Multi-Microgrid: Advancing Smart Grids through Hybrid IoT Architecture for Efficient Energy Management

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***Abstract*—In the current landscape, Smart Grids (SGs) grapple with critical challenges, notably their reliance on centralized networks and the absence of microgrid system integration. The concept of a multi-microgrid solution emerges as an approach that interconnects and orchestrates multiple microgrids, enhancing the electrical system's resilience, scalability, and capacity to integrate distributed renewable energy sources, enabling Demand-Side Management (DSM) for a more efficient and secure network. This study introduces a novel hybrid Internet of Things (IoT) architecture employing LoRaWAN and LoRaMESH to address these challenges. This approach, operating within a decentralized multi-microgrid framework, reduces message transmission time by over 50%, demonstrating its efficacy and relevance while streamlining communication between Smart Meters (SMs) and the Electric Power Company (EPC), ultimately fostering the adoption of DSM services by consumers and representing a transformative solution for the future of SGs.**

***Index Terms*—smart grid, multi-microgrid, internet of things, demand side management, Lora, LoRaWAN, LoRaMESH**

I. Introduction

Smart Grids (SGs) represent an evolution of the traditional electrical system, integrating advanced communication and monitoring technologies to enhance energy efficiency, reliability, and renewable energy source integration. However, SGs face significant challenges, particularly a single centralized network dependency, resulting in vulnerabilities and inflexibility. Additionally, the integration of diverse microgrid systems, with independent characteristics and demands, complicates the situation. To address these issues, the multi-microgrid approach emerges as a solution, facilitating interconnection and coordination among microgrids to enhance system resilience, scalability, and adaptability. This approach optimizes network efficiency, strengthens energy security, and supports renewable energy integration. Microgrids are self-sustaining energy systems that utilize local resources like solar panels, wind turbines, batteries, and generators to supply power to communities, campuses, and industries. The multi-microgrid concept involves interconnecting and coordinating these microgrids, enabling decentralized energy and information exchange, thus improving flexibility, efficiency, and resiliency. It promotes clean energy adoption, reduces emissions, and plays a crucial role in Demand-Side Energy Management (DSM), enhancing sustainable energy management and reducing dependence on traditional grids.

This work proposes a hybrid IoT architecture utilizing LoRaWAN and LoRaMESH for demand-side energy management within the multi-microgrid framework, based on the HyDSMaaS architecture [1]. This approach enhances the flexibility and resilience of SGs, enabling efficient IoT network communication that interconnects and coordinates multi-microgrids in a decentralized manner. Successful implementation with Radioenge LoRa modules demonstrated reduced message transmission times compared to conventional SG networks, validating its efficacy in addressing current SG challenges. Key challenges encompassed the integration and coordination of diverse microgrids, each with unique characteristics and demands, along with the imperative of reducing message transmission time and ensuring network efficiency. The hybrid IoT architecture employing LoRaWAN and LoRaMESH technologies, supported by Radioenge LoRa modules, successfully addressed these challenges. This technological advancement enhances power management efficiency, marking a significant milestone in the smart electricity grids domain. The paper's structure includes an overview of the current state of the art and this work (Section II), the advancing Smart Grids through Hybrid IoT Architecture for Efficient Energy Management implementation (Section III), results discussion (Section IV), and conclusions and future directions (Section V).

II. Overview

Traditional Smart Grids (SGs) integrate photovoltaic systems and energy storage, converting sunlight into electricity for grid injection or local consumption [2]. In the digitalized SG landscape, cybersecurity is critical due to vulnerabilities in infrastructure and control systems, necessitating robust measures such as protection of communication systems, continuous threat monitoring, authentication, data encryption, risk management, and incident recovery [3]. Additionally, Artificial Intelligence (AI) enhances SG efficiency, reliability, and sustainability across areas like energy demand forecasting, power flow optimization, fault detection, and predictive maintenance [4]. Modernizing existing electrical infrastructure to meet Smart Grid (SG) requirements, encompassing meter upgrades, distribution equipment enhancements, and the integration of communication and monitoring technologies, presents deployment challenges [5]. However, SGs offer substantial benefits, including improved energy efficiency, reduced losses, increased renewable energy integration, enhanced grid flexibility, and advanced consumer energy management.

