6G-IoT Technologies

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The advent of 6G-IoT promises a revolutionary leap, integrating AI, expanded coverage, and autonomy in a seamless manner, thereby reshaping industries such as smart agriculture. Presented here are the essential technologies that will make it possible to meet the 6G-IoT requirements.

6G-IoT artificial intelligence (AI) Internet of Things (IoT) wireless communications smart agriculture

1. Introduction

Following the revolution brought about by the convergence of IoT applications and 5G network technology, 6G is expected to outperform its predecessor in many aspects, thereby enhancing both our daily lives and business productivity [1]. **Figure 1** depicts the evolution of wireless communications over time, beginning with 1G communications developed in the 1980s and ending with 6G communications expected to be completed in the 2030s. As shown in the figure, 6G is expected to provide all of the features offered by previous network generations, as well as some new ones, such as full network coverage, the development of massive IoT and mobile applications using AI, improved satellite communications, and the development of fully autonomous systems [2].

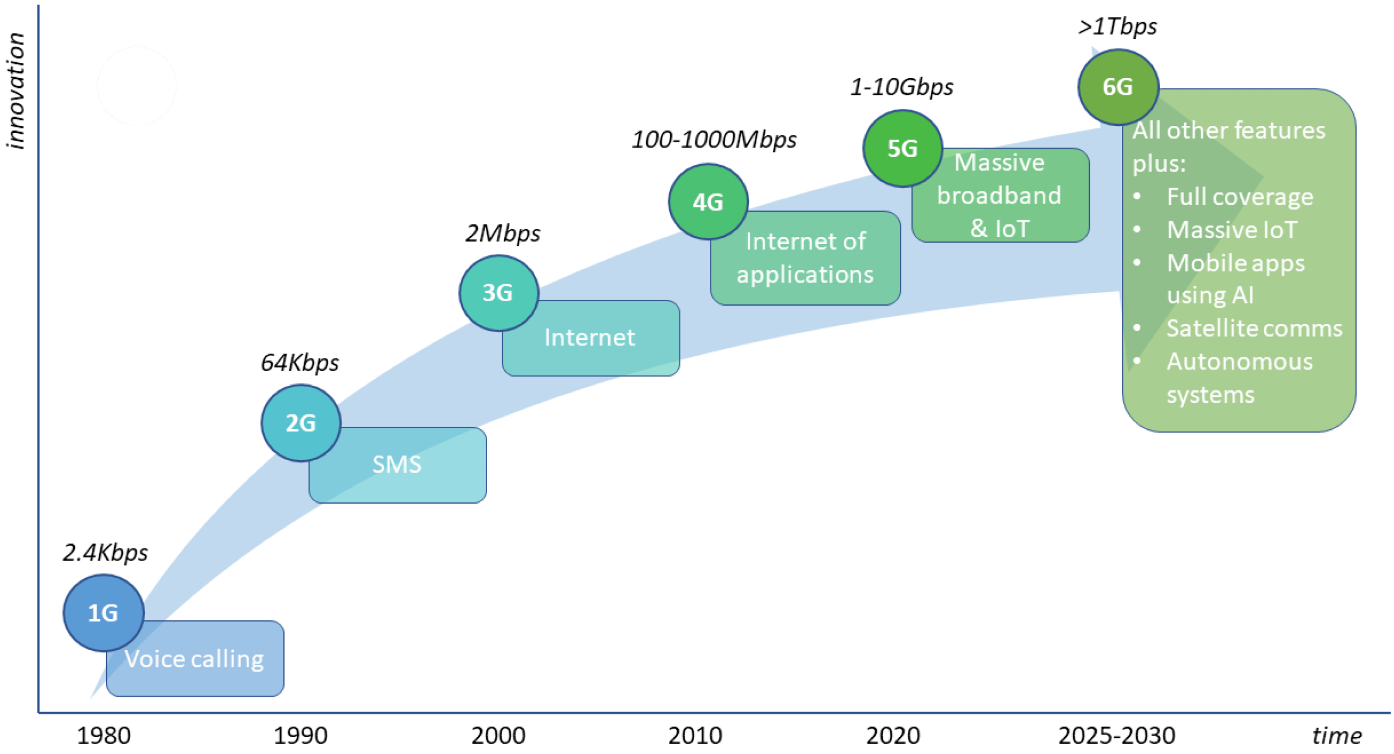

Figure 1. The evolution of wireless communications toward future 6G networks and applications.

In this context, 6G networking combines current and emerging technologies from the physical to the application network levels, creating a fully digitized and unified interface among users, services, computers, sensors, and smart objects in response to the new era's challenges [3]. In the areas of mobile broadband, end-to-end latency, geographical coverage, and mass connectivity, new horizons are opening, setting the foundation for the next generation of the Internet of Things.

