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IoT-Based Load Management System with Edge Computing For Real-Time Decision Making

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ABSTRACT

Intelligent load control solutions that can function in real time are necessary due to the quick expansion of electrical loads & the growing need for energy efficiency. The efficacy of traditional cloud-centered Internet of Things (IoT) devices for time-sensitive energy-related uses is generally limited by high latency, higher bandwidth consumption, and delayed decision-making. This research proposes an Internet of Things-Based Load Management Platform with Edge Technology for Real-Time Decision-making as a solution to these problems. The suggested system continually monitors electrical factors including voltage, current, consumption of energy, and load status by integrating IoT-enabled devices and smart sensors. Without depending on continuous cloud communication, computing edge nodes process the collected data locally, allowing for low-latency analysis and quick control actions. Deployed at the edge, intelligent decision-making algorithms dynamically control electrical loads according to predetermined thresholds, priority levels, and current demand conditions. Compared to traditional cloud-based methods, the system architecture increases reaction time, decreases congestion in the network, and improves reliability. The suggested edge-enabled IoT framework successfully optimises energy consumption, avoids overload situations, and facilitates scalable deployment in commercial, industrial, and residential settings, according to experimental results. For future-oriented smart energy management systems, the suggested solution provides a workable and effective method.

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1. INTRODUCTION

The combination of cutting-edge technology has opened the door for creative solutions to many problems in the current period of unparalleled technological advancement. Interconnected Intelligence (II), that combines the power of cloud computing [1], computing in the fog, & the

Internet of Things (IoT), is one of these revolutionary paradigms. The potential of II to transform data management and instantaneous choices across multiple domains is examined in this research.

Massive amounts of data are being generated by connected devices, from wearables and smart gadgets to sensors and actuators, as a result of the Internet of Things' explosive growth. This massive influx of data requires assistance for traditional systems [2] for data management to handle effectively, which frequently results in delays, inefficiencies, and higher resource use. Furthermore, the demand for sophisticated data processing capabilities has increased due to the necessity of real-time decision-making in crucial applications including industrial automation, health care, and autonomous cars.

Cloud computing evolved as a potent solution to these problems, offering vast processing and storage capacities. By providing scalable and unlimited access to centralised resources, cloud computing transformed data management by enabling individuals and enterprises to store and deal with data remotely [3]. However, there are challenges with data transfer delays and privacy because cloud infrastructures are centralised. To overcome the drawbacks of cloud computing, fog computing was developed as a layer in between IoT gadgets and the cloud. By bringing networking, storage, and compute closer to the edge of the network, fog computing lowers latency and eases the load on the cloud [4]. Time-sensitive applications benefit greatly from this distributed approach's ability to evaluate data more quickly and make decisions in real time.

Although cloud computing & fog computing have their own advantages, integrating them with the Internet of Things presents both new opportunities and difficulties. Unlocking the revolutionary potential of Interconnected Intelligence [5]—which includes the smooth integration of IoT devices with cloud and fog infrastructures—is the driving force behind this research.

IoT, cloud computing, & fog computing together provide a comprehensive solution that makes use of each component's advantages. Interconnected Intelligence offers a strong framework for improving data management & real-time decision-making by leveraging the cloud's scalability and enormous processing capacity in addition to fog computing's lower latency and closer access to data sources.

