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ELECTRONIC SHELF LABELS: PROTOTYPE DEVELOPMENT AND VALIDATION USING A DESIGN SCIENCE APPROACH

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ABSTRACT

For retailers, the ability to effectively manage dynamic pricing strategies is critical for various objectives such as managing customer demand, responding to competitors' pricing tactics, achieving internal price communication, maintaining multi-channel price integrity, and ultimately, maximizing revenue and profitability. In recent years, several retailers are relying on the use of electronic shelf labels for managing displayed prices in a dynamic manner. However, there has been very little research on the design and utility of electronic shelf labels. Addressing this gap, the current study outlines a systematic approach for designing effective electronic shelf label systems and develops a research agenda for advancing research in this emergent domain. Specifically, following design science principles, we design a prototype of an electronic shelf label system that uses asymmetric transmission power between a gateway and electronic shelf labels, and validate its performance in an urban marketplace. Subsequently, we develop a set of actionable recommendations for enhancing theory and practice in this domain.

Keywords: Electronic shelf labels; Dynamic pricing; Design science; Retailing

INTRODUCTION

In contemporary retail environments, the adoption of emerging technologies not only enables traditional retailers to compete better with offline and online retailers, but also redefines both retailer strategies and shopper behaviors. For instance, the integration of interactive channels and social media touchpoints has influenced channel strategy by supporting the migration of traditional retailers from a multi-channel paradigm to an omni-channel paradigm [7, 49]. Likewise, the adoption of innovations such as digital displays, smart shelves, and targeted digital promotions has revolutionized in-store retail strategy by enabling the dynamic provision of real-time, targeted information to customers and transforming shopping behaviors in the mobile environment [40, 44].

A particular phenomenon that has regained prominence is the adoption of *electronic shelf labels* (ESLs) by traditional retailers. ESLs enable retailers to represent and manage products' prices digitally, dynamically, and efficiently [11]. Although ESLs have been around for several decades, their functionality has been largely limited to providing price information; however, modern versions of ESLs are enabled to display product names, product descriptions, countries of origin, bar codes, and unit prices, in addition to product prices [11]. As ESLs facilitate linking of price information with a retailer's inventory management system through a wireless network, price changes are implemented more dynamically and economically, compared to manual adjustments [15, 30]. As a result, ESLs assist retailers in redeploying staffs from labeling activities to other store-related functions, complying with strict government mandates on accurate price labeling, competing better with online marketplaces, appealing better to the technologically-sophisticated shoppers, and improving overall shopping experience.

Not surprisingly, the adoption of ESLs is growing rapidly worldwide and retailers such as Kaufland Group (a German hypermarket chain) and Whole Foods (a US grocery chain) have already implemented them. Yet, despite their growing prevalence, empirical and theoretical research on ESLs is still nascent. The existing body of work on ESLs is scattered across disciplines and rigorous attention has not yet been afforded to design challenges, effectiveness, and tactical advantages of ESLs. Although, in the research field of electronic commerce, researchers have incessantly investigated some issues in dynamic pricing [e.g., 7, 22, 27, 28, 35, 45, 51, 54], their focus rarely stretches to some of the emerging technologies such as ESLs.

In this work, we provide a systematic approach to ESL system design. We first analyze practical requirements for developing effective ESL systems by studying the influence of wireless link environments in an urban crowded marketplace. We find that these wireless environments are highly affected by various store environment factors such as metal shelves, walls, human movement, item refilling, and prevalence of appliances. Based on the preliminary findings regarding such interventions, we design a prototype ESL system that uses asymmetric transmission power between a gateway and ESLs, and validate its performance in an urban marketplace. Our results show that using asymmetric transmission power, despite it not being a common design principle in wireless network architecture, can be a viable option for effective ESL systems. Different from typical wireless networks in research community, it shows the possibility of improving both battery lifetime and reliability of information delivery. As part of a new ESL solution, compared to conventional ESL systems in industry, it has the benefit of reducing costs and increasing manageability by reducing the number of gateways needed.

In the following sections, we review background research on price representations and ESLs, illustrate the development of an ESL system based on design science principles, and develop a set of recommendations for enhancing theory and practice in this domain.

BACKGROUND

Price Representations and Dynamic Pricing

Effective representation of price is important for retailers to meet their objectives, achieve financial gains, and realize competitive advantages [32]. For shoppers, price representations are simply responses to their questions, 'How much is it?' [1]. Defined more formally, price representations are "the various ways in which prices are made available to market participants" or "renderings of prices generated and disseminated by market actors" [17]. Retailers produce and post price representations in order to make prices available to potential buyers whereas buyers and third parties offer them to make price comparisons or track price changes. According to Hagberg and Kjellberg [17], particularly in the retail context, the practice of producing price representations can be complex and ambiguous due to a few reasons. First, prices change over time because of their strong signaling effects. Second, retailers strategically use different prices of the same goods to affect their sales. Third, the method to represent prices determines representing efforts [50].

While innovations in retail services span a broad spectrum of initiatives [44], innovations in price promotions that involve both process and technology create values by providing considerable opportunities to target customers or shoppers effectively both offline and online [15]. Recently, some retailers have employed dynamic pricing models that update prices frequently by using data from online and offline purchases or company enterprise resource planning systems to set prices based on changing supply or demand characteristics [33]. Dynamic pricing models allow companies to discriminate price on a small scale by using new technologies, such as wireless networks, global positioning system (GPS), and radio frequency identification (RFID) [15].

As a way of increasing revenue and profit, retailers drop prices when the user base is below a target level, and increase prices when above the target [37]. They also adjust their prices based on the prices of their competitors. Particularly, time-based pricing allows retailers to adjust prices according to how long a product has been on the market, inventory levels, or the time of day. These dynamic pricing approaches may increase the demand for older products through price reductions or increase retailer profitability through price optimization [29, 37].

