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Towards a Wireless and Low-Power Infrastructure for Representing Information Based on E-Paper Displays

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Academic Editor: Víctor Yepes

Received: 7 October 2016; Accepted: 3 January 2017; Published: 7 January 2017

Abstract: There has been much interest in replacing traditional information supports with more technological solutions in recent years. New technologies which allow paper-like perception with minimal power needs have emerged as low-power wireless scenarios. A priority for these new supports is to create the architecture for a scalable solution which maintains minimal power requirements. The retail industry demands a new information infrastructure that improves customer and employee satisfaction. In this work, authors propose an information provision architecture based on E-Paper and carry out an experiment where different smart labeling architectures based on Paper, E-Paper, LED liquid crystal display (LCD) and Dot-matrix LCD were tested in order to determine which is best suited for a real labeling environment. Enclosed in a research project called SMARKET, the authors pilot-tested the work in a real supermarket, having the opportunity to survey employees and customers about satisfaction and frustration with the use of the architectures proposed in this research work.

Keywords: information infrastructure; ubiquitous computing; low-power; E-Paper displays; subjective perception

1. Introduction

New technologies that are integrated into daily living environments want to promote seamless integration of digital elements in everyday tasks. These new elements are no longer mere passive collectors of information, but provide new possibilities to incorporate visual and interactive elements for and with the people using them. With this direction, technology wants to focus on providing more useful information to people and to help generate large amounts of data in order to improve subject knowledge and act on it in daily infrastructure. In this paper, the authors concentrate their efforts to build a scalable solution that helps information to reach people. Digital devices are an essential part of the technological ecosystem, as they achieve several improvements in terms of visibility, sustainability, consumption and mobility. In addition to these improvements, modern digital screens aim to fulfill multiple uses with wireless connectivity and extended battery time.

Replacing traditional information supports with a more technological solution is essential for applications focused on personal environment and industrial or commercial scenarios with dynamic information. Aspects like a better autonomy than typical devices achieve, and better connectivity that minimizes as much as possible the impact of wireless communication systems are key factors in the architecture. Developing new hardware architecture for E-Paper displays will lead to new paper replacement devices that support new display technologies in environments where traditional paper is extensively used to display information to customers or managers.

This paper proposes a wireless and low-power infrastructure for information representation based on E-Paper display, as an extension of authors' previous work [1], which described an infrastructure for using open-hardware and open-interfaces to develop an E-Paper display device for personal environments. This contribution aims to optimize the management procedures in commercial scenarios where a lot of information has to be presented and updated regularly. Retail industries as well as storage facilities can find these developments as an improvement over the classic methods of information dissemination. In addition to the previous work, the hardware prototype has been updated and expanded so different display technologies are accepted. A common routing device is used and the infrastructure can be used to compare between different solutions.

Furthermore, to validate the proposed infrastructure, authors analyze the performance of different display architectures in supermarket domain, where displays are labels that present dynamic pricing and product information to the customers, providing valuable savings to the managers.

To do that, a comparison of the autonomy of the devices and the usability of the system between other procedures of displaying information is made. The experimental validation carried out in order to evaluate the solution is guided through these two research questions:

RQ1: *How much better is the battery runtime of a system for personal tagging based on E-Ink and low consumption communications compared to others?*

RQ2: *What is the satisfaction with the use of the architectures proposed in this research work?*

These questions were studied in two experiments comparing different architectures and display technologies (traditional paper, Dot-matrix Liquid Cristal Display (LCD), LED LCD and Electronic Paper (E-Paper)) for information representation.

The first experiment consists of analyzing the power consumption of architectures proposed depending on the number of screen changes in a day; the second one is framed within the deployment of an experimental pilot in a real supermarket environment. In this pilot, the authors conducted a survey interviewing nine employees and thirty customers of the supermarket.