The Internet of Things (IoT) plays a crucial role in elevating modern SGs by providing interconnectivity for enhanced efficiency, reliability, and sustainability, addressing challenges such as cybersecurity, data privacy, interoperability, scalability, and data management [6]. Notable IoT applications in SGs include Smart Meters, long-range networks (LoRa) for distributed sensors and actuators, Energy Management systems, Electric vehicles, and Charging Infrastructure. Microgrids, as autonomous energy systems, operate independently or alongside the main power grid, featuring distributed energy sources and advanced energy management facilitated by Artificial Intelligence (AI) techniques, optimizing consumption, maximizing renewable energy utilization, and ensuring traditional SG stability [7], [8]. Demand Side Management (DSM) optimizes electricity consumption, especially within microgrids, by using sensors, smart devices, and AI algorithms to balance energy supply and demand [9]. In multi-microgrid setups linked to a citywide grid, AI analyzes real-time data to coordinate energy sharing, load balancing, and system resilience, maximizing efficiency and resource allocation [10]. Challenges include communication, data standards, security, privacy, and timing, necessitating robust solutions. This work also introduces a hybrid IoT architecture with LoRaWAN and LoRaMESH to enhance conventional SGs' communication infrastructure [11].

III. Advancing Smart Grids through Hybrid IoT Architecture for Efficient Energy Management implementation

The work followed this structure: first, a microgrid model was proposed, where each microgrid consists of houses with their energy generation and automation sensor networks, as shown in Figure 1. This allows microgrids to operate independently and disconnect from the main grid as isolated consumers. The microgrid concept was then scaled up to the multi-microgrid level, considering multiple microgrids within a city connected to the main grid. Various services executable in this infrastructure were introduced, and an IoT architecture was implemented using a hybrid approach of LoRaWAN and LoRaMESH networks to enhance scalability and robustness in the proposed scenario. Subsequent sections will explore packet types and adaptation strategies for microgrids in the network.

The proposed multi-microgrid network consists of interconnected microgrids, representing houses or small communities equipped with local energy generation capabilities, allowing autonomous operation and the flexibility to disconnect from the main electrical grid as needed. Advanced IoT technologies

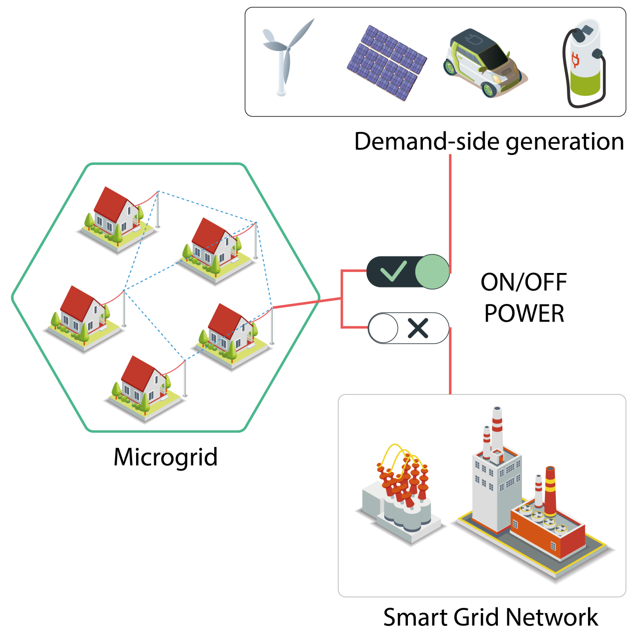

Fig. 1. Microgrid contextualization.

facilitate efficient communication and network management, enhancing resilience, energy efficiency, and adaptability within the electrical system. This multi-microgrid framework employs a hybrid communication infrastructure, utilizing LoRaWAN and LoRaMESH technologies to establish connections between microgrids, Data Aggregation Points (DAPs), and Concentrators (CONs). LoRaWAN serves for long-range communication, supported by Radioenge modules integrated with Arduino boards that function as LoRaWAN gateways, ensuring seamless connectivity across the multi-microgrid network. Concurrently, LoRaMESH operates within each microgrid, enabling direct device-to-device communication, ensuring scalability and network robustness. The system also incorporates a Meter Data Management Service (MDMS) optimizing energy consumption through strategies such as dynamic pricing, demand response programs, and energy-saving recommendations, empowering consumers to engage in sustainable energy management practices.

The implementation, depicted in Figure 2, employed Radioenge modules compliant with Brazilian regulations and Arduino boards, ensuring a reliable solution for the microgrid's communication needs within the Brazilian context. By utilizing both LoRaMESH and LoRaWAN technologies, the microgrid system achieves efficient and secure communication, enabling real-time data exchange, control, and coordination among components such as CON, DAP, and microgrids. In the scenario, three packet models were developed to accommodate varying communication conditions, as shown in Figure 3. The first model utilizes a complete 60-byte packet, optimized for lower Spread Factor (SF) configurations with higher bandwidth and reduced Time on Air (ToA) for faster transmission.

