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Challenges, Opportunities, and Future Research in the Integration of 5G/6G Networks, LEO Satellites, and IoT for Environmental Protection and Sustainable Development at ECSTAR

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Abstract: The rapid proliferation of connected IoT (Internet of Things) devices, along with the increasing demand for 5G mobile networks and ubiquitous high-speed connectivity, poses significant challenges in the telecommunications sector. To address these challenges, a comprehensive understanding of the integration of 5G/6G networks and LEO (Low Earth Orbit) satellite networks is required, forming the concept of "integrated networks". Integration offers valuable advantages, including service continuity, wide-area coverage, and support for critical communications and emerging applications. This paper provides a high-level overview of the convergence of 5G/6G, LEO satellites, and IoT devices, shedding light on the technological challenges and standardization issues associated with the transition from 5G to 6G networks using NTNs (Non-Terrestrial Networks) based on LEO satellites. Furthermore, this research delves into the emerging social issues, potential possibilities, and the paradigm shift from the IoT to the IoI (Internet of Intelligence), which is poised to revolutionize the landscape of 6G wireless networks. By highlighting the interconnectedness of 5G/6G networks, LEO satellite systems, and IoT devices, it underscores the importance of leveraging these converging technologies to address environmental protection and achieve the United Nations SDGs (Sustainable Development Goals). In addition to providing valuable insights for readers seeking to comprehend the convergence of 5G/6G networks, LEO satellite systems, and IoT devices, this paper represents the outcomes of a comprehensive analysis conducted at the ECSTAR (Excellence Center of Space Technology and Research). Through an examination of technological challenges and advancements, it identifies future research directions and potential avenues for exploration at ECSTAR, thereby contributing to a broader understanding of integrated networks and their profound impact on future telecommunications systems. This research serves as a significant resource for advancing the knowledge and discourse surrounding the linkages between the convergence of these technologies, environmental protection, and the pursuit of the SDGs.

Key words: 6G, beyond 5G, IoT, LEO satellite, SDGs, environmental protection.

1. Introduction

The convergence of 5G/6G networks, LEO (Low Earth Orbit) satellites, and IoT (Internet of Things) holds immense potential for addressing global environmental challenges and achieving the United Nations SDGs (Sustainable Development Goals). These technologies can play a crucial role in the fight against climate change and environmental problems by enabling innovative solutions and fostering sustainable development. The integration of advanced LEO satellite technologies with terrestrial networks offers global, ubiquitous, and continuous connectivity, surpassing the capacity limitations of 5G networks. NTNs (Non-Terrestrial Networks) leveraging air or spaceborne vehicles provide the means to extend coverage to remote areas and unlock novel possibilities in both satellite and terrestrial telecommunications. The amalgamation of

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these domains into a cohesive technical framework is crucial to fully harness the potential of these technologies for environmental protection and SDGs.

The long-lasting impact of 5G technology is expected to be transformative, spanning a decade until 2030. This advancement is poised to have profound consequences for society and various industries. Future networks, which were once beyond imagination, are set to play a fundamental role in almost every facet of human existence, enabling communication not only among individuals but also between humans and intelligent robotic systems. As expectations continue to soar, both the business and research communities are resolutely pursuing well-defined objectives. Notably, significant strides in aerial and space technology, coupled with the ongoing reduction in manufacturing and launch costs, have created new avenues for deploying sophisticated applications of the IoT in these domains [1].

Continuing to enhance 6G technology will considerably contribute to the ongoing change from connected people and things to connected intelligence that we are presently seeing. In summary, the aforementioned acts will bring intelligence to every individual, house, and company, ushering in what could be described as a new era of creativity. More applications will develop in the 6G future. Cloud-based XR (extended reality) services, as well as haptic feedback and holographic displays, are anticipated to become commonplace in human-centric applications. In terms of the vast capacity required, the exponential rise in traffic demand per device, along with rigorous latency and reliability requirements, would provide a big challenge for 6G network architecture [2].

It is imperative to acknowledge that with the emergence of advanced LEO satellite technologies, there will arise technological requirements that cannot be sustainably addressed by 5G networks. NTNs serve as a term commonly used to denote networks that leverage air or spaceborne vehicles to enable global, ubiquitous, and continuous connectivity, surpassing the capacity limitations of 5G networks [3]. NTNs are poised to become an indispensable component of future wireless networks, as their seamless integration with terrestrial networks unlocks novel possibilities in both satellite and terrestrial telecommunications. Consequently, there exists an urgent necessity to amalgamate these two domains into a cohesive technical framework [4].

Through ever-present intelligent, fast, and beneficial communication, 6G should and will most likely contribute to an efficient, human-friendly, and sustainable contemporary civilization in the not-too-distant future. 6G research is heating up, maybe unavoidably, raising expectations among many in society, many worldwide companies, and consumers. E2E (End-to-end) mobile communications systems for 6G will be created with optimal AI (Artificial Intelligence) and ML support—not just as a fundamental feature, but also for maximum efficiency [5]. In terms of architecture, executing distributed AI at the edge will allow us to achieve maximum speed while also resolving data ownership problems. What we have come to call “really ubiquitous intelligence”, when joined with fully integrated ICT systems that contain diversified connection, computation, and storage resources at the edge, will become a natural attribute quickly and without reluctance. The 6G network architecture we are waiting for, when combined with native AI support will help to create something called “Networked AI”, which will change the game as well as move us away from “Cloud AI”.

