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AI-Augmented Metasurface-Aided THz Communication: A Comprehensive Survey and Future Research Directions

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ABSTRACT

Terahertz (THz) communication is becoming an enabling technology in beyond-5G and 6G networks with capabilities of ultra-high data-rates, sub-millisecond latency, and connecting devices in a massive number. This is disadvantaged by harsh propagation losses, lack of substantial scattering, and the requirement of the urgent beam orientation. Dynamic and reconfigurable wireless environments A powerful solution to those problems will be the use of intelligent metasurfaces engineered surfaces that are able to dynamically manipulate electromagnetic waves, in combination with artificial intelligence (AI). In this survey, a detailed analysis of AI-augmented metasurface-aided THz communication systems is to be given with a special concern on the linkage between electromagnetic design and data-driven intelligence. We categorize the available literature into architectures, AI, optimizations in the system and deployment. The question of the application of supervised, unsupervised as well as reinforcement learning to tasks that include the beamforming, channel estimation, and real-time metasurface control is put into focus. We select some of the key performance indicators and benchmark datasets and point out the limitations of the systems and the standards that are emerging. The paper ends with further research directions that need to be explored in the future, such as hardware-in-the-loop experimentation, federated AI control and physics-informed learning models to optimize metasurfaces. Our results indicate that the metasurfaces enabled by AI use are not only possible in technical perspective but essential to enable adaptable, scalable, and high-performance THz systems within next generation wireless networks.

1. INTRODUCTION

High-bandwidth requirements of newly emerging augmented reality (AR), real-time holographic displays, and ultra-high-resolution sensing applications will require from terabit-per-second (Tbps) wireless communications. The latter extreme bandwidth and latency requirements have found a potential solution in the large spectral bandwidth available in terahertz (THz) communication: 0.1 THz to 10 THz [1]. The use of the THz system in practical applications is restricted however, by high path loss and molecular absorption, weak diffraction, and line-of-sight (LoS) requirements, which reduce the coverage and resilience [2].

To curb such limitations, intelligent metasurfaces which are artificially synthetically designed surfaces that can dynamically modulate electromagnetic (EM) wavefronts have been suggested, as such a breakthrough. Such metasurfaces, when enabled to learn and dynamically adapt by artificial intelligence (AI), will be able to dynamically optimise beam paths, interference control and improve link reliability in strenuous propagation settings [3], [4]. Though some studies have investigated methods of employing AI within the sub-6 GHz and mmWave bands, the full scope of AI and THz-band metasurface-aided systems are unrealized. Available publications tend to concentrate either on non-adaptive beamforming, special case assumptions, or under simplification of the channel model that cannot be applied to dynamic THz applications [5].

This survey fills these gaps by:

- Giving a consolidated taxonomy of AI-improved meta surface-assisted terahertz systems,
- Surveying the latest developments in the field of AI-controlled beam steering, channel prediction and metasurface control.
- Marks on the design trade-offs, standardization gaps,
- Describing the areas in which future research is essential in order to facilitate the deployment of adaptive, AI-native THz wireless environment.

2. RELATED WORK

The works in metasurface design and AI-intensive wireless systems have made large progress toward the creation of the next level of communication paradigm. In previous applications of THz metasurface-assisted systems, passive or semi-active surfaces were mainly implemented: the pattern of the surface is precomputed and then configured. To give an example, Li et al. [1] provided an example of fixed beam steering with static THz metasurfaces over line-of-sight (LoS). Although they would be adequate in an ideal situation, such fixed designs are lacking in real-time flexibility and are not easily applicable in a dynamic setting, or a mobile environment. They suggested Reconfigurable Intelligent Surfaces (RIS), which can change reflection coefficients according to the environment, to meet the need to increase flexibility. Wu and Zhang [2] developed the joint beamforming designs in RIS-aided systems, but recognized the level of optimization challenges particularly in the systems with mobility and uncertainty in CSI as a serious bottleneck.