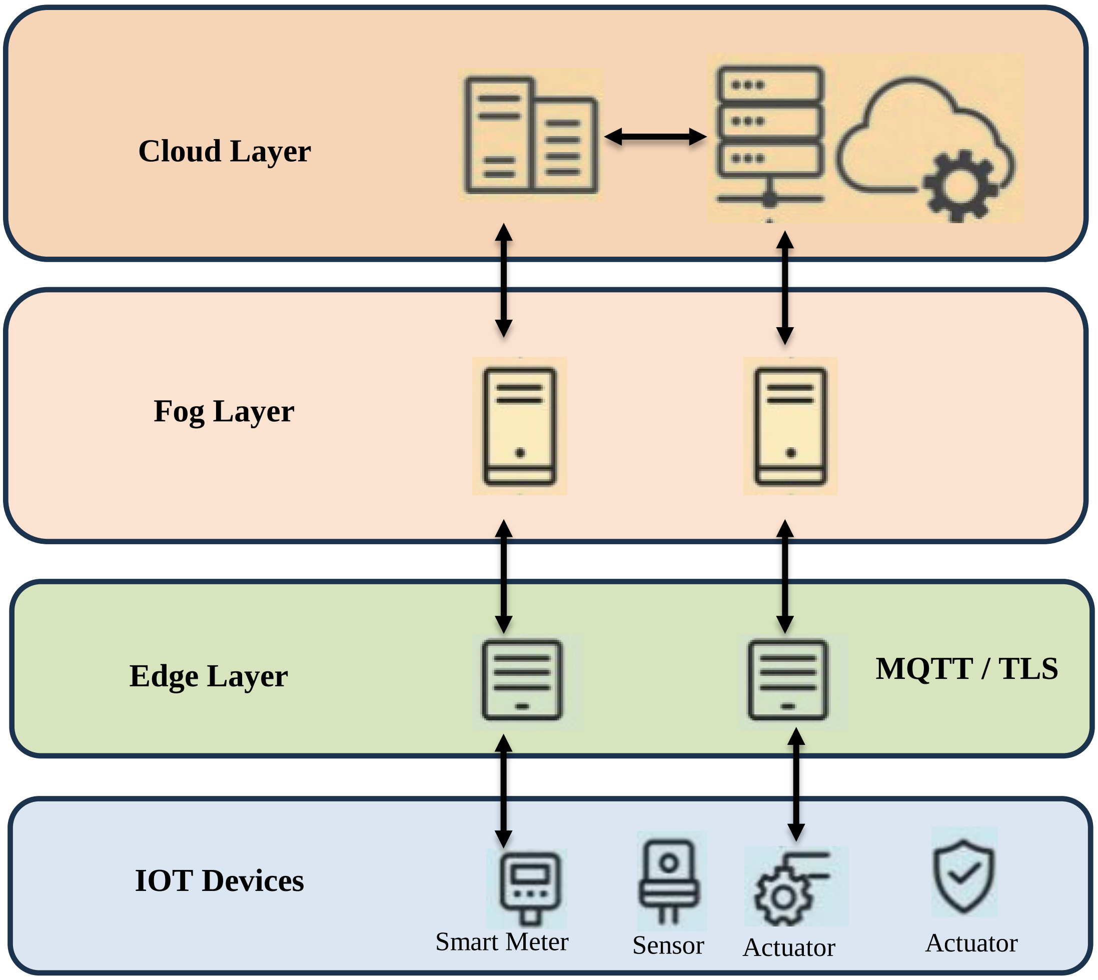

Figure 1. System architecture diagram

Our entire system architecture is shown in Figure 1 [6], which also highlights the security precautions put in place at each tier and the stacked processing technique.

1.1 Problem Statement

Due to centralised processing, slow reaction times, and ineffective managing of dynamic load conditions, current load management solutions are severely limited. IoT solutions that rely on the cloud are frequently unable to offer real-time control during periods of high demand or unusual operating conditions. An intelligent, scalable, low-latency load management system that can make independent local judgements is required. In order to solve this issue, this study suggests an Internet of Things (IoT)-based load management system that is coupled with edge computing to allow for real-time electrical load monitoring, analysis, and control.

1.2 Paper Organization

This is how the rest of the paper is structured. A review of relevant work in edge computing and IoT-based energy management is provided in Section II. The suggested block diagram and system architecture are explained in Section III. The system's software and hardware architecture are described in Section IV. The experimental findings and performance analysis are covered in Section V. The work is finally concluded and potential study directions are outlined in Section VI.

