International Journal on Advances in Networks and Services

2025 vol. 18 nr. 1&2

The *International Journal on Advances in Networks and Services* is published by IARIA.
ISSN: 1942-2644
journals site: http://www.iariajournals.org
contact: petre@iaria.org

Sponsored by IARIA
www.iaria.org

International Journal on Advances in Networks and Services
Volume 18, Number 1 & 2, 2025

International Journal on Advances in Networks and Services
Volume 18, Numbers 1 & 2, 2025

CONTENTS

NNEPS: A Power-efficient e-Paper Signage System with Remote Content Updates

Takafumi Akiba and Tsubasa Yumura
Hokkaido Information University
Ebetsu, Japan
e-mail: yumu@yumulab.org

***Abstract*—Digital signage is widely used in various fields, such as, public transportation, commercial facilities, and outdoor advertising. Some digital signage systems adopt low-power electronic paper displays, and among them, there are systems capable of updating content via a network. However, although electronic paper consumes power only when updating the display, the control PC remains constantly powered on to receive content updates in some cases, resulting in inefficient power consumption. To address this issue, we propose the Normally-off Network Electronic Paper Signage (NNEPS), which integrates an electronic paper display with a normally-off power control mechanism. Unlike conventional network-based e-paper signage, NNEPS minimizes standby power by turning off the control PC except during update operations. In this study, we developed two prototype versions: Ver.A, which employs a commercial smart plug for simple power control, and Ver.B, which implements a custom relay-based power control system using a microcontroller. Experimental results showed that NNEPS reduces standby power consumption by approximately 33% compared to conventional network-updatable electronic paper signage. Additionally, a field experiment was conducted in a university library, demonstrating that NNEPS maintains remote content update functionality while achieving energy-efficient operation. The proposed system offers both energy efficiency and remote content update functionality, contributing to sustainable digital signage applications.**

Keywords-digital signage; e-Paper; power saving.

I. Introduction

Digital signage has rapidly become widespread, particularly in urban areas, and is used in a variety of applications, including advertising, public infrastructure, transportation systems, commercial facilities, and educational institutions. According to a report by Berg Insight [2], approximately 91.5 million digital signage displays were in use worldwide as of the end of 2023, with the number projected to reach 149.4 million by 2028. In the retail industry, digital signage capable of real-time promotional updates is increasingly valued, replacing traditional printed posters with electronically updatable display systems. In transportation hubs such as railway stations and bus stops, digital displays capable of instant timetable and operational updates are enhancing convenience for passengers. Traditional digital signage primarily employs Liquid Crystal Display (LCD) and Light-Emitting Diode (LED) technology. While these technologies allow for dynamic content, such as videos and animations, they continuously consume power. As a result, depending on the installation environment and use case, operational costs can be significant. Furthermore, LCD displays suffer from reduced visibility under direct sunlight, often requiring increased brightness settings, which further increases power consumption. As a solution to these issues, electronic paper technology has gained attention due to its low power and high visibility.

Electronic paper technology was developed to provide a digital display with visibility similar to printed paper, offering high readability and low power consumption as key advantages. Unlike LCDs, electronic paper displays reflect ambient light to present images, ensuring excellent visibility even under direct sunlight and eliminating the need for a backlight. Moreover, E-paper consumes power only during updates, requiring none to retain images, enabling significant energy savings compared to conventional LCD displays.

Leveraging these characteristics, electronic paper is widely adopted in various fields [3][4], including e-book readers (e.g., Kindle), electronic shelf labels (ESL), and smartwatches [5][6]. The development of large-format color electronic paper has expanded its applications to commercial advertising and public infrastructure. For example, Praevar Inc. has introduced an e-poster solution utilizing a 32-inch color electronic paper display, enabling remote content updates via Wi-Fi[7].

Electronic Paper Signage (EPS) represents a category of digital signage optimized for displaying static images and is particularly suited for applications where power consumption must be minimized. Common EPS use cases include bus stop and train station timetables, office building floor directories, outdoor advertisements, and tourist information boards. In London, electronic paper signage has been deployed at bus stops to display real-time transit updates and advertisements with minimal power consumption [8]. Similarly, Visionect has developed urban information boards using electronic paper, which have been adopted in European smart city initiatives [9]. The high visibility and energy efficiency of electronic paper signage are widely recognized, making it especially attractive for deployment in regions prioritizing environmental sustainability.

There are two primary methods for updating content on electronic paper signage: local updates and network updates. Local updates involve manually transferring data using SD cards or USB drives, allowing administrators to update content without relying on network infrastructure. While this approach offers high flexibility in installation locations, it requires manual intervention, making it unsuitable for large-scale deployments.

In contrast, network updates utilize Wi-Fi, cellular communication (LTE/5G), or LoRaWAN to update content remotely. This method enhances operational efficiency by eliminating the need for on-site updates, but it necessitates constant connectivity to receive update commands.

For network-updatable EPS, the control PC must remain

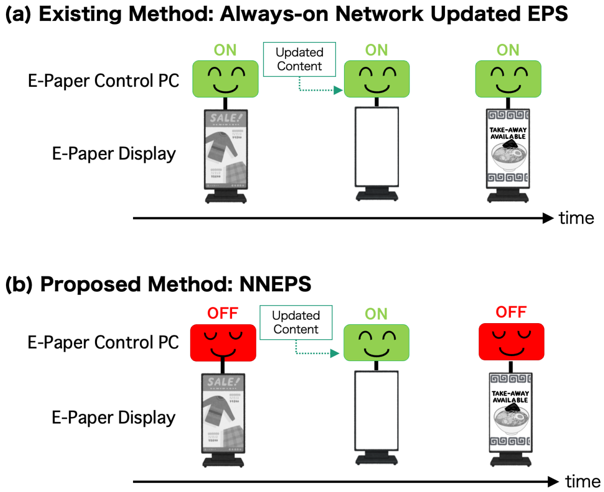

Figure 1. Comparison of methods. (a) Conventional method, (b) Proposed method.

powered on at all times to receive content updates, leading to continuous power consumption. This issue undermines one of the key benefits of electronic paper—low energy consumption—and addressing this inefficiency is a critical challenge.

In this study, we propose a Normally-off Network Electronic Paper Signage (NNEPS) system, designed to reduce power consumption in network-updatable EPS by incorporating a normally-off control mechanism. Specifically, the system keeps the control PC powered off under normal conditions, activating it only when content updates are required. This approach retains the convenience of network-based content updates while minimizing standby power consumption.

