CHAPTER

4 Role of non-terrestrial networks in achieving sustainability in IoT devices

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4.1 Introduction to NTNs

NTNs are an incomparable advancement in communication technologies. They extend complex connections beyond terrestrial borders with a constellation of specialized airborne and space-borne platforms. The space-borne platforms consist of satellites and are divided into three primary types: Geostationary Earth Orbit (GEO) satellites, Medium Earth Orbit (MEO) satellites, and Low Earth Orbit (LEO) satellites. GEO satellites are about 35,786 km from Earth and always occupy the same position above the equator. The best utility of this type of satellite is for continuous, wide-area coverage. GEO satellites are widely used in television broadcasting and meteorological monitoring applications. MEO satellites travel at distances from 2,000 km to 35,786 km above the equator. Mostly, MEO satellites are used in global positioning and navigation systems. MEO satellites offer a great compromise between the area over which coverage is provided and the delay in signal strength. LEO satellites operate above Earth in the range between 180 km and up to 2,000 km, providing much lower latency and increased bandwidth that are essential for real-time, data-intensive IoT communication [1–3].

Besides satellites, NTNs consist of airborne platforms consisting of High-Altitude Platforms (HAPs) and Unmanned Aerial Vehicles (UAVs), which are an essential part of NTNs [4,5]. HAPs encompass objects such as balloons or airships within the stratosphere, which can provide localized communications coverage that is close to that of a satellite. In addition, HAPs offer more operational flexibility and reduce the necessary operational costs. These platforms are particularly used to provide temporary solutions for connectivity during live events, emergency response situations, or other transient conditions that demand extra coverage with lower latency [4]. UAVs or drones augment the high flexibility of NTNs with their quick deployability to ensure

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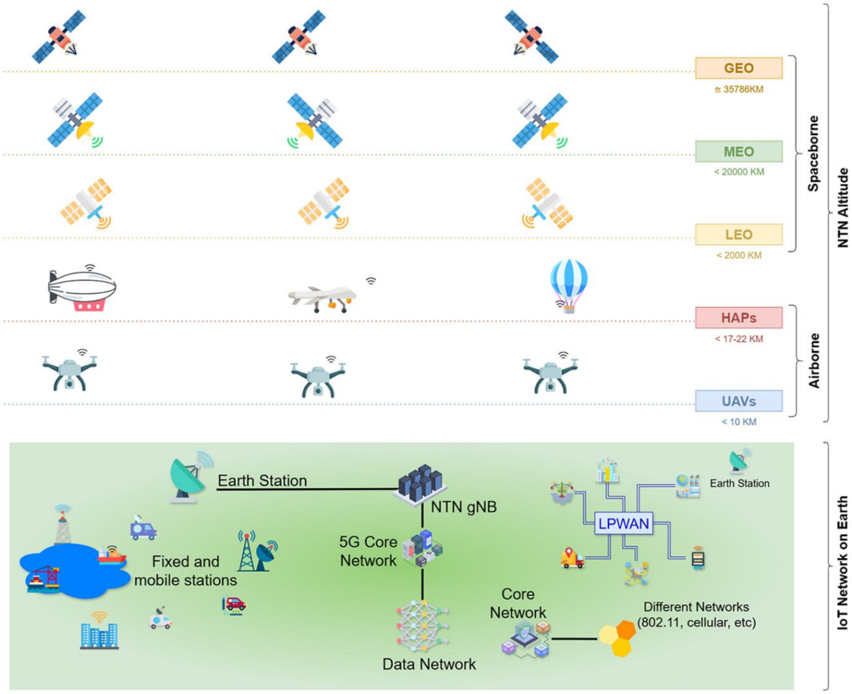

FIGURE 4.1

NTN layers supporting IoT connectivity.

disaster areas receive immediate ad-hoc network support. UAVs are also deployed to provide support in wide areas hosting important events, ensuring network availability in critical situations [5]. Fig. 4.1 shows the hierarchical arrangement of NTN components comprising GEO, MEO, LEO satellites, HAP, and UAV interconnected with terrestrial and core networks to enable seamless data exchange and Low-Power Wide-Area Network (LPWAN) for sustainable IoT applications.

The integration of NTN is critical in geographical or underdeveloped regions, where laying physical cables in the ground or installing cell towers and terrestrial infrastructure is not possible or economically viable [6]. NTNs in these regions catalyze the expansion of robust communication services, driving the world closer to seamless global connectivity. The integration of NTNs becomes especially important with respect to IoT, where seamless connectivity in a wide range of locations is essential for continuous data collection and delivery between devices [7]. IoT applications that support environmental monitoring in remote wilderness or real-time data management with offshore oil platforms are highly dependent on the wide coverage and support of NTNs. NTNs are also highly beneficial in enhancing network resiliency, as they provide alternative data routes, useful when the terrestrial network fails, particularly during calamities. In case of such natural disasters, readily available NTNs provide continued communication, aiding the key emergency services and coordination [8].

The strategic deployment of NTNs immensely relieves the congestion that exists on terrestrial networks by managing the excess overflow of information traffic. The network overburden is imperative given the exponential growth in the number of IoT devices, which tends to exert a strain on the existing network infrastructure. Through the use of NTNs, diversification of the data path occurs, hence enhancing the overall network performance. NTNs not only guarantee increased service quality, but also ensure that the network attains sustainability through optimized performance of the energy resources as well as minimized usage of extensive physical infrastructural expansions that cater to the modern-day challenges of network demand, connectivity reliability, and inclusivity on a geographically wide scale. As we move forward, the combination of terrestrial and NTNs would, without a doubt, be one of the pillars around which the revolution in the global communication landscape unravels, especially in the vast and variably connected space of the IoT [7] [9].