In a bid to mitigate these shortcomings, AI-enhanced control mechanisms have propped up. The surveys demonstrated by Huang et al. [3] and Di Renzo et al. [4] manage to thoroughly classify the machine learning (ML) and deep learning (DL) approaches in the configuration of RIS, especially at sub-6 GHz and mmWave bands. Chen et al. [5] implemented dynamic real-time deep neural networks to address directional optimization of beam within the THz domain which was much better with respect to those analytical methods in dynamic settings of a channel. Nevertheless, the currently available literature does not offer a unified model of application of AI to THz and consider physical-layer issues and system-level design constraints together. The majority of the existing literature focus on either a) isolating components (e.g., beam tracking, channel estimation or b) abstracting away many sources of practical difficulty (generating training data, limits on hardware, reconfiguration delay and system scale).

This gap will be filled as a part of this survey by:

- In proposing a unified taxonomy in AI-integrated metasurface-assisted THz systems,
- Carrying out the test of the feasibility and the restrictions of different AI methods,
- And providing design ideas and future research directions of real-time, energy-efficient, and deployable THz communications systems.

3. Background and Motivation

3.1 Terahertz Communication: Opportunities and Challenges

Terahertz (THz) communication specialized in 0.1-10 THz frequency band is a promising candidate of future 6G and beyond wireless, since it provides unprecedented data rates because of available high bandwidth contiguous band. It is potentially capable of allowing applications involving real-time holography, ultra high-speed backhaul, and immersive virtual environments.

Various technological obstacles would however have to be tackled in order to make good of its potentials. The THz signals are of high frequency and cause severe path loss giving rise to poor transmission range. Moreover, there is a problem of diffraction that limits the bends of the signal around the obstacles, and there is the issue of molecular absorption especially that of water vapor which brings about a significant attenuation. The effects contribute to poor mobility support and non-line-of-sight (NLoS) communication, which is specifically hard to achieve in THz systems.

3.2 Intelligent Metasurfaces

The limitations of THz signal propagation and control led to researchers acquiring intelligent metasurface engineering made planar structures that can control the properties of electromagnetic (EM) waves in a programmable way. Subject to its design and method of actuation, metasurfaces may be separated into:

- Passive: Non configurable EM response.
- active: Surface impedance changing electrically tunable components.
- Programmable:Operated under the direction of an external logic or software.
- Reconfigurable Intelligent Surfaces (RIS): Surfaces that are both dynamically adaptable so as to allow new beam formations and modification of the surroundings.

Such metasurfaces offer phase, amplitude, and polarization control applications including, signal redirection, energy focusing, beam shaping, wave front engineering at frequencies corresponding to THz. They draw a little bit of power and use a slim profile, which makes them viable to deploy in large quantities both indoors and outdoors.

3.3 Role of Artificial Intelligence in Metasurface-Aided THz Systems

When complexity of metasurface and the dynamism of an environment are great, the conventional model-based optimization methods cannot be adequate, owing to its scalability and computation features. Artificial Intelligence (AI) offers an extremely strong alternative that is capable of:

- Instantaneous adjustment: AI algorithms are fast at modifying metasurface parameters according to the altered inputs of the surrounding environment.
- Beam alignment and tracking via learning: AI models, in particular, deep reinforcement learning (DRL) can tune the optimum beam path in the event of mobility and blockages.
- Channel modeling and reconstruction: Different experimental measurements of the characterization of the THz channel can be obtained based on supervised and unsupervised learning techniques.
- Scalable optimization of resource-efficient systems: AI is capable of optimally balancing multi-objective trade-offs that affect the latency, energy consumption and spectral efficiency of a system and can do it in a scalable fashion.

In combination, AI and intelligent metasurfaces can provide self-optimizing context-aware THz networks that can dynamically match the needs of environments containing complexities and dynamically changing conditions in real time.

