Proposal of an Information Delivery Method for Electronic Paper Signage Using Human Mobility as the Communication Medium

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***Abstract*—In environments where communication infrastructure is unstable, remotely updating Electronic Paper Signage (EPS) is difficult. This study proposes a method that leverages human mobility as a communication medium to disseminate content progressively among EPS units. Mobile devices such as smartphones and wearables connect to EPS via short-range links upon encounter and, based on bidirectional version comparison, update to the newer content. On the EPS side, power consumption is reduced by controlling scanning intervals. We implemented a prototype using M5Paper v1.1 and confirmed basic operations, including content handover and display updates. We also outline a future direction to minimize standby power by introducing wake-up mechanisms triggered by touch/proximity and energy harvesting using piezoelectric elements.**

***Index Terms*—Electronic Paper Signage, short-range wireless communication, low-power control**

I. Introduction

Digital signage has become widespread as a medium for presenting advertisements and information in public spaces and commercial facilities.According to a report by Berg Insight [1], 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.Conventional digital signage based on liquid-crystal displays (LCDs) and organic light-emitting diode (OLED) displays offers high visibility and flexible video expression; however, it suffers from continuous power draw and limited readability under direct sunlight. Electronic paper displays are lightweight, highly readable, and energy-efficient. They have already been adopted for price tags [2] and e-book readers [3], and have also found applications in various fields such as bus stop timetables [4], advertising boards [5], and wristwatches [6] [7] [8] [9]. In addition, because power is consumed only when the screen is updated and almost none otherwise, their overall power consumption is low.

Among types of digital signage, Electronic Paper Signage (EPS) [5] leverages electronic paper technology for the display surface. By exploiting the characteristics of electronic paper, EPS is expected to enable long-term operation and outdoor installation. In outdoor deployments, combining EPS with solar panels has demonstrated operation even in locations where it is difficult to secure power [10]. Even during power outages and in situations where communication means are restricted—such as during disasters—EPS is expected to be useful as an information-providing medium owing to its low power consumption and high visibility.

Content updating methods can be classified into local updates and network-based updates. Local updates include directly updating data using an SD card or USB memory, and short-range wireless approaches. Because they do not require network infrastructure, they offer high flexibility in installation locations; however, they rely on manual operations and are unsuitable for large-scale deployments. Network-based updates utilize Wi-Fi, cellular communication (LTE/5G), or LoRaWAN to update content remotely. While management efficiency is high and the approach suits large-scale operation, immediate updates become difficult in environments where communication infrastructure is undeveloped or temporarily unavailable. In outdoor environments and disaster sites, network connectivity is often unstable in addition to constraints on power supply. Consequently, with network-based updates, ensuring stable operation from the standpoint of reliability is difficult under disasters or unstable infrastructure.

We previously proposed Normally-off Network Electronic Paper Signage (NNEPS) [11], which minimizes standby power and achieved approximately 33% reduction in standby power compared with conventional approaches by keeping the control PC normally off. However, NNEPS assumes content updates via IP networks; therefore, in environments where communication infrastructure is undeveloped or temporarily unavailable, updates are halted.

To address this, this study proposes an EPS system that delivers content by using human mobility as the communication medium, enabling updates to EPS units even under unstable communication infrastructure (Fig. 1).

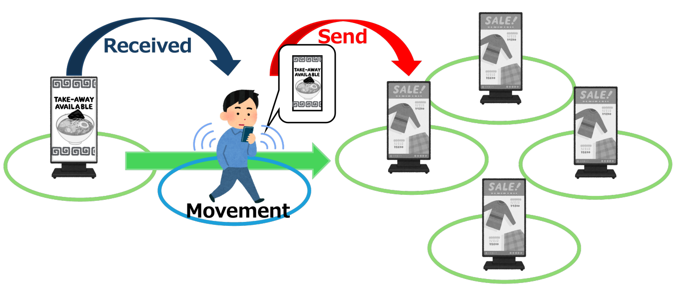

Fig. 1. System overview

II. Related Work

In this section, we review studies that deliver information in environments where communication infrastructure is difficult to use by leveraging human mobility and short-range wireless communication, and we clarify the positioning of this study.