Electronic Shelf Labels (ESLs)

Retailers have a strong need for dynamic pricing on various products to maximize profit in consideration of not only customer demand (e.g., high demand for barbecue products in fine weather) and competitors' pricing strategies (e.g., to remain competitive when shoppers compare prices), but also to achieve multi-channel price integrity (i.e., consistency in prices across online and in-store channels) [10]. However, most stores still manually update the prices of thousands of items deployed in a large area, which prevents them from achieving dynamic (or robust) pricing due to the costs for printing new labels, replacing labels, and resolving price mismatching between shelves and point-of-sale systems. In addition to the cost for price updating process, manual price changes consume valuable employee resources that could otherwise be spent on providing customer services. Price mismatches, that are likely to ensue due to human errors during the tagging process, not only provide unpleasant shopping experiences for customers, but can also cause regulatory penalties in some countries, such as France and Eastern Europe. Given such practical operational burdens associated with managing price displays in large-scale retail settings, an electronic labeling system that automates the price updating process provides distinct advantages.

At the system-level, a comprehensive ESL system consists of a low-power embedded computing unit, a wireless radio, and a low-power display module (e.g., electronic-link). A central server provides real-time updates on price changes to individual ESLs, which are deployed to display the price of each stock keeping unit at retail shelves. The central server and ESLs are connected through wireless networks, which allow them to update price information remotely. When a retailer has a need to change the price of a particular item, the central server transmits the updated price to the corresponding ESL to ensure that the displayed price is up-to-date. Using the same wireless radios from which the ESLs receive updates, information regarding available merchandise can be periodically sent to the central server so that store managers keep track of displayed inventory in real-time.

ESL systems offer retailers the opportunity for reducing labor cost, minimizing customer complaints due to pricing inaccuracies, improving shopper engagement, and ultimately increasing retailer profitability. Given frequent price updates in large-scale retail stores, this automation greatly reduces labor and associated costs, thus creating the opportunity for better deployment of human resources for customer services and customer satisfaction initiatives. In addition, by minimizing the delays and errors associated with manual price updates, ESLs help to reduce customer complaints, facilitate comparison shopping, and increase purchase likelihood and retailer profitability.

ESL systems also automate inventory monitoring and replenishment processes, which consume a significant amount of time when performed manually. They provide real-time monitoring services of available inventory and enable re-stocking before running out. These advantages not only reduce time spent by retail staffs in physically monitoring and ensuring appropriate stock levels, but also inform shoppers about available quantities and safeguards them from giving up on intended purchase due to the lack of availability of items sought.

Furthermore, real-time advertisement of important events for shoppers via shopping carts with an electronic display module can provide more profit seeking opportunities. The wireless infrastructure enables advertising information to be delivered in a more targeted manner than voice announcement. An electronic screen of a cart can display the location where an event takes place on the market map, which further motivates shoppers to move and make a purchase. The wireless infrastructure, once available, is easily extendable to support other intra-market applications. As an example, with wirelessly controllable display units on shopping carts, retailers may provide advertisements to shoppers who have interest in products located in a specific area. The diagram of Figure 1 illustrates these functionalities.

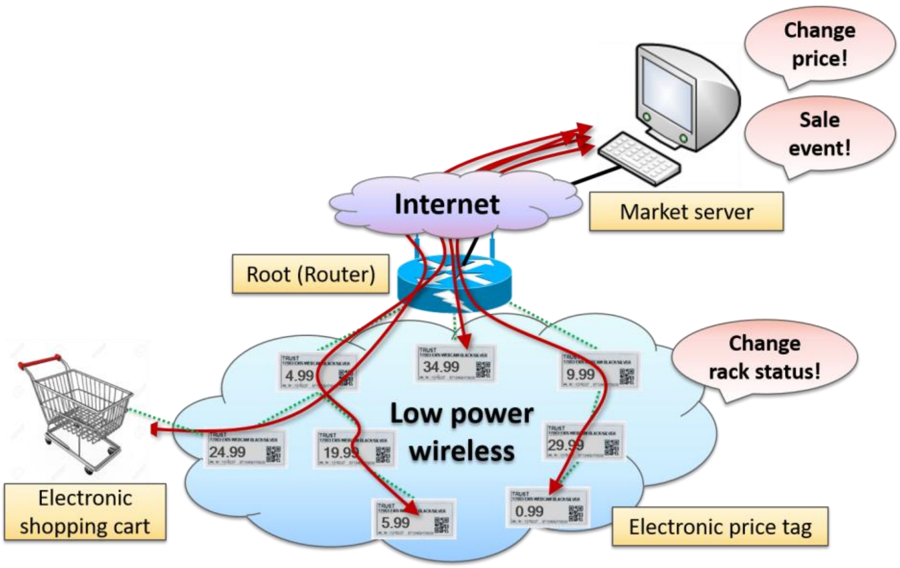

Figure 1: Illustration of an ESL System Architecture

DEVELOPING AN ESL SYSTEM

Research on electronic shelf interfaces at the retail store level has, thus far, yielded contradictory or inconclusive results. For example, Garaus et al. [11] found that ESLs, as compared to traditional price tags, are perceived by consumers as easier to use, enhance price information prominence, influence product quality perceptions, and store image perceptions. But, ESLs were not found to be any better in influencing price fairness or, in fact, more useful to consumers than traditional price tags. In a study on digital displays, which include price information, Roggeveen et al. [40] reported that digital displays enhance sales only in hypermarkets, but have minimal impact on sales in supermarkets and a negative impact on sales in smaller stores. Further, they found that price-related promotional information contributes to increasing sales much more than non-price related content. These studies indicate that the adoption of emerging technologies, such as ESLs, is not a trivial decision as available evidence is not compelling yet. However, beyond consumer research, there is very little information on the feasibility of ESLs for retailers. Therefore, whether or not an ESL system is beneficial for retailers is still an ill-structured problem.

To describe the process of developing an ESL system, which potentially offers the advantages discussed above, this study adopts an approach of design science. Across multiple research areas, the design scientific approach has gained legitimacy as an effective research framework [e.g., 3, 18, 34, 36, 41, 46]. Design scientific methods are as a whole based on the concept of design thinking (Brown, 2007), which is to a design scientific method as analytical thinking is to a traditional, normal scientific method. Design thinking as a way of thinking or an approach in cognitive activities differs from design science as a systematic form or scientific study of designing. As the name suggests, design refers to the act of creating an explicitly applicable solution to a problem. Correspondingly, design science implies that the design is a scientific activity itself. In a few research areas of business such as management information system, service management, and organizational studies, design science approaches have gained acceptance as a legitimate research paradigm [18].

