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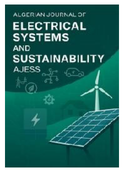

The Bluetooth-Based Smart Doorbell System for Hearing-Impaired Users

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Abstract

This study introduces a smart doorbell system that enhances the safety and independence of hearing-impaired individuals. The system delivers customizable vibration and light-based notifications through a mobile application, ensuring that users are promptly informed of visitors at their door. In addition to real-time alerts, notifications are stored in the app for later review, and a backup power supply ensures uninterrupted operation during electricity outages.

The system was validated through both simulation and real-world testing, confirming stable performance, quick response times, and reliable wireless communication. Designed to be affordable and energy-efficient, the proposed solution not only improves daily convenience for hearing-impaired individuals but also offers potential for wider use in assistive technology applications.

Keywords

Smart Doorbell; Bluetooth Low Energy; Vibration Alert; Visual Notification; Hearing Impairment; Assistive Technology

1. Introduction

Doorbell systems are crucial for daily interaction, yet they present accessibility barriers for individuals with hearing impairment. Conventional auditory alerts cannot provide adequate awareness for people who cannot perceive sound, creating safety and communication challenges in daily life. According to the Turkish Ministry of Family and Social Services, more than 179,000 registered hearing-impaired individuals were reported in 2023 **[1].** This highlights the societal need for alternative notification technologies that go beyond traditional acoustic signaling.

In recent years, assistive technology research has increasingly focused on multimodal interaction combining tactile and visual feedback. Brewster and Brown **[2]** demonstrated that haptic feedback significantly enhances user interaction, especially for individuals with sensory limitations. Gonzalez and Gonzalez **[3]** emphasized that vibration-based alerts can improve awareness in daily activities, while Crispin **[4]** reviewed the role of haptic technologies in mobile environments. Jiang et al. **[5]** extended this perspective by analyzing haptic feedback in IoT applications, showing how tactile systems can complement visual alerts for accessibility. Light-based notification systems have also been investigated as an effective complement to auditory methods **[6]**. Such multimodal systems not only improve awareness but also contribute to greater independence and safety for hearing-impaired users.

Wireless communication has been a cornerstone of recent innovations in assistive devices. Bluetooth-based notification and automation systems have demonstrated high reliability and efficiency in household contexts **[7]**. In particular, Bluetooth Low Energy (BLE) has been highlighted for its low power consumption and stable connectivity, making it suitable for portable notification systems **[8]**. Huang et al. **[9]** showed that BLE can significantly extend device battery life, while An et al. **[10]** confirmed its adaptability for smart home and IoT applications. Large-scale surveys of IoT technologies **[11,12]** further underline the importance of BLE-enabled microcontrollers for energy-efficient and secure communication.

The ESP32 microcontroller has received growing attention in this context due to its dual-mode Bluetooth support and high processing power with low energy demand **[13]**. Studies confirm its versatility for IoT and assistive applications, especially when combined with modular design approaches **[14]**. In addition, researchers emphasize that data security and backup power support are critical for the sustainable deployment of IoT-based notification systems **[15]**. In line with this approach, recent studies published in the Algerian Journal of Electrical Systems and Sustainability (AJESS) highlight the importance of sustainable, energy-efficient, and modular electronic system designs for assistive and smart systems **[16,17]**.

Despite these advances, current solutions often suffer from high costs, limited customizability, or a lack of seamless integration with everyday mobile devices. The system proposed in this study addresses these gaps by combining a low-cost ESP32-based platform, Bluetooth Low Energy (BLE) communication, and a user-friendly mobile application. The system offers customizable vibration and visual notifications, a timestamped event history, and backup battery support to ensure continuous operation during power interruptions. By integrating hardware and software into a compact and energy-efficient design, this work contributes to the ongoing development of inclusive and practical assistive technologies.