Lu et al. [12] proposed "TeamPhone," a system that integrates cellular, ad hoc, and opportunistic communications on smartphones for maintaining communications during disasters. They implemented two functions—messaging for rescue teams and "Self-Rescue," which groups victims' devices into low-power clusters to emit distress signals—and demonstrated performance on Android devices. Their design guidelines for decentralized operation that avoid single points of failure and account for power constraints are well aligned with evaluating the dissemination of evacuation information.

Hui et al. [13] proposed social routing based on human social ties and showed high delivery ratios and reduced costs using real-world contact traces. In situations such as disasters, where infrastructure is unstable and human flows act as information carriers, it is effective for devising strategies on whom to prioritize for forwarding.

Pentland et al. [14] conducted field deployments of an asynchronous store-and-forward network that physically carries data via buses and reported its effectiveness for low-cost connectivity in developing regions. As a classical demonstration of "networks carried by people and things" in sparse or disconnected environments, it provides a useful rationale for human-carrier designs.

These studies all share the goal of enabling information propagation under infrastructure outages by leveraging human mobility. However, they primarily target dissemination among mobile devices and do not address bidirectional content synchronization or energy-efficient operation across stationary EPS nodes.

Building on these precedents, this study employs smartphones and wearable devices as mobile nodes that temporarily store data while moving and forward it to other devices when connections become available, while setting EPS as fixed nodes. Upon encounter, communication is performed via low-power short-range wireless links, the content versions on both sides are compared, and bidirectional updates are executed as needed. In this way, we realize an information delivery method that disseminates content data gradually among EPS without relying on communication infrastructure.

III. Proposed Method

This study proposes a method that applies a data-delivery scheme requiring no communication infrastructure to EPS to enable content updates (Fig. 2).

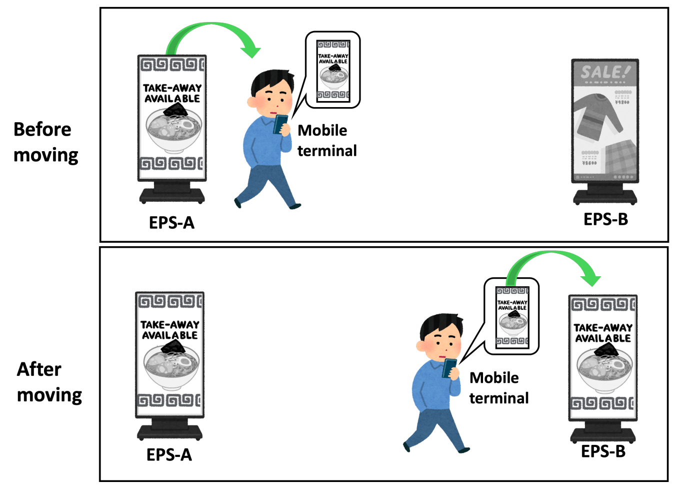

Fig. 2. Proposed method

In the proposed method, mobile devices carried by people—such as smartphones and wearable devices—temporarily store content data and transfer it when they come into proximity with an EPS at the destination. In this delivery process, the mobile device holds the data while in transit and, upon detecting proximity to an EPS, hands it over via short-range wireless communication. In this way, even where communication infrastructure is absent, data can be disseminated gradually through human movement and opportunistic encounters between devices.

IV. Design

This system is designed to gradually disseminate information by comparing content versions when a mobile device and an EPS communicate and updating data as needed. The objective is to ensure that, at each contact, the content freshness is reconciled so that the newer version prevails. The flow of version comparison and update processing is shown in Fig. 3. The detailed steps are as follows.

