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Energy Efficient IoT Networks Using AI-Driven Approaches

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Abstract

The idea of a connected world through the Internet of Things (IoT) has already materialized in this decade. The advancement of efficient hardware and high-capacity networks has made it possible for billions of devices to link, gather, and relay useful information. One of the main advantages of IoT devices is their capability to automate processes; however, the vast amount of energy needed for billions of connected devices to interact can pose a significant challenge to the full realization of IoT systems if not carefully managed. This paper introduces a system for managing energy in IoT devices, considering both hardware and software dimensions. Energy transparency has been achieved by modeling the energy utilized during sensing, processing, and communication activities. A multi-agent system has been developed to represent the IoT devices and their energy usage. To optimize the parameters of the multi-agent system, a genetic algorithm has been employed. Lastly, simulation tools like MATLAB Simulink and OpenModelica are utilized to evaluate the system. The results of the optimization indicate considerable energy savings when implementing the decentralized intelligence of the multi-agent system.

Keywords: Internet of things, Energy management, Multi-agent system, Genetic algorithm, Energy optimization, MATLAB Simulink simulation, Energy efficiency.

1 | Introduction

The expected number of massive Internet of Things (IoT) devices shortly is estimated to be in the billions and is continuously increasing in number. These devices will remain connected to extremely reliable and low latency networks while continuously transmitting the data during the whole life of their operation. Since the capacity to accommodate the IoT devices within the network is increasing with the introduction of 5G and similar technologies, the complexity of data management and energy optimization for IoT devices is becoming challenging for researchers [1]–[3]. The collaborative working of IoT devices in the swarm is necessary to implement IoT services and develop energy management protocols successfully. Implementing IoT in real-world environments with smart, ubiquitous, and live interconnections is still restricted by constraints like

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device battery life, network capacity, and the cost of maintaining both. Powering billions of such interconnected devices is still one of the biggest challenges IoT faces today [4], [5].

The core functionality of IoT devices is to reliably collect and share the perceived data with the physical world [6]. The hardware element of the IoT device consists of a battery-powered sensor, an actuator, and a communication system. The function of a sensor is to collect the data from its designated environment. The data can be flow rates, temperatures, pressures, physical movements, distance, mass, etc. The collected data is then processed on the device and sent to remote servers through the communication network.

Sensors are the IoT devices that acquire the data, processing and communicating it to its destination. Thus, sensors are the power hogs of an IoT system. The limited battery lives of these devices are a major obstacle in the full-fledged implementation of IoT. Large amounts of data collection and processing are only possible at the expense of higher energy consumption. Considering the limited battery life, data amount and accuracy are a tradeoff. The batteries of IoT devices may need to recharge intermittently and frequently for reliability and smooth operation, which is a significant obstacle task for billions of interconnected devices [7]–[10].

Traditionally, hardware optimization is considered a preferred solution to save energy by increasing efficiency. A similar approach has been adopted for IoT devices, and new ultra-low energy-consuming devices have been designed. More efficient and customized versions have been developed using the existing technologies, such as Bluetooth Low Energy (BLE) [11]. However, with billions of devices connected and communicating uninterruptedly, the role of software governing the devices becomes just as significant. The studies show that about 80% of the energy consumed by an embedded system relies on the governing software controlling the IoT devices. It has been observed that un-optimized software can poorly drive energy-efficient hardware, thus resulting in higher energy consumption. Moreover, the devices have no feedback system that can tell about the energy consumption of a specific algorithm. With the booming growth of new IoT devices being installed and operated, systems to measure and reform energy usage are increasingly needed. There are three significant constraints in gauging and optimizing the energy consumption of IoT devices:

I. Device selection is based mainly on hardware specifications and not on energy consumption. Thus, when devices are interconnected with other devices in the system, the overall energy consumption may increase.

II. The application developers do not have feedback on energy consumption for each device and algorithm, which makes it challenging to perform causal-effect analysis and minimize energy usage.

III. When many devices are working in a swarm, their overall energy consumption is dependent on several factors, including signal interference and mitigation. So far, the protocols defining energy management for IoT systems have not been fully implemented.

Due to the above-mentioned reasons, developing energy-efficient hardware and governing software is still challenging for developers.

