An Energy-Efficient Power Management System for PCs Requiring Remote Access

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***Abstract*—This study introduces an energy-efficient Power Management System for personal computers (PCs), designed to optimize energy consumption by reducing power usage during idle periods. The system automates transitions between active states and power-saving modes, including sleep, hibernate, or power-off, thereby reducing unnecessary energy usage. The system architecture consists four main components: a mobile application, a PC agent, a smart plug, and an MQTT service. Upon the user's arrival within the range of the AP, the mobile app establishes a connection and transmits an in-coverage signal to the smart plug. In turn, the smart plug transmits a Wake-on-LAN packet to the PC, initiating the power-on process automatically. Once the PC is operational, the PC agent ensures continuous communication with the mobile application and smart plug via the MQTT protocol. When the user leaves the range of the AP, the PC agent detects the disconnection and then puts the PC into a configured power saving state. When remote access is required, the mobile app sends an access request to the Smart Plug via MQTT and the Smart Plug wakes up the PC via Wake-ON-Lan. Experimental results demonstrate potential for significant energy savings in PCs with remote access requirements.**

Keywords—power management; energy consumption; wake-on-lan; smart plug; mobile application

I. Introduction

Electricity is essential for economic growth and human well-being, powering industries, transportation, communication, and daily life in modern societies [1]. Increasing global demand for electricity, driven by factors such as population growth, urbanization and the proliferation of electronic devices, has raised concerns about energy security and environmental sustainability [2]. Energy efficiency, defined as the reduction of energy usage while maintaining functional output, plays a vital role in reducing energy expenditures, alleviating pressure on power grids, and preserving the environment. To improve energy efficiency, reduce costs and support sustainable development, technological advances such as smart energy management systems have emerged as promising solutions [3].

Smart Home Energy Management Systems (HEMS) have become a prominent application in the field of electricity, enabling users to remotely control electrical devices through smartphones or other portable controllers [4]. HEMS are the broad implications of high power consumption at the home front. This has caught the attention of the current generation of scientists [5]. HEMS facilitate energy consumption management, helping users reduce utility costs and enhance energy efficiency while maintaining comfort and convenience [6]. These systems optimize appliance usage based on factors such as energy prices, load profiles, and environmental conditions, scheduling device operations to minimize consumption during peak demand periods [7]. A critical component of HEMS is the smart plug, which offers real-time monitoring and control of connected appliances. Smart plugs provide essential data on current, voltage, power consumption, and electricity usage, while also issuing alerts for potential voltage surges [8]. With the ability to be managed remotely via smartphone applications or voice-activated assistants, smart plugs offer a practical and user-friendly approach to reducing energy waste [9].

Thongkhao and Pora (2016) presented a Wi-Fi-based smart plug system managed through a web application, which demonstrated high measurement accuracy for effective energy management [10]. In office settings, the researchers proposed a system employing BLE beacons to detect user presence and automatically toggle smart plugs to regulate energy consumption. [11]. Horvat et al. (2015) developed a BLE-enabled smart plug designed to control household appliances and monitor energy consumption using mobile devices, eliminating the necessity for a dedicated gateway [12].

Polisave is a client-server system that enables users to remotely schedule and control the power states of PCs, utilizing client-side software to transmit IP and MAC addresses to a server, which aggregates status data and issues power management commands such as hibernate, standby, or shutdown [13]. EnergySave leverages the Wake-on-LAN protocol to remotely activate PCs from a centralized server, enabling efficient power management for both local and remote networks, while incorporating a mathematical model to simulate potential energy savings [14]. In [15] proposed a power-saving model for PCs that integrates a suspended mode with remote wake-up functionality, relying on a Wakeup Server to collect PC status data and send Wake-on-LAN signals via network devices, allowing users to remotely activate their PCs from a suspended state.

This study introduces a Smart Power Management System for PCs with remote access requirements, aimed at enhancing user convenience and promoting energy efficiency by automating power control processes. The system architecture is composed of four key components: a smartphone application, a smart plug, an MQTT service, and a PC agent. The smartphone application detects and connects to available Wi-Fi SSIDs within proximity, subsequently transmitting an in-coverage signal to the smart plug. In response, the smart plug initiates the PC's power-on process by sending a Wake-on-LAN packet. The PC agent facilitates communication among the PC, the smartphone application, and the smart plug, ensuring seamless system integration. By enabling automatic power control, the system eliminates the need for manual intervention, thereby improving operational efficiency. The system also reduces power consumption by automatically putting the PC into sleep or hibernation mode when the user leaves the area. For remote access, the system maintains PC availability through the smart plug, enabling users to access the PC from remote locations.