As Figure 1 demonstrates, AI, intelligent metasurfaces, and Terahertz communication elements interact as the possible feedback loop is the real-time one with the adaptive loop of control.

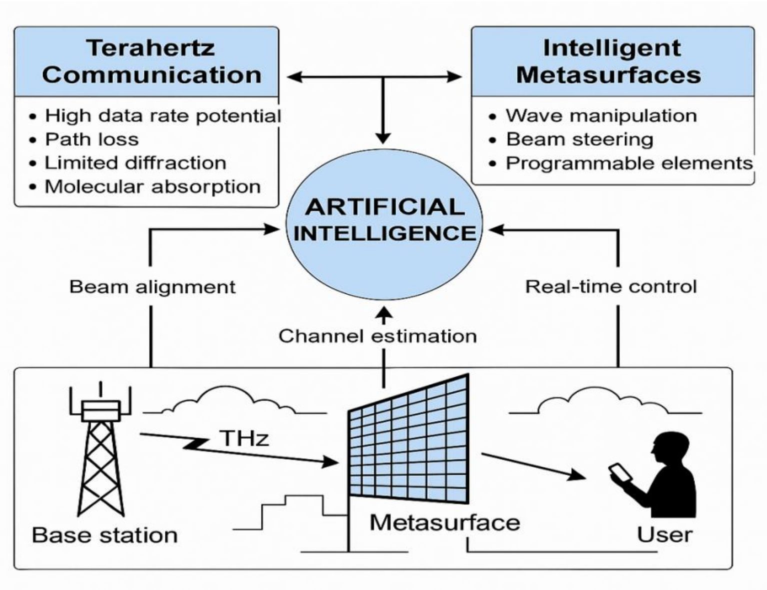

Figure 1. Illustration of the interplay between artificial intelligence, intelligent metasurfaces, and terahertz communication.

AI is used to perform real-time beam alignment, control, and channel estimation adding reliability and flexibility to THz wireless systems.

4. System Architectures and Use Cases

The use of AI-augmented metasurfaces in THz wireless networks provides a number of new architectural paradigms suited to high-capacity, low-latency, adaptive wireless connectivity. These design architectures are considered to scene the peculiarities of propagation and control in the THz bands and scalable implementation of the next-generation 6G services. We survey and discuss four exemplary system architectures and their overall main uses below:

4.1 Point-to-Point THz Links with Programmable Metasurfaces

The design philosophy In this architecture, programmable metasurfaces are positioned in various strategic locations between the transmitter(s) and receiver(s) to redirect or boost line-of-sight (LoS) and non-line-of-sight (NLoS) THz connections. The reflection coefficients of the metasurface are adapted dynamically in real time based on environmental feedback and channel state information (CSI) using AI algorithm.

- Examination: Great spectral efficiency and confidence; moderate installation complex level; excellent need of low latency AI control circles.

4.2 Indoor Ultra-Fast Connectivity for AR/VR Applications

Large scale architectures with metasurfaces embedded in surfaces can be applied to providing high-throughput, low-latency network connectivity within an indoor environment configured to provide AR/VR streaming and interaction, like a stadium, conference center or smart home. AI agents forecast the user movement and pre-position beam tracks prior to the position change with the view of reducing occlusion and keeping the links at a steady state.

- Evaluation: Extremely high support of data rates and user-centre optimization; Simplified to moderate deployment; needs predictive models of AI with sub-ms reconfiguration.

4.3 Reconfigurable Radio Environments for Smart Cities

Metasurfaces in urban infrastructure (e.g., on the building facade, on traffic lights, on signs) can be used to create large-scale reconfigurable intelligent environments (RIEs). These are smart relays or reflectors to direct the THz signals around obstructions, in robust urban coverage. AI is in a position to synchronize the actions of distributed metasurfaces in order to ensure continuous connectivity and real-time mitigation of interference.