4.2 NTNs and IoT connectivity

The integration of NTNs with existing terrestrial and IoT infrastructure is a step forward in achieving full global connectivity. This is important to create a connectivity mesh around the world that welcomes both traditional ground-based networks and advanced aerial and satellite systems [10]. To ensure the seamless operation of global IoT systems, it is important to have such a connected mesh, especially in providing reliable service delivery in areas with a sparse or non-existent terrestrial network. By providing stable internet connectivity, the NTNs enable these areas to be connected to the internet, allowing these populations to participate more positively in the global digital economy. This is not only for accessing information, but also for varied services including advanced health, education, and disaster management, in which the data exchange is of great importance [1] [11].

The integration of NTNs extends the capability of IoT to support massive deployments across a range of sectors. This promise of IoT technology for the transformation of industrial operations, agriculture, and urban management relies heavily on handling a big network of devices that work smoothly and efficiently. Here, NTNs are providing a major solution for increased bandwidth and wider coverage [10]. An example is in large agricultural lands, where traditional terrestrial connectivity can hardly cover all the areas, leading to the formation of blind spots. NTNs remove these gaps by offering farmers detailed real-time data from sensors. These sensors are spread across large fields and enable farmers to achieve an optimized irrigation system, including pest management, and crop health monitoring [12]. Similarly, in urban scenarios, where the density of devices and data demand is massive, NTNs take the load off the terrestrial networks by spreading the data traffic across the available spectrum [13]. This will not only make the operation of the IoT applications run smoother, but also enable the urban network service providers to achieve optimized infrastructure, and obtain higher spectrum efficiency and greater reliability [14].

Table 4.1 Comparison of NTNs and terrestrial networks for IoT connectivity.

Parameter	Terrestrial Networks	NTNs
Coverage Area	Limited to urban and suburban areas	Global, including remote and underserved areas
Bandwidth	High	Varies, typically lower than terrestrial
Latency	Low	Higher due to signal travel distance
Deployment Cost	High initial cost, lower maintenance	Lower initial cost, higher operational cost
Scalability	Limited by infrastructure	Highly scalable across vast regions
Reliability	High in covered areas	Consistent, even in challenging environments
Data Handling Capacity	High	Can handle large volumes from numerous devices

The NTNs support massive data from a large number of devices, a game changer for IoT deployments. It not only has the potential to support the current scale of IoT implementations, but also has to support future network expansions. The expandability that NTNs have in place ensures the network's growth with technological advances in the IoT and the expected resultant growth in data traffic, while maintaining service performance at full speed and quality [15]. In addition, NTNs improved connectivity, paving the way for the use of more sophisticated IoT applications. One such example is in industrial IoT applications, which require precision and efficiency, where the use of NTNs ensures that complex automated processes and machinery operate continuously [16]. NTNs significantly improve productivity and safety and reduce downtime due to connection issues, allowing real-time monitoring and maintenance. The merger of NTN with industrial IoT networks represents simply an incremental value addition to the existing system and is a step toward a global IoT infrastructure that is more accessible, more connected, and finally more capable [17]. Table 4.1 provides a comparison of NTNs and terrestrial networks for IoT Connectivity, highlighting differences in coverage, bandwidth, latency, deployment costs, scalability, reliability, and data handling, showcasing NTNs' strengths in global and remote IoT applications.

4.3 NTNs sustainability challenges and opportunities

The deployment and maintenance of NTNs inherently involve significant environmental and sustainability challenges, largely due to the energy-intensive nature of their lifecycle. The process begins with the manufacturing of components, such as satellites, UAVs, and HAPs, which require substantial amounts of various raw materials, including metals and composite materials that are often procured through environmentally taxing mining practices. Many of these materials, such as lithium for

Table 4.2 Life cycle of NTNs, environmental impacts, and sustainable solutions.

Life Cycle Stage	Environmental Impact	Sustainable Solutions
Manufacturing	Raw material extraction (e.g., lithium, rare earth elements)	Use of recycled materials, eco-friendly mining practices, material substitution
Launch	High carbon emissions from rocket propellants	Development of reusable rockets, green propellants, more efficient launch schedules
Operation	Energy consumption (satellites in orbit, ground stations)	Increased use of solar power, energy-efficient ground station designs
End-of-Life Management	Space debris, decommissioned satellites	Recycling/re-purposing satellites, safe de-orbit technologies, space debris mitigation
Broad Impact	Disruption from terrestrial infrastructure (e.g., deforestation)	Reducing terrestrial reliance through NTN connectivity
Resource Management	Efficient water and fertilizer use, renewable energy management	IoT applications for agriculture, real-time data collection for remote installations

batteries and rare earth elements crucial for electronic components, often have complex extraction processes associated with high environmental costs, such as habitat destruction, water pollution, and high carbon emissions [1]. Next, the launch phase of the satellites introduces another layer of environmental impact. The rocket launching process used to place satellites into orbit is the most carbon-intensive aspect of NTN operations. These launches utilize rocket propellants that release significant amounts of carbon dioxide and other pollutants into the atmosphere, contributing to both localized air pollution and global greenhouse gas emissions [18]. There is another environmental impact due to the satellite constellation that needs to be maintained by launching new satellites, especially as more and more satellites reach their end of life and require replacement [19]. Once operational, NTNs continue to consume energy, predominantly to power the satellites in orbit and the ground stations that control them. Although solar power provides much of the in-orbit energy needs, ground operations often rely on conventional energy sources that may not be sustainable. Furthermore, the end-of-life management of these technologies poses a critical sustainability challenge, as decommissioned satellites can contribute to the growing problem of space debris. Space debris not only poses a threat to other satellites and space missions, but also represents a long-term environmental concern in near-Earth space [20,21]. Table 4.2 illustrates the environmental impact throughout the NTN lifecycle and the solutions that support this with an effective green approach that supports sustainability across every stage in their life cycle, from manufacturing through to end-of-life management, to enable positive contributions towards overall global sustainability.

