying service to certain types, the resource management process could be simplified. It can also be fed with THz runtime status like SNR, CSI as input, and to predict THz communication requirements, therefore better prepare in advance for resource allocation, beamforming matrix optimization, and RIS configuration to improve THz communication performance. It focuses on recognizing specific entities within a dataset and deducing how to label or define them. On the other hand, regression analyzes the relationship between dependent and independent variables, often for making predictions, like forecasting traffic fluctuations in communication networks.

Unsupervised learning leverages ML algorithms to sift through unlabeled datasets, aiming to cluster similar data points without prior human guidance. This approach excels in uncovering underlying patterns and categorizations within the data, proving essential for tasks such as exploratory data analysis, strategizing resource allocation, and grouping downlink terminals in THz communication system. The core applications of unsupervised learning encompass clustering, association, and dimensionality reduction. Clustering involves grouping users or data points based on similarities, an invaluable tool in scenarios like THz communications for optimizing resource distribution, and when applied NOMA with THz communication, it guarantees the ability to differentiate between users without the prerequisite of identifying the exact number of clusters, all while preserving the operational efficiency of the primary users [32]. Furthermore, association seeks to identify inter-variable relationships within datasets, offering insights for refining resource allocation strategies. Dimensionality reduction aims to streamline the dataset, reducing its size to more manageable levels without significantly compromising its integrity, thereby easing computational demands. Techniques such as principal component analysis, SVD, and neural network-based auto-encoders are frequently employed for this purpose, each contributing to a more efficient analysis and processing of vast datasets.

Reinforcement Learning (RL) is conceptually designed to emulate human learning processes, where AI agents engage in learning through interactions and trials within their environment, guided by a reward system. RL algorithms could be classified into different types, shown in Fig. 6.

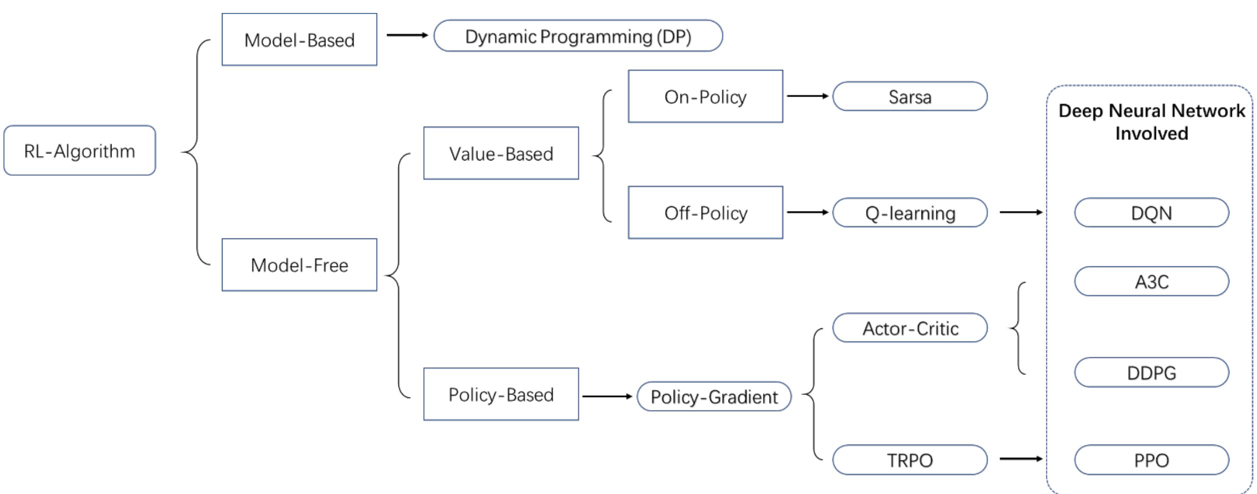

Fig. 6 Types of RL algorithms.

