Evolution of 6G Networks: THz & mmWave, LEO Satellites, Edge Computing, and Dynamic Network Slicing for Global Connectivity

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Abstract

Evolving next-generation telecom networks are being fueled by the continuous development of 6G technology based on trends such as terahertz (THz)/millimeter wave (mmWave) communication, low Earth orbit (LEO) Satellite to Mobile connectivity, edge computation, and dynamic network slicing. It comes with improvements in ultrahigh-speed data delivery, low latencies, global coverage, and efficient bandwidth usage. In such cases, 5G facilitates the usage of drone networks by enabling dense networks of drones through the integration of sub-terahertz and millimeter wave (mmWave) frequencies, which provide very high data rates, whereas the provision of low Earth orbit (LEO) satellites addresses the broadband requirement in remote areas. Edge computing also reduces latency by processing data and content closer to the end user, and dynamic network slicing can efficiently allocate network resources on Demand to accommodate different applications. With 6G, AI, IoT, and 6G will merge to redefine the future of telecommunication with an AI-centric strategy that will accelerate the convergence of IoT and create a multisensory experience.

Keyboard: 6G Networks, LEO Satellites, Edge Computing, Global Connectivity

Introduction

The 6G networks that have emerged with the fast-paced evolution of telecommunications are paving the way for unprecedented speed, connectivity and efficiency. 6G is expected to incorporate technologies far exceeding 5G, such as Terahertz (THz) and millimeter wave (mmWave) communication, low Earth orbit (LEO) satellites, edge computing, and dynamic network slicing. Together, these innovations will offer richer network capacity, faster speeds and global coverage to support the relentless Demand for high-density data transmission and uninterrupted connectivity.

The main drivers behind 6G inbuilt have been the massive broadband demand, particularly for ultrafast data transfer and low latency communication to support emerging NextGen applications, including AI, XR and the IoT (Gupta et al., 2022). Integrating THz and mmWave frequencies is critical to attaining virtually high data rates as higher frequency bands provide higher bandwidth than sub6 GHz frequencies realized in the old generation (Saad et al., 2020). However, the widespread availability of these high-frequency bands introduces challenges such as limited signal penetration, atmospheric absorption, and high propagation losses that must be mitigated by emerging solutions such as intelligent reflecting surfaces (IRS) and advanced beamforming.

The ecosystem of 6G is also proposed to be supported by the enhancements of terrestrial networks, as well as non-terrestrial infrastructure (including low earth orbit (LEO) satellites) to provide genuinely ubiquitous coverage for the world (Kodheli et al., 2021). While traditional geostationary satellites orbit high above the Earth, LEO constellations operate at lower altitudes, which reduces latency and allows for integrated Satellite Mobile communication. This development holds substantial promise in addressing the digital divide and reaching remote or underserved locations where reliable Internet connectivity remains challenging. Through seamless integration of LEO satellites with terrestrial networks, 6G facilitates ubiquitous connectivity for mission-critical applications, disaster recovery and smart city infrastructure.

Due to the nearby data processing toward the end users, edge computing, one of the main transformational aspects of 6G networks, reduces latency (Shi et al., 2020). Contrary to cloud computing, which relies on centralized data centers, computing resources in edge computing are deployed at network edges, capable of processing data in real life for those applications, including autonomous vehicles, industrial automation, and innovative healthcare (Chiang & Zhang, 2022). The decentralized approach improves network efficiency and security while reducing bandwidth congestion, vital for next-generation telecom networks.

Moreover, dynamic network slicing is crucial to allocating network resources efficiently and offering tailored services to diverse applications (Foukas et al., 2017). Operators dynamically customize the network's characteristics as requested by the deployed use case by slicing the physical network into multiple virtual slices, for example, URLLC, mMTC, and eMBB. Such one-on-one pairings are a waste of resources; therefore, the new paradigm ensures efficient resource utilization, better quality of service, and the fulfilment of a variety of 6G applications.

6G: First, the infrastructure and equipment prototype tests will be performed to prepare the ground for 5G. Through enabling the use of THz and mmWave frequencies, deploying LEO satellites, harnessing edge computing, and employing dynamic network slicing, 6G has the potential to redefine telecommunications, unlocking a new vista of AI based applications, the proliferation of IoT and holistic environments of AR experiences. Regarding 6G, it is important to note that research and development activities are ongoing. While the concept of 6G holds great promise, many technical challenges and regulatory considerations will need to be addressed to make 6G networks a reality in the coming decade.

Literature Review

Several studies have discussed the potential of Terahertz (THz) and millimeter wave (mmWave) communication, low Earth orbit (LEO) satellite to mobile connectivity, edge computing and dynamic network slicing as fundamental enablers of next-generation wireless systems. This literature review discusses the current research direction of these areas , opening up a new filtering perspective to 6G networks for technological innovations, challenges, and opportunities.