4.3.1 Opportunities for sustainable solutions

Despite these challenges, NTNs hold substantial potential for fostering sustainable IoT systems and reducing the environmental footprint of global connectivity infra-projects. One of the most pronounced benefits is their ability to minimize reliance on terrestrial infrastructure, which is often more invasive and resource-intensive to build and maintain. Terrestrial network components such as cell towers and ground cables necessitate extensive physical disruption, including deforestation and landscape alteration, to establish network coverage, especially in rural or environmentally sensitive areas. By providing connectivity from the sky, NTNs can drastically reduce these intrusions, thereby preserving natural habitats and decreasing the carbon footprint associated with constructing and maintaining terrestrial networks [14]. The expanded coverage offered by NTNs enables more effective management and utilization of natural resources, especially for IoT applications powered by NTNs in agriculture can optimize the use of water and fertilizers, reducing waste and environmental impact. Similarly, NTNs can support efficient renewable energy management by facilitating real-time data collection and control of remote installations, like wind farms, located in offshore or hard-to-reach areas. The remote connectivity achieved through NTNs ensures energy is harnessed and distributed more efficiently, aligning with goals for reducing greenhouse gas emissions [22].

There is also a growing trend towards incorporating sustainability into the design and operation of NTNs themselves. Innovations in technology are gradually reducing the size and weight of satellite components, which lowers the materials required and also decreases the fuel requirement needed for launches and daily operations. The advancements in propulsion and materials science are improving the lifespan of satellites and ultimately reducing the frequency of launches. There is a need to recycle older satellites and use them for different applications. The safe de-orbiting of satellites, when they reach their end of life, is also a promising avenue to explore for the reduction of space debris, and it also minimizes the environmental footprint of NTNs [23,24]. The integration of sustainable practices in NTNs reduces their ecological impact, and encourages eco-friendly IoT adoption. Since NTNs reduce dependence on terrestrial infrastructure and address sustainability challenges, they support global environmental goals and will, therefore, form a vital role in the road to greener, long-term strategies for a hyperconnected world [25].

4.4 Energy efficiency in NTNs

Energy efficiency is critical for all communication systems, especially for NTNs where the lifespan of the equipment is highly energy-constrained. The NTNs' energy dependency is driven by innovations in different technological domains. Solar energy is the most important domain for the NTNs as it drives the space-born and usually drives the air-born equipment. All the satellites and most of the HAPs and UAVs are equipped with state-of-the-art solar panels that convert sunlight directly into electrical energy to meet the power requirements of these systems [14]. Recent advancements in photovoltaic cell technology have led to increased efficiency and reduced weight, resulting in ultra-light materials. These innovations have significantly improved the power-to-weight ratio, enhancing the operational longevity and overall efficiency of NTN platforms [26].

The advanced signal processing algorithms achieved better energy efficiency for both uplink and downlink data [27]. These innovative error detection and correction solutions provide better signal integrity with minimum power consumption. Although the complexity of the system is often increased, the low power requirement makes them ideal for IoT and NTNs as both sides of the network are energy-constrained [28]. There are several modulation schemes available in the literature that demonstrate promising results in achieving energy efficiency, and if they can be implemented, they have the potential to improve the energy efficiency of NTN networks [14,29,30]. The adaptive communication protocols used in IoT and NTN dynamically adjust the energy used based on the quality of the communication link and data demands, and also conserve the energy on both the IoT and NTN side of the network [31]. The novel designs of UAVs also help them achieve better energy efficiency. Modern UAVs are usually designed with superior aerodynamics and equipped with lighter materials to reduce drag and energy consumption. The integration of AI results in intelligent navigation systems that allow for optimized travel paths, and reduce unnecessary maneuvers, thereby extending the battery life and operational duration [32]. In the following subsections, we will dive deep into the technologies enabling NTNs to achieve energy efficiency.

4.4.1 Advanced technologies for energy efficiency

Several emerging technologies, such as beamforming and massive Multiple-Input and Multiple-Output (MIMO) possess the potential to enhance the energy efficiency of NTNs. Beamforming is a technology that focuses the concentration of wireless signals toward a specific direction, resulting in a directional gain. Beamforming possesses the potential to improve the transmission and reception of signal energy, which not only improves signal quality but also reduces power wastage in other directions [33]. Beamforming, when combined with massive MIMO technology, further enhances the performance of the communication system. Massive MIMO is a technology where a large number of antennas are embedded in the base station. The base station serves the different devices simultaneously through spatial multiplexing, leveraging beamforming for focused signals, and also results in reduced interference for other nearby devices. The combination of massive-MIMO and beamforming enhances the energy efficiency of NTN and IoT networks by focusing the signal power on the intended users, minimizing energy wastage, and improving the coverage of the network in the remote areas [34,35].

4.4.2 Energy harvesting

The role of NTNs in enabling IoT devices to leverage energy harvesting technologies opens a new dimension of sustainability, especially in energy-constrained environments. Energy harvesting refers to the process by which energy is derived from external sources and converted to electricity to power IoT devices. These sources are easily available in the environment, and utilizing them reduces the dependency on conventional power sources. Energy harvesting improves the autonomy of devices and improves the self-sustainability of the devices and the overall network as well [14,36]. Table 4.3 provides a concise comparison of the solar, kinetic, and thermal energy harvesting options for NTN-IoT devices, including typical application areas, advantages, and implementation challenges.

Table 4.3 Comparison of energy harvesting methods.

Energy Source	Application Area	Advantages	Challenges
Solar Energy	Agricultural fields, remote areas	Sustainable power source, easy to deploy	Weather-dependent, initial setup cost
Kinetic Energy	Urban settings, roads, bridges	Utilizes ambient energy, reduces external power need	Low energy yield, device complexity
Thermal Energy	Industrial environments	Uses temperature gradients, reliable in high-temp areas	Initial setup cost, efficiency varies by environment

Solar energy harvesting

In remote areas, where IoT devices are deployed, such as agricultural fields or wildlife monitoring areas, solar energy provides a sustainable power source that can keep devices running indefinitely, depending on weather conditions. The solar panels on these devices capture sunlight, which is then converted into electrical energy to power sensors and communication modules [37]. The dependence on solar reduces battery and fossil fuel-based energy consumption and overall reduces the carbon footprint of the overall network. The longer life of high-quality solar panels, which is around twenty years, is a huge contributing factor towards the sustainability of this solution.