The subsequent sections of this paper are structured as follows: The Materials and Methods section provides a detailed explanation of the system's architectural components, including the Wake-on-LAN protocol and the Message Queuing Telemetry Transport (MQTT) communication framework, which are integral to the system's operation. Section III focuses on the primary system components, including the PC agent, the smartphone application, and the smart plug. The Experimental Study and Results section presents the experimental setup, procedure, and key findings. Lastly, the Conclusion summarizes the main outcomes and discusses the broader implications of the proposed system.

II. MATERIALS AND METHODS

This section outlines the key technologies and system components utilized in the proposed Power Management System. Central to the system's functionality is the Wake-on-LAN protocol, which enables the remote activation of PCs. Additionally, the MQTT protocol facilitates communication and data exchange among the system's components.

A. *Wake-on-LAN*

To optimize PC energy efficiency, both active and idle time power management strategies are employed. During periods of low activity, techniques such as dynamic voltage and frequency scaling are utilized to reduce the CPU's voltage and clock speed, thereby decreasing power consumption. For prolonged inactivity, operating systems like Windows and Linux implement suspension modes to further conserve energy. In this state, critical hardware components, including the CPU and graphics processing unit (GPU), are powered down, leading to a significant reduction in energy usage. However, while in suspension, the PC becomes unresponsive to external network requests, necessitating the use of remote wake-up mechanisms. The Wake-on-LAN protocol addresses this challenge by enabling the remote activation of PCs from a suspended state, ensuring they remain accessible when needed for remote access or network-based tasks.

The Wake-on-LAN protocol facilitates the remote activation of personal computers from low-power states such as sleep or hibernate, eliminating the need for manual interaction. This process relies on the computer's network interface card (NIC), which remains in a low-power standby mode, constantly monitoring network traffic for a specially formatted "magic packet." This packet, which contains the Media Access Control (MAC) address of the target PC, is broadcast across the local area network (LAN). When the NIC detects the matching MAC address, it signals the motherboard to initiate the boot process, bringing the PC out of its suspended state. For Wake-on-LAN to function, proper hardware and software configurations are required, including enabling Wake-on-LAN in the BIOS or Unified Extensible Firmware Interface (UEFI) settings and configuring the network adapter within the operating system. While the protocol provides significant benefits for remote access and energy savings, it also faces challenges related to network connectivity and the need for precise configuration in dynamic network environments.

B. *Message Queuing Telemetry Transport*

The Message Queuing Telemetry Transport (MQTT) protocol is widely used in Internet of Things (IoT) applications where efficient, small data exchanges are critical, particularly in environments with constrained resources such as low bandwidth and limited processing power [16]. MQTT operates on a lightweight publish-subscribe model, allowing publishers to send messages to specific topics, while subscribers receive messages based on their topic subscriptions. Built on top of the TCP/IP protocol, MQTT minimizes packet overhead, making it an ideal choice for resource-constrained devices. The system employs a many-to-many communication model, where messages are distributed to multiple clients subscribed to a central MQTT broker, ensuring efficient and scalable communication [17].

III. PROPOSED SYSTEM ARCHITECTURE

This section introduces the architecture of the proposed Power Management System for PCs, which consists of four essential components: the PC agent, a mobile application, a smart plug, and an MQTT service. The system's architecture, depicted in Fig. 1, is specifically designed to optimize power management for computers in both residential and office settings.

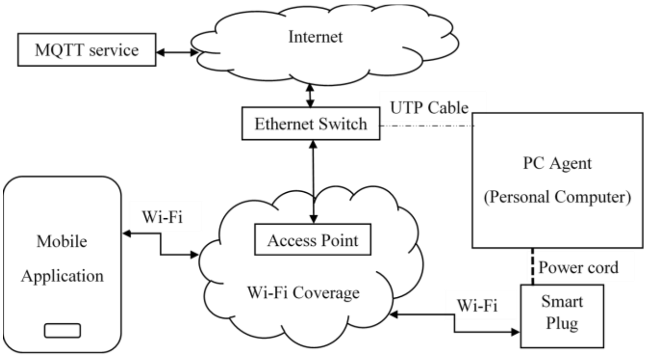

Figure 1 Architecture of PC power management system

A. PC Agent

Personal computers (PCs) constitute a substantial portion of IT devices in both office and home environments, playing a critical role in users' daily activities and overall productivity. Given their extensive usage, PCs and monitors present significant potential for energy savings [11]. The proposed system incorporates a PC Agent that operates in the background, continuously monitoring periodic heartbeat signals from the mobile application and smart plug to verify the PC's active status. Upon receiving these signals, the PC Agent confirms the device's operational state and relays this information back to the mobile application and smart plug. The PC Agent monitors the periodicity of heartbeat signals received from the mobile application. If the mobile application disconnects from the network or moves out of the Wi-Fi coverage area, the agent begins incrementing a heartbeat timeout counter. When this timeout value exceeds a predefined threshold, the PC Agent autonomously activates a power-saving mechanism, transitioning the PC to a sleep, hibernation, or shutdown state based on the configured settings. This process supports energy efficiency by reducing power consumption when the user is no longer present. Fig. 2 illustrates the main interface of the PC Agent software.

