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6G Digital Transformation for Climate-Resilient Systems: A Survey

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Abstract: Climate change has significantly increased the severity of natural disasters, causing serious issues in telecommunication infrastructures when connectivity is most needed, especially for saving lives. Although current 4G and 5G networks integrate resilience procedures, such as infrastructure reinforcement and temporary network that can be deployed, these solutions may fail under large-scale, or simultaneous climate disruptions. This paper presents a comprehensive survey of a climate-resilient 6G networks, proposing an architectural transition toward proactive, intelligent, and adaptive communication systems. The study reviews key 6G technologies that enable greater resilience during disasters, including Space-Air-Ground Integrated Networks (SAGIN) for flexible aerial and satellite connectivity, Integrated Sensing and Communication (ISAC) for real-time environmental awareness, AI-native self-healing mechanisms for autonomous network recovery, and ambient energy harvesting for sustainable operation beyond traditional power grids. Furthermore, the paper discusses major research challenges, including satellite–terrestrial integration, seamless handover management, and the energy efficiency of AI-Driven network intelligence.

Keywords: 6G Network, AI-Native Networks, Space-Air-Ground Integrated Networks (SAGIN), Integrated Sensing and Communication (ISAC), Climate Change, Disaster Recovery.

INTRODUCTION

Climate change is one of the most widely discussed topics in the world; it has received important attention over the years. The main takeaway is that over the past few decades, the planet has been facing a unique challenge: natural disasters have become progressively frequent and severe in many regions due to climate change. This phenomenon is predicted to increase the appearance of natural hazards, including floods, storms, high windspeeds, and wildfires.

As with other systems, there are notable impacts from these weather events on the telecommunication network, which is especially troublesome as it is most needed for serious emergency rescue response during these calamities [1-3]. In some places, people have lost their lives in floods, and entire areas were cut off from communication because underwater cables were severely damaged, while road access remained unavailable for extended periods [4]. Of course, many other weather-related disasters around the world have had even more devastating impacts [5]. Hurricanes, for example, can destroy up to 90% of cell sites and severely damage internet infrastructure. As a result, the damaged places were left without cable or wireline services for more than a year after the hurricane. Meanwhile, in other areas, wildfires impact the telecommunications infrastructure in different ways by destroying the power grid nourishing cell sites—burning either the power lines, the communication cables, or the base station itself [6]. Climate change is also making winter storms more severe, as a warmer atmosphere holds more moisture, and this moisture ultimately falls as rain, snow, or, in the worst case, freezing rain, which is the leading cause of damage to power lines. Despite the fact that network performance can also be heavily affected by heavy rains, which block up millimeter-wave satellite signals, it is common in disaster cases to experience unusually heavy communications traffic, as everybody wants to check in with relatives and friends [7,8].

Telecommunication networks have become a centric infrastructure for today's digital societies, ensuring economic growth and global connectivity through smart cities, autonomous systems, the Internet of Things (IoT), and low-latency, ultra-reliable communication. As telecommunication networks continue to evolve toward 5G and 6G architectures, they are becoming an important tool for addressing global challenges, particularly environmental sustainability and climate change. Emerging 6G technologies, including energy-efficient solutions based on Reconfigurable Intelligent Surfaces (RIS), AI-driven network management, and advanced smart antenna systems, are expected to further strengthen the role of telecommunications in supporting more sustainable and resilient infrastructures [9-11].

To contribute to this direction, this paper aims to provide a comprehensive overview of climate-resilient 6G networks by offering a structured roadmap either for researchers or network operators. It explores the key technologies and architectural approaches required to develop future communication systems, which will be capable of adapting to environmental challenges while maintaining reliable and efficient connectivity.

The remainder of this review paper is organized as follows: Section 2 discusses existing 4G/5G network architectures and their resilience mechanisms against disasters. Section 3 reviews emerging 6G technologies and architectural solutions aimed at improving network robustness under extreme climate conditions. Section 4 highlights open research challenges and provides concluding remarks.