Kinetic energy harvesting

Kinetic energy harvesting is the process of converting motion or mechanical vibration into electrical energy. Most kinetic energy harvesters depend on mechanical-to-electrical energy converters. Typically, this process consists of three stages. The first stage, energy capture, involves coupling externally provided motion or vibration to a mechanical structure, such as a spring or mass, to facilitate energy conversion. The second stage, energy conversion, transduces the captured mechanical energy into electrical energy using mechanisms such as electromagnetic induction, piezoelectricity, or electrostatic methods. The third and final stage, energy conditioning and storage, processes and stores the harvested energy in batteries or supercapacitors, ensuring a stable power supply for IoT devices. Several key components are involved in this process. The important ones among them are energy transducers. Energy transducers are classified as mechanical, magnetic, and electrostatic. Piezoelectric materials fall into the first category, converting mechanical stress into electricity using quartz or ceramic elements. Coming to electromagnetic generators utilize the motion of a magnet through a coil in order to induce an electric current, using Faraday's law. Finally, the electrostatic generators work on the principle of converting changes in capacitance caused by mechanical motion to generate power. The second constituent in this interaction is the source of vibration, such as ambient vibrations from machinery or wind, even from user activity in wearable devices, and it provides mechanical energy to actuate the system. Mechanical structures, such as cantilever beams, resonators, or springs, amplify the mechanical vibration to improve the capture efficiency of vibrational energy. Power management circuits will finally regulate the output voltage and current to match IoT devices for energy storage in batteries or supercapacitors. Kinetic energy harvesting is suitable for IoT in NTN scenarios, like satellites, UAVs, and remote sensors, where ambient motion is rich, such as wind, vibration, or body movement. It provides a renewable and sustainable power source to reduce the frequency of battery replacement and enhance the reliability of IoT networks [38].

Thermal energy harvesting

Thermal energy conversion is also an emerging trend in which temperature differences are used to generate electricity. Thermal energy harvesting works by converting heat into electrical energy using thermoelectric materials and leveraging the temperature difference between two surfaces or regions. The process is primarily based on the Seebeck effect, a phenomenon where a voltage is generated across two dissimilar conductors or semiconductors that experience a temperature gradient.

The thermal energy harvesting process is divided into several steps. First, the heat absorption, where a heat source, such as solar radiation, electronic devices, or natural geothermal heat, generates thermal energy. Heat collectors capture this energy and transfer it to the thermoelectric generator (TEG). Second, the creation of a temperature gradient. The TEG has two sides, one exposed to the heat source (hot side) and the other connected to a heat sink (cold side). A temperature difference is established between the two sides, which is crucial for generating electricity. Third, the electron movement via thermoelectric materials. Inside the TEG, thermoelectric materials such as bismuth telluride or silicon-germanium alloys facilitate the conversion of the temperature difference into an electric current. The hot side excites electrons, causing them to move towards the cooler side, creating a flow of charge. Fourth is the energy output stage. The resulting voltage from the temperature difference generates Direct Current (DC) electricity. The amount of electricity is proportional to the material's thermoelectric efficiency and the magnitude of the temperature gradient. The fifth step is power regulation, where the harvested electricity is typically low in voltage and requires regulation to be usable by IoT devices. A power management circuit, including voltage regulators and converters, ensures the output is stable and matches the device's energy requirements. The last step is energy storage, which is to provide continuous power, especially when the temperature gradient fluctuates. The harvested energy is stored in batteries or supercapacitors. This ensures IoT devices have a reliable energy supply even during periods of minimal heat availability.

Over the years, there have been several enhancements in thermal energy harvesting systems however there are several open research challenges that can further improve these systems, like the advanced thermoelectric materials with higher Seebeck coefficients and thermal conductivities improve conversion efficiency. The integration of Phase Change Materials (PCMs) which store excess thermal energy during peak heat and release it during cooler periods, maintains a steady temperature gradient. The development of hybrid harvesting systems combines thermal energy harvesting with other energy sources, such as solar or kinetic energy, for higher reliability and efficiency in NTN-IoT networks.

This seamless energy harvesting process ensures that IoT devices in NTNs operate autonomously in remote or harsh environments, reducing dependency on traditional power sources and supporting sustainable energy practices [39].

4.4.3 Optimization through low-energy protocols

Beyond enhancing hardware efficiency and incorporating energy harvesting strategies, energy efficiency in NTNs is achieved through the implementation of low-energy protocols. These protocols are designed to minimize energy consumption during data transmission and reception. This is crucial for the longevity and sustainability of NTN communication platforms [40–43].

An example of such protocol optimization is the use of LPWAN technologies in NTNs. LPWAN technologies are specifically designed for long-range communication between IoT devices while consuming very little power. Integrating LPWAN technology with NTN infrastructures significantly prolongs the operational life of individual IoT devices deployed in remote areas, reduces maintenance frequency due to battery depletion, and ensures continuous data collection and monitoring, all while maintaining minimal energy usage [44]. There are several subcategories of Low-Energy Protocols, and we will explore them in detail in the following sections. Complementing these protocol-level strategies, Table 4.4 summarizes representative energy-efficient signal-processing techniques, outlining their purposes and the benefits they offer in NTN deployments.

Table 4.4 Energy efficiency techniques in signal processing.