- Assessment: Good reliability and flexibility; high sophistication of deployments owing to its scale; decentralized control of AI must be facilitated with edge/federated learning.

4.4 THz-Enabled Backhaul/Fronthaul Links for 6G Networks

In 6G, metasurface-enabled THz connectivity (as a wireless approach to backhaul/fronthaul) can be used in small cells, with high-density coverage. These connections decrease fiber requirement and guarantee high throughput as well as low latency. The use of AI is actually on beam alignment and dynamic load balancing in dynamic network topologies.

- Evaluation: Very high spectral efficiency, overall network-optimization; needs strong, centralized or hierarchical AI control; medium to high complexity of deployment.

These application scenarios can illustrate just how adaptable the AI-driven metasurface can be to suit different needs of an application, starting at the personal level of an augmented reality to the city-level of infrastructure. The two architectures focus on the various elements of performance spectral efficiency, reliability, the feasibility of deployment, and the complexity of integrating AI to give a range of design trade-offs to researchers and system designers.

Table 1 lists a comparative analysis of the four use case, summarizing the performance across spectral efficiency, reliability, deployment complexity, and the need to provide AI control of the corresponding artifacts.

Table 1. THz Use Case Comparison Table

Use Case	Spectral Efficiency	Reliability	Deployment Complexity	AI Control Requirements
Point-to-Point THz Links	High	High	Moderate	Real-time CSI adaptation
Indoor AR/VR Connectivity	Very High	High	Low to Moderate	Predictive motion tracking
Smart City Radio Environments	High	Very High	High	Distributed control with edge AI
THz Backhaul/Fronthaul for 6G	Extremely High	Very High	Moderate to High	Centralized/hierarchical control

5. AI Techniques for Metasurface-Aided THz Communication

Introducing AI into the metasurface-compatible THz systems helps to overcome important issues, which include non-convex optimization, sparsity in channel and the user mobility. In this section, state-of-the-art AI approaches are classified to increase the intelligence, scale of the environment, as well as seamless and flexibility of reconfigurable wireless conditions within the terahertz regime.

5.1 Supervised Learning

Supervised learning has extensively been used in activities that incorporate the predictive modeling of labeled datasets. This paradigm is mostly applied in metasurface-assisted THz communications:

- Beam prediction: This is based on the estimating optimal directions of beams based on the surrounding features of the environment and historical channel realizations.
- CSI-to-config mapping: Training a one-to-appear mapping from channel state information (CSI) to metasurface reflection parameters to evade computationally demanding optimization operating with a model.
- Metasurface control: Train deep neural networks (eg convolutional neural networks (CNNs)) to produce real-time control commands to an RIS/programmable surface.

Although it works, supervised models demand mass amounts of labeled information which can prove to be challenging to obtain in varied THz settings.

5.2 Reinforcement Learning

Reinforcement learning (RL) provides a model-free paradigm, which is suitable to implement in a dynamic and partially observable environment. Here, an agent (e.g., the base station or edge controller) will be trained to learn how to program the metasurfaces by being given feedback in the shape of a reward signal, e.g. in shape of throughput or signal strength.
Major uses are:

- Internet reflection management: Maximizing reflection coefficients on a real-time basis to adapt to the change in channel or user location.
- Environment-sensitive adaptation: Policies learned in a generalized way across user routes and blockage in space.

Such variants as deep Q-learning and proximal policy optimization (PPO) allow continuous control with very little pretraining.

5.3 Unsupervised and Self-supervised Learning

These methods make no use of manually labelled data hence they are particularly applicable to THz systems in which there is only limited annotated training data. They are applied to:

- Sparse channel estimation: Reconstructing high-dimensional THz channels with small peak pilot overhead with autoencoders or generative distributions.
- Latent feature learning: Learning useful hidden representations of either the location of users, blockage patterns, or beam setups to use downstream, e.g. in prediction or clustering.

Contrastive objectives can be used together with self-supervised learning to extend the results towards generalization in unseen environments.