Throughout the next decade, in addition to multiple and plenteous continuous wireless innovations, the introduction and ultimate rise of massive AI and the creation of massive digital twins will more than likely be the two major catalysts that fuel more technology breakthroughs that have never been seen before. The result of this being 6G, will be a change in both our economy and society like never seen before. In fact, this will likely if not certainly lay a solid foundation for the future Intelligence of Everything. Also along this line, 6G will be a network of sensors and ML, where data centers will be transformed into neural centers, and something known as ML tasks will then be spread over the entirety of the network, from neural center to deep neural edges. Some examples of this may include mobile devices or even base stations [6].

In contrast to 5G networks, the forthcoming 6G networks are anticipated to exhibit superior and accelerated performance across various dimensions. While 5G networks are capable of achieving a peak data rate of 20 Gbps, the potential of 6G networks is staggering, with projected rates ranging from 1 to 10 Tbps, facilitated by leveraging Terahertz (THz) and optical frequency bands [7]. These higher frequency bands hold the promise of Gbps-level user experience data rates. Notably, the area traffic capacity is expected to surpass 1 Gbps. Spectrum efficiency is estimated to witness a notable enhancement of 3-5 times, while network energy efficiency must improve by over 100 times compared to 5G in order to compensate for the 100-fold increase in data rates. It is important to emphasize that achieving such efficiency gains will necessitate advancements in AI-driven network management and automation [8]. As a consequence, the proliferation of extremely heterogeneous networks, diverse communication scenarios, an abundance of antennas, and wider bandwidths will contribute to a substantial increase in connection density, ranging from 10 to 100 times.

In the foreseeable future, it is envisioned that 6G wireless networks will be the answer to the future of data-intensive smart societies with full automation through seamless integration of wireless network aspects spreading from the ground, air to space [9, 10]. It is very likely that the 6G mobile networks we are referring to will be virtualized, software-defined, and cloud-based systems with the motivation to create a substantial number of ubiquitously connected heterogeneous devices including the IoE (Internet of Everything), to enable an incredible range of network services [11, 12]. In this paper, we will discuss the significant role of the IoT in enabling promising applications that connect physical devices to the cyberspace of the communication world, as illustrated in Fig. 1, which demonstrates the network architecture of the satellite-air ground integrated network in the context of the paradigm shift towards 6G.

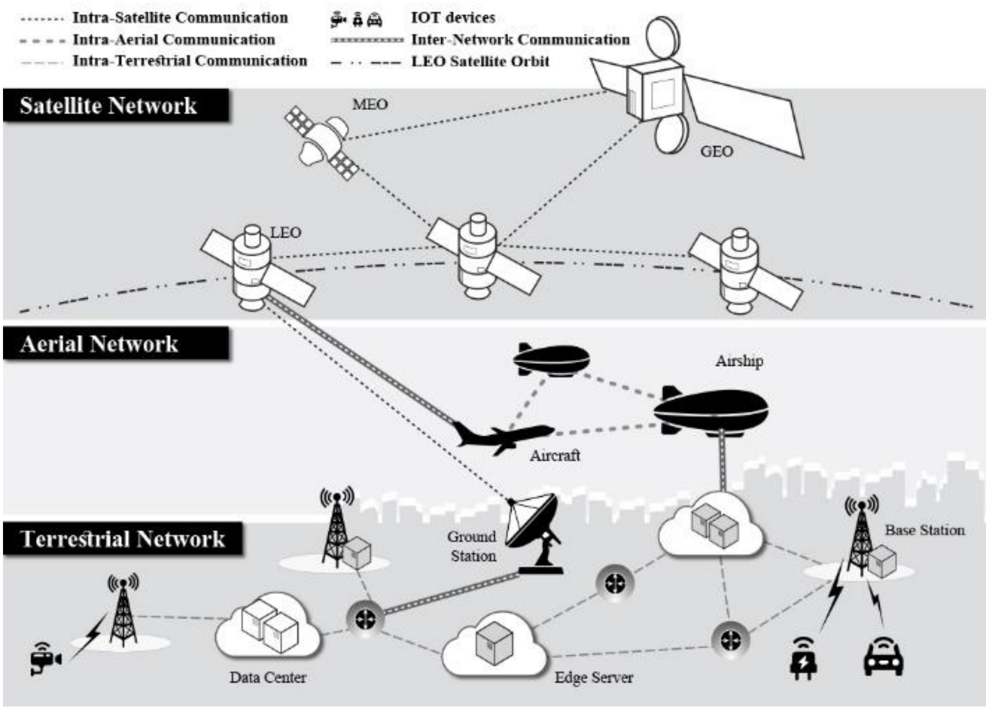

Fig. 1 Network architecture of the satellite-air-ground integrated network.