CURRENT TELECOMMUNICATION FRAMEWORKS (4G/5G) AND DISASTER PRECAUTIONS

The Current Network Architecture and Its Physical Dependencies

The architecture of 4G and 5G principally rely on a centralized, ground-based infrastructure. The radio access network (RAN) uses fixed base stations (eNodeBs and gNodeBs) installed on structures such as building rooftops or concrete poles. These sites connect to the core network through two main systems: the grid that provides power, and the terrestrial backhaul connections (*Figure 1*). Since these networks were designed based on the past climate circumstances, their fixed ground-based structure creates fragilities as climate change increases the intensity of extreme weather calamities [12,13].

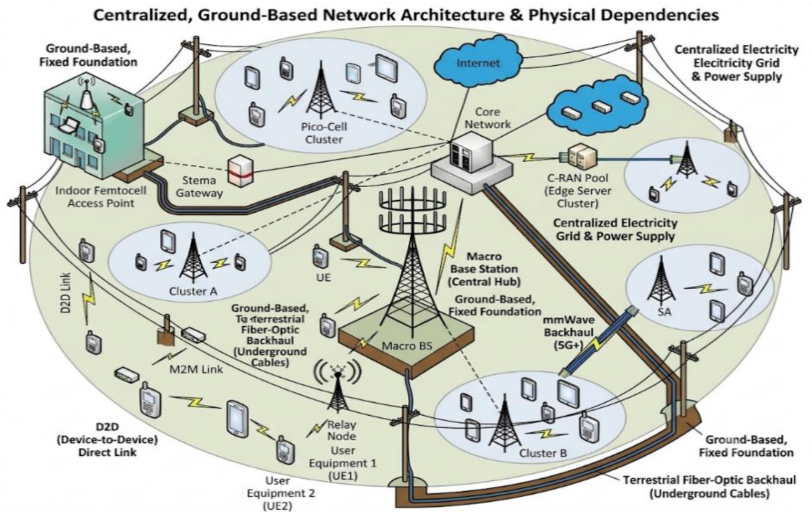

Figure 1: The 5G Infrastructure.

Standard Protection and Design Practices

According to the recommended practices developed by telecommunication operators, diverse strategies are typically used which cover the period before, during, and after an incident [14-16]. These plans of action can be divided into three main phases:

- **Anticipation:** Using historical data and geographical modeling to identify regional risks before weather events occur.
- **Prevention:** This strategy focuses on reducing power cut by improving the resilience of network infrastructure. This is done by deploying multiple fiber routes in different locations, strengthening cell towers against high winds, and relocating critical network equipment away from flood areas.
- **Limiting the Damage:** Protecting equipment from damage, removing nearby plants to reduce wildfire risks, and creating national roaming that allow users to connect to other networks if their main operator becomes unavailable.

Current Disaster Response Strategies and Their Limitations

When critical weather events damage earthly infrastructure, network operators execute scheduled procedures to quickly evaluate the damage, apply temporary solutions, and restore services. However, each solution hits a clear structural breaking point:

Deployable Network Units

- Operators use mobile solutions such as Cells on Wheels (COWs) and Cells on Pallets (COPs), which can be transported by trucks or helicopters (in critical cases) to quickly restore local emergency coverage within a limited area.
- The Breaking Point: As highlighted in the introduction, severe floods, landslides, and wreckage can block road access. If a region is isolated for an important period, heavy

trucks cannot physically reach the disaster zone, leaving operators sharing the limited emergency helicopter transport with civil rescue teams [17].

Backup Power and Alternative Connections

- Base stations are equipped with batteries to maintain fundamental services during short outages. For long outages, operators install transferable diesel generators. In the case when fiber connections are damaged, network equipment can be reconfigured to use other alternatives, such as microwave links or satellite terminals, to maintain the basic communications.
- <u>The Breaking Point:</u> Standard backup batteries support sites for a few hours. Portable generators require manual refueling as frequently as every seven hours. When wide-scale climate disasters knock out the regional power grid for days or even weeks, the manual fueling circuit completely falls down due to blocked roads and concurrent site failures [18].