A sound design scientific approach distinguishes experience-based prescriptive knowledge from "prescriptive knowledge based on systematic, methodological sound, and rigorous research" [20]. Based on several design science approaches in the literature [e.g., 3, 20, 34, 36], this study reiterates the process of our context for research in design science into three main phrases: *Problem Definition*, *Design and Development*, and *Evaluation*. A detailed design process should be well-defined to assure the quality as a scientific method and follow a consistent process. A three-stage approach is in line with the widely-accepted guidelines and sequences of activities that aim to build mental models, provide a solid ground for mutual understanding, and evaluate various camps of researchers [e.g., 34].

Initiated by problem definition, the first stage of the design science approach identifies an ill-defined problem for the given system, and defines the specific research problem or the objectives of the desired solution within the given system. It also justifies the value of its solution. The second stage of design and development crafts the course of design by determining its desired functionalities and architecture. Then, the final stage observes and measures how well the designed object supports a solution to the problem, and demonstrates the use of the design scheme in evaluation. According to the nature of the problem venue and the artifact, the evaluation takes various forms including quantifiable measures of system performance or any appropriate empirical evidence or logical proof [34].

PROBLEM DEFINITION

We identify ill-defined problems in ESL systems, which denotes the objectives of our planned system. They are addressed both at the application and technical level. First, the application level objectives are (1) reliability, (2) reducing labor cost, (3) cheap and resource-aware wireless communication, and (4) usability.

Application Level Objectives

Given that our application targets to address the remote reconfiguration of price information, our system should provide a reliable service with high packet delivery performance under wireless traffic patterns unique for market environments. This *reliability* issue should be addressed well in the ill-defined problem of price presentations.

A price-reconfiguring system for markets should be robust and easily deployable by market staffs. It necessitates *reducing labor cost*. For this, it needs to be a “full” wireless system which does not need power cable extensions. This suggests that devices in the markets should make use of battery power for their operations. Furthermore, given that battery replacement requires labor, the devices should consume low energy to prolong their battery lifetime.

The planned system needs to involve *cheap and resource-aware wireless communications*. While wireless communications such as LTE modems are widely used, they suffer from high energy usage and cost issues. A more affordable and sustainable approach would be using radios in the industrial scientific medical (ISM) band, such as WiFi. But, again, even for WiFi chipsets, lowering energy consumption is a significant challenge. The wireless module used in our application should be cheap, maintain a long battery lifetime, and achieve the deployment and management costs at a minimum.

Enhanced usability would also be important. Our system should be easy for market staffs to use and manage. Given that markets typically have network managers who are familiar with IP protocols, the underlying wireless network of our system needs to be IP compliant [25].

Technical Objectives and Challenges

On a technical perspective, deploying ESLs in markets encounters a number of challenges, which have not been observed from other wireless (potentially embedded) systems. First, a marketplace is a crowded environment in many situations. This naturally complicates the communication problem where ESL systems operate. Resolving such issues not only requires careful system deployment (e.g., location of each device when installed), but also functional improvements, especially at the level of wireless “protocols”.

Second, the fact that the reliability of the system, as in how properly price tags are updated, directly impacts user experiences (of both managers and customers) and potential system usage, asks for the wireless system to be designed with a customized set of wireless networking protocols that suit the target environment and assure high reliability.

Third, wireless traffic patterns in markets (i.e., how wireless data is exchanged over the network) are different from those observed in conventional wireless systems. Specifically, while most wireless systems focus on traffic headed towards a single point (i.e., gateway) in the system for remote monitoring [14, 26], an e-price tag system focuses more on data from a single point of the gateway to many price tag devices in real-time.

Fourth, the ESL system should be designed to tolerate man-made faults. Once deployed, devices installed on the marketplace face various man-made faults due to human activities such as unexpected tampering or mis-operation by non-technical professionals. Finally, given that most wireless systems operate on the ISM band, i.e., an un-authorized and free-to-use wireless band, the interference from other external systems should be taken into consideration seriously.

Lastly, similarly to other wireless systems, an e-price tagging system should assure long-time operation without frequent battery replacement. We have designed the ESL system, as an example of an end-to-end e-price tagging system, to address the aforementioned challenges [23].

DESIGN AND DEVELOPMENT

Link Measurement Study

As a first step to design a wireless system for market environments, while satisfying the application- and technical-level requirements above, we performed a preliminary study to understand wireless environments in real markets. Even for wireless systems researchers, the market environments, although very close to our everyday lives, remain unexplored, thereby possessing new insights for system development.

As part of our preliminary study, we used low-power wireless (e.g., IEEE 802.15.4 or Zigbee type) devices and performed link performance measurements in various locations of an urban market place in a nearby city of Seoul, Korea, as depicted in Figures 2 and 3 [23]. The market has the total size of 60 m x 90 m, displays more than 10,000 types of products, and hosts more than 5,000 customers per day. The goal of this preliminary study, on a technical perspective, was in understanding how low-power wireless signals would be transmitted or distracted in a busy market environment.