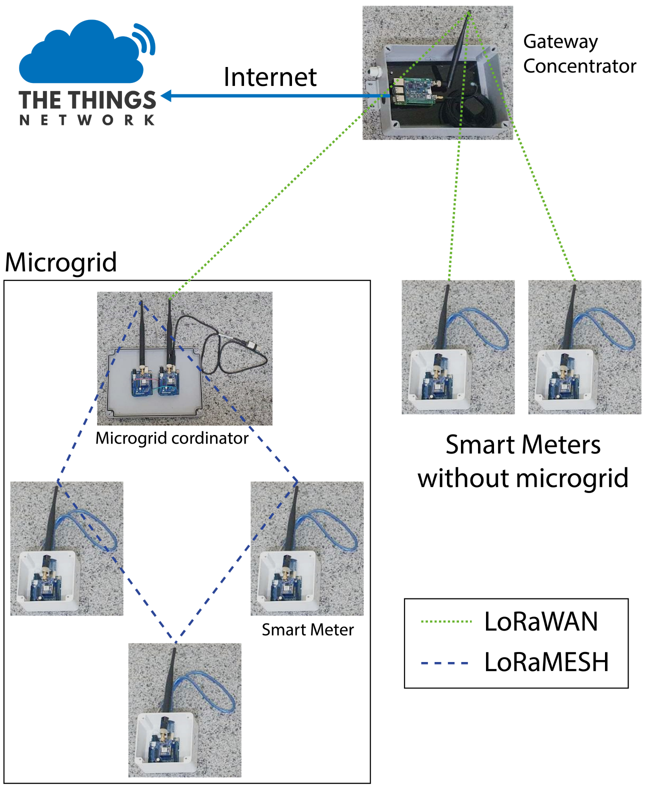

Fig. 2. LoRaWAN and LoRaMESH implementation.

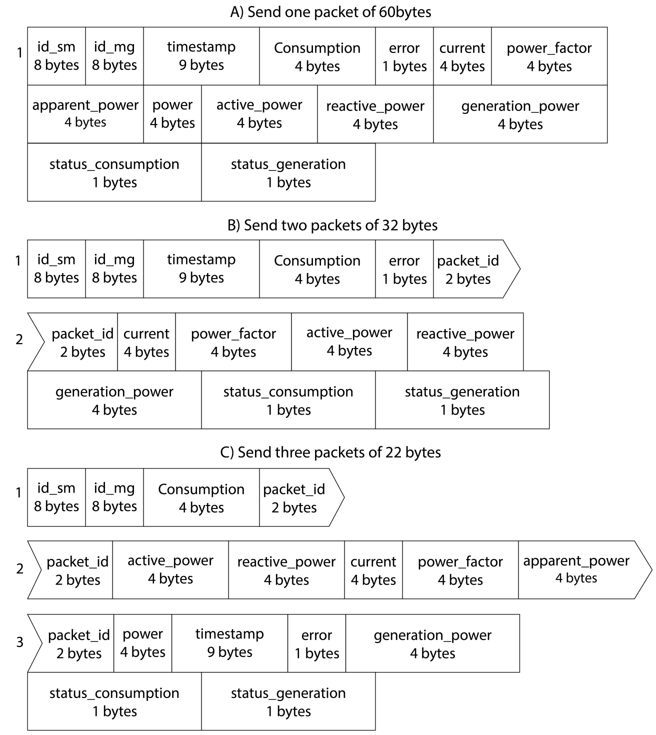

Fig. 3. Packet data organization.

The subsequent models divide the complete packet into smaller segments to enhance transmission in high SF settings with limited bandwidth, with the second model employing two 32-byte packets and the third model using three 22-byte packets. These packet models address specific communication system configuration needs, adapting data transmission to ensure efficient and reliable communication within the proposed microgrid infrastructure.

IV. Results and Discussions

This study successfully implemented and tested the proposed hybrid IoT architecture, multi-microgrid, in real-world environments, encompassing urban, suburban, and rural settings, with varying data packet sizes, offering insights for Smart Grids (SGs). The analysis focused on the relationship between airtime and distance, revealing findings. Urban areas exhibited the highest airtime due to obstructions from tall buildings and high population density, while rural environments had the lowest airtime, benefiting from a more open field of view. The analysis highlighted a substantial airtime disparity between the SG network and the multi-microgrid's communication infrastructure, primarily due to the reduced number of nodes in the microgrids and the hybrid network combining LoRaMESH and LoRaWAN technologies, resulting in significantly shorter on-air times in the multi-microgrid.

In Figure 4, is the result of the distance by ToA in the Urban, Suburban and Rural scenarios, where the results are close, but in the urban scenario it takes longer, due to the number of barriers, and less in the rural scenario, with a difference of up to 5000 seconds. In figure 5 visually demonstrates that the multi-microgrid achieved approximately a 50% reduction in airtime within distances of 800 to 1500 meters compared to the SG's communication infrastructure. This advantage became more pronounced at greater distances, with nearly 5 times less airtime at distances of 2000 and 2350 meters. These improvements result from the utilization of LoRaMESH and LoRaWAN technologies, enhancing transmission efficiency and range for faster and more reliable data transmission over extended distances. These findings provide insights for optimizing energy management and developing robust solutions for current and future energy challenges.

