MarketNet: An Asymmetric Transmission Power-based Wireless System for Managing e-Price Tags in Markets

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ABSTRACT

Updating price tags in a large-scale market is a recurrent task, still performed manually in most markets. Given that human-errors can easily lead to customer complaints and accounting inaccuracies, the ability to autonomously reconfigure price tags can be of significant benefit. With the introduction of low-power display techniques such as electronic-ink, applications of enabling electronic, wirelessly reconfigurable price tags show potential for future deployment. In this work, we examine networking architectures that can be applied in such scenarios. Through a series of preliminary pilot studies in an actual supermarket, we show that the performance of existing protocols are *not* ready to overcome the unique challenges of busy market environments. We identify underlying technical challenges and propose *MarketNet*, an asymmetric transmission power-based system designed for densely populated, obstacle-rich, downwards traffic-oriented environments. We evaluate *MarketNet* in a large indoor market visited by 5000+ customers per day. Our results show that *MarketNet* addresses the challenges of the target application and environment, while achieving higher packet delivery performance with noticeably lower radio duty-cycles than existing protocols such as RPL and SHDP.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*
; C.3 [**Special-Purpose and Application-Based Systems**]: Real-time and embedded systems

General Terms

Design, Experimentation, Measurement, Performance

SenSys'15, November 1–4, 2015, Seoul, South Korea..
© 2015 ACM. ISBN 978-1-4503-3631-4/15/11 ...$15.00.
DOI: http://dx.doi.org/10.1145/2809695.2809717.

Keywords

Wireless sensor networks, network architecture, routing protocol, low-power lossy network, RPL

1. INTRODUCTION

Low-power embedded wireless sensor networking technologies, with their ease of deployment and ubiquitous connectivity, have the potential to empower a number of real-world applications [17, 27, 28, 29, 32]. Many of these are designed around our everyday environments to simplify routine tasks that are straightforward, repetitive, and both time- and labor-intensive. Some applications, such as electronic price tagging in markets, are near commercialization, and a number of systems have been developed using various wireless technologies [5, 33]. Furthermore, technologies such as electronic ink for low-power displays have further catalyzed the potential deployment in these application domains.

Specifically, given that prices can change frequently in busy markets (e.g., due to changes in competitor prices or product freshness), updating price tags in a large-scale market is a tedious and error-prone task, still performed manually in most markets. For example, our collaborators and a number of previous work indicate that for items such as fresh grocery, on average, the prices change up to eight times a day. Given a large number of items carried in large-sized markets, manually updating prices not only incurs significant labor, but can increase customer complaints and accounting inaccuracies due to frequent human errors [5].

Despite electronic price tagging being an interesting application for low-power embedded systems, as a research community, we are still far from understanding the real wireless channel characteristics in such human-active and obstacle-present environments. Furthermore, while these electronic tags should be reconfigured wirelessly, we still lack knowledge on how these environments challenge existing wireless networking protocols. For example, it is unclear (practically) whether the use of multihop networking benefits or harms the application-level performance, or whether an alternate architecture such as asymmetric transmission power-based networks is a better fit in such scenarios.

In this work, we incorporate real-world networking constraints by taking a practical approach and design a prototype system for wireless electronic price tagging applica-

Figure 1: Our experimental market environment: a crowded indoor market with a size of 90×60 meters, >10k types of items, and >5000 customers per day.

tions. Specifically, our design and implementation addresses (1) low and fair energy consumption at price tag nodes, (2) automatic repeat request (ARQ)-based reliability considerations with minimal operational overhead and (3) optimizing downstream wireless communication for e-price tag updates.

Based on a literature survey of pre-existing networking protocols that suit our purpose, our design follows an asymmetric transmission power network architecture in which a basestation node can reach individual price tags via single hop (using high-power transmission), while the price tags transmit data to the basestation over multiple hop links (using low-power radios). To verify this intuition, we exploit the single-hop downlink protocol (SHDP) [13] and perform a preliminary deployment using low-power embedded networking platforms. The prototype system covers an urban, crowded large-scale indoor market place of dimension 90×60 meters which displays 10k+ items and is visited by over 5000 customers per day (Figure 1). We also compare this with RPL, the IETF standard IPv6 routing protocol for low-power and lossy networks [4], over the same deployment. From this preliminary pilot study we identify additional system-level design goals that address challenges of crowded indoor market environments. Chief among them, we find that large crowded markets exhibit bursty loss patterns, and external noise sources and active human movements heavily impact the link-level performance of wireless systems. With these findings, we design *MarketNet*, a system to address such unique challenges of a busy market.

We then evaluate *MarketNet* in two different real-world environments. First, we construct a 30-node indoor testbed to validate our proposed system architecture. Following initial validation, we move to the target market environment to confirm that real-world channel conditions are effectively mitigated by *MarketNet*. We also use RPL and SHDP-based networks for benchmark comparison. From these deployments and experimental evaluations, our results show that *MarketNet* adapts well to real-world wireless channels, and shows performances that match the best of the two other compared networking protocols while maintaining a radio duty-cycle of about half of those protocols in most cases.

Specifically, the contributions of this work are four-fold.

- First, we introduce application-level requirements and technical challenges in designing an electronic price-tag system for indoor markets, collected from a series of interviews with store managers.
- Second, we empirically measure the performance of various networking protocols in a real-world crowded indoor market place and identify performance issues and challenges that limit their effectiveness.
- Third, with the application requirements and real-world challenges at the basis, we present a set of key ideas that include a high transmission power root, a network-wide superframe architecture, and uplink period partitioning to design *MarketNet* for wireless electronic price-tagging in large crowded market environments.
- Lastly, we validate the performance of *MarketNet* under various environments including a large, real-world indoor market with 10k+ items and 5000+ customer base. Our results show that asymmetric transmission power-based tagging performs well under real-world channel conditions.

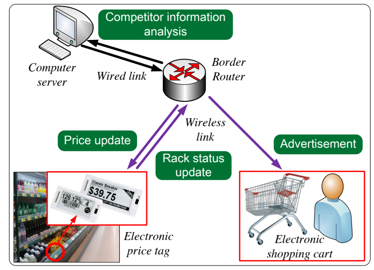


Figure 2: Application scenario for our wirelessly reconfigurable electronic price tagging system, consisting of a wireless-enabled central server and end devices such as price tags and shopping carts.

This paper is structured as follows. In Section 2 we introduce our application scenario and its requirements. We also discuss candidate network architectures for our application. Next, Section 3 presents results from our initial pilot deployment of a wireless price tagging system in an indoor market. We also perform experiments to better understand wireless channel environments of crowded markets and identify additional practical design issues. Section 4 introduces details on *MarketNet*, and we present testbed as well as real market deployment results in Section 5. In Section 6 we position our work among prior work, and conclude the work with discussions and a summary in Section 7 and Section 8.

2. ELECTRONIC PRICE TAGGING SYSTEMS

This section motivates the electronic price tagging application and describes its technical challenges. We present potential networking options for designing these systems and describe the basis for a preliminary pilot study in an urban indoor market environment.

2.1 Target Application: Wirelessly Re-configurable Electronic Price Tagging

Our work aims to design a low-power wireless system with the goal of providing a remotely reconfigurable price tagging system for large, indoor market environments as pictured in Figure 1. Specifically, we target to design a system where a large number of wireless-enabled e-ink-based price tags are used to present product prices, and additional sensors on each tag are used to track the supply level of each item for alerts when the rack becomes empty. In this application, a wireless-enabled central server manages and updates the price tags for all items in the market, and generates reports to the store manager (or related personnel) of rack statuses. Furthermore, we envision to include screen-mounted mobile shopping carts to the application to provide customers with discounts and promotions.

