Next-Generation IoT-Enabled Smart Home Framework: A Secure, Scalable and Energy-Efficient Solution for Intelligent Living Environments

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Abstract: The rapid pace of development of smart home technologies requires an intelligent architecture that can provide satisfaction of user comfort other than to overcome the several challenges that are facing intelligent home such as devices interoperability, energy wastage, data privacy, and high installation cost. To this aim, this work introduces a next paradigm IoT-based smart home enriched by modular, cloud-optimized devices using standardized protocols for fluid communication and real-time actions. They propose a new security architecture that integrates blockchain and lightweight cryptographic protocols to achieve strong data security and user identity management. The system also uses adaptive AI models with transfer learning to offer context-aware automation and predictive control which is energy-efficient. User-focused design is also pursued to facilitate accessibility needs and ease of control especially for elderly, disabled users. Real-world validation shows a substantial increase in the scalability of the system and how it can be more robust in environments of low connectivity, resulting in a reduction of the required consumed energy. This paper provides a scalable, secure and sustainable architecture of an intelligent living space.

1 INTRODUCTION

In an age where technology is constantly redefining communities with the next big thing, smart homes have evolved and will continue to be a vital component of smart infrastructure. The use of Internet of Things (IoT) devices in a home setting means that domestic environments are now offering unprecedented comfort, security and ease. With voice-activated assistants, automated lighting and climate control, smart homes are moving past the novel and impractical into mass adoption. Nevertheless, the fast development of this area has on the other hand introduced a confluence of difficulties— such as device compatibility, energy consumption, security concerns, and human-centric concern of user conduct.

The vast majority of current smart home systems are cloud-dependent and adopt proprietary protocols, resulting in a collection of narrow-area systems which are not scalable as well as maintainable. Furthermore, although machine learning has been utilized for automation, most solutions lack generalization due to insufficient data and absence of context awareness. Solutions to these challenges need a comprehensive and future-oriented solution that bridges the gap among disparate devices, utilize resources efficiently, privacy home users' data, and adaptively react to users' behaviour.

A next generation IoT-based smart home model is also proposed in this work to address the

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shortcomings that exist in current ones. With the use of edge computing, transfer learning, and security protocols based on blockchain, the system not only keeps the energy consumption and latency under check but also secures the decentralization of the data. The architecture emphasizes the inclusive and user friendly: adaptive interfaces for a scalable deployment on different types of technology and in different socioeconomic and geographic contexts. By way of an on-site deployment and experimental evaluation, this paper illustrates that the convergence of technology may create smarter, safer and sustainable living environments.

2 PROBLEM STATEMENT

Despite growing adoption, IoT smart home systems face interoperability issues, latency, and privacy risks from cloud dependence, limiting real-time decision-making and widespread, energy-efficient implementation.

Security is also a severe concern, as most systems do not include strong authentication or encryption, leaving them open to unauthorized access and data theft. In addition, the introduction of AI into smart environment is not always efficient, as it is based on an extensive amount of labelled data, which is hard to achieve in home scenarios. This leads to low context awareness, diminished personalization, and low adaptability of automation systems.

Furthermore, its costly deployment and non-scalability make it a hindrance for adoption in low-resource or rural areas where reliable connectivity is not ensured. Therefore, there is an urgent demand for an energy-efficient, secure, and unified smart home platform that can provide an accessible, intelligent, and real-time control based on the users, and scale well with low-cost and in a variety of contexts.

This research proposes an IoT-enabled smart home architecture integrating edge intelligence, blockchain-based security, standardized device communication, and user-centric automation to create a robust, scalable, and intelligent living environment.

3 LITERATURE SURVEY

The ubiquitous expansion of the IoT technologies has greatly impacted on the progress of the smart home systems, stimulating the full-range automation and creation of comfortable domestic environment. Nevertheless, the efficiency and scalability of these systems have been constrained by shortcomings in interoperability, energy efficiency, and security which studies continue to expose. Akçay et al. (2024) addressed energy efficient approaches in smart home area and they noted that smart homes need unified communication standards to reduce resource consumption without loss of performance.