Figure 2: Our Experimental Market Environment

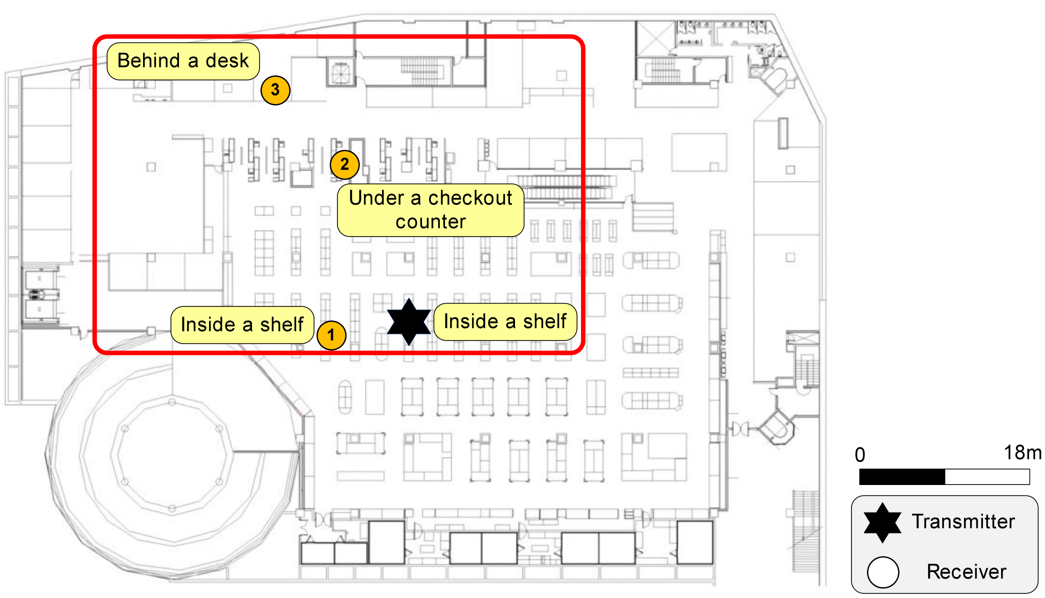

Figure 3: Link Testing Topology in a Market

In Figure 4, we plot the packet reception ratio (PRR) performance of three different wireless links that we measured through our study. Here the line-of-sight (LOS) case represents the baseline performance of an ideal environment without human movement, obstacles, and external dynamics that affect wireless performance very much. The results of the LOS case came from another set of experiments on a playground (free space) shown in Figure 5, where the distance between the transmitter and each receiver is the same as that of the market deployment in Figure 3. As we can see in Figure 4, the performance of wireless links measured in the market differs significantly when compared with the LOS case, validating that various factors in a market environment indeed complicate the performance analysis of wireless links. Specifically, the fact that the PRR in the night-time case is lower than that in the LOS case reveals that walls, products, and metal shelves in the market form an obstacle-rich environment and degrade wireless performance even without human movement and activities. Moreover, by comparing the day- and night-time cases within the market, we found that the performance degradation is mainly due to human activities throughout the day-time.

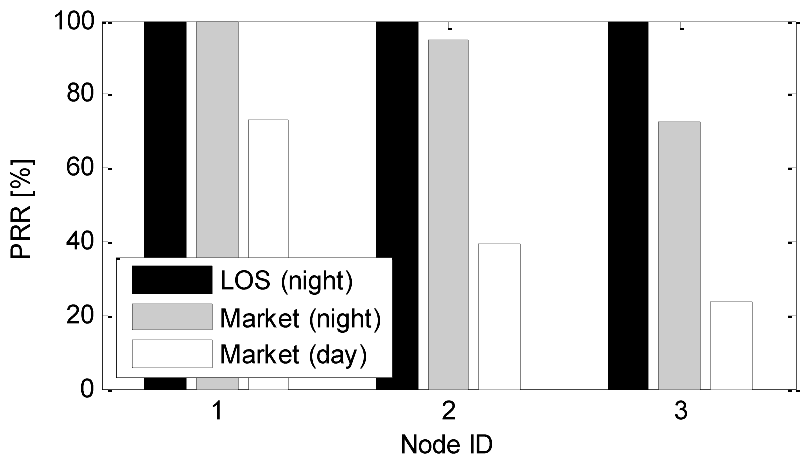

Figure 4: PRR Performance of Wireless Links in LOS and Market Environments

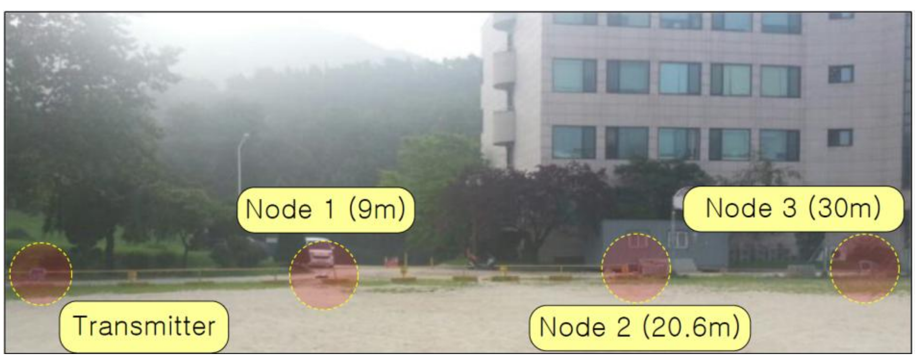

Figure 5: Link Testing Topology on a Playground (free space) for a Reference

To analyze human activities in markets in more detail, we use Figure 6, which plots the per-minute average received signal strength indicator (RSSI) of incoming packets observed at the link of our interest, where the transmitter node was positioned on an item rack. We first observe that the RSSI continuously fluctuates, which comes from customers' activities such as WiFi usage and movement. However, in markets, there are many other activities that are not necessarily related with customers' activities. For example, for some reason, the signal strength detected at a receiver, at time 13:30, dropped by ~10% instantaneously, and did not recover again during the rest of the day. Given that the samples in Figure 6 are per-minute average measurements, we conjecture that there occurred some unexpected activity on this link at and after 13:30. According to our observations and discussions with market staffs, we found that an item filling activity occurred at time 13:30 on the shelf where our transmitter was located. The items caused packets' signal strengths to drop, and this lowered signal strength continued throughout the day as the items were continuously present after 13:30. Likewise, while not human activities nor customer movement, a typical market has its own 'internal activities' that challenge the performance of wireless links.