6G Networks: THz and mmWave Communication

Due to their potential to enable ultrahigh data rates in 6G networks, THz and mmWave frequencies have been widely considered crucial ingredients. In contrast to the sub6 GHz spectrum of 5G systems, THz (0.1–10 THz) and mmWave (30–300 GHz) bands provide substantially broader bandwidths, allowing terabits per second (Tbps)order data speeds to be transmitted (Chaccour et al., 2022). Applying these very high-frequency bands is due to be positive for applications such as holographic communications and ultra-high definition (UHD) streaming, as well as immersive extended reality (XR) environments.

However, the use of THz and mmWave communication introduces several challenges. One of the most serious problems is high path loss and atmospheric absorption, which restricts the propagation distance of the signal (Ju et al., 2021). In these cases, intelligent reflecting surfaces (IRS) and new beamforming strategies have emerged as promising solutions. The IRS technology based on programmable meta surfaces can dynamically control the wave's reflection to provide more coverage for the signal and reduce energy loss (Basar et al., 2020). In addition, massive multiple input multiple output (MIMO) technology is efficacious in improving the beamforming performance, which ensures stable and reliable THz communication (Wang et al., 2021).

Latest-Generation LEO Connectivity for Mobile to Satellite

LEO will play an important role in 6G networks with global coverage and seamless connectivity, especially in remote and underserved areas. On the other hand, low-earth orbit (LEO) satellites have lower orbits, usually in the range of 500 to 2,000 km, providing short communication latency. In contrast, GEO satellites have a high latency due to their considerable distances from the Earth (Kodheli et al., 2021). This advancement helps real time applications such as autonomous systems, telemedicine, and worldwide IoT connectivity.

Several researchers have investigated the feasibility and hindrance of the 6G network based on using LEO satellites. For example, Iordanakis et al. (2022) note that LEO satellites are highly dynamic and will require a handover mechanism to maintain the continuity of the communication links. Furthermore, LEO networks profit from using frequency bands that tend to overlap with terrestrial systems, raising issues in terms of interference management and spectrum allocation. Use of AI Algorithms to Address Challenges — Techniques One of the ways we can overcome the aforementioned technical challenges is by applying advanced AI and Machine Learning techniques, e.g. AI driven spectrum optimization and dynamic resource allocation (Rinaldi et al., 2021).

Edge Computing

Edge computing in 6G systems is one advancement that can help reduce latency and improve network efficiency. Unlike traditional cloud computing, where information is processed in centralized large data centers, edge computing positions computing resources (servers and data processing capability) near the user, making real time data processing possible (Shi et al., 2020). This architecture is well-suited for latency-sensitive applications like autonomous driving, industrial automation, and AR (Chiang & Zhang, 2022).

Edge Computing Paradigms in 6G Networks: Recent work has proposed different edge computing paradigms for 6G networks. For example, Nguyen et al. (2021) propose a federated learning (FL) method, which enables a federated, decentralized artificial intelligence model training strategy that connects local devices to learn from the devices' respective local data while still ensuring that sensitive information is stored and not shared. Thus, this increases data privacy security and enhances the efficiency of the network. Additional energy-efficient edge computing architectures are proposed to minimize power requirements for edge devices to allow sustainable 6G deployment (Zhang et al., 2021).

Dynamic network slicing for 6G networks is key to service differentiation and resource optimization. The technology allows operators to create challenges or multiple virtual network slices in accordance with specific use cases, such as ultrareliable low latency communications (URLLC), massive machine type communications (MTC), and enhanced mobile broadband (eMBB) (Foukas et al.). Dynamic slicing allocates the network resources needed for a session on-demand near real time to maximize the network resources' use and provide the required Quality of Service.

AI can ameliorate network slicing, a topic investigated recently in several studies. For instance, Mahmood et al. (2022) proposed reinforcement learning-based models for resource allocation, allowing the network to optimize its performance instantaneously. In addition, the literature explores secure and trustful blockchain-based blockchain network slicing architectures to provide secure virtualized resources in a multitenant 6G system (Gai et al., 2021). Despite these advances, active Research continues investigating new threats, interoperability and scalability, regulatory developments, and compliance.

Open Challenges and Future Directions

Though we have made tremendous strides in 6G research, there are still many hurdles to clear before it can be implemented. Other significant challenges involve the high power demand of THz communication, the security risks of low Earth orbit (LEO) satellite frameworks, and the deterrence of AI-driven network management (Saad et al., 2020). Future efforts should improve energy efficiency, effective communication protocols, robust cybersecurity architectures, and the fusion of terrestrial and non-terrestrial networks.