2. MATERIAL AND METHODS

The proposed smart doorbell system is designed as an integrated hardware and software solution. The methodology involves hardware architecture design, power management optimization, firmware development, and system validation through simulation and physical testing in accordance with established engineering standards. The system architecture, which includes the ESP32 microcontroller, power management unit, and mobile interface, is illustrated in Figure 1.

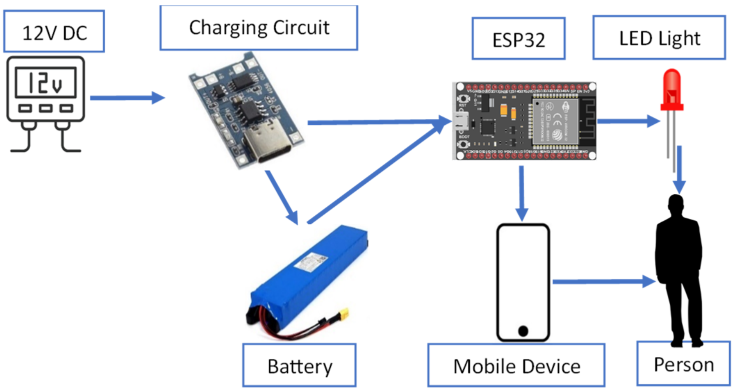


Fig. 1. Schematic representation of ESP32-based smart doorbell system

2.1. Hardware Design and Power Management

The core of the system is the ESP32-WROOM-32 microcontroller, chosen for its integrated Bluetooth Low Energy (BLE) capabilities and low power consumption **[18,19]**. The power unit is designed to handle 220 V AC input, which is stepped down to 12 V AC using a 10 W transformer. This signal is rectified via a KBU1010 full-wave bridge rectifier and filtered by a 1000 µF capacitor to provide a stable DC supply. To ensure uninterrupted operation during power outages, a 3.7 V / 1000 mAh Li-ion backup battery is integrated. The charging process is managed by a precision shunt regulator circuit based on the TL431 integrated circuit. The hardware was designed using EAGLE CAD software, and the single-layer PCB was fabricated using the toner transfer method. The circuit schematic is presented in Figure 2, while the final assembled device is shown in Figure 3.

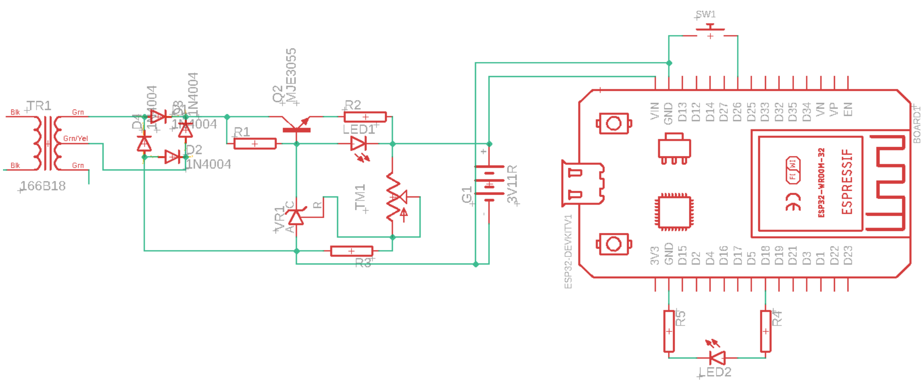
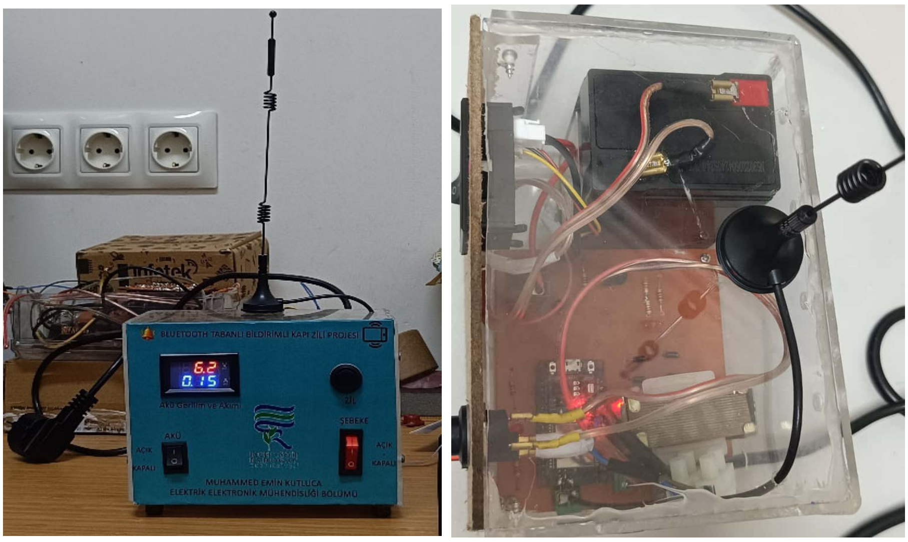


