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Are We There Yet? Low-cost Parcel Tracking System

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Abstract

In der Logistikbranche besteht eine anhaltende Diskrepanz zwischen dem physischen Standort von Paketen und ihrem digitalen Tracking-Status. Obwohl kommerzielle Lösungen existieren, schränken deren hohe Kosten die Verbreitung ein. Diese Arbeit untersucht die Machbarkeit der Entwicklung eines kostengünstigen RF-basierten Paketverfolgungssystems unter Verwendung von handelsüblichen Komponenten mit einer Budgetbeschränkung von 3 bis 5 EUR. Neun Hardwarekonfigurationen wurden implementiert und evaluiert, die drei RF-Technologien (433 MHz, 2.4 GHz nRF24L01+ und Bluetooth Low Energy) mit drei Mikrocontroller-Plattformen (ATtiny85, ESP8266 und ESP32-C3) kombinieren. Der Evaluationsteil konzentrierte sich auf Merkmale wie Stromverbrauch, Kommunikationszuverlässigkeit, Kommunikationsdistanzen und Skalierbarkeit mit mehreren Geräten in einem simulierten Logistikszenario. Die Ergebnisse zeigen, dass das Kostenziel mit der günstigsten Konfiguration erreicht werden kann, die nur 3,13 EUR kostet. Während der Evaluation erwies sich jedoch die Batterielebensdauer als größte Herausforderung, wobei empirische Messungen erhebliche Ineffizienzen beim Stromverbrauch im Vergleich zu den theoretischen Berechnungen aufzeigten. Alle Lösungen zeigten eine robuste Handhabung mehrerer Geräte, wobei nur die auf 433MHz basierende Lösung ein Interferenzproblem aufwies. Diese Forschung bestätigt, dass kostengünstiges RF-basiertes Tracking zwar machbar ist, jedoch grundlegende Kompromisse zwischen Kosten, Stromverbrauch und Zuverlässigkeit bestehen, die die praktische Implementierung beeinflussen.

There is a persistent gap in the logistics industry between the physical location of parcels and their digital tracking status. While commercial solutions exist, their high costs limit their deployment. This thesis investigates the feasibility of developing a low-cost RF-based parcel tracking system using off-the-shelf components within a budget constraint of 3 to 5 EUR. Nine hardware configurations were implemented and evaluated, combining three RF technologies (433 MHz, 2.4 GHz nRF24L01+, and Bluetooth Low Energy) with three microcontroller platforms (ATtiny85, ESP8266, and ESP32-C3). The evaluation part focused on characteristics like power consumption, communication reliability, communication distances, and scalability with multiple devices in a simulated logistics scenario. The results show that the cost target can be achieved with the lowest configuration, costing only 3.13 EUR. However, during the evaluation, battery life proved to be the biggest challenge, with empirical measurements revealing significant power consumption inefficiencies compared to the theoretical calculations. All solutions demonstrated robust handling of multiple devices, with only the 433MHz based solution exhibiting an interference issue. This research confirms that while low-cost RF-based tracking is achievable, fundamental trade-offs exist between cost, power consumption, and reliability that impact the practical deployment of such systems.

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Contents

Chapter 1

Introduction

The global logistics industry has undergone a significant transformation in recent years, driven by rapid growth in e-commerce, evolving customer expectations, and accelerated adoption of digital technologies [1].

However, despite these technological advances, the logistics industry continues to face significant challenges in accurately tracking parcels and maintaining real-time visibility throughout complex shipping processes. Evidence from existing warehousing and shipping operations reveals persistent problems with delayed, missing, and lost shipments [2]. Research also shows that the disconnection between the physical location of parcels and their digital status creates operational inefficiencies that impact both customer satisfaction and operational costs [3].

Today's modern logistics networks involve multiple carrier companies, various transportation modes, and numerous exchange points where parcels transition between different handling systems [4, 5]. This complexity makes continuous tracking increasingly more difficult [6].
Although companies are adopting newer tracking technologies and approaches in logistics, traditional tracking methods are still in use and rely predominantly on manual bar-code scanning, which leaves significant gaps in tracking visibility and is prone to human error [7, 8].

1.1 Motivation

The motivation for developing a low-cost RF-based parcel tracking system stems from the critical need to bridge the gap between expensive, sophisticated tracking solutions and the practical requirements of modern logistics operations. Current smart label technologies, while promising, face adoption barriers due to material costs and technological constraints. As noted in the report by the logistics company DHL on Smart Printables [9, 10], there is an urgent need for cost-effective, lightweight, and reusable tracking solutions that can enhance monitoring capabilities without imposing additional costs on customers.

Research also shows that operational problems in parcel delivery services are often connected. Analysis of customer complaints has shown that issues such as damage, misdelivery, or delays often occur together, suggesting shared underlying problems in logistics operations [2].

While Radio Frequency Identification (RFID) systems have demonstrated high accuracy in certain industry implementations, their implementation costs and continued reliance on human intervention remain significant barriers to widespread adoption. This creates a need for more affordable alternatives that can lower entry barriers while still enhancing parcel tracking capabilities [10, 11].

1.2 Thesis Goals

This thesis aims to determine whether a functional RF-based parcel tracking system can be developed within a budget of 3 to 5 EUR that addresses current logistic parcel tracking challenges. We will first analyze the technical and economic feasibility of such a system. Based on the analysis, a set of working prototypes will be developed using affordable and low-power micro-controllers and commercially available RF modules. The system must be capable of basic parcel identification and status communication with a base station at established intervals. The implementations of the prototypes will then be evaluated based on battery performance and using simulated logistics scenarios to test communication reliability and practicality.
It provides a comparison of all different hardware configurations to see which performed the best and which has the best viability for further investigation.

1.3 Thesis Outline

This thesis is organized into six chapters that build upon identifying the problem to provide a possible solution. The first Chapter 1 establishes our research context and motivation, explaining why low-cost RF tracking is needed in modern logistics and defining the specific objectives of this work. Chapter 2 then provides a common theoretical foundation, based on background definitions of the technologies used, and through a comprehensive review of existing tracking technologies, examining current RF-based systems and analyzing comparable solutions already deployed in the logistics industry.

With this background established, Chapter 3 utilizes the challenges and limitations of other solutions to identify the requirements of our system, including functional specifications, cost constraints, and power consumption targets. A common architectural design is established that is independent of the technology used and can be used as a basis for implementing the prototypes.
The practical realization of this design is described in Chapter 4, which outlines the implementation challenges encountered when attempting to meet the cost and power targets

while maintaining essential functionality. This implementation work serves as the basis for the comprehensive evaluation in Chapter 5, where the prototype's performance is measured against the established requirements through testing in simulated logistics environments. Finally, Chapter 6 summarizes the key findings to assess the overall feasibility and scalability of the solution and also providing concrete recommendations for future development of affordable tracking technologies in logistics applications.

Chapter 2

Fundamentals

2.1 Background

2.1.1 Processes in Logistics and the Delivery Supply Chain

Traditionally, supply chain management consists procurement, production, and distribution stages that have historically been managed independently, buffered by large inventories [12]. Logistics, in turn, explicitly addresses the physical movement and storage of goods through transportation, warehousing, and inventory management [13]. While parcels move through transportation networks utilizing road, rail, air, and sea modes based on distance, cost, and speed requirements, warehouse operations manage storage locations and inventory levels, with packaging decisions based on product characteristics [13]. Transportation in turn represents the primary component of logistics services and often comprises over half of total logistics costs [12].

In this field, a fundamental challenge emerges from fragmented operations across functional or corporate boundaries, making coordination difficult. Furthermore, poor information flow between stages can lead to demand amplification, resulting in alternating stockouts and surpluses [12]. While recent advances in communications and information technology provide opportunities to coordinate planning across supply chain stages, achieving effective coordination requires synchronization across multiple entities with conflicting priorities [12].

These coordination challenges in modern supply chains underscore the need for tracking approaches that maintain continuous visibility throughout the logistics network. The following sections examine radio frequency communication principles that enable such continuous monitoring, forming the technical foundation for the low-cost tracking solution proposed in this thesis.

2.1.2 Radio Frequency Transmission

Radio-frequency (RF) transmission is one of the simplest ways to leverage wireless communication. With a straightforward setup, RF communication is suitable for outdoor use, but more importantly, for this project's goal, indoor communication between a transmitter and receiver [14].

The 433 MHz band mainly provides a good balance between range and power consumption. Compared to higher frequency alternatives like 2.4 GHz (used in Wi-Fi and Bluetooth), signals in the 433 MHz range can penetrate obstacles more effectively with a similar power output [14]. This characteristic is particularly valuable in logistics environments where parcels may be surrounded by other packages, stored in metal containers, or transported through structures with varying levels of signal obstruction.

2.1.3 Wireless Communication

Wireless communication forms are at the core of modern parcel tracking systems, enabling data transmission without physical connections between devices. This foundational technology has transformed logistics operations by providing methods that deliver high visibility into the movement and status of parcels through the entire supply chain. Because of that, the principles of wireless communication are a key factor in understanding the capabilities and limitations of tracking technologies.

At the core of all wireless communication systems is the propagation of electromagnetic (EM) waves. These waves, composed of oscillating electric and magnetic fields, travel through space at the speed of light and can penetrate various materials with different levels of attenuation [14]. This frequency-dependent propagation behavior creates fundamental trade-offs in the design of tracking systems.

