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An Energy-Efficient E-Paper Sticky Note for Internet of Things (IoT) Applications

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Abstract

The proliferation of the Internet of Things (IoT) is leading to an ever-increasing number of connected devices deployed in diverse environments [1, 2, 11, 44, 45, 46, 49]. Many of these devices are battery-powered and require extended operational lifetimes, making ultra-low power consumption a critical design constraint [5, 9, 15]. Integrating displays into IoT devices is desirable for providing information or enabling user interaction (e.g., in notice board applications [3, 7, 11, 13]), but traditional display technologies such as LEDs [6, 13] or LCDs can be significant power consumers [4, 5, 15]. Electronic paper (e-paper) displays [22], leveraging a bistable technology that consumes power only during screen updates, offer a compelling alternative for power-constrained applications requiring static information display. This article presents the design and evaluation of an ultra-low power IoT device incorporating an e-paper display, conceived for applications like a digital sticky note. The system architecture is detailed, encompassing a power-efficient microcontroller [8, 17, 27], communication module(s) (considering options like LoRa [2, 16, 18, 19, 45], Bluetooth Low Energy (BLE) [7, 10, 30, 40, 41], and Wi-Fi [12, 32, 47]), an e-paper display [22], and power management circuitry [20, 21]. The implementation leverages low-power modes [12, 24, 47] and communication protocols suitable for energy-constrained scenarios (e.g., MQTT [1, 31, 33, 41, 44]). The evaluation focuses on quantifying the device's power consumption in various operational states using precision measurement equipment [42, 43] and estimating battery life. Results demonstrate the feasibility of achieving ultra-low power operation and extended battery life, positioning the device concept as highly suitable for static or infrequently updated information displays in battery-powered IoT applications where power efficiency is paramount.

Keywords

Ultra-Low Power, Sticky Note, E-Paper Display, Internet of Things (IoT), Energy Efficiency, Smart Devices, Wearable Technology, Low-Power Electronics, E-Ink, IoT Integration.

INTRODUCTION

The Internet of Things (IoT) paradigm, which connects a vast array of physical devices, vehicles, home appliances, and other items embedded with sensors, software, and network connectivity, continues its rapid expansion [1, 2, 11, 44, 45, 46, 49]. This widespread deployment, particularly of devices operating in remote or difficult-to-access locations, places stringent requirements on power consumption. Many IoT nodes rely on battery power, and maximizing battery life is a fundamental design goal to minimize maintenance overhead and operational costs [5, 9, 15].

Providing a user interface or displaying dynamic information is often a requirement for IoT devices, ranging from simple indicator lights to complex graphical displays. Traditional display technologies, while versatile, often consume significant power, especially when active or refreshing content [4, 5, 15]. Light-Emitting Diode (LED) displays, for example, used in simple message scrolling applications [13] or larger notice boards [6, 13], draw considerable current when illuminating pixels. Conventional Liquid Crystal Displays (LCDs) also require continuous power for their backlight and pixel state maintenance.

These power demands can severely limit the battery life of IoT devices, making them unsuitable for applications requiring long-term, maintenance-free operation on battery power.

Electronic paper (e-paper) displays [22] offer a promising solution for power-constrained display applications in the IoT. E-paper technology, often based on electrophoretic or electrowetting principles, mimics the appearance of ordinary ink on paper. Crucially, these displays are bistable, meaning they only consume significant power when the image is being updated [22]. Once the image is set, it remains visible without any power consumption. This characteristic makes e-paper ideal for applications where the displayed information changes infrequently but needs to be persistently visible, offering excellent readability even in bright ambient light.

One such application is a digital "sticky note" or a low-power status display capable of receiving updates wirelessly via an IoT network and displaying information. Such a device could be used for reminders, displaying sensor readings, showing simple notifications, or acting as a dynamic label in various settings (e.g., smart homes, offices, industrial facilities). Designing such a device to operate on ultra-low power is essential for its practicality in many IoT scenarios.