The 6th Generation of the Internet of Things (6G-IoT) is anticipated to address critical issues involving massively reliable and ultra-low-latency communication, efficient use of communication protocols, and extensive IoT network geographic coverage. Moreover, with the advent of AI, devices are becoming more sophisticated and, in conjunction with their increased computing capabilities, are able to interact actively with the network, as opposed to merely transmitting data [4]. Consequently, it is anticipated that the 6G-IoT framework will provide efficient solutions for industrial IoT, smart cities, and remote applications, which will have a significant impact on the next generation of smart agriculture [5]. The essential technologies that will make it possible to meet the 6G-IoT requirements and enable Agriculture 5.0 are depicted in **Figure 2** and described in the sections that follow.

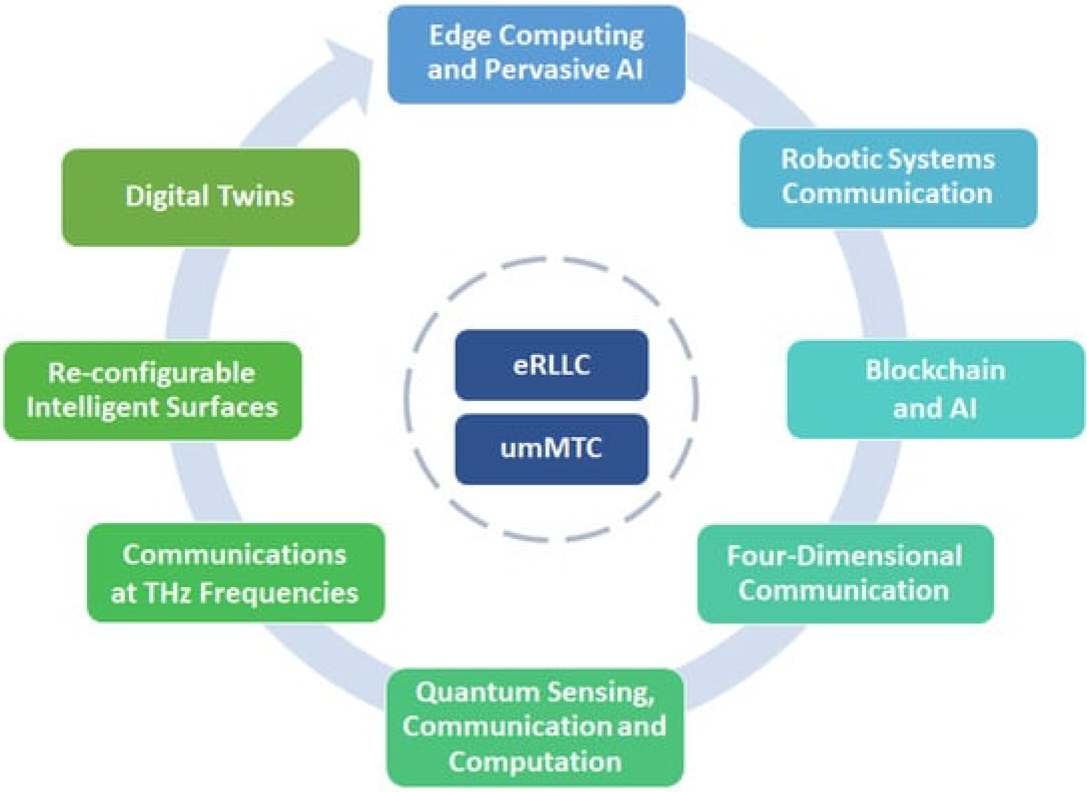

Figure 2. 6G-IoT enabling technologies in Agriculture 5.0.

2. Edge Computing and Pervasive Artificial Intelligence

Digital network devices, even those at the network's edge, have increasingly sophisticated computing capabilities. Therefore, we can utilize their computing power to assist with and, under certain conditions, optimize network performance [6][7]. Moreover, with the advent of AI, these devices will be able to extract information and expertise from the data they communicate with other entities on the network, identifying and categorizing services using learning models. Edge AI applications have emerged as a significant area of research, demonstrating their effectiveness in a variety of agricultural applications. For instance, cutting-edge computer vision methods utilizing deep learning can facilitate the extraction of navigation lines in intricate farmland environments for field robots [8]. Moreover, the integration of lightweight neural networks and edge computing enables real-time crop detection by harvesting robots [9].

The future of edge AI also involves a shift in the traditional approach of training models on powerful servers and then deploying them to edge devices. With the advent of federated learning (FL), the training process becomes decentralized, and the training data are stored on the edge devices where they originated [5]. In this approach, edge devices contribute to the training process by sending local model updates computed using their own data to a central server. The central server aggregates updates from multiple devices, modifies the global model, and then distributes the updated version to the edge devices. This iterative procedure continues until the global model reaches the desired performance level. As a result, the need for data transmission from the network's edge to the cloud is significantly reduced, leading to increased security and an accelerated training process [10][11].