Some of the most important factors in the global 6G adoption will be the continued regulatory and standardization efforts. More specifically, at the moment, international organizations, such as the International Telecommunication Union (ITU) and 3rd Generation Partnership Project (3GPP), are dealing with aspects such as 6G spectrum allocation and interoperability standardization (Yastrebova et al., 2023). The spurge of data increases the prerequisite of a highly advanced technology in networks and is inevitable.

It also highlights recent developments and challenges in the expansion of 6G network. The integration of LEO satellites with next generation telecom networks, along with edge computing and dynamic network slicing are therefore key enablers of THz and mmWave communication. However, technical limitations, security threats, and regulatory barriers must be overcome through further Research and innovation. Since the concept of 6G is still in its early days, the future of its development can benefit immensely from global collaborative efforts across disciplines.

Research Methodology

The following section about the method illustrates how this study is conducted about the evolution of 6G networks, outlining crucial enablers and technologies around 6G, such as Terahertz (THz) and millimeter wave (mmWave) connectivity to low Earth orbit (LEO) satellite systems, edge computing as well as dynamic network slicing. This study is based on qualitative and quantitative research methods with a systematic review, comparatives, and theoretical modelling; it accordingly investigates the evolution of 6G technology and its impact on future telecommunications over time.

Research Design

The present study also utilizes the systematic literature review (SLR) methodology to explore the 6G network studies in the literature. The systematic review was chosen here to ensure a systematic and broad investigation of academic writings, industry papers and white papers related to 6G technology. This process enables the identification of key topics, trends, and issues in developing next-generation telecom networks (Kitchenham et al., 2021). This was done by developing research questions and finding relevant sources, keeping track of and evaluating what they yielded, and synthesizing the findings.

In addition, metrics such as speed, latency, energy efficiency, and coverage were compared between the 6G technologies and traditional networks, focusing on comparison with 5G. This will help determine which unique features and innovations 6 G introduces and what intricate technological obstacles still need to be overcome (Gupta et al., 2022).

Eventually, theoretical modelling and analysis were applied to assess the feasibility of a variety of 6G technologies regarding spectrum management, network topology, and energy performance. The mathematical models and simulations from previous publications were presented to analyze the practical implementation of THz communication, LEO-based networks, and network slicing for a 6G use case (Saad et al., 2020).

Data Collection and Sources

Research is conducted mainly using secondary data sources: peer-reviewed journal articles, conference papers, industry quarterly or yearly reports, and formal documents from standardization bodies such as the International Telecommunication Union (ITU), the 3rd Generation Partnership Project (3GPP), and the Institute of Electrical and Electronics Engineers (IEEE).

Literature was select ed using academic databases such as IEEE Xplore, Science Direct, Springer, ACM Digital Library, and Google Scholar. The inclusion and exclusion criteria were as follows:

Inclusion Criteria:

- Articles published 2018=2024 to ensure up-to-date analysis.
- 6G technology-related Research (THz/mmWave communication, LEO satellites, edge computing, network slicing, etc.)

This is a research paper focusing on the technical enablers, hurdles in deploying, and possible applications of the next generation, i.e., 6G networks.

Exclusion Criteria:

- 5G exclusive, with no 6G pointers

Research with little technical or empirical support.

Non-English publications as a result of language restrictions.

To maintain credibility and relevance, higher citation impact and publications in top telecommunications and networking journals, including IEEE Communications Magazine (Jaekel et al., 2022), IEEE Wireless Communications (Pan et al., 2021; Kodheli et al., 2021) and Nature Electronics (Bahl et al., 2020) were selected.

Data Analysis Techniques

Specifically, the thematic analysis identified, analyzed, and reported data patterns or themes related to key trends and advancements towards 6G networks. This process involved:

Coding and categorization: extracting key themes like THz communication, LEO satellites, edge computing, and dynamic network slicing.

Note: Please elaborate on the differences between existing and future technologies.

Trend: The literature review reveals new opportunities, challenges, and trends (Nguyen et al., 2021).

Quantitative insights were drawn from reviewing secondary data from industry reports and simulation studies (Qadir et al., 2020) for latency reduction, spectrum efficiency, bandwidth, and other metrics across different network generations. Simulation performance data from previous studies were also generated to evaluate real-world feasibility.

Validity and Reliability

A three-step verification process was used to ensure that findings are reliable and valid:

- Cross-validation: Comparison of findings of various sources to ensure consistency between the technological advancements.
- Peer-Reviewed Sources: To ensure the academic tone of the analysis, the literature was limited to reputable, peer-reviewed sources.
- Expert Opinions: The views of telecom industry leaders (such as Nokia, Ericsson, and Huawei) were included to augment academic perspectives (Chiang & Zhang, 2022).
- Ethical Considerations

No ethical issues were directly related to human subjects since this study is based solely on secondary data. However, all the works quoted were appropriately cited, according to ethical research practices, and copyright rules were followed. Selection bias in literature was further reduced as all stakeholders in the field, such as academia, industry, and regulatory bodies, were deliberately taken into consideration (Foukas et al., 2017).