In Figure 6, the results for each tested packet type are presented. A single 60-byte packet had the longest airtime, operating up to 1500 meters before failing. Transmitting two 32-byte packets reduced airtime by over 50% and extended the maximum distance to 2350 meters. Sending three 22-byte packets reduced airtime by nearly one-third for shorter distances and almost 5 times less for longer distances. These findings underscore the importance of adjusting packet size based on distance and network constraints for efficient communication in various scenarios. In conclusion, this study demonstrates the superiority of the multi-microgrid's hybrid IoT architecture over traditional SG communication infrastructure. Reduced nodes and the use of LoRaMESH and LoRaWAN technologies resulted in shorter airtime and extended com-

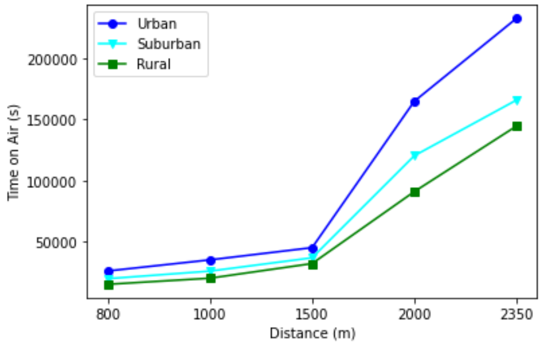

Fig. 4. Packet data organization.

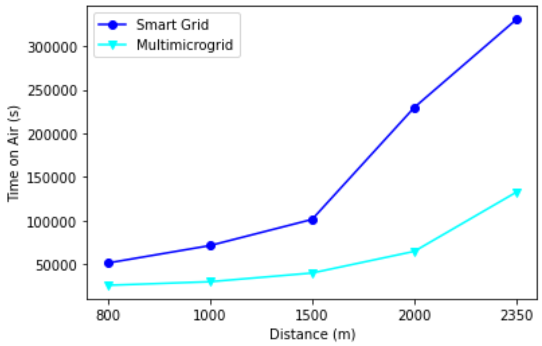

Fig. 5. Packet data organization.

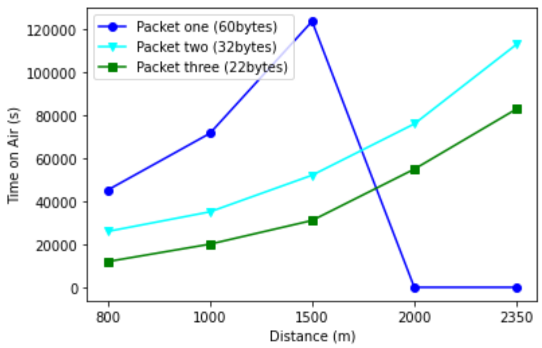

Fig. 6. Packet data organization.

munication range. Optimizing packet size based on distance significantly improved efficiency and reliability, showcasing the multi-microgrid's potential for large-scale applications, offering an efficient solution for energy management and robust SG implementations in urban and rural settings.

V. Conclusions, Lessons Learned and Future Work

This work proposes a hybrid IoT architecture for multi-microgrid scenarios, optimizing energy management with LoRaMESH and LoRaWAN technologies. It aims to reduce transmission time and expand communication range in urban, suburban, and rural settings, making electricity grids smarter and more resilient. By efficiently integrating renewable energy sources, it addresses challenges in traditional power grids, such as rising energy demand and limitations in the communication infrastructure. The results significantly advanced SGs by implementing the hybrid IoT architecture of the multi-microgrid with LoRaMESH and LoRaWAN technologies. Data transmission time was reduced by more than a third about 66% by dividing packets into three of 22 bytes. This hybrid architecture extended the communication range, improving energy management efficiency and reliability, especially over longer distances. The adaptability to diverse environments, including urban, suburban, and rural settings, was a key contribution, offering a versatile and scalable approach to enhance energy system sustainability and resilience. These findings underscore the potential of IoT technologies and microgrid interconnection in addressing current and future energy challenges, providing significant benefits to society and contributing to a more sustainable energy future.

As future works, it is important to optimize the use of LoRaMESH and LoRaWAN technologies, exploring different parameter configurations to increase communication efficiency. Additionally, studying the impact of system scalability, conducting comparisons with other IoT technologies, and performing experiments in diverse environments can provide valuable insights. Investigations into advanced energy management techniques and routing algorithms are also recommended for an enhanced implementation of the multi-microgrid architecture.

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