The foundational elements of RL's mathematical framework encompass state space $\mathcal{S}$, action space $\mathcal{A}$, reward $\mathcal{R}$, policy π and gain $\mathcal{G}$. In the realm of deep reinforcement learning, policies are articulated through deep neural networks, which dictate the agent's actions based on its current state. Throughout the training phase, these neural networks evolve in response to the reward function, enabling AI agents to adapt and learn from their experiences akin to human learning, which is fundamentally rooted in trial-and-error and environmental interaction. To explore the use of DRL algorithms to solve resource management problem in THz-communication, by designing appropriate reward functions, significant advantages are demonstrated in improving system performance [33, 34].

Nevertheless, it's crucial to recognize that in the practical applications of reinforcement learning within engineering contexts, immediate outcomes or "rewards" are often prioritized over "values". This prioritization stems from the foundational principle that value is derived from these rewards: without rewards, value ceases to exist. However, in the strategic development phase, the emphasis shifts towards value. This shift occurs because the overarching goal is to make decisions that are anticipated to yield the highest total returns in the long run. Defining and quantifying value, however, presents a significant challenge compared to identifying immediate reward. This complexity arises because rewards are directly acquired through interactions with the environment, while the assessment of value requires a thorough evaluation. Specifically, value estimation involves a comprehensive analysis and recalibration based on the sequence of rewards experienced by the agent throughout its interactions, making it a more nuanced and intricate process.

In THz resource management, reinforcement learning aligns more closely with the required adaptive strategies, primarily due to its capability to autonomously evolve, grasp the dynamics of communication systems, and iteratively refine its approach to resource allocation. This adaptability is especially pertinent for managing the fluctuating resource demands within THz communications and accommodating future system enhancements. While reinforcement learning currently stands as a favored approach for THz system resource management, the potential contributions of both supervised and unsupervised learning should not be overlooked, with combination of each sharing THz-communication system status, as shown in Fig. 7, an autonomous, intelligent and robust AI-driven resource management system may thrive. Supervised learning, through data collection and neural network training, might struggle to generate viable resource allocation strategies in the complex and varied environment of THz communications.

It is instrumental in extracting decision-related features with deep semantic insights, which can significantly expedite the training process of reinforcement learning algorithms through effective parameter initialization. On the other hand, unsupervised learning's direct application to resource management might be limited, given the challenge in linking it directly with resource allocation tasks. However, its capability to autonomously identify patterns within data can be invaluable. It enables the extraction and refinement of operational parameters of the THz system, such as CSI and signal quality. These insights can then streamline the selection of input parameters for reinforcement learning or facilitate the development of dimensionality reduction techniques, ultimately decreasing the computational demands of reinforcement learning algorithms within THz communication systems and enhancing the system's responsiveness.