This research has two objectives: 1) devising a protocol enabling energy transparency for the new IoT devices , and 2) optimizing the software aspect of the current devices using Artificial Intelligence (AI). We believe that the energy transparency protocol for IoT systems should enable hardware manufacturers to produce energy-efficient IoT devices and software programmers to develop energy-efficient systems. Moreover, implementing feedback mechanisms with optimization algorithms in software should minimize the energy consumption in current IoT systems.

2 | Literature Review

The widespread adoption of IoT-enabled Wireless Sensor Network (WSN) has changed data collection and monitoring in manufacturing, healthcare, agriculture, and environmental sensing [12]. These networks' sensor nodes need efficient power optimization to maintain functionality, reliability, and data accuracy. This literature review discusses power optimization in IoT-enabled WSN and reviews current research. It also lays the groundwork for the AI-DrivenPower optimization framework, emphasizing Deep Q Network (DQN) and

Dynamic Voltage and Frequency Scaling (DVFS). Much work has been done to optimize the energy consumption of IoT devices. However, a lot of work has been done to optimize the energy consumption of systems (smart grids, industry 4.0, smart cities, etc.) that use IoT devices as tools [13]. Considering billions of interconnected devices, their energy consumption cannot be ignored, and optimization using different hardware and software alterations is necessary. This section will first cover the relevant studies. Li and Kara [14] used WSNs and the IoT to monitor manufacturing. Research emphasizes the importance of sensor data in improving manufacturing processes and operational efficiency [15]. It also stresses the need for power-efficient strategies to extend network life. For low-power WSN, Fernandes and Brandão [16] developed a receiver-initiated Medium Access Control (MAC) protocol to optimize energy consumption. Theirresearch focuses on optimizing communication protocols to reduce energy usage in WSN.

Along with communication protocols, adaptive power management can boost WSN energy efficiency. Onasanya and Elshakankiri [17] examined cloud services and secure cancer care in IoT/WSN medical systems. According to the study, data security and patient care are crucial in healthcare applications. Energy-efficient sensor nodes extend battery life, ensure uninterrupted monitoring, and reduce maintenance. Izaddoost et al. [18] studied optimizing energy consumption during data transmission in IoT platforms. Their work emphasizes energy-efficient data transmission, which is essential to power optimization.

An energy-efficient strategy can significantly reduce WSN data transmission power usage. Co et al. [19] developed a time-synchronized WSN data collection and transmission protocol designed for low-cost IoT. As their research shows, power optimization requires effective data collection and routing. Effective routing can reduce energy use and improve network reliability.

3 | Energy Transparency in Internet of Things Devices

This section of the paper focuses on devising the protocols for energy transparency in IoT devices. We also propose a novel approach for minimizing energy consumption for IoT systems using energy transparency protocols and software optimization. We will also evaluate our approach to compare its performance with other known methods.

Energy transparency helps determine and gauge the energy consumed by an IoT device while measuring, processing, and communicating data.

4 | Artificial Intelligence-Based Internet of Things Energy Management

With millions of devices in place, it will become impossible to track, monitor, and manage their operation manually or use general controlling methods unless a significant amount of energy and processing power is consumed. AI-based techniques learn from events and improve output, productivity, and energy efficiency without human intervention. This study utilizes reinforcement learning-based, real-time, adaptive fuzzy logic systems coupled with genetics.

5 | Simulation Results

A feedback mechanism for IoT energy consumption is also implemented in the simulation. All the agents incorporate the feedback mechanism coming from IoT devices. The agents optimize energy consumption by observing the necessity versus frequency of transmitted data over the communication network. When similar data is being received and processed over a period, the reinforced learning algorithms reduce communication to the point where it is very necessary.

6 | Role of Artificial Intelligence in Power Optimization

WSN needs AI to optimize power usage. In resource-constrained environments, WSN must conserve energy to function properly. Reinforcement learning and DQN power consumption optimization are flexible and responsive.

DQN: DQN, a reinforcement learning deep learning model, optimizes power management policies by making sequential decisions. The system uses a Q-learning algorithm to learn the best actions in a state to maximize rewards. DQN seeks mathematical knowledge of the optimal action-value function (Q-function). The Q-functionQ(s, a) determines the best action given the current state, the action 'a' taken, the immediate reward 'r,' and the subsequent state's'. The Bellman equation updates the Q-function iteratively represented in *Eq. (1)*.

$$Q(s,a) \leftarrow Q(s,a) + \alpha[r + \gamma \max Q(s',a') - Q(s,a)], \quad (1)$$

where, α= "learning rate", γ= "discount factor", r= "immediate rewards", s= "current state", a= "action taken", s'= "next state", a'= "action in next state."