We conducted interviews with market managers and they indicated that price updates happen frequently (e.g., ∼8 times a day for some products). Prices are updated with respect to the products' freshness (e.g., meat, bread, produce) or due to real-time pricing of competing markets. Figure 2 illustrates this target application scenario. Currently, price updating occurs manually and customer complaints due to incorrect prices are one of the major challenges in large-scale markets. As a result, automating this process and providing additional profit seeking opportunities (e.g., real-time promotions on shopping carts) can benefit the market and improve the quality of service for the customers.

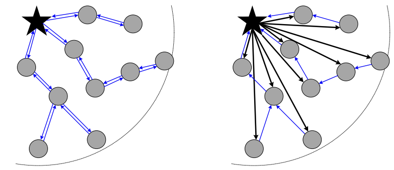
For this target application, our work began with a series of interviews with market managers where we gathered a set of application level requirements as below.

- **Downstream-focused Network Traffic:** For electronic price tagging, a majority of the traffic will be price updates that occur several times a day, along with promotional information updates for shopping carts from a central server. Most of the upstream traffic from tags to the server are acknowledgments and rack status updates. Overall, bottlenecks are more likely to arise in the downstream direction.
- **Mass-scale and Real-time Price / Status Updates:** For updating price tags, multiple products may require reconfiguration, or the promotion information on many carts may require simultaneous updates. Therefore, the system should effectively support mass-scale updates, specifically at least 100 products per minute, as indicated by market managers (and also in previous work [5]). Furthermore, managers requested that the system makes price updates within 10 seconds after updating the server.
- **Maintaining Low-power Non-root Nodes:** While the root node's energy consumption is less of an issue, for the system to be practically useful, the lifetime of the price tags' and shopping carts' radio modules should last for >3 months[1]. For energy efficiency, an e-ink-based display is preferred over LCD, and radio duty-cycling is a must.
- **Data Reliability:** Market managers selected reliability of product price updates as the highest priority system requirement. A system for electronic price tagging should assure that the prices are reliably updated with minimal transmission overhead.

2.2 Network Architecture Options for Electronic Price Tagging

For the application requirements identified above, there are several candidate solutions that we can adopt when designing a wireless system for our target application. We explore the possibilities by introducing two networking architecture paradigms; first, a homogeneous (symmetric) transmission power-based network (*HPN*), and second, an asymmetric (heterogeneous) transmission power network (*APN*).

[1] While a 3 month deployment may seem short for a WSN node (considering systems deployed in outdoor environments), our surveys show that this is within tolerable range for the market managing staff. Achieving a longer lifetime would be beneficial, but, we surveyed the staff for a minimum lifetime that the they could tolerate given the hardware constraints of our system. Note that, the sales items on the shelves need to be re-stocked manually by employees several times a day. Therefore, replacing a pair of AA batteries every 3 months adds only minimal extra labor. Thus, this is still a several orders-of-magnitude improvement to current practice with paper tags.



(a) HPN (b) APN

Figure 3: Network architecture of HPN and APN.

The first approach of configuring a network with homogeneous transmission power is a popular network architecture used in many wireless systems. In such systems, all nodes in the network use identical transmission power, except for cases where adaptive transmission power control schemes are applied [18, 21]. Multi-hop networking protocols rely on this homogeneity to compute link quality metrics for determining the route a packet should take [4, 9]. In RPL, a standard IETF IPv6 routing protocol for low-power and resource-limited platforms, a destination oriented directed acyclic graph (DODAG) is constructed towards a root, and this DODAG is used for both collection and downstream traffic patterns [4]. RPL can be layered on top of low-power MAC protocols such as low-power listening (LPL) [23]. By deploying low-power nodes in the market and connecting them using RPL and LPL, we can construct a low-power IPv6 multi-hop network supporting price reconfigurations upon request over the Internet.

The second networking paradigm utilizes asymmetric and heterogeneous transmission power-based networks (APNs). Specifically, given that a central node (e.g., gateway or basestation) is typically connected to a wall-powered device with no energy limitations, this node can utilize a higher-power radio to broadcast its messages via single-hop (or a reduced number of hops). We illustrate these approaches in Figure 3. Notice that in APNs, the gateway node has the capability to deliver downstream messages via direct connections, while upstream traffic follows a multihop architecture, similar to HPNs. The benefit of this second approach is in the efficient delivery of downstream price updates, with non-root nodes still maintaining a low-power profile. For upwards traffic, APNs may utilize RPL+LPL protocols to achieve energy efficient packet delivery.

We choose the single hop downlink protocol (SHDP) [13] to effectively exploit the asymmetry of the second approach. SHDP supports downstream traffic using local acknowledgments (ACKs), neighbor forwarding, and reduced neighbor contention to achieve reliable downstream packet delivery while allowing non-root nodes to perform low-power operations. In SHDP, due to the differences in transmission power, the destination node (i.e., a low-power node) is not required to send ACK packets to the root directly. Instead, SHDP achieves reliability by allowing the destination and its neighbors to exchange ACK packets "locally". Following this, the neighbors forward any missing packets opportunistically to account for transmission failures. Running SHDP on top of LPL helps to achieve a low-power network of many small-sized price tags with a central PC-connected gateway reconfiguring the entire network using (near) single hop links (at most two hops using local forwarding). The challenge here lies in ensuring that data is delivered to all nodes while obeying transmission power constraints imposed by regulatory organizations (e.g., FCC). While downward communication occurs via single-hop, upstream routes use RPL routes.

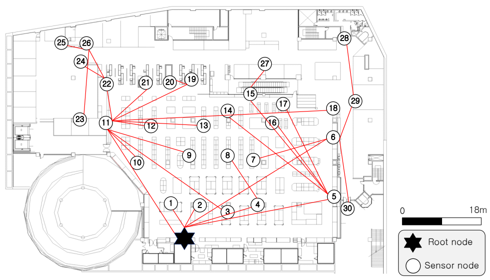


Figure 4: Topology map of our 30 node market environment with a snapshot of RPL routes.

Using these architectures, we implemented two prototype network systems, one with RPL and the other with SHDP. In the following section, we present results from a series of pilot deployments in a real-world large-scale indoor market.

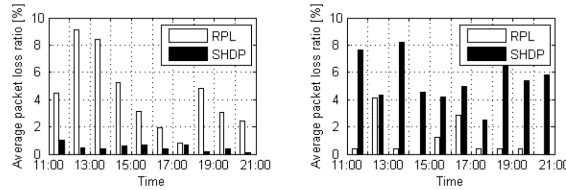
3. PRELIMINARY PILOT STUDIES

Using the two candidate network architectures, we perform a preliminary pilot study in an urban indoor market environment. Figure 4 shows the topology deployed at a single floor market with an area of 90m×60m. The goal of this study is to confirm whether the two aforementioned systems perform well in real environments, and further identify what characteristics of these channel environments challenge the performance of our two candidate network architectures.

3.1 Performance of Pre-existing Protocols

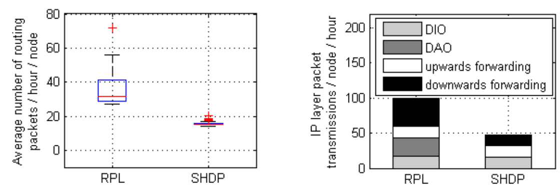
We start our preliminary performance testing in the market using 30 low-power nodes representing reprogrammable price tags, and one basestation node. We use TelosB [24] clone devices as the low-power nodes, and also for the root node in the HPN experiment. For the APN experiments, we use the MTM-CM3300MSP node as the high-power root, which is similar to a TelosB with a 10 dB power amplifier. The low-power nodes use a transmission power of -15 dBm while the high-power root uses 10 dBm. Each node (including the root) has an antenna of 5 dB gain. We consider a downward traffic-focused scenario where the interval of packet generation (IP packets with 20 byte payload) to and from each node are 90 and 450 seconds, respectively. Given our topology, from the basestation's perspective, this corresponds to sending one downwards packet every three seconds, and receiving one upwards packet every 15 seconds. With this configuration, we use RPL (on top of LPL) as a representative low-power multihop routing protocol (HPN), and SHDP (on top of LPL) to validate the performance of APN. We set the sleep interval of underlying LPL as 2 seconds, and RPL produced a 4-hop network in our topology.