Overall, edge computing and edge AI offer the benefits of local data processing, which reduces the need to send data to the cloud. This, in turn, helps to alleviate the traffic load on the backbone network. However, it is important to note that edge computing and edge AI cannot be universally applied to all deployment scenarios. They are primarily designed to provide immediate responses for real-time applications, such as navigation, coordination, and collaboration of autonomous vehicles and robots in farming operations. On the other hand, they are not well-suited for data-intensive tasks like large-scale analytics, high-resolution image processing, and augmented reality applications. Consequently, for complex tasks that require significant computational resources, it is still necessary to transmit data to the cloud. The extent to which edge computing and edge AI can reduce the need for communication with the cloud is dependent on the requirements of the specific application, the nature of the data, and the capabilities of the edge device.

3. Blockchain and Artificial Intelligence

Blockchain technology enables the creation of a distributed trust system. In fact, blockchain provides the same level of trust as traditional written contractual agreements due to its distributed and secure method of storing, managing, and transferring information and executing electronic transactions [12]. Specifically, the term blockchain refers to a public or private distributed ledger in which electronic transactions or data are connected in linked blocks of data. That renders them practically immune to malicious modifications due to a method that encrypts and hashes the block’s information in an irreversible manner (one-way encryption) [12].

While blockchain is extremely useful in order to provide security in the distributed IoT environment, its use will be further enhanced with a combination of artificial intelligence methods [13]. The use of blockchain’s digital record to track the rationale behind AI predictions and thus enable people to trust them will be a big benefit of the AI–blockchain combination in 6G systems. In addition, adopting blockchain technology for archiving and distributing AI learning models would provide an audit record, which would enhance security. Blockchain also facilitates the development of AI by granting it access to vast amounts of verifiable data, thereby enhancing the reliability of the decisions it makes [14].

4. Four-Dimensional Communication

Geographical coverage will exceed current boundaries, and communication will occur in four dimensions: on the ground, underwater or underground, in the air, and in space. Thus, a unified communication environment will be formed in which connectivity and services will be uninterruptedly provided by 6G-IoT [15]. Unmanned Aerial Vehicles (UAVs) and satellites are the key enabling technologies that will make this scenario feasible. Satellites provide wireless coverage in various earth orbits, including low (LEO), medium (MEO), and geostationary (GEO) earth orbits, thereby enhancing the current terrestrial telecommunications infrastructure and enabling the efficient network coverage of rural, remote, and geographically isolated areas [16]. Furthermore, new satellite systems in Very Low Earth Orbit (VLEO) will be developed, which will provide considerable advantages over traditional satellite systems, such as reduced satellite size and improved energy efficiency. VLEO systems also offer lower signal path losses and reduced latency communications, making them ideal for telecommunications applications [15].

In the airborne networking scenario, UAVs will be utilized as relays or even as mobile base stations in the event that a portion of the terrestrial network is compromised or destroyed during an emergency situation [17]. Additionally, they can be combined with satellite systems, forming a hybrid non-terrestrial network with advanced capabilities [18]. In addition, communications between submarines and specialized equipment for various ocean life monitoring services will be feasible in the underwater sector thanks to transponders linked to the terrestrial infrastructure. Following the concept of four-dimensional communication, underground sensors or devices embedded in the soil can also be employed in order to collect data on various parameters like moisture levels and nutrient content. In both cases, the main research challenge is to mitigate the increased signal attenuation caused by soil or water layer interference on the transmission path. This, in turn, impacts network topology, as there is a tradeoff between the energy consumption and communication range of underground/underwater sensor nodes. Thus, in this context, new technologies, such as the Internet of Underground Things (IoUT) [19], Wireless Underground Sensor Networks (WUSNs) [20], and Internet of Underwater Things (IoWTs) [21], are gradually advancing. Consequently, the enhanced monitoring, analysis, and prediction services that Agriculture 5.0 will offer will be substantially aided by the global continuous connectivity and reliable low-latency communication of 6G-IoT Non-Terrestrial Networks (NTNs) [22][23].

5. Quantum Sensing, Communication, and Computation

Quantum technology has been proposed for future networks as a promising technology capable of delivering super-high data transmission rates and significantly enhanced security [2][24]. The fundamental concepts of quantum mechanics are based on the superposition principle, which asserts that until a quantum system is measured, it can exist in multiple states simultaneously. Consequently, the quantum supercomputers of the future will not process information bits but rather quantum bits (i.e., qubits) that can be in a coherent superposition of both one and zero states. Quantum technology, which includes quantum sensing, quantum communication, and quantum computation, is expected to have a substantial impact on the design of future networked computing systems [5].

