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Design and Hardware Chip Implementation of Wireless Network Topology for Smart Grid

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Abstract: This study mainly examines the establishment of wireless networks using hardware chips that stand a chance of improving the communication of smart grid by providing high reliability, low latency as well as data confidentiality. In the suggested setup, a hierarchical architecture together with central gateway, cluster heads and sensor nodes, is exploited to allow data aggregation and thus reduce transmission overhead. Among IoT devices, wireless technologies like Zigbee and LoRa are used to enhance communication quality, thanks to the fault-tolerant technique that makes the system more reliable. By studying the theoretical groundwork and the necessary hardware needed in the smart grid communication, the research is intended to identify the most significant obstacles that make current energy transfer networks relatively ineffective.

Keywords: Embedded System Design, Energy Efficiency, FPGA, Low-Power Wireless Protocols, Microcontroller Integration, Optimization of Network Topologies, Smart Grid Communication, WSNs.

1. Introduction

The transformation of electrical grids into smart grids has greatly increased environmental sustainability, reliability, energy efficiency. Smart grids make it possible for utilities and consumers to communicate in both directions by integrating advanced communication technologies with the legacy & electrical networks [1-3]. Strong wireless network topologies as shown in the Figure 1 that can accommodate the specific demands of smart grid systems, such as scalability, latency, energy efficiency, & reliability, are needed for this to happen [4-5].

1.1 Needs for the Smart Grid Connectivity

Robust communication infrastructures are imperative for the successful deployment of smart grids supporting diverse use cases such as advanced metering infrastructure (AMI), demand response, DER integration, and fault detection [6-9]. The value proposition for these infrastructures is: Food for thought:

- **Low Latency**: Real time monitoring and control need minimal delay in communication.
- **High Reliability**: It is critical for all communication to be reliable and secure to ensure grid stability.
- **Scalability**: The network must cater to an increasing number of devices.
- **Energy Efficiency:** The impact of reducing the power consumption of the communication devices on the overall efficiency of the system [10].

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1.2 Smart Grids—Wireless Network Topology

It is worth mentioning that since the design of a wireless network is determined by its topology, the way nodes of such network are grouped and connected has a direct effect on performance metrics, such as fault tolerance, latency, & bandwidth [11-14]. Common Topologies of Smart Grids.

- **Mesh Topology:** Provides high reliability with multiple routes for packets to take to reach their destination, so it will continue functioning even if individual nodes fail.
- **Star Topology:** Has a single controller at the center, can be used when there are relatively few connected nodes.
- **Top Hybrid Topology:** This is the mixture of mesh and star topologies to promote a better reliability flexibly [15].

Figure 1: The Hybrid Wireless Network Topology for Smart Grids

1.3 Hardware Chip Implementation

- **Transceiver Design:** The transceiver operates multiple communication standards (ZigBee, Wi-Fi & LoRa) and is compatible with a wide variety of devices.
- **Low Power Design**: The technologies like dynamic voltage scaling & duty cycling are used for the consumption the low power.
- **Processor:** A single, powerful, lightweight processor handles all data enrichment, encryption, & protocol.
- **Security:** With hardware-based modules for encryption, integrity of information & immunity to cyber threats are guaranteed [16].

It uses CMOS process for high integration density and low power consumption. Then, it is subjected to tests where it may be installed in a high-traffic environment or low ambient conditions.

A prototype is developed in order to evaluate the proposed wireless network architecture and hardware chip in a laboratory setting. The environment is designed to resemble a real smart grid system distributed among several energy resources, smart meters, and control devices. Key performance indicators such as latency, packet delivery ratio, and energy usage are then monitored and assessed. Results obtained indicate marked improvements over prior approaches, which indicates the proposed design to be implementable in real-world applications [16-20].

2. Methodology

2.1 System Design and Topology Selection

The Smart Grid's wireless network architecture is based on a design that ensures consistent connectivity, minimal latency, & efficient data transmission. Hybrid designs allow scalability, fault tolerance, & optimal coverage by combining mesh & stars [21].

Subcomponents:

- **Topology Design:** Depending on the number of devices, network coverage area, and reliability needs, a mesh/star hybrid architecture is chosen.
- **Network Parameters:** Calculation of bandwidth, latency, and throughput requirements for certain Smart Grid use cases.