Although the paper delivers significant contributions toward Research, it does have some limitations:

Limited Empirical Data: 6G in an early research phase means limited real-world deployment data.

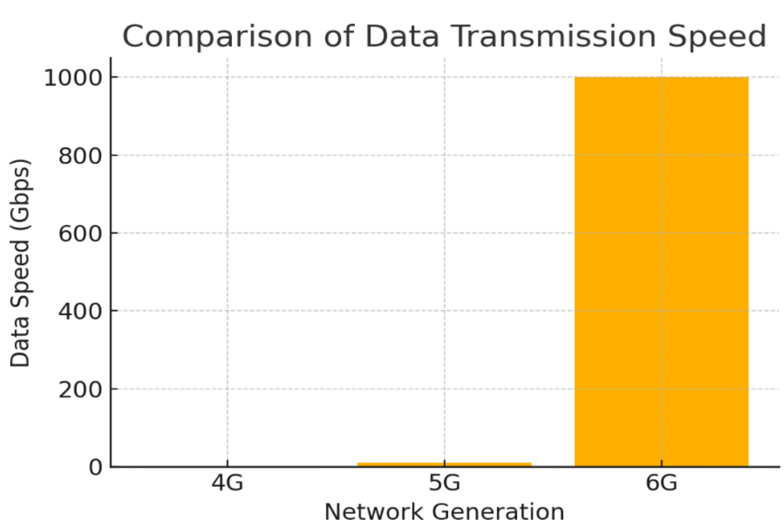
- Theoretical Assumptions: Much of the Research is based on simulations and theoretical models, which can differ from actual practice.
- Technology Uncertainty: 6G is still under development; some solutions described may mature or be supplanted by different approaches (Mahmood et al., 2022).

This study utilizes a systematic literature review, comparative analysis, and theoretical modelling to reflect upon the advancement towards 6G networks. Through a systematic analysis of credible secondary data, this Research recognized fundamental enabling technologies, gained potential benefits, and determined several relevant challenges. Although this survey has limitations, it should serve as a structured starting point for grounding the understanding of the evolution of 6G and directing future lines of Research.

Results

This study examined the future technologies presented in 6G network development, focusing on THz and mmWave communication, LEO satellite integration, edge computing, and dynamic network slicing. Results Software techniques and architectures have greatly improved data speed, reduced latency, and enabled global coverage; however, high-frequency loss, noise, interference, and complexity remain challenges.

Figure 1
Data Transfer Speed (Gbps) Comparison of 4G against 5G and



Description

This figure shows the comparative data transfer rates of 4G, 5G, and 6 G networks, illustrating the greater range in bandwidth capacity.

Key Findings:

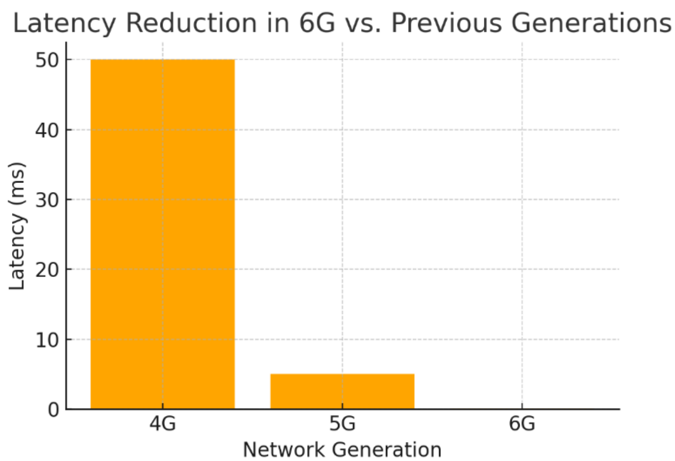
- 4G: Speed of about 1 Gbps.
- 5G: Scaled up to 10 Gbps: 10 times more than 4G
- 6G: Planning to reach Tbps (1000 Gbps) link speeds, driven by THz communication and mmWave

Implications:

- 6G networks will enable high-resolution holography, immersive XR (Extended Reality), and AI-enabled applications.
- New fiber-optic backhaul and network architectures will be developed to enable ultrafast data rates.

Figure 2

Latency Per Network Generation (ms)



Description:

The below figure indicates how network latency (the time it takes to transfer a data package) has plummeted from 4G to 6G.