Fig. 2. Circuit schematic of the smart doorbell system, designed using EAGLE software

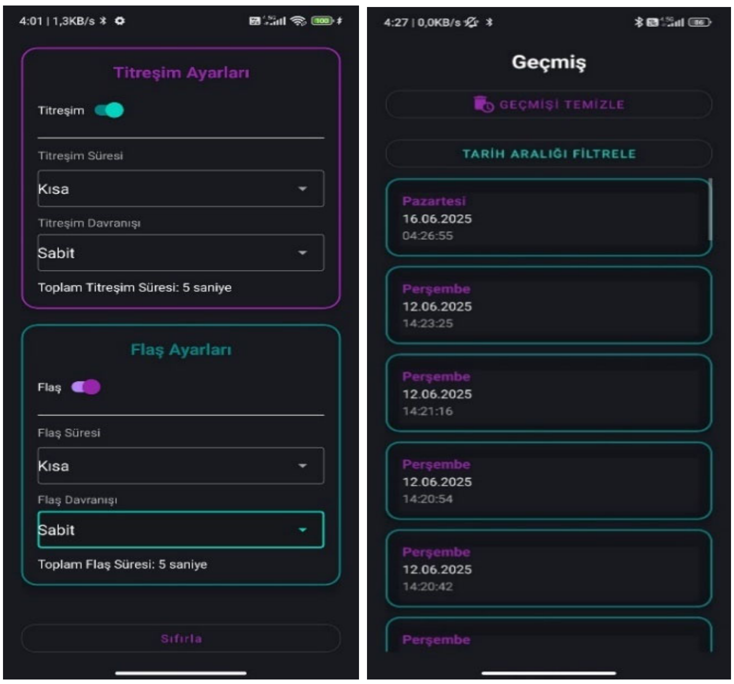


(a) (b)

Fig. 3. Completed implementation of the device: (a) front side, (b) inside view

2.2. Software Architecture and Mobile Integration

The mobile application was developed in the Android Studio environment using Java. The software architecture follows an event-driven model where the app remains in a listening state for BLE advertisements from the doorbell. The application allows users to customize vibration duration and LED notification patterns, addressing the need for haptic and visual feedback highlighted in previous studies (Brewster & Brown, 2005; Gonzalez & Gonzalez, 2018). It also includes a history panel that records and displays timestamps of doorbell events. The interface of the developed mobile application is shown in Figure 4.



(a) (b)

Fig. 4. Interface of the developed mobile application: (a) Settings panel, (b) History panel

2.3. System Simulation and Firmware

The firmware was developed using C++ and includes debouncing algorithms for the physical button to prevent false triggers. Before physical assembly, the entire logic and power state transitions were validated using the

Wokwi simulation platform **[20]**. This simulation verified the communication protocol and ensured efficient energy management **[9]**. The simulation setup is illustrated in Figure 5.

