Wirelessly Powered Bistable Display Tags

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ABSTRACT

Paper displays have a number of attractive properties, in particular the ability to present visual information perpetually with no power source. However, they are not digitally updatable or re-usable. Bistable display materials, such as e-paper, promise to enable displays with the best properties of both paper and electronic displays. However, rewriting a pixelated bistable display requires substantial energy, both for communication and for setting the pixel states.

This paper describes a bistable display tag that, from an energy standpoint, is capable of perpetual operation. A commercial off-the-shelf NFC-enabled phone generates RF signals carrying both the information and energy necessary to update the display. After the update is complete, the display continues to present the information with no further power input. We present one example implementation, a companion display for a mobile phone that can be used to capture and preserve a screenshot. We also discuss other potential applications of energy neutral bistable display tags.

Author Keywords

Near field communications, NFC, wireless power, companion display, e-paper, electronic paper, bistable display

ACM Classification Keywords

H.5.m Information interfaces and presentation: Miscellaneous.

INTRODUCTION

Despite decades of exponential improvement in the energy efficiency of computing [4, 8], visually presenting information to users has remained an energy costly process, confining the use of displays to applications in which they are tethered to a power source or a large and frequently charged battery. The invention of practical bistable display materials [3] was a key step to enabling ubiquitous displays capable of perpetual operation with zero added power. However updating such a display tag requires wireless communication and energy to change the pixel states. This paper presents what we believe to be the first pixelated electronic paper (e-paper) display that is powered and updated wirelessly. We use Near Field Communication (NFC) technology that is being widely integrated across mobile phone platforms, to power and communicate with the proposed display.

The electronic paper display tag receives energy and data for display updates from an NFC-enabled phone in close proximity to the display. One application, described in this paper, is the mobile phone companion display shown in Figure 1. Such an auxiliary display may preserve the information from the phone's main display after the phone has been placed in a sleep state; augment the phone's display to provide additional screen real estate, or may be physically separated from the phone and shared with others.

Figure 1. Display tag use scenario: companion display for mobile phone. The working prototype NFC display tag on the left shows travel directions captured from the screen of the phone on the right. All power and data to update the display is provided wirelessly by the phone's NFC reader.

NFC encompasses multiple 13.56 MHz radio frequency identification (RFID) standards including ISO 14443, used in this work. The NFC reader-to-tag link makes use of inductive coupling for both data and energy transfer to tags which often have no onboard energy source (passive tags). Inductive coupling is implemented by what is essentially an air-core transformer between the reader and the tag.

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There are a number of commercial products involving display tags making use of RFID for communications, mainly targeting industrial and logistics applications. Omni-ID's Visual Tagging System [2] consists of an ultra-high frequency (UHF) RFID tag with an LCD display. The Smart Tag, by AIOI Systems [1], is an RFID tag with an e-paper display that uses NFC for communications. Neither of these products are wirelessly powered, resulting in a bulky form factor and a limited lifetime due to battery requirements. While RFID has been extensively investigated for use in user interfaces and smart object applications [6], the number of academic publications which explore RFID-based displays is small. One research prototype demonstrated an RFID-powered e-paper display for a smart card applications [5], but the segmented e-paper display used could only display few numbers or letters.

Our contributions are as follows: In this paper we present the first pixelated e-paper display tag that uses NFC for power and communications. We evaluate how the e-paper performs in the energy constrained wirelessly-powered scenario. We present a mobile phone companion display application. Finally, we introduce the NFC Wireless Identification and Sensing Platform (NFC-WISP), on which the display tag is based.

The NFC-WISP is a software defined passive 13.56 MHz RFID tag. The NFC-WISP is based on a low-power MSP430 microcontroller (Texas Instruments), making the display tag easily re-programmable for future research and development efforts. The NFC-WISP was inspired by the WISP, a passive, software-defined 915 MHz tag for sensing applications [7].

