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Secured Wireless Sensor-Based Energy Efficient Smart Socket for Enhanced Power Monitoring and Conservation Using Internet of Things

AKIAKEME, E. [1,*], ***OKPOR, M. D*** [2], ***EBOKA A. O.*** [3], ***ODIAKAOSE, C. C.*** [4], ***EJEH, P. O.*** [5] ***AKO, R. E.*** [6], ***GETELOMA, V. O.*** [7], ***BINITIE, A. P.*** [8], ***AFOTANWO, A.*** [9]

[1,6,7]*Department of Computer Science, Federal University of Petroleum Resources, Effurun, Nigeria*
[2]*Department of Cybersecurity, Delta State University of Science and Technology, Ozoro, Nigeria*
[3,8]*Department of Computer Education, Federal College of Education (Technical) Asaba, Nigeria*
[4,5]*Department of Computer Science, Dennis Osadebay University, Asaba, Nigeria*
[9]*Department of Computer Sci., Federal Polytechnic Orogun, Nigeria*

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ABSTRACT

Transformative potential of smart sockets extends beyond energy monitor and conservation. It catalyses a paradigm shift towards proactive energy management and yields improved insights into energy consumption patterns. Thus, users can implement targeted interventions to optimize energy usage, mitigate wastage, and reduce operational costs. Moreover, the integration of smart sockets within larger IoT ecosystems engenders synergistic effects, enabling seamless interoperability with smart appliances, energy grids, and renewable energy sources. Through intelligent load balancing, demand response mechanisms, and predictive maintenance algorithms, smart sockets facilitate the seamless orchestration of energy resources, fostering a resilient and sustainable energy infrastructure.

1. INTRODUCTION

Energy monitor, conservation and alert emerged as a critical and crucial imperative in today's society. It is driven by the escalated energy demands, dwindling natural resources, and need to curb the societal repercussions of energy consumption (Aghware, Ojugo, et al., 2024; Sutikno et al., 2023). Smart sockets do harness the power of sensor-based networks, Internet of Things (IoT) and microcontrollers – and promises to tackles the challenges as above (Akazue, Okofu, et al., 2024; Obruche et al., 2024; Okperigho et al., 2024). Smart sockets are imbued with intelligence to offer a transformed mode to efficient management of energy as real-time monitor and control over consumption of connected items (Ojugo & Otakore, 2018, 2020b, 2020a, 2020c). Using data analytics and seamless integration with existing infrastructure, smart socket has ushered in and empower user with invaluable insights that supports decision-making, and fosters a culture of efficient energy utilization.

Extending enhanced energy efficiency, smart sockets have become potent tools that promotes eco-friendly, sustainable society to help mitigate carbon footprint from various pollutions (Omede et al., 2024). It empowers users with real-time feedback on energy use and help users to cultivate accountability and awareness that fosters a culture of conscious consumption and environ stewardship (An et al., 2015; Ihama et al., 2023). Integrating of demand management and renewable-energy

*Corresponding author, e-mail:maxwell.obiorah@gmail.com
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sources, smart sockets optimize distribution, minimizes reliance on fossil fuels, mitigates pollution and greenhouse gas emissions (Hurt, 2019; Westerkamp et al., 2018). It acts as catalysts for behaviour change and advocate sustained living practices; while, playing a pivotal role for harmonious existing between human activities and the environ (Malasowe et al., 2023; Malasowe, Edim, et al., 2024).

At its crux, is the fusion of sensor-based network, IoTs and microcontroller – to unveil and engenders a symbiosis of both hardware and software elements (Krishna et al., 2023; Vinoth et al., 2021). These, leverages on the ubiquity of the internet to allow connectivity with various other components; And can be used seamlessly to interface with a diverse range of other electronics appliances. It has been successfully adapted to both home and industrial frontiers – enabling comprehensive monitor and control consumption of energy across various areas (Brizimor et al., 2024; Obasuyi et al., 2024). Harnessing processing and computational prowess of embedded systems and microcontroller, these intelligent devices can process vast data-streams in real-time, facilitating granular insights into energy usage patterns, fluctuations, and anomalies. Through various refinements, it will evolve into adept energy management tools that can be dynamically adapted to users' preferences, societal conditions, and energy tariffs aimed at maximizing efficiency, and to minimize waste (Ojugo & Otakore, 2020d; Ojugo & Yoro, 2020b; Pradeepa & Parveen, 2020; Sedlmeir et al., 2020).

