A Survey of Beam Management for mmWave and THz Communications Towards 6G

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***Abstract*—Communication in millimeter wave (mmWave) and even terahertz (THz) frequency bands is ushering in a new era of wireless communications. Beam management, namely initial access and beam tracking, has been recognized as an essential technique to ensure robust mmWave/THz communications, especially for mobile scenarios. However, narrow beams at higher carrier frequency lead to huge beam measurement overhead, which has a negative impact on beam acquisition and tracking. In addition, the beam management process is further complicated by the fluctuation of mmWave/THz channels, the random movement patterns of users, and the dynamic changes in the environment. For mmWave and THz communications toward 6G, we have witnessed a substantial increase in research and industrial attention on artificial intelligence (AI), reconfigurable intelligent surface (RIS), and integrated sensing and communications (ISAC). The introduction of these enabling technologies presents both open opportunities and unique challenges for beam management. In this paper, we present a comprehensive survey on mmWave and THz beam management. Further, we give some insights on technical challenges and future research directions in this promising area.**

***Index Terms*—beam management (beam alignment/training/tracking), artificial intelligence, reconfigurable intelligent surface, integrated sensing and communication.**

I. Introduction

In order to meet the expected growth of wireless data traffic, millimeter wave (mmWave) technology, operating in about 30-100 GHz Radio Frequency (RF) band, has become one of the promising candidates for indoor and outdoor wireless communications. This is evident from the emergence of standards, which mainly include IEEE 802.11ad [?] and its evolution IEEE 802.11ay [?] for wireless local area networks (WLANs), IEEE 802.15.3c [?] for wireless personal area networks (WPANs), and a series of Releases standardized by the 3rd Generation Partnership Project (3GPP) for the 5th generation (5G) New Radio (NR) access networks. Since 3GPP completed the first release of 5G NR in its Release 15 [?], the 5G evolution has progressed swiftly in Releases 16 and 17 [?], [?]. Now 3GPP is entering the second stage of the 5G NR standardization, which is also known as 5G-Advanced and will be specified in Release 18 [?]. Although mmWave communications can greatly improve network speed and capacity, it may still not meet the future growth demand of wireless data traffic. It is because that, each year, various new devices in different form factors with increased capabilities and intelligence are introduced and adopted in the market. In order to meet the growing demand of the wireless communication industry and support Tbps-level data rates, the exploration and research on the RF spectrum with higher speed and greater bandwidth has been stimulated. Among the available frequency bands, the Terahertz (THz) band, which nominally occupies the spectrum of 0.1-10 THz, has attracted extensive attention. The first standard for wireless communications over the THz band, IEEE 802.15.3d [?], was officially approved in Fall 2017, where the defined switched point-to-point links operate at the sub-THz frequency around 300 GHz and enable data rates of up to 100 Gbit/s. The THz communications are envisioned as a key technology to fulfill future demands for beyond 5G such as the 6th generation (6G) wireless systems. In order to provide seamless high-quality services, *beam management*, which collectively encompasses initial beam training/alignment, monitoring and tracking, as well as recovery from beam failures, is crucial for 6G mmWave and THz communications.

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A. Review: 6G Vision

In response to the tremendous emergence of smart devices and the rapid expansion of Internet of Things (IoT) networks, 5G has made tradeoffs in terms of throughput, latency, energy efficiency, deployment cost, hardware complexity, and end-to-end reliability. Facing 2030 and beyond, 6G will be developed to jointly fulfill strict network requirements in a holistic fashion. 6G are envisioned to provide autonomous, ultra-large-scale, extremely dynamic, and fully intelligent services with high quality of experience (QoE). By now, there are a number of surveys on 6G networks, e.g., [?], [?], [?], [?], [?]. We here briefly review the core requirements and enabling technologies of 6G.

For 5G, the usage scenarios recommended by International Telecommunication Union (ITU)-Radiocommunication Sector (ITU-R) can be classified as enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC) [?]. With the advent of new technologies and the continuous evolution of existing technologies, many unprecedented applications can be cultivated in 6G era. The potential usage scenarios in 6G communication systems are expected to be featured by ubiquitous mobile ultra-broadband, extremely reliable and low-latency communications, ultra-mMTC, ultra-high data density, and extremely low-power communications. The key performance indicators (KPIs) for evaluating 6G wireless networks include:

- *Peak data rate:* $\geq 1Tbit/s$
- *User experienced data rate:* $10 \sim 100Gbit/s$
- *Over-the-air latency:* $0.01 \sim 0.1ms$
- *Mobility:* $\geq 1000km/h$
- *Reliability:* 99.99999%
- *Connection density:* $10^8 \sim 10^9 devices/km^3$
- *Network energy efficiency:* $10 \sim 100$ *times that of 5G*
- *Area traffic capacity:* $0.1 \sim 10Gbit/s/m^3$
- *Spectrum efficiency: at least* $2 \sim 3$ *times that of 5G*
- *Positioning accuracy:* $10cm$ *indoor and* $1m$ *outdoor*

To well achieve these KPIs, 6G is expected to integrate several new capabilities currently not covered by wireless communication systems, such as

- *Ubiquitous three-dimensional (3D) connectivity*: Integrating terrestrial, airborne (e.g., unmanned aerial vehicles, UAVs), and satellite networks into a single wireless system will be essential for 6G [?]. The network coverage will be globally ubiquitous and will be shifted from two-dimensional in traditional terrestrial networks to 3D in a space-air-ground integrated network.
- *Collective network intelligence*: As mobile networks are increasingly sophisticated and heterogeneous, many optimization tasks become intractable, which offers an opportunity for artificial intelligence (AI) [?], more specifically machine learning (ML) techniques. Additionally, 6G will bring intelligence from centralized computing facilities to end terminals to provide distributed autonomy, while improving security, secrecy, and privacy.
- *Integration of sensing and communication*: The function of mobile network is evolving from communication only towards integrated sensing and communications (ISAC) (a.k.a. joint communication and radar/radio sensing, JCAS) [?]. 6G networks will exploit a unified interface for sensing/localization and communications to improve control operations relying on context information.
- *Communication with large intelligent surfaces*: Reconfigurable intelligent surface (RIS) [?], also known under the names intelligent reflecting surface (IRS) and software-controlled metasurface, has positive significance in solving the pain points of small cells such as non-line-of-sight (NLoS) transmissions and reducing coverage holes. Large-scale RIS is envisaged as the massive multiple-input multiple-output (MIMO) technology 2.0 in 6G.
- *Other new paradigms* empowered by blockchain, digital twin, quantum computing and communications, etc.

6G wireless network is promising to significantly improve QoE and support a sustainable future. The unprecedented new technological trends will shape its performance goals.

B. Motivation

For 6G mmWave and THz communication systems, ultra-large-scale antenna arrays may be equipped at both base station (BS) and user equipment (UE) sides, such that high path loss can be compensated by generating narrow beams with strong beamforming gains. This leads to the fact that mmWave and THz communications rely heavily on beam management (beam training/alignment/tracking) to select the appropriate beam(s) during intra/inter-cell mobility in a quick manner to avoid any beam misalignment (transmit-receive beams do not point to each other) or beam/link failure. However, beam management is challenging because of the unfavorable propagation characteristics of mmWave/THz signals. Traditional schemes such as exhaustive search suffer from severe overhead, increased communication delay, and degraded spectral efficiency. To address these issues, various beam management mechanisms have been proposed to reduce beam training overhead or to enhance beam alignment accuracy [?], [?], [?], [?], [?]. The typical mechanisms for conventional mmWave networks have been investigated by several survey papers, which will be introduced in detail later. But after these surveys were published, a number of new beam management solutions based on 6G technology enablers have sprung up like mushrooms. In addition, the survey on THz beam management is now extremely lacking. Motivated by these facts, we conduct in-depth research on the latest 6G beam management schemes.