We have developed a prototype system named NNEPS (Normally-off Network Electronic Paper Signage) to implement this concept. Figure 1 illustrates the comparison between conventional network-updatable EPS and our proposed NNEPS system.

While electronic paper technology is well-known for its low power consumption and sunlight readability, most existing systems still rely on a continuously powered control unit to handle network-based content updates. This undermines the core energy-saving advantage of e-paper, especially in large-scale deployments where multiple devices remain on standby.

While network-based electronic paper signage is well studied, the issue of standby power consumption has received limited attention. In this work, we propose a normally-off architecture in which the control PC is kept powered off during regular operation and activated only when content updates are required. This approach enables both remote content management and substantial reductions in standby power usage.

Furthermore, our study goes beyond conceptual design by implementing and evaluating two functioning prototypes and conducting field validation. These efforts demonstrate the feasibility of the proposed system and its potential for energy-efficient public signage applications.

Our preliminary research was published as a conference short paper [1], which introduced the fundamental concept of reducing power consumption in network-updatable EPS, along with the initial design, implementation, and evaluation of NNEPS. This paper expands significantly on the previous work by providing detailed descriptions of the system design, implementation, and evaluation experiments, as well as additional field experiments conducted in a university library. Furthermore, we discuss potential advancements for NNEPS, including energy harvesting techniques and alternative content update methods.

Our key contributions of this paper are as follows:

1) **Proposal of a Normally-off Network Update Method**: We address the issue of standby power consumption in conventional network-updatable EPS by proposing a normally-off approach, where the control PC is activated only when content updates are required.
2) **Quantitative Evaluation of Power Consumption Reduction**: Through experimental analysis, we demonstrate that the proposed system achieves approximately 33% power consumption reduction compared to conventional network-updatable EPS.
3) **Verification Through Field Experiments**: We conduct a real-world deployment of NNEPS in a university library, collecting user feedback on its visibility and effectiveness in information dissemination.

II. Related Work

A. Utilization of Electronic Paper Signage

As mentioned in the previous section, electronic paper signage has been widely adopted in public transportation and commercial advertising, taking advantage of its low power consumption and high visibility. In particular, bus stops and railway timetables have integrated electronic paper displays in combination with solar panels, enabling off-grid operation while providing real-time information updates.

For instance, in Los Angeles, the LA Metro has introduced electronic paper-based bus stop displays, utilizing wireless communication for timetable updates [10]. Similarly, in Shanghai, over 6,000 bus stops have been equipped with electronic paper timetables, achieving zero-carbon operation. Compared to LCD-based displays, electronic paper consumes only 1/120th of the power, resulting in an annual electricity cost reduction of approximately 2,000 yuan [11]. In Tokyo, Tokyu Bus has conducted pilot trials of electronic paper signage at bus stops, displaying congestion information for passengers [12].

Beyond public transportation, electronic paper is also being used in tourist information boards and urban information displays. For example, in Germany's ski resorts and in Boston, solar-powered electronic paper kiosks have been introduced to enhance public services [13]. From an environmental perspective, electronic paper signage is considered a sustainable solution, contributing to reducing urban energy consumption and lowering carbon footprints. As smart city initiatives continue to develop, electronic paper-based sustainable information infrastructure is expected to expand further.

B. Network-updatable Electronic Paper

Research on integrating electronic paper technology with IoT has been actively conducted. Fernández-Caramés and Fraga-Lamas (2018) [14] investigated the use of electronic shelf labels and IoT-enabled electronic paper tags in Industry 4.0, analyzing their compatibility with communication protocols such as LoRa, Wi-Fi, and BLE.

Vochin *et al.* (2019) [15] proposed the SICIAD system, which utilizes Bluetooth Low Energy (BLE) beacons for electronic paper signage, demonstrating its effectiveness in providing context-aware information displays in office and university environments.

Regarding cloud-based remote content management for electronic paper signage, Sethi *et al.* (2015) [16] examined the implementation of a web-based digital signage system that leverages HTML5 and modern web technologies, proving the efficiency of cloud-based content distribution.

These studies highlight the significance of integrating electronic paper with IoT technologies, suggesting that further advancements in this field will play a crucial role in future developments.

C. Low-power Displays

To further reduce the power consumption of electronic paper, research on energy harvesting technology for display operation has been actively conducted. Grosse-Puppendahl *et al.* (2016) [17] developed a prototype electronic paper signage system that operates without an external power source by utilizing indoor light-based photovoltaic power generation. Their system, which combined a low-resolution E Ink panel with BLE communication, achieved an energy efficiency 35 times higher than conventional high-resolution panels.

Kortbeek *et al.* (2020) [18] proposed BFree, a framework designed to facilitate the development of battery-free embedded systems powered by energy harvesting. BFree provides hardware for energy collection and a power failure-resistant Python environment, supporting the development of sustainable embedded applications.

These studies suggest that integrating energy harvesting with electronic paper technology can further enhance its low-power advantages, enabling fully autonomous display systems in various applications.

III. NNEPS

In this study, we propose a network-updatable electronic paper signage system, Normally-off Network Electronic Paper Signage (NNEPS), designed to reduce standby power consumption.

Conventional network-updatable EPS systems require the control PC to remain powered on at all times to receive content updates. Although electronic paper itself consumes power only during screen updates and requires no power to maintain a display, the constant operation of the control PC negates the low-power benefits of electronic paper.

To address this issue, our proposed NNEPS system operates by keeping the control PC powered off under normal conditions and activating it only when content updates are necessary. This method preserves the convenience of remote content updates while significantly reducing standby power consumption.

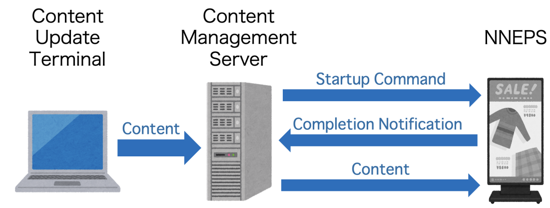

Figure 2. System architecture and content update flow of NNEPS.

