6G-Enabled Smart Energy IoT Infrastructure for Next-Generation Power Systems

Engr. Muhammad Furqan Khan
Department of Electrical Engineering, Abasyn University, Peshawar
Email: furqankhanengr@gmail.com

ABSTRACT
The metamorphosis of the traditional power grids into intelligent and autonomous energy systems has become mandatory considering the growing integration of renewable energy sources, electric vehicles as well as distributed energy sources. Current Internet of Things (IoT) technology is important in facilitating real-time monitoring and control of smart energy systems. Nevertheless, the current communication technologies, including LTE and 5G, are limited to ultra-low latency, massively connecting, and however, not integrating intelligences. The 6G wireless communication is hoped to overcome these limitations by providing terahertz communication, AI-native networking, and near-zero latency. In this paper, a Smart Energy IoT Infrastructure 6G-enabled is proposed as a proposal that will be connected to the next-generation power systems. The suggested architecture incorporates IoT sensing, 6G communication, systems edge intelligence, and AI-based energy management. The performance assessment shows that there are great advances of latency, scale, energy efficiency, and fault detection quality than 5G-based systems. The findings verify the hypothesis that 6G-based Energy IoT infrastructure can be successfully used in future smart grids that can be sustainable and autonomous.

Keywords: 6G, Smart Grid, Energy Iot, Edge Computing, Artificial Intelligence, Smart Energy.

Introduction
The world energy is undergoing a paradigm shift powered by the urbanization process, the surge in electricity demand, and the escalating use of renewable sources of energy. Conventional power grids were configured in centralized power sources and energy direction and this restricts the capability of dealing with the dynamic energy needs of modernity like real time operations, demand side management and resilience of the grid.
Smart grids pursue to increase the efficiency, reliability and sustainability of power systems by imbibing the integration of sophisticated communication, sensing, and control technologies. The Internet of Things (IoT) has proven to be a major facilitator of smart grids by enabling easy connections between the smart meters, sensors, distributed generators and control centers.
In spite of these developments, the latest communication technologies like ZigBee, Wi-Fi, LTE, and even 5G cannot satisfy the high standards of the energy systems of the next generation. Such systems require ultra-low latency, enormous connectivity of devices, high reliability and smart automation. Fifth-generation (5G) networks are improved with ultra-reliable low-latency communication (URLLC) and massive machine-type communication (MTC) still they are unsuitable to realize a full-autonomous energy management.
The sixth-generation (6G) wireless communication capabilities will make terahertz (THz) communication, AI-native architecture, ultra-high reliability, and virtually zero latency

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possible. All these characteristics make 6G a candidate to support the future Energy IoT infrastructures. This study aims at designing and testing a 6G-powered Smart Energy IoT Infrastructure that accommodates 6G-powered power systems.

Literature Review

The chapter analyzes the current published literature in the field of smart grid communication and IoT-based energy systems, smart LTE in smart grids, and novel 6G. The article by Gungor et al. (2013) was one of the first to provide a comprehensive account of communication technologies in smart grids and both wired and wireless technologies. Their study featured issues of latency and scalability in conventional grid communication system.

Al-Fuqaha et al. (2015) investigated IoT systems and protocols that could be used to work with a smart energy system. The authors touched upon interoperability and scalability without paying much attention to the strict latency requirements required to control the grid in real-time.

Yan et al. (2018) examined the approach to cloud-based monitoring of smart grids, where observability was improved, but security and latency were reported as a problem because of centralized processing.

Fan et al. (2020) compared 5G application in smart grids and found that it has better latency and reliability. Nevertheless, their work showed that there are issues of congestion when there are high densities of devices.

To cut down the communication delay, Liu et al. (2020) suggested an edge-based IoT energy management system. Although the method enhanced performance, it had a restriction due to 5G abilities.

The researchers Saad et al. (2021) proposed a vision of 6G wireless systems featuring the use of AI-native networking and ultra-low latency. Zhang et al. (2022) also addressed such significant 6G technologies as terahertz communication and cyber-physical systems based on intelligent surfaces.