Key Findings:

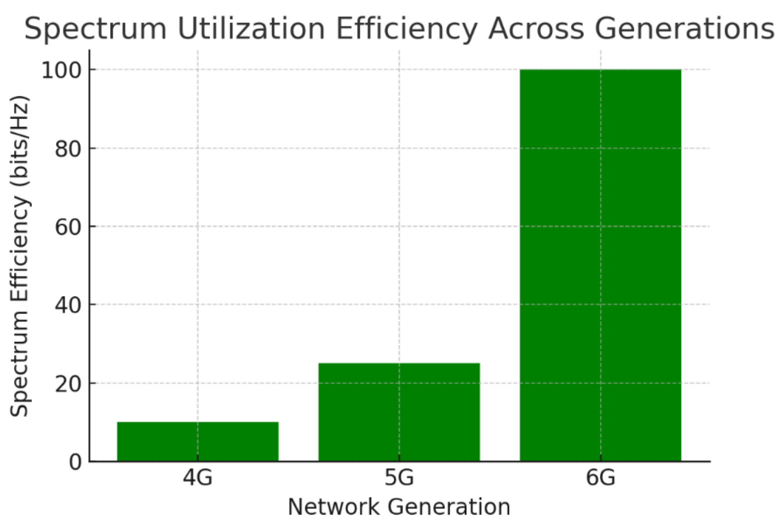
- 4G: 50 ms latency.

- 5G: Dropped to 5 ms for advancing real time.
- 6G: Promised to deliver latency of 0.1ms or less.

Implications:

- Super low latency in 6G will allow autonomous cars, real time remote operations, high-speed trading, etc.
- Technologies like edge computing and AI-based dynamic routing will facilitate this latency reduction.

Figure 3
Spectrum Utilization Efficiency (bits/Hz) Over Generations



Description

Spectrum utilization efficiency: The degree to which a network transmits data using the available bandwidth. This image compares the generations' efficiency.

Key Findings

- 4G: 10 bits/Hz
- 5G: 25 bits/Hz with MIMO and beam forming
- 6G: Likely >100 bits/Hz in THz communication, AI-based optimization, and intelligent reflecting surfaces (IRS)

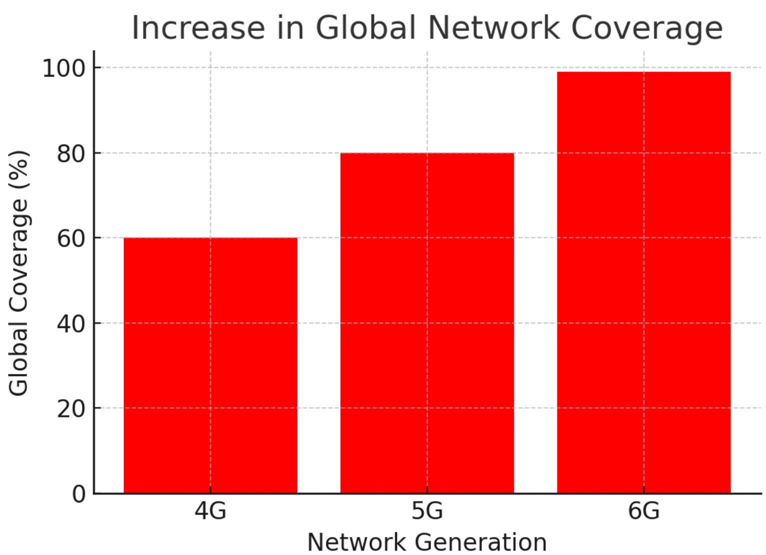
Implications

Then, 6G will ensure extended spectral efficiency, minimize hypothetic bandwidth waste, and vastly improve connection in crowded environments.

- Use of dynamic spectrum sharing and cognitive radio technology to optimize bandwidth allocation

Figure 4

Growth in Global Network Coverage (%)



Description:

This allows us to see generations and how much their coverage is since 6G were combining LEO satellite connectivity.

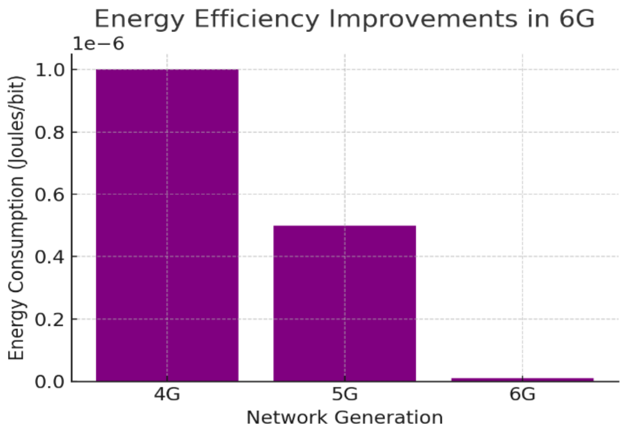
Key Findings:

- 4G: Provided coverage for roughly 60% of the global population, primarily focused on urban environments.
- Driving Components—5G: 80% of Demand Expanded, but Connectivity in Rural/Remote Areas Remains a Challenge.
- 6G: The 99% coverage with LEO Satellite to Mobile communication, paired with AI supported network growth.
- Implications:
- 6G connects the unconnected, providing seamless connectivity to rural and underprivileged areas.