5.4 Federated and Edge AI

Latency, bandwidths and privacy limitations might severely hamper centralized control of AI in dense THz deployments. Edge AI and federated learning (FL) have distributed solutions, which enable devices or edge nodes to:

- Train the models locally in an independent fashion without exchanging raw data.
- Collectively synchronize a worldwide model, augmenting the appearance of execution over the diversity of devices and areas of deployment.
- Ensure privacy of the users and allow smart metasurface control and channel estimation.

Such approaches aid scalable and privacy-preserving learning with large-scale metasurface-assisted THz networks.
The different AI learning paradigms used in metasurface-aided THz communication are classified in Figure 2 that gives their roles and areas of applications.

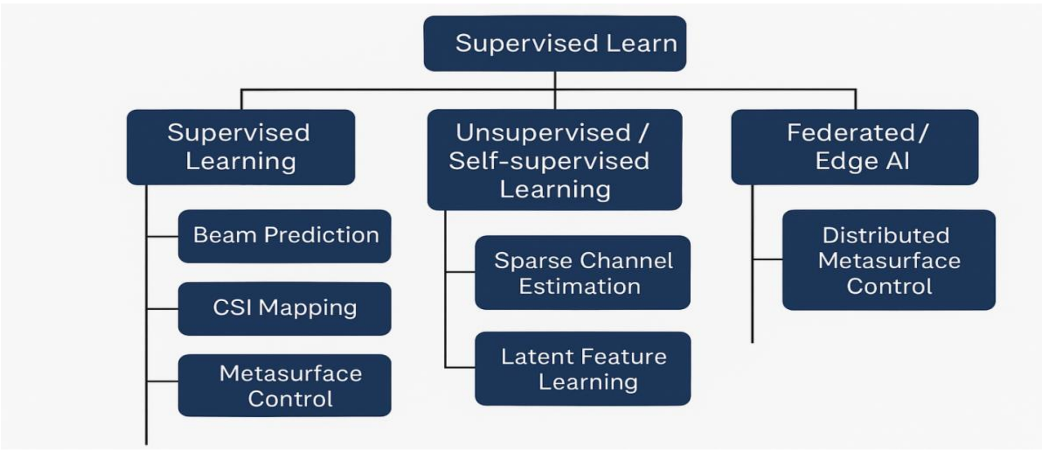

Figure 2. Taxonomy of AI techniques used in metasurface-assisted THz communication systems.

The figure describes supervised, unsupervised/self-supervised, reinforced, and federated learning methods and possible scenarios of their employment.

6. Performance Metrics and Benchmarks

The effectiveness of AI- incorporating metasurface-assisted THz communication systems should be assessed within the framework of a multidimensional performance that encompasses both system-level functions, as well as algorithm efficiency. This section identifies some of the main metrics employed to evaluate system-level performance as well as the representation of sets and tools offered to perform a simulation and benchmark.

6.1 Key Performance Metrics

- Spectral Efficiency
  Spectral efficiency, in bits / s / Hz, is a measure of how much data a system can get to flow through a bandwidth. It is one of the leading parameters to evaluate the ability of metasurfaces to guide THz signals to a user with different conditions of signals propagation.
- accuracy of beamforming
  The measure corresponds to the accuracy of the AI model when it determines the best beam direction or reflection pattern. Greater beamforming precision leads to an improvement in the quality of the links and minimization of the signal leakage or interference, which is especially necessary in the narrow-beam THz.
- Law of configuration latency
  The time gap between the environment sensing and metasurface reconfiguring is defined. This involves AIs inference latency, signaling overhead and physical tuning delay. Real-time applications like AR/VR and mobile THz access require a low degree of configuration latency.
- Energy Efficiency
  This quantity is measured in bits/Joule, and it is a ratio of the data rate which can be offered and the sum of the power that will be used, both in computational and hardware actuations. It plays a critical role towards the implementation of the green, sustainable 6G systems.
- Adaptation to the environment
  This qualitative measure is based on how well the system will support performance across a variety of and non-stationary setting like user mobility, blockages or multipath fading. Good versatility means strong learning models and generalizable control plans of metasurface.