Software-Defined Slicing

- During major catastrophe, network capacity is often reduced, 4G and 5G utilize software-defined quality of service (QoS) protocols to manage services. Besides that, and to manage resources, current networks use traffic management software to prioritize crucial services, such as emergency calls and messages, while reducing unnecessary activities; this technique is ensured by 5G Standalone (SA) core networks. Operators may also reduce power consumption by turning off some high-power features to extend battery life at cell sites.
- <u>The Breaking Point:</u> Although Software-Defined Networking (SDN) can improve the management of user data traffic, it does not fully prevent overloads in the control plane. When damaged fiber connections are restored or backup power returns after an interruption, a large number of devices may attempt to reconnect and authenticate at the same time. This unexpected increase in signaling traffic can affect the stability of the core network [19,20].

Alternative Backhaul

- When fiber connections are damaged by events such as fallen trees or ground movement, operators can manually reconfigure network equipment to use alternative links, including point-to-point microwave connections or portable low-earth orbit (LEO) satellite terminals.
- <u>The Breaking Point:</u> These alternatives also have weaknesses. Microwave relay stations often depend on local power sources, which may fail during the same disaster, interrupting the connection between sites. LEO satellite terminals also require significant power (around 80W), which can quickly reduce limited battery resources at remote sites. In addition, heavy rain or snow can weaken satellite signals, reducing their effectiveness during severe weather events [21].

6G ARCHITECTURE ENABLERS FOR CLIMATE RESILIENCE

To overcome the limitations of current terrestrial and reactive networks, the transition toward 6G requires a significant shift toward more autonomous and adaptive network architectures. The 6G aims to introduce a new level of network resilience, where communication systems can automatically sense changes, adapt to new conditions, recover from failures, and maintain service continuance during disasters [22-24].

Space-Air-Ground Integrated Networks (SAGIN)

The main structural weakness of existing 4G and 5G networks is their strong dependence on a two-dimensional (2D) terrestrial infrastructure. The 6G architecture aims to address these limitations by extending network connectivity beyond the traditional systems through a three-dimensional (3D) Space-Air-Ground Integrated Network (SAGIN). By combining terrestrial networks (TN) with non-terrestrial (NTN) one, such as satellites and aerial platforms, SAGIN provides additional layers of connectivity and alternative communication paths. This approach improves network resilience by reducing dependence on vulnerable ground infrastructure and enabling connectivity to be maintained during large-scale disruptions [25-29]. SAGIN provides connectivity through three complementary layers (*Figure 2*).

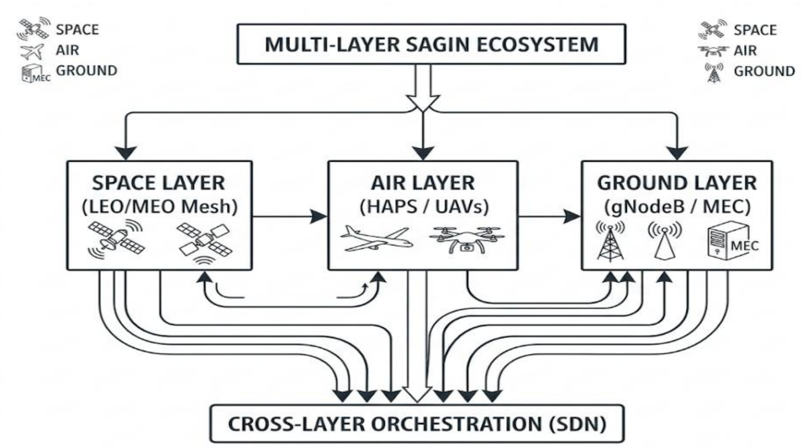

Figure 2: Multi SAGIN Layers.