The design of NNEPS is based on the following three principles:

1) **Low power consumption:** The control PC remains off when not in use and is powered on only when updating the display, effectively minimizing standby power consumption. Additionally, lightweight communication protocols such as Message Queuing Telemetry Transport (MQTT) are utilized to reduce power usage during data transmission.
2) **Remote content updates:** The system enables remote content updates via Wi-Fi or cellular networks, eliminating the need for manual intervention. This ensures ease of management without requiring direct access to each signage unit.
3) **Scalability:** The system enables remote content updates via Wi-Fi or cellular networks, eliminating the need for manual intervention. This ensures ease of management without requiring direct access to each signage unit.

By implementing these principles, NNEPS aims to achieve significant power savings while maintaining the benefits of network-based content updates.

IV. System Design

In this study, we developed a prototype of the Normally-off Network Electronic Paper Signage (NNEPS) system. NNEPS is an electronic paper signage system designed for remote content updates via a network, requiring the integration of a content management server to facilitate content distribution and system control.

Figure 2 illustrates the overall system architecture and content update flow. The content management server is responsible for transmitting content to NNEPS units via the network and issuing update commands. In our prototype implementation, the content management server not only distributes content but also controls the power state of the NNEPS control PC, ensuring that it is powered on only when necessary for updates. This mechanism enables NNEPS to maintain network-based content update functionality while minimizing standby power consumption.

A. NNEPS Components

NNEPS consists of three main components, as shown in Figure 3.

- **Electronic paper display:** This component is responsible for rendering content. It utilizes electronic paper technology,

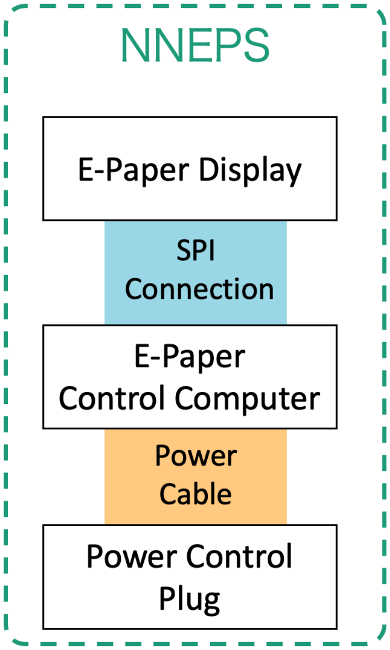

Figure 3. Main components of the NNEPS system.

which consumes power only during screen updates and does not require power to maintain a displayed image. Its high visibility under direct sunlight makes it suitable for outdoor applications.

- **Electronic paper control PC:** This unit handles content reception and display control. Under normal conditions, it remains powered off to conserve energy and is activated only when a content update is required. Once an update is complete, it shuts down to minimize power consumption.
- **Power control plug:** This component manages power supply to the control PC, ensuring that it is turned on only when content updates are necessary. It receives commands from the content management server and toggles the power state of the control PC accordingly. Various implementations are possible, ranging from simple on/off switches to advanced systems capable of managing multiple signage units.

By coordinating these components, NNEPS achieves energy-efficient operation while retaining the benefits of remote content updates.

B. Content Update Process

The content update process in NNEPS consists of three phases: the activation phase, the content update phase, and the shutdown phase. Figure 4 illustrates the sequence of these phases.

Activation Phase: Powering on the Control PC

1) A content management terminal (such as a PC or smartphone) uploads new content to the content management server.
2) The content management server prepares the new content and sends a command to the power control plug to turn on the control PC.
3) The power control plug activates the power supply to the electronic paper control PC, initiating the boot process.
4) Once the control PC has successfully powered on, it sends a status notification to the content management server.

Content Update Phase: Displaying Content on Electronic Paper

5) The content management server receives the status notification and transmits the new content to the control PC.
6) The control PC updates the electronic paper display with the received content.

Shutdown Phase: Turning off the Control PC

7) After completing the content update, the control PC sends a completion notification to the content management server and initiates the shutdown process.
8) The power control plug detects the completion notification and cuts off the power supply to the control PC.

By following this process, NNEPS ensures that the control PC remains powered on only during necessary content updates, significantly reducing standby power consumption while maintaining the benefits of remote content management.

C. Communication Protocol

To ensure low-power and reliable content updates, NNEPS adopts MQTT as its communication protocol. MQTT is a lightweight publish/subscribe messaging protocol widely used in IoT environments, particularly suitable for bandwidth- and energy-constrained systems. In the proposed system, MQTT is used to transmit control messages between the content management server and the power control plug in Ver. B.

MQTT offers several advantages for the NNEPS architecture. First, its small packet size and low overhead make it ideal for scenarios where the system remains idle most of the time and only requires short bursts of communication. Second, the asynchronous publish/subscribe model decouples the message sender and receiver, simplifying system management and allowing for scalable expansion. Overall, MQTT aligns well with NNEPS's design philosophy of minimal standby activity and efficient control signaling.

V. Implementation

A. Overview

In this study, we implemented two versions of the NNEPS prototype: Ver.A and Ver.B. Both versions share the fundamental system components, consisting of an electronic paper display, an electronic paper control PC, and a power control plug, but they were implemented based on different design principles.

- Ver.A: Utilizes a commercially available smart plug for a simple power control method.
- Ver.B: Implements a custom power control circuit using a microcontroller and a relay module.

Table I summarizes the key differences between Ver.A and Ver.B.

Ver.A features a simple implementation by leveraging an off-the-shelf smart plug, minimizing additional hardware