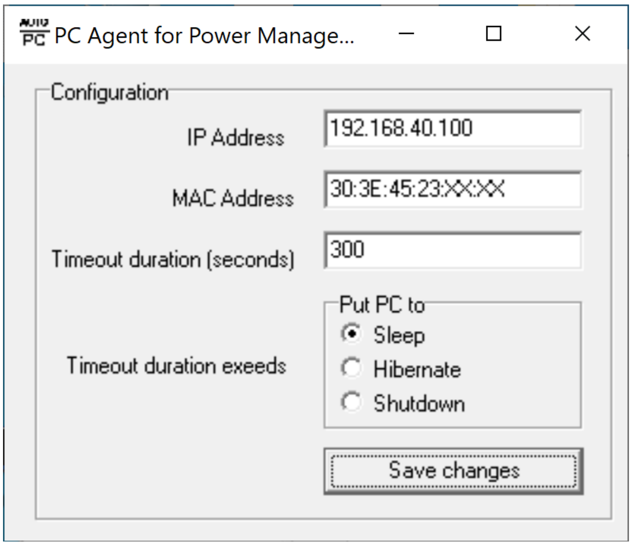

Figure 2 Main screen of PC Agent

B. Mobile Application

Modern smartphones are equipped with Wi-Fi technology designed to optimize battery usage during wireless communication. The mobile application developed for this study utilizes this capability by scanning for available Wi-Fi SSIDs in the background. When a preconfigured SSID is detected, the application attempts to connect to the associated access point (AP). Upon successful connection, the mobile application transmits a "coverage packet" to the smart plug via MQTT to initiate the power-on process. Upon receiving the coverage packet, the smart plug generates and sends a Wake-on-LAN packet to power on the PC and activate the PC Agent. Once the PC is powered up, the PC Agent automatically starts and begins monitoring periodic heartbeat signals from the mobile application and smart plug to maintain seamless communication and operation.

C. Smart Plug

The Smart Plug serves as a critical component of the proposed power management system, playing a pivotal role in enabling communication and power control. One of its primary functions is to sense and receive the coverage packet transmitted by the mobile application. In addition, the Smart Plug can send or receive data using the MQTT service with Wi-Fi connectivity. This bidirectional communication allows for the real-time transmission and reception of control signals and status updates. Another essential function of the Smart Plug is to manage the power state of PCs. Based on the user’s pre-configured settings, it automatically switch PCs power states on or off.

Managing the automatic shutdown of PCs requires careful handling due to the presence of active operating systems and running applications, which necessitate a proper shutdown sequence to avoid data loss or system errors. To address this, the agent software on the PC maintains constant communication with the Smart Plug. When the user selects the "power off" option as a pre-configured setting, the Smart Plug waits a controlled power-down process. It allows sufficient time for the PC to complete the shutdown sequence, ensuring that all active applications are properly closed and system data is saved before the device is fully powered off. Conversely, if the user selects "sleep" or "hibernate" as the preferred power state, the Smart Plug maintains the PC's readiness for remote access. In this state, the PC enters a low-power mode instead of shutting down completely, enabling faster reactivation when required. This configuration leaves the power state on or active to ensure that the computer continues to respond to remote Wake-on-Lan signals for remote access needs. If the Smart plug switches off the power to the PC and then switches it back on, it is often not possible to wake up the PC via Wake-on-Lan. Fig. 3 illustrates the block diagram of the proposed Smart plug.