Studies have intensified toward crafting more functional and user-centric smart socket. Some are poised to explore IoT-based smart energy meter using Arduinos, Wi-Fi modules and controller to advance real-time monitors with remote load control as revolutionized energy management technologies (Conte et al., 2008; Ojugo, Akazue, Ejeh, Ashioba, et al., 2023; Ojugo, Odiakaose, Emordi, Ako, et al., 2023). Similarly, Kizilkaya et al. (2022) explored IoT-driven energy monitors tailored for domestic use that leveraged the prowess of controllers and wireless comms to push toward democratized access and managing of energy. It fostered greater user empowerment and engagement, advancing a paradigm shift towards a more accessible and intuitive mode to conserve and manage energy (Akazue et al., 2022, 2023; Kizilkaya et al., 2022; Ojugo & Okobah, 2017, 2018; Shoeibi et al., 2022).

1.1 Smart Sockets and IoTs

Earlier on, researchers have underscored the significance of energy conservation and have embarked on use of diverse schemes to address this concern (Jolicoeur-Martineau et al., 2021). The transformative capabilities of IoTs and sensors in optimized consumption and to oversee electronics appliances (Ojugo, Ejeh, Akazue, Ashioba, et al., 2023; Okpor et al., 2024). Divakar (2020) investigate energy monitor and anti-theft system employing IoT technology, aimed at detecting and thwarting instances of electricity pilferage (Divakar et al., 2022). Others studies have also echoed similar sentiments that the potentials of IoT devices in orchestrating energy management within smart homes, accentuating critical role to monitor and regulate consumption patterns (Akazue, Edje, et al., 2024; Hasan et al., 2023; Ukadike et al., 2023). This underscore the burgeon interest and multifaceted potential of IoT solutions to resolve energy conservation to reshape the trajectory of sustained growth and development (Allenotor et al., 2015; Allenotor & Ojugo, 2017; Lee et al., 2020).

This also creates an imperative for robust security protocols to safeguard IoTs against sensor-based vulnerabilities. Yoro et al (2023) proposed innovative schemes aimed at efforts to monitor energy consumption as anti-theft system leveraging IoT, and focused aimed to thwart (as detected) energy pilferage (Yoro, Aghware, Akazue, et al., 2023; Yoro, Aghware, Malasowe, et al., 2023) – which has since become a menace that exacerbates energy wastage as well as inflicts substantial financial losses upon utility providers.

As the trajectory of research unfolded, a paradigm shift towards more sophisticated and intricate systems became evident. Bhalerao and Ansari (2018) unveiled a pioneering home automation framework employing Arduino and IoT technologies, seamlessly amalgamating energy monitoring functionalities with automation capabilities. Concurrently, Oliviera et al. (2016) devised an IoT-based electricity load management system, offering an efficacious mechanism for managing energy distribution during periods of peak demand (Oliveira et al., 2016). These advancements underscored a palpable evolution in the landscape of energy conservation and management, marked by a transition towards increasingly intricate and multifaceted solutions aimed at enhancing efficiency, resilience, and sustainability in energy utilization (Lucas et al., 2019).