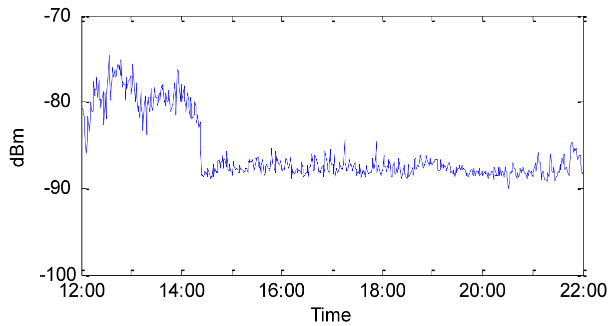

Figure 6: Per-minute Average RSSI of Link 2 over Time

In addition to item filling, activities such as microwave use for food samples also generate a significant amount of interference on the 2.4 GHz radio frequency band [19]. In Figure 7, we plot a radio frequency noise level trace sampled at the speed of 1 KHz. This trace shows that there took place some external activities on the wireless channel where our system operates. The time period of 8-17 seconds shows how an active microwave oven impacts the wireless link performance. Obviously, it causes the wireless link condition to fluctuate, resulting in packet losses.

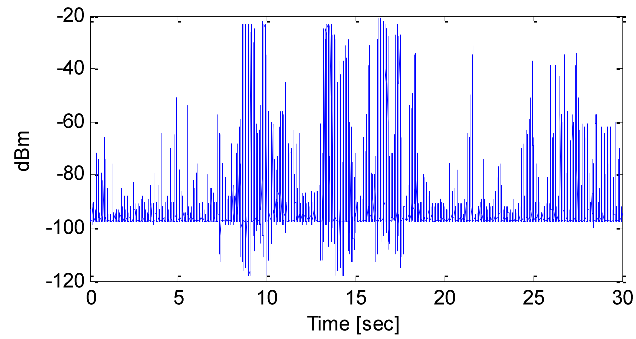

Figure 7: Noise Measurement near a Microwave Oven

Considering the potential of deploying low-power wireless networks under various environments, the wireless systems community has put effort in designing a standardized multi-hop routing protocol for low-power and lossy networks. Here, lossy network links imply that wireless modules are becoming cheap and difficult to provide high reliability. Rather, the reliable wireless packet delivery should be assured by software modifications. The wireless network routing protocol that we discuss in this work, i.e., the IPv6 Routing Protocol for Low-power and lossy networks (RPL) [52], provides each individual low-power device with a "route" for its packets towards a data collection destination (e.g., gateway) and also helps the gateway to send packets back to individual devices in the network. RPL's bidirectional connectivity makes it suitable for market deployments given that market applications ask for packets to travel both upwards (e.g., from individual low-power devices to the gateway) and downwards (e.g., from the gateway to individual nodes).

To experimentally validate the effectiveness of RPL under an actual market environment with realistic traffic patterns (e.g., e-price tag reconfiguring scenario), we deploy a network of 30 devices on a real market environment and present the performance results in Figure 8. Notice here that while the uplink performance of RPL is acceptable, the downlink performance is not. Furthermore, downlink performance fluctuates more over time than uplink performance, which reveals that RPL's downlink performance becomes poor under dynamic link environments. For electronic and wireless price updates, this is a critical issue to be addressed. From experimental investigations on the reasons for the high loss rate in downlink, we confirmed that RPL was originally designed to perform better for upward-centric traffic patterns. While keeping the benefit of a full IP-compliant end-to-end connectivity solution, for applications with more downward traffic than upward one (e.g., e-price tag updates), the RPL turned out to be a less suitable protocol.

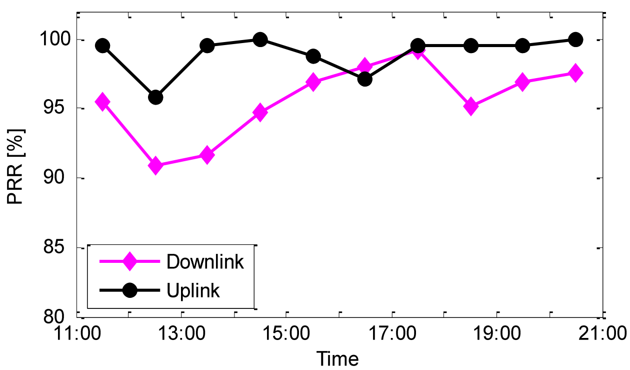

Figure 8: Packet delivery performance of RPL

To avoid these problems, the industry uses a single-hop network architecture for e-price tag systems where each e-price tag directly reaches a gateway, which is simple and does not require routing. However, this network architecture naturally requires deployment of many gateways to cover all e-price tags deployed over a wide area, resulting in high installation and management costs. This means that neither a conventional multi-hop (research community) nor single hop (industry solution) network is suitable to support e-price tag systems.

System Architecture

To design a system that suits our application's needs, we designed the ESL system, which employs a networking architecture more customized for market deployments, specifically e-price tag updating applications. In doing so, we start with switching from the traditional form of homogeneous transmission power-based wireless networks, in which all devices within the network including gateways use the same wireless transmission power, to an asynchronous transmission power-based network. In the asynchronous transmission power-based network, the gateway sends messages to individual nodes with a higher transmission power. As a result, the gateway's transmissions do not need to follow "multiple hops" to reach price tags. That is, downward transmissions (gateway to device transmissions) take place over a single hop, while upward transmissions still need "multi-hop" routing based on RPL to reach the gateway. We design this architecture given that in most cases, especially in our application scenario, the gateway device has a consistent power supply, whereas individual price tags operate from battery power and thus they need to conserve their limited energy resources in short and multi-hop transmissions. On the positive side-effect of this design, compared to using a "multi-hop" network in uplink and downlink, it reduces the number of packet transmissions occurring at individual nodes, which have limited energy budgets. As shown in Figure 9, compared to using a typical "single hop" network, our design shows the benefit of reduced number of gateways installed because it extends the communication range of each gateway which uses high transmission power, resulting in less installation and management burdens.