Technique	Purpose	Benefits
Error Correction Codes	Maintain signal integrity	Reduces power use, improves reliability
Power-saving Modulation	Minimize power requirement for data transmission	Increases energy efficiency, reduces power waste
Adaptive Communication Protocols	Adjust energy use based on link quality	Optimizes energy consumption, conserves power

Dynamic Power Management (DPM)

These strategies are very important and are considered an integral portion of the NTN power management system. DPM involves the use of software and hardware techniques that dynamically adjust the power state of network components based on current network load and performance requirements. The DPM is used to switch certain parts of a satellite payload to a low-power state during periods of low communication activity, thus conserving energy without impacting the overall performance of the networks [45].

Efficient network routing

Enhanced routing protocols also contribute significantly to energy conservation in NTNs. Efficient routing algorithms ensure that data packets sent from source to destination follow the most energy-efficient path, thus minimizing the power consumed during transmission across networks. The path-finding algorithms, such as Dijkstra's algorithm or Bellman–Ford algorithm, are among the most popular in obtaining the most suitable paths. Suitable route exploration, route selection, and dynamic route updates are the stages of these algorithms. These routes are calculated not only based on the shortest path but also take into account current network conditions and energy profiles of the nodes, optimizing energy use across the network architecture [46,47].

Energy-aware system design

Beyond protocols, the complete design philosophy for NTNs has the potential to embed energy-aware strategies at various levels of abstraction, which range from hardware design to operational and management strategies; this includes the use of materials or components that allow saving energy, or system designs that make more efficient heat dispersal possible, and leveraging software techniques, which reduce computational burdens, thus slashing the energy input required by a processing unit mounted on an NTN platform [48,49].

Implementation of smart sleep schedules

Smart sleep protocols are also employed across IoT and NTNs. These protocols are especially viable for satellite and UAV-operated networks. The smart sleep protocols intelligently determine inactive periods of the devices and put these devices into sleep mode or low-power modes. The sleep mode significantly reduces the power usage of devices and it is only used when full operation is unnecessary. Smart sleep schedules are dynamically adjusted based on real-time data usage patterns and predictions of network demand, optimizing energy utilization [14].

All these techniques, such as low-power protocols, dynamic power management, efficient network routing, energy-conscious system design, and smart sleep schedules, offer an avenue for NTNs to further their sustainability. The sustainability results in improved power savings and the improvement of network component life. Such strategies align with the United Nations' sustainability vision, but also provide a guarantee for NTNs to increase their reliability. The economic impact of sustainability is huge and results in further deployment and extension of services for IoT networks. By emphasizing low-energy software and network management techniques, a critical opportunity is opened to significantly enhance the environmental sustainability of next-generation network technologies, enabling a more resource-efficient future in the realm of global communications.

4.5 Case studies and real-world applications

The transformative impact of NTNs in sustainable IoT applications can be best understood through specific case studies that illustrate their deployment and functionality in various sectors. Each case study showcases the practicability and benefits of NTNs and contextualizes their role in enhancing IoT-driven sustainability.

4.5.1 Environmental monitoring

Rainforest Connection (RFCx)[1] is a San Francisco-based organization that develops a solution that utilizes innovative hardware, NTNs, and cutting-edge software to enable effective wildlife and forest conservation. RFCx built hardware, at the core of their innovative solution, termed "*Guardians*", which is fundamental in detection and data transmission. The Guardian is fabricated from recycled smartphones, making them very viable, cost-effective solutions that are sustainable. Smartphones have been converted to microphones, picking up sounds like chainsaws, gunshots, or even the call of animals in the forest. Guardians are also fitted out with extra hardware components: solar panels that allow the devices to continuously supply power from remote locations using renewable sources when traditional energy sources are not available. These solar panels are very efficient and, therefore, can allow these devices to operate 24/7 without maintenance, even in adverse weather conditions.

It combines NTN-based connectivity solutions, including satellites and HAPs, whichever solution is geographically feasible to facilitate communication in areas bereft of terrestrial network coverage. Guardians use terrestrial networks where available, but, in case of their absence, rely on satellite communication to transmit real-time audio data to the cloud. The NTNs form a critical link from these remote forest monitoring systems to the centralized data processing centers. This makes RFCx reliably transmit the data from locations considered so out of reach through satellites to have continuous monitoring in large-scale areas of the forests. By routine, a forest guard patrols through an area by vehicle or on foot. The work of these guard personnel was thus made smooth and effective since one need not patrol physically on the ground through the areas assigned.

Once the audio reaches the cloud, it is further analyzed on advanced ML and AI algorithms. The algorithms are engineered to identify shots, chainsaw sounds, or other animal distress calls associated with specific illegal logging, poaching, or other harms. The NTN supports this by allowing low-latency data transmission from Guardians to processing centers, so that possible threats can be identified quickly and a rapid response facilitated. It does this by distinguishing between all the natural sounds of the rainforest and those that are artificial, such as chainsaws, gunshots, or vehicles; thus, the alerts given are highly accurate.

The satellite-based communication system also contributes to RFCx being scalable and adaptable. Since NTNs mean an organization could deploy Guardians across diverse regions — from the dense Amazonian rainforests to isolated areas in Africa and Southeast Asia — without the use of any ground-based communications infrastructure, it enables RFCx to reach large swaths of forests while adjusting their systems according to varied environments. Incorporating IoT-enabled Guardians with any NTN creates an ecosystem with a powerful platform for making actionable insights using connectivity and data processing. RFCx works with local authorities, governments, and communities by giving them access to real-time alerts created

[1] https://RFCx.org/.

by the Guardians. This is further facilitated through the use of cloud computing services linked to NTN systems. NTNs fill in the gap in connectivity for conservationists to take quick action and contain deforestation, poaching, and other dangers to biodiversity. This seamless integration of hardware, NTNs, and AI-driven analytics underlines the technological sophistication and environmental impact of the RFCx method. Their work epitomizes how NTNs and IoT could shape the future in the name of global conservation, offering a replicable, sustainable model for the protection of natural ecosystems.