The Space Layer

The space layer consists mainly of Low-Earth Orbit (LEO) satellite constellations operating at altitudes between 500 km and 1,500 km, supported by Medium-Earth Orbit (MEO) satellites. These satellites act as communication nodes which are located atop of the area affected by disaster, this position is allowing data to be transmitted without depending on damaged infrastructure located in the earth. Through Inter-Satellite Laser Links (ISLs), satellites can create a dynamic network in space that allows to data to travel between satellites before being connected back to Earth through available ground stations, which can maintain connectivity even when terrestrial infrastructure is unavailable.

The Air Layer

The aerial layer provides an interface between satellites and ground networks. It uses High-Altitude Platform Stations (HAPS), such as solar-powered aircraft and autonomous airships, which is operating in the stratosphere at around 20 km altitude. These platforms can provide long-range regional coverage and support communication services in the areas that are affected by disasters. In addition, Unmanned Aerial Vehicles (UAVs) can be quickly deployed to specific locations as temporary airborne base stations, restoring local connectivity when needed.

The Ground Layer

The ground layer includes the odd terrestrial infrastructure, such as active macro base stations (gNodeBs), small cells, edge computing facilities (including the Multi access Edge Computing, MEC), and user equipment (UE), either mobile devices or emergency communication vehicles.

Global Switching and Cross-Layer Network Management

Under normal conditions, the air and space layers support terrestrial networks by improving coverage, reducing congestion, and providing connectivity. When a disruption, caused by climate, is detected, such as a damaged fiber backhaul connection, the network can automatically adjust its communication paths.

Using technologies such as Segment Routing over IPv6 (SRv6) and Software-Defined Networking (SDN), the network can quickly redirect traffic away from damaged infrastructure and use alternative connections through aerial or satellite links. Since these non-terrestrial components are integrated directly into the 6G architecture, the transition between network layers can take place fluidly without interrupting active connections [30,31].

Integrated Sensing and Communication (ISAC) for Environmental Awareness

Beyond providing alternative communication paths through satellites and aerial platforms, future networks must also be able to understand and respond to environmental changes automatically [32]. Current management approaches of disaster often depend on external weather sensors, satellite images, or human reports. However, during severe climate events, these systems may become inaccurate due to damage or limited visibility caused by extreme weather conditions [33]. The future 6G architecture addresses this limitation by including Integrate Sensing and Communication (ISAC) directly into the physical and MAC layers of the Radio Access Network (RAN). ISAC combines current wireless communication with sensing capabilities, which is allowing to the same network infrastructure to exchange data while also monitoring the nearby environment. By using higher frequency bands, such as millimeter-wave (mm Wave) and sub-terahertz (sub-THz) frequencies, 6G signals can act as electromagnetic sensors that is able to detect and analyze physical changes around the network [34]. As a result, base stations and connected devices can operate as a distributed sensing system that provides real-time information about environmental conditions. During emergencies, ISAC provides three main skills:

- **The Danger Detection:** The network can identify changes in the surrounding environment, by analyzing reflected wireless signals, using measurements such as signal arrival time, direction, and frequency changes. When combined with machine learning at the edge, this information can help create real-time maps of disaster areas. For example, the network can detect the spread of floods by identifying changes in water reflection patterns and can support wildfire monitoring by tracking smoke movement and fire progression, even when traditional optical systems are limited.
- **The Network Diagnostics:** The sub-THz signals allow 6G networks to monitor the nearby infrastructure and their own equipment. Base stations could detect the damaged structures, the blocked roads, or even the changes in antenna positioning which are caused by extreme weather conditions. This information can be used to automatically adjust network operations and can also support emergency response teams with updated situational information.
- **The Communication Adaptation:** High-frequency signals, such as the mm Wave, used in the next generation are sensitive to weather conditions such as heavy rain, snow, and the atmospheric changes. ISAC allows the network to measure these effects and use this information to adapt communication parameters before that the service quality is affected. For example, the network can adjust antenna settings, modify transmission parameters, or transmit critical traffic using lower-frequency bands that are more resistant to signal loss.