Using an asynchronous transmission power-based network architecture, as shown in Figure 10, we design ESL that consists of three main components: a server PC at the market manager's office equipped with software for updating the prices of all items in the market, a root (or gateway) node with high transmission power connected to the server PC, and a set of low-power nodes that are connected with e-price tags. The application-level operations of the ESL are as follows. First, market managers trigger remote price update of each individual item in the market by using the server PC. If the ESL system detects a price change of an item, it summarizes this information and initiates a packet transmission through the gateway node. The gateway node encapsulates updating information as a wireless packet and sends it, using a high transmission power, to the target node (e.g., e-price tag). A node receiving this message on the first attempt checks if it is the message's destination. If it is, the node sends an acknowledgement packet over the air, checks if the message contains update for the item, and updates the price through its e-ink platform if needed. Otherwise (the receiving node is not the destination; the node *overheard* the packet), the node helps the (overheard) packet to be reliably delivered to the destination node if it is in the vicinity.

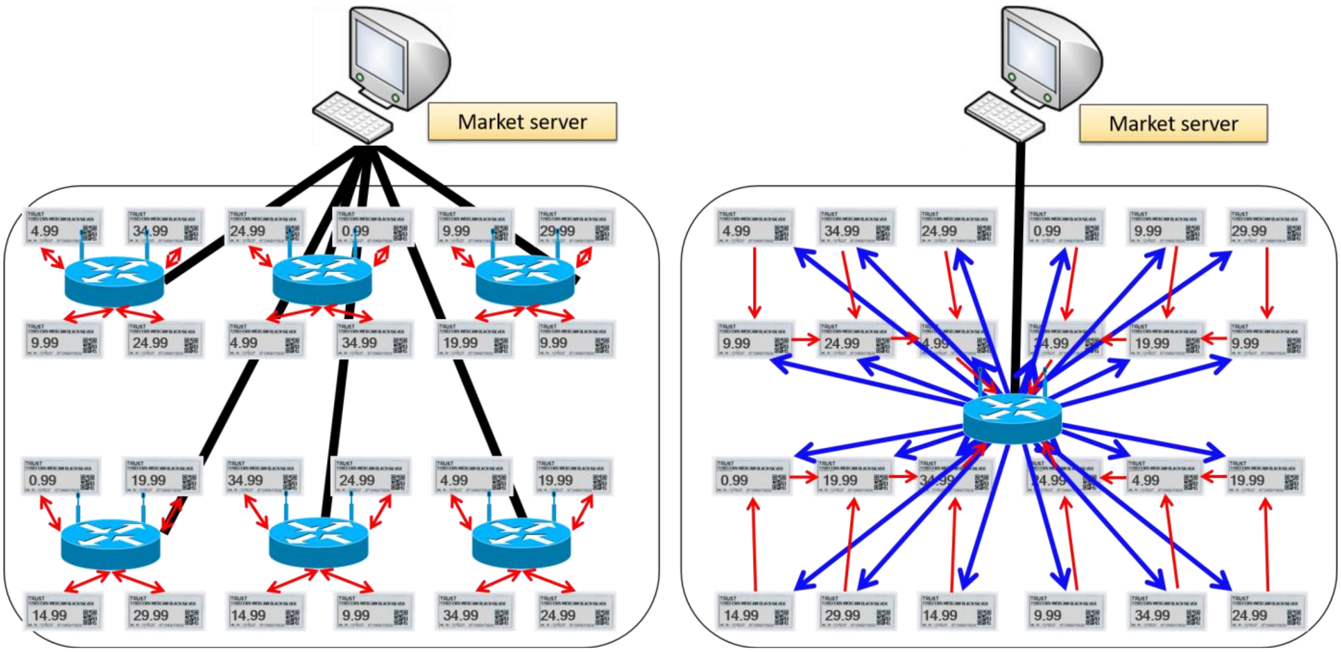

Figure 9: Comparison between a single hop network (left) and an asynchronous (right) transmission power-based network