The structure of the paper is as follows: Section 2 describes related work in dynamic information provision for environments requiring mobility and low-power consumption. Section 3 describes the labeling architecture for retail whereas Section 4 shows the proposed implementation of the wireless and low-power infrastructure using E-Paper technology. Section 5 provides an experimental validation to answer the defined research questions, and these are discussed in Section 6. Finally, Sections 7 and 8 describe some conclusions and future works.

2. Related Work

This section describes related work studying novel solutions for dynamic information communication and representation.

Research [2] studying how different product information services can improve the point of sale perception has identified a relationship between technology and customer perceptions applicable to the retail market. Other work [3] has analyzed how dynamic experiences change the customer's perception of lifetime value. Dynamic pricing [4] introduces new marketing strategies to obtain better outcomes and relationships with customers. Authors implemented a retail scenario where administrators easily configured price variability by using event, condition and action (ECA) rules [5]. Connecting the labeling infrastructure with the price provider resolves the problem of automated price change in an autonomous system [6]. This automatic infrastructure has to be supported by capable devices which allow information to be represented and updated without human interaction. The autonomy of the system depends almost solely on reducing the power consumption of the display devices by studying different sources of power draining.

One major power drain source is the display of the device [7]. The need to represent information has to deal with the permanent need of having the display powered on. Thus, related work involving power saving and increased autonomy is mainly focused on improving display consumption. Research works [8–10] have analyzed the image to be displayed and have adapted the luminosity and contrast in order to reduce the power usage by modifying the pixel intensity. These works have found a compromise between display brightness and readability in a bright light environment in order to reduce power consumption of the screen by reducing backlight illumination.

Kennedy et al. [7] state that screen energy consumption ranges from 0.25 W to 2 W, and mainly varies with pixel intensity or brightness levels. New E-Paper display technology [11] provides almost paper-like readability while only needing to be powered on when the displayed content is changing, and not when an image is maintained. In order to address the research question RQ1, authors analyzed the energy consumption of various display solutions by considering the battery run-time.

The objective of RQ2 is to discern the actual customer reception for the different technologies in a commercial or industrial scenario. Display technologies offer a wide spectrum of visualization methods. By comparing these methods and evaluating their ease-to-read to the human eye, the integration of a new display in an evolved scenario can be improved by choosing the more adequate display for a specific task. Berger et al. [12] analyzed the differences between users using E-Paper displays and traditional paper in terms of their willingness to choose between services. This research can inform monetary decisions in order to provide a mark-up value in retail commerce, and also to implement some dynamic price procedures common in a digital Internet marketplace to a traditional retail marketplace. Chou et al. [13] implemented novel applications of mobile advertising with E-Paper by using non-power requirements as an advantage to engage new customer groups, converting personal devices into wearable mobile advertising devices. The scenario for a wireless electronic price system has also been studied using an LCD display solution [14]. Furthermore, singular modes of wireless communication [15] like visible light modulation [16] can be a reliable option but at this time, they lack the low-power requirements of the considered scenario.

3. Information Representation Infrastructure

In a previous work, authors developed [5] a first prototype of a self-managed device with an E-Paper display screen. The device was connected by a wire to a computer to satisfy its requirements for power supply and communications in a simple way. After solving many information path problems with the prototype, authors were able to successfully study the display energy consumption rates of the device. An improved version was introduced [1] which solved the high energy consumption problems and minimized the communication intervals such that the device could operate wirelessly.

The infrastructure presented in this paper is used in the experimental validation to perform the required operations of the E-Paper display as well as the Dot-matrix LCD display. Both of them are driven by the same type of controller and, in both, displays are managed using a similar set of software instructions. A battery supplies energy to the device, as well as the display and other hardware-related components, such as the wireless communication peripherals. To allow external user applications to control the device, a router device has been added to the system infrastructure to receive contents that the external application sends to update the display, encoded as a text string or an image, depending on the final type of technology used in the prototype. Finally, the router device passes the data in a wireless transmission to the display device. Authors have called this router device the "distributor node".