Many elementary quantum systems, including atomic spin systems, NV (nitrogen-vacancy) center ensembles, and trapped ions, can serve as quantum sensors [25]. Due to the extreme sensitivity of quantum states to even the smallest changes, these sensors have a higher sensitivity than conventional sensors, and they have the potential for more precise monitoring of physical parameters such as electromagnetic fields and temperature.

Moreover, quantum communication is expected to revolutionize data transmission by utilizing the principles of quantum mechanics to ensure a secure and tamper-proof exchange of information. Quantum communication protocols have the ability to detect any interception or eavesdropping attempts, as the act of measuring quantum states disrupts their delicate properties. Furthermore, the implementation of quantum key distribution (QKD), a method that leverages quantum mechanics for securely creating and exchanging encryption keys between two parties, will further enhance the protection of sensitive agricultural data. Consequently, valuable data, including crop yields, market predictions, and sensor-derived information from the field, will be safeguarded, ensuring their integrity, confidentiality, and authenticity while mitigating the risks associated with unauthorized access and manipulation [26][27]. In addition to its applications in computer communication and high-precision sensing, the academic community has shown interest in quantum computing. The main advantage of quantum computing is quantum parallelism, which enables quantum computers to simultaneously compute multiple outputs of a function, exceeding the capabilities of classical computing. Quantum computing is anticipated to be widely utilized for accelerating the analysis of big data sets and minimizing the training phase of Machine Learning (ML) algorithms. By going beyond classical binary computing, quantum computing can significantly reduce the training and execution times of machine learning algorithms, making them suitable for real-time, computationally demanding applications. The new field of research that emerges from the combination of quantum computing with machine learning is referred to as Quantum Machine Learning (QML) [28][29].

6. Terahertz Communications

To address the spectrum and capacity shortage below 6 GHz, the adoption of higher frequency bands has already been standardized in 5G networks, primarily for frequencies between 24 and 48 GHz, permitting the development of new very-high-speed services. Future 6G networks are anticipated to employ frequencies over 100 GHz in the THz frequency range (0.1 to 10 THz) [30]. It is anticipated that systems designed to make use of these ultra-high-frequency bands will feature extremely low latency and enormously high data rates. As the number of IoT devices and the volume of generated data continue to increase, the development of high-bandwidth and low-latency communication links will provide a foundation for scalability, accommodating the growing demands of data transmission and processing.

However, THz communication systems are still in their infancy, and while some of their challenges are similar to those of 5G mm-wave systems, many others are unique and require the development of novel technological solutions [30][31]. Consequently, innovative transceiver designs, transmission techniques, and communication protocols must be devised to meet the requirements of 6G THz systems. Once these challenges are sufficiently addressed, the THz communication systems will be able to support new applications with higher requirements and, in light of next-generation agriculture, will be able to enable ultra-high-precision agriculture services [32][33]. These services are expected, for example, to offer plant-level data and therefore unparalleled accuracy in targeting and treating even individual plants, which will massively reduce chemical use. Clearly, such approaches necessitate extremely demanding real-time, ultra-high-resolution field monitoring, which could be efficiently supported by future 6G THz systems [30].

7. Reconfigurable Intelligent Surfaces

Despite the fact that current 5G networks are more energy- and spectrum-efficient than their predecessors, it is anticipated that future 6G networks will utilize the innovative technology of Reconfigurable Intelligent Surfaces

(RIS) to further enhance energy and spectrum efficiency [34]. The aim of RIS technology is to transform the wireless environment dynamically, thereby overcoming the stochastic nature of the propagation channel. In this sense, the wireless environment could be an additional variable in network design with specific, measurable, and modifiable properties. In addition, the use of RIS in THz communications could be more challenging but extremely promising in reducing the high propagation attenuation of ultra-high-frequency signals.

Consequently, the employment of RIS technology could be incredibly useful in a variety of Agriculture 5.0 scenarios, as it could extend the monitoring range (i.e., the coverage area) and reduce the amount of power consumed, both of which are essential for IoT systems [35]. RIS can also be combined with wireless power transfer systems to focus transmitted energy on the intended sensors, enhancing the overall efficiency of the procedure [36]. Additionally, RIS could be integrated with Simultaneous Wireless Information and Power Transfer (SWIPT) systems, allowing the end device to concurrently harvest energy and decode information [37]. Therefore, it is anticipated that RIS technology will be an essential component for efficiently powering edge IoT devices in 6G-IoT systems, thereby providing a number of benefits for Agriculture 5.0 deployment scenarios.

8. Digital Twin Technology

With the use of digital twin technology, engineers can create virtual replicas of physical objects or even systems to test and validate concepts before production. A digital twin can also be used in real time and, by regularly synchronizing and exchanging data with its real counterpart, it could greatly facilitate both its maintenance as well as its integration with other systems [30]. In addition, digital twins can be utilized in diagnostic or prognostic procedures employing historical data and leveraging big data and artificial intelligence technology [38]. The necessity to evaluate novel concepts, designs, and services is what motivates the deployment of digital twins in sixth generation IoT networks. As a result, the technology of digital twins is now included in 6G-IoT research and standardization processes.