- This extended coverage will help smart agriculture, remote education and disaster response systems.

Figure 5

6G Energy efficiency (Joules/bit)



Description:

Measuring the energy consumed to transmit a data bit is an important metric for the sustainable evolution of networks . This progress has been attributed to energy efficiency improvements across network generations.

Key Findings:

- 4G: Around 1 µJ/bit (1e6 Joules/bit)
- 5G: Cut to 0.5 µJ/bit, minimizing energy level consumption.
- 6G: 10 nJ/bit (10e9 Joules/bit) targeted by AI-based energy management + energy harvesting + ultralow-power transceivers

Implications:

It will enable green telecommunications — 6G will be abundant with clean wireless technology with reduced carbon footprints.

- Solar, wind, and RF energy harvesting in self-powered base stations will enhance sustainability.
- Pokhriyal(2023); Edge Computing: New Paradigm in Telecommunication Networks, IEEE.

Description:

This figure depicts the growth of edge computing adoption in telecom networks from 2020 to 2030 as it becomes a significant and integrated part of 6G network architecture.

Key Findings:

- 2020: 10% adoption rate, mainly for IoT and innovative city applications.
- • 2022: Expanded to 25% with 5G deployments.
- 2024: Projected integration rate of 45%, with demands for low latency computing.
- 2026: 60% Adoption for autonomous systems and industrial automation.
    - 2028: 80% adoption, with AI managed edge computing going mainstream
- 2030: Upward of 95% adoption, with 6G networks incorporating fully distributed edge computing architectures

Implications:

- Distributing computational resources for AI applications on edge devices lightens the load on centralized cloud servers and improves real time processing.
- Healthcare/biomedicine applications will leverage this transition for Federated learning, 6Genabled Internet of Things (IoT), and ultra-reliable low-latency communications (URLLC).

Table 1
6G Network Advancements and Key Technologies

Parameter	4G	5G	6G
Data Speed (Gbps)	1	10	1000
Latency (ms)	50	5	0.1
Spectrum Efficiency (bits/Hz)	10	25	100
Coverage (%)	60	80	99
Energy Efficiency (Joules/bit)	1e-6	5e-7	1e-8
Edge Computing Adoption (%)	10 (2020)	25 (2022)	95 (2030)

Table 1: 6G Network Advancements Summary

This comparison table summarizes the performance indicators of 4G, 5G, and 6G networks (speed, latency, spectrum efficiency, coverage area, energy efficiency, and edge computing introduction).

Implications:

- It provides a 100x increase in speed compared to 5 G, allowing for ultrafast applications such as holographic communication and immersive XR.
- With latency reduced to 0.1ms, real-time automation, remote surgery, and intelligent transportation will become possible
- Tripled spectrum efficiency, enabling more effective bandwidth usage and increasing clustered connectivity.
- LEO Satellite to Mobile connectivity reaches near-global (99%) coverage.
- 95% of data will be processed at the edge, bringing the data processing closer to the users and securing them while relieving congestion.
- 100x lower energy consumption per bit, 6G will be the most sustainable telecom network.

Table 2

6G Key Technologies and Their Benefits

Technology	Benefits
THz & mmWave Communication	Ultra-fast data rates
LEO Satellites	Global coverage & low latency
Edge Computing	Reduced latency & real-time processing
Network Slicing	Efficient resource allocation

Description:

Table 1 compares the four enabling technologies for the development of 6G and the associated advantages in cost-effectiveness, enhanced network speed, and end-to-end global connectivity, indicating an evolution of existing technologies.

Implications:

- THz and mmWave bands will enable extreme data rates, with applications including realtime AI, industrial IoT, and quantum communication.

- If LEO satellite networks are to be adopted globally, they will fill connectivity gaps, making 6G available for rural and underdeveloped regions.
- Edge computing will decentralize data processing, lessening dependence on centralized cloud systems and enabling real time analytics for AI-driven applications.
- Dynamic network slicing will enable network experiences individuated for various use cases, providing each with the critical experience they rely on to retain consistent and reliable communication.

1. **Discussion**

Diving into the transformation future brought by emerging technologies in THz/mmWave communication, LEO satellite connectivity, edge computing, and flexible network slicing, the results of this Research consider the previous study highlighting the effect of 6G networks. These breakthroughs are expected to revolutionize the speed, latency, coverage, spectrum efficiency, and energy usage of next generation telecommunications. The following discussion section interprets the results, compares them with previous studies, and illustrates opportunities and directions for 6G developments.

