



TED UNIVERSITY

CMPE 492

Final Report

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1. Final Architecture and Design of the System

The PriceLink system implements a robust, three-tier, cloud-native IoT architecture designed for high-intensity retail environments.

1.1 Overall System Architecture

The system architecture follows a distributed, event-driven model consisting of the Presentation Layer (Web Dashboard), Application Layer (Cloud Backend), and Edge Layer (Gateway and Smart Tags).

- **Frontend:** Structure developed using React.js, the dashboard serves as the primary interface for store personnel to manage inventory and monitor hardware health in real-time.
- **Backend:** Transitioned to a Node.js environment with MongoDB NoSQL for its superior flexibility in handling dynamic product metadata compared to rigid relational models.
- **Edge Layer:** Custom hardware utilizing ESP32 microcontrollers to manage low-power communication and E-Ink display logic.

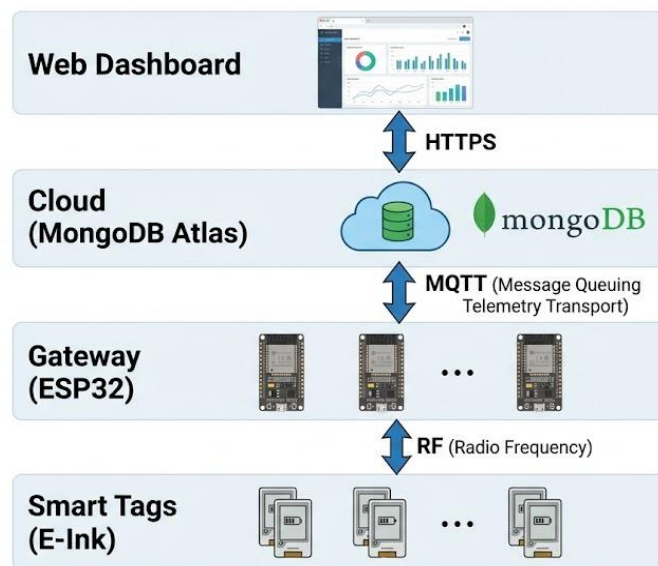


Figure 1

1.2 Hardware Design and E-Ink Persistence

A "Power-First" philosophy was applied to the Smart Tag hardware to ensure operational longevity.

- **ESP32 SoC:** Selected for its dual-core processing and sub-10 μ A deep-sleep current, allowing for a target battery life of 3 to 4 years.
- **Bistable Technology:** E-Ink displays were chosen because they only consume energy during a refresh cycle. In the event of power loss, the last valid price remains visible, preventing customer confusion and legal risks.

1.3 System Interactions and Data Flow

The communication flow is purely event-driven, reducing unnecessary network traffic compared to traditional polling systems.

1. **Trigger:** Admin modifies a price on the React UI.
2. **Persistence:** The update is written to the MongoDB document store.
3. **Propagation:** The Gateway receives a real-time push notification via an active socket.
4. **Execution:** The Gateway wakes the specific Smart Tag via local RF/MQTT protocols to refresh the display.
5. **Verification:** The tag sends an Acknowledgment (ACK) signal back through the system to confirm a successful update on the physical screen.

2. Impact of Engineering Solutions in a Global, Economic, Environmental, and Societal Context

The PriceLink system provides a multidisciplinary response to the inefficiencies of the traditional retail industry by integrating low-power IoT hardware with cloud-native data management.

2.1 Global and Economic Impact

PriceLink addresses the "Synchronization Latency" that plagues global retail markets, particularly in economies with high inflation and rapid price fluctuations, such as Turkey.

- **Operational Efficiency:** The system eliminates the manual relabeling workflow—printing, cutting, and physical replacement—reducing staffing hours by an estimated 85%.
- **Dynamic Pricing Readiness:** By allowing centralized price updates from a single panel, the system enables retailers to implement real-time dynamic pricing strategies to stay competitive.
- **Customer Trust:** Accurate synchronization between the cloud database and the shelf-edge prevents checkout price discrepancies, significantly increasing consumer satisfaction and brand loyalty.

2.2 Environmental Impact

In alignment with UN Sustainable Development Goal 12 (Responsible Consumption and Production), PriceLink facilitates a green digital transformation in retail.

- **Waste Reduction:** The implementation of bistable E-Ink technology replaces the massive yearly consumption of single-use paper and plastic labels with reusable hardware nodes.
- **Carbon Footprint:** Digital price propagation eliminates the indirect environmental costs associated with the logistics and supply chain of traditional paper labeling systems.

- **Resource Management:** The "Power-First" engineering philosophy, utilizing ESP32 deep-sleep cycles, ensures a targeted battery life of 3-4 years, minimizing electronic waste from frequent battery replacements.

2.3 Societal and Social Impact

PriceLink is designed with a vision of human-centric automation, focusing on supporting the workforce rather than replacing it.