(1) The mobile device sends content data to the EPS.
(2) Update processing (compare the version ID):
    1. Data are identical: no update.
    2. EPS data are older: update the EPS content.
    3. EPS data are newer: update the mobile device's content.
(3) (In Case 3)
    1. The EPS sends content data to the mobile device.
    2. The mobile device stores the content.

In this design, after the connection is established, the mobile device transmits the content data and the EPS performs the

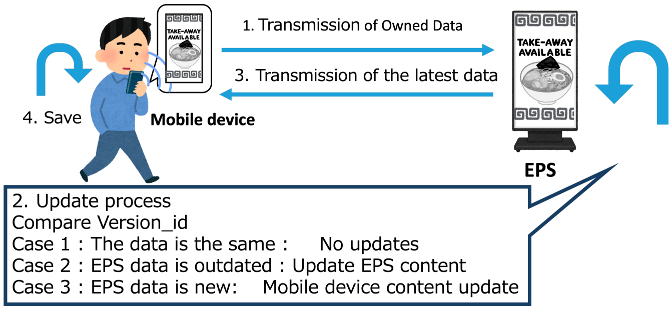

Fig. 3. Processing flow between the mobile device and the EPS

version comparison. On the EPS side, a low-power BLE scanner runs to minimize power consumption.

V. Prototype Implementation

To verify the effectiveness of the proposed method, we implemented a prototype in which both the EPS and the mobile device are realized on an M5Paper v1.1 by M5Stack (Fig. **??**). M5Paper is a development board equipped with an ESP32, enabling e-paper display control and wireless communication on the same hardware. Leveraging this characteristic, we implemented both the EPS and the mobile device on a unified hardware platform to improve software compatibility and development efficiency.

Development was conducted in C++, utilizing libraries publicly available for the ESP32. The standard EPD control library for M5Paper was used for e-paper control, and an ESP32 BLE library was used for BLE communication.

We adopted Bluetooth Low Energy (BLE) and limited the communication range to within 5 m. On the mobile device, we adjusted the transmit power (Tx power) to a lower level to physically limit radio reach. On the EPS, we used the received signal strength indicator (RSSI) to measure the signal strength from the peer; signals weaker than a predefined threshold were regarded as "too far" and rejected. In this way, we combined two mechanisms: range limiting at the transmitter and proximity filtering at the receiver.

The EPS operates as a BLE scanner, repeating a duty cycle of scanning nearby devices for 1 minute followed by entering deep sleep for 2 minutes. This maintains low power consumption while periodically discovering nearby mobile devices.

On the mobile device side, we implemented continuous BLE advertising. The device remains in the advertising state and is detected when the EPS scans, at which point a connection is established.

We designed a custom JSON-based exchange format (Table I). A logical structure named `ContentData` holds the fields `version_id`, `contents`, and `timestamp`. In the prototype, only textual data are transmitted; images are out of scope.

The communication sequence is shown in Fig. 5. First, the mobile device converts its held content data into JSON and, after the connection is established, sends it to the EPS. The

TABLE I
Fields of ContentData and their descriptions

Field	Description
`version_id`	Identifier indicating the data version; the larger numeric value is treated as newer
`contents`	String data to be displayed (text only; no images)
`timestamp`	Unix timestamp (seconds) indicating when the data were created

EPS restores the received data to an internal representation and compares it with the content data it holds. The version identifier is evaluated numerically, and the larger value is regarded as newer. If the received data are newer than the EPS's data, the EPS stores them in memory and performs a display update. Conversely, if the received data are older, they are discarded and the EPS converts its own content into JSON and returns it to the mobile device, which then converts and stores the returned data internally.

By combining deep sleep and scanning in a duty-cycled manner, the EPS does not need to remain fully active, thereby reducing power consumption.