Figure 5 presents the packet loss trends for downlink and uplink traffic when using RPL- and SHDP-based networks for 10 hours (11AM - 9PM). For downlink, SHDP outperforms RPL mainly due to the fact that RPL, to begin with, was not designed to provide optimized downwards routes. Rather, RPL typically achieves downwards routing using the reverse of the upwards routes, despite the asymmetry of wireless links [30]. In RPL, the routes are adjusted only by the children nodes; thus, if the parent experiences severe downlink packet loss, it takes a while for the parent to inform children of its status. Furthermore, control packet losses further delay these route updates. Thus, RPL results



(a) Per hour packet loss ratio (downlink) (b) Per hour packet loss ratio (uplink)

Figure 5: Packet loss ratio of RPL and SHDP for uplink and downlink traffic. SHDP shows a lower loss rate for downlink traffic, while RPL outperforms on uplink packet delivery performance.



(a) Routing overhead distribution of each node (b) Average transmission overhead per node per hour

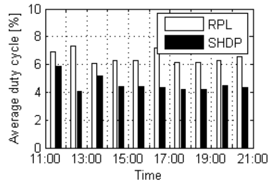
Figure 6: Transmission overhead of RPL and SHDP. SHDP provides lower overhead by suppressing DAO messages and multihop forwarding.

in high packet loss when focusing more on downwards traffic than upwards traffic in dynamic channel environments. On the other hand, SHDP uses higher power for downlink transmissions and local retransmissions to assure the reliability as well as to support two-hop nodes.

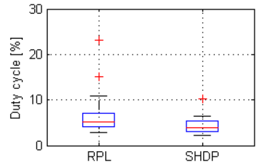
Nevertheless, for uplink, RPL outperforms SHDP despite SHDP constructing uplink routes using RPL. This is due to the interference caused by the high-power downward transmissions in SHDP. Specifically, uplink packets face communication challenges from the root's downwards transmissions, leading to high SHDP packet loss. Nodes distant from the root are more significantly affected by this interference since they are outside the root's clear channel assessment (CCA) range. Unfortunately, this cannot be resolved by simply provisioning new upward routes since the high-power transmission covers the entire network.

Figure 6(a) and Figure 6(b) plot the per hour routing overhead of each low-power node and their average transmission overhead at the IP layer, respectively. From Figure 6(a) we notice that the routing overhead of SHDP is approximately 52% lower than RPL. While SHDP uses RPL for its upwards routes, we see this reduction due to the fact that SHDP suppresses destination advertisement object (DAO) messages, which are periodically issued at each non-root node to initiate downwards RPL routes. Furthermore, Figure 6(b), where we present a breakdown of packet transmissions, shows that SHDP results in lower transmission overhead by removing multi-hop forwarding for downwards transmissions and minimizing route control packets.

Finally, Figure 7 shows the distribution of duty-cycle of each node, including the total radio-on time not only for its transmissions but also for reception, overhearing, and LPL idle listening. It shows that SHDP achieves a lower duty-cycle than RPL (i.e., 30% lower on average, and 66% lower



(a) Average per hour duty-cycle



(b) Distribution of duty-cycles of each node

Figure 7: Duty-cycle of RPL and SHDP. SHDP improves duty-cycle performance due to lower transmission overhead.

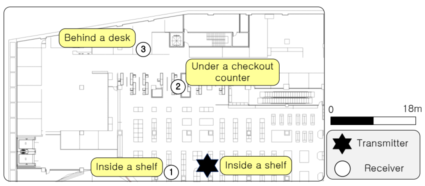
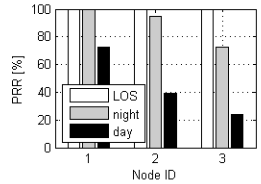
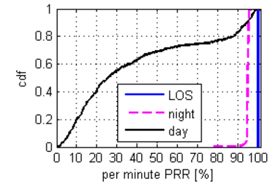


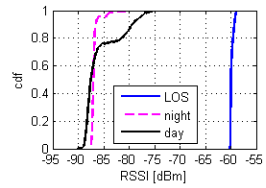
Figure 8: Link testing topology.



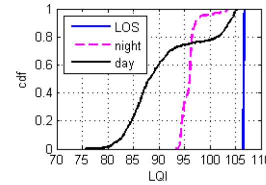
(a) Per-link PRR



(b) PRR CDF of link 2



(c) RSSI CDF of link 2



(d) LQI CDF of link 2

Figure 9: Link characteristics of our indoor market environment for channel 26. Packet delivery performance degrades due to the effect of metal shelves and human activities during the day-time.

for the worst performing node), which is due to the reduction in transmission overhead for each non-root node.

Overall, our preliminary studies show that RPL- and SHDP-based networks each possess their own advantages and disadvantages. While RPL provides reliable upward performance, SHDP operates exceptionally well for downwards traffic and improves the energy consumption by reducing the transmission overhead. With these results in mind, we emphasize once again that our target application asks for effective *downwards* traffic delivery. Nevertheless, it is also important that upwards delivery is reliable, given that messages such as rack status updates and application layer acknowledgments are carried via upwards packets.

3.2 Channel Characteristics of a Crowded Indoor Market Environment

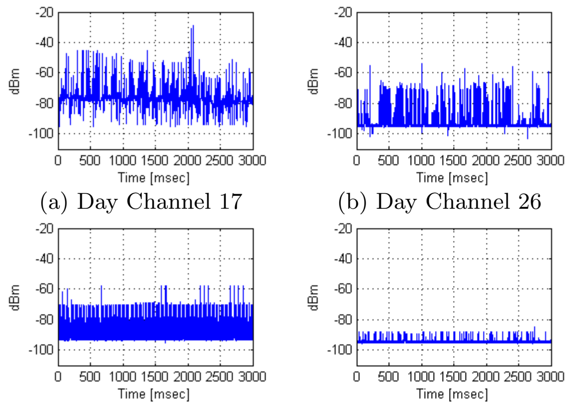
To better understand the wireless conditions in our target environment and also effectively address the limitations of RPL- or SHDP-based networks, we performed an additional study to investigate channel environments in various dimensions. For this, we set up a testing environment as in Figure 8. We install three receivers with a single transmitter broadcasting packets of 72 bytes (MAC payload) at an inter-packet interval (IPI) of 50 msec with 0 dBm transmission power. We select the receivers' locations so that we capture various aspects of the market including active human movements, RF propagation over metal shelves and long-distance communications. Unless specified, we take our measurements on IEEE 802.15.4 channel 26, which, in the U.S., is free from WiFi. For reference, we conducted another line-of-sight (LOS) experiment, where each link has the same distance as the market, but in a different environment[2].

Figure 9 presents various link-performance metrics from this experiment. First, Figure 9(a) presents the per-link packet reception ratio (PRR) both for the day-time (noon-10PM) and night-time (11PM-9AM). By comparing the PRR of LOS and market night-time cases, we observe that the metal shelves carrying items have impact on RF signal propagation, by lowering the night-time PRR of link 2 and 3 compared to the LOS PRR of the same distance. On the other hand, by comparing the PRR of the day- and night-times, we can deduce the impact of human activities, which also heavily impacts packet delivery performance.