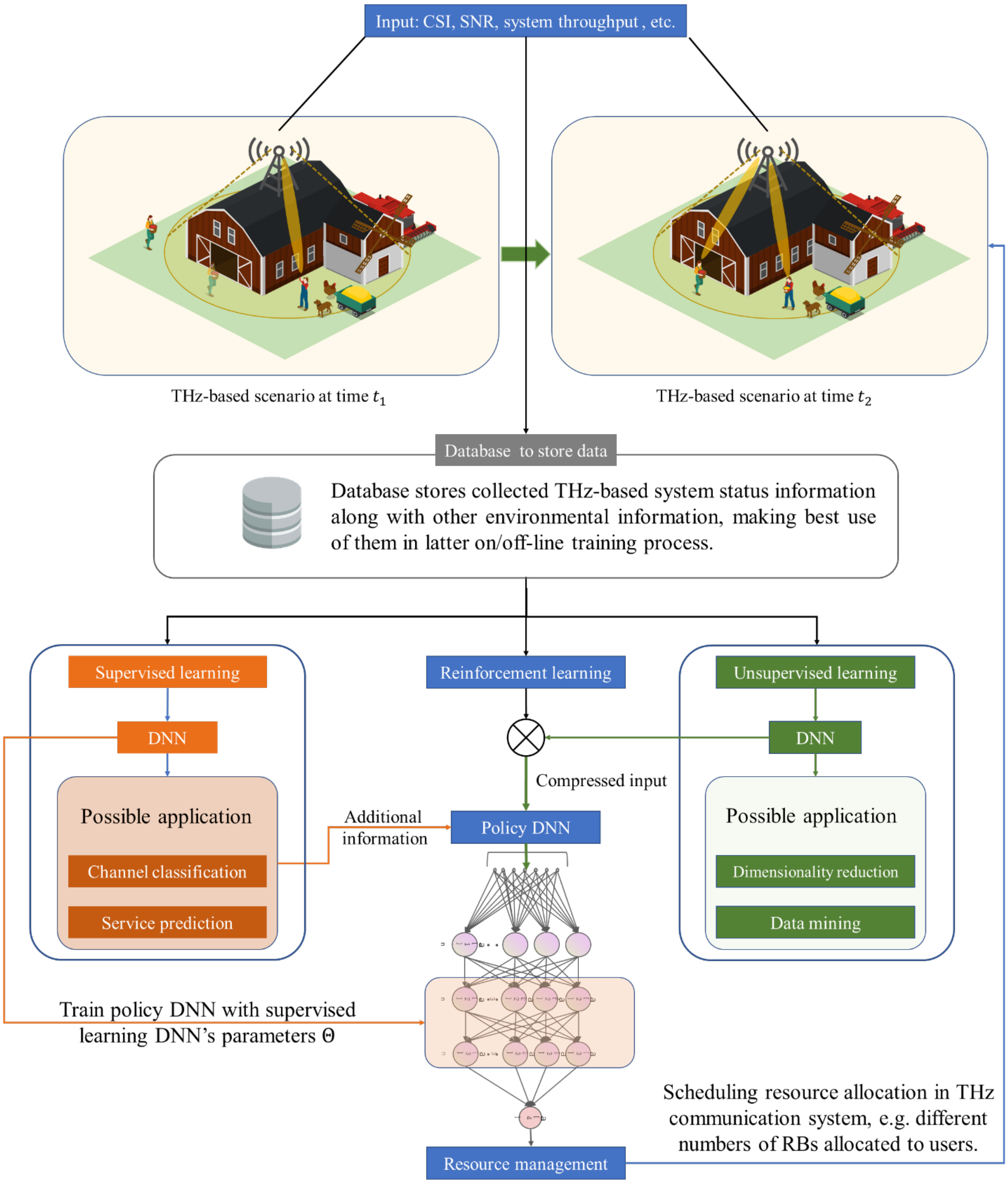

Fig. 7 An autonomous ML-based THz resource management system making full use of collected THz system status.

In summary of ML-based solutions, rapid derivation of outcomes from ML algorithms are obtained, particularly with neural network applications, which expedite the output process. Unlike traditional model-based approaches that tackle convex optimization problems with higher computational demands, ML-based methods can offer resource allocation solutions with less computational complexity. This advantage enables quicker results with equivalent computing resources. Specifically, deep neural networks, by virtue of being assemblies of matrices and nonlinear operations, eliminate the need for iterative calculations. Optimizing large-scale matrix operations alone suffices for efficient outcome generation. Such efficiency is crucial in THz communication environments characterized by their variability and the diverse, unpredictable demands of services. It ensures that resource allocation decisions are made promptly, facilitating adjustments in the THz communication system's resource distribution to significantly improve the overall user experience.

4. Future challenges in THz-based communication system

A. ISAC with multi-domain resource considerations

In the scenario of ISAC, sensing and communication modules generally need to be incorporated into a single hardware setup while sharing the same wireless resources. Notably, in such resource setups, performance in sensing and communication often ends up on either side of a trade-off balance. This trade-off at the physical layer is expressed using native communication/sensing metrics, within the previously mentioned framework of information theory. Here, it becomes crucial to allocate limited wireless spectrum resources based on task demands. Observing from the perspective of wireless resource utility, the resources can be categorized into those intended for sensing and those delegated for communication.