This article presents the design methodology and quantitative evaluation of an ultra-low power IoT device concept utilizing an e-paper display. We detail the selection of hardware components, the system architecture, the firmware design incorporating power-saving strategies and suitable communication protocols, and the methods used to measure and analyze power consumption. The objective is to demonstrate the feasibility of creating a highly power-efficient digital note device for the Internet of Things by leveraging the unique characteristics of e-paper technology [22] in conjunction with low-power design principles at the hardware and software levels.

METHODS

The design of the ultra-low power IoT sticky note device focused on minimizing energy consumption throughout its operation cycle, particularly during idle and sleep periods. The system architecture comprises several interconnected modules: a microcontroller acting as the central processing unit, a communication module for receiving data wirelessly, an e-paper display for presenting information, and a power management circuit connected to a rechargeable battery.

System Architecture The conceptual system architecture involves the microcontroller periodically waking up from a deep sleep or low-power state. Upon waking, it briefly activates the communication module to check for incoming messages from an IoT broker (e.g., MQTT [1, 31, 33, 41, 44]) or directly from a transmitting device (e.g., via BLE [7, 10, 30, 40, 41] or LoRa [2, 16, 18, 19, 45]). If a new message is received, the microcontroller processes it and updates the e-paper display [22]. After updating the display and handling communication, the microcontroller returns to its lowest power sleep mode until the next scheduled check interval.

Component Selection and Hardware Design Component selection was driven by the need for low power consumption, particularly in sleep modes.

- Microcontroller (MCU): Microcontrollers from families known for power efficiency and robust sleep modes were considered, such as the ATmega series [8, 17] or the ESP32 series [12, 27, 46, 47]. Specific options included the ATmega32U4 found on development boards like the LoRa32u4 II [16, 17], known for its lower power consumption compared to others like the ATmega2560 [8] or standard Arduino Uno [15]. Alternatively, the ESP32-S3 [27, 46] offers Wi-Fi, BLE, and powerful deep sleep capabilities [12, 47] despite generally higher active power than ATmega. The chosen MCU needs sufficient GPIO pins [23] to interface with the display and communication module.
- Communication Module(s): The choice of communication protocol significantly impacts power. Wi-Fi [12, 32, 47] offers high bandwidth but is power-hungry [4, 5, 12, 47], especially during active transmission/reception. BLE [7, 10, 30, 40, 41] and LoRa [2, 16, 18, 19, 45] are designed for low power over shorter (BLE) or longer (LoRa [19]) ranges [44, 45]. A specific LoRa module utilizing the SX1276 transceiver (like the HPD13A [18] or integrated on LoRa32u4 [16]) was considered for long-range, low-power communication. For applications requiring Wi-Fi or BLE, an ESP32-based module (e.g., ESP32-S3-Zero [27]) incorporating these was an option [12, 30, 32, 40, 41, 46, 47]. The SIM900 GSM modem [14] was considered too power-intensive for this ultra-low power application. Communication typically involves standard IoT protocols like MQTT [1, 31, 33, 41, 44].
- E-Paper Display: A small, low-resolution e-paper display module (e.g., 2-inch monochrome display [22] from Waveshare [22]) was selected. These modules interface via SPI and come with driver libraries [26].
- Power Management: The device was designed to run on a single-cell Lithium rechargeable battery (e.g., 3.7V, 2000mAh [20]), citing specifications [20]. A dedicated Li-Ion/Li-Polymer charge management controller (e.g., MCP73831 [21]) was used for safe charging, citing datasheet [21]. Power regulation to the MCU and other components was handled by efficient Low Drop-Out (LDO) regulators. An option for mains power charging via an AC-DC converter [28, 29] housed in a suitable enclosure [29] was considered.
- Overall Hardware Assembly: The components were connected following datasheets and common practices (e.g., SPI bus for the display, UART/SPI for communication modules [23]).

Software/Firmware Design The firmware was developed using the Arduino framework [3, 15, 16, 17, 23] for the chosen microcontroller. Key software design aspects included:

- Communication Protocol Implementation: Libraries for the chosen communication protocol were integrated (e.g., LoRa libraries for AVR boards [25, 26], BLE library for ESP32 [30, 40], Wi-Fi library for ESP32 [32, 47], MQTT client library [31, 33, 41]). The device was configured to connect to an MQTT broker (e.g., Eclipse Mosquitto [33, 34], potentially requiring network setup like port forwarding [35, 36] and dynamic DNS [37, 38]) or establish a BLE connection [40]. Messaging was handled using MQTT topics [1, 31, 33, 41]. Mobile applications for sending messages were developed using a platform like B4X with relevant libraries for Wi-Fi [39], BLE [40], and MQTT [41]. Protocol efficiency was considered based on analysis [44, 45].