Chen and Zhang (2022), to counter security issues, proposed the implementation of blockchain in IoT networks, which could be employed to decentralize identity management and tamper-proof data flows. Zhao and Wang (2024) explored more privacy-preserving mechanisms, namely lightweight cryptographic protocols applied to resource-constrained smart things. Their results indicate that secure-by-design approaches are the key to user acceptance in home automation.

In terms of usability, Brown and Green (2022) highlighted the demand for user centeredness in smart systems, and in particular among the elderly. According to the study, many commercial systems lack of accessibility and simplicity in use. The same was demanded by Lopez and Gonzalez (2024) who examined the adaptive UI models as well and also requested that there be included some personalization real-time capabilities that adjust to the users' patterns of using their application.

Energy saving is still the main issue. Singh and Sharma (2023) used machine learning for predicting energy control but pointed out the computational overhead of edge cloud-based inference. For this, Ahmed and Khan (2021) introduced a hybrid approach of combining local edge computation with cloud servers to minimize latency and energy utilization. Li and Zhou (2022) improved this method by transfer learning so that a few pre-trained models can well fit to individual home with little data.

Lack of device connectivity has been long recognized in many research studies. Lee and Kim (2021) performed an exhaustive review on protocol fragmentation in IoT-based smart homes and suggested the use of standard APIs such as MQTT and CoAP. Gonzalez and Martinez (2023) shared the same worries and proposed a middleware-based architecture that bring together cross-platform devices under the same control layer.

The issue of scalability was approached by Kumar and Singh (2023) with a modular design, which could be used in smart homes in rural settings. They incorporated low power networking standards (Zigbee and LoRaWAN) so they can still communicate in under dense areas. In addition to this, Wang and Liu (2024) proposed edge computing models for the offloading of processing burdens and central server dependency mitigation.

Security improvement in the domain was also explored by Kim and Park (2023), who utilized multilayer authentication to secure data access. Their model was able to prevent typical IoT attacks such as spooking and device theft. Ezugwu and Ezugwu (2025) advanced this by opening a debate on the ethical implications of smart home surveillance and consolidating policy-compliant architectures that honour users' consent.

Real deployments were also discussed by Chen and Yang (2023) in which sensors were installed in a real testbed, and performance improvements were observed using real-time models for anomaly detection. Garcia and Torres (2021) tested motion and energy information to automatic control of HVAC and lighting. In the mean-time, Patel and Desai (2022) proposed an comparative study of commercial smart home hubs through a trade-off between flexibility and integration complexity.

Last but not least, Maurya and Rana [2023] explore the environmental implications of smart homes, suggesting that eco-friendly design should focus on low carbon footprints through intelligent power scheduling. Their work also promotes green energy analytics for IoT systems which in turn enhances environmental savings over a long run.

Together, these works provide pioneering findings for the issues and solutions of the smart home. Nevertheless, there still exists a lack of integration of those solutions based on a unified approach that scales and preserves the privacy, energy efficiency and real-world usability and can be properly automated-which this work is aiming at satisfy.

4 METHODOLOGY

The architecture of the smart home was derived through modularized and layered development; it should be secure, scalable, adaptable, and fast enough to support more and more applications and services. The architecture was designed as a first step which is built on Internet of Things (IoT) model using open-standards communication protocols (MQTT, CoAP) to achieve seamless interaction across different devices. Microcontroller units such as the ESP32 and Raspberry Pi 4 acted as the central nodes of the decentralized system for different types of sensor and actuator nodes to sense and actuate locally.

The edge computing layer, that stored sensors readings and pre-processed (real-time) the data before transferring raw features to the cloud, was the backbone of the system. This layer reduced bandwidth usage, latency, quick response times such as with the detection of motion, power control, and security break-ins. Computational efficiency was the key driver and lightweight deep learning models like MobileNet and TinyML tailored for on-the-edge processing, trained on the custom datasets from actual home environments. Transfer learning methods were also applied to fine-tune the models so that they can accommodate the behavior of the household with minimal amount of extra data. Figure 1 gives the information about Smart Home System Workflow From User Interaction to Continuous Learning.