Table 2 contains the main performance indicators concerned with metasurface-aided THz systems describing their definitions and context-relevance in high-frequency wireless communication.

Table 2. Performance Metrics Comparison Table

Metric	Definition	Importance in THz Systems
Spectral Efficiency	Data rate achieved per unit bandwidth (bits/s/Hz)	Maximizes throughput in bandwidth-constrained THz channels
Beamforming Accuracy	Precision in aligning the beam to optimal direction or target	Ensures reliable links and reduces misalignment at narrow beams
Configuration Latency	Time taken to reconfigure the metasurface in response to environment	Crucial for real-time services like AR/VR and mobile access
Energy Efficiency	Ratio of throughput to total energy consumption (bits/Joule)	Supports energy-constrained deployment for 6G and IoT devices
Environmental Adaptability	Ability to maintain performance under changing channel or mobility conditions	Enables robustness against blockage, mobility, and environmental shifts

6.2 Datasets and Open-Source Tools

Experimentally, although gaining interest, comparatively few standardized sets of data are available to train and test AI models in THz and metasurface their use. A number of programs and sites are however supportive of simulation and benchmarking:

- DeepMIMO: An informed open-source creator of deep learning-based MIMO systems is calibrated, and it supports user customization to study RIS/THz.
- ViWi (Vision-Wireless): Combines wireless learning schemes with AI-based ray-tracing, meaningful when it comes to simulating dynamic scenes.
- Remcom Wireless InSite: Commercial quality ray-tracing tool in order to generate channel data and train AI models in an emulated THz propagation environment.
- Sionna and QuaDRiGa: AI-native simulators that are upcoming and already offer Python/TensorFlow interfaces to PHY-level experimental design, offering extensibility to metasurface geometries and the terahertz region.

This has been a challenge by the absence of benchmark tasks and often used performance evaluation pipelines. The standardized testbed, reproducible codebase, and hardware-in-the-loop frameworks are in obvious demand to test the use of AI-driven metasurface control in realistic contexts.

7. Challenges and Open Problems

Although the involvement of artificial intelligence (AI) in metasurface-aided terahertz (THz) communications has undergone massive developments, some important issues still need to be addressed. Such challenges range in three dimensions including physical-layer restrictions, system-level design, and data-driven learning constraints.

7.1 Real-Time Adaptation in Dynamic Environments

The environments of THz communication are very susceptible to being blocked, mobility, and fast dynamics of the channel. In order to sustain strong connectivity, AI models will have to deliver sub-millisecond inference and reconfiguration of metasurface elements. Nonetheless, existing solutions do not provide the latency promises required of real time closed-loop control. Lightweight, hardware-aware AI model, and rapid training-free (e.g., zero-shot or meta-learning) are required to deploy in practice.

7.2 Joint Design of AI Algorithms and Metasurface Hardware

The existing works frequently consider AI control algorithms and metasurface hardware as two completely independent parts. The physical limit to metasurface tunability (e.g., discrete phase states, delay tolerances, control signal granularity) must, in practice, be co-optimized with learning model architectures. This demands a multiple-discipline collaborative approach to co-design to collectively address electromagnetics, the complexity of AI models and circuit-level control.

7.3 Channel Sparsity and Non-Linearity at THz Frequencies

Characterizations of THz channels include high sparsity, little to no multipath diversity, and complicated non-linear interactions, in particular with reconfigurable surfaces. These characteristics contradict the assumptions of most deep learning structures that assume a lot of training data and distribution of channels that is stationary. Advanced neural networks considering the principles of physics especially incorporating electromagnetic priors will be required to model THz propagations more effectively.