For mmWave and THz communications toward 6G, the most powerful tools are the AI, RIS, and ISAC. In this regard, four key trends are as follows.

- *Empowered by AI.* AI-empowered beam management can quickly adjust beam parameters to continuously provide considerable QoE and maintain network health by monitoring real-time network dynamics. In addition to the popular deep learning (DL), a few cutting-edge AI techniques represented by federated learning (FL) and transfer learning (TL) are beginning to show strong potential in 6G beam management because they pose a chance to distributed collaborative learning tasks and improve training speed.
- *Enabled by Sensing.* In 6G, sensing function will be tightly integrated with communications to support autonomous systems, which motivates the recent research theme of ISAC. The sensing function can be used to track UE for beam prediction/tracking in mmWave/THz communications. We expect that ISAC will become more popular in beam management in the near future, especially in practical dynamic environments where wireless channels vary fast.
- *Enhanced by RIS.* Among all potential candidates to alleviate blockage (channel drop caused by obstacles, device movement, or rotation) and expand coverage of mmWave/THz communications, RIS is widely considered promising for 6G as it offers a cost-effective solution. In addition to the benefits, the deployment of RIS complicates the system architecture and poses a significant challenge for beam management which coordinates BS-RIS to jointly manage two-hop transmission.
- *Driven by Combination.* In some scenarios, AI, RIS and sensing functions may be coupled with each other, bringing new opportunities and challenges to beam management.

As new technologies constantly emerge to improve the future generation communication networks, some existing tech-

TABLE I
KEY TERMS AND DESCRIPTIONS IN BEAM MANAGEMENT.

Term	Description
Beam	The main lobe of the radiation pattern of an antenna array.
Beam pair	A pair of beams (transmit and receive patterns) for transmission and corresponding reception.
Beam management (3GPP)	A set of beam-related procedures for fine alignment of the transmitter and receiver beams.
Beamforming	A signal processing technique used in antenna arrays for directional signal transmission or reception.
Beam alignment	The operations of searching for candidate beam directions at the transmitter and/or receiver to find the optimal beam pair.
Beam training	A set of operations to estimate the beam steering directions for beam alignment.
Beam tracking	The priori-aided beam training to track beams (or channels) in mobile environment.
Beam steering	A technique for changing the direction of the main lobe of a beam (radiation pattern).

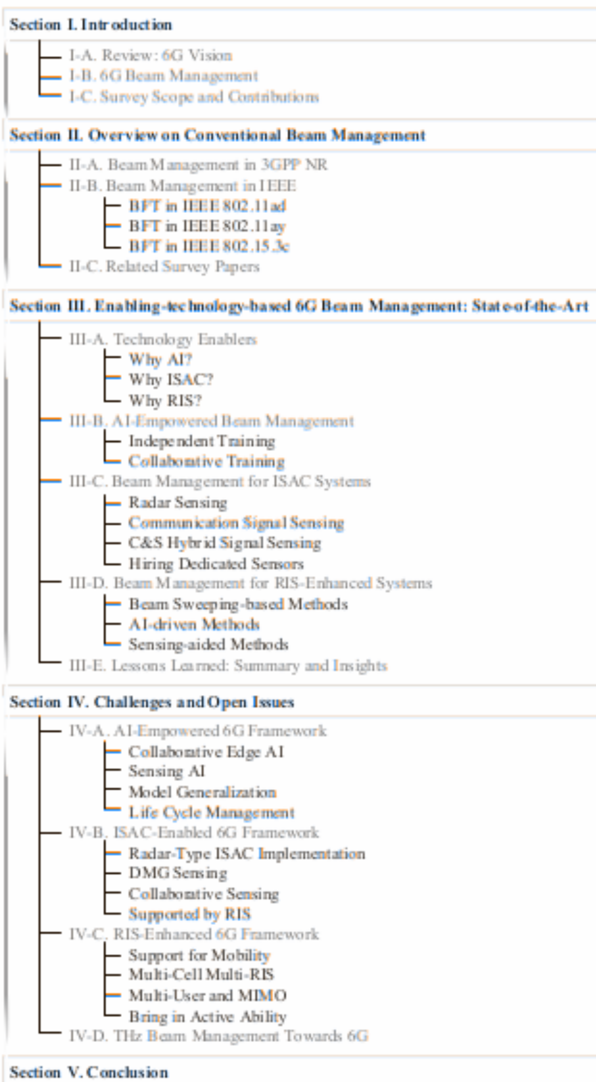

Fig. 1. The outline of this survey paper.

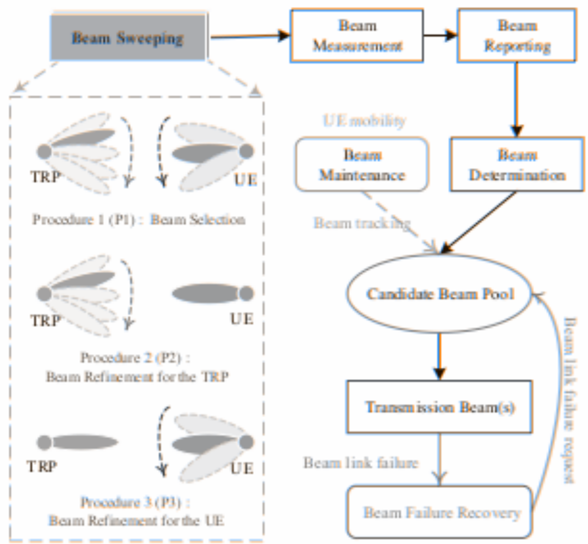

Fig. 2. 3GPP beam management procedure.

- ✓*Beam measurement*: an operation for transmission-reception points (TRPs) or UE to measure characteristics of received and/or transmitted beamformed signals.
- ✓*Beam reporting*: an operation for UE to report information of beamformed signal(s) based on beam measurement.
- ✓*Beam determination*: an operation for TRP(s) or UE to select at least one of its own transmit/receive beam(s).

The measurement process is carried out with an exhaustive search, also known as beam sweeping, at pre-specified intervals and directions. During beam sweeping, the TRP/UE measures the received power of beamformed reference signals (RSs) to derive the beam quality, which is typically expressed in terms of reference signal received power (RSRP). Measurement of the signal-to-interference-plus-noise ratio (SINR) of RSs is also supported in Release 16 of 5G [?]. The measurement results (beam quality and beam decision information) of the UE will be send to the BS. Based on the measurement, the TRP/UE selects the optimal beam (or set of beams) to set up a directional communication link. These beam management operations are periodically repeated to update the optimal beam pair(s) over time. Further details of the beam management procedure in 5G NR can be found, for example, in [?]. During communication, the environment may change, which may lead to beam failure. Beam failure event (link blockage or beam misalignment) occurs when the quality of beam-pair link(s) of an associated control channel falls low enough (e.g., comparison with a threshold, time-out of an associated timer). In general, beam misalignment between the transmitter and receiver is most likely to occur with narrow beamwidth, especially in a high mobile network. 3GPP NR supports that UE can trigger mechanism to recover from beam failure. This procedure is known as *beam recovery* which can be broken down into four steps: beam failure detection, candidate beam identification, recovery request transmission, and monitoring response for recovery request. To accomplish

TABLE II
EXISTING SURVEYS ON BEAM-MANAGEMENT-RELATED TOPICS AND OUR NEW CONTRIBUTIONS.