4.5.2 Precision agriculture

CropX[2] is a leading digital agronomy platform that integrates advanced hardware and software solutions to provide comprehensive farm management. Founded in 2013 in New Zealand, the company has expanded its expertise globally, offering tools that aggregate data from various sources to monitor field and crop health effectively. The CropX system comprises several key components like Soil Sensors, which are patented spiral-designed sensors that measure soil moisture, temperature, and electrical conductivity, providing real-time data essential for informed irrigation decisions. Telemetry devices facilitate the wireless data transmission from the sensors to the cloud-based platform, ensuring seamless integration and accessibility. The Actual Evapotranspiration (ETa) sensors of CropX measure and monitor the water use of crops daily in real-time, enabling precise irrigation planning. The rain gauges are precisely the tipping-spoon rain gauges that capture accurate precipitation data, contributing to effective water management strategies.

The combined data collected is synthesized into a specially designed, user-friendly application capable of managing multiple farms and fields from a single account. This holistic approach allows farmers to make data-driven decisions about irrigation, disease control, nutrition monitoring, and effluent management. While CropX primarily utilizes terrestrial IoT devices for data collection and transmission, the integration of NTNs, such as satellite communications, holds the potential for enhancing connectivity, especially in remote agricultural areas. NTNs can provide reliable data transmission where traditional cellular networks are unavailable, ensuring continuous monitoring and management capabilities. The CropX solution is promoting sustainable agricultural practices. By incorporating advanced technology, the company has achieved a 36% reduction in greenhouse gas emissions and a 47% decrease in water usage compared to traditional irrigation methods. These efforts contribute to environmental conservation and support the long-term viability of farming operations. CropX's innovative agronomy platform exemplifies how the integration of IoT technologies can drive sustainable and efficient farming practices. The potential incorporation of NTNs further enhances these capabilities, offering robust solutions for modern agriculture.

2 https://cropx.com/.

4.5.3 Disaster management

The American Red Cross[3] requires no introduction. It has enormously upgraded its response to disasters by introducing advanced technologies that allow it to intervene at the quickest possible time in disaster situations. This technological advancement has been headlined by the Disaster Services Technology (DST) team that installs and operates communication networks in disaster areas. The DST team deploys various equipment, including radios, computer networks, cell phones, tablets, and laptops, and manages to keep connectivity for the Red Cross operations. This integrated arrangement thus provides great coordination among the response teams and timely dissemination of information to people in need. The Red Cross uses Geographic Information Systems (GIS), and UAVs, where the GIS allows analysis and visualization of data on disaster impact, resource allocation, and logistical planning for better decision-making during relief operations. These UAVs provide immediate aerial views of affected areas, thus enabling responders to gauge the extent of damages, locate areas inaccessible, and effectively marshal assistance efforts.

Central to the Red Cross's technological framework is the disaster management system — previously RC View, which was recently replaced by Arc GIS Online[4] developed by Esri — an innovative IT support system that integrates real-time data into a unified platform, offering a comprehensive view of disaster situations. This system enables the Red Cross and its partners to share visual situational awareness, manage disaster operations more effectively, and coordinate responses with greater precision. The organization is also exploring the use of AI to further streamline disaster response. By automating tasks and analyzing data swiftly, AI has the potential to reduce the need for extensive on-ground personnel, accelerate response times, and allow teams to focus on mission-critical activities.

Satellites feature in several different initiatives within the disaster response and preparedness activities of the American Red Cross. Current weather and forecast monitors, including observations, watches, warnings, and radar graphics from satellite imagery, are available through the organization's Map, Weather, and Hazard Catalogs. The Red Cross uses satellite images in its effort to map the most vulnerable communities using a project called Missing Maps[5] for risk reduction planning and assistance. The Red Cross Volunteers examine massive satellite imagery to locate rural hamlets and villages, then ensure humanitarian organizations reach those in need; Humanitarian Organizations at the Red Cross encourage each one to join disaster preparedness through the Humanitarian OpenStreetMap Team (HOT)[6] to utilize satellite imagery for developing newer, more complete and accurate geographic data. These initiatives show the commitment of the Red Cross to taking up space technology in effective disaster management and humanitarian assistance.

[3] https://redcross.org/.
[4] https://www.esri.com/en-us/arcgis/products/arcgis-online/overview.
[5] https://www.missingmaps.org/.
[6] https://www.hotosm.org/.

Through the integration of these advanced technologies and volunteer efforts, the American Red Cross has developed a robust system capable of delivering rapid and effective disaster response. The integration of NTN and IoT technologies empowers organizations like the Red Cross to enhance disaster management through real-time connectivity, rapid response, and improved resource allocation, even in the most remote and underserved regions.

4.6 Technological innovations and future directions

In this section, we delve into the dynamic interfacing between NTNs and the IoT, investigating recent technological innovations and studies developed to improve NTN and IoT networks. We also discuss promising future research directions aimed at further integrating and improving NTN into eco-friendly IoT solutions.

4.6.1 Review of current technologies

Recent technological developments have been gradually improving the integration of NTNs with IoT devices. These improvements are focused on energy optimization and increased robustness in communications between terrestrial IoT networks and their non-terrestrial counterparts. We will discuss a few of these solutions in the following section.

Innovative antenna designs

Antennas in wireless communication play a vital role in both IoT and NTN systems for data transmission and reception using electromagnetic waves. Compact and energy-efficient antennas are used in IoT to support low-power devices, while NTNs require high-gain, directional antennas that maintain reliable communication over long distances or in remote areas [50]. Recent developments in antenna technology represent a significant step forward. Antennas with improved energy efficiency not only reduce the power requirements for maintaining communications but also help enhance signal quality with superior directionality [51]. phased-array antennas, known for their ability to electronically steer the direction of their beam without moving parts, ensure focused communication that dramatically cuts down the energy lost in signal spread [52]. This technology is ideal for dynamic environments, like those encountered in satellite or UAV-based communications, where traditional directional antennas would require constant mechanical adjustments [53].