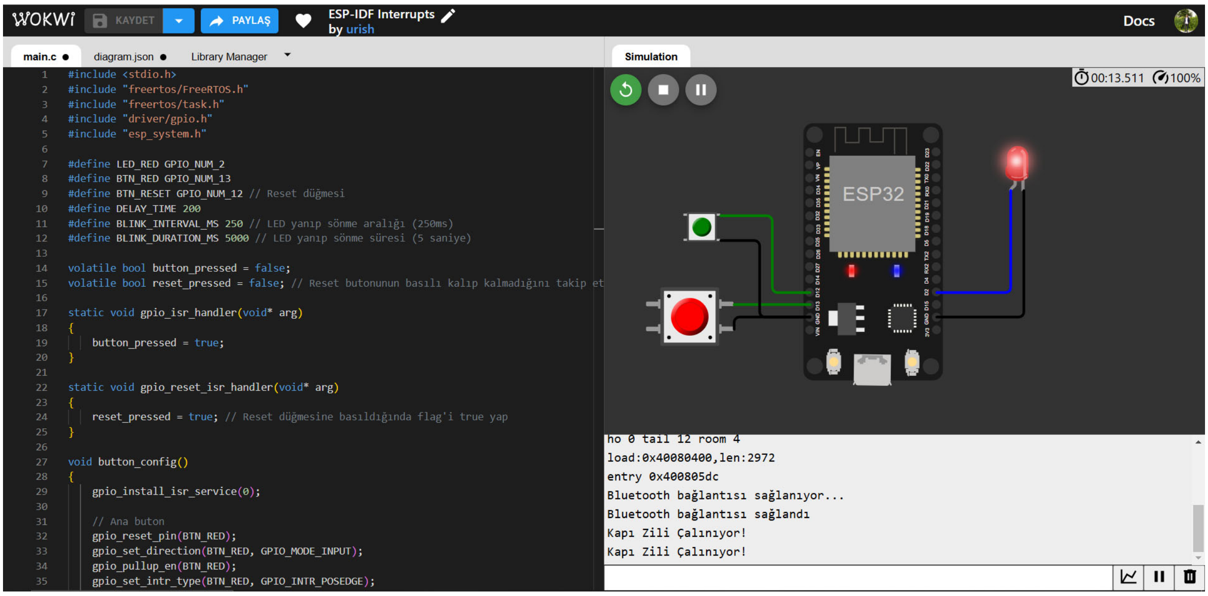


Fig. 5. ESP32 firmware simulated in Wokwi environment.

2.4. Electromagnetic Compatibility and Test Setup

To ensure signal reliability and compliance with safety standards **[21]**, electromagnetic compatibility (EMC) tests were conducted using the SRM-3006 selective radiation meter. The measurement setup used during the data collection process is shown in Figure 6 **[22]**. Furthermore, to analyze the signal propagation and device placement, an AutoCAD layout of the residential indoor test environment was prepared, as presented in Figure 7.