Selecting the appropriate frequency bands affects system performance in terms of range, power consumption, and interference. Lower frequencies offer better penetration through obstacles and extended range, but provide lower data rates. In contrast, higher frequencies enable higher data rates but suffer from reduced range and penetration capability [14]. These trade-offs directly influence design choices for feasible tracking solutions.

Additionally, regarding the proposed solution in this thesis, the 433 MHz band is license-free in Switzerland, allowing legal operation without special permits [15]. This enables the tracking devices developed to be deployed immediately in logistics operations without navigating complex compliance requirements, further supporting the project's low-cost goals.

2.1.4 Radio Frequency Identification

Radio Frequency Identification (RFID) technology, specifically RFID tags, has become a key component of automatic identification across various industries, including logistics, with the global market experiencing significant annual demand for RFID tags [16]. The basic functionality of RFID enables automatic identification through radio waves between readers and tags, eliminating the need for direct line of sight. In addition, RFID tags can be classified by their type of power source. Active RFID tags contain batteries and allow for reading ranges of 20 to 100 meters, while the passive tags use energy from the reader's electromagnetic field [17]. In terms of cost, RFID tags are hard to compete with by other RF-based solutions, with some units costing only a few cents apiece [17, 18].

2.1.5 Bluetooth (IEEE 802.15.1)

The term Bluetooth (BT), also standardized as IEEE 802.15.1, operates in the 2.4 GHz ISM band, and the underlying protocol allows for devices to find and connect in a process called pairing, where the secure transfer of data is also possible [19].

The BT architecture consists of small networks called piconets, each comprising one master device and up to seven active slave devices, with communication controlled by the master unit through a time division multiplexing (TDM) scheme [14]. Additionally, up to 255 devices may remain parked, conserving power while maintaining synchronization with the piconet [14]. BT also offers significant advantages through its power management capabilities and network topology. Power consumption is minimized through multiple operational states [14]. This is a reasonable basis for a parcel tracking system to operate for extended periods on small batteries, making BT-based solutions viable for analysis in this thesis.

2.1.6 Received Signal Strength Indication

The Received Signal Strength Indication (RSSI) is used to measure the power level of received radio signals and is commonly used in Wi-Fi and Bluetooth systems for proximity estimation. While RSSI values can provide rough distance estimates, the relationship between signal strength and distance is also influenced by environmental factors, such as obstacles or other forms of interference [20, 21]. In this thesis, RSSI measurements are utilized in the implementation of specific hardware configurations that support them.

2.1.7 Wireless LAN (IEEE 802.11)

Wi-Fi (IEEE 802.11) operates in the 2.4 GHz and 5 GHz bands and is widely deployed in commercial and industrial facilities [21]. However, Wi-Fi's protocol stack, designed for high-bandwidth communication between non battery powered devices, exhibits power consumption levels largely incompatible with battery-operated tracking tags [22].

Due to the protocol overhead required for network scanning, authentication, and maintaining connection state, it prevents the use of proper deep sleep modes necessary for extended battery life in tracking applications. Unlike simple beacon-based transmission, where devices wake up only to transmit, Wi-Fi requires continuous protocol participation, which can significantly reduce battery life. For this reason, the solutions here do not consider Wi-Fi-based approaches.

2.1.8 Serial Peripheral Interface

The Serial Peripheral Interface (SPI) is a synchronous serial communication protocol that allows for high-speed, full-duplex data transfer between a host and a one or more peripheral devices as clients. The SPI technology, which was first developed by Motorola in the 1980s has become a widely used standard in short-distance, high-speed serial communication in embedded systems applications. [23]

To interface with other device SPI use the following four control wires: COPI (Controller Out Peripheral In) for sending data to peripherals, CIPO (Controller In Peripheral Out) for receiving data from peripherals, SCK (Serial Clock) for synchronization, and CS (Chip Select) for device selection [24, 25]. It should be noted that hardware documentation, like in our case, often uses legacy terminology, such as MOSI (Master Out Slave In), MISO (Master In Slave Out), and SS (Slave Select), instead of COPI, CIPO, and CS [24]. In the context of our proposed tracking system, it is also relevant because SPI acts as the primary interface between any chosen microcontroller and the 2.4Ghz nRF24L01+ module.

2.1.9 Universal Asynchronous Receiver Transmitter

The Universal Asynchronous Receiver Transmitter (UART) is a communication protocol that enables asynchronous serial data transmission between microcontrollers and other devices, without the need for a shared clock signal between communicating devices. The UART utilizes a two-wire interface consisting of TX (transmit) and RX (receive) lines to facilitate full-duplex communication [26].
In the context of the proposed tracking system, the UART serves as the communication interface between the Raspberry Pi base station and the HM-10 Bluetooth Low Energy (BLE) module, as well as the HC-12 433MHz transceiver module.

2.2 Related Work

2.2.1 Overview

In the following, Table 2.1 provides an overview of wireless technology approaches analyzed in this chapter, drawing from dedicated parcel tracking solutions and general asset tracking systems. The evaluation focuses on three key requirements: cost, energy efficiency, and reliability in logistics environments. Including diverse tracking technologies ranging from industrial asset monitoring systems to consumer item trackers enables a comprehensive understanding of available approaches and their potential adaptation for parcel logistics. While some listed technologies were not designed explicitly for parcel tracking, their underlying principles and implementation strategies offer valuable insights for achieving cost-effective tracking within our constraints. The cost categories reflect the economic viability for large-scale logistics deployment, where "Low" indicates solutions within the 3-5 EUR target range, "Medium" represents the 5-10 EUR range that already compromises deployment feasibility, and "High" and "Very High" denotes solutions exceeding 10 EUR or more that are economically impractical for this scale of tracking applications.

2.2.2 Categorization Criteria

The discussion of wireless tracking technologies employs three primary dimensions: cost, energy efficiency, and reliability in logistics environments. Each dimension uses a multi-tier classification system to compare different technological approaches systematically.

2.2.3 Cost Classification

The cost categorization is established relative to the 3-5 EUR target defined for this thesis project. This target represents the critical threshold for economically viable parcel tracking at scale, where even small cost increases can significantly impact deployment feasibility when thousands or millions of units are required:

1. **Low (3-5 EUR per unit)**: Achievable with minimal component designs utilizing basic MCUs, simple RF transmitter modules, and standard power sources. This represents the target range for viable logistics tracking, where devices may be semi-disposable or require minimal cost recovery. At this price point, large-scale deployment becomes economically feasible.

2. **Medium (5-10 EUR per unit)**: Solutions requiring enhanced features, bidirectional communication capabilities, or additional sensing functionality. While technically feasible, this cost range already compromises the economic viability for large-scale logistics deployments. The doubled cost compared to the target range significantly impacts return on investment calculations.

3. **High (>10 EUR per unit)**: Systems incorporating advanced communication protocols, certified modules, or sophisticated processing capabilities. These solutions exceed practical cost constraints by more than 200% of the target, making them unsuitable for applications where tracking devices cannot be guaranteed to be recovered or reused.

It should be noted that while economies of scale could potentially reduce costs in high-volume production, this analysis focuses on achievable prototype costs to demonstrate real-world feasibility. The classification intentionally uses conservative estimates to ensure that proposed solutions remain viable even without massive production volumes.

2.2.4 Energy Efficiency Classification

Energy efficiency in battery-powered RF tracking systems is a critical performance aspect that directly affects the deployment viability of a given solution. Based on battery performance, this classification, which uses four levels, is used to evaluate power efficiency across different operational modes. This can be categorized in the following

1. **Very High Efficiency**: Systems operating through passive reflection, or very low duty operation
2. **High Efficiency**: Implementations utilizing sleep modes, efficient protocols, and minimal active transmission time
3. **Medium Efficiency**: Solutions requiring periodic wake-up cycles, moderate processing requirements, or regular status updates
4. **Low Efficiency**: Systems with continuous operation, high-power transmission, or more complex signal processing

2.2.5 Reliability Classification

Reliability refers to multiple performance metrics relevant to common logistics tracking applications:

1. **Very High Reliability**: System has advanced error correction, multiple redundancy mechanisms, or sophisticated signal processing
2. **High Reliability**: Implementations providing reliable operation through established protocols and effective interference mitigation
3. **Medium Reliability**: Solutions offering acceptable performance under typical conditions but potentially degraded under more challenging circumstances
4. **Low Reliability**: Implementations with minimal error handling, limited range capabilities, or susceptibility to environmental interference

2.2.6 Discussion

The comparative analysis of wireless tracking technologies presented in Table 2.1 reveals trade-offs between cost, energy efficiency, and reliability that guide the design choices for this thesis project.