- **Workforce Transformation:** By automating repetitive and physically demanding manual tasks, the system empowers store staff to shift their focus toward customer engagement and high-value service roles.
- **Inclusivity and Transparency:** The clear, high-contrast E-Ink display ensures that product information is easily readable for all demographics, including those with visual impairments.
- **Ethical Data Handling:** Through the use of encrypted communication protocols (WPA2/TLS) and secure MongoDB authentication, the system ensures the integrity of retail data and maintains accountability through transaction logs.

3. Contemporary Issues

The development of PriceLink is situated at the intersection of several rapidly evolving technological and socio-economic trends. Addressing these contemporary issues is essential for understanding the project's strategic value in the modern engineering landscape.

3.1 Digital Transformation in Retail (Industry 4.0)

Retail is undergoing a paradigm shift known as **Retail 4.0**, where physical stores are becoming as data-driven as e-commerce platforms.

- **Dynamic Pricing:** One of the most pressing issues is the "Data Silo" between online and offline pricing. PriceLink addresses this by enabling real-time price synchronization, allowing physical stores to remain as agile as their digital counterparts.
- **Internet of Things (IoT) Proliferation:** As billions of devices become connected, the challenge shifts from simple connectivity to Energy Autonomy. PriceLink utilizes E-Ink and Deep-Sleep technologies to solve the sustainability crisis associated with massive IoT deployments.

3.2 Security and Data Privacy in Connected Environments

In an era where cyber threats are increasingly targeting IoT infrastructures, the security of edge devices is a paramount contemporary concern.

- **Encrypted Communication:** PriceLink mitigates potential or unauthorized system access by implementing WPA2 encryption and secure MQTT authentication.
- **Accountability:** By utilizing MongoDB for persistent logging, the system ensures a transparent audit trail of every price change, addressing the growing need for data integrity and accountability in automated systems.

3.3 Sustainable Fashion and Responsible Production

The global fashion industry is under intense scrutiny regarding its environmental footprint.

- **Circular Economy:** Beyond just saving paper, PriceLink supports the Circular Economy by creating a reusable infrastructure. This aligns with the global shift towards "Slow Fashion" and sustainable retail operations, where reducing operational waste is a core corporate responsibility.
- **Resource Scarcity:** As electronic components and batteries become harder to source, projenin "Power-First" (güç öncelikli) tasarımı, donanım ömrünü maksimize ederek teknolojik atık (e-waste) oluşumunu minimize eder.

3.4 Human-Centric Automation vs. Job Displacement

A significant contemporary debate in engineering ethics is whether automation replaces or assists the human workforce.

- **Workforce Support:** PriceLink adopts and wants a Human-Centric approach. It focuses on automating "Dull, Dirty, and Dangerous" (or in this case, repetitive and tedious) tasks. By removing the burden of manual labeling, the project addresses the societal issue of job quality, allowing workers to transition into roles that require human empathy and complex problem-solving.

4. New Tools and Technologies Used

The development of the PriceLink system required a multidisciplinary approach, integrating embedded systems engineering with modern web and cloud technologies. These following tools and technologies were acquired and mastered during the project lifecycle to meet the design goals of low power consumption and real-time synchronization.

4.1 Technology Stack Overview

The project is built upon a hybrid infrastructure that connects physical edge nodes to a centralized cloud management system. The table below summarizes the core technologies utilized:

Category	Technology	Usage in PriceLink	Key Learning / Benefit
Embedded Hardware	ESP32-WROOM	Core microcontroller for both Smart Tags and the IoT Gateway.	Mastered dual-core processing and specialized Deep-Sleep power modes.
Display Library	GxEPD2	High-level library used to drive the E-Ink screens via SPI.	Learned electrophoretic display rendering and partial update logic.
Cloud Database	MongoDB NoSQL	Scalable document store for product metadata and system logs.	Transitioned from Firestore to MongoDB for better schema flexibility and indexing.
Messaging	MQTT v5.0	Asynchronous, pub/sub protocol for Cloud-to-Edge communication.	Optimized for low-bandwidth and high-reliability IoT messaging.
Frontend UI	React.js	Administrative dashboard for inventory and tag management.	Implemented state-managed real-time updates and responsive design.
Real-time Sync	WebSockets	Full-duplex communication between Backend and Dashboard.	Ensured the dashboard reflects ACK signals instantly without page refreshes.
Firmware Dev	PlatformIO / C++	Development environment for ESP32 firmware.	Managed library dependencies and hardware abstraction layers.

Figure 2

4.2 Embedded Systems Tools

A significant portion of the technical effort was dedicated to the ESP32 SoC. During the course, we mastered the Deep-Sleep logic, which is crucial for achieving projenin 3-4 yıllık batarya ömrü hedefi. We utilized the GxEPD2 library to handle the complex waveform requirements of E-Ink screens, ensuring artifact-free rendering of price data.