1.2. IoT-Enabled Track and Monitor

With the traction gained by IoT systems, studies have begun to integrate these techs into smart socket solutions. Tsai et al. (2016) advanced residence energy control system – a wireless smart socket that explores IoT to limit energy consumption without the extra sensors. It streamlined energy management and offered a low-cost, effective solution to mitigate energy wastage (Muhammad et al., 2019). Similarly, Ma et al. (2018) devised an energy-efficient smart socket built upon the STM32F103 controller platform. Engineered to combat standby waste and ramifications, this solution exemplifies a concerted effort to optimize energy utilization via embedded systems use. It leverages the computational feats in microcontrollers and IoT connectivity, Ma et al. (2018) smart sockets embody a holistic approach to energy conservation, emphasizing not only energy efficiency but also cost-effectiveness and user convenience. These pioneering endeavours underscore the transformed potential of IoT and embedded systems in reshaping energy management paradigms and advancing the agenda of sustainable development.

As research endeavours progressed, the fusion of IoT and embedded systems within energy management systems gained notable traction among scholars. Dike et al. (2016) pioneered the development of an IoT-based electricity load management system, employing an Arduino microcontroller and Wi-Fi connectivity. This innovative system facilitated effective regulation of electrical energy distribution, particularly during periods of peak demand, thereby obviating the necessity for additional infrastructure investments and larger generator capacities. Concurrently, Janaki and Ramamoorthy (2016) conducted a comprehensive survey of various IoT-based energy management systems, delving into the intricacies of establishing IoT architectures for data collection and load control, thus laying the groundwork for future research endeavours in the domain.

Despite these advances in smart socket, several challenges remain. Manickam et al. (2022) addressed these challenges in energy selection and demand response management on smart grids via a reinforcement learning with game-theory mode (Manickam et al., 2022). Both Aworonye et al. (2024) and Onya et al. (2024) proposed an open-source smart socket that fuses price awareness and energy monitoring as important to its management solutions (Aworonye et al., 2024; Ibor et al., 2023; Omoruwou et al., 2024). Despite the progress made, several issues persist today – so that tailored solutions are used to resolve specific scenarios and limit their widespread adoption. In addition, interoperability, data privacy and security between various vendors must be addressed also (Ejeh et al., 2024; Figueiredo et al., 2013; Ojugo et al., 2021a, 2024).

With a extensive review of literatures, we documented current efforts with extended integration with existing techs to result in improved functionality and reliability. The study (Ojugo & Yoro, 2020a) as thus:

1. **Compatibility / Interoperability:** Many smart sockets are designed for specific systems, making them incompatible and inoperable with a wide range of devices. With this barriers to seamless integration, it in turn limits the scalability of energy management across different frontiers for

use (Ojugo, Allenotor, Oyemade, et al., 2015).

2. **Complex Configuration:** Sockets often requires extensive configuration, making them a challenge for non-technical users to adopt. This complexity can discourage widespread adoption and hinder effective implementation of energy conservation measures (Estes & Streicher, 2022).
3. **Interfaces:** Energy monitors often suffer from unintuitive or poorly designed user-interfaces, that are difficult to understand. This lack of user-friendliness can lead to frustration and reduced engagement with the system (Hennink & Kaiser, 2022).
4. **Real-Time Monitor:** Smart sockets often lacks real-time control monitoring feats that restricts users' ability to prompt reply to energy consumption patterns and make timely adjustments to optimize energy use (Yoro & Ojugo, 2019a, 2019b).

To overcome these, we implement the smart socket as thus: (a) explore a comprehensive knowledge of existing system aimed at understanding their capabilities and limitations, (b) we adapt current trends in IoTs crucial to energy consumption, (c) identify design requirements for the smart socket for reliability, and user-friendliness, (d) implement a prototype system, and (e) evaluate its effectiveness and usability via realtime test (Ojugo, Ejeh, Odiakaose, Eboka, et al., 2023; Wemembu et al., 2014). It promises revolutionary change in the monitor of energy consumption with improved user-friendly interface for functions, and assured reliability.