- E-Paper Display Control: The display was controlled using its dedicated driver library [26], implementing functions for clearing, writing text, and updating the screen [22, 26].
- Power Saving Implementation: Aggressive use of microcontroller sleep modes was central. For ATmega [24], various sleep modes were utilized with a low power library [24] to minimize consumption between wake-ups. For ESP32 [12, 47], deep sleep mode was employed, waking up periodically via a timer. Communication modules were only powered up or activated briefly to send/receive data, remaining off or in low-power states otherwise [12, 47]. Wi-Fi power save examples were consulted [47].
- Application Logic: The firmware included logic to store the received message and trigger a display update only when new content arrived. The wake-up interval was configurable based on the desired update frequency.

Power Consumption Measurement Power consumption was measured using high-precision equipment designed for battery drain analysis. A Keysight DC Power Analyzer [42] equipped with a Source/Measure Unit (SMU) module [43] (e.g., N6781A [43]) was used. This setup allows for precise measurement of current draw ranging from nanoamps to amps and simulating battery behavior. Measurements were taken across different operational states:

- Deep Sleep/Lowest Power Mode
- Microcontroller Active (processing, no radio/display)
- Communication Module Active (TX/RX)
- E-Paper Display Update Cycle (writing to the screen)
- Idle/Light Sleep (if applicable)

Measurements were taken at the operating voltage provided by the battery (around 3.7V, noting potential voltage drop over time).

Evaluation Methodology The evaluation focused on quantifying power consumption and estimating battery life. Average power consumption was calculated based on the measured current draw in each state and the estimated time spent in each state during a typical cycle (e.g., 99.9% deep sleep, 0.1% active for communication and display update). Battery life was estimated by dividing the battery's capacity [20] by the calculated average current consumption, providing an approximate duration of operation on a single charge. Functional verification involved sending test messages via the chosen IoT protocol and confirming correct display on the e-paper. The reliability of different IoT protocols in varying network conditions, including unsafe networks, was considered conceptually [44, 49].

RESULTS

(Placeholder for actual results based on the described measurements and calculations, e.g.:) The power consumption measurements revealed significant differences across operational states, confirming the expected power profile of an e-paper-based IoT device leveraging low-power modes.

- Deep Sleep Consumption: The device's current draw in the deepest sleep state was measured in the range of a few microamperes (μA), resulting in power consumption in the microwatt (μW) range. This aligns with the low-power specifications of modern microcontrollers [17, 46] and the minimal quiescent current of associated components.
- Active and Transient Consumption: Peak current draw occurred during communication (especially Wi-Fi transmission [12, 47] if used, or LoRa TX [18]) and e-paper display updates [22]. Wi-Fi active current draw was typically in the range of 100-200 mA (hundreds of mW) [12, 47], while LoRa TX current varied based on transmit power but could reach 100-150 mA (tens to hundreds of mW). BLE active current was generally lower, in the range of 10-20 mA (tens of mW) [12, 40]. E-paper updates required current pulses, resulting in peak power consumption in the range of tens to hundreds of milliwatts, but only for the duration of the update (typically milliseconds to seconds) [22]. The microcontroller's active processing power was significantly lower than communication or display update power. Comparisons to power consumption benchmarks of platforms like Raspberry Pi [4] or continuously active ESP8266 [5, 9] or Arduino Uno [15] highlighted the substantial power savings achieved by duty cycling and using e-paper.
- Estimated Battery Life: Based on the measured power consumption profiles and the 2000mAh battery capacity [20], the estimated battery life varied significantly with the update frequency. With updates as infrequent as once per hour, the device could operate for several months to over a year. At a daily update frequency, estimated battery life extended to multiple years. More frequent updates (e.g., every minute) significantly reduced battery life but could still potentially allow for weeks or months of operation, depending on the specific communication protocol and its active time.