The use of digital twins to improve urban aquaponics farming is detailed in [39]. Aquaponics, which employs hydroponic farming principles, aims to create closed nutrient cycle systems that permit the concurrent cultivation of plants and fish. In this project, digital twin technology was used to provide an aquaponics system with the capacity to adapt to and foresee potential problems. Additionally, the study presented in [40] that uses digital twins, IoT, and big data may have accurately predicted future greenhouse conditions, which can assist in securing the planet’s sustainability in the future. Even though using digital twin technology has many advantages, there are still a number of issues that need to be addressed as part of the 6G-IoT research and standardization process, particularly with regard to security issues and the accuracy with which digital and real-world systems can be matched [41].

9. Sustainable End-to-End Network Architecture: The Role of Green Technologies

Sustainability is a primary consideration for 6G networks, with an emphasis on the reduction of energy consumption and the employment of green technologies. The objective is to design an end-to-end network architecture that operates efficiently while minimizing its environmental impact. Consequently, the concept of energy optimization is not restricted to a single 6G network component. Instead, it incorporates the entire network architecture with the objective of reducing energy consumption and maximizing the use of renewable energy sources [42].

In this context, it is anticipated that 6G networks will employ artificial intelligence to optimize energy consumption via intelligent power management processes. By employing AI and ML algorithms to monitor and optimize energy usage, it will be possible to reduce the energy consumption of 6G networks without impacting their performance [43]. This will not only reduce the ecological footprint of 6G networks, but it will also help extend the battery life of wireless IoT devices. Furthermore, it is anticipated that energy-efficient hardware will be one of the most significant green innovations utilized by 6G-IoT. As the demand for wireless communication increases, so does the energy requirement to power wireless devices. Through the use of energy-efficient hardware, it is possible to reduce the amount of energy required for data transmission, thereby reducing the carbon footprint of 6G networks.

Energy harvesting is also an essential technology that is expected to be employed in 6G networks. This technology captures and transforms ambient energy sources like heat, light, and motion into electrical energy and is typically used for powering low-power devices or sensors in remote or inaccessible areas. Moreover, it is anticipated that 6G networks will make extensive use of renewable energy sources such as solar, wind, biomass, and hydroelectric power, which are becoming increasingly efficient and cost-effective. By utilizing renewable energy sources to power 6G networks, it will be possible to decrease their reliance on fossil fuels and, in turn, their carbon emissions [44][45][46].

10. Anticipated Advancements in 6G Services: umMTC and eRLLC

In order to support massive Machine-Type Communication (mMTC), Ultra-Reliable Low-Latency Communication (URLLC), and enhanced Mobile Broadband (eMBB) in 5G systems, the 3rd Generation Partnership Project (3GPP) has standardized a number of technical advancements, starting with release 16’s 5G New Radio (NR) deployments [47][48]. It is anticipated that after release 17, subsequent releases (releases 18, 19, and 20) will provide significant technological advances toward 5G Advanced and 6G. Specifically, 3GPP Release 17 targets existing use cases, such as mobile broadband and industrial automation, and aims to improve 5G system performance by enabling new use cases and providing ubiquitous connectivity for a variety of use case scenarios. Releases 18, 19, and 20 will usher in the era of 5G Advanced, where artificial intelligence, augmented reality, and NTN integration will be further enhanced [18]. Thus, the prerequisites for the creation of the next generation of networks will be satisfied, and it is predicted that the initial specifications for 6G networks will be released in 2027 [16][49].

It is anticipated that 5G network services focused on massive connectivity and reliable low-latency communication, especially in IoT environments, will continue to advance along this path of technological innovation. Therefore, it is anticipated that mMTC and URLLC services will evolve into umMTC (ultra-massive Machine-Type Communication) and eRLLC (extremely Reliable Low-Latency Communication), respectively [2][31][50]. Regarding umMTC, it is expected that it will be capable of supporting a density of over one million IoT connections per square kilometer. Given the exponential growth of IoT connections in industrial complexes, smart city environments, as well as semi-urban and remote rural areas, it is predicted that numerous umMTC services will emerge, although their characteristics (e.g., bulk, critical, scalable, and zero-energy MTC) and consequently their requirements will vary considerably [51]. 6G will also enable the use of eRLLC services in a significant range of Industry 4.0 and beyond applications, including the ubiquitous use of robots, UAVs, and new Human–Machine Interfaces (HMIs) in manufacturing and autonomous driving, as well as in next-generation agriculture [22].

As shown in **Table 1**, which compares the characteristics of 5G-IoT and 6G-IoT, it is anticipated that 6G-IoT will provide a significant increase in throughput and a corresponding decrease in latency.