The paper is structured into several sections to facilitate a comprehensive exploration of the topic. The next section delves into LEO satellite-based NTNs, providing an in-depth examination of their significance in achieving continuous and ubiquitous connectivity while also highlighting the numerous advantages brought about by the convergence of 5G/6G networks, LEO satellites, and IoT. By seamlessly integrating these technologies, enhanced connectivity, improved service quality, and novel applications become possible, revolutionizing various sectors and facilitating advancements in fields such as remote sensing, sustainable development, environmental monitoring, and management. The subsequent section focuses on the 6G spectrum, discussing advancements and considerations related to potential frequencies and technologies that will contribute to the substantial performance improvements of 6G networks. In addition in this section, the ongoing research and advancements in the field of next-generation antenna design for 6G networks highlight the crucial role of innovative antenna technologies in realizing the envisioned capabilities of integrated networks. Furthermore, the paper explores the paradigm shift from the IoT to the IoI (Internet of Intelligence), shedding light on the concept of intelligent machines and their enhanced collaboration with humans. This section provides insights into the transformative potential of this shift, considering the implications for environmental protection and the achievement of the SDGs. Moreover, the paper examines various domains of human-machine interaction within a connected intelligent ecosystem, illustrating the coexistence and interaction between humans and intelligent machines. Lastly, the paper presents future research directions and potential avenues for exploration at ECSTAR, highlighting the center's commitment to advancing integrated networks and addressing environmental challenges. It concludes by emphasizing the significance of integrated networks in shaping the future of telecommunications systems, emphasizing the potential for these systems to contribute to environmental protection, sustainable development, and a more connected and intelligent society.

2. LEO Satellite-Based NTNs

Because they have both circular and equatorial orbits, GEO satellites are the most frequent in the spaceborne category. Interestingly, they orbit at an astounding 35,786 km. It is a common misconception that these satellites are stationary given the fact that they appear so from the perspective of a ground observer, however, this is not the case. Another interesting feature is that their normal beam footprint size may range from 200 to 3,500 km. Non-geostationary satellites are those that operate at lower altitudes and are referred to as MEO (Medium Earth Orbit) and LEO satellites (NGSO) [13].

The reason they have been given this name is that their rotational speed is even quicker than the rotational speed of the Earth and from the perspective of someone on the ground, they appear to be moving. Their orbits, on the other hand, are circular or elliptical, with an altitude ranging from 7,000 to 25,000 km for MEO and 300-1,500 km for LEO. Finally, their typical beam footprint size extends from 100 to 1,000 km. Notably, NTNs and LEO satellites have gotten a lot of press in recent years, prompting numerous businesses to submit plans to the FCC (Federal Communications Commission) to deploy their LEO constellation in space [14]. This is mostly owing to a clear need for a number of desirable characteristics, such as high capacity and low latency. Furthermore, recent successful LEO network installations, such as Starlink's, have prompted other businesses to follow suit. In the past, satellite and terrestrial wireless networks grew independently, but these two "unstoppable forces" are now working together to improve coverage and connection in future wireless networks.

The 3GPP (3rd Generation Partnership Project) is one of the most influential standardization groups, working on a variety of technical elements of the technology in order to give ubiquitous access to 5G networks via NTNs. Several first initiatives have been done to align 5G state-of-the-art technology and ideas with the circumstances encountered in NTNs. 6G will combine terrestrial and NTNs to provide global coverage and connect the previously disconnected [15].

Huge fleets of LEO satellites will become a reality in NTNs as the cost of manufacturing and launching spacecraft drops. There is a good chance that 6G will include LEO satellite mega constellations. A LEO satellite system provides a variety of additional capabilities and advantages in addition to providing global coverage [16]. It, for example, solves the communication delay problem that plagues traditional geostationary and MEO satellite systems. It can also give coverage to locations where terrestrial networks are unavailable, allowing for additional radio access. LEO satellites can also give more precise location, which is vital for autonomous driving and earth sensing and imaging.

The mega constellation can be defined as a constellation that consists of a series of low-cost, miniaturized low-orbit communication satellites with a capacity of more than Gbit/s and a transmission delay of less than 50 ms that achieve global coverage via intersatellite links or on-board processing, when combined with current universal knowledge on mega-constellations in academia [17]. Rain, fog, snow, dust, and other meteorological conditions have a little impact on it. THz communication, in comparison to mmWave frequency bands, has greater frequency resources and is easier to achieve high-speed transmission. To put it another way, the THz band is a compromise between mmWave and optical. It is the most preferred frequency band in terms of 6G application scenarios.

New radio nodes, such as drones, UAVs (Unmanned Aerial Vehicles), and HAPSs (High Altitude Platform Stations), will be a vital feature of 6G, serving as either mobile terminals or temporary infrastructure nodes, in addition to satellite communications [18]. 6G will set itself distinct from its predecessors by merging both terrestrial and NTNs. Currently, NTNs are developed and operated individually. Their activities and operations, as well as their resources and mobility management, are projected to be tightly linked in the 6G future.