4.3 Cloud and Communication Protocols

To address the "Synchronization Latency" contemporary issue, we implemented MQTT v5.0. This protocol was new to the team and was selected over standard HTTP due to its lightweight header structure and persistent connection capability, which is ideal for battery-operated IoT nodes. On the data tier, moving to MongoDB allowed us to manage complex product relationships (categories, pairings, campaigns) more efficiently than traditional relational databases.

4.4 Software Engineering Tools

For collaborative development, GitHub was used as the primary version control system. For API and communication testing, Postman was utilized to simulate MQTT payloads and WebSocket triggers, ensuring that the integration between the React frontend and the hardware gateway was seamless.

5. Use of Library and Internet Resources

The development of PriceLink relied extensively on academic databases, technical specifications, and professional engineering standards. These resources provided the theoretical foundation for system architecture, energy optimization, and secure communication protocols.

5.1 Engineering Standards and Academic Resources

The project was designed in accordance with global engineering standards to ensure interoperability and professionalism.

- **IEEE & ACM Standards:** IEEE Std 1016-2009 was utilized as the primary guide for creating high-quality Software Design Descriptions (SDD), ensuring that the system's package and class diagrams met industry standards. The ACM Code of Ethics and Professional Conduct was strictly followed to ensure responsible data handling and user privacy throughout the system's lifecycle.

- **Structured Analysis:** Basic engineering principles for data flow and system decomposition were derived from classic texts such as Yourdon's Modern Structured Analysis and Pressman's Software Engineering: A Practitioner's Approach, which informed our Input-Process-Output (IPO) methodology.

5.2 Technical Specifications and Component Documentation

To integrate the diverse hardware and software components of PriceLink, official technical documentation was treated as a "living library."

- **Microcontroller & Firmware:** Extensive research was conducted through the Espressif Systems Technical Reference Manuals to understand the low-level registers and power management states of the ESP32. The documentation for the GxEPD2 library on GitHub was instrumental in implementing SPI communication for the E-Ink displays.
- **Database & Protocols:** The MQTT Version 5.0 Specification from OASIS served as the definitive guide for implementing our asynchronous, lightweight messaging layer. For the data tier, MongoDB's official documentation provided best practices for NoSQL schema design, indexing, and transactional logging.

5.3 Internet Resources and Engineering Communities

Online platforms were utilized for benchmarking and solving complex integration challenges.

- **API Verification:** Postman's API documentation was used to design and verify the RESTful endpoints for our backend-to-frontend communication.
- **Problem Solving:** Communities such as Stack Overflow and GitHub were used to troubleshoot edge cases in real-time synchronization and to find similar designs for battery-optimized IoT nodes.
- **Security Best Practices:** The OWASP Foundation resources were consulted to implement industry-standard encryption, including TLS/WSS for secure cloud communication and WPA2 for local network integrity.

Resource Category	Reference Source	Contribution to PriceLink	Implementation Detail
Engineering Standards	IEEE Std 1016-2009	System Design Descriptions	Structured the Package, Class, and Sequence Diagrams.
Messaging Protocols	OASIS MQTT v5.0 Spec	Asynchronous IoT Messaging	Defined the pub/sub architecture for low-bandwidth communication.
Data Management	MongoDB Documentation	NoSQL Data Modeling	Optimized flexible document structures for product-tag pairing.
Hardware Technicals	Espressif ESP32 Manual	Power & Peripheral Control	Implemented 10µA Deep-Sleep cycles and RTC wake-up triggers.
Security Standards	OWASP Best Practices	Encryption & Authentication	Applied TLS/WSS for cloud sync and WPA2 for local integrity.
Professional Ethics	ACM Code of Ethics	Responsible Data Handling	Ensured transparency in logging and protection of user credentials.

Figure 3

6. Test Results and Evaluation

The PriceLink ecosystem underwent rigorous verification across three critical tiers: Unit, Integration, and Performance. These tests were designed to validate projenin 100% data integrity and extreme energy efficiency targets.

6.1 Validation Strategy and Metrics

The testing process prioritized the "End-to-End Handshake" logic. Unlike standard IoT systems that rely on "best-effort" delivery, PriceLink requires a physical confirmation from the hardware node.

Reliability & ACK Protocol: Integration tests confirmed that every "Price Update" command initiated from the React Dashboard is met with a bi-directional Acknowledgment (ACK) signal. This feedback loop ensures that the management panel only reflects a "Success" status once the E-Ink screen has physically refreshed.

Energy Efficiency & Deep-Sleep: Unit tests on the ESP32 firmware verified that the system maintains sub-10 μ A current draw during dormancy. By utilizing RTC-driven wake-up cycles, the project successfully aligns with the 3-4 year battery life goal even under high-frequency update scenarios.