To understand the impact of human activities further, we analyze the characteristics of link 2 in detail, where the receiver is located at one of the most crowded areas in the market. Figures 9(b), 9(c) and 9(d) plot the cumulative density function (CDF) of the per-minute PRR, received signal strength indicator (RSSI) and link quality indicator (LQI) of link 2 for LOS, day- and night-times. These figures show that all performance metrics in the market are significantly worse than the LOS case: suggesting that an urban market introduces a challenging wireless environment. Combining Figures 9(a) and 9(b) shows that, not only is the average PRR for the day simply lower than the night, the per-minute PRR patterns are widely spread. This suggests that the day-time PRR varies heavily with dynamic channel conditions. The fact that per-minute PRR during the night is mostly >95% serves as evidence that day-time human movements not only degrades the average packet delivery performance, but also gives heavy impact to the link's dynamics. Other metrics such as RSSI and LQI show a similar trend, in which the values are much more dynamic during the day.

It is meaningful to point out that the average RSSI is higher during the day than the night despite its low PRR in Figure 9(c). We explain this using Figure 10, where we plot the channel noise in the market sampled at 1 KHz. Notice here that there is a substantial amount of noise on channel 26, comparable enough to channel 17, which actively interferes with WiFi traffic. After some investigation, we identified that there was a significant amount of WiFi traffic on channel 26 as well, which is authorized in South Korea, where our experiments were conducted. Therefore, active WiFi on channel 26 caused the day-time background noise levels to increase. While many sensor networking protocols utilize RSSI as an easy-to-gather, low-complexity, and robust networking metric [8], our results imply that using RSSI in our target environment is not a good design choice in selecting high quality links.

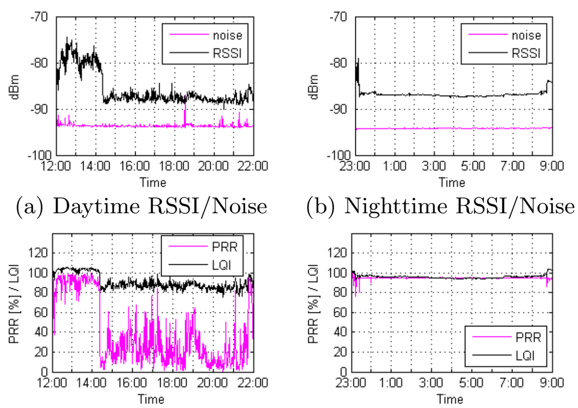
[2]We omit the picture of this deployment due to the lack of space.



(a) Day Channel 17 (b) Day Channel 26

(c) Night Channel 17 (d) Night Channel 26

Figure 10: 1 KHz RSSI sampling traces. The country we test in allows for WiFi traffic on channel 26, causing noise spikes during the day.



(a) Daytime RSSI/Noise (b) Nighttime RSSI/Noise

(c) Daytime PRR/LQI (d) Nighttime PRR/LQI

Figure 11: Characteristics of link 2 over time for channel 26. Human activities cause links fluctuation on both short and long term perspectives.

We can see similar phenomena in Figures 11(a) and 11(b) as well, where we plot the per-minute average RSSI and noise floor levels of link 2 for 10 hours during the day- and night-times, respectively. The long term measurement plots provide us with a longitude perspective of the short-term noise sampling presented in Figure 10. Here, we make another interesting observation. The sudden decrease in RSSI during the day (between 2PM and 3PM) was caused from the filling in of items (i.e., water bottles) on the shelves at which the transmitter was located. Once items were refilled, the RSSI level dropped and this lower RSSI was continuously maintained throughout the day. As Figure 11(c) shows, this same artifact impacted the LQI and PRR performances as well. Likewise, our target environment introduces many man-made hard-to-predict challenges (similar to those reported in [12][31]), which are unique to the indoor market environment, causing the wireless links to fluctuate on both short- and long-term perspectives.

Lastly, we examine the packet loss patterns of link 2 by analyzing the conditional packet delivery function (CPDF) in Figure 12. The CPDF (introduced in [19]) corresponds to the probability of a packet being successfully received after n consecutive failures or successes. Negative numbers represent consecutive successes, while positive numbers represent consecutive failures. For example, $CPDF(20)$ is the probability of a successful delivery after 20 consecutive failures on the link. Likewise, $CPDF(-20)$ is the probability of a successful reception after 20 consecutive successful receptions. Therefore, the CPDF is a good measure of link burtiness and the channel coherence time.

Figure 12(a) through 12(g) sequentially plot the per hour CPDF of link 2 from 3PM to 10PM, after the refilling event occurred at the rack near the transmitter between 2PM and 3PM. We can first notice from the non-uniformity of the CPDF plots that links in the market environment are heavily bursty. Furthermore, since the length of the CPDF's negative (e.g, left) tail represents the maximum number of consecutive successes (or maximum time duration of good link quality, when combined with IPI), we can see here that the link burstiness varies over time. We conjecture that this was an impact of human movement activities, and to validate this we present the correlation between the negative tail length (i.e., maximum consecutive successes per hour) and human movements (manually collected on the link between the transmitter and receiver node 2) in Figure 12(h). Here we validate the fact that the positive burstiness decreases with an increasing number of customers, naturally suggesting that human activities impact the link burstiness

In addition, using Figure 13, where we plot the 1 KHz noise sampling traces for when a near-by microwave oven is active, we noticed that the microwave oven, frequently used to provide samples of cooked food at several points in the market, impacted the burstiness of the wireless links [34].

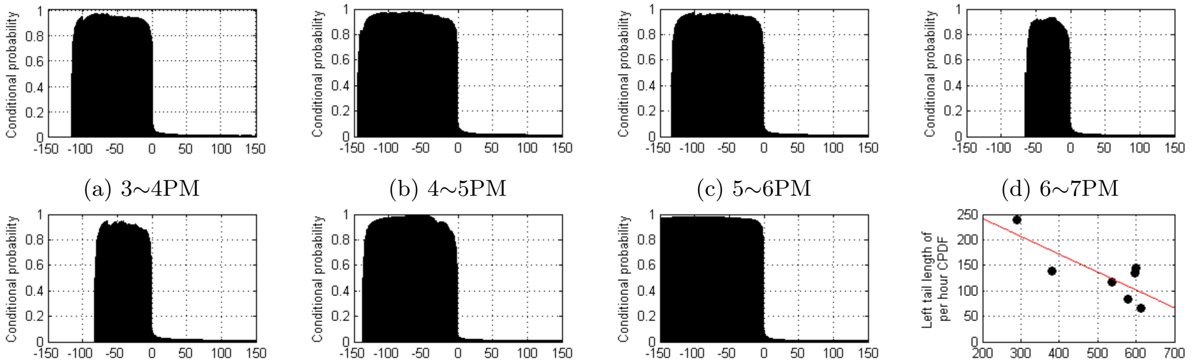
3.3 Technical Issues to Overcome

Based on the above observations, we summarize unique technical challenges of the market environment as below:

- **Human Movements and Market Activity:** Human activity is one of the main reasons for link dynamics during the day. Specifically, the impact of human movements prevents the links from making successful transmissions for long durations. Furthermore, the impact of typical market activity, such as the use of the microwave oven, causes market's link conditions to continuously fluctuate. These issues create the need for a robust networking layer.
- **Metal racks and items:** Metal racks and their items impact the link characteristics in two ways. First, they become an obstacle for RF signals. Second, the item stock status cause long term fluctuation on the link quality.
- **Noise Statistics:** Unlike the U.S., our market environment is not free from WiFi interference even on IEEE 802.15.4 channel 26. The interference problem is difficult to overcome by simply identifying alternative routes since the impact of other radios is prevalent in most cases.

4. ADDRESSING THE CHALLENGES WITH MarketNet

The lessons from Section 3 suggest that constructing a two-way multihop network of symmetric transmission power links (with RPL) provides 'reasonable' performance for our target environment, but is not ideal in terms of overhead and downwards packet delivery reliability. On the other hand, an APN provides satisfactory downlink performance, but fails in providing satisfactory uplink performance due to the



(a) 3∼4PM (b) 4∼5PM (c) 5∼6PM (d) 6∼7PM (e) 7∼8PM (f) 8∼9PM (g) 9∼10PM (h) Correlation between human population and CPDF

Figure 12: Per hour conditional packet delivery function (CPDF) for different hours during the day, along with the negative tail (or left tail) lengths' correlation with human population.