Currently, frequency interference has not been a major issue for existing satellite constellations since they are not yet large enough. Due to the visibly different channel parameters and satellite payload limits, it is typically not easy to apply several commonly used interference reduction technologies to the near future LEO mega-constellations for 6G worldwide coverage. As a result, it is time to batten down the hatches, and here are some ideas. First, create interference protection standards and technologies that are appropriate for mega-constellations. There are no mature ITU standards at this time, and the application of traditional interference evaluation methodologies, protection standards, and simulation methods must still be investigated further.

The communication satellite constellation is still somewhat limited at the moment, and most users are only covered by double stars. The system simply requires a good channel allocation mechanism when users do handover [19]. The majority of satellite selection procedures are based on the designer's concepts, and their weight factors are also chosen based on experience [20]. Traditional satellite handover faces new hurdles when mega-constellations for 6G global coverage are deployed. Existing handover algorithms do not include algorithm complexity, which might result in a significant computing strain on the system. It will be critical in the future to develop appropriate satellite handover procedures and algorithms for mega-constellations based on their features.

MCCs (Mission Control Centers), terrestrial stations, ocean TT&C ships, relay satellite systems, global satellite navigation systems, and accompanying communication support systems are all included in tracking, telemetry, and command TT&C systems. The satellite TT&C system receives the operational state of each satellite subsystem as well as external space environment parameters, monitors the satellite's operating and health condition, and issues warnings when a parameter's value exceeds a set threshold. The satellite TT&C system sends remote orders to the satellite and controls its movement as well as its operational state. The TT&C system uploads emergency plans or self-destruction directives when a satellite malfunction or fails. It is evident that neither the ground-based nor the space-based TT&C systems are capable of handling the massive TT&C activities required by mega-constellations for 6G worldwide coverage. There are various transmission pathways for TT&C information due to a large number of satellite network nodes, greatly boosting resilience. We feel that the networked TT&C system is more appealing for TT&C jobs involving hundreds or thousands of satellites, based on the preceding arguments [21].

In addition to environmental protection and SDGs, the convergence of 5G/6G networks, LEO satellites, and IoT brings about several advantages. One notable advantage is the deployment of non-geostationary satellites, such as MEO and LEO satellites, which operate at lower altitudes and offer improved coverage and connection capabilities compared to traditional geostationary satellites. These LEO satellite systems solve the communication delay problem and provide coverage to areas where terrestrial networks are unavailable, enabling additional radio access and precise location services for applications like autonomous driving and earth sensing [16].

Another advantage lies in the potential of LEO satellite mega-constellations, which consist of low-cost, miniaturized satellites operating in low orbits. These mega-constellations can achieve global coverage, provide high-speed transmission, and exhibit resilience to various meteorological conditions. Additionally, the integration of drones, UAVs (Unmanned Aerial Vehicles), and HAPSs as mobile terminals or temporary infrastructure nodes further enhances the capabilities of 6G networks. By merging both terrestrial and NTNs, 6G sets itself apart from previous generations, paving the way for tightly linked activities, operations, resources, and mobility management in the future.

However, the deployment of large-scale LEO mega-constellations for global coverage in 6G networks presents certain challenges. Interference protection standards and technologies suitable for mega-constellations need to be developed, and effective satellite handover procedures and algorithms specific to mega-constellations must be designed to ensure seamless connectivity. Moreover, the tracking, telemetry, and command TT&C systems that monitor and control satellites need to adapt to the massive scale of operations in mega-constellations, potentially requiring a networked TT&C system to handle the increased workload and ensure efficient communication among satellite network nodes.

Addressing these challenges and leveraging the advantages of the convergence of 5G/6G networks, LEO satellites, and IoT will contribute to the realization of environmentally sustainable and socially impactful applications. The utilization of these technologies in future telecommunications systems aligns with the global pursuit of sustainable development, enabling enhanced connectivity, improved resource management, and the fulfillment of SDGs.

The next section will discuss the significance of spectrum in wireless communication systems and its allocation for 6G. Spectrum is a crucial resource, and a globally uniform allocation mechanism is essential. 6G is expected to extend beyond mmWave frequencies and explore sub-THz bands. The section will cover the exploration of various frequency bands, including low-band, mid-band, mmWave, THz, and optical bands, to enhance data rates. A multilayered frequency band structure will be employed in 6G. The roadmap of 6G in comparison to 5G will be illustrated, emphasizing the continued importance of low and mid-bands. Challenges and drivers associated with mmWave and THz bands, such as the need for large bandwidth, centimeter-level sensing resolution, and improved radio technology, will be discussed. The potential of THz bands for ultra-wide bandwidth and enhanced sensing capabilities will be highlighted. Advancements in semiconductor technology and antenna designs will also be explored, supporting the development of 6G wireless technology.

3. 6G Spectrum and Impact of Next-Generation Antenna Design

A spectrum is the most important concern for wireless communication systems since it is the major resource. Furthermore, for greater economies of scale and more easy worldwide roaming, a globally uniform spectrum allocation mechanism is essential. The utilization of spectrum continues to extend to higher frequency bands as mobile communication technologies grow into new generations. While 5G was the first to employ mmWave frequency ranges, 6G is planned to go much beyond, maybe to (sub-) THz. All spectra, including sub-6 GHz, mmWave, THz, and optical frequency bands, will be completely researched to deliver a better data rate. Despite the need of low- and mid-band frequencies for mobile communication systems to ensure extensive coverage, 6G will use a multilayered frequency band structure [22].