2. LITERATURE REVIEW

Numerous studies on Internet of Things (IoT)-based energy tracking and load control solutions have been prompted by recent developments [7] in smart energy systems. Numerous research have concentrated on enhancing energy efficiency through the use of IoT-enabled devices and smart sensors to enable real-time evaluation of electrical characteristics.

Cloud-based IoT designs for load control and energy monitoring have been suggested by a number of researchers. To provide energy usage data to servers in the [8] cloud for storage and analysis, these systems usually use intelligent meters and wireless connection modules. Although cloud-based solutions offer centralised data management and scalability, they frequently experience increased latency, excessive bandwidth usage, and slow response times during periods of peak load. Their applicability for time-sensitive control of load applications is diminished by these constraints.

Some research has incorporated both edge computing and fog computing concepts into IoT-based power systems to address latency-related problems [9]. By facilitating data [9] processing in between IoT devices & cloud servers, fog computing lowers communication latency. Fog-based designs do, however, still rely in part on centralised nodes, which could result in processing bottlenecks and raise system complexity.

By processing data at or close to the data source [10], edge computing has become a viable option for real-time energy management. Recent research has shown that edge-based IoT systems may greatly speed up response times and boost dependability in load management and smart grid applications. Without constant reliance on the cloud, these systems use local decision-making techniques to carry out load shedding, balance of loads, and power optimisation.

To improve decision-making accuracy [11], several researchers have incorporated sophisticated algorithms at the edge, such as rule-driven control as well as lightweight models for machine learning. Despite the fact that these methods increase system responsiveness, many current implementations prioritise monitoring over autonomous load control. Furthermore, in real-world implementations, safety, scaling, and real-time flexibility continue to be unresolved issues.

It is clear from the studied literature that although IoT-based energy surveillance systems have been thoroughly investigated, there is currently little integration of cutting-edge computing for continuous autonomous load management. By putting forth an edge-powered IoT [12] load control system that can make decisions in real time with lower latency, increased dependability, and effective energy use, this article seeks to close this gap.

3. METHODS AND MATERIALS

The materials and development process for the suggested IoT-based load control system with cutting-edge computing for continuous decision making are described in this part. To lower latency and boost system performance [13], the entire strategy focusses on edge-level processing, autonomous load control, and local data collecting.

A. System Materials

1. Hardware Components

The suggested system's hardware is made to allow for real-time electrical load monitoring and control. The real-time electrical use of linked loads is measured by a current sensor, which provides crucial information for load analysis and power computation. In order to evaluate power quality and identify anomalous operating situations, a sensor that detects is used to track changes in line voltage. The key hardware component is an ESP32-based Internet of Things microcontroller that interfaces with the sensors and permits wireless communication. Local data processing & real-time decision making near the data source are made possible by the microcontroller's integrated edge computing functionality [14]. As a load control interface, a relay module allows electrical loads to be automatically switched, disconnected, or reconnected based on decisions made at the edge level. All system components receive steady, dependable power from a controlled power supply unit, guaranteeing continuous functioning.

2. Software Components

Data collection, processing, and visualisation are supported by the software components. The Arduino IDE is used to create embedded firmware that manages data acquisition, control, and sensor interfacing. The firmware incorporates edge processing logic to carry out analysis of data in real time and carry out predetermined decision rules. For for a long time data storage, visualisation, and historical analysis, an optional online platform is incorporated. Users can remotely set load priorities, monitor energy usage, and view system status through a web-based user interface.

B. Data Collection

Electrical sensors that are interfaced to the IoT microcontroller are used to collect data in real time. At predetermined sampling intervals, the system continually records important electrical parameters like voltage, current, energy use, and load status. The microcontroller's inbuilt analog-to-digital converter (ADC) transforms sensor outputs from their original raw analogue form into digital values. Sensor calibration is done before system deployment to provide precise and trustworthy results. In order to minimise communication overhead and guarantee continuous monitoring even in the event of network connectivity problems, data collection is carried out locally at the border without instantaneous transfer to the cloud.