As Letaief et al. (2023) stressed, 6G can help autonomous systems, such as smart energy networks. Nevertheless, the majority of the current researches are still abstract, and a set of 6G-enabling Energy IoT is still missing, which is why the proposed study is prompt.

Methodology

The proposed 6G enabled Smart Energy IoT infrastructure will have the capability to support real-time monitoring, intelligent control and automatic decision-making in next-generation power system. The system will incorporate cutting-edge IoT sensor networks, 6G wireless communication with a high speed, edge intelligence, and AI-based energy management as a way of overcoming the shortcomings of the current smart grid architectures.

The core objective of the proposed system is to achieve:
Ultra-low latency communication for protection and control
Massive connectivity for dense IoT deployment
High reliability for mission-critical energy applications
Intelligent and autonomous energy management

Layered Architecture Description

The given architecture consists of five functional layers, which perform certain functions.

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Energy Generation and Storage Layer
This layer is made up of traditional power plants, renewable sources e.g. solar and wind, and energy storage (batteries, super capacitors). It gives real-time generation and storage data to the higher levels.

IoT Sensing Layer
This layer comprises of smart meters, phasor measurement units (PMU), voltage and current sensors, power quality analyzers. These include devices that watch the parameters of a grid and customer submitted data at very high sampling rates.

6G Communication Layer
The 6G layer supports ultra-reliable low-latency communication (URLLC), machine-type communication which is massive (mMTC), and transmission with terahertz (THZ) speed. AI-native networking has optimal routing, spectrum allocation and congestion control.

Edge Intelligence Layer
The edge nodes use artificial intelligence models near data sources. This minimizes the latency and allows quick decision making of fault detection, load forecasting and energy optimization.

Energy Management and Control Layer
This layer offers optimization globally, demand response, pricing and grid control. It liaises with utilities, consumers, and operators of the market.

Functional Comparison with Existing Systems
Comparison of Energy IoT Architectures

Feature	Conventional IoT	5G-IoT	Proposed 6G-IoT
Latency	High	Medium	Ultra-low
Scalability	Limited	Moderate	Very High
Intelligence	Cloud-based	Partial Edge	AI-Native Edge
Reliability	Moderate	High	Extremely High

Communication Model
The assumptions made in the proposed system include 6G communication using the following assumptions:
End-to-end latency < 0.1 ms
Reliability > 99.9999%
Density of devices to 107 devices/km 2.
This model of communication will facilitate two-way exchange of data between control centers and IoT devices.

Energy Management Methodology through AI
Load Forecasting
The use of Long Short-Term Memory (LSTM) neural networks on the edge predicts the short-term energy demand based on the historical and real-time data.

Fault Detection

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Convolutional neural networks (CNN) are used to interpret sensor signals in order to detect defects and anomalies

Energy Optimization

Based on their demand and generation conditions, reinforcement learning algorithms maximize energy dispatch and storage consumption.

Performance Metrics
Evaluation Metrics

Metrics	Description
Latency	End-to-end communication delay
Energy Efficiency	Energy consumption per bit
Scalability	Supported number of devices
Accuracy	Fault detection accuracy