The cost distribution among technologies analysed demonstrates a correlation between system complexity and implementation costs. Traditional RFID-based solutions, including backscatter applications and standard HF/LF RFID systems, achieve the lowest costs

Publication	Cost	Efficiency	Reliability	Protocol/Technology
Balocchi et al. [27]	Low	High	High	Harmonic RFID
Pan et al. [28]	High	High	High	UHF RFID
Sarkar et al. [29]	Low	High	Medium	HF/LF RFID
Priyanta et al. [30]	Very High	Medium	High	LoRa/LoRaWAN
Vyshak et al. [31]	Low	High	Medium	HF/LF RFID
Kotaru et al. [32]	Low	High	High	WiFi backscatter
Abedi et al. [33]	Low	High	High	WiFi backscatter
Song and Han [34]	High	Low	High	LoRaWAN
Mekhaznia and Bennour [35]	High	High	Medium	ZigBee WSN
Grasegger et al. [36]	High	High	Medium	ZigBee WSN

Table 2.1: Comparison of Wireless Technologies for Tracking Applications

through their simplicity because they require only passive tags and basic readers. These align closely with our target budget of 3-5 EUR per unit. In contrast, LoRaWAN implementations consistently fall into the high-cost category (>20 CHF), mainly due to their requirement for certified modules, advanced MCUs, and supporting circuitry. The backscatter approaches (WiTAG and commodity WiFi backscatter) present an interesting middle ground, achieving low costs despite their technical sophistication by leveraging existing infrastructure rather than requiring dedicated hardware.

A pattern can be observed in energy consumption: passive technologies are most times in the high-efficiency category. RFID systems and backscatter approaches achieve very good energy efficiency through their fundamental operating principle by consuming energy from intercepting signals rather than requiring internal power sources. This battery-free operation represents the ideal for logistics applications where device replacement is impractical. Battery-powered systems in our survey like the LoRaWAN implementation, demonstrates the energy penalty of active transmission, achieving only 80 hours of continuous operation despite LPWAN's low power consumption. This reinforces the value proposition of passive or ultra-low-power approaches for parcel tracking applications.

Reliability metrics reveal interesting observations across technologies. While most systems claim high reliability, the nature of this reliability varies significantly. Backscatter approaches achieve high reliability for tracking individual or small numbers of objects but may face scalability challenges in dense deployments. RFID systems demonstrate a critical limitation: despite their inherent reliability, they require readers to be in close proximity to tags, which constrains their applicability in distributed logistics networks. The harmonic transponder approach notably claims immunity to metal and humidity interference, addressing common environmental challenges in logistics. LoRaWAN's high reliability stems from its long range and multi-node capability, though this comes at the before mentioned cost and energy penalties.

A critical differentiator among technologies is their infrastructure requirements. WiFi backscatter approaches, while technically promising, depend entirely on existing WiFi networks. This poses a significant limitation for logistics operations spanning diverse environments. RFID systems require dedicated readers at every checkpoint, which creates deployment complexity and additional costs beyond the tags themselves. LoRaWAN necessitates gateway infrastructure, though with broader coverage than RFID readers. For our application, which targets flexible deployment across various logistics scenarios, minimizing infrastructure dependencies becomes paramount.

Beyond the technical metrics, practical implementation considerations have a significant influence on technology selection. While backscatter approaches demonstrate very good energy efficiency, they typically require custom hardware design, including specialized RF switches, impedance matching circuits, and carefully tuned antennas. This hardware development process demands significant expertise, specialized test equipment, and iterative prototyping cycles that extend beyond the scope of this thesis. In contrast, our approach prioritizes using off-the-shelf components which are readily available microcontrollers, standard RF modules, and commercial antennas, that can be integrated without extensive RF engineering expertise. This design philosophy not only accelerates development and reduces technical risk but also ensures reproducibility and maintainability of the solution in practical logistics deployments.

The analysis reveals that simultaneously achieving all three objectives of low cost, high energy efficiency, and high reliability remains challenging. RFID approaches achieve two of three goals but fail on infrastructure flexibility. Backscatter technologies excel in efficiency and can achieve low cost, but they depend on specific infrastructure and require complex custom hardware development. LoRaWAN provides reliability and range but fails cost and energy targets.

This gap in existing solutions validates the thesis approach of developing a system using off-the-shelf components. By accepting compromises in sophistication (compared to backscatter) and range (compared to LoRaWAN), we can evaluate whether it is possible to achieve the critical combination of very low cost (3-5 EUR target), reasonable battery life through simple beacon operation, and infrastructure independence crucial for logistics applications.

Chapter 3

Design

The following chapter presents the design of an RF-based parcel tracking system that combines insights from the fundamental concepts and existing solutions examined in previous chapters. The analysis of current tracking technologies reveals a gap between complex but expensive commercial solutions and the practical requirements of cost-effective parcel tracking. While technologies excel in specific metrics, such as energy efficiency, range, and reliability, few to none of the surveyed approaches successfully balance all three critical factors within the described parameters.

By establishing a technology-independent design, the thesis can explore multiple implementation options, ranging from different RF protocols to hardware configurations. This will provide valuable data to assess the suitability of the proposed solution for real-world applications based on the defined metrics of performance, cost, and reliability.

3.1 System Requirements

This Section defines the functional and non-functional requirements that guide the design of the RF-based parcel tracking system. The requirements are derived from the challenges identified in previous chapters and the operational constraints of modern logistics environments.

3.1.1 Functional Requirements

The functional requirements specify the core capabilities that the system must provide to achieve its tracking objectives. These requirements can then be organized into three categories: core tracking functionality, onboarding and lifecycle management, and data handling.

Beginning with the core functionality, the basic tracking capabilities form the basis of the system's operation. This means each tracking module must transmit a unique identifier

ID	Description
	Core Tracking Requirements
FR1	Each tracking module shall transmit a unique persistent identifier
FR2	The modules shall broadcast keep-alive signals at a set interval
FR3	The system shall support communication between the base station and tracking module
FR4	The base stations shall detect and log all modules within communication range
FR5	The system shall implement geofencing-based automatic state transitions
	Onboarding and Lifecycle Requirements
FR6	The system shall provide a programming interface for unique identifier assignment
FR7	The onboarding process shall not exceed 10 seconds per parcel
FR8	The system shall support bulk initialization of multiple modules simultaneously
FR9	The modules shall be deactivatable and reprogrammable for reuse
	Data Management Requirements
FR10	The system shall maintain a complete tracking history for each parcel
FR11	The system shall provide real-time status updates via standardized interfaces
FR12	The system shall support data export in industry-standard formats

Table 3.1: Functional Requirements Overview

that allows unambiguous parcel identification throughout the logistics chain. This identification must then persist during the entire delivery process, from initial attachment to final delivery.

Furthermore, the system must implement a keep-alive mechanism where tracking modules periodically broadcast their status. This approach ensures users have continuous visibility even when parcels transition between different handling systems or remain stationary in storage. The interval between transmissions must be configured to be balanced between tracking information and battery life constraints.

Communication between tracking modules and base stations needs to support bidirectional data exchange, enabling the remote activation and deactivation of modules. This is essential for implementing automated state management, allowing modules to transition between operational states based on various triggers, such as proximity to base stations or predefined boundaries. Such functionality ensures that modules can be dynamically controlled without manual intervention throughout the logistics chain.

Continuing with onboarding and lifecycle requirements, the onboarding process represents a critical phase where tracking modules are initialized, programmed with unique identifiers, and associated with specific parcels. This process must be both efficient and reliable to avoid bottlenecks in high-volume logistics operations.

The complete onboarding workflow, from module initialization to parcel attachment, should not exceed 10 seconds per item to maintain efficiency in the entire process. Furthermore, the system must support the full lifecycle of tracking modules, including deactivation at delivery and potential reprogramming for reuse in other shipments.

The system must maintain comprehensive tracking histories for each parcel, recording all state transitions and location updates throughout the delivery process. This data needs to be accessible in real-time to support operational decision-making and customer information systems.

Lastly, integration with existing logistics infrastructure requires the use of standardized data formats and well-defined interfaces. The system must provide mechanisms for both real-time tracking updates and export of historical data for analysis and reporting purposes.

3.1.2 Non-Functional Requirements

ID	Description
NFR1	The tracking modules shall operate an extended period of time on single power source
NFR2	The communication shall be guaranteed in the range of operating environments
NFR3	Each base station shall support multiple concurrent modules
NFR4	Total tracking module cost shall not exceed 5 EUR per unit

Table 3.2: Non-Functional Requirements Overview

Besides functional requirements, the non-functional requirements define the quality attributes and operational constraints that describe the system's design and implementation. These requirements ensure that the system provides the necessary functionality and also meets practical deployment needs.

Firstly, battery life represents a critical performance parameter for tracking modules. Each module must be able to operate continuously for an extended period on a single power source, supporting typical logistics timelines without requiring frequent maintenance. This requirement directly influences design decisions regarding transmission frequency, power management, and component selection.

Communication reliability depends on achieving adequate range in challenging environments. The system must maintain reliable communication in typical logistics scenarios, taking into account obstacles such as stacked parcels, metal shelving, and concrete structures, as well as considering a high volume of tracking modules in one location.

Scalability requirements indicate that each base station must be able to handle a high number of concurrent tracking modules without performance loss. This ensures that the system can manage high-density scenarios such as loaded delivery vehicles or busy sorting facilities.

Cost constraints are another fundamental design aspect to consider, because the total cost for each tracking module, including all components and assembly, must not exceed

5 EUR. This limit ensures that tracking remains economically viable even for low-value shipments where modules may not be recovered. The thesis limits the constraint to the tracking module itself and does not take into account the cost of the base station, as it is not as impactful as the tracking module.

The physical design of tracking modules must accommodate the constraints of typical parcel handling operations. Modules should not exceed a practically manageable size to avoid interfering with parcel processing. The attachment mechanism must be secure and robust enough to withstand automated sorting systems while also being removable without damaging the parcels.