Table 1. Comparison between the 5G-IoT and 6G-IoT requirements.

Requirements	5G-IoT	6G-IoT
Throughput (Gbps)	20	100
Latency (ms)	1	[0.01–0.1]
Energy Efficiency	×1000 of 4G	×10 of 5G
Network Coverage (global %)	70	99
Spectral Efficiency (bps/Hz)	30	100
Massive Connectivity (devices/km2)	106	107
NTN Integration	Partially	Fully (Satellites & UAVs)
AI	Partially	Fully

In addition, a quite substantial improvement in energy and spectrum efficiency is anticipated. It is also projected that network coverage will expand to 99% on a worldwide scale, which can be attributed to the full integration of terrestrial and non-terrestrial networks. A tenfold rise in the density of connected devices per square kilometer is also expected, while at the same time edge network devices will support pervasive AI services [3].

References

1. Abdel Hakeem, S.A.; Hussein, H.H.; Kim, H. Vision and research directions of 6G technologies and applications. J. King Saud Univ. Comput. Inf. Sci. 2022, 34, 2419–2442.

2. Alsharif, M.H.; Kelechi, A.H.; Albreem, M.A.; Chaudhry, S.A.; Zia, M.S.; Kim, S. Sixth Generation (6G) Wireless Networks: Vision, Research Activities, Challenges and Potential Solutions. Symmetry 2020, 12, 676.
3. Guo, F.; Yu, F.R.; Zhang, H.; Li, X.; Ji, H.; Leung, V.C.M. Enabling Massive IoT Toward 6G: A Comprehensive Survey. IEEE Internet Things J. 2021, 8, 11891–11915.
4. Nguyen, D.C.; Ding, M.; Pathirana, P.N.; Seneviratne, A.; Li, J.; Niyato, D.; Dobre, O.; Poor, H.V. 6G Internet of Things: A comprehensive survey. IEEE Internet Things J. 2021, 9, 359–383.
5. Imoize, A.L.; Adedeji, O.; Tandiya, N.; Shetty, S. 6G Enabled Smart Infrastructure for Sustainable Society: Opportunities, Challenges, and Research Roadmap. Sensors 2021, 21, 1709.
6. Alkhalaileh, M.; Calheiros, R.N.; Nguyen, Q.V.; Javadi, B. Performance Analysis of Mobile, Edge and Cloud Computing Platforms for Distributed Applications. In Mobile Edge Computing; Mukherjee, A., De, D., Ghosh, S.K., Buyya, R., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 21–45.
7. Zhu, G.; Lyu, Z.; Jiao, X.; Liu, P.; Chen, M.; Xu, J.; Cui, S.; Zhang, P. Pushing AI to wireless network edge: An overview on integrated sensing, communication, and computation towards 6G. Sci. China Inf. Sci. 2023, 66, 130301.
8. Yu, J.; Zhang, J.; Shu, A.; Chen, Y.; Chen, J.; Yang, Y.; Tang, W.; Zhang, Y. Study of convolutional neural network-based semantic segmentation methods on edge intelligence devices for field agricultural robot navigation line extraction. Comput. Electron. Agric. 2023, 209, 107811.
9. Zhang, Y.; Yu, J.; Chen, Y.; Yang, W.; Zhang, W.; He, Y. Real-time strawberry detection using deep neural networks on embedded system (rtsd-net): An edge AI application. Comput. Electron. Agric. 2022, 192, 106586.
10. Al-Quraan, M.; Mohjazi, L.; Bariah, L.; Centeno, A.; Zoha, A.; Arshad, K.; Assaleh, K.; Muhaidat, S.; Debbah, M.; Imran, M.A. Edge-Native Intelligence for 6G Communications Driven by Federated Learning: A Survey of Trends and Challenges. IEEE Trans. Emerg. Top. Comput. Intell. 2023, 7, 957–979.
11. Letaief, K.B.; Shi, Y.; Lu, J.; Lu, J. Edge artificial intelligence for 6G: Vision, enabling technologies, and applications. IEEE J. Sel. Areas Commun. 2021, 40, 5–36.
12. Ali, O.; Jaradat, A.; Kulakli, A.; Abuhalimeh, A. A comparative study: Blockchain technology utilization benefits, challenges and functionalities. IEEE Access 2021, 9, 12730–12749.
13. Jadav, N.K.; Rathod, T.; Gupta, R.; Tanwar, S.; Kumar, N.; Alkhayyat, A. Blockchain and artificial intelligence-empowered smart agriculture framework for maximizing human life expectancy. Comput. Electr. Eng. 2023, 105, 108486.