Ref.	Year	Focus of Discussion	Frequency		Advanced Approaches		
			mmWave	THz	AI	RIS	Sensing
[?]	2016	Tracked the evolution of antenna beamforming for mmWave communications and focused on mmWave channel characteristics and indoor use.	✓				
[?]	2017	Provided a survey of hybrid beamforming in massive MIMO systems, and focused on hybrid beamforming structures on the basis of the CSI types (instantaneous or average).	✓				
[?]	2018	Provided a review of hybrid beamforming in mmWave massive MIMO systems, and focused on the implementation, signal processing, and application aspects.	✓				
[?]	2018	Provided an overview of key features pertaining to CSI reporting and beam management for the 5G NR standardized in 3GPP Release 15.	✓				
[?]	2018	Presented some technical challenges for mmWave communications in IEEE 802.11ay standardization activities, especially the enhancements of beam training to 802.11ad.	✓				
[?]	2019	Presented a tutorial on beam management frameworks for 3GPP NR and focused on the measurement techniques for beam and mobility management in Release 15.	✓				
[?]	2020	Provided an overview on the standardized MIMO framework supporting beam management and CSI acquisition in 5G NR and focused on the beam management procedures standardized in 3GPP Releases 15 and 16.	✓		Partially		
[?]	2021	Provided an overview of the beam-level and cell-level mobility management in 5G mmWave V2X communications and focused on overcoming mobility interruption.	✓		Partially	Partially	
[?]	2021	Surveyed the mmWave system hardware technologies, and investigated the hierarchical search and Bayesian filter-based beam management algorithms.	✓		Partially		
[?]	2022	Presented a survey of beam alignment and initial access in mmWave and THz 5G/6G systems and highlighted the new trends towards deploying RISs and DL approaches.	✓	✓	Partially	Partially	
[?]	2022	Adopted a structured approach to describe the various Wi-Fi areas where ML is applied and showed that ML has a positive impact on beamforming.	✓		Partially		
[?]	2022	Provided a comprehensive review on PMN using the ISAC/JCAS techniques and investigated the sensing-assisted beamforming.	✓				Partially
[?]	2023	Provided an overview of the existing ML-based mmWave/THz beam management techniques.	✓	✓	Partially		
This work		Presents a comprehensive survey on the state-of-the-art beam management schemes for 6G communications.	✓	✓	✓	✓	✓

[?]. Andreas F. Molisch *et al.* [?] provided a comprehensive survey of the various incarnations of such hybrid multiple-antenna transceiver structures that have been proposed in the literature till 2016. Irfan Ahmed *et al.* [?] also provided a review of hybrid beamforming methods, both existing and proposed till the first quarter of 2017. In comparison, the previous survey on hybrid beamforming [?] tends to focus on beamforming structures on the basis of the channel state information (CSI) types (instantaneous or average), while the latter paper [?] focuses on the implementation, signal processing, and application aspects of the hybrid beamforming.

Besides mmWave beamforming [?], some papers surveyed the beam management process in the aspects of 5G standardization. Eko Onggosanusi *et al.* [?] provided a good overview of modular and high-resolution CSI acquisition and beam management procedures such as measurement, reporting, and recovery for 5G NR globally standardized by the 3GPP in Release 15. In [?], which is a tutorial on the design and dimensioning of beam management frameworks for 5G cellular networks, Marco Giordani *et al.* reviewed the most relevant downlink and uplink measurement signals supported by 3GPP Release 15 for beam management purposes and presented three measurement collection frameworks for both initial access and tracking purposes. The three considered measurement schemes are standalone-downlink scheme, non-standalone-downlink scheme, and non-standalone-uplink scheme, where the standalone/non-standalone architecture is a deployment configuration of NR networks. In the same year, they compared the performance of standalone and non-standalone deployments for the beam management of users in both connected and idle modes [?]. It showed that a non-standalone configuration exploiting multi-connectivity can offer more potential, including improving end-to-end performance in mmWave networks, ensuring higher resilience and improved reactiveness in case of link failure, and reducing the impact of beam reporting overhead. Meanwhile, not only 5G cellular networks, but also WLANs are widely concerned about mmWave communications. Several mmWave WLAN standards have been designed such as IEEE 802.11ad and its evolution standard IEEE 802.11ay. Pei Zhou *et al.* [?] highlighted some MAC-related technologies in IEEE 802.11ad and presented some technical challenges for mmWave communications in the IEEE 802.11ay standardization activities, especially the beamforming training for both SU-MIMO and MU-MIMO.

These above papers provide an excellent survey on mmWave beam management, but they are not recent achievements and do not address emerging 6G technologies. Typically, AI-based methods are drawing unparalleled research interest. AI including ML/DL algorithms is a tool to help network to make a quicker and wiser decision based on training data in the past. Researchers are exploring the potential of AI to solve problems specific to the mobile networking domain. For beam management, AI can be applied in the two aspects, beamforming training and beam tracking, as investigated in [?], [?], [?], [?]. Yu-Ngok Ruyue Li *et al.* [?] provided overview of beam management procedure in 3GPP NR Releases 15 and 16 and particularly considered the topic of AI-based beam management for future beam prediction in 3GPP standard. Abdulkadir Kose *et al.* [?] summarized the ML-based beam mobility management approaches proposed in the literature until 2020, and mainly surveyed the cell-level and beam-level mobility management in 5G mmWave vehicle-to-everything (V2X in short) communications focusing on the

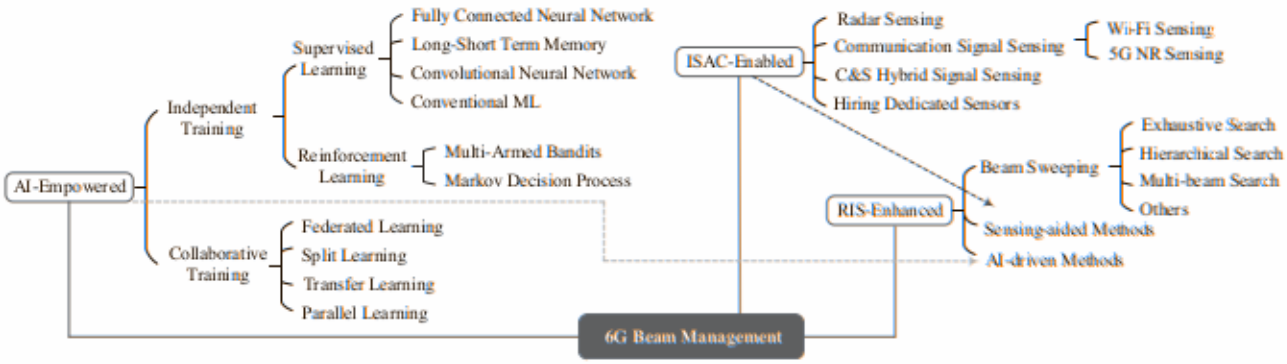

Fig. 3. Classification of existing algorithms for beam management.

Fig. 4. Roadmap to edge AI. In particular, 3GPP R17 introduced AI's FL technology in the global 5G communication field for the first time, and IEEE Std 3652.1^{TM}-2020 [?] approved the first FL standard.

wireless communication decision-making, ISAC has aroused interest in different use cases, such as autonomous driving, drone, and virtual/augmented/extended reality (VR/AR/XR). ISAC is envisioned to be an integral part of future wireless systems, especially when operating at the mmWave and THz frequency bands. In particular, leveraging sensory data to guide mmWave/THz beam management problem has gained increasing interest for the following reasons:

- Sensing could provide environment-awareness to communications, with potentials to improve security and performance. Sensing information about the surrounding environment, such as the geometry of scatterers and the locations/directions of transmitters/receivers, can help with beam tracking, blockage prediction or proactive handoff.
- The sensing information can be used to identify promising beamforming directions and avoid extensive (blind) beam training, and can also potentially help the mmWave/THz transceiver manage its beams to avoid interference with adjacent users. By periodically monitoring the location/direction of the target user, the AP/BS can track the user's beams and model its movement pattern.
- In highly mobile communication scenarios, like V2X, UAVs [?] and high-speed trains, mmWave/THz channels are highly dynamic, and the communication link needs to be reconfigured frequently, which requires a large training overhead. The sensing-assisted strategy can significantly reduce this overhead, which is particularly useful in NLoS scenarios.