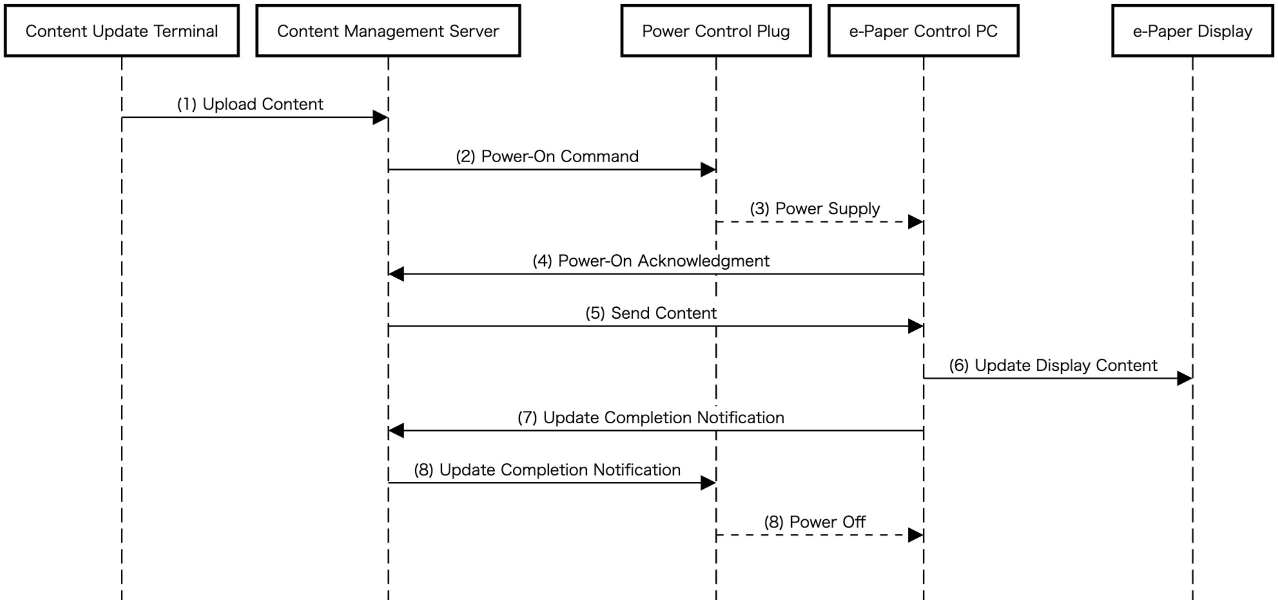

Figure 4. Sequence diagram of the content update process in NNEPS.

TABLE I. HARDWARE COMPARISON BETWEEN VER.A AND VER.B.

Component	Ver.A	Ver.B
e-Paper display	10.3-inch E Ink	10.3-inch E Ink
Control PC	Raspberry Pi 4	Raspberry Pi 4
Power control plug	Smart plug (Wi-Fi control)	Relay control (via microcontroller)
Communication	HTTP API	GPIO control

TABLE II. COMPARISON OF POWER CONTROL METHODS IN VER.A AND VER.B.

Feature	Ver.A	Ver.B
Ease of setup	High (uses commercial product)	Low (requires circuit assembly)
Response time	Some delay (several seconds)	Near real-time
Customizability	Low (controlled only via API)	High (flexible relay control)

Figure 5. Prototype implementation of NNEPS Ver.A.

development. On the other hand, Ver.B incorporates a custom power control circuit using a relay module, enabling low-latency and precise power management.

Ver.A and Ver.B differ in their power control methods. Since Ver.A uses a commercially available smart plug, it is easy to configure and integrates well with existing infrastructure. In contrast, Ver.B adopts custom control using a microcontroller and relay, allowing for more precise power management.

Table II compares the characteristics of both power control methods.

The following sections provide detailed explanations of each implementation.

B. *Ver.A: Normally-Off EPS*

NNEPS was implemented using a SwitchBot Smart Plug Mini as the power control plug. The SwitchBot Smart Plug Mini provides a power control Web API that allows switching the power supply on and off, which can be accessed via Wi-Fi. By accessing this Web API, the power supply to the electronic paper control PC is managed.

For the electronic paper display, we used a 10.3-inch electronic paper display manufactured by Waveshare. The electronic paper control PC, content management server, and power management PC were implemented using a Raspberry Pi 4 Model B, as shown in Figure 5. The programs for the electronic paper control PC, content update server, and power management PC were implemented in Python.

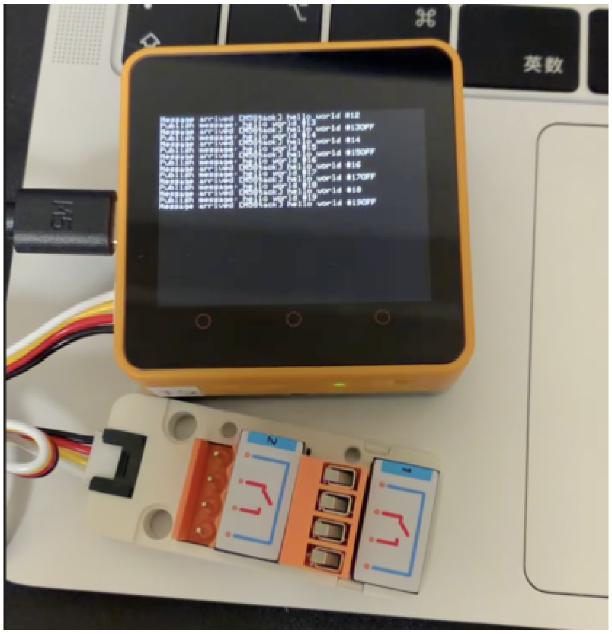

Figure 6. Power control plug of NNEPS Ver.B, consisting of M5Stack Core2 for AWS and a relay module.

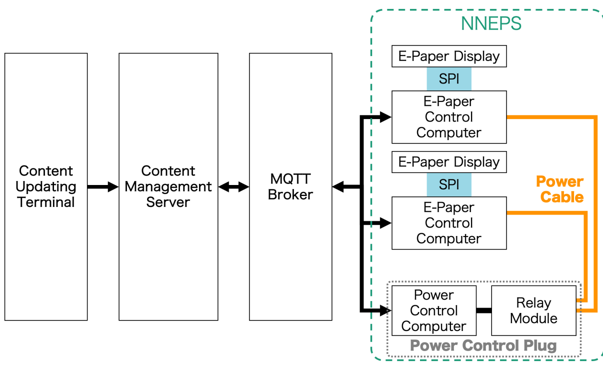

Figure 7. System architecture of NNEPS Ver.B.

C. Ver.B: Relay-Controlled Multiple EPS

To address the limitations of Ver.A, Ver.B was implemented to allow a single power control plug to manage multiple EPS units. Instead of the SwitchBot Mini Plug used in Ver.A, Ver.B utilizes a microcontroller and a relay module to implement the power control plug, as shown in Figure 6.

The relay module is capable of switching an electrical circuit on and off in response to an electrical signal. For controlling the relay module, we used M5Stack Core2 for AWS. Firmware was implemented on the M5Stack to switch the relay module on and off based on MQTT notifications.

The system architecture of NNEPS Ver.B is illustrated in Figure 7. By using a relay module, multiple EPS units can be connected, and power on/off management is enabled, as shown in Figure 8.