14. IBM. Blockchain and Artificial Intelligence (AI)|IBM. Available online: https://www.ibm.com/topics/blockchain-ai (accessed on 26 March 2023).
15. Vaezi, M.; Azari, A.; Khosravirad, S.R.; Shirvanimoghaddam, M.; Azari, M.M.; Chasaki, D.; Popovski, P. Cellular, Wide-Area, and Non-Terrestrial IoT: A Survey on 5G Advances and the Road Toward 6G. IEEE Commun. Surv. Tutorials 2022, 24, 1117–1174.
16. Lin, X.; Rommer, S.; Euler, S.; Yavuz, E.A.; Karlsson, R.S. 5G from Space: An Overview of 3GPP Non-Terrestrial Networks. IEEE Commun. Stand. Mag. 2021, 5, 147–153.
17. Michailidis, E.T.; Maliatsos, K.; Skoutas, D.N.; Vouyioukas, D.; Skianis, C. Secure UAV-Aided Mobile Edge Computing for IoT: A Review. IEEE Access 2022, 10, 86353–86383.
18. Azari, M.M.; Solanki, S.; Chatzinotas, S.; Kodheli, O.; Sallouha, H.; Colpaert, A.; Montoya, J.F.M.; Pollin, S.; Haqiqatnejad, A.; Mostaani, A.; et al. Evolution of Non-Terrestrial Networks from 5G to 6G: A Survey. IEEE Commun. Surv. Tutorials 2022, 24, 2633–2672.
19. Cariou, C.; Moiroux-Arvis, L.; Pinet, F.; Chanet, J.P. Internet of Underground Things in Agriculture 4.0: Challenges, Applications and Perspectives. Sensors 2023, 23, 4058.
20. Sambo, D.W.; Forster, A.; Yenke, B.O.; Sarr, I.; Gueye, B.; Dayang, P. Wireless underground sensor networks path loss model for precision agriculture (WUSN-PLM). IEEE Sens. J. 2020, 20, 5298–5313.
21. Bello, O.; Zeadally, S. Internet of underwater things communication: Architecture, technologies, research challenges and future opportunities. Ad Hoc Netw. 2022, 135, 102933.
22. Dixit, S.; Bhatia, V.; Khanganba, S.P.; Agrawal, A. 6G: Sustainable Development for Rural and Remote Communities. Lect. Notes Netw. Syst. 2022, 416, 1–104.
23. Ray, P.P. A review on 6G for space-air-ground integrated network: Key enablers, open challenges, and future direction. J. King Saud Univ. Comput. Inf. Sci. 2022, 34, 6949–6976.
24. Zhang, Z.; Xiao, Y.; Ma, Z.; Xiao, M.; Ding, Z.; Lei, X.; Karagiannidis, G.K.; Fan, P. 6G wireless networks: Vision, requirements, architecture, and key technologies. IEEE Veh. Technol. Mag. 2019, 14, 28–41.
25. Yu, Q.; Dong, D.; Wang, Y.; Petersen, I.R. Capability comparison of quantum sensors of single or two qubits for a spin chain system. IFAC-PapersOnLine 2020, 53, 263–268.
26. Batra, G.; Gschwendtner, M.; Ostojic, I.; Queirolo, A.; Soller, H.; Wester, L. Shaping the Long Race in Quantum Communication and Quantum Sensing; McKinsey & Company: Atlanta, GA, USA, 2021.
27. Cao, Y.; Zhao, Y.; Wang, Q.; Zhang, J.; Ng, S.X.; Hanzo, L. The evolution of quantum key distribution networks: On the road to the qinternet. IEEE Commun. Surv. Tutorials 2022, 24, 839–894.