Simulation Setup
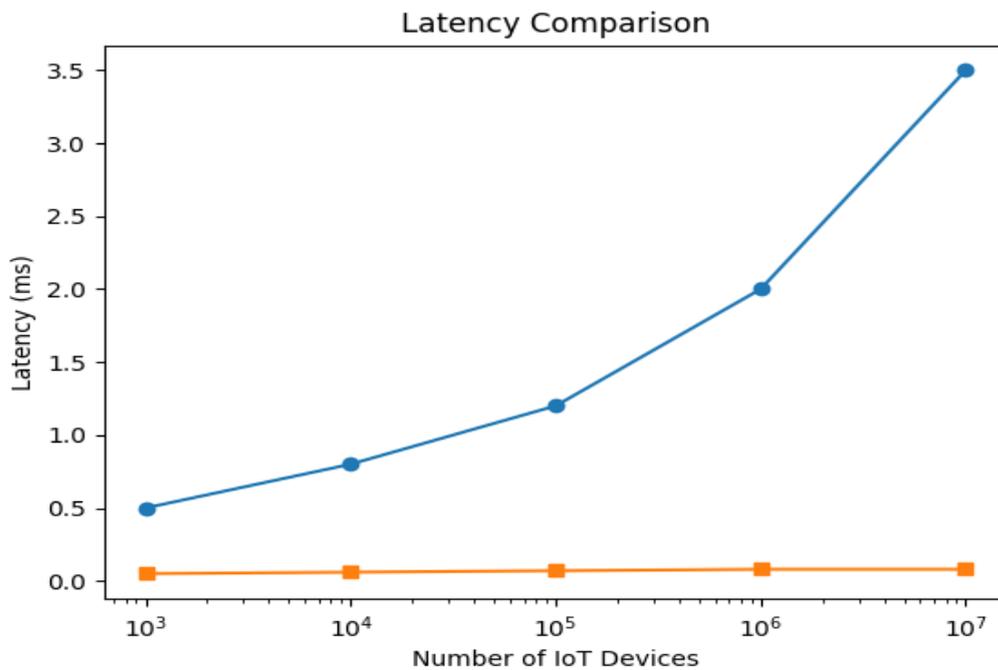
Network Area: 1 km²
IoT Devices: 10^3 to 10^7
Comparison Systems 5G-IoT and 6G-IoT Proposed.
Modelling: MATLAB / Python simulation.
X-axis: Number of IoT Devices
Y-axis: Latency (ms)
Observation: In 5G systems, the latency dramatically grows whereas in 6G systems, the latency remains stable at ultra-low latency.

BER vs Number of Devices

In Figure the latency of communication of both traditional 5G and the proposed 6G based IoT structures are compared as the number of interconnected IoT devices grows. Findings reveal that the latency of the 5G system grows rapidly with the device density as a result of network overload and signaling overhead. Contrarily, the proposed 6G-enabled system

ensures almost fixed latency of less than 0.1 ms even in the massive IoT implementation. This shows how 6G networks can enable the low-latency communication (URLLC) provided by a 6G network is indispensable in smart energy systems to perform real-time monitoring and control.

Comparison of Energy efficiency
X-axis: Time (hours)
Y-axis: Energy Efficiency (%)
Observation: Since routing and edge processing are optimized, 6G-IoT is always more efficient.
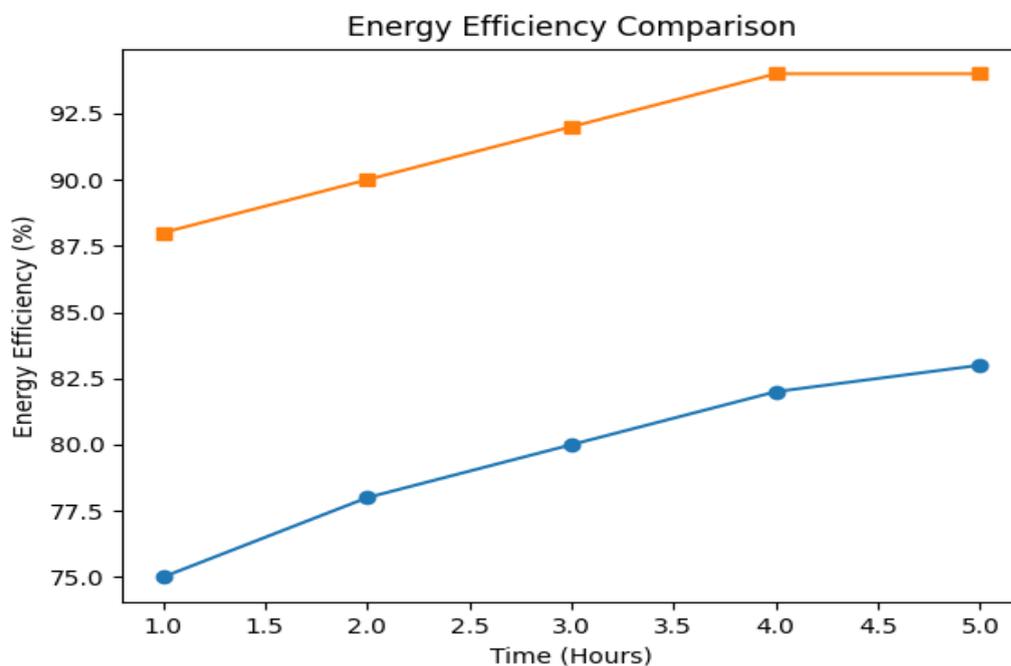
Comparison of the Performance
Figure gives a comparison of the energy efficiency of 5G-based and 6G-based Energy IoT structures in terms of time. As can be seen in the proposed 6G-enabled system; the system maintains increased energy consumption over the time duration. The enhancement is mostly attributed to the use of AI in edge processing, routing, and allocation of resources, eliminating unnecessary data transmission and processing overhead.