★ *Why RIS?* RIS, which is generally a planar surface consisting of a large number of low-cost and passive reflecting elements, can help reshape the wireless channel/radio propagation environment in a programmable manner. By densely deploying RISs in wireless networks and skillfully coordinating their reflections, the radio signal propagation between transmitters and receivers can be flexibly reconfigured to achieve the desired realization and/or distribution. Recent research progress shows that RIS, as an auxiliary device, has great potential in improving spectral and energy efficiency, reducing interference, enhancing physical security, and so on, which thus improves the capacity and reliability of the RIS-assisted systems. Due to the increasing number of active antennas/RF chains, mmWave/THz system incurs significantly higher energy consumption and hardware cost than sub-6 GHz wireless systems. Meanwhile, the mmWave/THz communication links are more susceptible to blockage and suffer from higher propagation loss in general. These critical issues can be efficiently tackled by properly deploying RISs in the system.

- On the one hand, since RIS can passively reflect impinging signals to the desired direction by phase shifters, it can be operated in a green and low-carbon way without involving any sophisticated signal processing, and thus the energy consumption can be reduced by orders of magnitude compared with traditional active antenna arrays.
- On the other hand, when the direct link between an access point (AP)/BS and its served user is not feasible due to severe pathloss or blockage, an RIS-aided virtual line-of-sight (LoS) link (i.e., AP/BS-RIS-user) can be

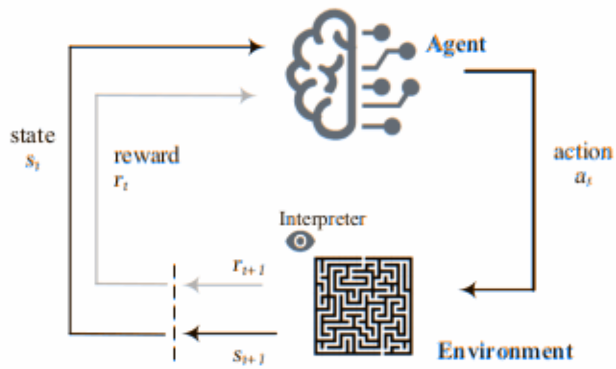

Fig. 5. The agent-environment interaction in an MDP.

This partial observability is described by a partially observable MDP (POMDP). The two most widely used RL algorithms to solve the beam management problems modeled as MDPs or POMDPs are as follows.

- *Deep Q-network.* The deep Q-network (DQN) represents the optimal action-value (Q-value) function as an NN, instead of a table as in Q-learning. Combining Q-learning with a DNN, DQN is considered the main algorithm used in environments with unlimited states and discrete actions. J. Zhang *et al.* [?] formulated the beam training problem as an MDP, where each action was defined as a subset of the codebook for beam training and each state was defined as a matrix stacked by the real vector formed by the modulus of all components of the user's equivalent channel vector. Because the states are continuous while the actions are discrete, DQN was used to solve the MDP. Unfortunately, one drawback to DQN is that it sometimes substantially overestimates the values of actions. If an overestimation do occur, this negatively affects performance in practice. As an improvement on DQN, double DQN (DDQN) with two NNs decomposes the max operation in the target into action selection and action evaluation, resulting in more stable and reliable learning [?]. In [?], the joint design of beam selection and digital precoding for mmWave MU-MIMO systems was investigated to maximize the sum-rate. The beam selection problem was formulated as an MDP and a DDQN algorithm was developed to solve it, where the BS was treated as an agent, the selection of each beam was modeled as an action, and the channel matrix and an indicator tensor used for beam selection composed the state space, of which the dimension was reduced by exploiting the sparsity of beamspace channel. Undoubtedly, real-world tasks more often feature incomplete and noisy state information resulting from partial observability. Considering a user-centric ultra-dense mmWave communication system, Q. Xue *et al.* [?] modeled the decision-making process of user association as a POMDP, applying DQN to intelligently select multiple mmWave BSs for simultaneous access, wherein the reward represents a compromise between the user achievable rate and network load balance. Seriously though, by replacing the first fully-connected layer of DQN with a recurrent LSTM layer of the same size, deep recurrent Q-network (DRQN) better handles the information loss in POMDPs than does DQN [?]. J. Park *et al.* [?] presented a DRQN approach for tackling the beam tracking task in mmWave massive MIMO system as a POMDP problem, in which the state was set to the channel matrix, an action was related to an angular bin in the search range, and the observation was chosen as the received signal matrix.

- *Actor-Critic.* RL algorithms can be either model-free or model-based. Two major paradigms in model-free RL are value-based (e.g., Q-learning) and policy-based (e.g., Monte Carlo policy gradient and deterministic policy gradient). The actor-critic (AC) framework combines the advantages of both value-based and policy-based approaches. AC consists of two components, i.e., actor and critic, who uses a value-based critic to improve updates to the actor (or policy). T. Zhang *et al.* [?] employed AC to solve the problem of joint beamwidth management and resource (transmit power, channel, and bandwidth) allocation in a mmWave backhaul heterogeneous network with hybrid energy supply aiming to maximize long-term cost efficiency. They first converted the discrete variables in the action space as continuous ones to get a continuous state-action space, and then adopted DNN as function approximator for the AC network. There were two critic DNNs in their algorithm to evaluate the given policies. One was an extrinsic critic DNN who used direct experience sampled from the environment to generate external advantage values, and the other was an intrinsic critic DNN that used exploration rewards to calculate internal advantage values. In intelligent beam management, one main AC RL algorithm to train deep RL (DRL) agent is deep deterministic policy gradient (DDPG), who works on continuous action space. In [?], V. Raj *et al.* explored a blind beam alignment method based on the RF fingerprints of users in a multi-BS multi-user scenario, and modeled the problem of BS selection and beam direction prediction as an MDP to improve the effective SINR experienced by the users. For handling the action space that mixes discrete (BS selection) and continuous (selection of beam alignment angles) actions, they proposed a new neural function approximator structure based on DDPG. The difference between their proposed method and vanilla DDPG is that the agent based on the proposed method has a user sub-net augmented actor-network. In [?], D. Zhang *et al.* investigated the beam tracking problem for a time-varying mmWave multiple-input single-output (MISO) channel when the AoD transition function is unknown to the transmitter, i.e., model-free scenario, and rephrased the problem as a POMDP problem, where the transmit training beams in one beam tracking period was defined as the action in that period. To handle such a continuous and high-dimensional action space, they resorted to DDPG to gain an efficient training beam sequence design policy.