Fig. 6. Measurement setup for electromagnetic compatibility tests using SRM-3006

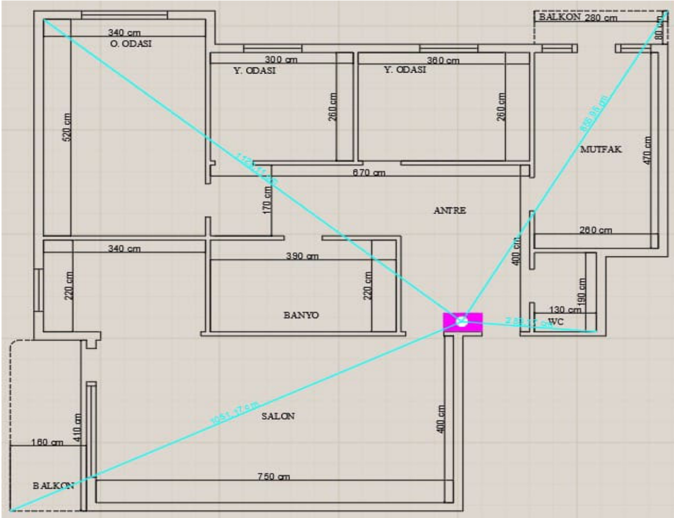


Fig. 7. AutoCAD layout of the indoor test setup used in analysis

3. RESULTS AND DISCUSSION

System simulations and real-world implementations demonstrated efficient signal propagation and energy management. The ESP32 microcontroller consumed less than 0.15 A during active notification periods and near-zero current in its idle state. Bluetooth range testing, conducted in a residential environment, indicated a reliable connection up to 30 meters indoors. The summary of power consumption patterns according to the frequency of usage is presented in Table 1. This table illustrates how usage intensity directly affects the current draw and the expected operational time of the backup battery system.

Table 1. Power consumption versus usage frequency.

Scenario	Power Consumption (W)	Working Hours
Continuous Bell (0.15A)	0,8175 W	~26,67 hours (1,11 day)
10 Times a Day Bell	~1,3168 Wh/day	~16,5 day
Standby only (0.01A)	0,0545 W	~400 hours (~16,6 day)

PCB durability and battery backup efficiency were validated over multiple power cycle scenarios, ensuring the system remains functional during grid failures. Electromagnetic compatibility (EMC) tests confirmed that the system complies with safety regulations. The electromagnetic radiation results obtained from the device under test using the SRM-3006 meter are illustrated in Figure 8 **[22]**.

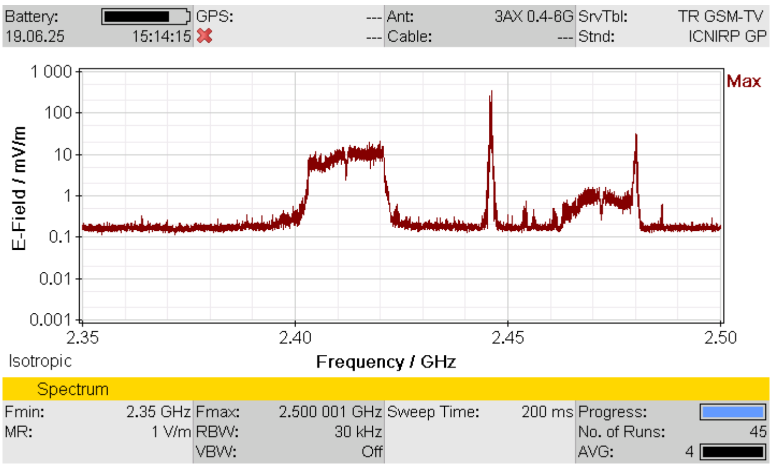
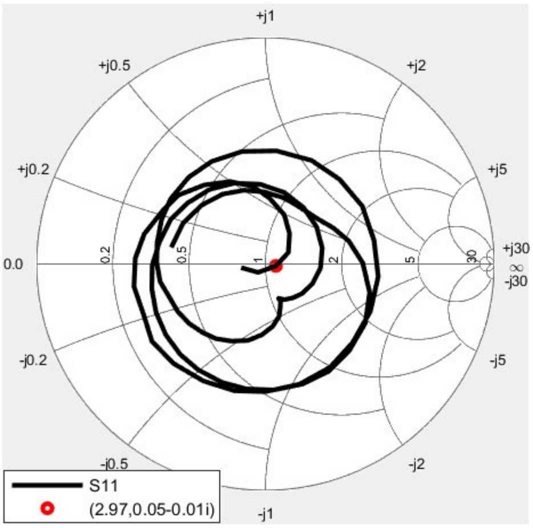