In the current implementation of Ver.B, two EPS units were connected to the power control plug. It is important to note that this configuration does not represent a technical limitation of the system. The underlying architecture, based on a microcontroller-controlled relay module, is inherently scalable and can support three or more EPS units with appropriate hardware expansion and scheduling logic.

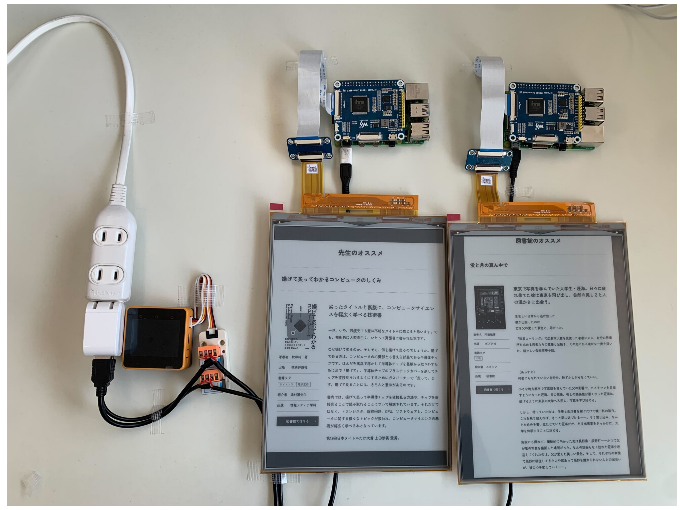

Figure 8. Prototype implementation of NNEPS Ver.B.

The decision to use two units in this study was made to maintain a manageable scope for evaluation and demonstration purposes. In practical deployments, the number of supported EPS devices can be increased as needed, limited primarily by available power control channels and update latency considerations.

D. Content Update System Details

To centrally manage NNEPS content and facilitate the content update process, a content management page was implemented, as shown in Figure 9. The implemented content management functions include screen update operations, image uploads, deletions, and browsing for NNEPS. The content management page was developed as a web application using Flask, a Python web framework.

VI. Evaluation

A. Overview

In this study, we conducted two types of evaluation experiments to assess the power-saving effectiveness of NNEPS. In Evaluation Experiment 1, we verified the reduction in standby power consumption and confirmed the effectiveness of the normally-off mechanism in NNEPS for power savings. In Evaluation Experiment 2, we measured the total power consumption under a real-world operational scenario and compared it with a conventional network-updatable electronic paper signage system that remains continuously powered, thereby evaluating the overall power efficiency of NNEPS.

For these experiments, we used NNEPS Ver.B, the normally-off network-updatable electronic paper signage proposed in this study, and compared it with a conventional network-updatable EPS. Power consumption measurements were conducted using a commercially available plug-in power meter.

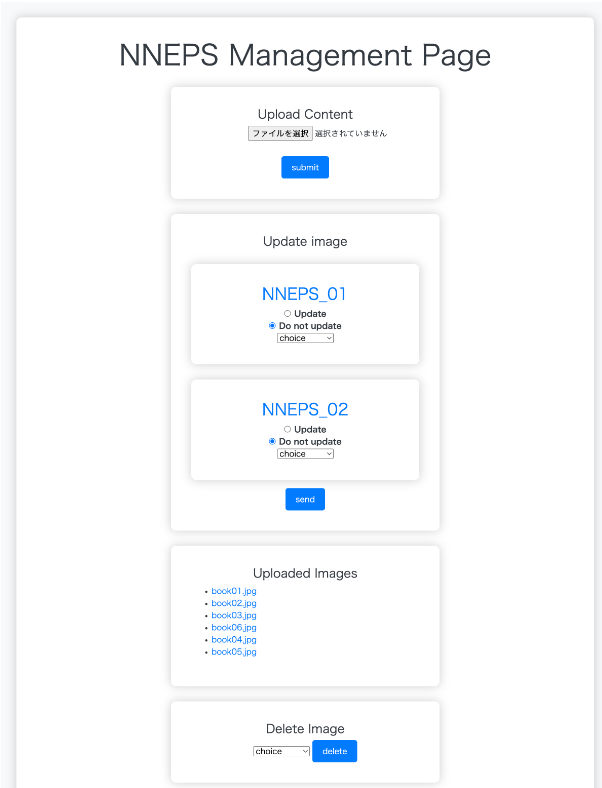

Figure 9. Content management page.

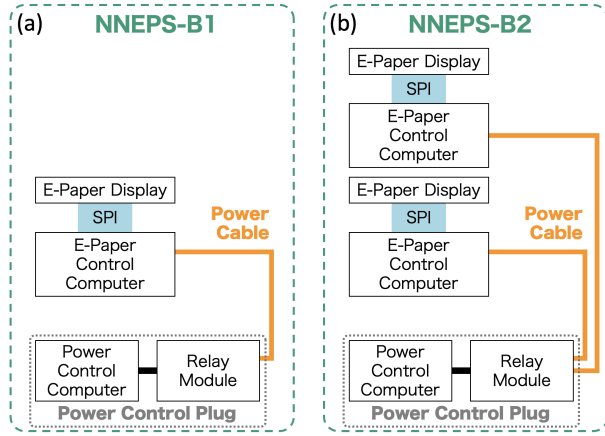

Figure 10. System architecture of NNEPS-B1 and NNEPS-B2.

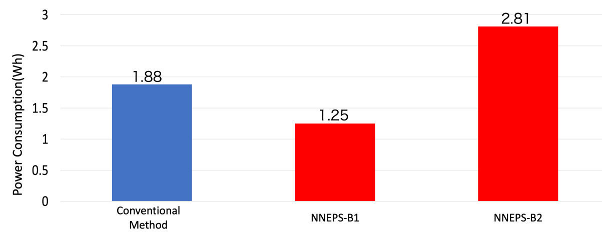

Figure 11. Power consumption comparison between the conventional method and the proposed method.

B. *Evaluation Experiment 1: Comparison with Conventional Methods*

In Evaluation Experiment 1, we measured the power consumption of NNEPS and compared it with a conventional method that supplies power continuously. The power consumption of NNEPS is defined as the total power consumed by the electronic paper control PC and the power control PC. We measured power consumption under two configurations: one where a single EPS unit was connected to the relay module and another where two EPS units were connected. The system with a single EPS connection is referred to as NNEPS-B1, while the system with two EPS units is referred to as NNEPS-B2, as illustrated in Figure 10. The screen update frequency was set to once every 5 minutes, and the power consumption over one hour was recorded.