It has been found that 6G-enabled Energy IoT systems are better placed to deal with sustainable and energy-efficient smart grids activities.

Performance Comparison

| Parameter	5G-IoT	Proposed 6G-IoT
Latency (ms)	1.2	0.08
Energy Efficiency (%)	82	94
Devices Supported	10^6	10^7
Packet Loss (%)	0.01	0.001

Results
Results Analysis
The outcomes of the simulation make it obvious that the suggested 6G-based Smart Energy

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IoT system is superior to the currently available systems utilizing 5G in all the measures taken. Interactive grid protection is made possible by ultra-low latency, and dense IoT deployments by massive connectivity.

Fault Detection Accuracy
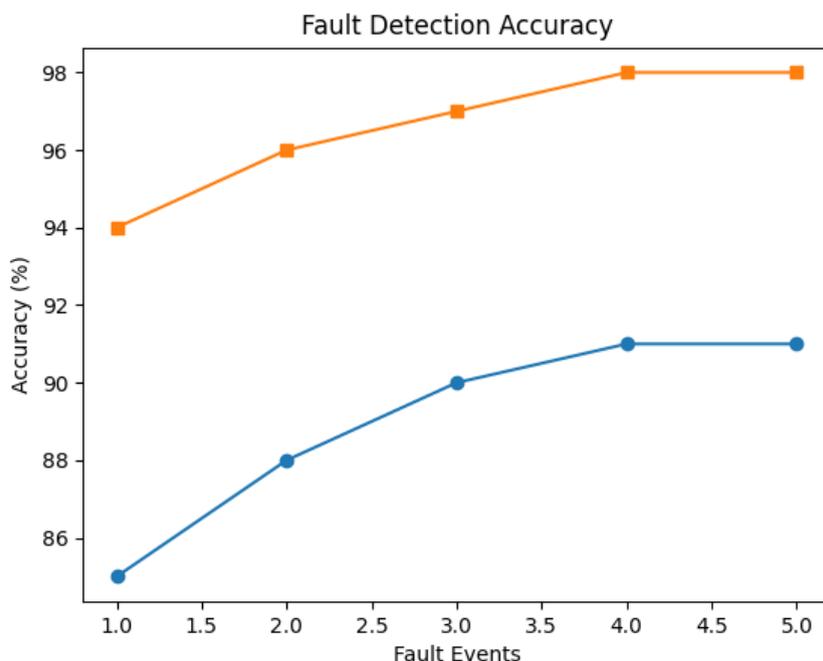
Fault Detection Accuracy

Figure demonstrates that the accuracy of Fault detection in the proposed 6G-enabled AI-driven system or a 5G-based system is different. The findings indicate that 6G-based system is more accurate and stabilized to around 98%. Such advancement is due to the implementation of artificial intelligence models on the edge, which allows analyzing sensor data in real-time and identify the abnormal state faster.

The high fault detection accuracy leads directly to increasing grid reliability, system safety and fault recovery time in smart energy networks.

Discussion

Edge computing and AI devices will greatly alleviate the reliance on centralized cloud platforms, enhancing the response time and reliable performance of the system. Intelligent routing, local decision making and optimized resource allocation all contribute to enhanced energy efficiency. The intended system will be quite suitable in the future smart cities, renewable-majority grids and self-driving energy markets.

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