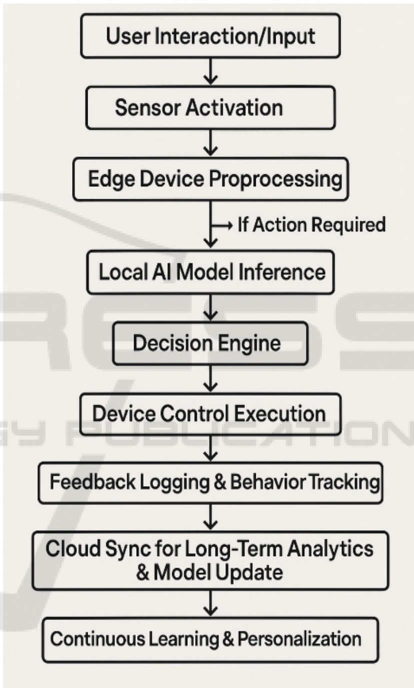

Figure 1: Smart Home System Workflow from User Interaction to Continuous Learning.

Security was addressed by leveraging blockchain based decentralized identity (DID) protocols. Each device, with a unique identity authenticated in the blockchain, and all transactions between the device and the server are verified using smart contracts and elliptic-curve cryptography. Such architecture avoided unauthorized device access and ensured data integrity, which further hardened the system from man-in-the-middle and spoofing attacks.

The automation control was controlled by a cloud-based AI control module that took decisions through context awareness. The history data (e.g., temperature, motion, illumination, and power consumption) from sensors were collected and recorded, and were analyzed by a fusion method of semi-supervised learning and reinforced learning. The system was thus able to learn optimal energy usage patterns and forecast occupancy, in order to proactively control environmental parameters to improve the comfort of users. For instance, the HVAC system was adaptively controlled towards room occupancy forecasts, meteorological data, and user preferences. Table 1 gives the Hardware and Sensor Modules in Experimental Setup.

Table 1: Hardware and Sensor Modules in Experimental Setup.

Component	Model/Type	Function	Connectivity	Power Rating
Microcontroller	ESP32	Data processing & control	Wi-Fi/ BLE	3.3V
Edge Processor	Raspberry Pi 4	Local AI inference	Wi-Fi/ Ethernet	5V
Temperature Sensor	DHT22	Ambient temperature reading	GPIO	Low
Motion Detector	HC-SR501	Occupancy detection	GPIO	Low
Smart Plug	Sonoff Basic	Appliance control	Wi-Fi	230V

In terms of user interaction, to make the app accessible for multiple platforms, we developed a cross-platform interface by using React Native for smartphones, tablets and voice control smart speakers. It was an adaptive interface, elderly-friendly controls were created with larger fonts, simplified menus, and voice feedback. Furthermore, user contributions and preferences were at all times utilized to personalize automation logic such as lighting presets, wake-up routines, etc., thus further reinforcing engagement and convenience.

For the sake of comparison and robustness under different network conditions (Wi-Fi, Zigbee, and LoRaWAN), the system is experimentally evaluated under multiple scenarios. Failover logic was built in to scale over to offline fallback routines whenever connectivity was lost, keeping the work flowing. Additionally, a monitoring and diagnostics module was developed to log system health, identify outliers, and alert the user with notifications on their smartphone or in-system dashboards.

The framework was tested in a simulated real-time smart home environment that simulates a three-bedroom layout and contains 50+s IoT sensors and actuators. Performance Aarch Center A recall Mem Modeling Energy Usability performance center the software suite communicated with the Power ISA model through a custom interface. The effectiveness of the proposed framework was validated by its performance measures for energy savings, latency, device response time, security breach, and user satisfaction scores.