Under these competencies, ISAC transforms the 6G network from a simple communication system into an intelligent platform capable of sensing, adapting, and responding to climate issues in real time.

Autonomous Self-Healing and Energy-Efficient Networks

A major limitation of current 4G and 5G networks is depending on human teams to respond to network failures in dangerous environments. To achieve greater climate resilience, 6G introduces an AI-Native Zero-Touch Network (ZTN) management approach combined with ambient energy harvesting technologies, allowing networks to operate more independently during extreme events [35,36].

Autonomous Self-Healing Networks

6G integrates artificial intelligence directly into network management processes. Through a Zero-Touch Network (ZTN) framework, supported by Self-Organizing Networks (SON) and advanced data analytics, the network can continuously monitor conditions, identify problems, and automatically take corrective actions using a closed-loop approach based on the MAPE-K (Monitor, Analyze, Plan, Execute, Knowledge) model [37,38].

Predictive Failure Detection:

By combining real-time information from Integrated Sensing and Communication (ISAC) with weather data and historical climate patterns, AI models can predict potential failures before they happen. This allows the network to move virtualized network functions (VNFs) and active user connections away from vulnerable sites and transfer them to safer edge computing locations before an outage happens.

Autonomous Routing and Device-to-Device Communication (D2D):

When an important number of base stations fail during a disaster, the AI-driven control system can automatically reorganize network connectivity. It can enable nearby user devices to create temporary Device-to-Device (D2D) network, which is allowing smartphones and IoT devices to relay information across affected areas. This procedure is active until communication reaches an active ground station or a SAGIN-based aerial or satellite connection.

Maintaining Network Stability:

During disasters, many disconnected devices may attempt to reconnect at the same time, creating excessive signaling traffic that can overload the network. 6G AI-based management can prevent this by using intelligent traffic control and network slicing. This helps critical services, such as emergency communications, to be assigned.

Energy-Efficient Networks

The future generation introduce energy harvesting directly into network infrastructure. Instead of depending only on traditional battery backups, which can last only a few hours during power failures, future 6G base stations and IoT devices can collect energy from their surrounding environment. These systems can combine multiple energy sources, which can be solar power, small-scale wind energy, or radio frequency (RF) energy harvesting [40]. AI-based energy management systems can automatically reduce energy consumption by combining local energy generation, intelligent power management, and battery optimization [39].

DISCUSSION

Future research on 6G networks is focusing on the development of robust, scalable, and energy-aware systems, which is capable of operating under extreme and unpredictable climate changes. The key for that is that research should move beyond conception studies toward experimental validation, either the realistic simulation environments or the economic evaluations. Despite the significant advancements introduced by emerging 6G architectural concepts, several open challenges remain in achieving fully autonomous and climate resilient networks. The key issues include:

- The hands-on deployment of the non-terrestrial networks, and the interoperability between terrestrial and non-terrestrial sections.
- The complexity of ensuring stable AI-driven control in highly dynamic and partially disconnected network environments.

- The standardization of cross-layer orchestration mechanisms, remains an ongoing research concern.

CONCLUSIONS

This paper has examined the limitations of current 4G and 5G networks under climate changes and highlighted how the 6G architecture addresses these challenges through integrated non-terrestrial connectivity, AI-driven automation, and adaptive energy systems. However, particular attention is required for improving the resilience of AI-native network management, enhancing the accuracy and reliability of Integrated Sensing and Communication (ISAC) in real-world disaster scenarios, and optimizing the architectures for low-latency connectivity. Furthermore, advancements in distributed intelligence and energy-efficient hardware design will be essential to support long-term autonomous operation.

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