The results of Evaluation Experiment 1 are shown in Figure 11. In the conventional method, where the electronic paper control PC remains continuously powered on, the power consumption was 1.88 Wh. In contrast, NNEPS-B1 consumed only 1.25 Wh, achieving approximately 33% power savings compared to the conventional method.

On the other hand, NNEPS-B2 consumed 2.81 Wh, more than twice that of NNEPS-B1. This result is attributed to implementation constraints. When controlling multiple EPS units with NNEPS, the screen update process is executed sequentially for each unit, leading to an increase in the update duration as the number of connected units increases. For NNEPS-B1, the average time required for a screen update was 85 seconds, whereas for the NNEPS-B2 configuration with two EPS units, the average update time increased to 108 seconds. In NNEPS-B2, the power supply to both electronic paper control PCs is cut off only after the later-updated EPS completes its screen update. As a result, both electronic paper control PCs remained powered on for a longer duration, leading to an overall increase in power consumption exceeding twice that of the single EPS configuration.

Figure 12 illustrates the temporal variation in power consumption during screen updates for each system. In the proposed NNEPS method, significant power consumption fluctuations are observed during both standby and screen update phases for both NNEPS-B1 and NNEPS-B2. This behavior is attributed to the high power demand during the startup phase of the electronic paper control PC.

C. *Evaluation Experiment 2: Impact of Content Update Interval*

In Evaluation Experiment 2, we calculated the power consumption of both the conventional method and NNEPS under

TABLE III. COMPARISON OF POWER CONSUMPTION CONDITIONS.

	Conventional Method	Proposed Method
Power consumption during update processing (W)	2.3	2.85
Power consumption during standby (W)	1.75	0.7
Update completion time (s)	17	85

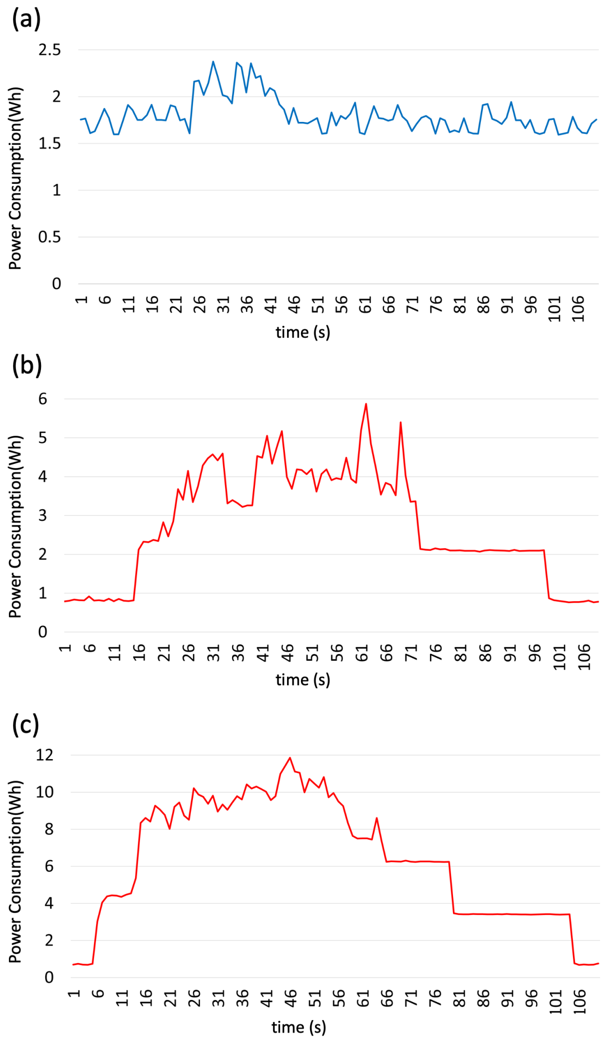

Figure 12. Power consumption during screen updates: (a) Conventional method, (b) NNEPS-B1, (c) NNEPS-B2.

different content update intervals. Based on the measurement results from Evaluation Experiment 1 (Table III), we estimated the power consumption for four different update intervals: 1 hour, 3 hours, 12 hours, and 24 hours. The system operation time was set to 24 hours, and a single EPS unit was connected to NNEPS.

The results of Evaluation Experiment 2 are presented in Table IV. NNEPS achieved a significant reduction in power consumption compared to the conventional method. When multiple EPS units are in operation, NNEPS is expected to provide even greater energy-saving benefits.

VII. Demonstration Experiment

A. Overview

To investigate potential use cases for NNEPS, we conducted a demonstration experiment (Figure 13). NNEPS was installed in the library of Hokkaido Information University for two weeks, during which we conducted a survey among visitors. The survey was administered using Google Forms.

TABLE IV. Power consumption over 24 hours for different screen update intervals in the conventional EPS and NNEPS. (Unit: watt-hour (Wh))

Interval	Conventional Method	NNEPS
1 hour	42.062	18.018
3 hours	42.021	17.206
12 hours	42.005	16.902
24 hours	42.003	16.851

Figure 13. Demonstration experiment in the university library.

In this experiment, NNEPS updated the displayed content every 15 minutes, switching between images introducing recommended books selected by the library staff. A total of six visitors participated in the survey. The survey questions are listed in Table V.

Note that the original survey was conducted in Japanese, but the translated version is presented in this paper.

B. Results

For Q2, "Do you find the information provided by NNEPS useful?" (rated on a scale from 1: No to 5: Yes), the average rating was 4.0. Among the five levels, ratings of 3, 4, and 5 were each selected by two respondents.

In Q3, "Please explain why you find it useful", respondents provided the following open-ended answers:

- "It can be installed anywhere. There is no need to prepare book display racks."
- "It seems to be an efficient way to promote a large number of books."
- "It takes up less space compared to a traditional display."

Many respondents found the thin and lightweight nature of the electronic paper display useful, as it allows for greater flexibility in installation locations compared to LCD displays.

For Q6, "Is the information displayed by NNEPS easy to read?" (rated on a scale from 1: Hard to see to 5: Easy to see), the average rating was 3.83. Among the five levels, four respondents rated it as 4.

In Q7, "Please explain why you find it easy to read", two respondents provided the following open-ended answers:

TABLE V. SURVEY QUESTIONS FOR LIBRARY VISITORS.