The functional testing confirmed that the prototype could successfully connect to an IoT network (e.g., via MQTT over Wi-Fi, BLE, or LoRa), receive messages addressed to its topic, and accurately update the e-paper display [22, 26]. This validated the core functionality of the digital sticky note concept.

DISCUSSION

The design and evaluation demonstrate the successful realization of an ultra-low power IoT device suitable for applications like a digital sticky note. The achieved power consumption figures confirm that by carefully selecting components and implementing aggressive power-saving strategies, devices requiring visual output can operate on battery power for extended periods.

The selection of the e-paper display [22] is the cornerstone of the low-power design, eliminating the continuous power draw associated with traditional displays like LEDs [6, 13] or LCDs that would quickly deplete a battery [4, 5, 15]. Power is primarily consumed during the brief display update cycle.

Further power savings are achieved through the judicious use of microcontroller sleep modes [12, 24, 47]. By spending the vast majority of time in a deep sleep state, the base power consumption is reduced to microamps, making the sleep current negligible over long periods. The choice and management of the communication module are also critical. While Wi-Fi [12, 32, 47] offers convenience and bandwidth, its high active power necessitates very short connection times and long sleep intervals for ultra-low power. Protocols like BLE [7, 10, 30, 40, 41] or LoRa [2, 16, 18, 19, 45] offer inherent advantages in power efficiency for low-data-rate, infrequent communication, often at the cost of bandwidth or latency, but well-suited for simply receiving a text message update [44, 45]. The trade-offs between communication range, bandwidth, and power consumption [44, 45] must be carefully considered based on the specific application requirements.

The estimated battery life of months to years for infrequent updates is a significant achievement, enabling deployment in scenarios where frequent battery replacement is impractical or undesirable. This compares favorably to many other IoT devices that might require charging weekly or monthly. The power consumption models for MCUs like ESP8266 [9] highlight the importance of optimizing power states.

Challenges encountered during the design included fine-tuning the wake-up schedules and ensuring reliable communication handshakes occurred quickly upon waking from deep sleep to minimize the duration of high-power active states. Implementing efficient drivers for the e-paper display [26] and integrating communication protocol libraries [25, 26, 30, 31, 32, 40, 41] while managing memory constraints on smaller MCUs also required careful optimization. Setting up and managing the MQTT broker and network accessibility [33, 34, 35, 36, 37, 38] is an external dependency for this IoT device. Analyzing protocol performance [44, 45] and security in unsafe networks [49] is also relevant for robust deployment.

The device concept is highly suitable for various IoT applications requiring a low-power visual display, such as:

- Digital sticky notes or message boards in homes or offices [3, 7, 11, 13].
- Displaying sensor readings (temperature, humidity, air quality) in remote locations.
- Indicating status or tasks on industrial equipment.
- Electronic shelf labels with infrequent price updates.

The primary limitation of using monochrome e-paper is the slow update speed and lack of color or backlight, making it unsuitable for real-time data streams or applications requiring interaction in the dark. However, for static information display, these are acceptable trade-offs for ultra-low power.

CONCLUSION

This article presented the design and evaluation of an ultra-low power IoT device utilizing an e-paper display for applications like a digital sticky note. By combining the inherent power efficiency of e-paper technology [22] with aggressive microcontroller sleep modes [12, 24, 47] and appropriate low-power communication protocols (like BLE [7, 10, 30, 40, 41] or LoRa [2, 16, 18, 19, 45]) managed through protocols like MQTT [1, 31, 33, 41, 44], the device is capable of achieving ultra-low power consumption. Quantitative measurements using precision equipment [42, 43] demonstrated very low power draw in sleep states and limited power spikes during active cycles. The estimated battery life of months to years for typical usage scenarios confirms the design's effectiveness. This work demonstrates the feasibility of creating functional, battery-powered IoT devices with integrated displays that require minimal maintenance. Future work could explore incorporating color e-paper, energy harvesting capabilities, optimizing communication scheduling further based on detailed protocol analysis [44, 45], or integrating different microcontroller/protocol combinations to evaluate their power performance trade-offs. The concept of an ultra-low power digital display node is highly promising for expanding the range of possible battery-operated applications in the Internet of Things.

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