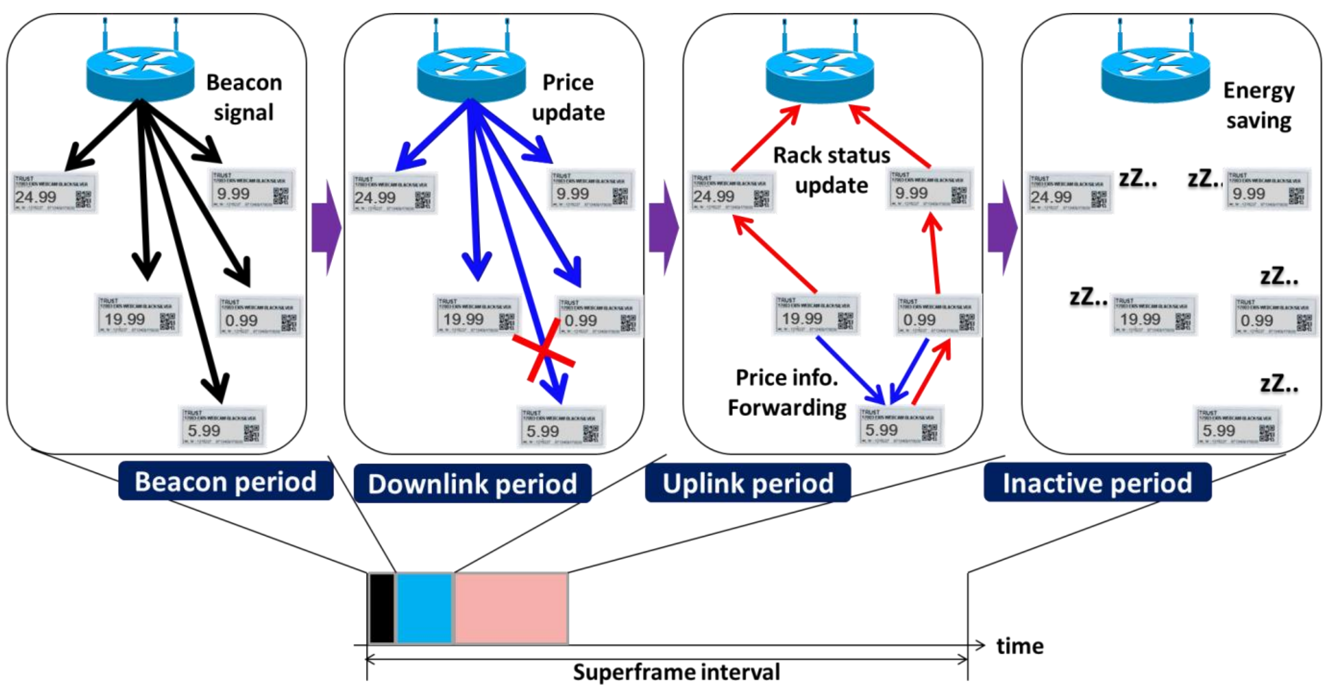

Figure 10: ESL Architecture

If a (destination) node would not receive this message (due to instantaneous wireless channel fluctuation), its neighbor nodes may notice that the node has not issued an acknowledgement packet. In such a case, the neighboring nodes that overheard the message resend the packet on behalf of the gateway (Kim et al., 2016). We select such a retransmission scheme given the fact that individual nodes are designed for low-power operations and their transmission power is significantly lower than the gateway; therefore, distant nodes will be able to receive packets from the gateway directly but not able to reply back to the gateway with the acknowledgements in single hop communication.

In addition, in ESL, we utilize high-power transmissions from the gateway node for synchronizing individual nodes' timers within the network [23]. This synchronization naturally notifies the network when the network will be active after dividing the physical timeframe in multiple small slots, where each slot is as small as 5 milliseconds. With network-wide time synchronization, low-power nodes with e-price tags can turn off their radios for the inactive period, which allows them to maximize their operational lifetimes – leading to minimal effort in replacing the batteries of wirelessly controlled e-price tags.

Evaluation

Figure 11 presents the packet delivery performance of ESL. We can see that the performance of ESL, over time, is fairly stable during the entire testing period. Especially for downlink, which is of our main interest for e-price tag updates, the performance of ESL is near-perfect. Compared to the performance of RPL in Figure 8, this is a large improvement.

In addition to the packet delivery performance, another important performance metric is the radio duty-cycle. To conserve limited energy resources, devices in a low-power loss network typically turn off their radios when not active. The best operation is to make their radio module awake only when there is a packet to send or receive. While we omit the detailed procedures, in RPL, we apply the low-power listening protocol [31], i.e., a widely used radio duty-cycling protocol, to allow for low-power operations. In Figure 12 we can see that despite employing a low-power radio duty-cycling scheme, the radio duty-cycle of ESL is much lower than that of RPL. This indicates that the devices in ESL perform better than RPL in terms of packet delivery performance, and at the same time conserve more energy, leading to lengthen their lifetime.

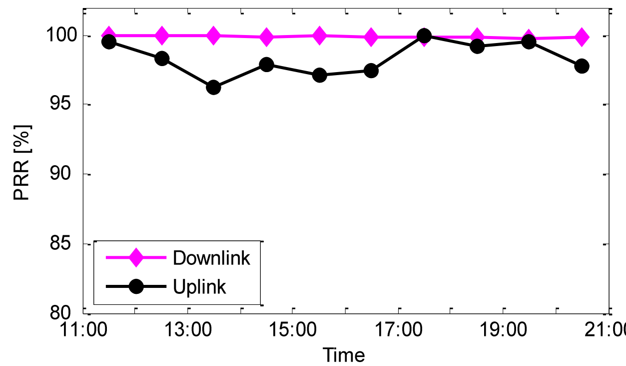

Figure 11: Packet Delivery Performance of ESL

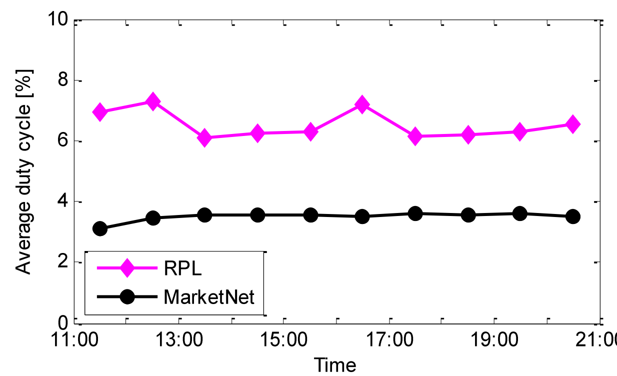

Figure 12: Duty Cycle Performance of RPL and ESL

DISCUSSION AND CONCLUSION

Limitation and Possible Improvement of ESL Systems

This work provides wireless link characteristics in urban crowded marketplaces, a prototype ESL system design, and evaluation of its performance based on field tests. However, we still have room for further research concerned with link measurements and performance improvement. While our link measurement study revealed link dynamics and its various causes in urban crowded marketplaces, what lacks here is the investigation of the effect of node density on link characteristics. Given that wireless link quality in indoor environments significantly varies with slight location differences, in real use cases where ESLs are densely deployed, it is possible that some ESLs may not receive packets reliably even when they are close enough to the gateway [9]. Another link measurement study in crowded market places with a large number of densely deployed nodes may provide a deeper understanding of ESL environments.

It is widely accepted that gateways are with more capability than ESLs in terms of computation, memory and power supply, and that the number of gateways is typically much less than that of ESLs. In the perspective of deployment and management costs, it is a reasonable approach to enhance gateways instead of ESLs for better system performance, as ESL does (i.e., higher transmission power). Another possible improvement is to make gateways equipped with multiple antennas for reliable communication. Multi-antenna techniques have been developed in communication community for over decades and used for WiFi and LTE, and they are also applicable to ESL systems.

As for ESL lifetime, although we reveal that ESL improves it compared to the prior work, it does not necessarily mean that it is long enough to be applied in reality. For further improvement, use of several plugged-in routers for relaying packets can be a great help since it relieves communication burden of ESLs. Since these routers are not fancy gateways but simply plugged-in ESLs, no additional cost is required. Energy harvesting techniques can also improve the lifetime of ESLs by using lighting in indoor marketplaces and movement of cart wheels.

Future Technologies for Better Shopping Experiences

Beyond currently proposed and available basic ESL systems, there are many opportunities for up-to-date technologies to contribute better shopping experiences. First, ESL systems provide more elaborative services to consumers by applying a different set of techniques according to the various purposes of ESLs. A combination of small two (or three)-color electronic-ink display, low power communications, and a battery power source can be used for price representation. For more detailed information or eye-catching images (e.g., for luxury items), a set of wider full-color displays, high-speed communication techniques such as WiFi and UWB, and an electric power source may be considered.