C. Data Extraction and Preprocessing

At the edge of the computing layer, the gathered sensor data is retrieved for additional processing and analysis. Simple moving average approaches are used to filter raw data in order to remove noise and transient changes. Important characteristics including instantaneous electrical usage, average demand for load, peak load figures, and load ranking are extracted from the filtered data. After being extracted and preprocessed, the data is formatted into unstructured records so that it may be used for immediate analysis and edge decision-making.

D. Edge-Based Decision-Making Technique

Rule-Based Load Management Technique

Real-time monitoring of electrical loads is made possible by the implementation of a rule-driven load management approach at the edge computer layer. This method was selected because of its quick response time, minimal processing complexity, and adaptability for deployment on edge devices with limited resources.

The method's basic idea is to compare the retrieved electrical parameters with load prioritisation rules and predetermined threshold values. A priority level is given to each electrical load according to its significance and criticality. The technology immediately starts load control procedures to avoid overload situations and guarantee effective energy use when the overall power consumption beyond a certain level.

The decision logic functions as follows: all connected loads continuing to function correctly as long as the overall load stays below the threshold limit. Low-priority loads are instantly disconnected if the overall load over the threshold limit. Sensitive loads are shielded from harm when there are voltage swings. To prevent unexpected load surges, the detached loads are successively reconnected after regular operating conditions are restored. There is no need for internet-based intervention because all decision-making procedures are carried out locally at the edge.

Minimal delays, deterministic system behaviour, less reliance on network connectivity, and excellent reliability for continuous load control applications are only a few benefits of this method.

E. Load Control Mechanism

The relay module receives the proper control signals to manage the linked electrical loads depending on the judgements made by the edge-based approach. To avoid electrical transients and guarantee safe operation, load switching activities are carried out with appropriate time delays. In order to ensure steady system performance and confirm the efficacy of the applied actions, the system continuously tracks the post-control parameters.

F. Data Storage and Visualization

Periodically, system status data and summarised energy usage data are sent to the cloud service for storage and visualisation. Through a website's user interface, users may monitor system performance, examine past energy usage trends, and set load priorities. System optimisation and long-term analysis are also supported by cloud integration.

Figure 2. The Power of Edge Computing and Cloud Integration

Servers, memory, database systems, hardware, connectivity, software, statistics, among other technologies are all made available remotely through cloud computing.

Cloud-based service models fall into three main categories:

- The core component of cloud computing, including networking, storage, and processing, is the infrastructure as a service (IaaS).
- Platform as a Service (PaaS) is an application development, deployment, and management platform.
- Full software programs are made accessible as Software as a Service (SaaS), housed in the cloud, and accessible via the internet.

4. IMPLEMENTATION AND EXPERIMENTAL RESULTS

This section summarises the experimental results achieved under real-time operational settings and explains how the suggested IoT-based load administration system with computing on the edge was implemented. To assess the system's efficacy in real-time loading monitoring, decision-making, and load control, it is deployed in a controlled environment.

A. System Implementation

An ESP32-based IoT microprocessor combined with voltage and current sensor for collecting data in real time is used to create the suggested system. Local processing of data and rules-based decision making are made possible by the microcontroller firmware's embedded edge computing feature. Relay modules connect electrical loads with varying priority levels, enabling controlled control of loads based on current power usage.

The Arduino IDE is used to construct the firmware, which has modules for relay control, edge-based decision logic, processing, and sensor data collecting. It is optional to employ a platform in the cloud for historic analysis and information visualisation. Without depending on continuous cloud communication, the system runs continually, monitoring electrical conditions and dynamically controlling loads.

B. Experimental Setup

Several electrical loads divided into high-priority & low-value groups make up the experimental setup. To measure electrical parameters in real time, the current and voltage sensors are mounted at the load input. Normal functioning, peak demand, & overloaded scenarios are among the load circumstances under which a system is assessed. Performance measures including power consumption, response time, and load control efficiency are assessed.

C. Experimental Results and Analysis

1. Load Monitoring Performance

Real-time monitoring of power, current, and voltage utilisation is accomplished by the system. The measured electrical characteristics for various load scenarios are shown in Table 1.