3.2 Delivery Vehicle Scenario

The primary operational scenario for our RF-based tracking system focuses on a mobile base station deployed within a delivery vehicle. This approach represents the most practical way for validating the system's core functionality while minimizing initial infrastructure requirements.

The system operates within a single delivery vehicle equipped with a base station controller, representing a typical last-mile delivery scenario where 250 to 300 [**amazon2024delivery**] parcels are loaded into a delivery truck for distribution within a defined geographic area. This configuration eliminates the need for external infrastructure while providing comprehensive tracking within the vehicle boundary.

The delivery vehicle environment presents unique RF propagation challenges that must be addressed in the system design. The metal enclosure of typical delivery vans creates a partial Faraday cage effect, attenuating external signals while containing internal transmissions. Parcels are densely packed with minimal spacing, creating multiple signal paths and potential interference. The arrangement of parcels changes continuously as deliveries progress, requiring the system to adapt to dynamic RF conditions.

3.2.1 Operational Workflow

The operational workflow consists of four distinct phases that encompass the complete delivery cycle from morning loading through end-of-day reconciliation.

The loading phase occurs at the distribution center establishing the initial inventory of tracked parcels. During this phase, the driver loads pre-tagged parcels into the vehicle, where each parcel carries an active tracking module transmitting at a set interval. The vehicle base station initializes upon power-up and begins scanning for RF beacons within its coverage area. The base then station detects and registers all loaded parcels, creating a local inventory that records each module's unique identifier, timestamp, and operational status.

The transit and delivery phase spans the entire journey as the vehicle traverses its assigned delivery route. Throughout this phase, the base station maintains continuous monitoring of all tracking modules while the driver executes individual deliveries.

At each delivery stop, the vehicle arrives at the designated address while the base station continues monitoring all modules within range. When the driver removes parcels for delivery, the system detects changes in signal strength or complete signal loss for the removed items. The remaining parcels continue their periodic transmissions, allowing the base station to maintain an accurate inventory of items still present in the vehicle. Parcels removed from the vehicle are automatically marked as delivered based on signal loss detection, eliminating the need for manual confirmation.

During transit between delivery locations, all modules maintain their transmission cycle. At the same time, the base station logs data including timestamps, module identifiers, and transition events. This continuous monitoring creates a comprehensive log of the delivery process without necessarily requiring external connectivity or driver interaction.

Finally, delivery confirmation occurs automatically when a parcel is removed from the vehicle for delivery. The tracking module continues transmitting outside the vehicle, but the base station loses signal reception due to distance and vehicle body attenuation. After waiting for a prolonged interval without beacon activity, the system marks the parcel as delivered with the corresponding timestamp.

The local database updates after this, recording the delivery status and timestamp while decrementing the count of remaining parcels. Edge cases receive special handling through timeout mechanisms. Brief signal losses, such as when the driver remains near the vehicle, are resolved by waiting for the complete timeout period before confirming delivery. Multiple parcels delivered to the exact location are tracked independently, each with its own signal loss detection.

3.3 System Architecture

The proposed tracking system shows a three-layer architecture that separates concerns between data collection, processing, and management functions. This approach ensures modularity, scalability, and a good separation of responsibilities across different system components. Using this architecture as the basis for implementation options provides a good framework to compare each implementation.

3.3.1 Architectural Overview

Figure 3.1 illustrates the system's three-layer architecture, comprising the Parcel Layer, Gateway Layer, and Backend Layer where each layer serves a distinct function but still being able to communicate between each other.

The **Parcel Layer** consists of individual tracking modules attached to parcels throughout the logistics chain. These modules operate as separate units, periodically broadcasting

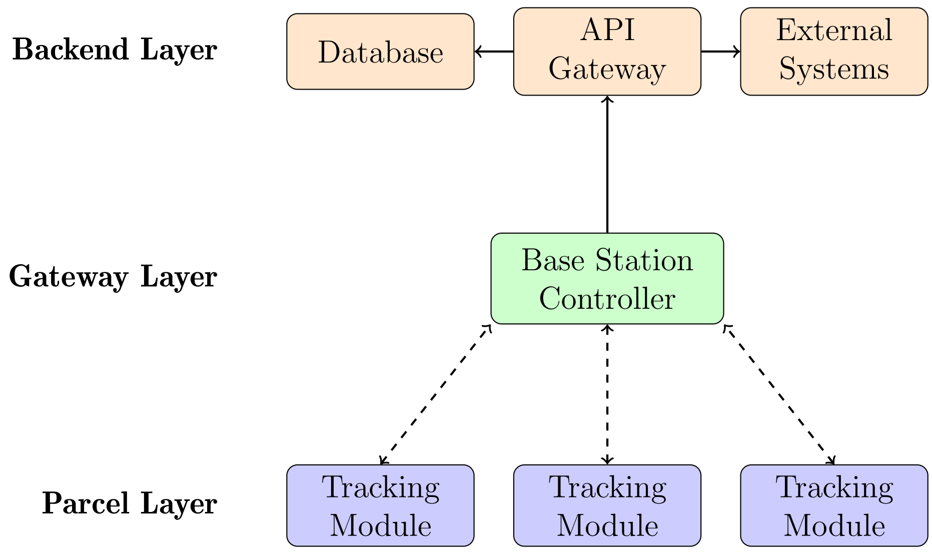

Figure 3.1: System Architecture Overview

identification and status information in the form of wireless RF communication. Using this distributed approach enables flexible scaling as the number of parcels increases.

The **Gateway Layer** serves as the intermediary between the resource-constrained tracking modules and the backend infrastructure. Base station controllers in this layer aggregate RF transmissions from multiple tracking modules within their coverage area. These controllers act as hubs to handle the complexities of RF communication, including signal processing, collision management, and protocol handling. By centralizing these functions, the architecture allows tracking modules to remain cost-effective and straightforward.

The **Backend Layer** provides persistent storage, business logic, and integration capabilities. While not the primary focus of this thesis, this layer is included for architectural completeness and consists of standard components such as databases for tracking data storage and API gateways for system integration. However, the design and implementation of backend components follow standard patterns in software engineering and are, in parts, considered outside the scope of this work. This thesis focuses on the design of a low-cost tracking module and the RF communication challenges at the Parcel and Gateway layers.

3.3.2 Communication Protocol

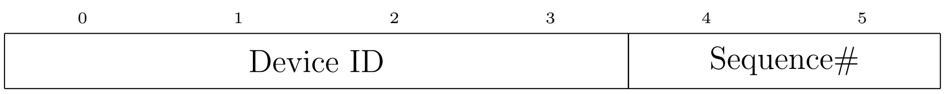

Figure 3.2: 6-byte beacon packet structure

To enable communication between each layer in our proposed architecture, we need to define a standard protocol for how tracking modules, base stations, and the backend system interact. This communication protocol employs a beacon-based approach, where the tracking modules in the parcel layer periodically broadcast their status, and the base stations listen and respond accordingly by sending commands with further instructions.

3.3.3 Technology Selection

The selected RF technologies for this thesis are directly reflected by the insights gained from the analysis of the Related Work Section, which shows that most existing solutions that were reviewed do not manage to balance all three factors: low cost, energy efficiency, and reliable operations in logistics environments. While the comparative review of existing publications reveals that some solutions exhibit very good performance in certain individual dimensions, they still compromise in others.

To address this gap, this thesis implements three complementary RF technologies: 433 MHz transceivers, 2.4Ghz nRF24L01+ modules, and Bluetooth Low Energy HM-10 modules. Each of these technologies was selected based on specific factors that aligned well with the potential solutions requirements.

The 433Mhz transceivers provide a simple and very low-cost implementation. Because these modules operate with sub-GHz frequency bands, they offer superior penetration through obstacles, which is a favorable feature in logistics and delivery environments. Furthermore, besides the low-cost that comes with the simplicity of these modules, the minimal protocol overhead also provides a good baseline for reduced power consumption. These aspects make it a valid candidate for evaluating its tracking capabilities.

With the nRF24L01+ modules operating at 2.4GHz, they introduce more sophisticated features such as automatic acknowledgment and improved addressing capabilities, while still keeping protocol overhead manageable. This choice allows for evaluation of more enhanced protocol features and whether justify their additional complexity and cost in a logistics tracking context.

The HM-10 BLE modules utilize the Bluetooth Low Energy protocol, which incorporates more robust error detection and correction mechanisms compared to the 433Mhz and nRF24L01+ modules. BLE's protocol uses features like CRC error checking, automatic retransmission, which are not found in basic 433MHz implementations.

This selection of technologies with a common architectural design enables direct comparison for the cost-performance trade-offs between them and extends existing literature by systematically evaluating multiple different RF protocols in the same set of operational constraints and cost limitations.

3.3.4 Communication Flow

Communication within the architecture follows a bottom-up data flow pattern. Tracking modules initiate communication by transmitting RF signals containing their unique identifiers and status information. These transmissions occur at regular intervals or in response to specific events.

Then, base station controllers continuously monitor for RF transmissions within their coverage area. Upon receiving a signal, the controller validates the data, performs any necessary protocol translation, and forwards the information to the backend layer using network protocols. In this way, the base station can operate independently from the back-end.