Advancements in low-power communication protocols

The low-power communication protocol has been a driver of much development in IoT and NTN energy efficiency by enabling device communication with minimum energy consumption. Long-range protocols such as LoRa [54] and Sigfox [55] enable IoT devices to send limited amounts of data over long distances and, hence, are particularly appropriate for NTN applications such as satellite-enabled remote monitoring. LoRaWAN [56] has enabled the realization of bidirectional wireless communication with very low energy consumption, which allows sensors in agricultural fields to communicate information toward NTN-connected gateways. Another example is Bluetooth Low Energy (BLE) [57], which enables short-range IoT applications, such as wearable health devices, to reduce power usage while maintaining reliable connectivity. Another important development in this regard is Narrowband IoT (NB-IoT) [58], which enables huge IoT deployment at low power consumption, allowing devices like smart meters and environmental sensors to function efficiently for several years on a single replacement of batteries. These protocols are particularly advantageous in supporting IoT applications in remote or difficult-to-access areas, because they enable reliable connectivity and long battery life by transmitting small amounts of data over long distances without demanding much power and ensuring sustainability [59].

4.6.2 Future research directions

As we look to the future, several research initiatives are poised to further cement the role of NTNs in sustainable IoT applications. These efforts focus on enhancing network intelligence, reducing environmental impacts, and extending the capabilities and application scopes of NTN systems.

Integration of AI

Future research is increasingly focusing on harnessing AI to enhance the efficiency and functionality of NTNs in IoT applications. AI could lead to smarter data processing algorithms that predict network loads and adjust energy use accordingly. Moreover, AI can enhance decision-making processes within IoT devices, allowing for autonomous operations based on real-time data, which would be particularly useful in dynamic or unpredictable environments [60].

Exploration of advanced materials and technologies

The ongoing fascination with reducing the cost and improving the lifespan of NTNs has led to research into next-generation materials and battery technologies. Innovations such as graphene-based materials for lighter and stronger satellite structures, or cutting-edge energy storage solutions like solid-state batteries, are expected to redefine the operational parameters of NTNs. These advancements could lead to smaller, lighter, and more efficient satellites, UAVs, and IoTs that are cheaper to launch and operate and have a longer service life [61].

Satellite mega-constellations

The concept of deploying large numbers of smaller satellites in carefully planned constellations offers the potential for global coverage and resilient connectivity for IoT devices anywhere on the planet. Research into managing these mega-constellations effectively—and sustainably—concerns both the optimal design for coverage and the development of sustainable practices for dealing with satellite end-of-life scenarios, such as through automated deorbiting systems to prevent space debris [62].

Emerging applications in deep-sea and remote monitoring

The potential for NTNs extends into novel applications such as deep-sea IoT connectivity and real-time environmental monitoring in geographically isolated regions. Developing communication technologies that can withstand harsh underwater environments or provide consistent performance in polar regions represents a leading edge of current research efforts [14].

As NTNs continue to evolve, their role in enabling a connected, sustainable world appears increasingly crucial. The ongoing advancements in antenna technology, communication protocols, and the integration of AI, along with the explorations into new materials and satellite constellation management, underscore a future where NTNs are pivotal in deploying extensive, eco-friendly IoT solutions globally. This progressive trajectory highlights the importance of continued innovation and research in overcoming the existing challenges and unlocking the full potential of NTNs and IoT networks.

4.7 Policy and regulatory considerations

We now delve into the complicated landscape of policy and regulatory considerations that surround the deployment and operation of NTNs. These networks are indeed facing a host of regulatory hurdles that need to be negotiated with care in order to make sure the solutions are effective and compliant. This section debates specific policy recommendations that could facilitate the sustainable development of NTNs.

4.7.1 Regulatory challenges

The implementation of NTNs introduces several regulatory challenges, such as spectrum management, space traffic management, and cross-border coordination. We will discuss each one in the following section.

Spectrum management

One of the most critical regulatory challenges for the NTNs has to do with the efficient management of the radio frequency spectrum, which is extremely limited and hotly contested. Ensuring that NTNs operate seamlessly, causing no interference to the terrestrial networks nor any other types of non-terrestrial communications, is highly important [63]. Regulatory bodies like the International Telecommunication Union spearhead this cause by overseeing how the spectrum will be allocated, among other factors, and building global standards into place. These are measures put in place to avoid conflicts, ensure coexistence, and make the spectrum resource available to all stakeholders equitably [64].

Space traffic management

It is important to cope with the growing need for effective space traffic management while satellites continue to multiply, especially under large-scale constellations already under deployment by different organizations like SpaceX,[7] OneWeb,[8] and many others. This creates great necessities regarding setting and observing robust regulatory frameworks that would sort out a few of the critical aspects involving satellite operations. Key issues also include satellite deorbiting protocols that make sure non-functional or end-of-life satellites are taken out of orbit safely and sustainably to reduce collision risks and further the creation of debris. Besides, collision avoidance can be ensured only if safe orbital operations are maintained, which again requires highly developed tracking systems, reliable communication between satellite operators, and adherence to predefined maneuvering standards.

All these go hand in hand with regulatory frameworks provided by relevant bodies such as the International Telecommunication Union and other national space agencies involved in their development and enforcement to encourage the sustainable use of space. It is critical to their enforcement, not only in terms of mitigating most of the immediate risks that come with space debris, but also to safeguard the usability of this environment as a common heritage. It follows that without an adequate management regime, there will probably be cascading collision events in effect, something often termed Kessler syndrome, where such orbits could well become unavailable to later missions. Rigorous management of space traffic will go hand in glove with sustainable space operation, especially with continuing growth into the satellite-based application, including NTNs and IoT solutions-appropriately looking after the environment for space into the future [65].

Cross-border coordination

The NTNs operate within many different national jurisdictions; any meaningful cross-border coordination must handle these regulatory and operational challenges robustly. Some of the central issues include data sovereignty: many nations require data collected within their borders to be stored, processed, and managed subject to that nation's laws and regulations. It will be particularly hard on NTNs since often they deal with data transferring between satellites, ground stations, and users in different countries. The environmental regulations also have many differences depending on the nation; hence, going into making NTNs compliant with several different standards over sustainability, emissions, and environmental impacts.