2. MATERIALS AND METHODS

2.1. The Existing Framework

Existing monitor is based on Ma et al. (2021). It sought to address the issues raised with a critical feat of realtime energy monitor and consumption for home fronts. With the gaps like (Ako et al., 2024; Ojugo & Eboka, 2014, 2018b, 2018a, 2019, 2020, 2021). They deployed an energy-efficient smart socket based on STM32F103. Its development has gained significant attention to reduce standby energy waste associated with household item (Ojugo & Ekurume, 2021; Oyemade et al., 2016; Oyemade & Ojugo, 2020; Setiadi et al., 2024) as seen as in Figure 1.

Existing technical solutions overlook the techno-economic benefits at its development process. They used STM32F103-controller, which incorporates Cortex-M3 operating at a maximum speed of 72MHz. The solution was to address standby energy waste in household electronics (Ojugo, Ugboh, Onochie, et al., 2013; Ojugo et al., 2021b). It curbed energy losses by using an input-output analysis of monitored voltage and current to assess system performance and precision. The socket was designed to be compatible with remote and wireless microcontrollers, and enhanced operation ease. Experimental results showed it accurately measured current voltage values to prevent over-voltage with enhanced security; while, monitoring current values with high precision to support energy-saving control. Its function testing along with lifecycle assessment, validated the economic attractiveness of the system.

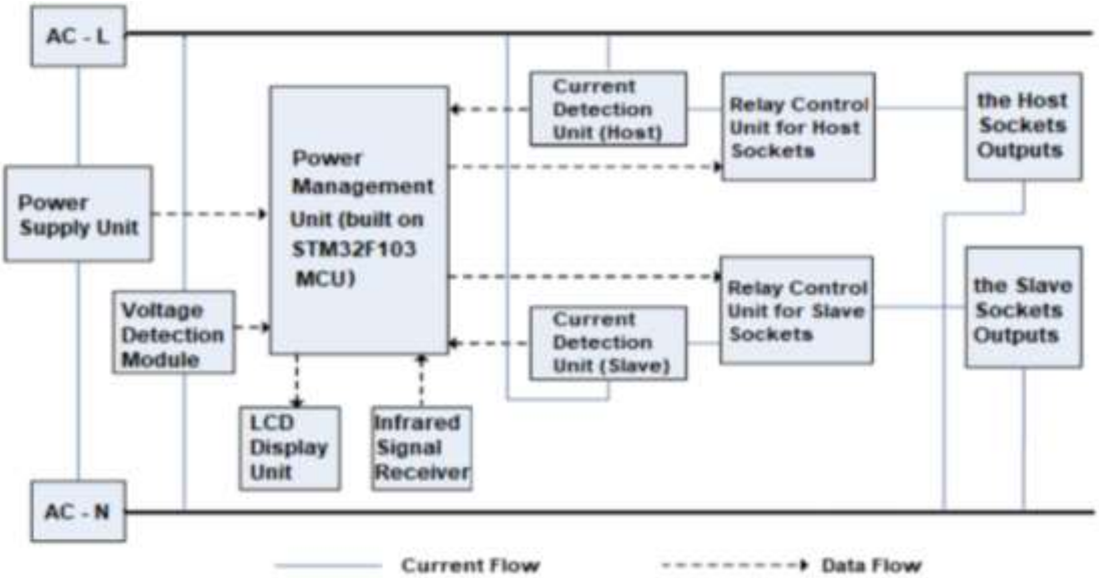

Figure 1. The Hardware Assembly of the Existing System (source: (Ma et al., 2021))

2.2. The Experimental Framework

Our framework yields the Figure 1 with both hardware and software units. It consists of the sensors and microcontrollers, each of is designed to monitor energy consumption.

Ensemble detects instantaneously via the ESP8285 and it is sensors ensure energy use is traced/monitored in real-time (Kakarlapudi & Mahmoud, 2021; Singh & Sharma, 2017). To ensure faster system response, all sensors and components are connected via the node-MCU to detect coordinates within 30.3metres (i.e. 100feets). This ensures that indoor and outdoor data generated via wireless sensors, are sent as fastest time possible as in Figure 1 and Figure 2 respectively. The node-MCU analyses all data, and compares output with set threshold to determine the point of origin with set features such that if it exceeds the pre-set energy threshold value(s), it indicates the existence of change in consumption. This occurs in real-time to yield a more reliable, efficient monitor of energy.