3.3.5 End-to-end Workflow

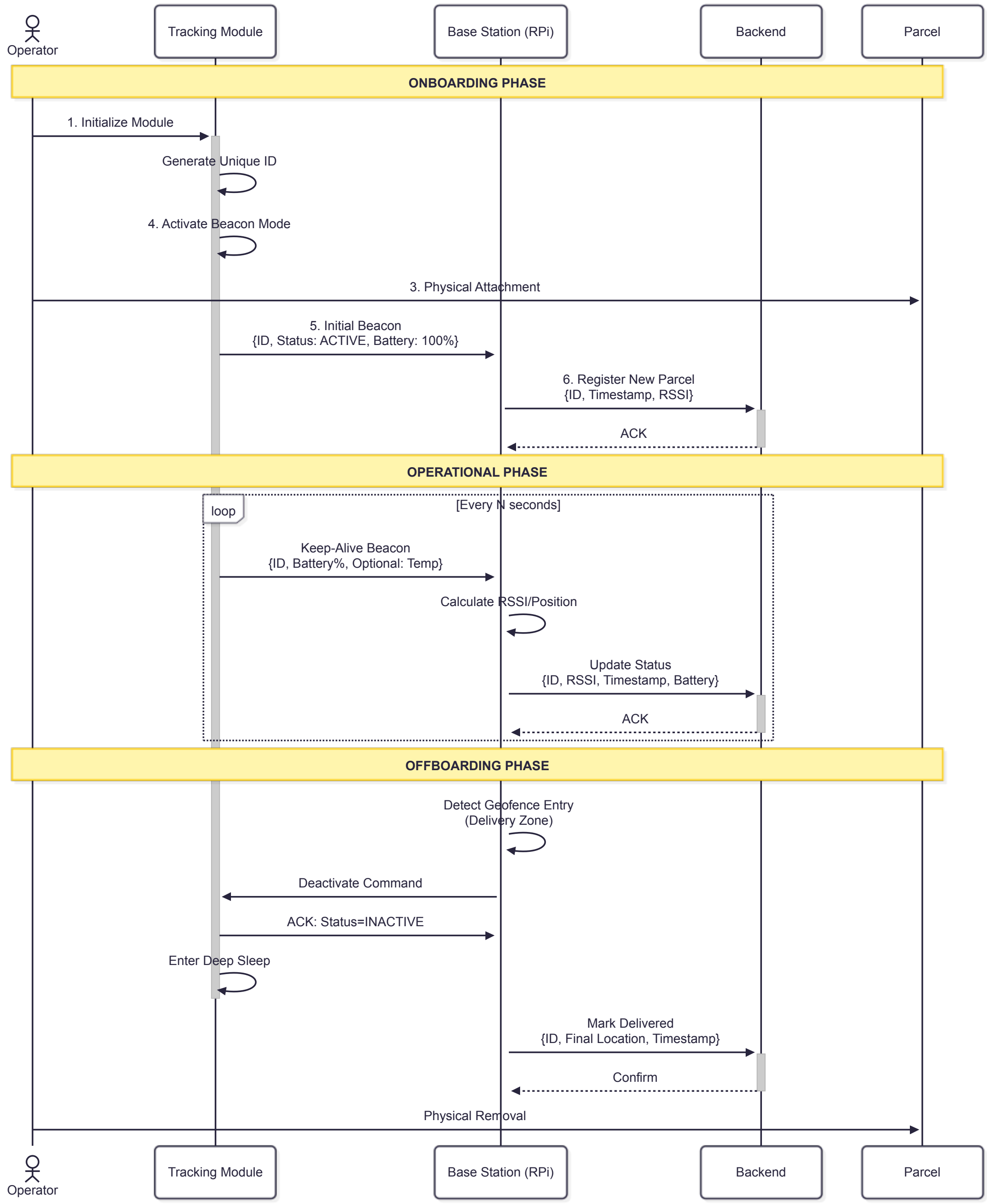

Figure 3.3: Sequence overview showing main phases in the tracking process

The complete tracking workflow, illustrated in Figure 3.3, demonstrates the overall approach that remains consistent across all RF protocol implementations. Using this universal sequence of steps enables systematic evaluation, independent of the hardware configurations. The process presented here covers the entire workflow. In this thesis, however, we focus primarily on validating the operational tracking phase described here, as this represents the core technical challenge when implementing and evaluating the feasibility of the proposed tracking system. While the other phases, such as onboarding, offboarding, and data management, are illustrated here in our architectural design for completeness, they are abstracted or simplified in the implementation and evaluation phases.

The onboarding phase defines the initial association between a tracking module and a specific parcel. In a productive deployment of the system, an operator can initialize the module, which generates a unique identifier and stores it in non-volatile memory. Configuration parameters, including beacon interval and transmission power, can be set according to specific operational requirements. With this simplification, the evaluation can later focus on the core operational tracking performance.

After activation, the module transmits its initial beacon, which contains the unique identifier and status flag. The base station receives this transmission, calculates the received signal strength indicator for proximity estimation, and registers the new parcel with the back-end system.

During transit, the tracking module operates in a low-power beacon mode, transmitting periodic keep-alive signals at configurable intervals. The base station continuously monitors for these beacons, processing received signals to determine approximate location through RSSI analysis. This information is forwarded to the backend for real-time tracking updates. The duty cycle optimization, characterized by brief transmission periods followed by extended sleep intervals, ensures battery longevity.

The off-boarding phase occurs when the device can no longer establish a correct connection to the base station or is marked as completed. The base station would transmit a deactivation command to the module, which acknowledges and enters deep sleep mode. In the prototype evaluation this is simulated by a signal loss when the parcel with the tracking module moves out of range of the base station and no more signals are received. This provides a basic design for the system's geo-fencing capabilities.

The physical removal of the module from the delivered parcel enables potential reuse, supporting the sustainability goals of the system. The module can be reset and reprogrammed for subsequent deployments.

This universal workflow ensures consistent evaluation metrics across all implementations, enabling direct comparison of power consumption, range, and reliability characteristics detailed in the following chapters.

3.4 Evaluation Strategy

Following the implementation of the functioning prototypes, a systematic evaluation is required to validate if the given requirements specified in Section 3.1 are met in order to allow for a systematic comparison across the all hardware configurations. This section outlines the evaluation methodology that will be used to test the prototypes implementation of the design, providing the actual empirical results that are compared in Chapter 5 with a detailed overview.

Firstly, the evaluation of the economic viability is simply based on the total bill of materials (BOM) for each implemented configuration. This will include microcontroller units, RF transceiver modules, power supply components and other passive components. Component pricing will be derived from actual procurement costs at prototype quantities, establishing whether each configuration satisfies the NFR4 constraint of being under EUR 5 per unit cost.

In the next part, analysing power consumption is done in a dual approach combining empirical measurement with theoretical analysis and calculations. Direct current measurement utilizes a digital multimeter in series with the power supply path to measure current in sleep states and average current during RF transmissions for each implemented prototype.

However, recognizing that prototype implementations often show inefficiencies due to development board overhead, voltage regulator losses, and sub-optimal components, theoretical calculations based on datasheet specifications are also performed and included. These calculations use manufacturer-reported power consumption values for the core components like MCU sleep currents and RF module transmission currents to illustrate achievable performance in a more optimized production designs that relies on higher quality components. Both empirical measurements and theoretical projections, combined with the nominal capacity of the battery cells and the configured beacon interval, enable calculation of realistic and also optimal operational values, validating requirements established in NRF1 for extended autonomous operation. By providing both empirical measurements and performing theoretical calculations, it acknowledges the gap between prototype performance and production potential. This provides a conservative estimates based on actual measurements but also an optimistic projection based on component specifications.

The evaluation of system reliability is done through three distinct testing approaches addressing different operational scenarios. By comparing the ratio of packet delivery to packet loss during transmission we can measure the successful reception rate of sequential beacon transmissions at predetermined distances (1m, 5m, 10m, over 10m), that are typical in a given operational scenario. This establishes the relationship between range and reliability for each configuration. Interference testing then addresses scalability requirements by operating four tracking modules concurrently in a simulated environment, characterizing base station's capability to differentiate between simultaneous transmissions as required by NFR3.

Finally, another important aspect of practicability evaluates whether tracking modules can integrate into existing logistics workflows without disruption. The physical specifications of the tracking module are measured against typical parcel sizes. Modules should occupy less than 5% of parcel volume and weigh under 40 grams to avoid impacting shipping categories. By testing attachment capabilities simple mounting methods such as wrapping and adhesive tape are evaluated. Here attachment time, damage-free removal, and retention during normal handling are tested. Consequently also robustness must be validated to ensure modules survive standard logistics operations. By evaluating these aspects we can evaluate that the technical solutions remain practical for real-world deployment.

Chapter 4

Implementation

4.1 Common Implementation Elements

With modularity in mind, all hardware configurations share core implementation elements that ensure consistent behavior and comparable evaluation metrics. These elements implement the core requirements defined in the previous chapter while also considering hardware-specific requirements.

As specified in the design requirements (FR1 and FR2), each tracking module transmits a 6-byte packet at a configurable interval, which acts as a beacon. Using this structure ensures that transmissions always have a fixed length and, therefore, have predictable transmission timing across the various protocols used while also encoding the chosen tracking information.

```c
typedef struct {
    uint32_t device_id;      // unique identifier (4 bytes)
    uint16_t sequence_num;   // packet counter (2 bytes)
} BeaconPacket;
```

Listing 1: Beacon structure definition

The beacon structure uses a fixed 6-byte format where the first 4 bytes contain the device ID, allowing for a sufficient number of unique identifiers. Positioning the ID at the beginning enables the base station to quickly filter packets without needing to process the entire payload. The 2-byte sequence counter increments with each transmission, allowing for reliable tracking of packet loss by detecting missing values in the sequence.