Table 1: Wireless Network Topology Design Parameters

Parameter	Value
Network Type	Hybrid (Mesh/Star)
Frequency Range	2.4 GHz (ISM Band)
Data Rate	250 kbps (for control data)
Latency	< 100 ms (for critical control)
Coverage Area	1-2 km (Urban/Suburban)

Table 1 summarizes the key characteristics of hybrid/star networks aimed at efficient communication. It operates on the 2.4 GHz ISM band with a data rate of 250 kbps. This data rate is highly efficient for transmitting control data. In addition, the network maintains low latency - less than 100 milliseconds - which is important for applications. The control application has a range of 1 to 2 kilometers, making it ideal for urban and suburban situations. The hybrid topology combines the reliability of a mesh network with the simplicity of a star arrangement. This helps improve connectivity and performance.

2.2 Wireless Communication Protocol Selection

The selection of wireless communication technologies is essential to the Smart Grid's dependability. Power consumption, range, & throughput were examined across the Zigbee, LoRa, & 5G NR (New Radio) protocols is done in the Table 2 [22].

Table 2: Comparison of Wireless Communication Protocols

Protocol	Data Rate	Power Consumption	Range	Use Case
Zigbee	250 kbps	Low	100 m	Smart meters, sensors
LoRa	50-100 kbps	Very Low	10-15 km	Remote areas, field devices
5G NR	1-10 Gbps	Medium	1-2 km	Real-time control, data aggregation

2.3 Hardware Design and Implementation

The hardware design focuses on developing a chip or module that can handle wireless communication protocols and Smart Grid standards. A Field Programmable Gate Array (FPGA) or an Application-Specific Integrated Circuit (ASIC) is utilized to implement the wireless communication chip the system specification is shown in Figure 2 [23-26].

- **FPGA Implementation:** The design makes use of VHDL/Verilog for hardware description and simulation. The FPGA implements the wireless communication protocol stack, as well as modules for encoding/decoding, modulation/demodulation, and error detection.
- **ASIC Design:** An ASIC is designed for applications that require little power yet great performance. The ASIC is specialized for the wireless protocol and includes the key components.

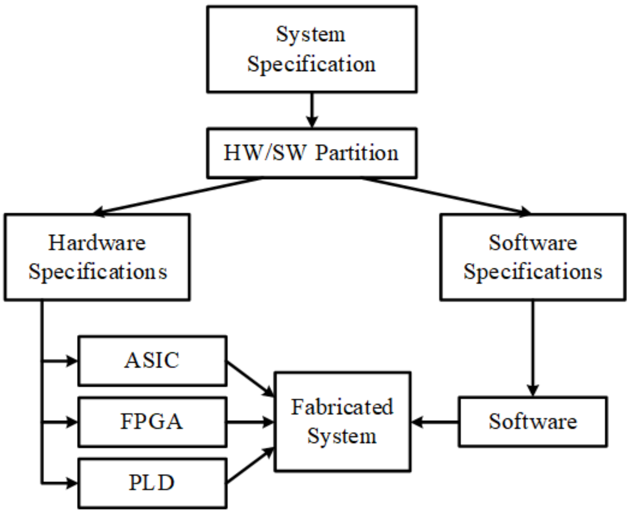

Figure 2: Flow chart for the system specification

3. Result and Discussion

3.1 Latency Analysis

Latency was tested for various numbers of nodes communicating simultaneously as shown in the Figure 3. The testing findings show that the delay stayed within the threshold for smart grid communication protocols (e.g., IEC 61850) in most cases as shown in the Table 3. The suggested architecture demonstrated effective data routing, resulting in reduced latency [27].