The roadmap of 6G in comparison with 5G life cycle can be illustrated, as shown in Fig. 2 [23]. Low bands (from 700 to 900 MHz) and mid-bands (from 3 to 5 GHz) are critical in 5G and will continue to be important in 6G. To sustain the projected rise of traffic in 2030 and beyond, at least 1 to 1.5 GHz of extra mid-band spectrum will be required, especially when considering multi-operator coexistence. The 6 GHz (or 5,925-7,125 MHz) and 10 GHz (or 10-13.25 GHz) bands are also viable options. Propagation attenuation will be raised in an acceptable range as compared to 3.5 GHz, while path loss will be further minimized by improved radio technology.

The mmWave band is more difficult to work with than the low- and mid-bands due to more severe radio propagation characteristics. In the 6G era, however, new drivers will arise. For starters, the ultra-high data rates required in 6G necessitate a large amount of accessible bandwidth in the mmWave frequencies. Second, the mmWave bands are the only spectrum capable of centimeter-level sensing resolution, which is critical for mapping network infrastructures. Due to practical constraints like as limited bandwidth and antenna aperture size, this is challenging for mid-bands. Third, the advancement of more complex radio technology may increase mmWave spectrum use. IAB (Integrated Access and Backhaul) would be a critical technology for efficient spectrum usage in the future, and the E-bands (71-76 and 81-86 GHz) are good possibilities to handle bigger contiguous blocks [24].

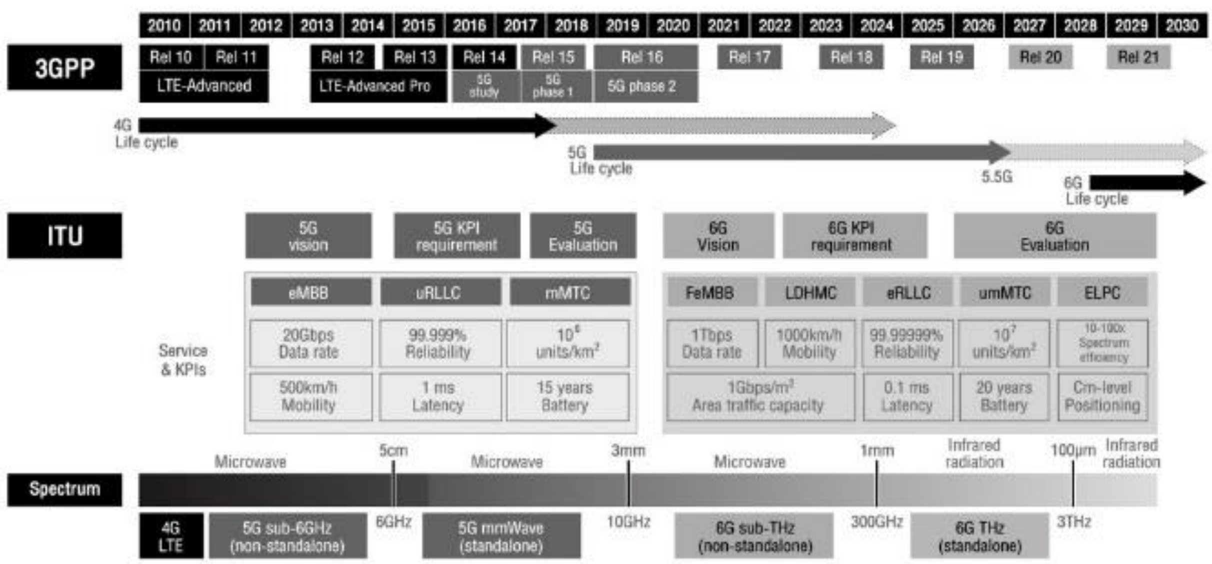

Fig. 2 The roadmap of 6G in comparison with 5G life cycle [23].

The ability to provide ultra-wide bandwidth is one of the most prominent properties of the THz bands. In the THz band of 100 to 450 GHz, about 230 GHz of spectrum has been assigned to mobile services. Short-distance (less than 10 m) and mid-distance (e.g., 200 m) communication can now sustain extremely high data rates. THz bands also provide improved sensing resolution due to their ultra-wide bandwidth and shorter wavelengths. Smart phones using THz sensing technology will be able to supplement human senses in the future, detecting calories in food, finding pinprick leaks in water pipes, facilitating security checks, and monitoring skin and subcutaneous vascular health, for example [25].

The significant advance made in semiconductor technology may be credited to the rapid evolution of digital communication during the last several years. With 6G on the horizon, new material technologies will continue to advance, allowing for the use of additional spectrum and antennas in new applications. Silicon technologies have long been utilized to power next-generation applications in communication, photography, computing, and other fields because of its inherent low cost, high yield, tiny geometry, and low power. Advanced methods enable more efficient and compact hybrid integration of photonic and electrical components on the same silicon, which is expected to happen in the near future. The use of 6G wireless technology is vital [26].