All implementations use a form of deep sleep between transmissions to minimize power consumption as much as possible, as shown in Listing 2.

```
void beacon_loop() {
    while(1) {
        // active period
        prepare_beacon_packet();
        transmit_beacon();

        // sleep period
        enter_deep_sleep(BEACON_INTERVAL_MS);
    }
}
```

Listing 2: Beacon transmission loop

The `BEACON_INTERVAL_MS` parameter defines the sleep duration between transmissions. For testing purposes and to maximize battery life, a minimum of 5 minutes was used as the interval.

4.2 Base Station Implementation

For the base-station, a Raspberry Pi 5 (RP5) is used as a receiver platform that can interface with all receiver modules based on the current configuration that is being tested. Using a modular approach also enables a more direct comparison between the different hardware configurations.
The RP5 was selected as the receiver platform for multiple technical reasons. The GPIO interface provided by the RP5 enables easy connectivity to all three RF receiver modules, simplifying quick reconfiguration between subsequent test scenarios. Furthermore, the RP5 is more than capable of processing concurrent transmissions from multiple tracking modules, ensuring that the base station performance will not become a bottleneck during evaluation. Finally, the Python ecosystem commonly used on Raspberry Pi platforms offers a wide range of libraries for serial communication, SPI interfacing, and Bluetooth connectivity. This further reduces implementation complexity for each specific receiver module. Each hardware configuration requires its own receiver script that can handle the protocol-specific reception of incoming packets and then transform this into data that is logged for further evaluation. The following subsections highlight important implementation details for each receiver configuration.

4.2.1 433MHz Receiver

The implementation of the HC-12 module uses UART for serial communication. Because of this, a key implementation challenge was how to detect packet loss, without having built-in acknowledgment or error correction functionality.

```python
# packet loss tracked through sequence number gaps
if device_id in self.packet_count:
    expected = (self.packet_count[device_id] + 1) % 65536
    if sequence != expected:
        lost = (sequence - expected) % 65536
        print(f"Device {device_id:08X}: Lost {lost} packets")

self.packet_count[device_id] = sequence
```

Listing 3: HC-12 packet loss detection using sequence numbers

The code snippet in 3 shows that the receiver stores the last received sequence number for each device and compares incoming packets against the next expected value. When gaps are detected, the modulo arithmetic calculates the number of missing packets, considering the 16-bit sequence counter wraps back to zero after reaching the sequence number of 65535. This logic can compensate the receiver modules lack of other reliability features.

4.2.2 2.4 GHz nRF24L01+ Receiver

The basic implementation of the nRF24L01+ receiver follows a similar structure in general, however whats interesting in this case, is that instead of using UART, this module uses SPI for the interface. To configure the correct communication parameters here, the correct register adresses need to be set for the correct configuration.

```python

...

# SPI configuration
write_register(0x01, 0x00)  # Enable auto-ack
write_register(0x04, 0x5F)  # retry delay, 15 attempts
write_register(0x11, 6)     # 6-byte payload size

# Poll status register for reception
if read_register(0x07) & 0x40:  # Check RX_DR flag (data ready)
    lgpio.gpio_write(h, CSN, 0)            # Pull chip select low
    payload = spi.xfer2([0x61] + [0xFF]*6)  # Read command + 6 bytes
    lgpio.gpio_write(h, CSN, 1)            # Pull chip select high

    # Unpack beacon structure
    device_id = struct.unpack('<I', bytes(payload[1:5]))[0]
    sequence = struct.unpack('<H', bytes(payload[5:7]))[0]

....

```

Listing 4: nRF24L01+ SPI-based configuration and reception

The code snippet in Listing 4 demonstrates the SPI-based approach, where configuration is achieved by writing to the register that enables specific hardware features, such as auto-acknowledgment or retransmission behavior. The lower-level programming is a contrast to the other UART-based programming interfaces.

4.2.3 Bluetooth Low Energy Receiver

Another interesting implementation is that for communicating with BLE modules, the RP5 does not need to have a BLE module, such as the HM-10, connected. Since RP5 features built-in Bluetooth functionality, an external module is not required. Using this approach still allows other BLE modules to connect to the base station.

```
...

# Scanning for advertising beacons
scanner = Scanner()
devices = scanner.scan(scan_duration=5.0)

for dev in devices:
    for (adtype, desc, value) in dev.getScanData():
        if desc == "Complete Local Name" and value.startswith("TRACK"):
            device_id = int(value[5:], 16)    # Extract ID from name
            rssi = dev.rssi                   # RSSI in dBm
            log_packet(device_id, rssi, time.time())

...
```

Listing 5: BLE scanning and advertisement packet processing

Compared to the other approaches shown, BLE does not rely on continuous listening but periodically scans for advertisement packets, as illustrated in Listing 5. Device IDs and also RSSI values can then be extracted from the advertisement data to be logged for further evaluation.

4.3 Hardware Configurations

The tracking modules themselves are the other key component in the implementation of the tracking system. The three selected MCUs are each paired with the respective RF module. The overview in Figure 4.1 shows the complete pin mapping for all different combinations.

ESP8266 D1 Mini			
Pin	**HC-12**	**nRF24**	**HM-10**
D1 (TX)	RX	-	RX
D2 (RX)	TX	CE	TX
D3	SET	-	-
D5	-	SCK	-
D6	-	MISO	-
D7	-	MOSI	-
D8	-	CSN	-
D0	RST (sleep)		

ATtiny85 (Digispark)			
Pin	**HC-12**	**nRF24**	**HM-10**
PB0 (P5)	RX	MOSI	RX
PB1 (P6)	TX	MISO	TX
PB2 (P7)	SET	SCK	-
PB3 (P2)	-	CE	-
PB4 (P3)	-	CSN	-
VCC/GND shared			

ESP32-C3		
Pin	**HC-12**	**nRF24L01+**
GPIO0	RX	-
GPIO1	TX	CE
GPIO2	SET	-
GPIO4	-	SCK
GPIO5	-	MISO
GPIO6	-	MOSI
GPIO7	-	CSN

Table 4.1: Pin mapping configurations for all MCU-module combinations

The hardware configurations across all three microcontroller platforms have consistent patterns for connecting the UART-based and SPI-based modules. However, the specific pin connections differ in practice, as also illustrated in the overview shown in Figure 4.1.

Both the HC-12 (433MHz) and the HM-10 (BLE) module use similar UART connections, as can be seen in Table 4.1, while the nRF24L01+ module uses SPI with the five control signals, just as on the receiver side.

What makes the implementation of some of the transmitting modules challenging, however, is that, unlike the base station side, not all transmitter modules have a sufficient number of pins available for connection. While this implementation is still simple for the ESP8266 and ESP32-C3 due to many available GPIO pins, it becomes challenging when setting up the ATTiny85 MCU with the nRF24L01+ configuration. Here, the MCU reaches its limits in connectivity.

4.3.1 Physical Implementation

Figure 4.3 serves as an example of the MCU platform implementations with the tracking module configurations that will be used later for evaluation.

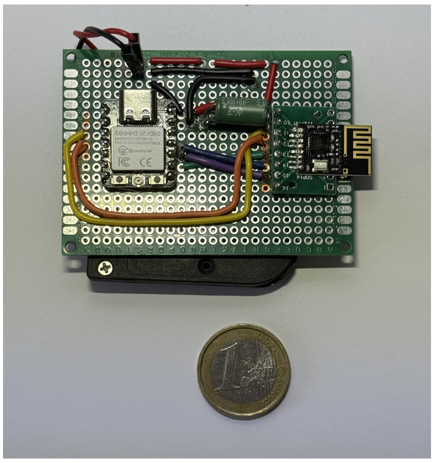

Figure 4.1: ESP32-C3 & nRF24L01+

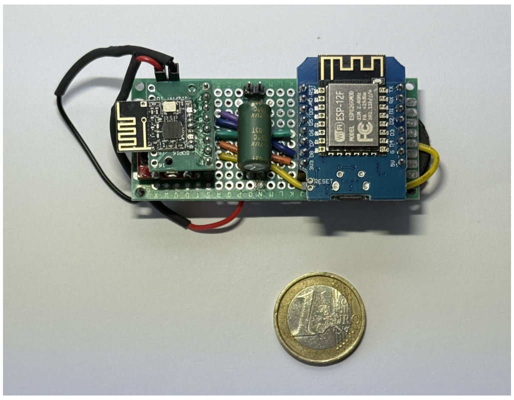

Figure 4.2: ESP8266 & nRF24L01+

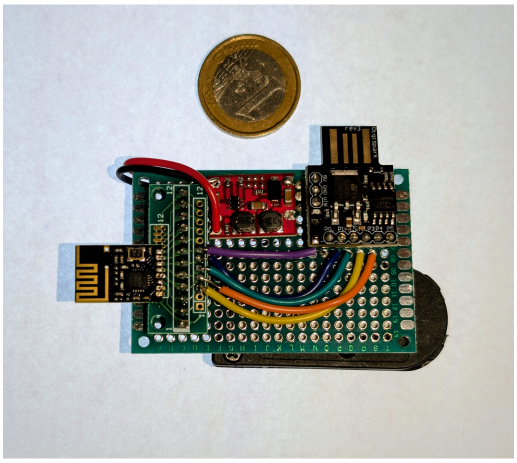

Figure 4.3: ATTiny85 & nRF24L01+

4.4 Transmitter Power Management

After handling hardware connectivity, implementing power management to extend the tracker's operational lifetime (NFR1) was also a key implementation challenge, as each MCU platform implements sleep differently, which has a direct impact on battery life.