Figure 1 shows the solution infrastructure in a functional architecture diagram, though it is not restricted to one device. All devices present in the scan area are searched by the distributor node, and so, the user application can select the precise display. Decoding of the received data is handled by the Data Management module, followed by the extraction of the compressed image as selected by the compression modes, and finally by an update of the device's information.

Although the E-Paper display technology does not consume any energy until a change of its content is required, a control board is needed to succeed the power down and power up display routines and sending the final image data to the screen. In case of the Dot-matrix LCD display, the driver has to be powered all time for the display to show data. It is important to dissociate the power source between the different components of the device, such as communications, signal processor or the E-Paper display. This is why a digitally controlled power switch is introduced for both cases (as shown in Figure 1), and unwanted current leaks are avoided by turning the power off in certain states.

A control layer allows the device to receive data at any time using low-power technologies with low-energy communications, minimizing the consumption of the system processor. If a connection is detected, the system wakes up and the display starts to update.

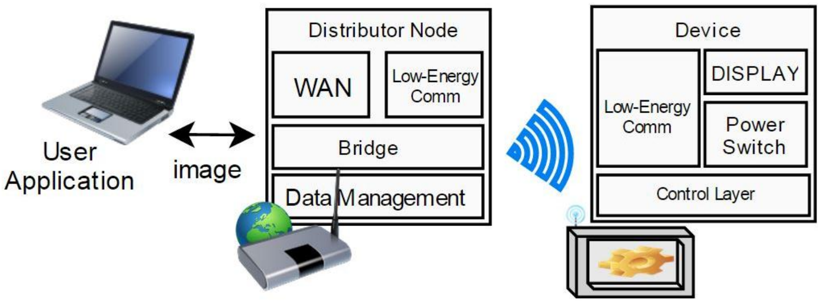

Figure 1. Functional architecture of the proposed infrastructure solution for information representation.

4. Infrastructure Implementation

To implement the proposed infrastructure, authors first explored the multiple uses required by the final device during an evaluation experiment. The portable device has to be used either with an E-paper display or the Dot-matrix LCD. The process of choosing the necessary elements which have to be included in the device starts with a component selection and an integration environment decision to obtain compact and usable prototypes. Low-energy protocols are indicated to offer communications in energy-saving scenarios. Authors selected Bluetooth Low Energy (LE), which allows higher ranges than the previous prototype version and a real application throughput of 58.48 kbps [17], which in our case, is enough for a proper text and image transmission. In the E-Paper display case, the total sent bytes in a regular image update varies with the display panel size, resulting in 5808 bytes for the 2.7″ test E-Paper display of our prototype.

Figure 2 shows the hardware setup in our prototype. The main board uses an Arduino development platform, which includes the main processor unit and a Bluetooth LE chip on the same board, making it easier to prototype and improve the device. The main processor is an ATmega328p microcontroller at 8 MHz with 32 KB of flash memory and 2 KB of Static random-access memory (SRAM). Regarding the Bluetooth device, it is managed by a Texas Instruments CC2540. Moreover, an adaptation printed-circuit-board (PCB) has been designed by authors to provide additional functions such as data bus adaptation, power switching and a voltage regulator to provide a 3 V line from a lithium polymer (Li-Po) battery in order to power up all components, including the E-Paper display panel. The integrated circuits used in the additional board are: an LM1117 linear regulator and a TPS22941 voltage and current protection. The connection occurs through a 10 pin flexible flat cable (FFC). The Dot-matrix LCD display is driven by the i2c bus available in the main processor. The E-Paper display has two components: the E-Paper display panel and a Timing Controller (Tcon) board which offers a common serial peripheral interface (SPI) to interact with the panel. In our prototype, the E-Paper panel is a black and white display that is coupled to the Tcon module. The latter receives the image data sent by the main processor and prepares it to relay the information to the display, performing the actual refresh of the pixels. This data is a bit per pixel transformation of an image, converted to real black and white format. Authors designed a case, minimizing the empty space given the physical measurements of the components. The device is powered by a 1050 mAh battery that is permanently connected to the circuit. Our measurements indicated a standby current of 0.2 mA in an idle state waiting for connections, giving a theoretical battery life of 7 months, which was tested in the experimental validation. Figure 2 shows the final prototype. When the device is connected to the battery, the system initializes and the Bluetooth connection is discoverable and ready to accept connections.