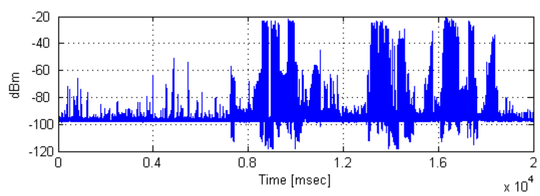


Figure 13: 1 KHz RSSI sampling on channel 26, performed near a microwave oven. Microwave oven is another major factor of link quality fluctuation.

contention and interference occurring near the high-power transmitting basestation. Given these characteristics, we now design a more suitable solution for our application.

In doing so, we take the observation that our application heavily relies on satisfactory downwards packet delivery performance (e.g., price updates). Therefore we borrow some of the concepts proposed in SHDP in enabling APN-based systems to design *MarketNet*. Specifically, *MarketNet* puts RPL at its basis in order to provide end-to-end multihop IPv6 routing, but it is a complete re-design of RPL with the concept of APNs that adopts the advantages of both RPL and SHDP. As our results will later show, *MarketNet* enhances the performance over both RPL and SHDP in our target environment of interest.

The main issue with SHDP-based APN is that it faces high contention and interference near the basestation due to its high-power transmission. In order to compensate for the increased interference range of the root, the APN should provide an end-to-end latency significantly shorter than the one-hop latency of the HPN. Naturally, as the work in [13] also shows, APNs reduces this latency by design. However, reducing the latency to be below that of one-hop packet transmission latency of HPN is non-trivial; thus, this suggests that we need to significantly redesign and improve SHDP to achieve reliable upward packet delivery.

4.1 MarketNet System Design

Our approach to minimize the end-to-end latency of downward packets in an APN combines the high transmission power at the root to achieve single hop downwards packet delivery with the *network-wide time synchronization*. Specifically, *MarketNet* synchronizes all nodes in the network with the high transmission power root and exploits a network-wide superframe architecture. This allows all low-power nodes in *MarketNet* to wake-up and sleep their radios simultaneously. Compared to LPL, which requires half of the sleep interval, on average, for one hop packet delivery (due to the uncertain neighbors' wake-up schedules), our superframe-based scheme significantly reduces the packet delivery latency to only a packet length while reserving more time for upward packets and radio sleep. Furthermore, the superframe dedicates and separates transmission periods for the root and individual low-power nodes using time division duplex, which protects low-power nodes from the root's high power transmission interference. Lastly, the reduction in packet transmission time allows nodes to maintain very short radio active periods to improve their energy efficiency.

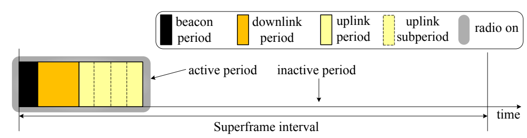


Figure 14: Superframe structure of *MarketNet*. Downlink and uplink transmission periods are designated using a beacon message sent by the root.

4.2 Network-wide Superframe Architecture

This section describes *MarketNet*'s superframe architecture in detail, including the basic superframe operations, uplink period partitioning, and initial synchronization.

4.2.1 Basic Operation

Figure 14 illustrates *MarketNet*'s network-wide superframe structure. A superframe consists of an inactive period and an active period, where the active period is further divided into the beacon, downlink, and uplink periods. At the start of a beacon period, the root broadcasts a *regular beacon* frame with high transmission power, which contains three types of information: (1) A *beacon timer* which is the time interval until the next regular beacon transmission (i.e., start of the next superframe), (2) next downlink period duration, and (3) next uplink period duration.

A non-root node wakes up just before the start of the agreed upon beacon period and receives the next incoming (expected) beacon frame. Using the information in the beacon, a non-root node configures its downlink, uplink and idle durations. Given that these event times are controlled centrally at a single point, a positive side effect is that the duty-cycle (and in turn the lifetime) can be easily estimated and controlled at the central server. Furthermore, although the downlink period starts directly after the beacon reception, the periodic nature of the beacon interval allows the non-root nodes to wake up accurately at a level of reasonable synchronization, despite missing several beacon messages. While many time synchronization schemes exist (e.g. FTSP [22]), we take a simple approach since our application requirements are at millisecond-level accuracy.

When nodes enter the downlink period, only the root is allowed to transmit. All other nodes simply receive packets and transmit ACKs when required in between transmissions. Our current design of *MarketNet* makes multiple unicast IPv6 packet transmissions to individual nodes from the root instead of transmitting batches of downwards messages via multicast. We take such a design choice due to three reasons. First, we try to reduce the implementation complexity at the low-power non-root nodes (e.g., avoid complex multicast addressing). Second, unicast message transmission would mean that the entire network is idle except the destination node that transmits its ACK packet for the downwards message; therefore, minimizing the contention during ACK transmissions and avoids ACK-explosion. Third, the aggregation of price update messages can cause additional latency at the central server. Nevertheless, we foresee the issue of aggregating messages and making multicast transmissions as an interesting future work.

MarketNet includes a best-effort retransmission scheme to increase the reliability of data delivery using a predefined maximum number of retransmissions. In APNs, while the root's transmission successfully reaches the destination, the ACK cannot reach the root over single-hop. To provide reliable delivery in such cases, *MarketNet* utilizes "local ACK packets" rather than end-to-end ACKs, and borrows the neighbor forwarding scheme in SHDP [13]. Specifically, neighbor nodes of the destination confirm the downward packet delivery on behalf of the root by overhearing both the data and ACK packets. If an ACK is not overheard, neighboring nodes locally retransmit the overheard downlink packet to the destination during the following uplink period. Once the downlink duration ends, the uplink period starts for its pre-defined duration (as specified in the beacon) so that low-power nodes can send their messages or perform neighbor forwarding. Following this, the superframe specifies an idle period for the nodes to turn off their radios until the next beacon reception.

4.2.2 Uplink Period Partitioning

Unlike the beacon-enabled mode in the IEEE 802.15.4 standard which requires each cluster head to have an independent superframe duration (i.e., wake-up at different times) for mitigating inter-cluster interference [11], *MarketNet* allows all low-power nodes to share a single superframe since it has a root enabled to cover the entire target area using high-power transmissions. This naturally brings reduced implementation complexity and a common wake-up schedule for messages such as RPL control messages. However, such operations can cause congestion as multiple nodes compete for channel access within a limited uplink duration.

To alleviate this problem, as Figure 14 shows, we partition the uplink period into several sub-periods so that each is just long enough to transmit one packet assuming a maximum IEEE 802.15.4 frame length. The intuition behind this partitioning is to combine the benefits of CSMA with a TDMA-based approach. Specifically, a node that intends to send packets selects a sub-period (at random) and suppresses its packets unless they are at the beginning of this sub-period *and* its CCA succeeds. This constraint helps reduce the number of contenders on the channel [14]. Furthermore, *MarketNet* uses priority-based random backoff as a function of the queue occupancy to allow congested nodes to utilize relatively more sub-periods in the uplink period.

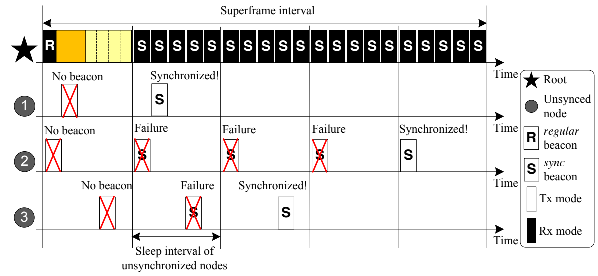


Figure 15: An example of *MarketNet*'s initial synchronization procedure. The root broadcasts sync beacons in the inactive period for new (unsynchronized) nodes to join the superframe architecture.