The ESP8266 utilizes hardware deep sleep with automatic reset via the D0-to-RST connection, enabling very low theoretical power consumption during sleep periods.

```
// ESP8266: Hardware deep sleep with auto-reset
void loop() {
    transmit_beacon(&beacon);
    ESP.deepSleep(BEACON_INTERVAL_MS * 1000);
}
```

Listing 6: ESP8266 power management implementation

The ATtiny85 takes a different approach by reducing clock speed from 8MHz to 4MHz and using the watchdog timer to periodically wake from power-down sleep mode.

```
// ATTiny85: Clock reduction and watchdog-based sleep
void setup() {
    CLKPR = (1<<CLKPCE);
    CLKPR = (1<<CLKPS1);
}

void enter_sleep() {
    set_sleep_mode(SLEEP_MODE_PWR_DOWN);
    WDTCR = (1<<WDE) | (1<<WDIE) | (1<<WDP3) | (1<<WDP0);
    sleep_cpu();
}
```

Listing 7: ATtiny85 power management implementation

The ESP32-C3 also supports deep sleep but requires reinitialization of the BLE stack after each wake cycle, adding slight overhead compared to the ESP8266 approach.

```
// ESP32-C3: Deep sleep with BLE reinitialization
void loop() {
    ble_init();  // Reinitialize BLE stack after wake
    pAdvertising->start();
    delay(100);
    pAdvertising->stop();

    esp_deep_sleep(BEACON_INTERVAL_MS * 1000);
}
```

Listing 8: ESP32-C3 power management implementation

4.5 Transmission Logic Implementation

Although the common beacon structure defined in Listing 1 remains the basis for all implementations, each platform does require some protocol-specific transmission code.

```
...
// HC-12 (433MHz): UART transmission
void transmit_beacon() {
    Serial.write((uint8_t*)&beacon, sizeof(BeaconPacket));
}

...

// nRF24L01+: SPI-based transmission
void transmit_beacon() {
    const byte address[5] = {0xE7, 0xE7, 0xE7, 0xE7, 0xE7};
    radio.openWritingPipe(address);
    radio.write(&beacon, sizeof(BeaconPacket));
}

...

// ESP32-C3 BLE: Encoding in advertisement name
void transmit_beacon() {
    char name[20];
    snprintf(name, 20, "TRACK%08X", beacon.device_id);
    BLEDevice::setDeviceName(name);
    pAdvertising->start();
    delay(100);  // Advertisement window
    pAdvertising->stop();
}
...
```

Listing 9: Protocol-specific beacon transmission logic

Listing 9 illustrates the variation in transmission logic across the different platforms. The HC-12 implementations utilize simple UART serial transmission, writing the beacon structure directly to the serial port. In comparison, the nRF24L01+ module needs to be configured a 5-byte address and relies on the external RF24 library to write data [37]. BLE implementations use another approach, where the transmitter encodes the ID directly in the advertisement name, which simplifies parsing on the receiver side while maintaining compatibility with standard BLE scanning functionality.

Chapter 5

Evaluation

This chapter presents a systematic evaluation of the proposed RF-based parcel tracking system across multiple hardware configurations. The evaluation methodology focuses on practical deployment metrics relevant to the delivery vehicle scenario, assessing not only technical performance but also operational feasibility for logistics applications.
The evaluation framework assesses each hardware configuration against three primary dimensions: technical performance, economic viability, and operational practicality, corresponding to those established in previous chapters, and addresses the fundamental trade-offs identified in the analysis of existing solutions.

5.1 Test Environment

The evaluation took place under standard indoor conditions without specialized equipment or specifically controlled parameters. Environmental factors, such as temperature and humidity, were not controlled for. This approach, although not providing the rigor of controlled laboratory testing, still provides practical data that is representative of actual deployment conditions, because real-world tracking systems must also operate alongside other wireless devices and handle typical RF interference.

For the hardware setup, the Raspberry Pi 5, acting as the base station, handled connections and communication from the tracking modules. The tracking modules were tested at distances ranging from 1 to 5 meters or further for connectivity tests. Power consumption was measured using a typical commercially available digital multimeter connected in series with the power supply.

Because the testing environment has not been controlled for external RF interferences, it included typical interference sources, such as WiFi networks at varying distances and signal strengths, as well as other active Bluetooth devices.

Furthermore, the current measurements captured only the prototype power consumption, which also included overhead from development board configurations, voltage regulators, LED indicators, and other supporting circuitry. These empirical values were then compared with theoretical calculations based on the provided component datasheets to better estimate achievable performance in a more productive setting, utilizing optimized hardware and circuitry.

Finally, the scope of testing was limited to core tracking functionality. This means that more complex onboarding procedures were simplified to automatic ID assignment by the base station, while backend integration and data management with external logistics systems were also abstracted. This allowed for setting a focus on the fundamental requirements of cost, communication reliability, and power consumption characteristics for comparing the proposed tracking systems.

5.2 Hardware Configurations Under Test

The evaluation encompasses distinct configurations that combine RF technologies with three microcontroller platforms. This matrix approach enables a systematic comparison across different architectural choices, identifying optimal combinations for the target application.

5.3 Economic Analysis

This section now evaluates the bill of materials for each prototype and hardware configuration against the 5 EUR per unit cost constraint established in NRF5. The prices listed reflect component costs as they were at time of purchase on AliExpress at single-unit quantities.

5.3.1 433 Mhz Module Configurations

The first configuration uses the 433 Mhz transceiver modules. This implementation represents the simplest configuration without complex protocol overhead using basic ASK modulation.

Component	**ATtiny85**	**ESP8266**	**ESP32-C3**
Microcontroller Module	1.84	2.02	4.42
433MHz HC-12 Module	1.93	1.93	1.93
Voltage Regulator (3.3V)	0.31	0.31	0.31
Battery Holder	0.20	0.20	0.20
CR2032 Battery	0.14	0.14	0.14
Total Cost	**4.42**	**4.60**	**7.00**

Table 5.1: Bill of Materials - 433MHz Configurations (all prices in EUR)

The 433MHz configurations show clear cost differences across the microcontroller platforms. Both the ATtiny85 (4.42 EUR) and ESP8266 (4.60 EUR) configurations meet the 5 EUR budget constraint, with the ATtiny85 offering the most economical implementation. The ESP32-C3 variant at 7.00 EUR exceeds the budget by 40%, primarily due to the higher cost microcontroller with the module itself costing 4.42 EUR alone.

5.3.2 NRF24L01+ 2.4Ghz Module Configurations

Component	**ATtiny85**	**ESP8266**	**ESP32-C3**
Microcontroller Module	1.84	2.02	4.42
nRF24L01+ Module	0.64	0.64	0.64
Voltage Regulator (3.3V)	0.31	0.31	0.31
Battery Holder	0.20	0.20	0.20
CR2032 Battery	0.14	0.14	0.14
Total Cost	**3.13**	**3.31**	**5.71**

Table 5.2: Bill of Materials - nRF24L01+ Configurations (all prices in EUR)

The nRF24L01+ configurations achieve the best cost performance across all RF technologies tested. The ATtiny85 variant at 3.13 EUR represents the lowest-cost implementation, 37% below the 5 EUR budget. The ESP8266 configuration at 3.31 EUR provides additional processing capability while maintaining excellent cost efficiency. Even the ESP32-C3 variant at 5.71 EUR, though exceeding the budget by 14%, may justify its premium through better deep-sleep performance and more robust SPI handling. The significantly lower cost of the nRF24L01+ module (0.64 EUR) compared to other RF technologies enables all configurations to achieve competitive pricing.

5.3.3 HM-10 BLE Module Configurations

The HM-10 Bluetooth Low Energy modules represent the most feature-rich RF option, incorporating full BLE protocol stack with built-in error correction and standardized communication protocols.

Component	**ATtiny85**	**ESP8266**	**ESP32-C3**
Microcontroller Module	1.84	2.02	4.42
HM-10 BLE Module	2.45	2.45	-
Voltage Regulator (3.3V)	0.31	0.31	0.31
Battery Holder	0.20	0.20	0.20
CR2032 Battery	0.14	0.14	0.14
Total Cost	**4.94**	**5.12**	**5.07**

Table 5.3: Bill of Materials - HM-10 BLE Configurations (all prices in EUR)

5.3.4 Base Station Infrastructure

The base station infrastructure comprises a Raspberry Pi 5 (8GB model) serving as the centralized receiver for all tracking module configurations. This platform provides the necessary computational resources and connectivity interfaces for all three RF technologies: GPIO pins for 433MHz HC-12 modules, SPI interface for nRF24L01+ modules, and built-in Bluetooth capability for BLE configurations. The common hardware platform ensures consistent processing capabilities across all tests which allows for direct performance comparison between RF technologies.

While the base station represents a high cost expenditure of approximately 80 EUR, this cost is excluded from the per-module budget analysis as it represents more of a fixed infrastructure investment rather than a variable unit cost. In deployment scenarios with hundreds of tracked parcels per vehicle, the amortized base station cost becomes negligible relative to individual module costs.