The distributor node has been implemented in a computer with a USB Bluetooth dongle and internet connection to simplify the process. The routine is developed in Python and handles the reception of the image data from the internet through a web socket and relays it to a serial port assigned to the Bluetooth device, acting as a bridge element for device interoperability [18].

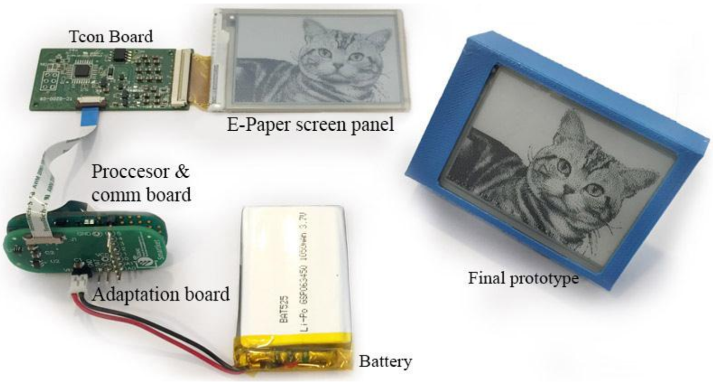

Figure 2. E-Paper display device prototype for the experimental validation.

5. Experimental Validation

An experimental validation was designed and carried out in order to analyze and answer the research questions proposed in this research work. These research questions were answered using the architecture for low-power display devices proposed in the previous sections. The experimental validation was divided in two different experiments to answer each research question; context, design and planning are different between the experiments. During this section, the research questions will be used as a guide for each sub-section.

No cost comparison has been made between the selected technologies as the cost of the chosen products is a very relative variable. Thus, any cost comparison would become obsolete in a short time.

The experimental validation was divided in two different experiments (one per research question) where different actors have been involved in order to validate the experiment:

RQ1: *Different architectures and display technologies were tested in a controlled environment to analyze the battery runtime.*

RQ2: *Thirty-nine people were asked to rate different aspects of the proposed system as well as a variety of existing devices.*

The architectures compared in these experiments include four different display technologies: traditional paper, Dot-matrix LCD, LED LCD, and E-Paper display.

The first experiment was designed in order to analyze the runtime of the selected display systems in a labeling scenario, comparing the approach proposed in this paper with other architectures.

The second experiment analyzed the subjective perception of several people who participate in different roles in retail business scenarios, where a digital labeling system may be deployed.

Authors of this research work had little control of the people involved in the experimentations. With this approach the experiment is suitable to be replicated in similar contexts. Authors guided, executed, and evaluated each experiment. The anonymity of all participants was considered by the application and the authors. No personal data were diffused or stored.

The different phases for each experiment are explained below using the research questions proposed in this paper as a guide.

5.1. RQ1: How Much Better Is the Battery Runtime of a System for Personal Tagging Based on E-Ink and Low Consumption Communications Compared to Others?

5.1.1. Context

The experimental validation was designed, planned, monitored and analyzed by authors of this research work, who have more than 10 years of experience in information systems, ubiquitous programming, machine-to-machine technologies and the Internet of Things.

For this validation authors tested different architectures, along with the one proposed in this work, which are available for smart tagging: E-Paper, LCD (Dot-matrix display), LCD (LED) and traditional paper. The technologies other than E-Paper were chosen because they are the most commonly used ones in information systems and are the base for current commercial systems, where paper is the most common. For this research work, a particular set of technologies has been selected and other commercial options dismissed due to the fact they are based on the same technology; therefore their behavior is similar to those included.

We performed a run-time test for each architecture in order to evaluate its energy consumption. All devices started to operate with a new and fully-charged battery and all the batteries had the same characteristics: 3.7 V LiPo battery with 1.050 mAh. The experiments were carried out in four batches depending on the number of screen changes made in a day. These were: 1, 3, 10 and 20 daily changes.

