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Emerging Protocol and Architecture Requirements for 6G-Enabled Wireless Sensor Technologies in Space-Air-Ground Integrated Networks (SAGIN)

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***Abstract*— The convergence of space, air, and ground networks into a unified Space-Air-Ground Integrated Network (SAGIN) is a promising paradigm for enabling ubiquitous, low-latency, and reliable connectivity in the era of 6G. Wireless Sensor Networks (WSNs), empowered by 6G technologies, play a vital role in mission-critical applications such as disaster management, intelligent transportation, and global IoT services. This paper discusses emerging requirements in protocol design and network architecture for 6G-enabled WSNs within SAGIN.**

Specifically, we focus on (i) edge-enabled data aggregation and redundancy elimination, (ii) machine learning (ML)-driven security and intrusion detection, (iii) multi-modal communication integrating RF, VLC, and satellite links, (iv) support for Quality of Service (QoS) and Quality of Experience (QoE), (v) deployment cost and scalability of VLC and satellite infrastructures, and (vi) the need for global standards to harmonize SAGIN protocols. Insights from recent research are integrated to highlight challenges and opportunities toward achieving intelligent, cost-effective, and secure SAGIN ecosystems.

***Index Terms*— SAGIN, 6G, Wireless Sensor Networks, Data Aggregation, Machine Learning Security, Multi-modal Communication, QoS, Standardization.**

I. Introduction

The proliferation of Internet of Things (IoT) devices, cou pled with emerging applications such as autonomous driving, smart cities, and industrial IoT, demands network architectures that extend beyond terrestrial infrastructure.

While 5G has introduced enhanced capabilities, its limitations in coverage, reliability, and scalability have motivated the development of 6G networks. Space-Air-Ground Integrated Networks (SA GINs) integrate satellites, aerial platforms, and terrestrial nodes to provide global, flexible, and resilient communication infrastructures [1][4].

In this context, Wireless Sensor Networks (WSNs) enhanced by 6G capabilities must adapt their protocols and architectures to meet stringent latency, reliability, and scalability requirements.

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II. SYSTEM OVERVIEW OF SAGIN

SAGIN is composed of three interconnected layers: (i) space networks (satellites in LEO, MEO, and GEO orbits), (ii) aerial networks (UAVs, balloons, and high-altitude platforms), and (iii) terrestrial networks (cellular, WLANs, and sensor networks) [3][4]. The integration of these layers enables seamless connectivity with heterogeneous characteristics. Recent advances in software-defined networking (SDN), network function virtualization (NFV), and machine learning (ML) allow for efficient orchestration of SAGIN resources [6]. In particular, 6G-enabled WSNs within SAGIN must leverage edge computing and AI-driven decision-making for performance optimization.

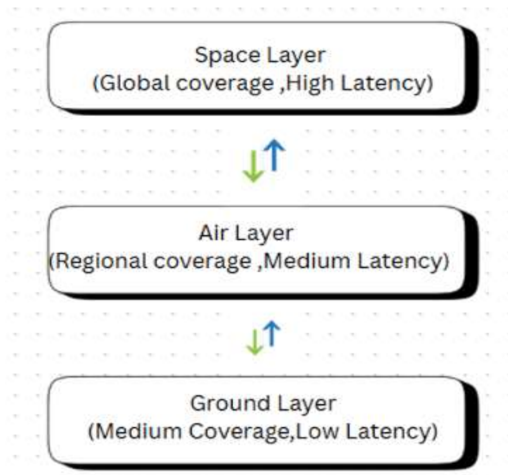

Fig 1 Showing Proposed Architecture of SAGIN Network

From the most significant new study areas and revolutionary technologies that will alter our understanding of society, lifestyle, and companies. As 5G continues its development and deployment, the imperative for next-generation mobile communication technologies becomes increasingly evident, with 6G poised to exert an even more profound impact on the global economy [1]. The distinct requirements for 6G, which diverge significantly from those of 5G, necessitate the exploration of novel architectural paradigms and technological advancements to support unprecedented applications and services. For instance, 6G is anticipated to be a cornerstone for commercial enterprises, healthcare, and advanced automotive systems, integrating artificial intelligence and impacting numerous academic, professional, and business sectors [2]. Consequently, a robust body of research has already begun to ad dress the multifaceted factors influencing 6G development and its potential applications. A paradigm shift is underway where current technologies are being fundamentally re-envisioned and reconstructed in the era of 6G connectivity, profoundly reshaping daily life, societal structures, and industrial operations. The distinct requirements for 6G, which diverge significantly from those of 5G, necessitate the exploration of novel architectural paradigms and technological advancements to support unprecedented applications and services.