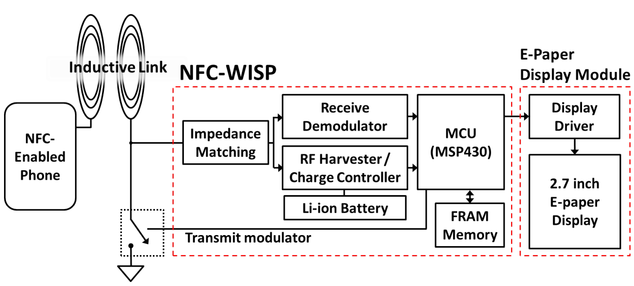

Figure 2. Display tag hardware block diagram.

SYSTEM DESIGN

A hardware block diagram of the display tag is shown in Figure 2. An MSP430 microcontroller is used to implement software defined NFC communications, and to control the e-paper driver chip embedded in the 2.7 inch e-paper display (Pervasive Displays). The purpose of the driver chip is to address the individual e-paper pixels and generate the 15 V needed to change those pixels. An onboard 2 Mbit non-volatile ferroelectric (FRAM) memory (Ramtron FM25V20) allows for 20 images to be stored for future retrieval. Nexus S and Galaxy Nexus (Samsung) phones with Android 4.2.2 (Jelly Bean) operating system are used as NFC readers.

Physical Design

The display tag integrates NFC-WISP and the e-paper display on a compact 4-layer FR4 circuit board, shown in Figure 3. Display tag dimensions are: 100 mm by 50 mm, with a maximum thickness of 3 mm. All components are placed on one side to reduce thickness. Two tactile buttons provide a simple user interface.

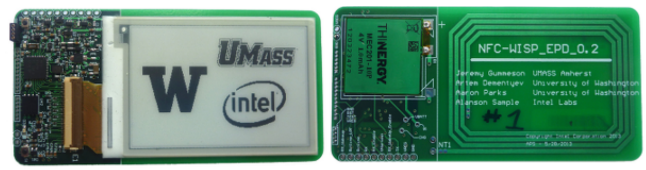

Figure 3. Display tag without the plastic case: front and back

Wireless Power Harvesting

To utilize the incoming radio frequency (RF) energy, the MAX17710 (Maxim) harvester IC is employed. The primary purpose of this IC is to boost the incoming RF voltage to the 3.3 V necessary for powering the display and the microcontroller. Furthermore, the harvester provides over-voltage protection and a battery charge controller. A rechargeable Lithium-ion battery (Thinergy MEC201) with 1 mAh capacity stores the harvested energy. The thickness of the battery is 0.17 mm. The battery buffers the energy to update the e-paper display, since more power is required to start up the display's boost converter than the RF harvester can deliver instantaneously. Furthermore, the battery stores the excess energy harvested during the NFC transaction, allowing for display updates away from the phone. The system does not fundamentally require a battery; a capacitor could instead be used for energy storage.

NFC Communications Hardware

Communication from the reader to the NFC-WISP is done by amplitude-shift keying (ASK) of the 13.56 MHz RF carrier field, as per the ISO 14443 specification. The tag's demodulator consists of a low-power analog comparator circuit that detects the ASK fluctuation in the carrier, converting it to a clean logic level signal which then enters the MSP430 microcontroller for the decoding process.

The tag-to-reader uplink is accomplished by modulating the RF field produced by the reader. This technique, known as load modulation, is commonly used in RFID systems to eliminate the power consumption and complexity of implementing an active radio on the tag side. It is accomplished simply by controlled shorting of the NFC-WISP's receive coil, which in turn produces detectable changes in the reader's transmit coil voltage.

Software Defined NFC Communications

The communication software for the NFC-WISP is designed around the 13.56 MHz ISO 14443-4 type B RFID protocol. ISO 14443B was chosen because of its high reader-to-tag data rate of 106 kbps, and because it is supported by Android NFC-enabled phones. The NFC-WISP also supports ISO 15693 with 1-out-of-256 coding, but this is not used due to its slower data rate of 1.6 kbps.

In reader-to-tag communication, bits are encoded with non-return-to-zero (NRZ) line coding, where logical ones are represented by the unmodulated 13.56 MHz carrier and zeros by the modulated carrier. The NFC-WISP sends data back to the phone by modulating its receive coil load with an 847 KHz subcarrier. Bits are coded using binary phase-shift keying (BPSK), where change of logic is determined by 180 degree phase shifts in the subcarrier. Because each bit is represented with eight periods of the 847 KHz subcarrier, the resulting data rate is 106 kbps.