4.2.3 Initial Synchronization

While the method above is effective once the entire network is synchronized, there are a couple more considerations to make when the network is not fully synchronized or when a new node joins the system. Failing to do so will cause a node to continuously miss the beacons that advertise transmission schedules.

To this end, as we show in Figure 15, an unsynchronized node wakes up periodically and monitors the wireless medium, similar to LPL operations. In the mean time, during the idle times in the aforementioned superframe while the low-power nodes are sleeping, the root broadcasts *sync beacons* continuously, which contains only the start time of the next *regular beacon*. Once an unsynchronized or newly joined node hears this message, it also enters radio sleep mode until the next beacon interval. This scheme allows nodes to maintain their low-power sleep cycles while quickly joining the synchronized network. To achieve reliable *sync beacon* delivery, we set the initial sleep interval of unsynchronized nodes to be much smaller than the superframe interval. This allows new nodes to put multiple efforts for picking up the *sync beacon* message, resulting in robust synchronization under dynamic link conditions.

Lastly, the high-power root does not transmit a *sync beacon* for every inactive period but only at a larger periodical intervals (e.g., 100 superframe intervals). This prevents the procedure from monopolizing the wireless medium. Since all nodes in each network use a single superframe and the *sync-beacon* occupies the channel only shortly, *MarketNet* can construct a larger network consisting of multiple roots.

4.3 IPv6 and Routing Layers in MarketNet

4.3.1 Neighbor Forwarding Suppression

From the preliminary evaluations of SHDP, we noticed that even when a destination node successfully receives a downward packet from the root, the ACK delivery towards its neighbors could fail due to natural link dynamics, such as external channel noise in our environment (Figure 10). This unreliable ACK delivery results in unnecessary local packet retransmissions, which lowers the nodes' energy efficiency. The unnecessary local retransmission also comes from high node densities, since each node has many neighbor nodes.

Since inefficient neighbor forwarding causes uplink period contention, *MarketNet* implements a scheme where a destination's neighbor node will *probabilistically* suppress downward packet forwarding based on the expected number of neighbors of the destination node. Assuming that we aim to deliver a missing downward packet to the destination with N neighbors with a successful delivery probability denoted as P_{succ}, each neighbor node suppresses its transmissions with probability of P_{supp}, determined by

$$P_{supp} = (1 - P_{succ})^{\alpha/N} \tag{1}$$

where α is a predefined parameter which balances reliability and transmission overhead. With increasing α, each node aggressively participates in neighbor forwarding, which impacts the reliability positively (more retransmissions) at first, and negatively (more packet drops due to congestion) after some point. This neighbor retransmission suppression allows for best-effort downlink packet delivery with minimal traffic overhead in dynamic channel conditions. To distribute the neighbor count N to the neighboring nodes, we include this information in the routing beacon messages used for multihop routing (as an optional field in the RPL DODAG Information Object (DIO) messages).

4.3.2 DIO Transmission Interval Adjustment

RPL uses DIO messages for route advertisement to construct multihop routes to the root, and the trickle timer is used to control the DIO transmission interval [4, 20]. This allows RPL to achieve both low overhead and fast route recovery. For this purpose, the trickle timer initializes the DIO interval to be small, and doubles the timer after each DIO transmission until a maximum value (e.g., 256 msec and 262 sec in TinyRPL, respectively [15]) is reached.

However in *MarketNet*, if the DIO transmission interval is smaller than the superframe interval, severe contention can occur during the uplink period, given that multiple DIOs can be stacked at the packet queue during the inactive period. Through our preliminary studies, we observed that *MarketNet* suffers from DIO collisions during the initial phases since all nodes transmit DIOs at the minimum interval when joining the network. To overcome this issue, we configure the initial DIO transmission interval as the superframe interval in *MarketNet*. This cross-layer approach allows *MarketNet* to quickly construct and recover its base routing topology without causing congestion from DIO transmissions.

5. SYSTEM EVALUATION

We now present empirical evaluations of *MarketNet* using an indoor testbed and a market environment as in Section 3.

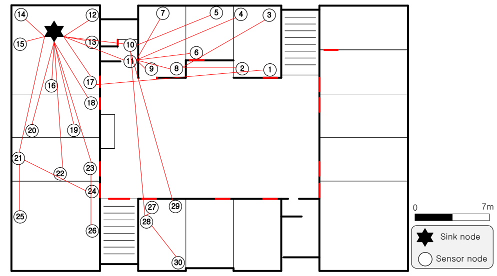


Figure 16: Topology map of indoor 30-node testbed with a snapshot of RPL's routing paths.

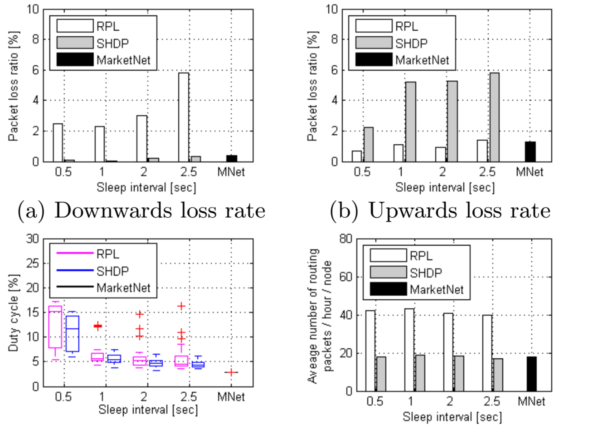
5.1 Testbed Evaluations

Figure 16 presents the topology of our testbed where a total of 31 nodes were deployed on a single floor office with one node acting as the root of the network, resulting in a 4-hop network. Using this testbed, we first present results for the packet loss rate, duty-cycle and networking overhead for varying sleep intervals.

In this experiment, we generate periodic uplink packets (from the low-power nodes to the root) at an interval of 450 seconds, while sending downlink packets (from the root to low-power nodes) at an interval of 90 seconds (i.e., traffic rate of 3 seconds/packet at the root). We select such a balance between the two types of traffic based on an interview with market mangers. Furthermore, for RPL and SHDP, we vary the sleep intervals of the underlying LPL operations to be 0.5, 1, 2 and 2.5 seconds so that the LPL interval is below the traffic rate of 3 seconds/packet at the root. We empirically set $\alpha = 2$ for *MarketNet* to minimize transmission overhead while providing reliable downward packet delivery.

We use a superframe interval of 6 seconds for *MarketNet*, and the downlink and uplink transmission durations are configured to be 90 and 120 msec, respectively, allowing for a steady 5.79 seconds of radio off time per superframe interval. We select these values for two major reasons. First, our goal was to achieve at least 3 months lifetime for our price tags on two AA batteries based on the interviews with the market managers. Given that a typical AA battery has a capacity of 900 mAh, and calculating for ∼60 mW of active power consumption on our nodes, our target duty-cycle was 3.5% or lower. Secondly, from our literature survey which suggested a price update throughput of over 5000 messages per hour [5], our target downlink throughput is 100 packets per minute. This requires for at least a 90 msec downlink period each 6 seconds. The uplink period duration was configured to allow sufficient time for forwarding the given uplink traffic (for all low-power nodes) over multiple hops.