The proposed system addresses several weaknesses identified in the existing system with significant improvements (Sarwar et al., 2019; Sendra et al., 2020; Sungheetha & Sharma R, 2020) with ESP32 microcontroller that fuses advanced data analytics feats, the proposed system offers enhanced capabilities for energy management. Unlike the previous system, which primarily focused on basic voltage and current monitoring, the proposed system will leverage the ESP32's abilities to implement sophisticated energy management strategies (Laxmi et al., 2018; Lukmam et al., 2021; Martinus et al., 2021; Nartey et al., 2021; Uddin et al., 2021; Xu et al., 2019).

It includes real-time analysis of energy consumption patterns, allowing for dynamic optimization of energy use based on demand fluctuations. Additionally, integrating of data analytics features will enable the system to identify trends and anomalies in energy usage, facilitating proactive energy-saving measures and predictive maintenance (Eboka & Ojugo, 2020; Oyemade & Ojugo, 2021; Zhang et al., 2019). Also, the ESP's compatibility with a range of devices ensures greater flexibility and inter-operability across various domain electronics (Ojugo, Aghware, Yoro, et al., 2015b; Ojugo, Eboka, Okonta, et al., 2015).

Proposed system yield significant move, offering improved energy efficiency and intelligence, with adaptable management to energy conservation cum consuming (Ojugo, Aghware, Yoro, et al., 2015a; Ojugo, Akazue, Ejeh, Odiakaose, et al., 2023; Ojugo, Eboka, Yoro, et al., 2015; Sathyakala et al., 2018; Shahraki et al., 2018; Sharma et al., 2020; Srivastava et al., 2020).

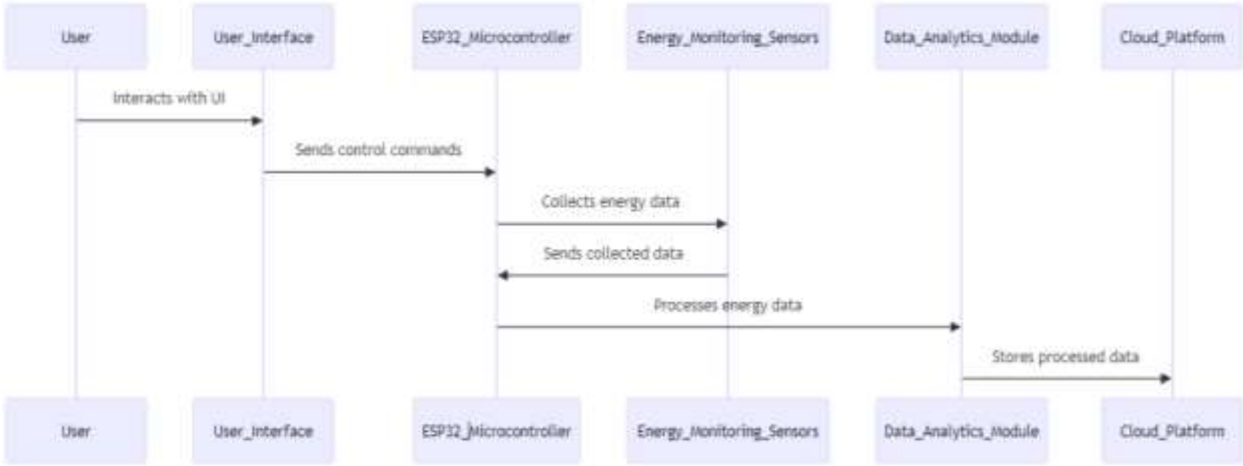

Figure 2. Sequence Diagram of the Proposed Smart Socket System (Source: (Parameswaran & Bhuvaneswari, 2021; Radouan Ait Mouha, 2021))