Table 1. Electrical Parameter Measurements

Load Condition	Voltage (V)	Current (A)	Power (W)
Light Load	228	0.6	137
Medium Load	230	1.2	276
Heavy Load	229	2.0	458

The findings show that while electricity and power consumption rise in direct proportion to load demand, voltage levels remain steady throughout a range of load circumstances. This validates the sensing & data gathering units' accuracy.

2. Edge-Based Decision Response

A cloud-based IoT strategy is contrasted with the suggested edge-enabled system's reaction time. Table 2 provides a summary of the findings.

Table 2. Response Time Comparison

System Type	Average Response Time (ms)
Cloud-Based IoT	850
Edge-Based IoT	120

When contrasted to the cloud-based method, the edge-based technology exhibits a noticeably faster response time. Because local processing removes network latency, load control choices can be made instantly during periods of high demand.

3. Load Management Effectiveness

The behaviour of the system under overloading circumstances and the accompanying control actions are displayed in Table 3.

Table 3. Load Control Actions

Condition	Total Load (W)	Action Taken
Normal Operation	300	No Action Required
Threshold Exceeded	520	Low-Priority Load Disconnected
Restored Condition	280	Load Reconnected Sequentially

Low-priority loads are automatically disconnected by the system when the overall load surpasses the predetermined threshold. Loads are systematically reconnected after regular circumstances are restored, guaranteeing system stability.

D. Graphical Analysis

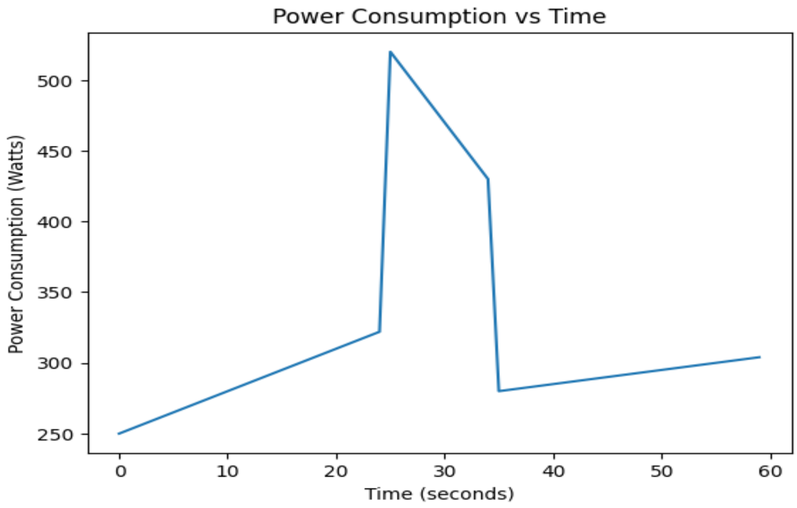

Figure 3. Power Consumption vs Time

The real-time power usage over time under various load circumstances is shown in graph 3. There is an abrupt rise in power usage at periods of peak demand. The edge-based selection module starts load shedding when the threshold is surpassed, which causes a discernible drop in power usage.