A full factorial design was used for the experiment where each architecture (E-Paper, Dot-matrix LCD, LED LCD) were tested with four kinds of daily changes. The experiment was repeated five times; in order to synthesize the data, the medians of the data obtained are presented. Although traditional paper does not have electric nature and obviously does not consume any power, authors wanted to include it in the results because it has an important role when the second research question is addressed. It was of course not included in the run-time test process, since paper is considered to have an infinite run-time.

5.1.2. Plan

The experiment was divided into three phases for each architecture as shown in Figure 3: device preparation, device testing and measurement, and data evaluation.

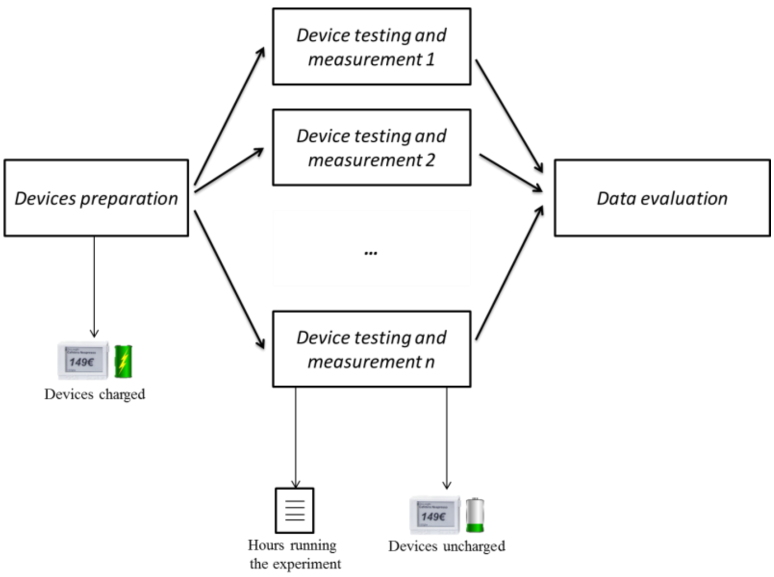

Figure 3. Experimental phases.

Device preparation: The first phase consisted of the preparation and initialization of all devices. First of all, the devices were connected to a data gateway to receive data from the application server. At this step, the devices were powered with no use of batteries. Afterwards, the devices were connected to their batteries going into the standard mode with the standby power consumption.

Device testing and measurement: This phase aimed to measure the runtime of the devices. In this phase, the authors turned on the devices with the battery fully charged.

The measurements were taken hourly from the time the devices were switched on until they reached what was considered the discharge voltage. Measurements were performed with a calibrated and automated multimeter, under the same environmental conditions of temperature and humidity.

Data evaluation: When all measurements were completed, authors analyzed the data to synthesize the information and present it. They also filtered the information eliminating outliers and measurement errors.

5.1.3. Data Collection

The information collected to address the first research question (How much better is the battery runtime of a system for personal tagging based on E-Ink and low consumption communications compared to others?) was the time when each device started and when each device's battery reached the calculated final voltage. The information about the electric charge of the battery [19] was measured using a remotely controlled multimeter connected by USB. The experimental setup can be seen in Figure 4.

Figure 4. Test setup.

To reduce the experimental time, an extrapolation of the results has been made by considering the final voltage a fixed value in all the experiments except the LED LCD case. To characterize the discharge curve of the battery, the state of charge (SOC) is extracted from the linear mapping of the relation between the open-circuit voltage (VOC) and SOC (1) proposed by H. Rahimi-Eichi et al. [20].

$$Voc = f(SOC) = b_0 + b_1 SOC \tag{1}$$

Using the 8th linear segment defined by H. Rahimi-Eichi, the extracted parameters are b_0 = 3.1442 and b_1 = 1.0509. To keep the linear calculation inside the chosen segment, two SOCs are selected and calculated in Table 1.