The above rich achievements indicate that it is feasible to transform the dynamic beam management problems into MDPs or POMDPs and solve them through various DRL algorithms. Generally, it is difficult to capture the changes of the true environment perfectly, exploiting the beam dynamics via POMDP is more practical. Therefore, towards 6G mmWave and THz communications, we should probably focus more on developing beam management scheme based on a well-defined POMDP framework, and using the DRL algorithms with good

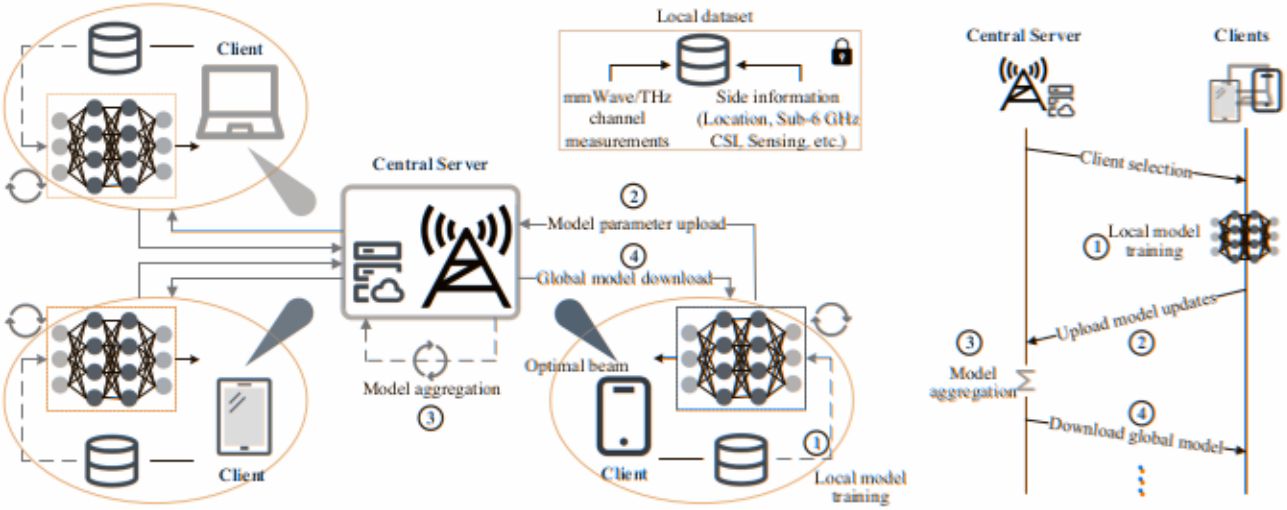

Fig. 6. General architecture and communication process of centralized FL-based beam management.

clients. Each edge node trains only a portion of the full model. This model splitting architecture enables a higher level of privacy and a better tradeoff between communication and computation. It is thus particularly suitable for large-sized DL. While FL helps mitigate data privacy concerns, most existing FL algorithms rely on that each client has sufficient storage and computing resources to locally update AI models, especially DNNs. Compared to FL, split DL provides a flexible way to train a DNN even under small memory and battery-limited clients (e.g. for mobile/IoT devices). In [?], M. Tian *et al.* proposed a LiDAR and position-aided mmWave V2I beam selection method based on an improved split learning, where vehicles and a server jointly trained an NN in a private way to find the optimal beam pair, improving the probability of correct prediction while preserving user privacy. In the method, the input of the NN was a 2D matrix containing LiDAR and position information, and the output was the predicted top-k beam pairs. During the training, the communication between the vehicles and the server was forwarded by a roadside BS. This work is an exploration of applying split learning to the beam selection task in mmWave V2I communications and presents a new option for AI-empowered beam management that requires both user information and privacy protection.

As opposed to FL that periodically exchanges model updates, split learning requires to exchange instantaneous model updates in forward and backward propagations [?]. In consequence, while effective in terms of accuracy and privacy, the communication efficiency of split learning in beam management is still questionable. Instead of directly applied, split learning may need to be improved according to actual beam management scenarios to be more effective, have better generalization ability, or be more robust to non-independent and identically distributed (non-IID) data. Furthermore, the communication cost of split DL-based beam management depends on the architecture of the trained NN and how to cut its layers, calling for more investigation on NN architecture design and layer cutting.

- *Transfer Learning.* Usually, a lot of data is needed to train an AI model from scratch but access to that data is not always available. This is where TL [?] comes in handy. The general idea is to reuse the knowledge of a pre-trained model from one domain, usually with a large dataset, on a new task in another domain that doesn't have much data. In terms of beam management, [?], [?], [?] proposed beam selection algorithms based on TL. Specifically, In [?], H. Chen *et al.* developed a parallel DNN with TL to speed up the beam search process of a mmWave multi-connection system, where the spatial correlation between sub-6 GHz and mmWave frequency band was exploited to map the sub-6 GHz channel information to the mmWave beam index. The two DNNs in the parallel DNN structure shared the common input, i.e., the sub-6 GHz channel information from the user to two BSs. They first trained one of the DNNs to output the best beam index of one BS, and then transferred the learned features to the other DNN for predicting the beam of the other BS. Clearly, TL was used to tackle the same task here, rather than a "different" but related task, in order to boost the system performance in reducing the training complexity. The major bottleneck of using DNNs in location-aided beam alignment procedure is the need for large datasets to tune their trainable parameters. S. Rezaie *et al.* [?] showed that TL could be leveraged to significantly reduce the training data requirements of DNNs in performing location/orientation-aware mmWave beam alignment. In [?], H. Zarini *et al.* focused on the problems of beamspace channel tracking and analog beam selection in a hybrid analog-digital THz beamspace massive MIMO system. First, a time-series-based DL approach was proposed to track and predict the beamspace channel over the sequences of time. Relying on the predicted beamspace channel, an analog beam selection strategy was presented to be learned as a classification task by fine-tuning an off-the-shelf pre-trained GoogleNet classifier based on TL. That is, the fine-tuned GoogleNet learned analog beam selection at the transceivers based on the beamspace channel feature space, while its internal weights, biases, and other parameters remained basically unchanged.

Due to its applicability across domains and tasks, the TL

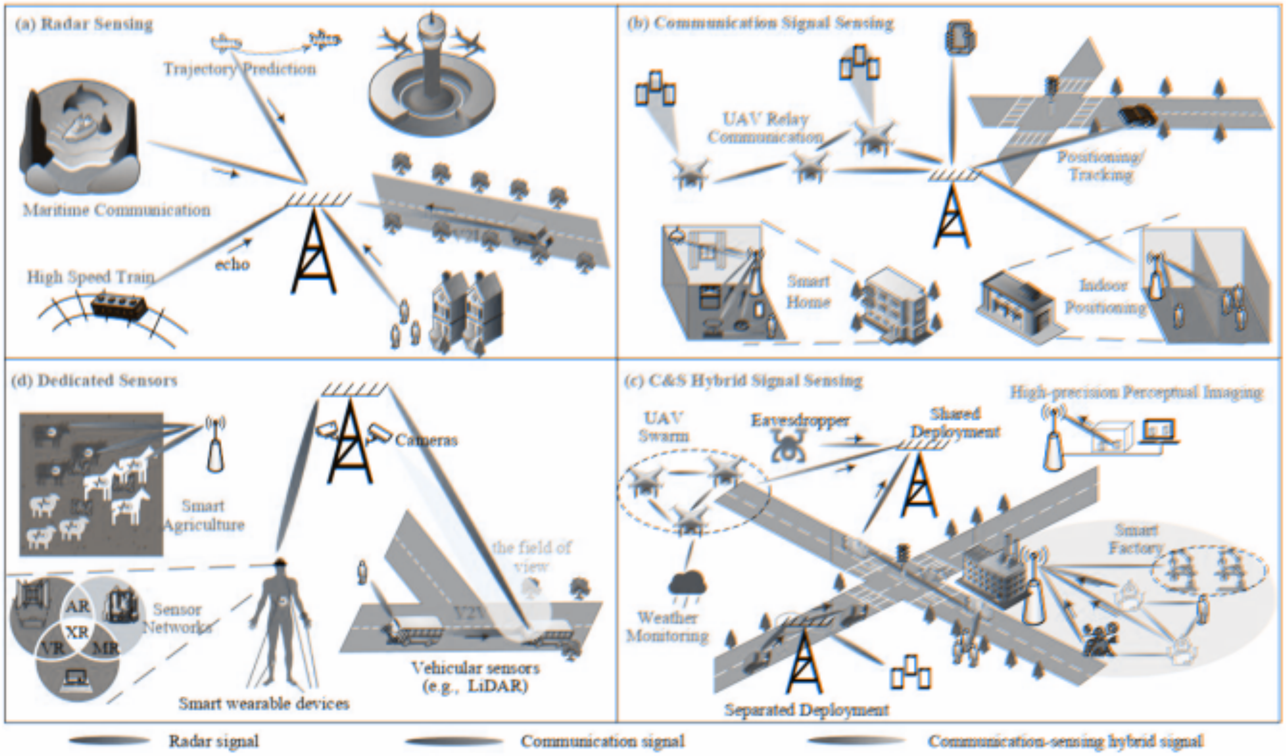

Fig. 7. Typical use cases of ISAC systems with (a) radar sensing, (b) communication signal sensing, (c) hybrid signal sensing, and (d) dedicated sensors.