Because of the abundance of untapped and underused spectrum, frequencies above 100 GHz are the most potential frequency bands for 6G wireless communication systems. The research of peak capabilities of massive MIMO (Multi-Input-Multi-Output) wireless access technology at THz bands (0.1-10 THz) is motivated by the growing worldwide need for ultra-high spectral efficiency, data rates, speeds, and bandwidths in next-generation wireless networks. The shorter wavelengths (order of microns) of these frequencies enable the creation of high-gain antennas with reduced physical dimensions, allowing for huge spatial multiplexing [27].

We were able to create a THz integrated circuit because of advances in semiconductor technology (IC). Using SiGe HBT (Heterojunction Bipolar Transistor) technology, we can currently produce ICs with frequencies up to 700 GHz. According to estimates, the performance limit of SiGe HBT might soon reach or even exceed 1 THz [25]. Silicon THz ICs provide a number of benefits, including low cost, small size, high yield, and ease of integration. Another option is an antenna-in-package, albeit the connectivity loss between antennas and MMICs (Monolithic Microwave Integrated Circuits) is significant. The design and deployment of efficient and low-loss THz antennas is both desired and hard at THz frequencies. In many circumstances, fine-tuning the electrical characteristics of materials is desirable because it allows for devices with more functionalities, smaller dimensions, and lower prices. As a result, a number of tunable materials have been proposed and integrated into systems for flexible and dynamic control. RISs (Reconfigurable Intelligent Surfaces) are now possible because of this tuning function, which is managed via a digital platform.

Improved antenna designs with decreased size, weight, aerodynamic drag, and cost are now possible because of recent breakthroughs in materials and manufacturing technology. Composite materials and new selective metallization methods are two key advances impacting next-generation antenna designs. These advancements work together to enable the production of three-dimensional antennas that are mechanically strong and resistant to extreme weather conditions at a reasonable cost. The use of conductively-coated composite technology allows for the production of innovative antennas that are smaller, lighter, and less expensive. Injection molded composites are a good way to mass produce antenna substrates and radomes in large quantities. Three-dimensional antennas, circuit traces, and ground plane structures may be created using selective metallization with conductive coatings. These methods work together to provide electrically and mechanically robust antennas and arrays in conformal, lightweight form factors that are ideal for next-generation mobile communication.

The next section will discuss the launch of next-generation network systems with revolutionary technologies and their impact on access networks. The transition from the IoE to the IoI will be explored, highlighting the need for improved connectivity, coverage, latency, robustness, and self-adaptation. The concepts of Industry 4.0 and IIoT (Industrial IoT) will be introduced, focusing on the shift to smart manufacturing and the significance of edge-driven AI. The section will also cover the challenges posed by data transfer in future networks and the role of data-driven machine learning and AI approaches in real-time network adaptability. Anticipated advancements in 6G networks, including superior performance, spectrum efficiency, energy efficiency, and increased connection density, will be discussed. The societal impact of 6G networks, such as the integration of satellite and terrestrial networks, human-machine collaboration, and revolutionized human-machine interaction, will be explored. The section will conclude by highlighting the importance of ongoing research and development in realizing the vision of 6G networks and the integration of AI for maximum efficiency and pervasive intelligence.

4. Transformation of IoT to IoI

The launch of the next-generation network system with revolutionary technologies (such as intelligent surfaces, cell-free architecture, massive MIMO, space-air-ground integrated networks, and cyber-twin) is expected to transition the role of access networks from carrier of data to carrier of intelligence, accelerating the advancement of machine learning-enabled paradigms over the synergy of smart networking. Big data have enabled ubiquitous AI for a wide range of unique technologies that continue to reshape our environment as we go from the IoE to the IoI. However, current 5G network deployments rely on centralized management and model-based analytics over fixed-configured infrastructures, exposing limitations in terms of unlimited connectivity, space-air-ground coverage, extremely low latency, strong robustness, and self-adaptation capability for humans and ubiquitous things.

Industry 4.0, or the fourth industrial revolution, refers to a smart factory setup with intelligent IoT devices. IIoT, on the other hand, is a subset of IoT that focuses on the shift from traditional to smart manufacturing. The interconnectedness of our digital society and the prominence of IoT devices have improved 4.0. The move from cloud to cloud intelligence will need the creation of a “Intelligent Internet of Intelligent Things” to make the internet more dependable, efficient, robust, and secure. This is precisely where 6G connectivity combined with edge-driven AI may make a big difference [28].

A number of new services and applications with diverse features in terms of produced traffic, mobility, and varying QoS (Quality of Service) needs have been conceptualized in the last few years owing to the rapid evolution of the IoT. On the next-generation communication network nodes, this will result in a massive quantity of data transfer. In this situation, real-time network state adaptability is critical for offering a high-quality user experience in ultra-dense and uncoordinated future networks. The deployment of solutions based on data-driven machine learning and AI approaches is critical for these reasons. Although the capabilities offered by the remote cloud satisfy the current resource and energy hungry requirements of AI due to the large amount of data to be analyzed, the ability to consider highly distributed AI solutions with small memory footprint is critical with the implementation of the Edge Computing paradigm. Edge Intelligence is the result of combining AI with Edge Computing, with the goal of transferring intelligence from the central cloud to edge resources, allowing the IoIT (Internet of Intelligent Things) [29]. Edge Intelligence provides an effective means to handle different parts of the edge computing approach, from resource management to data organization provided by devices, as well as the instantiation of appropriate software for edge computing and storage facilities.