No.	Question	Response options
Q1	How often do you visit the library per week?	4–5 days / 2–3 days / Less than 1 day
Q2	Were you aware of electronic paper signage before?	Yes / No
Q3	Do you find the information provided by NNEPS useful?	1. No – 5. Yes
Q4	Please explain why you find it useful.	Open-ended
Q5	Please explain why you do not find it useful.	Open-ended
Q6	Is the information displayed by NNEPS easy to read?	1. Hard to see – 5. Easy to see
Q7	Please explain why you find it easy to read.	Open-ended
Q8	Please explain why you find it hard to read.	Open-ended
Q9	Please provide any additional comments on readability.	Open-ended
Q10	Can you suggest any potential applications of NNEPS within the university?	Open-ended
Q11	Can you suggest any other possible applications of NNEPS?	Open-ended

- "Since it is not an LCD, it does not reflect light."
- "The digital font is clearer and easier to read compared to handwritten text."

In Q8, "Please explain why you find it hard to read", common concerns included display size and color limitations:

- "Since it is monochrome, text becomes small when displaying a large amount of information."
- "It is difficult to recognize book covers due to the black-and-white display."

VIII. Discussion

A. Update Latency

In the current implementation, the typical time required for a complete screen update is approximately 80 to 100 seconds. This latency is primarily due to the sequential nature of the update process across multiple EPS units, as well as the boot-up time of the control PC. While this duration is acceptable for static or infrequently changing information, it may be unsuitable for scenarios requiring rapid content updates.

To address this issue, several improvements can be considered. First, parallelization of update processing—such as activating multiple control PCs or using multi-threaded update handling—could reduce total update time. Second, replacing the Raspberry Pi-based control PCs with lightweight microcontroller-based systems or embedded boards with faster startup times may further reduce latency. Additionally, optimizing the e-paper display interface and content rendering pipeline could help shorten the refresh cycle.

These enhancements will be explored in future work to extend the applicability of NNEPS to more time-sensitive information displays.

B. Potential for Energy Harvesting

The proposed NNEPS successfully reduced power consumption compared to conventional network-updatable electronic paper signage. However, to achieve further power savings, it is desirable to introduce a power supply method that does not rely on external power sources. One possible approach is energy harvesting.

Energy harvesting is a technology that collects small amounts of energy from the surrounding environment and utilizes it as electrical power. In particular, the following power generation methods are expected to be applicable to NNEPS.

1) Solar Power Generation: Since electronic paper operates with low power consumption, it can function as a fully autonomous device when combined with a small solar panel. This approach is particularly suitable for bus stops and information boards used outdoors, where ample sunlight is available. By integrating a solar panel with a secondary battery (e.g., lithium-ion battery), continuous operation can be achieved. Previous studies have successfully developed devices that integrate electronic paper with solar cells, further reducing power consumption[19][17].

2) Vibration Energy Harvesting: In locations with high pedestrian traffic, such as bus stops and train stations, vibration energy harvesting (Piezoelectric Energy Harvesting) is a promising option. By incorporating piezoelectric elements into the casing or installation surface of NNEPS, it is possible to generate power from pedestrian movements or wind vibrations. For instance, a system could be developed in which piezoelectric devices embedded in the floor store energy each time a person walks over them, using this stored energy to update the electronic paper display.

3) Wireless Power Transfer: Recent advancements in wireless power transfer technologies utilizing Wi-Fi and RF (Radio Frequency) have made them a viable option for powering low-energy devices [20][21][22]. Since NNEPS remains in standby mode most of the time, it is possible to accumulate small amounts of power over long durations and activate the system when needed. This method has the advantage of leveraging existing network infrastructure, eliminating the need for additional power supply installations.

C. Content Updates Using Local Networks

In this study, NNEPS adopted an internet-based content update method. However, in environments where internet connectivity is unstable or when aiming for even lower power consumption, utilizing a local network for content updates can be an effective approach. This section discusses the potential of using BLE Advertise and mesh networks for content updates.

1) Content Updates Using BLE Advertise: BLE Advertise is a communication method in which BLE devices broadcast information over short distances without requiring pairing. This allows for low-power transmission of data.

For NNEPS, the following operational model can be considered: A content management device, such as a smartphone or tablet, broadcasts information to NNEPS using BLE Advertise. NNEPS receives the BLE Advertise signal and updates the electronic paper display if new content is detected.

The advantages of using BLE Advertise in NNEPS are as follows:

It does not rely on network infrastructure, allowing operation even in offline environments. BLE consumes significantly less power compared to Wi-Fi or cellular communication, making it well-suited for electronic paper. Using smartphones or tablets eliminates the need for additional network equipment. However, BLE Advertise has limitations. The maximum data payload per transmission is only 31 bytes, making it unsuitable for large content updates. Thus, techniques such as image compression and segmented transmission would be necessary. Additionally, the communication range is typically limited to 10–30 meters, which makes it unsuitable for updating multiple NNEPS units over a large area simultaneously.

2) Content Updates Using Mesh Networks: To overcome the communication range limitations of BLE Advertise, introducing a mesh network is a promising alternative. A mesh network is a communication system in which multiple devices communicate with each other and relay data across a wider area. By utilizing protocols such as Bluetooth Mesh or LoRa Mesh, it becomes possible to update content over a large area while maintaining low power consumption.

In this approach, a content management device first transmits content to a nearby NNEPS. The receiving NNEPS then relays the data to surrounding NNEPS units, adopting a relay-based transmission method. This enables all devices within the network to share the latest content.

The advantages of using a mesh network include:

BLE or LoRa-based communication can cover a range from hundreds of meters to several kilometers, making it suitable for large-scale deployments. It does not require an internet connection or a central server, reducing communication costs. Since communication infrastructure does not experience increased load as more devices are added, the system is highly scalable. However, mesh networks also present some challenges:

Designing optimal communication paths between nodes requires careful network management. Since data is relayed through multiple nodes, update times may increase, introducing potential latency issues. Nodes acting as relays must remain on standby at all times, leading to higher power consumption, requiring optimization of power-saving algorithms. Considering these advantages and challenges, further investigation is needed to determine the most suitable mesh network architecture for NNEPS.