the sensing direction to the same as that of the communication. Directed against this problem, several recent work has raised the idea of conducting *multi-beam design* [?], [?], [?], where the system integrates separate simultaneous beams for C&S functionalities by considering antenna arrays with multiple elements. L. Yan *et al.* [?] designed a joint C&S wireless network architecture for high-speed railways, where the remote radio units operating at mmWave bands point two beams at trains for communications and at the target areas for sensing, respectively. In the design, the sensing and communication beams are mutually orthogonal in the spatial domain, but share the same antenna array. To mitigate inter-beam interference, the authors proposed a beam management scheme based on DRL, in which the beamwidth and inter-beam spacings are adaptively adjusted according to the dynamic wireless environment. In [?], a multi-beam framework with two analog antenna arrays is presented by J. A. Zhang *et al.* to simultaneously support C&S. Then a beamforming design approach considering different requirements is proposed, in which stable and high-gain beams for communication and direction-varying beams for environment sensing. Similarly, the multi-beam technique is applied in [?]. The proposed beamforming approach jointly optimizes the beamforming weights of the transmitter and receiver to maximize the sensing performance and mitigate the possible interference from the communication beam, while also ensuring the target beamforming gain for the communication link. It is demonstrated that using the multi-beam technology can significantly reduce leakage and clutter signals. Nevertheless, multi-beam techniques are investigated for full-duplex ISAC systems that are very challenging to implement, particularly for MIMO systems. The main reason is that in a MIMO system, a large number of leakage signals between the transmitter and receiver antennas need to be dealt with simultaneously.

Although the systems of radar sensing and communications may be co-located or even physically integrated, they transmit two different signals that may overlap in the time domain and/or frequency domain. So they need to operate cooperatively to minimize interference with each other.

Communication Signal Sensing. Conventionally, radio signals are widely used for data transmissions in a wireless communication network. Recently, applying the communication signals to sense the environment in which they propagate has become an interesting topic. The IEEE and 3GPP have put substantial effort into the development of ISAC-related specifications.

- *Wi-Fi Sensing*. Today, Wi-Fi is ubiquitous and widely used in almost all public and private spaces to provide plug-and-play Internet connection. Wi-Fi devices, such as smartphones, tablets, personal computers, televisions, sensors for smart homes, placed in extremely dense and heterogeneous concentration create an excellent opportunity to continuously "draw" the surrounding environment using Wi-Fi signals as sensing waveforms.

The IEEE 802.11 working group has formed a new Task Group (TGbf), namely *802.11bf*, to develop a new amendment that defines modifications to the IEEE 802.11 MAC and to the

TABLE VI
SUMMARY OF THE LITERATURE ON BEAM MANAGEMENT MECHANISMS FOR ISAC SYSTEMS.

Techniques	Ref.	Year	Frequency	Scenarios	Sensing Source	Sensing Information	Focus
Radar	[?]	2016	mmWave	V2I	BS	Covariance estimates from radar signals	Beam alignment
	[?]	2020	mmWave	V2I	RSU and vehicle	Radar signals' spatial covariance	Beam training
	[?]	2021	mmWave	MU-MIMO V2X	RSU	Azimuth information of vehicles	Beamforming
	[?]	2022	mmWave/THz	Cellular connected UAV	BS	UAV state	Beam alignment for backhaul
	[?]	2022	mmWave	Dual-band communications for high-speed railways	Remote radio units	SINR	Beam management
	[?]	2022	mmWave	BS serves a mobile user	BS	User's range, angles, and velocity	Beam prediction
Commu.	[?]	2022	Sub-7 GHz mmWave	WLANs (Wi-Fi)	Wi-Fi devices	Channel measurement for IEEE 802.11ad/ay, range-Doppler-angular map (R-D-A map), target-related parameters	Wi-Fi sensing
	[?]	2022	mmWave/THz	SSB sensing based ISAC	BS	SSB measurement report	Beam alignment
	[?]	2022	THz	SSB-RS sensing based ISAC	BS	SSB measurement report, user speed	Blockage detection, User tracking
Hybrid	[?]	2020	mmWave	ISAC V2I	RSU	Vehicle's angle, distance and velocity	Beam tracking
	[?]	2021	mmWave	ISAC V2I	RSU	Vehicle's range, speed, angle, path loss	Beam tracking
	[?]	2021	mmWave	ISAC V2I	RSU and vehicle	AoD and distance at station, AoA and velocity from vehicle	Beam tracking
	[?]	2022	mmWave	SS-OTFS-enabled ISAC	BS	AoA, delay and Doppler shifts	Beam tracking, AoA estimation
	[?]	2022	mmWave	ISAC V2I	RSU	Communication receiver's angle, distance and velocity	Beam tracking
	[?]	2022	mmWave	ISAC V2I	RSU	System noise, the distance and velocity of vehicle	Beam tracking
Dedicated Sensors	[?]	2018	mmWave	Motion beam misalignment	Sensors in mobile device	UE movement, rotation deviation	Beam alignment
	[?]	2019	mmWave	V2I	LiDAR on vehicle	LiDAR point cloud	Beam selection
	[?]	2020	mmWave	BS serves a single mobile user	Camera	Point clouds of buildings	Beam selection
	[?]	2020	mmWave	Sub-6GHz and mmWave dual-band system	Camera on BS	RGB images	Beam and blockage prediction
	[?]	2021	mmWave	Downlink massive MIMO	Environment-sensing nodes	Channel knowledge map, user location	Beam alignment
	[?]	2021	mmWave	BS serves a moving user	Camera	Features extracted from images	Beam tracking
	[?]	2021	mmWave	Internet of Vehicles	Cameras on BS	RGB images	Beam tracking
	[?]	2021	mmWave/THz	BS serves mobile users	Camera on BS	RGB images	Blockage prediction
	[?]	2022	mmWave	Camera sensing enabled testbed	Camera at the transmitter	Image features of receiver's phased array antenna	3D beam tracking
	[?]	2022	mmWave	Connected automated vehicles	Onboard camera	Vehicles' speed and acceleration by analyzing the image frames	Beam tracking
	[?]	2022	mmWave	BS serves a group of users	Satellite image	Pixel characteristic-based feature	BS beam management
	[?]	2022	mmWave	BS serves a mobile user	Camera on BS	RGB images	Beam prediction
	[?]	2022	mmWave	BS serves a mobile user	Camera on BS	RGB images	Beam tracking
	[?]	2022	mmWave//THz	BS serves a flying drone	Camera on BS	RGB images	Beam prediction
	[?]	2022	mmWave	V2I	LiDAR on vehicle	LiDAR point cloud	Beam selection
	[?]	2022	mmWave	Multiuser MISO	Camera on BS	RGB images and the field of view	Beam selection
	[?]	2023	mmWave	V2I	LiDAR on vehicle	3D point cloud	Beam selection
	[?]	2023	mmWave	V2I	LiDAR on BS	LiDAR point cloud	Beam tracking

DMG and EDMG PHYs to support *WLAN/Wi-Fi sensing*[3] in all spectrum bands, including license-exempt frequency bands (sub-7 GHz) as well as its mmWave counterpart (above 45 GHz). In January 2023, TGbf completed a major milestone with the release of IEEE 802.11bf draft D1.0 [**?**], which specifies the necessary protocols to enable Wi-Fi sensing. IEEE 802.11bf is the world's first international standard for ISAC, and its standardization is still ongoing at the time of writing this survey. In [**?**], R. Du *et al.* provided a comprehensive overview on the efforts of TGbf through July 2022, including the new use cases, WLAN sensing procedure, candidate technical features, and evaluation methodology.