To calculate the final runtime, measurements are multiplied by 1/0.05 to obtain a linear estimation of the battery drain time.

Table 1. State of charge and related VOC.

SOC	VOC (V)
100%	4.1951
95%	4.1425

5.2. RQ2: What Is the Satisfaction with the Use of the Architectures Proposed in This Research Work?

5.2.1. Context

This research work is framed in a research project called SMARKET. One of the main tasks of SMARKET was the deployment of a pilot test in a supermarket that consisted of, among other things, investigation of the infrastructure for information representation therein. The pilot worked for three months and authors had the opportunity to ask the clients and employees (hereafter, participants) in the supermarket to complete a survey. In total, authors had the participation of 30 available clients and 9 employees. The participants were asked about several metrics for evaluation of different usability attributes [21] that were subjective satisfaction and frustration of the four information infrastructures presented in this paper. They were asked about these architectures using a six-level Likert scale (from 0 to 5) for the answers.

5.2.2. Plan

The survey was created by authors who have conducted this research, and asked employees and clients in supermarket about usability factors of these technologies. The surveys were created during the deployment of the pilot and participants responded at the end of it. Authors compiled the data from the surveys in order to present it in this research work.

6. Results

This section presents and discusses the results obtained in the experiment and survey according to the research questions proposed in this paper.

6.1. Analysis of the Run-Time of the Different Architectures

Table 2 summarizes the results obtained with the experimental validation of this research work. The table shows the median of battery run-out time for the devices in each architecture in relation to the number of display changes. Authors used median because the experiment was run five times and the table also shows the standard deviation. Values for the architecture based on paper are not included in Table 2 because, as stated in the experimental validation section, it is assumed for this research work that paper has an infinite duration with no possibility of information change.

Table 2. Runtime (Hours) and standard deviation.

# Changes/Day	Dot-Matrix LCD		LED LCD		E-Paper	
	Median	SD	Median	SD	Median	SD
1	3628	86.71	4	0.36	4308	33.5
3	3456	143.81	4	0.38	3916	104.3
10	3276	174.59	4	0.38	3220	128.8
20	3084	180.78	3.5	0.15	1944	151.8

The results show that architectures based on Dot-matrix LCD and E-Paper have very similar battery life results whereas LCD LED-based architecture has very low battery life scores regardless of the number of screen changes. This is logical because the LED LCD screens consume the same energy independently of what is shown on screen.

However, it can be seen in Figure 5 that there are differences between architectures based on Dot-matrix LCD and E-Paper. It shows how with Dot-matrix LCD the battery life decay seems to be linear with respect to the number of screen changes. Nevertheless, using E-Paper, the decay seems to be exponential. This fact cannot be confirmed because this experiment did not examine more than 20 changes in a day, as this would be unusual in a normal scenario.

Figure 5 shows that there is a cut-off between the two functions at the point of ten changes per day. That means that the architecture based on E-Paper is more economical when there are ten or less changes of screen a day, in terms of battery life. Conversely, the architecture based on Dot-matrix LCD is better when there are ten or more changes in a day, in terms of battery life.

As seen in Table 2 and Figure 5, the architecture developed based on the LED LCD technology is very expensive from the battery life point of view and authors do not recommend this type of display to be used for wireless systems. As discussed in the next section, LED LCD screens produced a lot of frustration for people as these systems required a battery recharge at least two times a day.