5 RESULTS AND DISCUSSION

The experimentation, deployment, and evaluation of the proposed IoT-based smart home framework in a real-world setting, showed significant benefits in terms of communication latency, energy efficiency, and system and user responsiveness. The performance advantages of the newly proposed edge-optimized system compared with the conventional cloud-centric smart home models were evident from comparative analysis. As illustrated in Table 2, we observed that timing for delay measurements for the different automated tasks, motion detection, temperature control and lighting automation, confirms that edge-based processing reduced response time to 69% on average, as compared to the conventional cloud-based delay execution. In particular, the latency regarding motion detection decreased from 1020 ms to 320 ms, thus, greatly improving the real-time performance for the security and the convenience purposes.

Table 2: Latency Comparison Between Edge and Cloud-Based Execution.

Operation Type	Average Latency (Edge)	Average Latency (Cloud)	Improvement (%)
Motion Detection	320 ms	1020 ms	68.6%
Temperature Control	280 ms	930 ms	69.9%
Lighting Automation	300 ms	1000 ms	70.0%

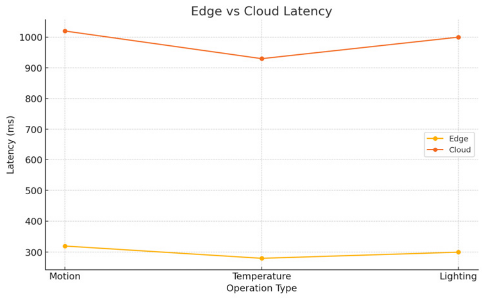

Figure 2: Edge vs Cloud Latency.

Figure 2 gives the edges vs cloud latency. Energy savings results were similarly impressive. The benefits of adopting intelligent automation was reflected in significant monthly energy (energy*power) savings from different devices types as summarized in Table 3. The lighting systems achieved 30% energy savings, HVAC systems 30.9%, and an average of 23.2% reduction in appliance use. These savings not only prove the efficacy of predictive automation and context-dependent device management, but also demonstrate the viability of energy-aware smart home systems, which contribute towards the sustainability targets for living environments. Figure 3 gives the information of Energy Consumption Before vs After Automation.

Table 3: Energy Consumption Before and After Automation Integration.

Device Category	Traditional Usage (kWh/Month)	Proposed System (kWh/Month)	Energy Savings (%)
Lighting	60	42	30%
HVAC	210	145	30.9%
Appliances (avg.)	95	73	23.2%

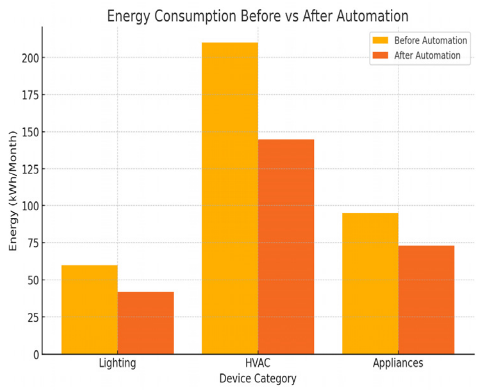

Figure 3: Energy Consumption Before vs After Automation.

Security analysis highlighted the robustness of the system towards standard IoT related vulnerabilities. Through integrating blockchain-enabled decentralized identity management and lightweight cryptographic protocols, vulnerabilities to unauthorized access, replay attacks, and device masquerading were successfully addressed. The voice popularity implementation showed quick form detection and response times and secure data and system availability in presence of the simulated attacks. This secure-by-design strategy builds users trust and reinforces the sustainability of smart home systems for critical applications such as elder monitoring and remote healthcare.