3. RESULT FINDINGS AND DISCUSSION

3.1. Model Performance and Benchmark

Shortest path heuristic includes a single-path between a source to all other vertices and all-pair path which evaluates the shortest path between all vertices in a graph. To determine the chosen route for a child as we extend the coverage, we consider a single-source yields fastest responses – comparing Dijkstra versus Bellman's Ford to identify the shortest, most efficient path between any 2 nodes (Allen et al., 2024; Sinha, 2024). Dijkstra out-does the Bellman Ford in both (un)directed nodes with positive weights, and on a comparative time analysis. Dijkstra's algorithm yields a time complexity of $O(|E|+|V| \text{Log}|)$, which agrees with (Abernathy, 2021; Tomar & Manjhvar, 2015). While, the time required is $O(|V|\times|E|)$ and agrees with (Otorokpo et al., 2024).

The comparison shows Dijkstra is faster than Bellman-ford. For the longest amount of nodes (Muslikh et al., 2023; Oladele et al., 2024; Safriandono et al., 2024), Djikstra yielded a 2.072secs response time; while the Bellman-Ford yielded a response time of 9,577secs. And it is supported by the works of (Ojugo, Abere, Orhionkpaiyo, et al., 2013). Proposed system integrated various units to enable efficient energy management within household environments. It used the ESP32 to aid data collection, analytics, and device control. Connected to the ESP32 are energy monitors that capture real-time energy consumption from electric appliances. These are processed by the data analytics module, to analyse consumption patterns and identify anomalies. Its friendly user-interface makes accessibility via web to effectively manage and control connected devices remotely. In addition, it explores cloud-platform to store and process data, with improved scalability, reliability, and security. This framework enable an optimize energy use, enhance user convenience, and contribute to sustainable energy management practices.

3.2. Findings and Discussion

Findings further demonstrated system is user-friendly, cost-effective, and independent of additional wiring or network environment, making it highly accessible. Additionally, the system extends the lifespan of appliances and enhances safety with benefits beyond energy use efficiency (Jabbar et al., 2021; Laddha et al., 2022; Ojugo, Yoro, Oyemade, et al., 2013; Ojugo, Yoro, Yerokun, et al., 2013). Robust emergency response abilities that proves crucial in timely response and resolution of high-risk scenarios (Binitie et al., 2021; Malasowe, Aghware, et al., 2024).

As the tech continues to evolve, future research in this area is expected to focus on developing more integrated and intelligent smart socket systems that can adapt to user preferences and behaviour patterns. The

*Corresponding author, e-mail:maxwell.obiorah@gmail.com
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integration of advanced machine learning and artificial intelligence techniques may further enhance energy management capabilities, leading to more efficient and sustainable energy consumption practices. Overall, the development of energy conservation and monitoring smart sockets using IoT and embedded systems has garnered significant attention from researchers and industry alike. While substantial progress has been made, there is still room for improvement and innovation to address the evolving energy challenges in our society (Aghware, Adigwe, et al., 2024; Emordi et al., 2024).

4. CONCLUSION

Study models a fuzzy system that fuses sensors and ESP8285 controller to determine fire probability output. It alerts users via a send algorithm having monitored energy conditions as they quickly change. Previous systems were found to have provided false alarms owing to their configuration logic. Experimental design that yielded the proposed ensemble however notifies residents of the source and location using a shortest distance algorithm (Okonta et al., 2013, 2014). The proposed ensemble is efficient, reliable and can handle dynamic changes as in the send algorithm. It efficiently was integrated on to the existing infrastructure so as to effectively reduce loss of life and properties. Increased the adoption of machine learning scheme with automated processes with industrial IoT technologies both on the home frontiers and industrial applications has continued to drive up demand for adaptation of advanced flame detection solutions.

Conflict of Interest

The authors declare that there is no conflict of interest.

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