Comprehensive international agreements on the operations of NTN make for smooth operations. Organizations such as the International Telecommunication Union (ITU) and regional regulation bodies are very important in making these regulations agree on a set of global standards. These will help in conflict resolution, smoothing out data management policies, and enforcing interoperability across borders as NTNs remain operationally effective and sustainable in their manner [66].

[7] https://www.spacex.com/.
[8] https://oneweb.net/.

4.7.2 Policy recommendations

This section elaborates on some policy recommendations that can effectively address regulatory challenges to NTNs while contributing to their sustainable development. The following recommendations seek to achieve a proper balance between technological development and environmental concerns through innovation and global coordination.

Incentives for green technology

The policy frameworks by governments have to be worked out that would incentivize firms to adopt or develop green technologies within NTNs; these incentives, in the form of tax breaks, grants for research and development, and subsidies, act to encourage them to integrate their NTN infrastructure using energy-efficient technologies. It is expected that incentives or special regulatory treatment will be given to the companies deploying satellites or building renewable energy-powered ground stations using solar, wind, or hybrid systems. Energy-efficient communication protocols, sustainable manufacturing, and advanced recycling for satellite components are also encouraged by the policies. If there is an increased innovation in renewable energy technologies and environmentally friendly design of equipment for NTN, the carbon footprint from NTN can be reduced. These will be instrumental in bringing in an environment that will make technological growth keep up with global sustainability objectives to help NTNs become greener and more efficient in communication [67].

Guidelines for Environmental Impact Assessments (EIAs)

The development of detailed, specific, and standardized guidelines for EIAs concerning NTNs will be very important for the sustainable development of NTNs. The EIAs should be made to cover all the possible environmental impacts of NTN activities, including atmospheric pollution from rocket launches, which would involve the emission of Greenhouse Gases (GHGs) and particulate matter, and impacts on local ecosystems from ground stations, including land use change, noise pollution, and interference with wildlife habitats. EIAs should contain lifecycle analyses of NTN infrastructure manufacturing, operation, and end-of-life phases, which will allow regulators and companies to find the most critical environmental risks. The implementation of mitigation strategies is allowed, for instance, by the adoption of greener propellants, renewable energy used in ground stations, or the design of deorbiting systems that reduce space debris. Incorporating EIAs as a mandatory regulatory requirement will align NTN deployments with global sustainability goals and foster responsible innovation in the satellite and IoT ecosystem [68,69].

Frameworks for international cooperation

Since the coverage and impact of NTNs are global, robust international frameworks will be vital for policy harmonization and effective cross-border collaboration. International frameworks should, therefore, aim at data sharing and joint monitoring of environmental and operational impacts of NTNs to make the stakeholders operating NTNs more transparent and responsible. Unified standards should be set to manage fundamental issues such as radiofrequency spectrum allocation, space debris mitigation, and safe deorbiting of defunct satellites. The same would also apply to internationally collaborative research undertakings, combining resources and expertise in advanced development toward sustainable NTN technology. This could be achieved by jointly working on low-impacting propulsion, optimization of energy efficiency in NTN operations, and elaboration on a global protocol related to space debris. An effective regulatory approach that aligns worldwide should foster NTNs working well while being environmentally friendly, and it creates one path toward sustainability in satellite communication [70].

The regulatory landscape is complex, and the implementation of effective policy frameworks will be crucial to make NTN deployment successful and sustainable. The main regulatory challenges, such as spectrum allocation, space traffic management, and cross-border coordination, require comprehensive and forward-looking strategies. Simultaneously, incentivizing the adoption of green technologies, rigorous environmental impact assessments, and international collaboration in policy recommendations are critical for embedding sustainability into NTN operations. In that way, with early mitigations of such challenges, along with the integration of sustainable practices, NTNs could be designed to handle ever-increasing global demand for connectivity without having to make compromises in environmental responsibility and long-term viability.

4.8 Conclusion

This chapter has examined the role of NTNs in providing a sustainable and greener future for IoT technologies. NTNs are revolutionizing connectivity and playing a critical role in the expansion of IoT access into remote and underserved areas, while promoting environmentally conscious technological deployments. They become major enablers of transformation in IoT, offering connectivity solutions that enable very important applications: environmental monitoring, precision agriculture, disaster management, urban air quality assessment, and maritime surveillance. These use cases strengthen the real impact that NTNs may have on global goals for sustainable development by scaling up our capability to collect, analyze, and act on environmental data. The technological development in NTNs is highly committed to sustainability, ranging The integration of NTNs with IoT technologies does not come without challenges. The regulatory complexities involve spectrum management, space traffic control, and cross-border coordination. High costs and technical difficulties in deploying and maintaining NTNs also stand in the way of widespread adoption. Such challenges require collaborative efforts in engineering, environmental science, information technology, law, and international relations. Only collaborative approaches can overcome these obstacles while ensuring ethical, sustainable, and effective NTN implementations. Such challenges require collaborative efforts in engineering, environmental science, information technology, law, and international relations. It is only through collaborative approaches that these obstacles can be overcome while ensuring ethical, sustainable, and effective NTN implementations. NTNs hold immense promise for changing the paradigm of IoT connectivity and fostering global sustainability. However, their eventual success will depend upon sustained innovation, robust policy frameworks, and international cooperation in accordance with environmental imperatives. NTNs are indeed a technological milestone, but they also form a cornerstone in framing IoT strategies that are ecologically sensitive and globally impactful. The NTNs, supporting various IoT applications while integrating sustainability, have opened ways toward a much more connected, equitable, and efficient future. Further innovation, interdisciplinary collaboration, and policy alignment are all required in the context of realizing full NTN potential and assuring that IoT advances contribute toward a sustainable and prosperous future for generations to come.

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