TABLE I: LAYERS OF SAGIN

Layer	Coverage	Latency	Advantages	Limitations
Space (Satellites: LEO/MEO/GEO)	High (40–270 ms)Global cover age	bypass ground failures Air (UAVs, Bal loons, HAPS) Regional Medium (tens of ms)	Flexible deployment, wide cover age cost efficient	High deployment cost long propagation delay Limited energy, unstable links
Air (UAVs, Bal loons, HAPS)	Regional Medium (tens of ms)	Flexible deployment, wide cover age cost efficient	High deployment cost long propagation delay	Limited energy, unstable links
Ground (Cellular, WLAN, WSNs)	Local Low (10 ms)	High through put	Mature infrastructure	Limited coverage, vulnerable to disaster

For instance, 6G is anticipated to be a cornerstone for commercial enterprises, healthcare, and advanced automotive systems, integrating artificial intelligence and impacting numerous academic, professional, and business sectors [2]. Consequently, a robust body of research has already begun to address the multifaceted factors influencing 6G development and its potential applications. A paradigm shift is underway where current technologies are being fundamentally re-envisioned and reconstructed in the era of 6G connectivity, profoundly reshaping daily life, societal structures, and industrial operations. Paper[11] by WaelHosny Fouad Aly presents the Controller Adaptive Load Balancing (CALB) model to enhance fault tolerance in Software-Defined Networks (SDNs). Addressing the issue of controller failures, CALB utilizes a novel algorithm within a master-slave controller architecture to dynamically distribute load. The model's effectiveness was validated through Mininet simulations with Floodlight, where its performance was mea sured by throughput and response time in scenarios involving two and three slave controllers. The primary contribution is a new load-balancing algorithm that adjusts to the real-time load of each slave controller. Integrating machine learning into Software-Defined Networking (SDN) provides a powerful solution for intelligent load balancing. Unlike conventional methods that rely on fixed rules, this approach uses ML algorithms to analyze a wide range of network metrics—such as latency, bandwidth, and utilization. Based on this analysis, the SDN controller dynamically re-routes traffic flows in real time. This proactive adaptation ensures optimal resource uti -lization and prevents the formation of congestion bottlenecks, thereby maximizing overall network performance. These are key findings of Aashish [10] As per techniques stated by Ayeh Mahjoubi Load Balancing and Fault Tolerance (LBFT) is a core strategy for building resilient and high-performing Software-Defined Networks (SDN). It works by distributing the workload across multiple controllers to prevent bottlenecks (load balancing) while also ensuring the system can automatically recover from failures to maintain service (fault tolerance). [9]

- Load Balancing: LBFT ensures network efficiency by distributing traffic evenly. This prevents any single controller from becoming a choke point, leading to faster and more responsive network performance.
- Fault Tolerance: LBFT guarantees network reliability by providing redundancy. If a controller fails, a backup can instantly take over, preventing service outages and keeping the network running smoothly.By combining these two principles, LBFT creates a robust and scalable network architecture that is both highly efficient and reliable. New method proposed by Xiaodong Ren[8] approach leverages Software-Defined Networking (SDN) to enhance the scalability and resilience of a multi-controller environment. To address the critical issue of controller failures, it introduces an adaptive recovery mechanism that automatically redistributes the network load from a failed or underperforming controller to other suitable ones. This mechanism uses a Support Vector Machine (SVM) to classify and select the best recovery controllers.

The selection is based on a recovery pool defined by three vital parameters:

- Reliability: The dependability of the controller.
- Energy: The energy consumption of the controller
- Latency: The communication delay.