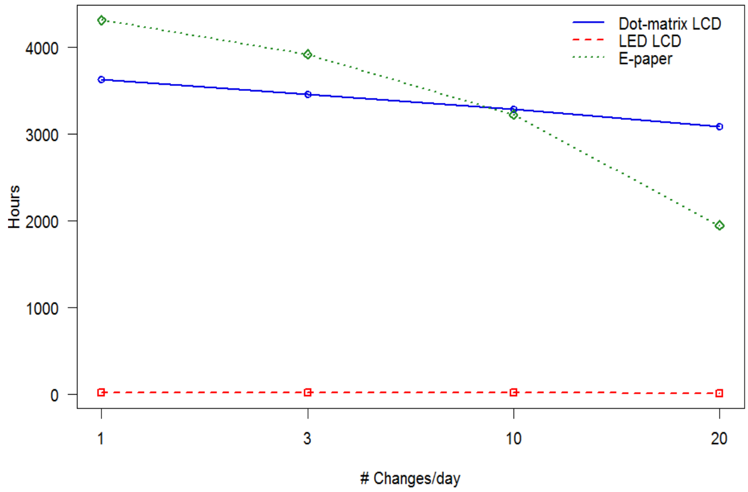

Figure 5. Battery runtime for each technology in relation to the number of display changes per day.

6.2. *Subjective Perception with the Use of the Proposed Architectures*

Thirty-nine people (30 clients and 9 employees) were asked about the four architectures compared in this work. Authors decided to separate the responses by the various roles involved in the project because of the disparity of opinions regarding the four architectures. Clients perceive the satisfaction with smart labels based on the quantity of information offered or the aesthetics of the information presented, whereas employees perceive more satisfaction with tags, which save them time.

As shown in Figure 6, the preferred architecture for customers was the one based on LED LCD screens with a score of 4.2 out of 5. This is because LED LCD screens allow the display of a lot of information, color graphics, video, etc. making this architecture very attractive to the clients. However, it got a high score in frustration with 1.93 out of 5; this was due to the limited battery life of the tablets used to display product information and because clients often found the tablets with their batteries discharged and switched off.

The architecture using the E-Paper screens were the second best rated in satisfaction (3.9 out of 5), and generated very little frustration (0.9 of 5). Smart Tags using E-Paper screens were usually found switched on and they always showed information even when device batteries had run out, since E-Paper technology does not consume electric power while displaying information.

The next best valued architecture was the classical method based on paper (3.3 out of 5) but it had high values in frustration (1.87 out of 5). Authors suppose these scores were obtained because customers are accustomed to the use of paper labels, but in the experiment they discovered the benefits of other types of smart tags, extended information, QR-codes, graphics, etc.

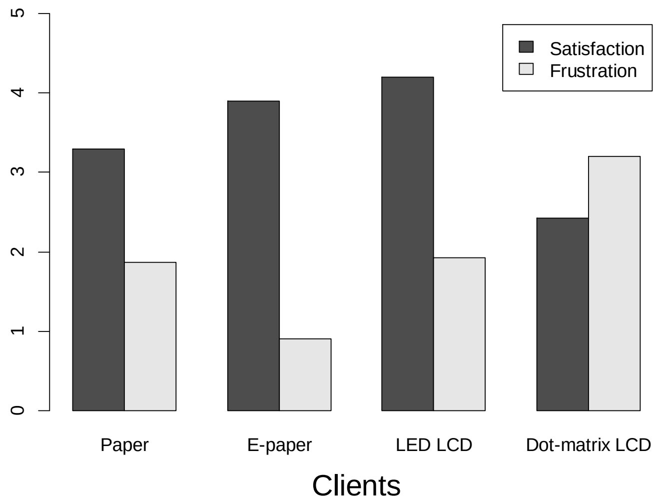

Figure 6. Subjective perception of clients.

The worst-valued architecture by clients in the experiment in terms of satisfaction were the “Dot-matrix LCD” with a score of 2.43 and 3.2 for frustration. Clients described the smart labels with Dot-matrix LCD as very unhelpful as they have a limited display which cannot accommodate information with graphics, images, etc. The screen composed of a matrix of dots was a handicap that the customers perceived quickly.

The supermarket employees had a different view of satisfaction and frustration with the different architectures. They valued the time-saving potential of the architectures. From the point of view of employees, the most valued architecture was the E-Paper (4.1 out of 5) because they saved a lot of time with it, although it also got a high score in frustration (2.0). Through several interviews with employees, authors discovered the reason for such high values in frustration was the perception of the smart tags as a threat, because they could be a reason for downsizing. See Figure 7.