Given this varying resource usage, an effective performance measure is required to depict the impact of resource allocation. The performance metrics for communication primarily focus on effectiveness and reliability, represented by factors like transmission rate or bit error rate. Sensing performance, on the other hand, is largely dependent on the type of sensing task. Detection-based tasks, such as indoor personnel fall or breach event detection, can be represented using the mean square error measure. Estimation tasks, like predicting kinematic features of a moving object, can be expressed using the Cramér–Rao lower bound. Recognition tasks, like indoor human action identification, can be represented using an accuracy metric. Currently, sensing task in ISAC can be divided into 2 classes, detection and estimation [35]:

1) **Detection vs. Communication:** In ISAC systems, the transmitter emits a sensing waveform $s_R(t)$ and a communication waveform $s_C(t)$ under a total power constraint. The two signals use orthogonal resources (time-frequency) to prevent mutual interference. The sensing receiver SR receives $s_R(t)$ from both the direct channel and the supervisory channel, hoping to detect the presence or absence of a target later. On the other hand, the communication user receives $s_C(t)$ containing useful information. The key issue below is how to allocate power to sensing/communication functions, denoted by P_R and P_C with constraint to the total system power P_T, which can be modeled as the following optimization problem:

$$\arg\max_{P_R,P_C} \mathcal{P}_D \ \ s.t.\ R \geq R_{t\square},\ P_R + P_C \leq P_T. \tag{1}$$

$\mathcal{P}_D$ represents the radar's detection probability, $R = log(1 + P_C\gamma_c)$ is the achievable rate, where γ_c is the normalized gain of the noisy channel, and $R_{t\square}$ is a threshold. The detection problem can be modeled as a binary hypothesis testing problem, with hypotheses of target absent (null hypothesis) and target present. Detection is then evaluated through a generalized likelihood ratio test, and the corresponding $\mathcal{P}_D$ can be approximated with a first-order Marcum Q-function while considering the constraints on system power P_T [36].

2) **Estimation vs. Communication:** Consider a communication node that equipped with ISAC transceiver capabilities [37], as shown in Fig. 8. The ISAC base station is equipped with N_t antennas dedicated to transmitting signals and at least as many, N_r, for receiving signals, ensuring that $N_r \geq N_t$. It's designed to cater to the communication needs of K users, each equipped with a single antenna. Beyond facilitating communication, this advanced setup is also engineered to perform target detection tasks simultaneously. This dual functionality underscores the node's ability to seamlessly integrate the roles of communication and sensing, serving multiple users while also keeping an eye out for specific targets in its environment.

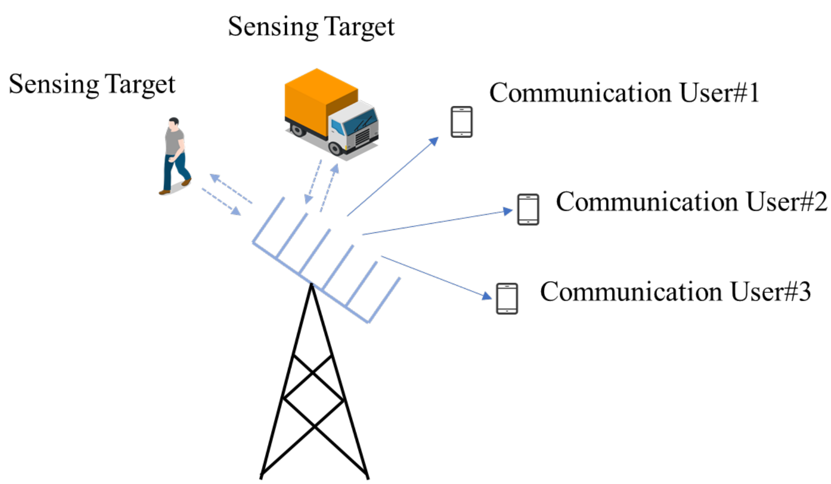

Fig. 8 MISO Downlink ISAC system.