Furthermore, given that an ESL system shares in-store information through the Internet, it has the potential to create a synergy effect when combined with other systems. For example, logistics systems may be enhanced to reduce shoppers' frustration by providing the monitoring service of real-time stock status through ESL systems. When an ESL system is connected to a smartphone APP, shoppers can easily check a product's price, location, and stock online. When an ESL of a product has an NFC module, shoppers get detailed information on the product by simply putting a smartphone on the ESL without having searching overhead. Apart from ESL systems, there are some applications for which technology development has the potential to improve shopping experiences. For example, by combining multi-color lamps and wireless communication techniques, advanced lightening control can be used to increase visual impact on shoppers (e.g., red light for meats and green light for vegetables).

An Agenda for Future Research

ESLs have the opportunity to transform the retailing landscape by empowering both customers and retailers with accurate and dynamic information. With the addition of more sophisticated functionalities, they could yield shape or even disrupt retailer strategies [47]. In this section, we discuss directions for further systematic research on ESLs. These directions are organized into four major domains with illustrative topics within each category: (1) Customers, (2) Retailers, (3) Competitive Landscape, and (4) Macro Environment.

Research Domain 1: What is the impact of ESLs on customers' evaluations of retailers and retail shopping behavior? Although much research attention has been afforded to the effects of technology on customers and shopping behavior, there is very little knowledge about the effects of ESLs in particular. As such, there is need for rigorous examination of customers' acceptance of ESLs. As with other in-store retail technologies such as self-service technology (e.g., self-checkout), price scanners, and interactive touch screen displays, shoppers' motivations, individual differences, behavioral intentions, and technology use pertaining to ESLs need rigorous attention [48]. There is some preliminary evidence that ESLs influence consumer perceptions, especially regarding product quality and store image [12]. However, this domain remains fertile for additional research. For instance, theoretical attention needs to be devoted to whether ESLs increase shoppers' processing of in-store promotions and generate favorable responses. As ESLs continue to evolve, sophisticated forms of ESLs will feature price and quantity discounts as well as targeted promotions. When customers encounter messages presented to them through unconventional and surprising ambient media sources in retail settings, they are more likely to pay attention, focus intensely on the information, and demonstrate favorable responses [21]. In addition, retail atmospherics such as ambient factors can influence purchase of healthier food items [4]. Given these findings, it would be worthwhile to examine whether ESLs are effective in attracting consumers' attention in crowded store environments, trigger more intense processing of price or quantity discounts, generate favorable attitudes toward the advertisement or featured brands, and influence consumers to purchase healthier options. Furthermore, as ESLs provide more accurate price representation and enable greater interactivity with price information – both of which are task-facilitative informational tools that enhance trust [16] – it would be interesting to examine the role of ESLs in fostering trust toward the retailer. As a final illustrative topic in the consumer domain, consider the effect of ESLs on showrooming or the act of doing research in one channel and shopping in another [39]. Showrooming by technology enabled shoppers cause problems for retailers especially when posted prices are not accurate or changed dynamically to reflect changes in competitors' prices. The role of ESLs in reducing showrooming behavior or in reducing customer churn due to uncompetitive prices would be of significant interest to retailers affected by multi-channel competition.

Research Domain 2: What is the impact of ESLs on retailers' strategies, employees, and performance? ESLs promise significant efficiency advantages over traditional price tags. However, the adoption rate for ESLs has been slow since their introduction more than a couple of decades ago, although prominent retailers such as Whole Foods, Kohl's, and Kroger's have now embraced this technology. These trends beget the question: why do retailers differ in their adoption of ESLs? In this context, there is great potential to examine whether adoption decisions are influenced by strategic issues such as technology orientation [12, 53], structural issues such as relative advantages, complexity, functional risk and financial risk [8], and contingencies such as availability of resources or enhancement of capabilities [47], among others. In addition to examining the drivers of adoption, it would be relevant to shed light on the bottom-line implications of adoption of ESLs? For instance, just as in-store promotions influence shopping basket size and composition [38], do ESLs increase key retail performance metrics such as shopping basket size, frequency of customers' visits to the store, frequency of product returns, and profitability? Another area of interest in this domain pertains to the effect of ESLs on retail salespeople. As retail salespeople's work responsibilities will be redefined when ESLs are deployed, the resultant influence on employee-related outcomes such as job satisfaction, self-efficacy, motivation, job insecurity, and turnover intentions need to be better understood. In general, given that retail employees play a vital role in customer engagement and customer experience management, the effect of ESLs on employees' morale and job performance needs to be carefully studied [2].

Research Domain 3: What is the impact of ESLs on a retailer's competitive and operational landscape? ESLs enable retailers to rapidly change or respond to marketplace conditions. From a competitive standpoint, therefore, research is needed on ability to successfully deploy offensive (e.g., initiating price cut) and defensive (e.g., retaliating to price cut) strategies, competitors' response to a retailer's adoption of ESLs, and effect on competitiveness against other offline and online retailers. In addition, the exploration of whether adoption of ESLs create avenues for better collaborations with suppliers and vendors is a promising avenue for future research.

Research Domain 4: How do ESLs enable retailers to navigate opportunities and threats in their macro environment? Given the regulatory concerns regarding price fairness and accurate price representations [13], providing evidence on how ESLs enable conformance to regulatory and legal standards is important from a policy perspective. As for the technological environment, ESLs are likely to evolve with technological improvements. Investigation of whether ESLs can establish compatibility with established and emerging technologies such as smartphones, wearable smart technology, digital wallets, smart carts, etc. can offer insights into heightening the experience of today's technology-enabled shopper. Finally, as for the changes in the demographic environment, it would be useful to investigate whether adoption of ESLs by retailers would enable them to connect better with a particular generation (e.g., Baby Boomers vs. Millennials), draw Millennials' attention away from online and mobile shopping, and greater store loyalty among younger generation of shoppers that gravitate from one store to the other.

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