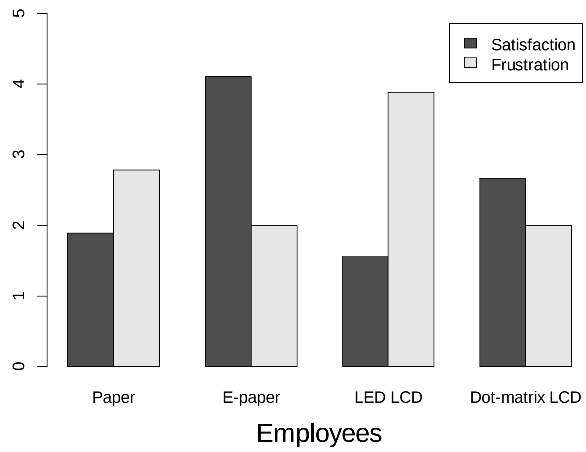

Figure 7. Subjective perception of employees.

The next best valued technology was based on Dot-matrix LCD, although it had high values in frustration as employees discovered the limitations of a Dot-matrix screen.

The architectures with the worst scores were the ones based on paper and LED LCD. The paper labels were considered very frustrating for employees because the labeling and relabeling processes are very time-consuming and tedious. The most frustrating architecture was the LCD LED-based, because the employees had to constantly recharge the batteries of the tablets that served as smart tags, making the employees spend a lot of time with this task.

7. Conclusions

In this paper, an infrastructure for representing information in a commercial environment that focuses on low-power consumption and wireless communications is presented. A distributor node is included and allows detecting display devices and information updates to show in an E-Paper display. The validation of the system was provided by analyzing different information architectures along with traditional paper to evaluate the adequacy of the proposed system for the selected environment. The proposed infrastructure also permitted evaluation of different display technologies than E-Paper, in order to ascertain the validity of the E-Paper technology as the final technology of the proposed system.

E-Paper technology with its zero consumption operation helps the realization of very low-power devices that can provide dynamic information with a certain refresh rate. This can help in the provision of new forms of information representation in complex environments or in low-maintenance scenarios. The evidence and findings obtained during the experimental validation are very enlightening and indicate that the proposed system resolves many of the current problems. By incorporating E-Paper technology, besides retaining the readability, the needs to permanently power the screen and concentrate the limited battery energy to increase the autonomy by using low-power communications, are eliminated. The proposed infrastructure has power benefits over traditional paper and the LED LCD-based infrastructure. Finally, in cases of a maximum number of 10 display changes per day, an E-Paper system has a better battery runtime than that of the Dot-matrix LCD system.

8. Future Work

As future works, some next steps to continue in this research area are suggested:

- Study the architectures presented in this research work in terms of time saved by the supermarket, since a dynamic labeling system provides an automatic synchronization with the prices stored in the supermarket management systems;
- Analyze the quantity, quality, significance, and usefulness of information that can be displayed by each of the architectures proposed in this research work;
- Experiment with more varied kinds of users, for example providers, supermarket managers, supermarket CEOs, etc.;
- Replicate the experiment in another environment different from the supermarket where there is a need for smart and complex labeling, for example in a hospital or a hotel.

Acknowledgments: This work is funded by the Ministry of Economy and Competitiveness through SEMOLA project (TEC2015-68284-R) and from the Autonomous Region of Madrid through MOSI-AGIL-CM project (P2013/ICE-3019), co-funded by EU Structural Funds FSE and FEDER. We would like to thank the staff of the Tien21 supermarket for their valuable contribution.

Author Contributions: The contributions described in this work are distributed among the authors in the way that follows: All the authors wrote the paper; Diego Sánchez-de-Rivera and Ramón Alcarria propose the information infrastructure architecture and perform the run-time analysis, Borja Bordel proposed and built the prototypes and Diego Martin and Tomás Robles perform the deployment of the pilot and subjective perception surveys.

Conflicts of Interest: The authors declare no conflict of interest.

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