A utility matrix is computed from these parameters to guide the SVM in choosing the most appropriate controllers to balance the load and maintain network performance. In a FinTech environment proposed in research article , the desired network characteristics are low latency, high bandwidth, high bit rate, and negligible congestion [8] The amount of 6G connections is ready to go on to a major restructuring and redefining existing technologies. These technological changes are expected to affect many aspects of life, society and industry. In particular, the Internet of Things (IoT) undergoes conceptual transformtion and develops from everything (IOE) to the Internet, thus facilitating the development of a wide range of pioneering technologies. One of the most important innovations made possible by the IOE is intelligent cities, advanced healthcare systems (intelligent wearables and the Internet of Medical In ternet). This includes all industrial Internet (IIOE), intelligent power grids and autonomous robots. The IOE is expected to play a central role in the design of 6G communication environments. Moreover, 6G technology is expected to deliver enhanced security, confidentiality, and privacy, ensuring robust protection for users and data. In addition, 6G is envisioned to operate in a three-dimensional framework encompassing the time, space, and frequency dimensions, thus facilitating more efficient and versatile communication capabilities. The transi tion from ”smart” to ”intelligent” in the context of 6G will be driven by the inherent intelligence of the Internet of Everything (IoE). Consequently, devices that were previously considered ”smart” will evolve into truly intelligent entities, with many of these devices powered by advanced AI capabilities. These intelligent devices, regardless of their size, will possess the ability to anticipate, make decisions, and communicate with other intelligent devices based on shared experiences. In this regard, 6G communication technology, in conjunction with artificial intelligence, is facilitating a paradigm shift from the traditional smart era to a new intelligent era. The 6G technol ogy is set to redefine user-centric communication by ensuring both high Quality of Experience (QoE) and high Quality of Service (QoS). This will be achieved through the integration of advanced technologies, such as holographic communication, virtual and augmented reality, five-sense communication, and the tactile Internet. Enhancing QoE is expected to drive transformative improvements across various sectors, including intelligent devices, autonomous vehicles, drones, and ambu lances.[2] To realize these advancements, 6G must effectively implement all the necessary characteristics required to deliver a superior QoE. Furthermore, the concept of Quality Life (QoL) in healthcare will be significantly enhanced through 6G technology, improving lifestyle through optimized QoS and QoE. Key applications contributing to QoL include intelligent ambulance services, hospital-to-home (H2H) systems, tele surgery, precision medicine, intelligent accident detection, and remote health monitoring, particularly for elderly patients. These innovations collectively aim to elevate the quality of life through the capabilities of 6G communication technologies.

TABLE II: SUMMARY OF TECHNIQUES OUTCOME IN SDN

Author/paper	Focus Area	Technique/Model	Key contribution	Findings
Wael Hosny Fouad Aly [11]	Fault tolerance in SDN	Controller Adaptive Load Balancing (CALB) with master-slave controller architecture)	Novel algorithm for dynamic load distribution among slave controllers	Validated on Mininet and Floodlight; improved throughput and response time
Aashish [10]	Intelligent load balancing Fault	Machine Learningenabled SDN load balancing	Uses ML algorithms to analyze metrics (latency, bandwidth, utilization) and adaptively re-route flows	Prevents congestion, maximizes resource utilization, improves overall network performance ensures no single controller
Ayeh Mahjoubi [9]	tolerance and efficiency	Load Balancing and Fault Tolerance (LBFT) strategy	Combines traffic distribution (load balancing) and redundancy (fault tolerance)	Enhances resilience and responsiveness bottleneck and guarantees service continuity
Xiaodong Ren [8]	Scalability and resilience in SDN	Adaptive recovery with Support Vector Machine (SVM)	Classifies/selects best recovery controllers based on reliability, energy, and latency	Provides robust recovery mechanism, auto-redistribution of load, improves fault tolerance in multi-controller setups

III. KEY RESEARCH DIRECTIONS

- Data Aggregation and Redundancy Elimination at the Edge Edge-enabled data aggregation helps reduce redundant sensor transmissions, conserving bandwidth and energy while ensuring reliable information delivery [1]. Techniques include clustering, in-network processing, and adaptive filtering to optimize transmission efficiency in SAGIN-enabled IoT environments.
- Security Enhancements through ML-enabled Intrusion Detection Security is a major concern due to the heterogeneous and distributed nature of SAGIN. Machine learning and deep learning methods can enable anomaly detection, intrusion prevention, and adaptive security models in dynamic environments [12][15]. ML-based IDS can handle evolving cyber threats by learning from real-time data streams in space, air, and ground segments.