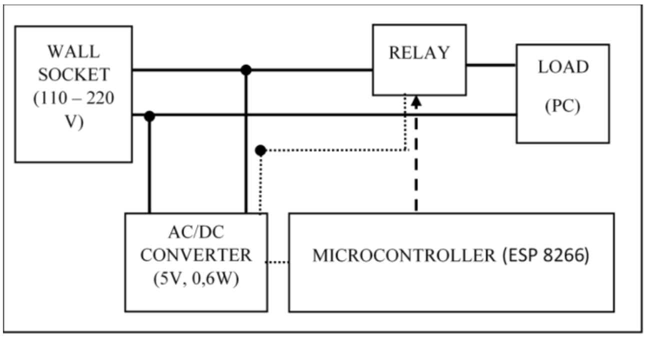

Figure 3 Block diagram of Smart Plug

The proposed Smart Plug design incorporates the ESP8266 microcontroller, a widely adopted Wi-Fi-enabled module known for its versatility and reliability in IoT applications. The design integrates three primary pathways for functionality: solid lines represent the 220V AC line voltage, dotted lines indicate the 5V DC power supply, and dashed lines denote the data communication routes. The AC line voltage is connected to the relay module, which subsequently interfaces with the load. To power the system, an AC-to-DC converter module is utilized, converting an input range of 100V to 230V AC into a stable 5V DC output. This 5V output supplies power to both the relay module and the ESP8266 microcontroller, ensuring operation of the Smart Plug's power management and communication functionalities.

D. *MQTT service*

To ensure seamless operation across the entire system, a local MQTT service was employed, with the capability to function both locally and over the internet. Additionally, the system is designed to support integration with widely recognized MQTT platforms, such as Google Cloud IoT and ThingSpeak, among others, offering flexibility and scalability.

IV. EXPERIMENTAL STUDY AND RESULTS

The experimental study was carried out in a real-world office setting with an employee, utilizing the PC for his daily work activities. The office infrastructure included an access point (AP) providing Wi-Fi connectivity for mobile devices, while the employee's PC, known as PC1, was connected to the network via a UTP cable. To implement the proposed energy-saving mechanism, the PC Agent software was installed on the PC, and the mobile application was deployed on the employee's smartphone. The mobile application was configured with essential details, including the Wi-Fi SSID, username, password, and the corresponding MAC and IP addresses of the PC. Employee was instructed to keep the mobile application running in the background continuously to ensure seamless operation of the system.

The employee required remote access to his PC after work hours. Therefore, the PC Agent has been configured to put the PC into sleep mode when it is idle. This employee worked on weekdays, arriving at 8:30 AM and leaving at 5:30 PM, with no work activities conducted on weekends. Figure 4 shows the hourly power consumption data before and after the integration of the power management system for this employee's PC on a weekday.

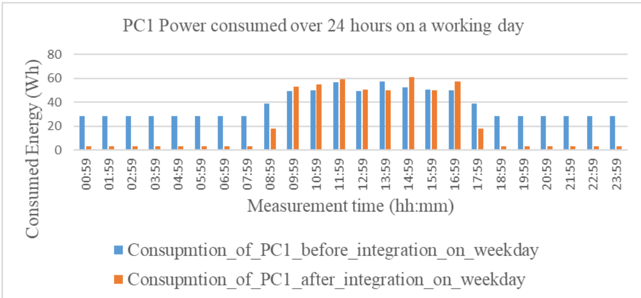

Figure 4 24 Hours Power Consumption of PC1 in a Weekday.

Fig. 5 shows the hourly power consumption data for the same employee's PC on a weekend day.

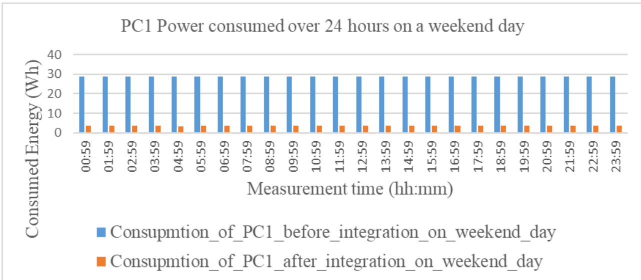

Figure 5 24 Hours Power Consumption of PC1 in a Weekend day.

The experimental results demonstrated a significant reduction in energy consumption following the implementation of the proposed system. Over a 24-hour test period on a typical workday, the energy consumption of PC1 decreased from 897.16 W to 541.20 W, reflecting an energy savings rate of 41.90%. Similarly, during a 24-hour test period on a weekend day, the energy consumption of PC1 was reduced from 689.16 W to 81.94 W, corresponding to an energy savings rate of 88.11%.

V. CONCLUSIONS

This study presented the design and implementation of an energy-efficient Power Management System for PCs with remote access requirements. The proposed system effectively minimizes energy consumption during idle periods by automating the transition of PCs to sleep states. It integrates four core components: a mobile application, a PC agent, a smart plug, and an MQTT-based communication service. Experimental evaluations in a real office environment have shown that significant energy savings can be made, particularly during off-hours, while maintaining remote access functionality. These results showed a 41.90% reduction in energy consumption during a typical working day, while a weekend test period showed a remarkable 88.11% reduction in energy consumption.

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