IX. Conclusion

In this study, we proposed and implemented Normally-off Network Electronic Paper Signage (NNEPS) to reduce the power consumption of network-updatable electronic paper signage (EPS). NNEPS adopts a mechanism where the electronic paper control PC remains powered off under normal conditions and is activated only when necessary, thereby reducing the standby power consumption that conventional EPS continuously requires. Experimental results confirmed that NNEPS achieved approximately 33% power savings compared to conventional methods. Furthermore, through a demonstration experiment conducted within a university, we collected user evaluations regarding the practicality and visibility of NNEPS, suggesting its usefulness.

In the future, we aim to expand NNEPS to control a larger number of EPS units. Since NNEPS reduces power consumption by managing the power supply to EPS units and minimizing the number of computers that remain in standby mode for communication, its effectiveness increases as more EPS units are connected. In the current implementation, up to two EPS units could be connected, but screen updates could not be processed in parallel, resulting in additional power consumption. Future work will focus on parallel processing of screen updates, reducing update time, and optimizing the electronic paper control PC.

Additionally, this study discussed further developments of NNEPS, including the introduction of energy harvesting technologies and the adoption of local network-based content update methods. By utilizing energy harvesting, it is expected that fully autonomous EPS can be realized without reliance on external power sources. Furthermore, leveraging BLE Advertise and mesh networks instead of the internet could enable more energy-efficient and large-scale EPS deployments.

Acknowledgment

This research was supported by the Hokkaido IT Creator Discovery and Development Project (Shinsetsu Program). We would like to express our sincere appreciation.

References

[1] T. Akiba and T. Yumura, “NNEPS: Network-Updated E-Paper Signage with Reduced Standby Power Consumption”, in *The Eighteenth International Conference on Sensor Technologies and Applications*, 2024, pp. 8–9.

[2] B. Insight, *The global installed base of digital signs reached 91.5 million units in 2023*, https://www.berginsight.com/the-global-installed-base-of-digital-signs-reached-915-million-units-in-2023.

[3] P. F. Bai *et al.*, “Review of paper-like display technologies (invited review)”, *Progress In Electromagnetics Research*, vol. 147, pp. 95–116, 2014.

[4] J. Heikenfeld, P. Drzaic, J.-S. Yeo, and T. Koch, “A critical review of the present and future prospects for electronic paper”, *Journal of the Society for Information Display*, vol. 19, no. 2, pp. 129–156, 2011.

[5] WIRED, *How pebble kickstarted a trend*, https://www.wired.com/story/how-pebble-kickstarted-a-trend/.

[6] Y. Wang, Z. Luo, G. Qiu, and G. Zhou, "Design of Smart Watch system based on E-paper", in *10th IEEE International Conference on Nano/Micro Engineered and Molecular Systems*, IEEE, 2015, pp. 327–330.

[7] R. Mertens, *Praever launches a new ePoster solution based on 32" 2560x1440 E-Ink Spectra 6 displays | E-Ink-Info*, https://www.e-ink-info.com/praever-launches-new-eposter-solution-based-32-2560x1440-e-ink-spectra-6-displays.

[8] C. Maconie, *Papercast launches ultra-low power alternative to LED bus stop displays - Papercast*, https://www.papercast.com/product/papercast-launches-ultra-low-power-alternative-to-led-bus-stop-displays/.

[9] isionect, *Find your outdoor fun in Oberstdorf – helped by e-paper tourist information!*, https://www.visionect.com/blog/find-your-outdoor-fun-in-oberstdorf/.

[10] R. Mertens, *LA Metro to use E Ink panels for passenger information displays | E-Ink-Info*, https://www.e-ink-info.com/la-metro-use-e-ink-panels-passenger-information-displays.

[11] RayClouds, *E-PAPER BUS STOPS HELP BUILD SMART CITIES*, https://www.rayclouds.com/e-paper-bus-stops-help-build-smart-cities.html.

[12] C. Tusinski, *Tokyu Group and GDS Create Smart Bus Stops with e-Tela displays and E Ink Digital Paper*, https://blog.eink.com/tokyu-group-and-gds-create-smart-bus-stops-with-e-tela-displays-and-e-ink-digital-paper.

[13] M. Ramírez, *Solar E-ink signs in Boston: Innovation and sustainability for the urban future*, https://en.renovablesverdes.com/soofa-displays-signals-and-ink-works-solar-energy-boston/.

[14] T. M. Fernández-Caramés and P. Fraga-Lamas, "A review on human-centered IoT-connected smart labels for the industry 4.0", *IEEE Access*, vol. 6, pp. 25 939–25 957, 2018.

[15] M. Vochin, A. Vulpe, L. Boicescu, S. G. Obreja, and G. Suciu, "An intelligent low-power displaying system with integrated emergency alerting capability", *Sensors*, vol. 19, no. 3, p. 666, 2019.

[16] M. Sethi, M. Lijding, M. Di Francesco, and T. Aura, "Flexible management of cloud-connected digital signage", in *2015 IEEE 12th Intl Conf on Ubiquitous Intelligence and Computing and 2015 IEEE 12th Intl Conf on Autonomic and Trusted Computing and 2015 IEEE 15th Intl Conf on Scalable Computing and Communications and Its Associated Workshops (UIC-ATC-ScalCom)*, IEEE, 2015, pp. 205–212.

[17] T. Grosse-Puppendahl *et al.*, "Exploring the design space for energy-harvesting situated displays", in *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, 2016, pp. 41–48.

[18] V. Kortbeek *et al.*, "BFree: Enabling Battery-free Sensor Prototyping with Python", *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, vol. 4, no. 4, pp. 1–39, 2020.

[19] M. Rodriguez Fernandez, E. Zalama Casanova, and I. González Alonso, "Review of display technologies focusing on power consumption", *Sustainability*, vol. 7, no. 8, pp. 10 854–10 875, 2015.

[20] V. Talla *et al.*, "Powering the next billion devices with Wi-Fi", in *Proceedings of the 11th ACM Conference on Emerging Networking Experiments and Technologies*, 2015, pp. 1–13.

[21] H. Zeb *et al.*, "Zero Energy IoT Devices in Smart Cities Using RF Energy Harvesting", *Electronics*, vol. 12, no. 1, p. 148, 2022.

[22] N. U. Khan, F. U. Khan, M. Farina, and A. Merla, "RF energy harvesters for wireless sensors, state of the art, future prospects and challenges: a review", *Physical and Engineering Sciences in Medicine*, vol. 47, no. 2, pp. 385–401, 2024.