This is a type of multi-user multiple input single output (MISO) downlink communication system, also known as monostatic/active MIMO radar. The ISAC waveform matrix $X \in \square^{N_t \times L}$ is used for transmission, subject to the power constraint P_T. The channel matrix is known to the base station, so the waveform design for ISAC can be modeled as minimizing the trace of reverse of sample covariance matrix of X, subject to constraints on the norm of X, which essentially ensuring the power used does not exceed a certain threshold, and additional conditions in waveform design. This task strikes a balance between efficient power use and the effectiveness of both estimation and communication.

The strategic utilization of sensing to enhance communication capabilities, or conversely, leveraging communication technologies to augment sensing functions, represents a pivotal area of exploration. Furthermore, the development of innovative metrics to accurately assess system performance is a critical challenge. These considerations underscore the importance of addressing resource allocation intricacies as part of the ongoing efforts to harmonize THz communications with ISAC, marking a crucial frontier in the evolution of next-generation wireless networks.

B. ML-based solutions challenges

Since the advent of AlexNet [38] in 2012, deep learning has not only flourished but also revitalized numerous sectors. From its origins in image processing to recent advances in natural language processing and the surge in artificial intelligence generated content (AIGC), AI is continually injecting new perspectives and vigor into various industries. This includes attempts to apply deep learning theories for the modeling, optimization, and resolution of communication resource management issues, albeit with inherent limitations. Chief among these is the black box nature of many deep learning models, which, despite their design potentially incorporating physical principles, inherently remain statistical models. This design aspect often results in a lack of interpretability regarding the model's decision-making processes. Research [39-41] led by Ma Yi has delved into white box deep learning models, advocating for simplicity and self-consistency as foundational principles of deep learning. Information theory and control theory emerge as pivotal, ensuring models are interpretable and their parameters optimally updated. This synergy is crucial for the vibrant growth of deep learning models. Resource allocation faces new challenges with the convergence of communication technologies and the broadening scope of resource management. More optimization goals, increased constraints, and the complexity of modeling THz communication scenarios pose significant hurdles for traditional model-based algorithms.

To conclude, deep learning offers an end-to-end modeling approach that could bypass extensive theoretical modeling, focusing instead on adjusting neural network structures, loss functions, and training methods. This approach holds promise for addressing complex communication resource allocation models; however, it grapples with issues of physical relevance, computational demand, and notably, stability and robustness. The limited semantic information of inputs typical in communication complicates the development of a stable, universally applicable deep learning model capable of perceptively managing communication systems. Overcoming these obstacles to develop a comprehensive wireless communication perception model that intelligently allocates resources based on system performance insights represents a pivotal research direction.

5. Conclusions

In recent decades, significant hardware advancements in THz technology have paved the way for its incorporation into emerging communication technologies. This progress, coupled with advancements in other communication fields, is steering the development of smart and efficient communication systems. The trend towards integrating THz technology with other scientific and technological disciplines signals a promising direction for future advancements. Consequently, addressing resource allocation challenges in THz communication necessitates a consideration of the impacts stemming from such integrations. It prompts a reevaluation of the approaches to modeling and solving resource management issues in light of new technological contexts. Predominantly, resource management algorithms have been developed based on traditional models, with an increasing number of studies exploring the integration of ML techniques to enhance problem-solving capabilities. This paper delves into the unique aspects of THz communication, highlighting specific challenges such as molecular absorption and transmission losses that distinguish it from conventional wireless communication. It provides a comprehensive overview of how resource management issues within THz communication systems are modeled and addressed, underscoring the considerations required when merging THz technology with other advancements. By examining these integration challenges and exploring potential solutions, this research aims to contribute to the ongoing development of THz communication technology and the broader field of wireless resource management. Through this exploration, we seek to offer insights that could facilitate the advancement of more capable and efficient communication systems in the era of THz technology.

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