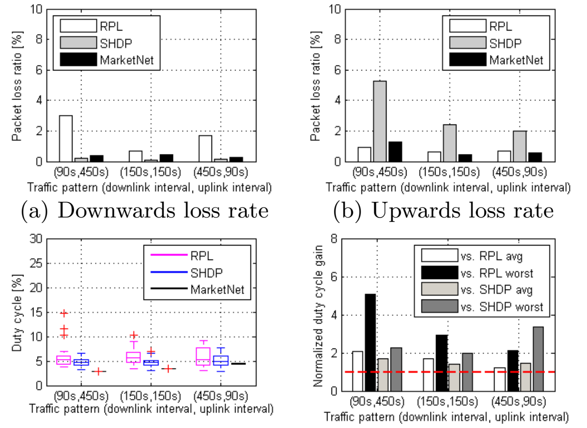
As a result, as Figure 17(c) shows, this configuration leads to achieving a radio duty-cycle of 3.5% for all low-power nodes in *MarketNet*. In contrast, the radio duty-cycles of RPL and SHDP converge at a higher value due to the transmission inefficiency and networking overhead (Figure 17(d)) while maintaining the same level of reliability as *MarketNet*. If we configure the LPL sleep interval of RPL and SHDP higher hoping to improve the duty-cycle, nodes would not be able to handle the given traffic and the duty-cycle will further increase. We note that *MarketNet*'s superframe architecture allows us to further adjust its radio duty-cycle with respect to the energy consumption of the e-price tags' sensors and display units to match the target lifetime.



(a) Downwards loss rate (b) Upwards loss rate

(c) Duty-cycle (d) Overhead

Figure 17: Loss-rate and radio duty-cycle results from the testbed for varying sleep intervals and *MarketNet*. *MarketNet* provides the lowest networking overhead and duty-cycles.



(a) Downwards loss rate (b) Upwards loss rate

(c) Duty-cycle (d) Normalized duty-cycle

Figure 18: Loss-rate and duty-cycle results from the testbed for varying uplink and downlink traffic interval patterns. *MarketNet* shows the lowest packet loss and duty-cycles.

We can see from Figures 17(a) and 17(b) that *MarketNet* shows reduced uplink packet loss ratios compared to the other two protocols. Especially, compared to SHDP, we noticed that the explicit separation of uplink and downlink packets allows the upwards packet delivery performance to match that of RPL. Given that RPL is used as its basis, this is the most ideal performance for *MarketNet*.

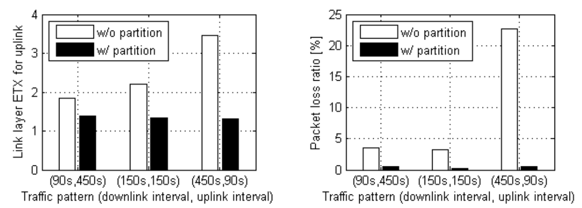
On a different perspective, we vary the uplink and downlink traffic intervals (i.e., [90sec, 450sec], [150sec, 150sec] and [450sec, 90sec]), while maintaining an LPL sleep interval of 2 seconds. Under such conditions, Figures 18(a) and 18(b) show that the performance of *MarketNet* takes the best of RPL and SHDP for both uplink and downlink traffic. The benefits of reduced radio duty-cycle also holds in this experiment as we plot in Figures 18(c) and 18(d). Figure 18(d) plots the normalized duty-cycles of RPL and SHDP against the duty-cycle of *MarketNet*. In many cases, the duty-cycle of *MarketNet* outperforms others by two-fold.

Finally, on the testbed, we examine the impact of utilizing uplink partitioning (c.f., Section 4.2.2) using Figures 19(a) and 19(b). Here, we compare the performance of *MarketNet* with and without uplink partitioning. These experiments were performed during the night-time to focus solely on the effect of congestion. The results show that uplink partitioning improves both link layer ETX and uplink packet delivery performance. The improvement becomes more significant with increasing uplink traffic, which confirms that our uplink partitioning scheme reduces packet collisions by designating slots for the nodes' transmissions.

Overall the results from the testbed suggest that *MarketNet*, on an operational perspective, successfully addresses the performance limitations of RPL and SHDP.

5.2 Market Deployments

For evaluating *MarketNet* in the market, we deploy nodes identically to our preliminary measurements in Section 3 (c.f., Figure 4). Furthermore, we select the same set of networking parameters as in the testbed experiments (e.g. LPL sleep interval of 2 seconds). While experiments were not performed simultaneously (i.e., 11AM-9PM on different days),



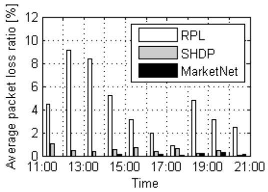
(a) Link layer ETX for uplink. (b) Uplink packet loss ratio.

Figure 19: Impact of uplink partitioning. Uplink partitioning minimizes both the per-link ETX and packet loss ratios for uplink traffic by separating transmission slots.

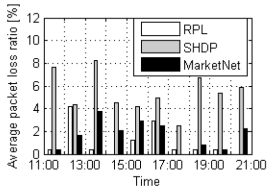
which could lead to inconsistent results due to potential interference from other systems and differences in WiFi activities over different wireless channels, we confirmed that for the three days of testing (e.g., one for each system), the number of market customers were roughly similar.

We first present the packet loss ratio for uplink and downlink traffic in Figures 20(a) and 20(b), respectively. We noticed that *MarketNet* maintains reliable (< 1%) downlink packet delivery regardless of the number of customers during the day, as SHDP does. In contrast, the downlink performance of RPL fluctuates mostly due to dynamic channel conditions during busy times, especially due to human activities. During these periods, link qualities may change frequently, but RPL's route changes cannot keep pace with the link fluctuations. Therefore, even if a RPL node changes its route with respect to the fluctuations, without frequent DAO updates, the parent node is unaware of changes, leading to non-optimal path selection and packet losses for downward traffic. On the other hand, uplink performances of all three protocols vary as time passes due to unstable low-power links in dynamic environments as discussed in Section 3.2, where SHDP provides the worst performance.

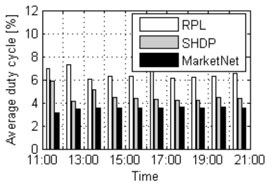
Specifically, the main reason behind the slightly better performance of RPL in some cases compared to *MarketNet* is owing to LPL used under RPL. A link layer transmission



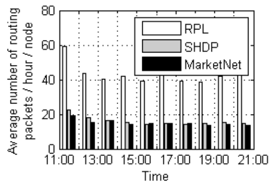
(a) Downwards loss rate



(b) Upwards loss rate

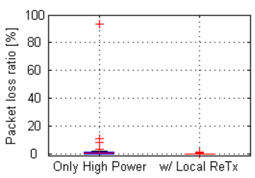


(c) Duty-cycle

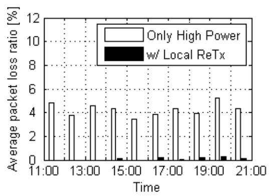


(d) Overhead

Figure 20: Network performance over 10-hour period for RPL, SHDP and *MarketNet* in the market environment. While the real market environment introduces an additional level of fluctuation over time, the performance trends of *MarketNet* match our testbed results.



(a) Loss rate of each node.



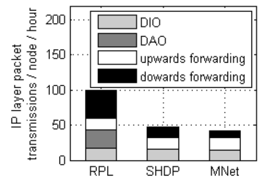
(b) Loss rate vs. time.

Figure 21: Downwards loss rate of *MarketNet* with and without neighbor forwarding scheme. Neighbor forwarding significantly improves reliability when transmission of high power root suffers from link dynamics or path loss.

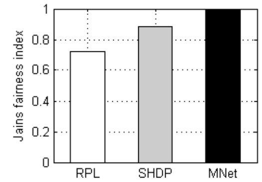
of LPL involves a set of repetitive transmissions for a sleep interval, which produces a dense retransmission effect. With retransmissions at the link and LPL layers, RPL holds a higher chance of delivering packets in dynamic channel conditions. Furthermore, since RPL also uses DAO messages to determine link qualities, it has a higher chance of selecting higher quality links compared to SHDP and *MarketNet*. Nevertheless, Figure 20(c) shows that *MarketNet* achieves the lowest duty-cycle by sacrificing such retransmissions and removing DAO overhead (as plotted in Figure 20(d)).