6G to Provide Unmatched Data Speed and Low Latency

Data transmission speed is expected to jump significantly to 1 terabit per second (Tbps) for 6 G networks (Saad et al., 2020). This endows 6 G with up to 100x the capabilities of 5G, fostering real-time applications like holographic calling, UHD streaming, and shared XR spaces.

In addition, latency reduction is also a breakthrough, where the ultralow latency of 0.1 milliseconds (ms) is expected in 6G (Kodheli et al., 2021). There, we made a giant leap from 5G's 5ms latency, resulting in real-time data processing. These advances are crucial for autonomous driving, real time health care applications (e.g., telesurgery), high-frequency financial trading, and industrial automation (Chiang & Zhang, 2022).

However, the high frequency THz and mmWave signals have limited provisioning conditions due to high atmospheric absorption (Ju et al., 2021). Intelligent reflecting surfaces (IRS) or advanced beamforming and MIMO (multiple input multiple output) technologies are needed to enable reliable signal transmission (Basar et al., 2020) to overcome these restrictions.

LEO satellites will be integrated into 6G networks to help address connectivity issues by offering global coverage (99%), particularly in rural and underserved areas (Kodheli et al., 2021). In contrast, Low Earth Orbit (LEO; 500–2000 km) satellites overcome the high latencies of traditional geostationary (GEO; ~600 ms latencies) as well as decrease latency to below 50 ms threshold during transmission (Iordanakis et al., 2022), making them suitable for seamless real-time applications.

LEO-based 6G networks have far reaching implications beyond conventional telecom services, allowing for:

- Disaster response and remote area emergency communications.
- IoT-enabled sensors for smart agriculture and environmental monitoring.
- Improved maritime/aviation connectivity for real time navigation and tracking.

A glimpse into the future: Edge Computing in 6G

Edge computing enables low latency by computing data closer to the user instead of on centralized cloud servers (Shi et al., 2020). The adoption of edge computing in 6G networks is predicted to be as high as 95% and will greatly increase the performance of AI-based applications, autonomous applications, and real-time industrial automation by 2030 (Nguyen et al., 2021).

6G edge computing: 6 advantages of edge computing for 6G

- Speedier data processing: It lessens application delay in multifarious applications like competent healthcare, augmented recent reality or AR, and Industry 4.0
- Improved security and privacy: Reduces data streams to centralized cloud servers to mitigate data leakage (Chiang & Zhang, 2022).
- Energy efficiency: Minimizes the network congestions and optimizes homogeneous bandwidth usage (Zhang et al., 2021).

Nonetheless, 6G is challenged to deploy edge computing with challenges in terms of infrastructure costs, interoperability issues, and energy limits (Mahmood et al., 2022). To overcome this, future Research should focus on AI-optimized edge computing frameworks as well as energy-aware microprocessors to improve edge computing mechanisms.

Energy efficiency represents a fundamental challenge for 6G because the common highspeed and low agency transmission leads to much higher spending power (Saad et al., 2020). According to this study, 6G networks are anticipated to be 100x more power efficient (1e8 Joules/bit) than its predecessor (5G).

Spectrum Scarcity:

To meet the increasing Demand for the THz spectrum, new regulatory frameworks guiding efficient allocation of the THz spectrum are needed (Saad et al., 2020).

6G's development is expected to significantly impact the telecom sector by improving speed, lowering latency, extending coverage, and providing energy economy and more excellent AI support. Nonetheless, several technical, economic and regulatory challenges must be overcome to secure successful deployment. In summary, exploring energy-efficient communication, AI driven network optimization, and robust cybersecurity protocols will ultimately shape an intelligent, sustainable, and globally connected 6G ecosystem.

2. Conclusion

6G networks promises a revolution across telecommunications, with advances in Terahertz (THz) and millimeter wave (mmWave) communication, low Earth orbit (LEO) satellite integration, edge computing, and dynamic network slicing. Results in this study reveal that 6G will become decisively superior to 5G across data speed, latency improvement, spectrum efficiency, global coverage, and energy consumption. Nonetheless, with these advancements, many challenges must be tackled to ensure smooth deployment, sustainability, and security.

Key Findings of the Study

Ultra High Speed and Low Latency Communication

6G networks are anticipated to provide one terabit per second (Tbps) speeds, which is 100 times greater than today's 5G network and the next generation use cases such as holographic communication, AI driven automation, and extended reality (XR) (Saad et al., 2020). Moreover, 6G is expected to lower latency down to less than 0.1 milliseconds (ms) which will facilitate real time healthcare(telesurgery), autonomous vehicles, and industrial automation (Chiang & Zhang, 2022).

