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6g-Enabled Internet of Things: A Survey of Enabling Technologies, Network Architecture, Applications and Open Challenges

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Abstract—The Internet of Things (IoT) links sensors, machines, vehicles and everyday objects so that they can exchange data and act with little human intervention. Fifth-generation (5G) networks introduced dedicated support for massive machine-type and ultra-reliable low-latency communication, but emerging applications such as autonomous transport, remote surgery, immersive extended reality and large-scale digital twins demand still higher data rates, lower latency, greater reliability, precise positioning and far denser connectivity. Sixth-generation (6G) networks, now being defined under the IMT-2030 framework, aim to meet these needs and to make artificial intelligence a native part of the network. This survey reviews 6G-enabled IoT. It summarises the requirements and key performance indicators, and explains the enabling technologies: terahertz and sub-terahertz communication, intelligent reflecting surfaces, integrated sensing and communication, edge intelligence, AI-native network management and non-terrestrial networks. A five-layer architecture for 6G-enabled IoT is presented, linking devices, access, edge, core and applications under a cross-layer security and energy plane. Applications in smart cities, connected vehicles, healthcare, industrial automation, precision agriculture and environmental monitoring are discussed. Finally, open challenges including infrastructure cost, spectrum regulation, energy consumption, security and privacy, and the management of billions of devices are identified.

Index Terms—6G, Internet of Things, IMT-2030, terahertz communication, intelligent reflecting surface, integrated sensing and communication, edge computing, artificial intelligence, network security.

I. INTRODUCTION

The Internet of Things (IoT) describes a world in which physical objects carry sensors, processors and communication interfaces, allowing them to report their state and respond to commands over the network [1]. Smart meters, environmental sensors, wearable health monitors, industrial robots and connected vehicles are all examples. The number of such devices continues to grow rapidly, and their data increasingly drive automated decisions.

Wireless networks are the backbone of IoT. Earlier cellular generations were designed mainly for human users, while 5G introduced three service categories: enhanced mobile broadband, ultra-reliable low-latency communication (URLLC) and massive machine-type communication. These made cellular networks much more suitable for IoT. However, applications now being envisioned, including fleets of autonomous vehicles, tactile internet, remote surgery, holographic communication and digital twins of entire factories or cities, require capabilities beyond those of 5G [2], [3].

Research on sixth-generation (6G) networks therefore began around 2019, and the International Telecommunication Union (ITU) has published the framework for IMT-2030, which sets the objectives and usage scenarios for 6G [4]. Visions of 6G emphasise very high data rates, sub-millisecond latency, extreme reliability, centimetre-level positioning, sensing as a network function, and artificial intelligence (AI) embedded throughout the network [5], [6]. These features are particularly significant for IoT, because they allow the network not only to connect devices but also to sense their environment and make intelligent decisions on their behalf [7].This survey reviews 6G-enabled IoT. Its contributions are:

- A summary of 6G requirements relevant to IoT and a comparison with 5G.
- A review of the key enabling technologies and their benefits for IoT.
- A layered architecture for 6G-enabled IoT systems.
- A discussion of applications, open challenges and future research directions.

Section II gives the background, Section III reviews enabling technologies, Section IV presents the architecture, Section V discusses applications, Section VI compares approaches,

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Section VII discusses challenges, and Section VIII concludes.

II. BACKGROUND

2.1 Evolution From 5g To 6g

Each mobile generation has extended the network's capabilities. 5G added new spectrum in millimetre-wave bands, network slicing, edge computing and URLLC. Yet surveys of 6G point out that 5G still cannot meet the joint demands of very high rates, extremely low latency and very high reliability required by applications such as extended reality and autonomous systems [2], [8]. 6G is expected to address these through new spectrum, new air-interface technologies and a more intelligent, flexible architecture.

2.2 Requirements For Iot

Table I compares indicative capabilities of 5G and 6G. The 6G values reflect the IMT-2030 framework and research visions; final values will be set during standardisation [4], [8].

Table I Indicative Comparison Of 5g And 6g Capabilities

Parameter	5G (IMT-2020)	6G (IMT-2030, indicative)
Peak data rate	20 Gbit/s	50–200 Gbit/s; up to 1 Tbit/s in visions
Latency	About 1 ms	0.1–1 ms
Connection density	106 devices/km2	106–108 devices/km2
Reliability	1 − 10−5	Up to 1 − 10−7
Positioning	Metre level	Centimetre level
New functions	Slicing, MEC	Native AI, sensing, NTN

Beyond raw numbers, IoT devices in 6G must be energy-efficient, often battery-free or powered by harvested energy, low in cost, and secure. The network must support diverse devices ranging from simple sensors sending a few bytes per day to vehicles exchanging high-definition sensor data in real time [7].

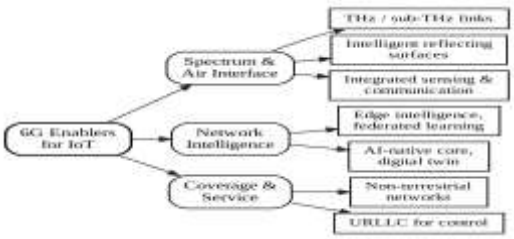


Fig. 1. Key enabling technologies for 6G-enabled IoT.