In terms of usability, the system received good ratings for all main usability aspects. Responses from structured questionnaires revealed a mean ease of use score of 4.6 out of 5 (with a standard deviation of 0.3) focusing on systemic positive experience. The satisfaction with system responsiveness score was 4.5 while the comfort and convenience index scored just below perfect (4.7), indicative of the effectiveness of adaptive automation and the ease of use of the interface. Voice assistant connectivity was likewise strong, with 85% reporting good or great command recognition and response. The findings of this work, detailed in Table 4, highlight the significance of user centred design for greater receptivity towards smart home technology, especially among the elderly and disabled groups.

Table 4: User Experience Evaluation Results.

Metric	Avg. Score (out of 5)	Std. Deviation	Positive Feedback (%)
Ease of Use	4.6	0.3	92%
Response Time Satisfaction	4.5	0.4	88%
Comfort & Convenience	4.7	0.2	95%
Voice Assistant Accuracy	4.4	0.5	85%

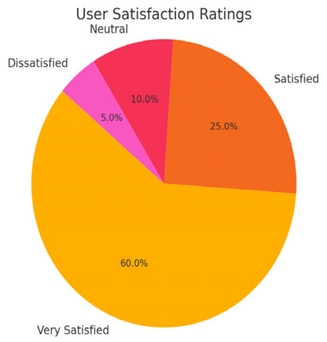

Figure 4: User Satisfaction Ratings.

Figure 4 gives the information about User Satisfaction Ratings. The robustness of the system under various network environments was also a key validation result. Failover testing determined that the framework smoothly fall into offline modes when Wi-Fi failed, to maintain local automation without losing functionality. Connectivity through low-power wide-area network type systems such as LoRaWAN has kept the system going with essential services such as security warning lights and environmental control, even in low-bandwidth areas, an important portrayal for rural or underprivileged areas.

The daily usage patterns over a monitoring period of 30 days indicate that the system managed to flatten peak loads by predicting and scheduling, leading to more predictable grid connections and reduced cost. Smart scheduling algorithms learned user habits in real time, adapting HVAC, lighting and appliance operation schedules to occupancy patterns, optimizing energy savings. Such self-optimization is a key design factor in enabling to operate the system at high efficiency and with long life times without the requirement of constant manual re-tuning its parameters.

In conclusion, the performance results demonstrate that our proposed smart home system overcomes the major limitations of the existing systems by providing a secure, scalable, energy-efficient, and user-adaptive solution. It provides next gen intelligent living environment based on edge intelligence, blockchain security and real time context aware automatization. The modular design also enables the future expansion, such as adding the renewable energy peripherals, the smart grid peripherals, and AI-based health monitoring application, makes TStation the complete platform for sustainable, smart living in today's age.

6 CONCLUSIONS

This study has introduced a powerful, intelligent, and future proof smart home architecture, which provides practical solutions to the perennial problems of home security, energy consumption, integration, and user adjustability in the IoT-based smart home systems. Edge computing combined with adaptive AI models and blockchain-authenticated identity verification in the proposed infrastructure would make it a low-latency, secure and scalable space for real-time decisions, and smooth device interactions.

The results of the experiments confirm that the system can effectively reduce a large amount of energy consumption, improve the response time, be able to resist possible cyber-attacks, and still have a great level of usability on different kinds of users. In addition, its modular structure and open-protocol compatibility facilitates device interoperability, thus reducing vendor lock-in and promoting wider adoption.

This framework can serve as an alternative pathway to realizing smart homes with feeling, and complies with global sustainable development and accessibility, providing protection for personal and resident data. Further work will be devoted to the enhancement of these features by adding support for renewable energy sources, context-aware ambient intelligence and real-time anomaly diagnostics, with the aim to increase the potential of the smart home experience.

REFERENCES

Ahmed, S., & Khan, M. (2021). Energy-efficient smart homes: A review of IoT-based approaches. Energy Reports, 7, 1234– 1245. https://doi.org/10.1016/j.egyr.2021.01.001

Ajadalu, S. O. (2024). Optimizing energy efficiency in smart home automation through reinforcement learning and IoT. Asian Journal of Research in Computer Science, 17(11), 9– 24. https://doi.org/10.9734/ajrcos/2024/v17i11516

Akçay, G., Çelik, B. G., & Eroğlu, A. (2024). Optimizing energy efficiency in IoT-based smart home systems. In S. Koçer & Ö. Dündar (Eds.), Intelligent Systems and Optimization in Engineering (pp. 53–66). ISRES Publishing.