IEEE 802.11bf reuses existing Wi-Fi waveforms and channels defined by earlier IEEE 802.11 standards to support Wi-Fi sensing. It allows recognition of large motions (e.g., whole body motion) using the sub-7 GHz band, and subtle motions (e.g., finger movements or head swing) using the mmWave band to provide higher resolution and improved recognition accuracy. In particular, sensing measurements in the mmWave band, denoted as *DMG sensing procedure*, are

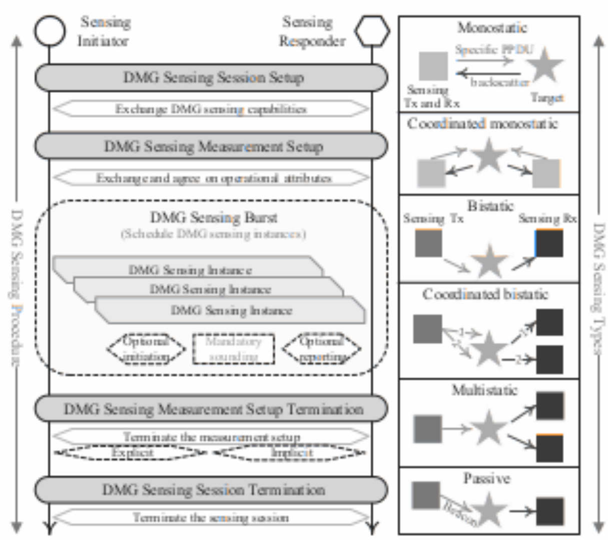

Fig. 8. Overview of the DMG sensing procedure and DMG sensing types.

built on the standards of IEEE 802.11ad and 802.11ay, which define DMG and EDMG Wi-Fi communications in the 60 GHz band. Compared with sub-7 GHz sensing, DMG sensing is the focus of this paper. As shown in Fig. **??**, the general DMG

[3]Because of its simplicity, reliability and flexibility, Wi-Fi has gradually become a synonym for WLAN. In the 802.11 standard group, "Wi-Fi sensing" can be regarded as the equivalent term of "WLAN sensing". The two can be used interchangeably.

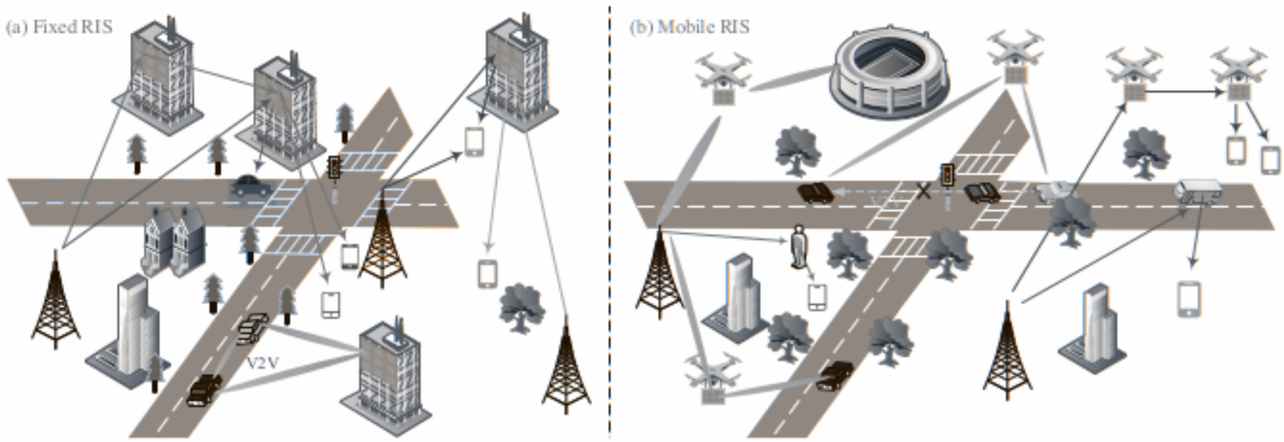

Fig. 9. Typical application scenarios of RIS, where (a) fixed RIS deployment and (b) mobile RIS deployment.

codeword searched by the previous layer codebook. Therefore, the performance of hierarchical search is highly dependent on training codebook design and the spatial resolution increases with the number of layers. B. Ning *et al.* [?] presented a cooperative beam training scheme that combines *partial search* at RIS and ternary-tree hierarchical search at BS and users. In particular, only a subset of candidate RIS phase shift solutions needs to be searched, which helps to reduce the complexity. To realize the ternary-tree search, two codebooks are designed, namely tree dictionary codebook and phase shift deactivation codebook. Thanks to low cost and low power consumption, RIS is more likely to develop into super-scale RIS for future 6G communications to efficiently boost the system capacity. X. Wei *et al.* [?] points out that the scatters are more likely to be in the near-field region of the super-scale RIS and the far-field codebook [?], [?] mismatches the near-field channel model. The existing far-field beam training scheme will cause severe performance loss in the super-scale RIS assisted near-field communications. To solve this problem, they designed a hierarchical near-field codebook which consists of several different levels of sub-codebooks determined by different sampling ranges and sampling steps. Based on the codebook, the corresponding beam training scheme is further proposed.

- *Multi-beam Search:* Conventional beam training usually searches over possible beam directions by a single beam. The single-beam search is practically challenging for systems assisted by RIS with large reflecting elements that can generate pencil-like beams, because it requires a large number of beam directions in the training codebook to cover the space of interest. To reduce the single-beam training time, multi-beam training has attracted the attention of some researchers [?], [?], [?], [?]. For instance, a multi-beam sweeping method based on grouping-and-extracting was proposed by C. You *et al.* [?]. They divided the RIS reflecting elements into multiple sub-arrays and designed their multi-beam codebook to steer different beam directions simultaneously over time. Then, the user can detect its optimal RIS beam direction via simple comparison of the received signal power/SNR. For simplicity, this work assumes that the AP-RIS link and the RIS vertical beamforming has aligned, and then only focuses on the horizontal beam training between the RIS and the user. Nevertheless, in practice, the information of RIS location may not be available to the BS, in which case one needs to perform a joint BS-RIS-user beam training. W. Mei *et al.* [?] proposed a more general multi-path beam routing scheme by exploiting active beam splitting and passive beam combining techniques. Specifically, the BS sends the user's information signal via multiple orthogonal active beams pointing towards different RISs, and then these beamed signals are subsequently reflected by selected RISs via their cooperative passive beamforming in different paths, and finally coherently combined at the user. In addition to the active multi-beam, the passive multi-beam has also been considered by P. Wang *et al.* [?], [?]. That is, they proposed to let both the BS and the RIS form multiple pencil beams simultaneously and steer them towards different directions. It is worth mentioning that whether passive multi-beam training is effective in practice needs further verification, as the inter-beam interference, the achievable passive beamforming gain, and the codebook size at RIS may increase the overall training complexity.
- *Other Advanced Methods:* Instead of exhaustively or sequentially searching over the combinations of active and passive beam patterns, several other beam training methods have been tried to reduce the complexity. For instance, W. Wang *et al.* [?] proposed to break down beam training of multi-RIS assisted mmWave MIMO into two mathematically equivalent sub-problems. They further perform random beamforming and maximum likelihood estimation to jointly estimate AoA and AoD of the dominant path in each sub-problem. A beam training method with combined offline and online distributed beam training is proposed in [?], by exploiting the (nearly) time-invariant BS-RIS and inter-RIS channels and the cooperative training among the BS and RISs' controllers. In order to provide a zero overhead training procedure for RIS-assisted single-input multiple-output (SIMO) orthogonal frequency-division multiplexing (OFDM) system, K. Chen-Hu *et al.* [?] investigated a differential-data-aided beam training combined with a codebook, relying on data transmission and reception based on non-coherent demodulation.