We analyze the performance of high power transmissions in *MarketNet* using Figures 21(a) and 21(b). Firstly, high power root successfully transmits 95% of downwards packets via single hop. However, direct downward transmissions suffer from unfair reliability among nodes due to different path loss, which leads to 93.23% of loss rate for the worst node (i.e., node 25) as shown in Figure 21(a). Furthermore, Figure 21(b) shows that link dynamics impact the performance of high power transmission, which causes unstable reliability in the time domain. These observations confirm that neighbor forwarding (i.e., local retransmission) is necessary to achieve reliable downward packet delivery in *MarketNet*.

We now look deep into the performance of the three protocols, especially on the packet transmission perspective at



(a) Transmission breakdown



(b) Duty-cycle fairness

Figure 22: Transmission overhead and duty-cycle fairness in the market for RPL, SHDP and *MarketNet*. The reduction in transmission overhead is due to the suppression of DAO transmissions and packet forwarding for downwards delivery. Furthermore, *MarketNet* shows a fair duty-cycle performance among the deployed nodes.

the low-power nodes using Figure 22(a). The number of DIO packets used to maintain the base multihop topology is almost identical, implying that the overall network stability of the systems is similar despite testing them on three different days. By suppressing DAO transmissions, SHDP and *MarketNet* successfully reduce the traffic overhead on low-power nodes. Furthermore, SHDP and *MarketNet* allows low-power nodes to forward downlink packets only when they detect failure of high-power transmissions, which noticeably reduces the frequency of downward forwarding.

Lastly, Figure 22(b) plots the Jain's Fairness Index for the radio duty-cycle of low-power nodes in the network. We see that the use of superframes and synchronized wake-ups lead the nodes in *MarketNet* to achieve a fair duty-cycle. On the other hand, the multihop packet forwarding participation forces RPL to show the lowest fairness in terms of duty-cycle distribution among nodes. The low and fair duty-cycle of *MarketNet* synchronizes the lifetime of all low-power nodes. It also minimizes the need for irregular human intervention, compared to RPL and SHDP, where some nodes deplete their batteries earlier than the others.

Comprehensively, our evaluations show that the performance of *MarketNet* takes the positive ends of both RPL and SHDP in several ways. Compared to RPL, *MarketNet* significantly improves downlink performance with much lower transmission overhead. Compared to SHDP, *MarketNet* provides greatly improved uplink performance. Most importantly, *MarketNet*'s network-wide synchronization allows nodes to enjoy a longer and fairer lifetime.

In our evaluations, we compare *MarketNet* with RPL because, given that is considered to be the *de-facto* standard IPv6 routing protocol for low-power and lossy networks. As alternative comparisons, recently proposed networking protocols such as ORPL [3] or LWB [6] can also be considered. Nevertheless, ORPL in which nodes in the network "anycast" messages through the RPL DODAG, the fairness between the nodes and routing overhead cannot outperform RPL. Moreover, the anycast overhead of ORPL can lead to sacrificing the radio duty-cycle for improved packet delivery performance over RPL. As for LWB in which the Glossy protocol [7] is used as it basis, we believe it could potentially be a candidate protocol that can be compared to *MarketNet* to see their respective advantages and disadvantages. We leave this as an interesting future work.

6. RELATED WORK

Electronic price tagging in large-sized markets has gained interest for several years, and a number of systems have been developed around various wireless networking technologies. Yu et al. [33] discusses the implementation of the Electronic Intelligent Tag (EIT) system on wireless sensor networks for intelligent management of supermarkets. EIT is an electronic display device that replaces the traditional paper price tag. It also provides a way to distribute frequent and effective promotional activities. Although the paper proposes an architecture and design, it does not provide details of the implementation nor performance evaluations. Furthermore the authors do not discuss wireless communication challenges of the environment as we present in Section 3.2. The work closest to ours is the electronic price label (EPL) system [5], which provides a similar electronic replacement for paper labels. The EPL system features two-way communication between a controller and electronic price labels to ensure price accuracy and reliability. Nevertheless, the evaluation of EPL does not consider variability of wireless link characteristics in real-world market environments.

A number of works have investigated the performance of RPL [4] and IEEE 802.15.4 in various network configurations. Ko et al. experimentally evaluated the performance of RPL and 6LoWPAN using TinyOS [16] and showed that the performance is similar to the widely used collection tree protocol (CTP) [9], while benefiting from an IPv6-based architecture. Ancillotti et al. and Bressan et al. studied the performance of RPL in the context of smart grids. The former proposed a cross-layering design for RPL which provides enhanced link estimation and efficient management of neighbor tables [1]. The latter discussed the deployment of a smart monitoring system using LLNs and performed RPL simulations for a smart grid scenario [2]. As simulation studies, the results do not incorporate wireless channel characteristics of the real-world. Gungor et al. measured IEEE 802.15.4 link qualities in real power grid environments and discussed associated opportunities and challenges [10]. Their work was limited to the link layer and did not consider the routing or application layer performance.

7. DISCUSSIONS

The purpose of this work was to propose a suitable networking solution for e-price tagging applications given their system-level requirements. We summarize some interesting future research directions and discussions below.

- There is always a possibility that a single root and its associated APN cannot cover the entire market environment as a single network. In such cases, the use of multiple roots, interconnected in a tiered architecture would be more suitable [26]. In such cases, each root can use a orthogonal superframe with other root nodes either in the time or frequency domain to avoid interference. *MarketNet* allows for this extension to take place easily, but the exploration of practical and systematic issues regarding such deployments is left as future work.
- While *MarketNet* achieves 99.9% and 98.3% data delivery reliability for downlink and uplink traffic (98.7% and 93.8% for the worst nodes), respectively, for some markets, this may not be enough. For guaranteed reliable transport, standard TCP or other reliable protocols such as RCRT [25] can be employed on top of *MarketNet* to complete the price updating procedures.
- Although we test the performance of *MarketNet* using 30 nodes, in practice, price tags are more densely deployed in urban markets. (e.g., +10k tags in our test field). *MarketNet* addresses this challenge using its uplink period partitioning and neighbor forwarding suppression. While we explore the initial steps to form a networked system for the market environment, at-scale testing an how we can resolve any systematic issues in the deployments remains as an important next step of research.
- Optimally provisioning an e-Price tag network given a store layout by performing offline analysis and then placing the devices would be an interesting direction for future research as well. While we do not explore this direction in the scope of this work, we conjecture that this will be a challenging approach given the dynamics of the wireless environment within the market.

The key points of our work are in proposing the use of asymmetric (heterogeneous) transmission power to achieve both (1) downlink reliability and (2) low-power end devices for battery operation. In other words, if we increase the transmission power of the end devices to form a single-hop topology, this would sacrifice the nodes' energy efficiency. On the other hand, reducing the root's transmission power and forming a symmetric multihop topology, would reduce the downlink reliability as in the RPL experiments. Our goal is to achieve the best of both worlds, given the constraints introduced from our devices and the application itself.

8. CONCLUSION

For over a decade, many wireless systems have been designed to automate routine tasks that were previously performed manually. Our work builds on past works by showing how low-power wireless systems can help improve a busy market environment using electronic, wirelessly reconfigurable price tags. This work started with a critical examination of existing networking architectures that could potentially be used for such applications. We performed experiments to gather empirical data and gauge how real-world wireless environments impact their performance. Furthermore, we present *MarketNet*, which addresses the challenges of the application and environments, then evaluate *MarketNet* through a deployment in an actual market. We envision that by addressing additional systematic and deployment-specific challenges, and combining such experiences with the *MarketNet* network architecture, we will be able to enhance *MarketNet*'s practical utility in busy market environments.

Acknowledgments

We would like to thank the reviewers for their insightful comments and Prof. Bhaskar Krishnamachari for his efforts in shepherding the paper. This work was supported in part by a grant to Bio-Mimetic Robot Research Center Funded by Defense Acquisition Program Administration and by Agency for Defense Development (UD130070ID), and in part by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2014R1A1A2056626).

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