III. ENABLING TECHNOLOGIES

3.1 Terahertz And Sub-Terahertz Communication

The spectrum above 100 GHz offers very wide bandwidths, which can support data rates of hundreds of gigabits per second. Rappaport *et al.* examined the opportunities and challenges of communication above 100 GHz, including high path loss, absorption by atmospheric gases and the need for highly directional antennas [9]. For IoT, these bands are suited to short-range, high-capacity links, such as wireless connections within factories, data centres and between vehicles, and to high-resolution sensing.

3.2 Intelligent Reflecting Surfaces

An intelligent reflecting surface (IRS), also called a reconfigurable intelligent surface, is a thin panel containing many low-cost elements that can adjust the phase of reflected signals. By configuring these elements, the surface can steer signals around obstacles and improve coverage and energy efficiency without active transmitters. Wu and Zhang showed that jointly optimising the base-station beamforming and the IRS phase shifts significantly improves received signal power [10]. IRSs are attractive for IoT because they can extend coverage to devices in shadowed locations at low energy cost.

3.3 Integrated Sensing And Communication

Integrated sensing and communication (ISAC) uses the same spectrum, hardware and signals for both data transmission and radar-like sensing of the environment. Liu *et al.* reviewed ISAC and its role in 6G [11]. For IoT, ISAC allows the network to detect, locate and track objects such as vehicles, drones and people, even when these objects do not carry devices, which supports smart transport and security applications.

3.4 Edge Computing And Edge Intelligence

Mobile edge computing (MEC) places computing resources close to users, at base stations or local servers, so that data can be processed with low latency and without sending everything to a distant cloud [12], [13]. In 6G, edge servers will also train and run AI models. Federated learning lets devices train a shared model without uploading raw data, which helps protect privacy. Edge intelligence is essential for IoT devices that lack the processing power to run complex models themselves.

3.5 Ai-Native Networks

Letaief *et al.* described a roadmap in which AI is used throughout 6G networks, for tasks such as channel estimation, resource allocation, mobility management and fault detection [5]. With billions of IoT devices and highly variable traffic, manual configuration is impractical, and AI-

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based self-organising networks can allocate spectrum, power and computing resources automatically.

3.6 Non-Terrestrial Networks

Satellites, high-altitude platforms and unmanned aerial vehicles can extend coverage to oceans, deserts, mountains and rural areas. Integrating these non-terrestrial networks with terrestrial ones is a key 6G goal and enables IoT applications such as global asset tracking, environmental monitoring and agriculture in remote areas [3], [6].

3.7 Ultra-Reliable Low-Latency Communication

Bennis, Debbah and Poor showed that achieving very high reliability with low latency requires attention to rare events in the tail of the latency distribution rather than only average performance [14]. 6G extends URLLC to support control loops for robots, vehicles and medical devices where a missed deadline can cause physical harm.

Table Ii Summary Of Representative Studies On 6g And 6g-Enabled Iot

Ref.	Focus	Contribution	Relevance to IoT	Limitation
[2]	6G vision	Applications, trends and open problems	Identifies IoT-driven use cases	Vision paper
[5]	AI-native 6G	Roadmap for AI across the network	Automated management of massive IoT	High-level framework
[7]	6G IoT survey	Comprehensive review of 6G for IoT	Direct mapping of technologies to IoT	Broad; limited depth per topic
[9]	THz bands	Propagation and hardware above 100 GHz	High-capacity short-range IoT links	Severe path loss, short range
[10]	IRS	Joint active and passive beamforming	Coverage for shadowed devices	Channel estimation overhead
[11]	ISAC	Dual-function sensing and communication	Device-free sensing and tracking	Waveform design trade-offs
[15]	Security	Survey of 6G security and privacy	Protecting massive IoT	Many open problems

IV. ARCHITECTURE OF 6G-ENABLED IOT

The **device layer** contains sensors, actuators, wearables, vehicles, drones and robots. Many devices will use energy harvesting or backscatter communication to operate without batteries. The **access layer** connects devices through sub-6 GHz, millimetre-wave and terahertz links, assisted by intelligent reflecting surfaces and integrated sensing [9]–[11]. Satellites and aerial platforms provide coverage where terrestrial infrastructure is absent. The **edge layer** processes data close to devices, runs AI inference and federated learning, and supports latency-critical control [12]. The **core and cloud layer** provides an AI-native core with network slicing, digital twins of the network and physical systems, and large-scale analytics [5]. The **application layer** delivers services such as smart cities, autonomous vehicles, remote healthcare, industrial automation, precision agriculture and environmental monitoring. A cross-layer plane manages security, privacy, trust and energy, because these must be considered at every level [15].