AI-driven Methods. The AI technique is a powerful technology that has gained significant interest in wireless commu-

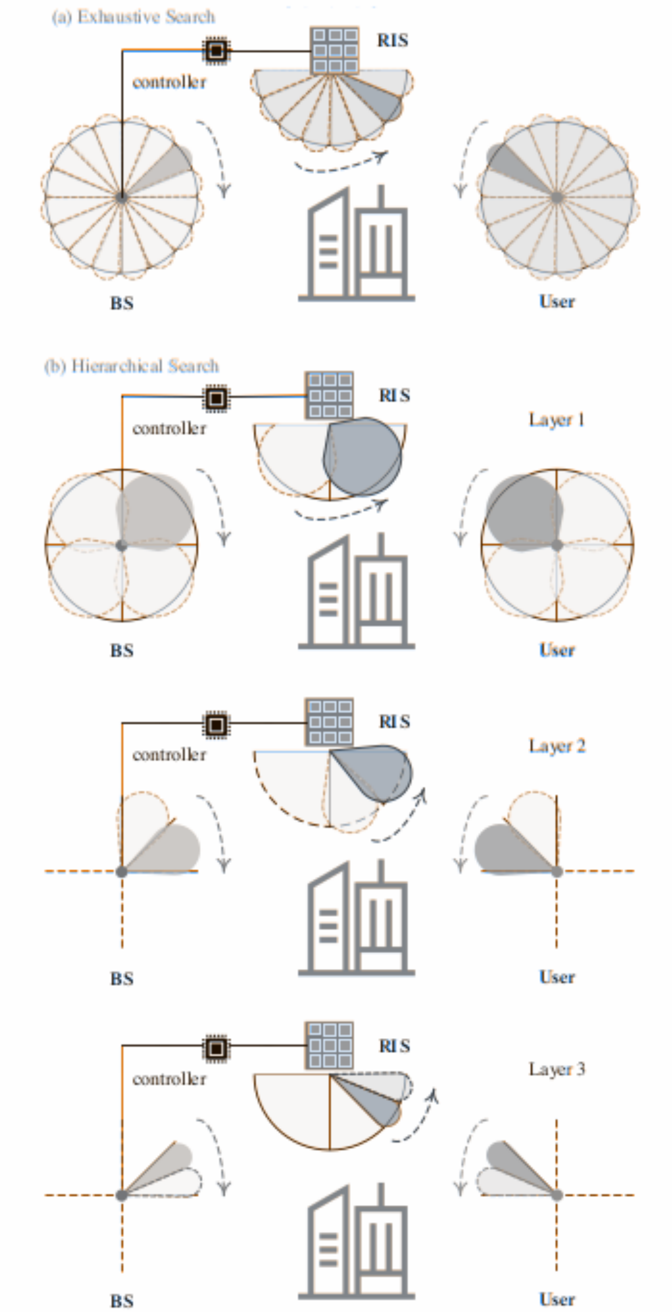

Fig. 10. Typical beam search approaches for RIS-assisted systems, where (a) exhaustive search and (b) a 3-layer hierarchical search.

based on quantile regression is developed to model the probability distribution of rate. Compared to the conventional or traditional model-based approaches, AI-based technology can help better extract the inherent relationship between input and output signals and enable more reliable channel estimation, phase shift configuration and beamforming. M. A. S. Sejan *et al.* [?] provided a comprehensive overview of the state-of-the-art on ML/DL-based RIS-enhanced wireless communications, and classified ML applied in RIS for phase shift configuration and beamforming into DL, RL, SL, unsupervised learning, and FL. They concluded that the AI/ML-based approaches have a comparable performance to conventional methods while reducing computational complexity.

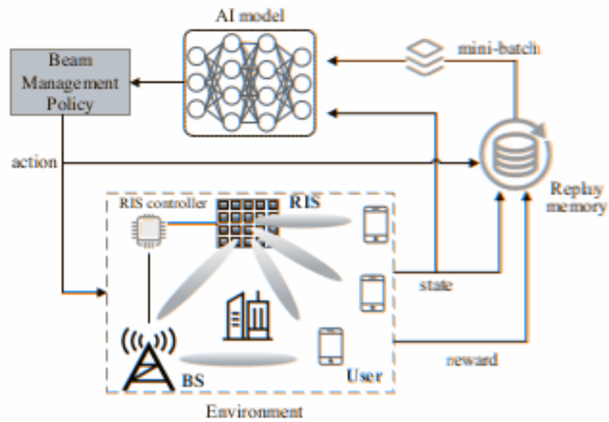

Fig. 11. DRL-based beam management in RIS-aided communication system.

Back to beam management, in order to alleviate the heavy overhead of the passive beam alignment in RIS-assisted communications, different AI techniques are recently introduced for beam tracking under various wireless communication environments [?], [?], [?], [?], [?], [?]. A typical DRL approach is shown in Fig. ??. For instance, C. Rizza *et al.* [?] proposed a Genetic algorithm to integrate a reconfigurable meta-surface as computing unit and perform real-time beam steering functions in a mobile scenario. C. Xiao *et al.* [?] constructed an indoor wireless communication prototype for verifying the passive beamforming using RIS and proposed an architecture of adaptive beam alignment and indoor positioning by using DNN. The beam alignment is realized by using the relationship between an energy array image and the beam direction of the RIS. To integrate a flying RIS into THz drone communications, N. Abuzainab *et al.* [?] considered a RNN solution for beam prediction and proactive hand-off based on the prior observations of drone location/beam trajectories. F. Sohrabi *et al.* [?] developed an adaptive active and reflection beam alignment strategy to the high-dimensional analog channel sensing problems by using a LSTM framework. L. Jiao *et al.* [?] proposed an RIS-assisted handover scheme by leveraging DDQN to deal with the frequent mmWave channel blockages, where the DRL agent manages to reduce the cumulative handover overhead by jointly adjusting beamformers and RIS phase shifts. W. Liu *et al.* [?] proposed two DL-based near-field beam training schemes for large-scale RIS-assisted communication systems, where deep residual networks are employed to determine the optimal near-field RIS codeword.

While AI can improve communication performance for RIS-assisted systems in different ways, the privacy of user data has often been ignored in previous work. Against this background, a privacy-preserving paradigm combining FL with RIS in the mmWave/THz communication system needs to be designed. L. Li *et al.* [?] proposed two FL-based mmWave wireless communication scenarios. One is RIS-assisted outdoor mmWave communication, where the user participating in communication under the FL framework is regarded as a client/agent that trains a local model, and the controller of RIS is regarded as the central server for local model aggregation.