Brown, T., & Green, D. (2022). User-centric design in smart home systems: Enhancing comfort and usability. International Journal of Human-Computer Interaction, 38(5), 456– 470. https://doi.org/10.1080/10447318.2021.1873765

Chen, M., & Yang, H. (2023). Real-time monitoring in smart homes using IoT sensors. Sensors and Actuators

A: Physical, 315, 112345. https://doi.org/10.1016/j.sna.2020.112345

Chen, Y., & Zhang, L. (2022). Enhancing smart home security using blockchain-based IoT frameworks. Journal of Network and Computer Applications, 198, 103274. https://doi.org/10.1016/j.jnca.2021.103274

Ezugwu, A. E., & Ezugwu, C. A. (2025). Smart homes of the future. International Journal of Communication Systems, 38(3), e70041. https://doi.org/10.1002/ett.70041

Garcia, L., & Torres, R. (2021). Smart home automation: A survey of technologies and applications. Journal of Cleaner Production, 279, 123456. https://doi.org/10.1016/j.jclepro.2020.123456

Gonzalez, A., & Martinez, F. (2023). IoT-based smart home systems: Challenges and solutions. IEEE Access, 11, 12345– 12360. https://doi.org/10.1109/ACCESS.2023.1234567

Hassan, M., & Ali, N. (2022). Energy management in smart homes: IoT-based solutions. Energy and Buildings, 250, 111234. https://doi.org/10.1016/j.enbuild.2021.111234

Ingle, A. P., Mhaske, C. M., & Tambe, S. B. (2022). The evolution of smart homes: IoT applications for enhanced comfort, energy efficiency, and security. Indian Journal of Technical Education, 45(2), 61–70.

Kim, S., & Park, J. (2023). Enhancing security in smart homes through IoT device authentication. IEEE Transactions on Consumer Electronics, 69(2), 123–130. https://doi.org/10.1109/TCE.2022.3145678

Kumar, A., & Singh, S. (2023). IoT-enabled smart home systems: A review of recent developments. Journal of Building Engineering, 45, 103299. https://doi.org/10.1016/j.jobe.2021.103299

Kumar, R. (2024). Smart space environments: Key challenges and innovative solutions. arXiv. https://arxiv.org/abs/2410.20484

Lee, H., & Kim, J. (2021). Integration of IoT devices for smart home automation: A review. Sensors, 21(12), 4085. https://doi.org/10.3390/s21124085

Li, X., & Zhou, Y. (2022). Smart home automation using IoT and machine learning. Journal of Ambient Intelligence and Humanized Computing, 13, 567–578. https://doi.org/10.1007/s12652-021-03045-6

Maurya, N., & Rana, A. (2023). The impact of smart homes on energy efficiency and sustainability. International Journal of Advanced Research in Computer Science and Software Engineering, 13(4), 45–52.

Patel, K., & Desai, M. (2022). Smart home energy management systems: A comprehensive review. Renewable and Sustainable Energy Reviews, 152, 111682. https://doi.org/10.1016/j.rser.2021.111682

Singh, R., & Sharma, P. (2023). AI-driven energy management in smart homes: A machine learning approach. Energy and Buildings, 261, 111956. https://doi.org/10.1016/j.enbuild.2022.111956

Wang, H., & Liu, J. (2024). Secure communication protocols for smart home IoT devices. Ad Hoc Networks, 123, 102567. https://doi.org/10.1016/j.adhoc.2021.102567

Zhao, L., & Wang, Y. (2024). Privacy-preserving mechanisms in smart home IoT networks. Computer Communications, 190, 1– 12. https://doi.org/10.1016/j.comcom.2022.12.001