In the not-so-distant future, 6G wireless networks are poised to revolutionize data-intensive smart societies by seamlessly integrating wireless network aspects across ground, air, and space [14]. These advanced 6G mobile networks will likely be virtualized, software-defined, and cloud-based systems with the primary objective of facilitating ubiquitous connectivity for a diverse range of devices, including the IoE. The paradigm shift towards 6G will also leverage the power of the IoT, enabling transformative applications that bridge the physical and digital realms.

One of the key advancements expected in 6G networks is their superior performance compared to 5G in terms of speed and capacity. While 5G networks can reach peak data rates of up to 20 Gbps, 6G networks are projected to achieve an astounding 1-10 Tbps using THz and optical frequency bands [7]. These high-frequency bands will enable user experience data rates in the Gbps range. Furthermore, 6G networks are anticipated to achieve spectrum efficiency improvements of 3-5 times and network energy efficiency gains of over 100 times compared to 5G, necessitating advancements in AI-driven network management and automation [8]. This will pave the way for significantly increased connection density, ranging from 10 to 100 times, facilitated by the use of heterogeneous networks, diverse communication scenarios, a multitude of antennas, and wider bandwidths.

Looking beyond mere technological enhancements, 6G networks will foster the realization of a fully automated, data-driven society. Future networks, encompassing both terrestrial and non-terrestrial components, will play a critical role in achieving global, ubiquitous, and continuous connectivity that surpasses the capabilities of 5G networks. The integration of satellite and terrestrial networks, along with advancements in aerial and space technology, will enable sophisticated IoT applications and extend the boundaries of connectivity [14]. With the evolution of intelligent machines, which can sense and interpret the environment differently from humans, novel forms of human-machine communication will emerge. Intelligent machines will increasingly transition from human-assistance to human-collaboration, coexisting and harmoniously interacting with humans. Communication protocols and languages used by machines will dynamically evolve, and machines will gain the ability to comprehend human senses, earning the trust of their human counterparts. This coexistence of humans and intelligent machines within society will revolutionize various domains of human-machine interaction, paving the way for new possibilities and unprecedented advancements.

To achieve the vision of 6G networks, ongoing research and development efforts are crucial. The design of end-to-end mobile communication systems for 6G will be centered around optimal AI and machine learning support, enabling maximum efficiency. The network architecture will be characterized by distributed AI at the network edge, ensuring high speed and resolving data ownership challenges. This amalgamation of ubiquitous intelligence and integrated ICT systems will propel the realization of networked AI, shifting the paradigm from cloud-based AI to truly pervasive intelligence [5]. Consequently, the next decade will witness remarkable breakthroughs driven by the introduction of massive AI and the creation of massive digital twins, which will shape the foundation of the future Intelligence of Everything [6]. This evolution will not only transform the economy and society but also establish 6G as a network of sensors and machine learning, with data centers transformed into neural centers and machine learning tasks distributed throughout the network, from neural centers to deep neural edges [6].

The next section of this paper will focus on the promising areas for future research and development identified by the ECSTAR (Excellence Center of Space Technology and Research). ECSTAR aims to contribute to the advancement of integrated networks combining 5G/6G, LEO satellites, and IoT [30]. The section will outline key research projects that will be pursued. Finally, the conclusion section will summarize the contributions of this paper, highlighting ECSTAR's dedication to driving the progress of space technology and its commitment to sustainable development on a global scale.

5. Future Research Directions and Potential Avenues for Exploration at ECSTAR

The convergence of 5G/6G networks, LEO satellites, and IoT holds significant promise in addressing critical global challenges related to environmental protection and the attainment of the United Nations SDGs. By harnessing the power of these technologies, new opportunities emerge to create a sustainable and interconnected world. One of the key drivers for utilizing the convergence of 5G/6G networks, LEO satellites, and IoT is their potential to enable environmental monitoring and conservation efforts. These technologies can facilitate real-time data collection, analysis, and decision-making, leading to more effective resource management and reduced environmental impact. For instance, the integration of IoT devices and LEO satellites can provide valuable insights into climate patterns, deforestation, pollution levels, and wildlife conservation. This wealth of information can inform evidence-based policies and actions to mitigate environmental degradation and foster sustainable practices.