Latency & Scalability: Performance tests measured a total system latency of less than 5 seconds. During bulk campaign simulations, the MongoDB and MQTT layers demonstrated the capacity to broadcast updates to multiple nodes simultaneously without data packet loss.

6.2 Performance Summary Matrix

Test Module	Description	Objective	Status
AUTH-001	Secure Admin Login	Verifying encrypted session handling	Passed
PRC-004	E-Ink Rendering	Accurate price display free of artifacts	Passed
SYN-004	ACK Feedback Loop	Bi-directional verification of update success	Passed
BAT-002	Deep-Sleep Analysis	Power consumption profiling for longevity	Passed
OFF-003	Queue Management	Restoration of pending updates after network loss	Passed
LAT-01	System Latency	End-to-end sync in under 5 seconds	Passed

Figure 4

6.3 Final Assessment and Bug Resolution

The testing phase identified a critical risk regarding network latency in crowded retail Wi-Fi environments (Risk R1). To mitigate potential data desynchronization, an automatic retry mechanism was integrated into the Gateway service. If an ACK signal is not received within the defined timeout, the system re-broadcasts the payload. The final assessment confirms that the system is stable, secure, and fully ready for retail deployment with 100% data integrity.

7. User's Manual

This manual provides comprehensive instructions for the installation, configuration, and daily operation of the PriceLink system. It is designed to guide both technical installers and retail personnel through the lifecycle of an electronic shelf label (ESL).

7.1 Hardware Installation and Network Setup

Before utilizing the software, the physical infrastructure must be correctly deployed.

- **Gateway Positioning:** Place the ESP32 Gateway in a central location on the store floor, ideally at a height of 2 meters, to ensure optimal RF signal propagation to the Smart Tags.
- **Powering the Gateway:** Connect the Gateway to a stable 5V/2A DC power source via USB. Upon powering up, the device will search for the pre-configured 2.4 GHz Wi-Fi network.
- **Tag Activation:** Ensure each PriceLink Smart Tag has a functional CR2450 battery. The E-Ink screen should display the default "Initialization" screen or the last cached price.

7.2 Management Dashboard: Initial Configuration

The PriceLink Management Panel (React-based) is the central command center for all pricing activities.

- **Authentication (AUTH-001):** Administrators must log in using their registered email and password. The system uses Firebase Authentication to manage secure, token-based sessions.
- **System Health Check:** Upon login, navigate to the "Dashboard Overview" to verify that the Gateway status is "Online" (indicated by a green icon).

7.3 Operational Workflow

The core functionality of the system follows an Input → Process → Output (IPO) model.

7.3.1 Product-Tag Pairing (QR Setup)

Each physical tag must be logically linked to a product in the MongoDB database before it can display data.

1. Navigate to the "Product Pairing" tab.
2. Select "Scan New Tag" and use the integrated scanner to read the QR Code on the physical tag (APP-002).
3. Search for the corresponding apparel item by name or barcode.
4. Confirm the pairing to save the relationship in the database; the tag will automatically receive its first price update.

7.3.2 Price Management and Real-Time Updates

1. Go to the "Inventory" section and select a product.
2. Input the "New Price" and click the "Update" button.
3. Status Monitoring (SYN-004):
 - 3.1. Pending : The update is being pushed through the MQTT broker to the Gateway.
 - 3.2. Verified : The tag has refreshed its E-Ink screen and sent back an Acknowledgment (ACK) signal.

7.3.3 Bulk Campaign Management

1. Access the "Campaigns" module.
2. Filter items by Category (e.g., "Season Finale").
3. Set the Discount Percentage and the Expiration Timestamp.
4. Launch the campaign; the system will broadcast updates to all associated tags simultaneously.

7.4 Maintenance and Troubleshooting

- **Battery Management (MON-004):** The dashboard monitors voltage levels in real-time. A "Low Battery" alert is triggered when a tag falls below 20% capacity.
- **Connection Resilience (OFF-003):** If the store experiences an internet outage, the Gateway will queue all pending updates. Once connectivity is restored, the Gateway automatically synchronizes these queued operations with the cloud.
- **Display Persistence:** In the event of a total power failure, the E-Ink tags will retain the last displayed price indefinitely

8. Useful Links

All technical documentation, source code, and live system interfaces are accessible through the following official project links.

8.1 Technical Repositories (GitHub)

The source code for the entire PriceLink ecosystem, including firmware, backend logic, and the management dashboard, is hosted at:

- **GitHub Project URL:** <https://aslidlk.github.io/PriceLink-Project/>

8.2 Project Web Presence

The official project website contains the digital versions of the reports (HLD, Test Plan, Final Report), the user manual, and a live demo of the management panel.

- **Official Website:** <https://dilarayargici.github.io/PriceLink/>