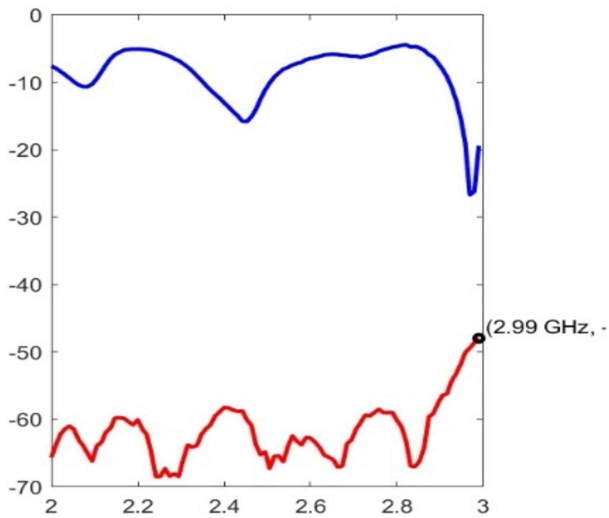
Fig. 8. Electromagnetic radiation results obtained from the smart doorbell system

3.1. Antenna Result

Antenna reflection (S_{11}), energy consumption, and Bluetooth coverage tests were conducted in real-world settings. At 2.4 GHz, the reflection coefficient was measured as $S_{11} \approx -14.5$ dB. According to the reflection calculation, only about 3.5% of the input power was reflected, indicating that the antenna operates with high efficiency at the target frequency band **[23,24,25]**. The integration of the external antenna led to a 300% improvement in signal integrity compared to the default setup **[26]**. The S11 measurements and Smith Chart analysis are shown in Figure 9.

(a)





(b) (c)

Fig. 9. (a) Real-time S11 measurement, (b) Smith Chart, (c) MATLAB S11 and S21 analysis

3.2. Mobile Application Performance

The developed mobile application allowed seamless configuration and alert logging. It provides users with the ability to customize vibration and flash settings, reset preferences, and review a detailed history of past alerts. The user interface, featuring a dynamic settings panel and a dedicated history screen, was rated as highly intuitive and user-friendly during testing. Real-time performance measurements indicated sub-second latency between the physical doorbell press and the mobile alert, confirming the system's reliability in practical scenarios. The application ensures that hearing-impaired users receive immediate and reliable notifications, bridging the communication gap as highlighted in previous assistive technology research **[3]**.

4. Conclusion

This study introduces a smart doorbell system that enhances the safety and independence of hearing-impaired individuals. The system delivers customizable vibration and light-based notifications through a mobile application, ensuring that users are promptly informed of visitors at their door. In addition to real-time alerts, notifications are stored in the app for later review, and a backup power supply ensures uninterrupted operation during electricity outages.

The system was validated through both simulation and real-world testing, confirming stable performance, quick response times, and reliable wireless communication. The ESP32-based hardware architecture, combined with BLE protocol, proved to be highly energy-efficient and cost-effective. Antenna optimization significantly increased the indoor range, while the backup power circuit provided reliability against grid failures. Designed to be affordable and energy-efficient, the proposed solution not only improves daily convenience for hearing-impaired individuals but also offers potential for wider use in assistive technology applications.

Future work may include the integration of cloud-based notification logging, the addition of camera modules for visual visitor identification, and the expansion of the system to include wearable device support (e.g., smartwatches) for improved accessibility. Such modular and energy-efficient designs align with the focus on sustainable electronic systems emphasized in recent literature **[27, 28]**.

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Biography

Muhammed Emin Kutluca is an undergraduate student in Electrical and Electronics Engineering at Recep Tayyip Erdoğan University. He has experience in electronic system design, microcontroller programming, wireless communication, and mobile app development. He developed a BLE-based smart notification system for hearing-impaired users using the ESP32 and a Kotlin-based Android app. This project was supported by TÜBİTAK under the 2209-A program.
He is proficient in C++, Python, Java, Kotlin, and Arduino, and skilled in tools such as Android Studio, Arduino IDE, LTspice, Proteus, and EAGLE. He has a good command of technical English and basic German knowledge, with additional training in communication and teamwork.
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