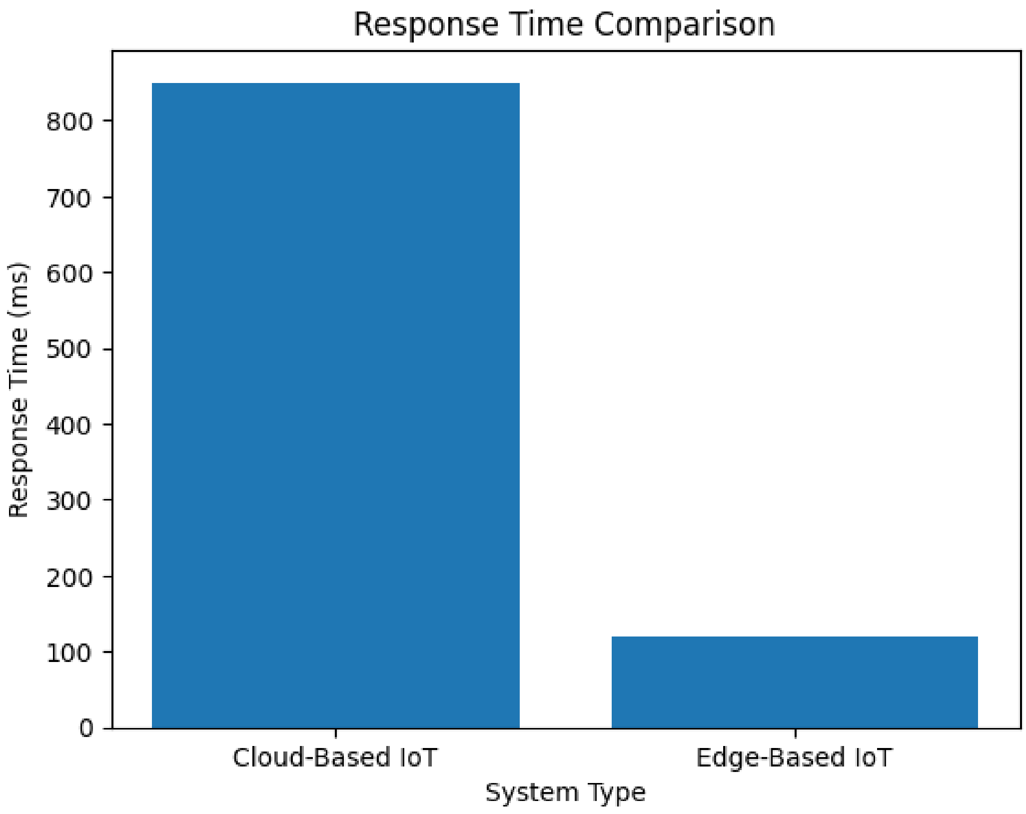

Figure 4. Response Time Comparison

The reaction times of cloud-based & edge-based IoT systems are contrasted in graph 4. Because of local processing, the edges-based system always responds faster, but the cloud-based system has higher latency because of network latency.

E. Discussion

The outcomes of the trial confirm that the suggested IoT-based load control system using edge computing is effective. The system accomplishes dependable load control, a low latency choice-making, and precise monitoring. The edge-enabled strategy greatly reduces network dependency while increasing response time and system dependability when compared to conventional cloud-based solutions.

5. CONCLUSION

In order to facilitate real-time selection for effective energy management, this article introduced an IoT-based loads management structure combined with edge computing. Low-latency and dependable load control solutions are essential due to the growing demand for electrical power and the constraints of conventional cloud-centric IoT systems. The suggested solution successfully resolves problems with response time, network reliance, and scalability by moving data processing and decision-making closer to the data source.

Using IoT-enabled sensors, the built system effectively exhibited immediate tracking of electrical characteristics as power, current, and voltage usage. The gathered data was processed locally using edge computing, which also carried out a rule-based decision-making process for autonomous load control. Without requiring constant cloud connectivity, this method enabled the system to promptly identify overload problems and take corrective action, such as eliminating low-priority loads and safeguarding sensitive equipment.

The efficacy of the suggested strategy was validated by experimental findings. When compared to traditional cloud-based IoT systems [15], the edge-based solution achieved noticeably faster response times, guaranteeing prompt load control during periods of high demand. The system's capacity to regulate energy consumption and avoid overload scenarios through cognitive load shedding was further confirmed by the power consumption study. These findings show increased operating efficiency, decreased latency, and greater reliability.

All things considered, the suggested IoT-based load control system using edge computing provides a workable and expandable solution for contemporary smart energy applications. It is ideal for use in commercial, industrial, and residential settings where immediate load control is crucial. To enable upcoming smart grid and intelligent systems for managing energy, the system framework can be further expanded by including cutting-edge machine learning techniques, energy from renewable sources, and improved security measures.

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