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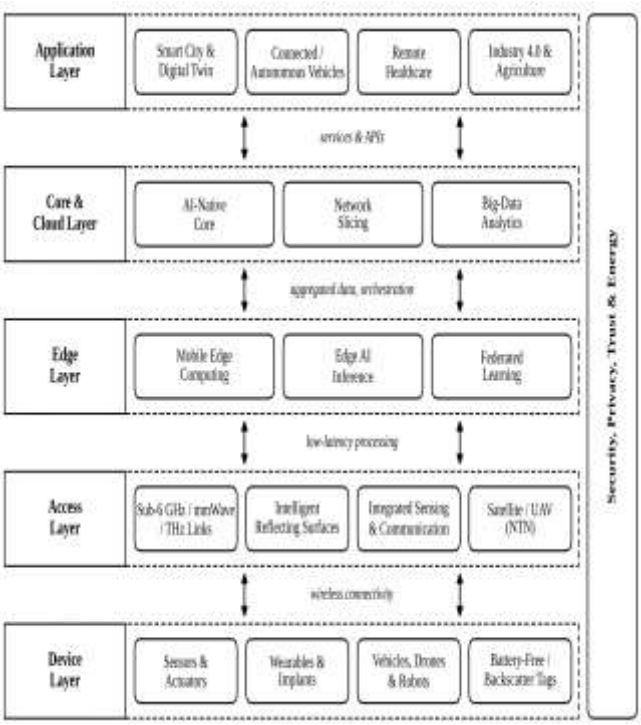


Fig. 2 presents a five-layer architecture for 6G-enabled IoT that brings together the technologies discussed above.

Fig. 2. Five-layer architecture of 6G-enabled IoT with a cross-layer security, privacy and energy-management plane.

V. APPLICATIONS

5.1 Smart Cities

6G-enabled IoT can connect traffic sensors, street lighting, waste management, water networks and public safety cameras. Digital twins of city infrastructure, updated in real time, can be used to plan and optimise services [7].

5.2 Autonomous And Connected Vehicles

Vehicles exchange sensor data with each other and with roadside units to extend their perception beyond line of sight. High data rates, low latency and accurate positioning support cooperative driving, while ISAC helps the network track road users [2], [11].

5.3 Remote Healthcare

Wearable and implantable devices can stream health data continuously, and remote diagnosis or even tele-surgery requires reliable, low-latency links with haptic feedback [8].

5.4 Industrial Automation

Factories can replace wired connections with wireless links for robots and sensors, allowing flexible production lines. URLLC and time-sensitive networking support closed-loop control [14].

5.5 Precision Agriculture And Environmental Monitoring

Soil, crop and weather sensors, drones and satellites can monitor fields and forests over large rural areas, enabled by non-terrestrial coverage and low-power devices. These support irrigation, pest control, pollution monitoring and early warning of natural hazards [3].

VI. COMPARATIVE ANALYSIS

Table III compares the main enabling technologies in terms of their benefits and costs for IoT.

Table Iii Comparison Of 6g Enabling Technologies For Iot

Technology	Main Benefit	IoT Use Case	Key Challenge
THz communication [9]	Very high data rate	Industrial and vehicular high-capacity links	Path loss, hardware cost
IRS [10]	Coverage and energy efficiency	Indoor and shadowed sensors	Channel estimation, control
ISAC [11]	Sensing without extra hardware	Traffic and security monitoring	Interference between functions
Edge intelligence [12], [13]	Low latency, privacy	Real-time analytics, control	Limited edge resources
AI-native network [5]	Autonomous management	Massive device management	Explainability, training data
Non-terrestrial networks [3]	Global coverage	Remote agriculture, tracking	Delay, integration cost

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VII. CHALLENGES AND FUTURE DIRECTIONS

Several challenges must be addressed before 6G-enabled IoT can be deployed widely. **Infrastructure cost** is high, because higher frequency bands require many more small cells, and IRSs and edge servers must be installed widely [8]. **Spectrum** above 100 GHz must be allocated and regulated internationally, and its propagation characteristics require new channel models [9]. **Energy consumption** of networks and devices must be reduced; energy harvesting, low-power hardware and energy-aware scheduling are active research topics [6]. **Security and privacy** become harder with billions of resource-limited devices; lightweight authentication, physical-layer security, trustworthy AI and preparation for quantum-era threats are needed [15]. **Scalability and management** of massive numbers of heterogeneous devices require automated, AI-based orchestration [5]. Finally, **standardisation** is still in progress, and interoperability among vendors and with existing 5G systems must be ensured [4]. Future research is expected to address these through joint communication–computation–sensing design, green network operation and secure-by-design architectures.

VIII. CONCLUSION

6G-enabled IoT aims to provide faster, smarter and more reliable connectivity for billions of devices. This survey has reviewed the requirements that motivate 6G and the technologies that will enable it, including terahertz communication, intelligent reflecting surfaces, integrated sensing and communication, edge intelligence, AI-native management and non-terrestrial networks. A five-layer architecture has been presented, and applications ranging from smart cities to precision agriculture have been discussed. Significant challenges remain in cost, spectrum, energy, security and management, but addressing them will allow 6G-enabled IoT to play a central role in a fully connected and automated digital ecosystem.

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