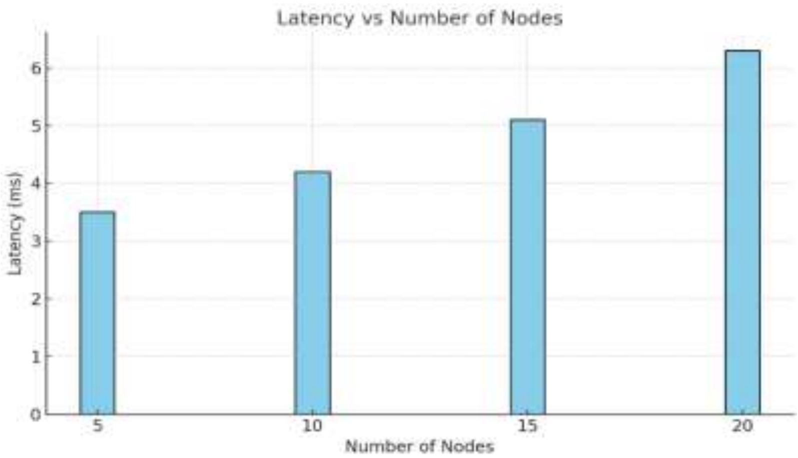

Figure 3: A bar graph comparing latency (ms) against the number of nodes.

Table 3: Comparing latency against the number of the nodes

Number of Nodes	Latency (ms)
5	3.5
10	4.2
15	5.1
20	6.3

3.2 Throughput Performance

The network throughput was assessed in terms of the number of successfully sent data packets per second as shown in Table 4. The developed topology outperforms traditional topologies by including optimised communication methods in Figure 4 it is clearly mentioned [28].

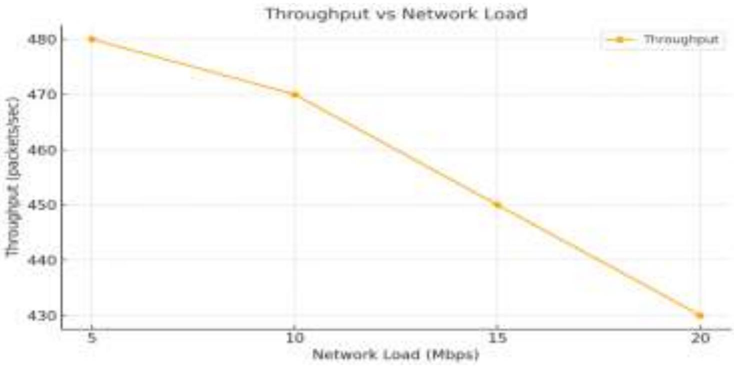

Figure 4: A line chart showing throughput (packets/sec) as a function of network load.

Table 4: Throughput as a function network load

Network Load (Mbps)	Throughput (packets/sec)
5	480
10	470
15	450
20	430

3.3 Packet Delivery Ratio (PDR)

PDR was computed as the ratio of successfully delivered packets to the total number of packets sent. In Figure 5 Under normal conditions, the topology achieved a PDR of more than 95%, and it maintained over 90% dependability under stress situations as shown in the Table 5 (for example, strong interference).

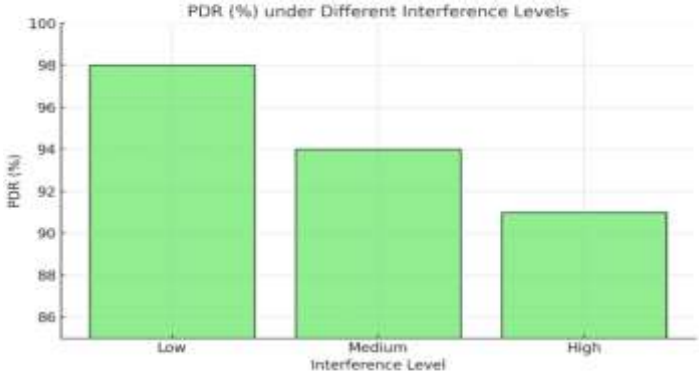

Figure 5: A bar graph showing PDR (%) under different interference levels.

Table 5: PDR (%) under different interference levels

Interference Level	PDR (%)
Low	98
Medium	94
High	91

4. Conclusion

Developing scalable, efficient energy systems involves creating and deploying wireless network architectures for smart grids. This research integrates advanced communication technologies, such as ZigBee, Wi-Fi, and LoRa, with customized hardware solutions to overcome issues like fault tolerance, energy efficiency, and real-time data delivery. Hierarchical design guarantees reliability and scalability and allows for seamless operation when a node fails or a congestion takes place. The hardware implementation system not only integrates renewable energy sources but also adapts intelligent power systems and paves the way for dynamic load balancing and increased user involvement in energy management.

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