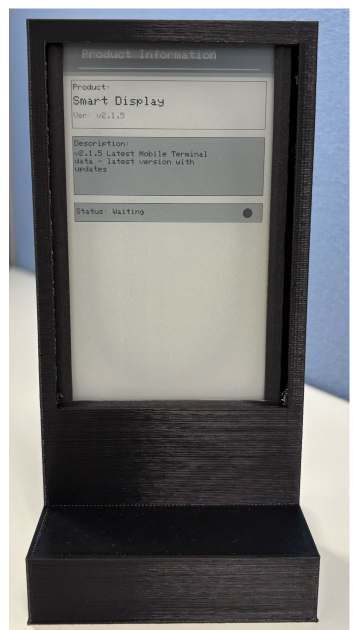

Fig. 4. Prototype of the EPS

VI. Conclusion

In this study, we developed a prototype. The implementation adopts a simple hardware and software configuration that remains extensible, enabling future feature additions such as support for image data. Regarding image data support, it will be necessary to address fragmentation during data transmission when extending the implementation.

In addition, in a low-power environment with M5Paper devices, we confirmed that content transfer via mobile devices and subsequent screen updates can be performed reliably. To

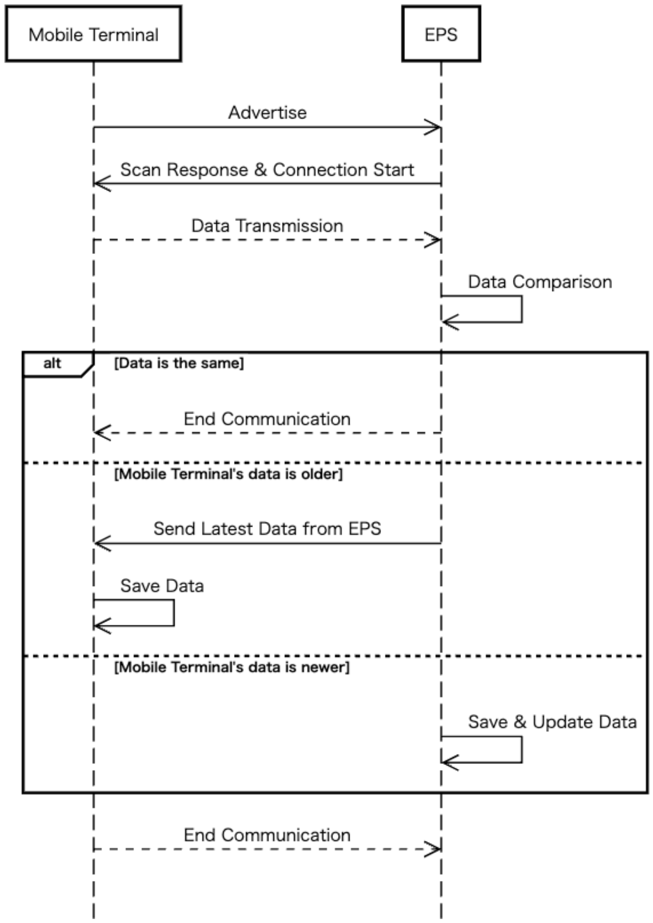

Fig. 5. Communication sequence between the mobile device and the EPS

ensure security, we plan to prevent unauthorized updates by introducing authentication with a PIN code.

Another challenge lies in handling outdated content. Because of the normally-off architecture, it is difficult to enforce explicit display period restrictions with timestamps. Instead, if no update occurs for a long period, this situation can be interpreted as an absence of user visits, and thus the continued display of outdated content is considered to have little impact.

Further reduction of system power consumption requires minimizing the standby power of the microcontroller to nearly zero. An electronic paper display inherently consumes power only during screen rewriting. To maximize this advantage, we are considering a wake-up mechanism triggered by physical contact or proximity. In particular, piezoelectric elements can generate a small voltage from user contact, and this signal can be detected to wake up the microcontroller from deep sleep. Through this mechanism, we aim to construct an EPS system that fully leverages the low-power characteristics of electronic paper displays.

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