A deep neural network estimates the Q-function in the DQN algorithm, allowing it to handle state spaces with many dimensions, which are common in sensor networks. Engaging with the environment trains the network to make power-efficient decisions. DQN adaptability to dynamic network conditions benefits WSNs.

DVFS: hardware-based DVFS optimizes processor voltage and clock frequency to save power. Sensor nodes in WSN can use DVFS to adjust their voltage and frequency based on computational workload. This saves a lot of energy. Digital circuit power (P) is usually expressed mathematically as in *Eq. (2)*.

$$P = (½). C. V. V. f, \quad (2)$$

where, p= "power consumption", c= "total capacitance", v= "operating voltage", = "clock frequency".

DVFS adjusts processor voltage (V) and frequency (f). This adjustment reduces power consumption during low computational demands and boosts performance when needed. This adaptive mechanism ensures that sensor nodes use the minimum power needed to achieve their goals, conserving energy and extending network life.

AI-powered DQN and DVFS in WSN enable flexible and intelligent power management. DVFS optimizes hardware parameters for energy efficiency, while DQN learns from network conditions and adjusts power management strategies. All of these methods address energy efficiency in IoT-enabled WSNs [20].

7 | Conclusion

This study encompasses the imminent problem of IoT device energy consumption. With billions of such devices operating constantly and transmitting and receiving data, a model that can organize and control their energy consumption was needed. The paper focused on both the hardware and software aspects of energy conservation. The hardware aspects of energy consumption have been divided into four major parts.

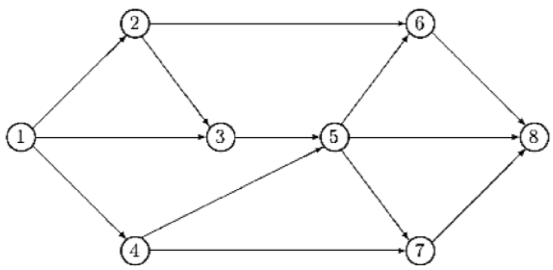

Fig. 1. Network with eight vertices.

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Author Contributaion

Conceptualization and research design

Vaibhav Singh initially proposed and developed the primary concept of the study on energy-efficient IoT networks through AI-driven approaches.

Methodology and model development

Vaibhav Singh led the development of AI-based models and energy optimization strategies, designing novel algorithms and conducting initial testing to ensure the models aligned with the study's energy efficiency goals.

Data collection and analysis

Vaibhav Singh managed the data collection processes, ensuring the quality and relevance of the data sets used for training and testing the AI models.

Software development and testing

Vaibhav Singh developed the implementation code for AI-driven optimization, managed software integration, and supported the software testing phase, troubleshooting, and debugging to ensure reliable performance across different IoT network conditions.

Funding and project administration

Vaibhav Singh managed project funding and resource allocation.

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Any opinions, findings, or conclusions expressed in this work are those of Vaibhav Singh and do not necessarily reflect the views of the funding organization.

Data Availability

The data sets used in this study on energy-efficient IoT networks using AI-driven approaches were sourced from publicly accessible repositories and, where applicable, proprietary IoT network datasets to model real-world scenarios. Specific data on IoT network traffic, energy consumption, device usage patterns, and network performance were anonymized to protect privacy and were preprocessed for the study.

Public datasets

The research relied on publicly available datasets, including those related to IoT network performance, energy consumption metrics, and simulation models that provide general patterns applicable to energy-efficient IoT applications.

Proprietary datasets

Where necessary, proprietary data from specific IoT network case studies were employed under restricted use conditions to validate model performance. Access to proprietary data may be subject to institutional permissions and data-sharing agreements.

Generated data

Additional synthetic data were generated to model edge cases and optimize the AI models. These synthetic datasets have been made available in the project repository for reproducibility.

Researchers interested in proprietary or sensitive data used in this study may request access by contacting Vaibhav Singh, subject to institutional approvals and confidentiality agreements.

Conflicts of Interest

Vaibhav Singh declares no conflicts of interest in this research paper on energy-efficient IoT networks using AI-driven approaches. The research was conducted independently, and no financial or personal relationships influenced the outcomes or interpretations presented in this study.

If any potential conflicts arise in the future, Vaibhav Singh is committed to disclosing them transparently to uphold the integrity of the research.

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