Furthermore, the convergence of these technologies can significantly contribute to achieving the SDGs. The SDGs provide a comprehensive framework for addressing global challenges, encompassing areas such as poverty eradication, health, education, clean energy, sustainable cities, and responsible consumption [31, 32]. By leveraging the capabilities of 5G/6G networks, LEO satellites, and IoT, innovative solutions can be developed to advance progress across various SDG targets. For example, the deployment of smart city initiatives powered by these technologies can enhance urban planning, transportation efficiency, energy management, and waste reduction, thereby promoting sustainable cities and communities. In light of these opportunities, the research conducted at ECSTAR is driven by a strong commitment to environmental protection and the realization of the SDGs. By exploring the convergence of 5G/6G networks, LEO satellites, and IoT, ECSTAR aims to unlock novel approaches, methodologies, and solutions that contribute to a more sustainable and inclusive future. Through interdisciplinary collaborations and cutting-edge space technology expertise, ECSTAR is poised to make significant contributions in this vital field of research, ensuring the convergence of technologies aligns with global environmental priorities and the SDG agenda.

The comprehensive analysis conducted at the ECSTAR has identified several promising areas for future research and development in the convergence of 5G/6G networks, LEO satellites, and IoT. ECSTAR aims to contribute to the advancement of integrated networks and their potential impact on future telecommunications systems, with a strong focus on environmental protection and the achievement of the United Nations SDGs. Building upon ECSTAR's objective and its competency in cutting-edge space technology, further research endeavors will delve into these key directions for exploration, fostering innovation and pushing the boundaries of scientific understanding. The following research projects highlight key directions for exploration:

1. Prototype of Portable Satellite Terminals: ECSTAR will focus on the development of portable satellite terminals that can effectively leverage the integration of 5G/6G networks and LEO satellites. These terminals will enable seamless and reliable connectivity for IoT devices in various scenarios, including remote areas, disaster-stricken regions, and mobile applications. The research will involve

designing efficient communication protocols, optimizing the terminal size and power consumption, and ensuring compatibility with both terrestrial and satellite networks.

2. Prototype design for an LEO satellite constellation for broadband internet and remote sensing: ECSTAR will investigate the design and implementation of an LEO satellite constellation specifically tailored for providing broadband internet services and remote sensing capabilities. This project aims to overcome the limitations of traditional terrestrial networks by leveraging the global coverage and low-latency characteristics of LEO satellites. The research will involve optimizing the satellite constellation configuration, developing advanced signal processing techniques, and exploring novel applications in areas such as precision agriculture, environmental monitoring, and disaster management.

3. Prototype of a remote sensing satellite for methane detection: ECSTAR recognizes the pressing need for monitoring and mitigating greenhouse gas emissions, particularly methane, which has a significant impact on climate change. In this research project, ECSTAR will focus on the development of a remote-sensing satellite dedicated to methane detection. The satellite will leverage advanced sensing technologies and data analytics algorithms to provide accurate and real-time monitoring of methane emissions from various sources, such as industrial facilities and natural gas infrastructure. The research will involve satellite system design, sensor integration, data processing techniques, and validation through ground-based measurements.

These ambitious research projects not only contribute to the advancement of space technology but also reflect national policies and support the United Nations SDGs [31]. Moreover, if ECSTAR successfully accomplishes the development of a remote sensing satellite for methane detection, Thailand will emerge as the first country in ASEAN to launch such a pioneering satellite system, further establishing the nation’s leadership in space technology and its commitment to addressing global environmental challenges. Through these research initiatives, ECSTAR is dedicated to driving the progress of space technology, fulfilling national objectives, and making significant contributions to the global pursuit of sustainable development.

6. Conclusion

The analysis conducted at the ECSTAR has shed light on the future of telecommunications by exploring the convergence of 5G/6G networks, LEO satellites, and IoT. The study has identified key technological challenges and advancements, paving the way for future research directions and potential avenues for exploration at ECSTAR. ECSTAR’s commitment to addressing these challenges is evident through three major research projects. The development of portable satellite terminals aims to leverage the integration of 5G/6G networks and LEO satellites to provide seamless connectivity for IoT devices in various scenarios. The design of an LEO satellite constellation for broadband inter-net and remote sensing offers the potential for global coverage and low-latency connectivity, revolutionizing applications in precision agriculture, environmental monitoring, and disaster management. Additionally, the development of a remote sensing satellite dedicated to methane detection addresses the pressing need for monitoring greenhouse gas emissions and combating climate change. These research projects at ECSTAR are aligned with the goal of environmental protection and the achievement of the United Nations SDGs. By leveraging the convergence of 5G/6G networks, LEO satellites, and IoT, ECSTAR aims to contribute to the broader understanding of integrated networks and foster innovation in telecommunications. The results and insights gained from these endeavors will enhance the potential for seamless connectivity, improved service quality, and novel applications across various domains. The advent of 6G networks holds great potential for the integration of LEO satellite-based NTNs and IoT, enabling ubiquitous connectivity and extending coverage to remote areas. This integration opens doors to transformative applications in sectors such as agriculture, logistics, environmental monitoring, and disaster management. By exploring these re-search directions and embracing the opportunities presented by the convergence of 5G/6G networks, LEO satellites, and IoT, ECSTAR aims to shape the future of tele-communications and contribute to the advancement of integrated networks. These efforts will have a profound impact on society, driving innovation and paving the way for a connected, intelligent, and sustainable future. ECSTAR's commitment to environmental protection and the pursuit of SDGs underscores its dedication to making a positive impact on both local and global scales.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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