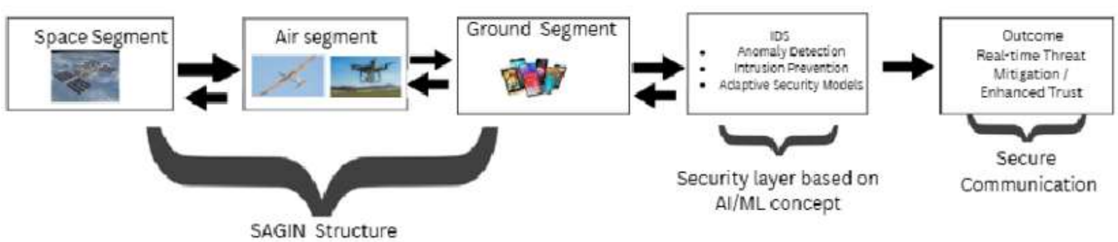

Fig 2 Intrusion handling in SAGIN network

- Multi-Modal Communication Integrating RF, VLC, and Satellite Links To ensure high-capacity and low-latency communication, SAGIN leverages multiple modalities, including RF, visible light communication (VLC), and satellite backhauls [13]. VLC offers high bandwidth and security for short-range communi cation, while RF and satellite links extend coverage. Multi modal integration improves reliability and flexibility, enabling mission-critical applications.
- Support for QoS and QoE in Mission-Critical Applications SAGIN must meet stringent QoS metrics such as latency, throughput, and reliability, along with user-centric QoE requirements [2] [5]. Mechanisms like dynamic resource allocation, slice and AI-driven traffic management are essential for mission-critical domains such as disaster management, defense, and intelligent transportation systems.

- Deployment Cost and Scalability of VLC and Satellite Links While VLC and satellite technologies improve coverage and bandwidth, they pose cost and scalability challenges [3] [5]. Hybrid deployment strategies, cooperative satellite constellations, and resource virtualization approaches are needed to balance cost with performance. Establishing Global Standards for 6G-Enabled WSN Protocols Interoperability and standardization are critical for the global adoption of SAGIN-enabled WSNs. International bodies such as ITU, IEEE, and 3GPP are working to harmonize non-terrestrial and terrestrial protocols [6]. Unified standards will enable seamless integration, cross border services, and consistent QoS delivery in heterogeneous environments. IV.

IV. OPEN CHALLENGES AND FUTURE DIRECTIONS

Despite progress, several challenges remain to be overcome in realizing intelligent SAGIN architectures for WSNs. These include interoperability across heterogeneous systems, minimizing latency in dynamic environments, AI model generalization across diverse contexts, and the economic feasibility of large-scale VLC and satellite deployments [4] [6]. Future research should focus on distributed intelligence, flexible spec trum management, and cross-domain security frameworks.

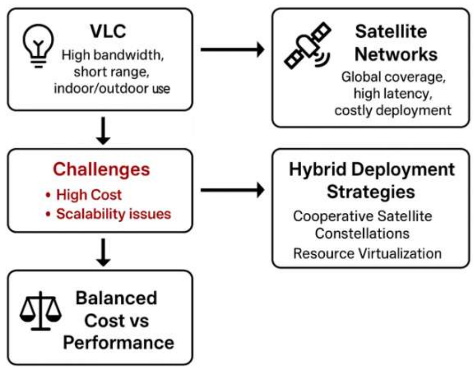

Fig 3 Challenges perspective in SAGIN Network

V. CONCLUSION

This paper outlined the emerging requirements for 6G enabled WSNs within SAGIN, emphasizing protocol and architectural considerations. Key aspects include edge-based data aggregation, ML-driven security, multimodal communication, QoS /QoE guarantees, deployment scalability, and global standardization. Addressing these issues will be essential to realize secure, intelligent and globally interoperable SAGIN ecosystems.

DECLARATION

The above work is free from any conflict of interest.

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