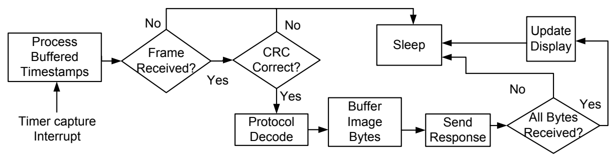

Figure 4. The NFC-WISP firmware flow diagram. While waiting for data from a phone, the NFC-WISP remains in a low power sleep state

The NFC-WISP uses the MSP430's hardware timers and serial communication modules to adhere to strict protocol timing requirements. A 13.56 MHz crystal oscillator is used as a stable and accurate timing reference for decoding phone-to-tag communications. To get byte values sent by the phone, the NFC-WISP uses its UART (Universal Asynchronous Receiver/Transmitter) unit and an interrupting input pin. All messages begin with a start of frame (SOF) delimiter which is captured by the interrupting input. Once a valid SOF is found, the UART begins capturing ISO 14443B messages to a receive buffer. Data is transmitted back to the phone using the pulse width modulation (PWM) capability of a hardware timer module. To guarantee the integrity of image data received by the display tag, the NFC-WISP validates a 16-bit cyclic redundancy check (CRC) across each frame sent by the phone. When sending a response back to the phone, the MSP430's 16-bit CRC module is used to generate and append a CRC to the response.

To ensure that all bytes of an image are successfully received, we use a simple stop-and-wait transmission protocol; the phone uses ISO 14443B's higher layer protocol field (INF) to embed our NFC-WISP protocol's "write block" command, which can send 8 blocks (32 bytes) of image data and will only send another chunk of data once the previous block has been acknowledged by the NFC-WISP. Figure 4 illustrates the software procedure implemented for transferring an image to the display tag.

Power Optimization

Since the display tag needs to be powered wirelessly, unique design constraints are introduced. Display tag operation is divided into two tasks: first, the display tag harvests energy as it receives the image data from the phone. Second, when enough energy is stored or all the data is received, the e-paper display is updated. This scheme is energy efficient because it updates the power-hungry display all at once, thereby minimizing the time during which the display is powered on.

The display tag presents an interesting tradeoff between computation and communication. For example, implementing data compression will decrease communication energy and time but will increase the computational load imposed on the display tag to decompress the image. Preferably, any significant computation should be done on the phone, as it has a relatively abundant energy supply.

E-paper Power Consumption

Since the display has a large impact on the overall energy consumption, its energy behavior was optimized. For each image update, the display consumed on average 5.2 mJ to initialize, 2.8 mJ for each frame update, and 5.9 mJ to finalize the update operation. Although the energy consumed to initialize and finalize is fixed, the number of frame updates performed can vary, and this dictates the total energy required. Unique to e-paper, the display needs to be updated multiple times with the same image to avoid ghosting (the overlapping of new and previous images). Figure 5 illustrates the contrast difference between 1, 2, 3, and 4-frame updates, and the total measured energy required in each case. In our tests, the old image was not visible to the eye after four frames, so four frames is used in the final implementation.

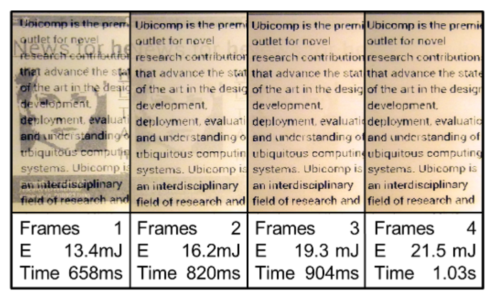

Figure 5. Overwriting old image (face) with the new (text). The figure shows 1, 2, 3 and 4 repeated rewrites and the total energy and time required in each case.

PERFORMANCE EVALUATION

The time the display tag needs to be in contact with the phone to update its image is an important aspect of the user experience. This update time depends on two factors: Communication data rate and harvested power level.