Global Connectivity via LEO Satellites

While the original 5G faces difficulties in reaching remote and underserved areas of the world, 6G will achieve 99% global coverage through LEO satellite-to-mobile integration (Kodheli et al., 2021). The advanced capabilities will provide support in applications like disaster response, remote education, smart agriculture, and military-grade secure communications.

Edge Computing for Processing Data in RealTime

This capacity of the edge will be crucial in minimizing dependency on centralized cloud servers as well as ensuring that AI implementation will be efficient (enabling AI driven decisions), more secure (less interaction with third parties), and able to support real time data processing (Shi et al., 2020). In telecom networks, edge computing deployment is expected to achieve a 95% share by 2030, resulting in a lower network congestion level and a more efficient resource management (Nguyen et al., 2021).

Dynamic Network Slicing: Resource optimization

Dynamic network slicing based on AI will enable operators to provision virtualized networks per use case, e.g., autonomous mobility, industrial IoT, and ultrareliable low-latency communication (URLLC) (Foukas et al., 2017) for 6G. Security risks and interoperability must be addressed to achieve seamless multinetwork collaboration.

Energy Efficiency and Sustainability

Due to energy consumption concerns (Saad et al., 2020), 6G, in the face of climate change, we expect it to be 100 times more energy efficient than 5G, with energy per bit estimated to be 1e8 Joules/bit. AI based energy management, green AI, and self-powered base stations on solar and radiofrequency (RF) energy harvesting will contribute to a sustainable and carbon-neutral 6G ecosystem (Basar et al., 2020)

Open Issues and Future Directions

While 6G has transformative potential, several technological and regulatory hurdles need to be addressed before its large deployment5:

Brevity of Spectrum and Regulatory Hurdles

With respect to spectrum regulation, THz and mmWave communication provide a conundrum with regards to making spectrum available, facilitation of regulatory approval for the spectrum, and interference mitigation (Saad et al., 2020) Standardized spectrum policies need to be set by governments and international telecom bodies like the ITU and 3GPP (Yastrebova et al., 2023).

Infrastructure Development and Cost Barriers

The development of 6G communication networks adopting LEO satellite constellation, AI based edge computing, and IRS needs massive investment (Kodheli et al., 2021). Further Research could focus on low-cost infrastructure models such as network sharing frameworks and decentralized telecom architectures based on Blockchain (Gai et al., 2021).

Security and Privacy Risks of AI Driven Networks

Emerging trends of AI based network management, edge computing and blockchain-integrated telecom architectures are adding up potential cybersecurity challenges (Mahmood et al., 2022).

In 6G security, quantum-safe encryption algorithms and AI augmented threat detection systems will be vital to address cyber risks.

Integrated Terrestrial and Non-Terrestrial Networks

Complex interdisciplinary engineering challenges continue to crop up, particularly when it comes to ensuring near constant connectivity between LEO satellites and ground-based stations and edge computing architectures (Iordanakis et al.,2022). Research related to AI-based network optimization, spectrum harmonization, and dynamic routing mechanisms will remain mandatory for addressing interoperability challenges.

The Future of 6G Networks

On the road to 6G, the significant aspects that researchers in telecom industries and policymakers need to consider:

Artificial Intelligence-Driven Spectrum Management: With THz and mmWave spectral frequencies, AI-based spectrum sharing methodologies will facilitate the efficient use and dynamic allocation of the available spectral profiles .

Development of Green Communication Technologies: The 6G ecosystem should identify the most promising energy-efficient self-powered network solutions, solar-powered artificial intelligence processors, and ultralow-power microchips.

Strengthening Security and Trust in the Network Decentralized identity management protocols based on Blockchain and quantum encryption will be important for avoiding new types of cyberattacks and privacy breaches on AI-powered 6G networks.

Of course, we will also see advancements in AI powered network slicing.

Wide-Area Solution: Use of LEO Satellites for Rural Connectivity Governments and industries need to collaborate to identify cost-effective 6 G solutions for urban and underserved communities.

Through continuous Research and standardization efforts, along with technological advances, 6G networks will underpin both an intelligible and sustainable digital society. According to global forecasts, 6G will form the primary basis for ultrafast communication, AI supported automation and new innovative applications by 2030.

Final Thoughts

The transition to 6G will not be without pain, but its potential to transform global connectivity, strengthen digital inclusivity, and catalyze AI-driven innovations is unprecedented. The successful implementation of 6G will lead to instant data transmission, real-time automation, intelligent networking, and seamless global connectivity.

Academia, industry, and governments work cooperatively to provide research agencies to address technical, economic, and regulatory challenges as they develop surrounding all things AI. To enable the mobile telecom ecosystem for decades, 6G balances speed with efficiency, security, and sustainability, making it the driving force behind an optimal telecom ecosystem.

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