28. Suriya, M. Machine learning and quantum computing for 5G/6G communication networks—A survey. Int. J. Intell. Netw. 2022, 3, 197–203.
29. Huang, H.Y.; Broughton, M.; Mohseni, M.; Babbush, R.; Boixo, S.; Neven, H.; McClean, J.R. Power of data in quantum machine learning. Nat. Commun. 2021, 12, 2631.
30. Zhang, F.; Zhang, Y.; Lu, W.; Gao, Y.; Gong, Y.; Cao, J. 6G-Enabled Smart Agriculture: A Review and Prospect. Electronics 2022, 11, 2845.
31. Alwis, C.D.; Kalla, A.; Pham, Q.V.; Kumar, P.; Dev, K.; Hwang, W.J.; Liyanage, M. Survey on 6G Frontiers: Trends, Applications, Requirements, Technologies and Future Research. IEEE Open J. Commun. Soc. 2021, 2, 836–886.
32. Ge, H.; Lv, M.; Lu, X.; Jiang, Y.; Wu, G.; Li, G.; Li, L.; Li, Z.; Zhang, Y. Applications of THz Spectral Imaging in the Detection of Agricultural Products. Photonics 2021, 8, 518.
33. Usman, M.; Ansari, S.; Taha, A.; Zahid, A.; Abbasi, Q.H.; Imran, M.A. Terahertz-Based Joint Communication and Sensing for Precision Agriculture: A 6G Use-Case. Front. Commun. Networks 2022, 3, 3.
34. Basharat, S.; Hassan, S.A.; Pervaiz, H.; Mahmood, A.; Ding, Z.; Gidlund, M. Reconfigurable Intelligent Surfaces: Potentials, Applications, and Challenges for 6G Wireless Networks. IEEE Wirel. Commun. 2021, 28, 184–191.
35. Zhang, J.; Zhang, Y.; Zhong, C.; Zhang, Z. Robust Design for Intelligent Reflecting Surfaces Assisted MISO Systems. IEEE Commun. Lett. 2020, 24, 2353–2357.
36. Liu, Y.; Li, D.; Du, B.; Shu, L.; Han, G. Rethinking Sustainable Sensing in Agricultural Internet of Things: From Power Supply Perspective. IEEE Wirel. Commun. 2022, 29, 102–109.
37. Khalili, A.; Zargari, S.; Wu, Q.; Ng, D.W.K.; Zhang, R. Multi-objective resource allocation for IRS-aided SWIPT. IEEE Wirel. Commun. Lett. 2021, 10, 1324–1328.
38. Ghandar, A.; Ahmed, A.; Zulfiqar, S.; Hua, Z.; Hanai, M.; Theodoropoulos, G. A Decision Support System for Urban Agriculture Using Digital Twin: A Case Study With Aquaponics. IEEE Access 2021, 9, 35691–35708.
39. Jans-Singh, M.; Leeming, K.; Choudhary, R.; Girolami, M. Digital twin of an urban-integrated hydroponic farm. Data-Centric Eng. 2020, 1, e20.
40. Anthony Howard, D.; Ma, Z.; Mazanti Aaslyng, J.; Nørregaard Jørgensen, B. Data Architecture for Digital Twin of Commercial Greenhouse Production. In Proceedings of the 2020 RIVF International Conference on Computing and Communication Technologies (RIVF), Ho Chi Minh City, Vietnam, 14–15 October 2020; pp. 1–7.
41. Batty, M. Digital twins. Environ. Plan. B Urban Anal. City Sci. 2018, 45, 817–820.

42. Huang, T.; Yang, W.; Wu, J.; Ma, J.; Zhang, X.; Zhang, D. A survey on green 6G network: Architecture and technologies. IEEE Access 2019, 7, 175758–175768.
43. Mao, B.; Tang, F.; Kawamoto, Y.; Kato, N. AI models for green communications towards 6G. IEEE Commun. Surv. Tutorials 2021, 24, 210–247.
44. Benhamaid, S.; Bouabdallah, A.; Lakhlef, H. Recent advances in energy management for Green-IoT: An up-to-date and comprehensive survey. J. Netw. Comput. Appl. 2022, 198, 103257.
45. Bradu, P.; Biswas, A.; Nair, C.; Sreevalsakumar, S.; Patil, M.; Kannampuzha, S.; Mukherjee, A.G.; Wanjari, U.R.; Renu, K.; Vellingiri, B.; et al. Recent advances in green technology and Industrial Revolution 4.0 for a sustainable future. Environ. Sci. Pollut. Res. 2022, 1–32.
46. Popli, S.; Jha, R.K.; Jain, S. Green IoT: A Short Survey on Technical Evolution & Techniques. Wirel. Pers. Commun. 2022, 123, 525–553.
47. Lien, S.Y.; Hung, S.C.; Deng, D.J.; Wang, Y.J. Efficient ultra-reliable and low latency communications and massive machine-type communications in 5G new radio. In Proceedings of the GLOBECOM 2017-2017 IEEE Global Communications Conference, Singapore, 4–8 December 2017; pp. 1–7.
48. Zhang, L.; Liang, Y.C.; Niyato, D. 6G Visions: Mobile ultra-broadband, super internet-of-things, and artificial intelligence. China Commun. 2019, 16, 1–14.
49. Imadur, R.; Sara, M.; Olof, L.; Christian, H.; Henning, W.; Claes, T.; Paul, S.; Patrik, P.; Dirk, G. 5G evolution toward 5G Advanced: An overview of 3GPP releases 17 and 18. Ericsson Technol. Rev. 2021, 2021, 2–12.
50. Ji, B.; Han, Y.; Liu, S.; Tao, F.; Zhang, G.; Fu, Z.; Li, C. Several Key Technologies for 6G: Challenges and Opportunities. IEEE Commun. Stand. Mag. 2021, 5, 44–51.
51. Nawaz, S.J.; Sharma, S.K.; Mansoor, B.; Patwary, M.N.; Khan, N.M. Non-Coherent and Backscatter Communications: Enabling Ultra-Massive Connectivity in 6G Wireless Networks. IEEE Access 2021, 9, 38144–38186.

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