7.4 Scalability of AI Control in Large Metasurface Arrays

State-of-the-art metasurfaces can contain in the thousands the programmable elements, all of which need to be controlled in time and concert. Centralized AI models have the problem of scalability in point of computation, signaling overhead, and model generalization. Distributed, federated, or hierarchical framework resolutions are the potential solutions, yet, they still must be developed to sustain scalable, real-time decision-making under constraints on resource sources.

7.5 Data Scarcity and Generalization

There is a lack of high-fidelity training data of THz bands particularly in the case of dynamic, mobile, or multi-user environments. this makes it hard to train powerful AI models that can generalize across settings and hardware changes. Disciplines like self-supervised learning, synthetics, and transfer learning will have to be exploited to reduce a lack of data as well as to allow greater generalizability in deployment contexts.

Such difficulties justify the prospect of interdisciplinary cooperation between communication engineers, machine learning researchers, and materials scientists to fully open up the potential of AI-powered metasurface control in upcoming THz wireless networks. Table 3 shows a brief overview of the major issues that might arise in an AI-based metasurface-aided THz communication.

Table 3. Challenges in AI-Augmented THz Metasurface Systems

Challenge	Description
Real-Time Adaptation	Ensuring low-latency inference and metasurface reconfiguration in dynamic environments
Joint AI-Hardware Design	Co-optimizing AI models with metasurface hardware constraints (e.g., quantization, delay)
THz Channel Sparsity & Non-Linearity	Modeling sparse and nonlinear THz propagation with physics-aware learning techniques
Scalable AI Control	Managing control and computation across large-scale metasurface arrays with distributed AI
Data Scarcity for Training	Lack of annotated or realistic data to train robust, generalizable AI models for THz systems

8. Future Research Directions

The interaction of artificial intelligence (AI), reconfigurable metasurfaces, and terahertz (THz) communication open up revolutionary prospects of wireless networks of the next generation. Nevertheless, implementing this vision fully will involve producing resolution of a number of strategic and fundamental research problems. This section provides the major future research directions that can enable the realization of scalable, adaptive and standard compliant AI native THz networks.

8.1 Physics-Informed Neural Networks (PINNs) for Metasurface Control

Throughout the traditional neural networks, EM behavior remains in the form of a black-box and its physics is not observed. An alternative with great potential is to use physics-informed neural networks (PINNs) with the Maxwell equations and the boundary conditions built-in to the training process. Any physical laws can be used to constrain the AI models and this may allow PINNs to come up with more accurate, generalizable, and data-efficient control of metasurface parameters in a range of propagation conditions.

8.2 Hybrid Metasurface–RIS–MIMO Architectures

Although both metasurfaces and reconfigurable intelligent surfaces (RIS) are commonly considered independently, it is possible that hybrid architectures that integrate RIS functionality of beam deflection and combine it with the conventional MIMO capabilities and programmable metasurfaces can achieve even better spatial diversity, robustness and energy efficiency. The combined optimization of these elements and how they can be used to combine their respective advantages within THz systems requires research enabled by the aid of AI.

8.3 Hardware-in-the-Loop (HIL) Testing and Prototyping

Most current AI-metaware frameworks are tested through simulation. To make it practically viable, it is important to develop hardware-in-the-loop (HIL) testbed incorporating programmable metasurface prototypes, real-time controllers, and AI accelerators (e.g., edge GPUs or TPUs). HIL testing will allow real-world benchmarking such as delays, actuation limits and power constraints.

8.4 Cross-Layer Optimization for AI-Native 6G THz Systems

Research in the future must not be limited to physical-layer optimization but extend into cross-layer AI design where metasurface behavior is co-optimized with MAC, transport, and application-layer protocols. The presence of such systems would allow adjustable resource allocations, context-aware management and quality-of-experience (QoE)-based decision making, which would be mandatory in 6G use cases of ultra-reliable and low-latency communications.