Wireless communications

In the current prototype the time to transfer the 5.67 kilobyte image frame from the phone to the tag is measured to be 3.4 seconds, achieving an average data rate of 13.3 kbps. This data rate is slower than the theoretical maximum of 106 kbps because of protocol overhead (control bits, CRC, etc) and occasional data errors. The data rate for an NFC communication system can get as high as 424 kbps using the ISO 18000 protocol, implying a theoretical 100 ms to transmit an image frame to the tag. To further decrease transmission time, the image file size could be reduced with compression; simple run-length encoding (RLE) will work well for black and white images with extensive white space.

RF Energy Harvesting

Fundamentally, the time needed to update the display tag is determined by how much RF energy can be harvested. Fortunately, NFC provides a significant amount of RF power in comparison to other wireless protocols due to the use of inductive coupling at close range. The energy that is stored on the battery is largely determined by the difference between the harvested RF power and the power consumed to run the MSP430 microcontroller and other peripherals (including leakage current of these devices).

The phone radiates about 200 mW, of which 17.7 mW (12.3 mA at 1.44 V) is harvested by the display tag. We measure that 8.25 mW (2.5 mA at 3.3 V) is consumed by the display tag during communications, mostly by the microcontroller. The remaining 9.4 mW is stored on the battery. The surplus of energy required to update the display is 21.5 mJ, which could be accumulated in 2.3 seconds if the harvester and battery efficiencies are not considered. Taking into account the practical inefficiencies of the battery and harvester, the amount of time required to collect the 21.5 mJ needed for a display update will still remain within the length of one 3.4 sec communication transaction. Although it is not practical in a standard phone reader to increase the transmitted RF power, the microcontroller firmware can be optimized to make use of low-power modes at opportune moments during communications, to improve the total power surplus.

MOBILE PHONE COMPANION DISPLAY

To demonstrate the capabilities of the display tag, we developed an Android application which takes a screenshot of the phone's display when the phone is shaken, and sends it to the display tag automatically once the tag is detected. Up to 20 images can be stored on the display tag's nonvolatile memory, and can then be cycled through using tactile buttons even when the tag is away from the reader.

The screenshot needs to be processed by the phone to be presented on the e-paper display. The 32-bit screenshot bitmap is resized, rotated, restructured, converted to gray scale and finally to black and white by simple thresholding. The black and white thresholding produces good quality text images on the companion display and can be reliably used for mirroring directions, barcodes, or maps. Since the e-paper display is black and white it inherently doesn't show colored images well, but quality could be significantly improved by halftoning or adaptive thresholding instead of the simple thresholding used here. All these operations could be done quickly and easily on the mobile phone using existing image processing tools. The Android OS doesn't generally allow applications to take screenshots, so root access was gained on the phone to enable full control of the system.

CONCLUSION

In this paper we present a wirelessly powered pixelated e-paper display tag. We show that the display tag can receive data as well as power from an NFC-enabled mobile phone. The display tag is based on the NFC-WISP, a software defined passive NFC tag. We show an application example using an e-paper display as a mobile phone companion display.

The display tag makes use of software defined communications, and therefore is flexible with respect to the various 13.56 MHz NFC RFID protocol standards. Two standards were implemented, ISO 14443B and ISO 15693. Currently the display update time is 3.4 seconds, and we have described how this time can be reduced to 2.3 seconds.

The major technical restriction of the NFC display tag is the limited operational range of a few centimeters between the reader and the tag. Furthermore, e-paper products currently have a slow update rate, and lack in visual quality and versatility compared with traditional LCD displays, limiting the type of information that can be displayed to text or static, simple black and white images. However, it is foreseeable that future e-paper products may rival LCDs in quality and versatility.

With further optimization, the display tag shown can become an inexpensive, ubiquitous display platform. We envision many useful applications for the display tags, such as enhanced security identification badges and sharable information tiles. Furthermore, since the display tags contain a low-power microcontroller, display tags can interface with sensors and other devices. In future work, the display tags will be tested with different phone models, to understand the issues around compatibility and performance. We also plan to conduct user studies in order to better understand the value of the display tag. Finally, the NFC-WISP and display tag hardware and software will be open-sourced.

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