8.5 Standardization and Interoperability for AI-Metaware Systems

Sooner rather than later, there must be global standardization of AI-metaware interfaces, data structures, and control languages so that ecosystems can be integrated. Instead, interoperability frameworks of both programmable metasurfaces and AI agents should be determined, so that they can be compatible with vendors and platforms. Alliance with organizations like 3GPP, IEEE and ITU-T will play a central role in developing regulatory and operational standards in implementing AI-empowered metasurface systems in 6G.

The future directions advance as a roadmap towards embeddability of the AI-augmented metasurfaces as the building block of the next-generation of the THz communication system. The example of an estimated timeline of major development milestones in the world of AI-augmented metasurface-aided THz communications may be seen in Figure 3.

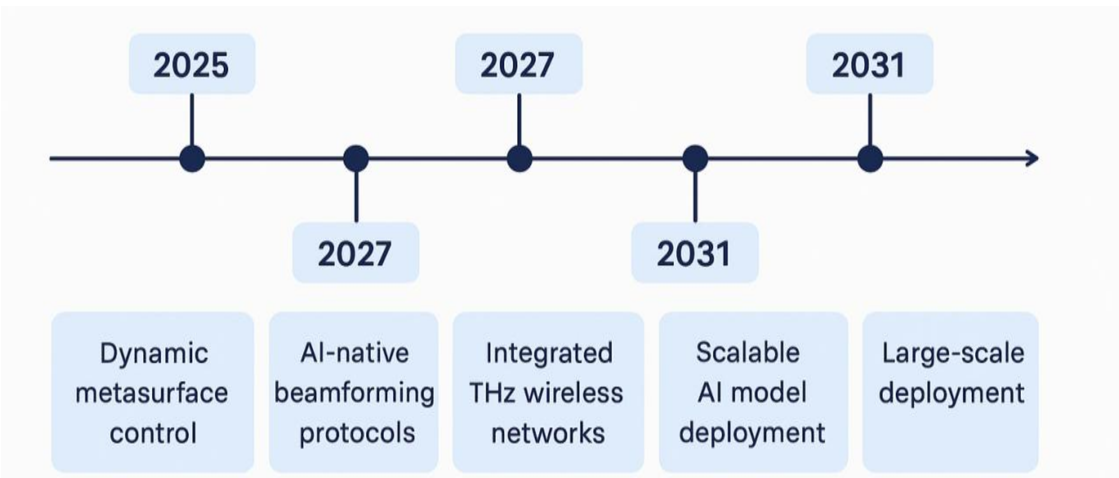

Figure 3. Research roadmap outlining major milestones in the evolution of AI-enhanced metasurface-assisted THz communication from 2025 to 2035.

Major aspects among them are on dynamic metasurface control, AI-native beamforming, compatibility with THz networks, scalable deployment, and large-scale realization.

9. CONCLUSION

AI- assisted metasurfaces have also shown a promising technology that can help resolve the inherent constraints of terahertz (THz) communication: severe propagation loss, misaligned beam, and adaptation to the environment. Integrating intelligence on reconfigurable electromagnetic surfaces, these systems are expected to provide energy-efficient, context- and real-time wireless connectivity, which is consistent with challenging needs of 6G and beyond.

This survey has portrayed a thorough overview of the architectures, AI and deep learning methods, system models, and performance metrics, and deployment strategies that constitute the current scene of the metasurface-aided terahertz (THz) communication. We have evaluated the existing approaches, listed key research gaps, including scalability, data limitation, hardware-Software co-design, and proposed future research directions, which have included physics-informed learning, cross-layer optimization, federated intelligence, and standardization frameworks.

We anticipate a new generation of adaptive, self-organizing wireless systems that can provide ultra-high-speed communication, low latency and mobile resilience using the combination of data-driven intelligence and programmable metasurfaces. Such a convergence will lie at the heart of the intelligent, immersive and infrastructure-aware wireless environments of the 6G era.

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