5.4 Technical Performance

This section presents empirical measurements of power consumption and communication reliability for each hardware configuration. Measurements were conducted using the test environment described in Section 3.1, with results compared against theoretical calculations to identify implementation inefficiencies.

5.4.1 Power Consumption Analysis

Power consumption measurements were taken in two operational states: powered on with active transmission and sleep mode. The table in 5.4 presents the measured values.

Configuration	**Avg. Current**	**Sleep Current**
433 MHz Configurations		
ATtiny85 + HC-12	42.1	8.1
ESP8266 + HC-12	73.4	12.14
ESP32-C3 + HC-12	110.9	11.32
nRF24L01+ Configurations		
ATtiny85 + nRF24L01+	20.18	6.45
ESP8266 + nRF24L01+	70.2	9.62
ESP32-C3 + nRF24L01+	90.15	8.41
BLE Configurations		
ATtiny85 + HM-10	73.17	9.9
ESP8266 + HM-10	127.2	1.1

Table 5.4: Power consumption (in mA) for configurations with 300 s beacon interval

What can be seen clearly in table 5.4 is that the reliability of power consumption values from datasheets are not always guaranteed, as most development boards introduce many

inefficiencies. Additionally, the quality of the hardware acquired from online marketplaces from overseas regions, is most often not easily assessable which leads to poor real-world measurements.
Because of this it useful to provide a better perspective using theoretical calculations based on datasheet values alongside empirical measurements. To calculate these values, we use the standard duty cycle formula that gives us the average current consumption over an interval:

$$I_{avg} = \frac{I_{active} \times t_{active} + I_{sleep} \times t_{sleep}}{t_{total}} \tag{5.1}$$

where I_{active} and I_{sleep} are the current consumption during active cycle and sleep mode, and t_{active} and t_{sleep} are the respective times spent in each mode, while t_{total} represents the entire interval.

The results in table 5.5 present the theoretical calculations based on manufacturer datasheet specifications for each hardware configuration.

Configuration	**Avg. Current**
433 MHz Configurations	
ATtiny85 + HC-12	24.83
ESP8266 + HC-12	27.29
ESP32-C3 + HC-12	27.94
nRF24L01+ Configurations	
ATtiny85 + nRF24L01+	1.48
ESP8266 + nRF24L01+	3.93
ESP32-C3 + nRF24L01+	4.58
BLE Configurations	
ATtiny85 + HM-10	0.90
ESP8266 + HM-10	3.36

Table 5.5: Theoretical average power consumption (in mA) based on datasheet values

The comparison between measured and theoretical values shows substantial differences, with measured consumption often being much higher than the theoretical predictions. This difference highlights how development board inefficiencies, including voltage regulators, LEDs, and other circuitry, affect real-world performance. Based on the theoretical calculations, however, it can still be argued that a solution using more optimized or higher quality hardware is still feasible for an actual deployment in a logistics environment.

5.4.2 Reliability Analysis

Communication reliability was evaluated by testing multiple devices simultaneously to verify whether data could be transmitted consistently between the tracker and the base station. For each configuration, three devices were deployed simultaneously to simulate a logistics scenario with multiple tracking devices in proximity to one another. Here, all configurations successfully established a connection to the base station and transmitted their beacon data to it. The amount of tested devices for each configuration manage to operate in parallel without significant interference.

To evaluate the practicality of the tracking system beyond controlled measurements, physical deployment characteristics of the tracking modules were tested across different hardware configurations. To have a better systematic comparison, the following classification is used to align with the categorization framework established in Section 2.2.2:

1. **High Practicability**: Lightweight modules (<15g) with simple attachment mechanisms that integrate seamlessly into existing packaging workflows without modifications
2. **Medium Practicability**: Moderate weight (15-25g) modules requiring standard attachment methods but potentially impacting stacking or automated handling in high-volume operations
3. **Low Practicability**: Heavy modules (>25g) or those requiring specialized mounting hardware, package modifications, or significantly affecting shipping logistics

All tested configurations achieved compact form factors suitable for attachment to parcels. The total weight, including battery, varied by configuration:

Configuration	**Weight (g)**
ATtiny85 + nRF24L01+	14.3
ATtiny85 + HM-10	15.1
ATtiny85 + HC-12	13.5
ESP8266 + nRF24L01+	24.8
ESP8266 + HM-10	26.6
ESP8266 + HC-12	23.9
ESP32-C3 + nRF24L01+	13.4
ESP32-C3 + HC-12	13.8
ESP32-C3 alone	12.1

Table 5.6: Weight comparison of tracking module configurations

The weight range of 12.1g to 26.6g makes the addition of the tracker negligible for most shipping cost calculations. Three configurations achieve high practicability (ATtiny85-based and ESP32-C3 variants under 15g), while all ESP8266 configurations fall into the medium category due to their bigger form factor. By eliminating development board overhead and switching to custom circuit boards, these weights could be further reduced, making the attachment process easier as well.

The attachment of tracking modules was accomplished using double-sided adhesive tape, requiring no specialized hardware or package modifications. The attachment process was straightforward and rapid. However, integration into existing workflows at packaging and handling centers was not evaluated and requires further investigation for actual deployment scenarios.

The prototypes, built using standard development boards, exhibit heights ranging from 1cm to 2cm. This dimension could impact real-world deployment by affecting package stacking efficiency or interfering with automated handling equipment in high-throughput facilities. For this, custom PCB implementations would significantly reduce both vertical profile and overall dimensions, improving practicability across all configurations.

5.5 Operational Test Scenarios

To evaluate typical logistics workflows, the hardware configurations were tested in different simulated scenarios to assess their viability in the real world. All tests were conducted using a typical shipping cardboard box (23cm x 30cm x 14cm).

5.5.1 Single Parcel Tracking

First, each configuration was tested individually by attaching the tracking module to a shipping box. In this test, after turning on the tracking modules and simulating the beacon attempting to connect to a basestation, all configurations successfully connected within 13 seconds and continued transmitting beacon data at the configured interval.

5.5.2 Multiple Parcel

To simulate warehouse and delivery vehicle conditions, three modules of each configuration were attached to separate parcels and put together in close proximity, with the parcels side by side and stacked. Key observations were that while the nRF24L01+ and BLE-based implementations showed no signs of interference, the 433 MHz implementations exhibited minor problems with interference, as evidenced by corrupted data received or missed transmissions. Overall, however, all solutions maintained communication throughout the test duration and continued transmitting their beacon data to the base station. This result indicates that multiple tracking modules are viable; however, limitations can already be observed at a low number of trackers with certain implementations, such as those based on 433 MHz RF technologies. Further tests, with higher numbers of tracking modules would be required to increase the accuracy of this evaluation.

5.5.3 Range and Disconnection Behavior

Testing the tracking behavior at different and increasing ranges to the base stations revealed variations between the various configurations.

The 433 MHz HC-12 configuration achieved the most extended range, spanning 15-20m, and maintained communication even through walls and obstacles. This behavior was expected because as as previously established the lower frequencies allow for better propagation through solid materials.

The BLE HM-10 modules provided a consistent range of 10-12m, while the 2.4GHz nRF24L01+ had the shortest distance, ranging from 5m to 8m before losing connection across tests.

All modules automatically reconnect when returning to range without manual intervention, which is preferable for logistics operations when parcels are moved to different warehouses, for example.

The disconnection behavior differed between technologies, with the 433 MHz technology exhibiting gradual signal degradation that increased with distance, while the nRF24L01+ showed a more abrupt disconnection. The BLE tracking modules provided the most graceful state transitions, with clear connection and disconnection events, which are a result of the BLE protocol implementation.

5.6 Overall Comparison of Hardware Configurations

Overall, the evaluation results indicate that the patterns identified in the Related Work analysis in Chapter 2 can be validated, as no single technology evaluated in this thesis can achieve optimal performance across all required dimensions. However, while most analysed literature often required custom or costly hardware, this thesis shows that acceptable tracking capabilities can potentially be achieved using off-the-shelf components when considering cost.

The visualizations in Figures 5.1 and 5.2, based on the classification established in Chapter 2.2.2, illustrate how each configuration has its trade-offs based on the RF technology used. Each metric is scored on a 1-5 scale, where the higher scores indicate better performance in that metric.

We can see that no individual configuration presents an optimal solution, but each has its strengths and weaknesses.

The nRF24L01+ configurations demonstrate exceptional cost efficiency, with the ATtiny85 variant achieving the lowest implementation cost at just 3.13 EUR, which is within our 5 EUR budget and comparable to the "Low" cost classification typically observed with passive RFID tags in the analysed literature. With the low cost and theoretical power consumption below 2mA, these configurations show potential when keeping costs as low as possible, a key requirement. However, this cost optimization comes at the price of communication range, with operation limited to 5-8 meters as of testing. This constraint is no problem in a delivery vehicle scenario, which was the focus here, but can be a limitation in larger warehouse environments that require multiple basestations closer to each other, which would then drive up costs.

The 433MHz implementations prioritize range over all other metrics, achieving 15-20m, which is comparable to more expensive LoRaWAN solutions surveyed in Chapter 2. This increased distance through obstacles solves the limitation identified in RFID and backscatter approaches, which require line-of-sight or near-field proximity.

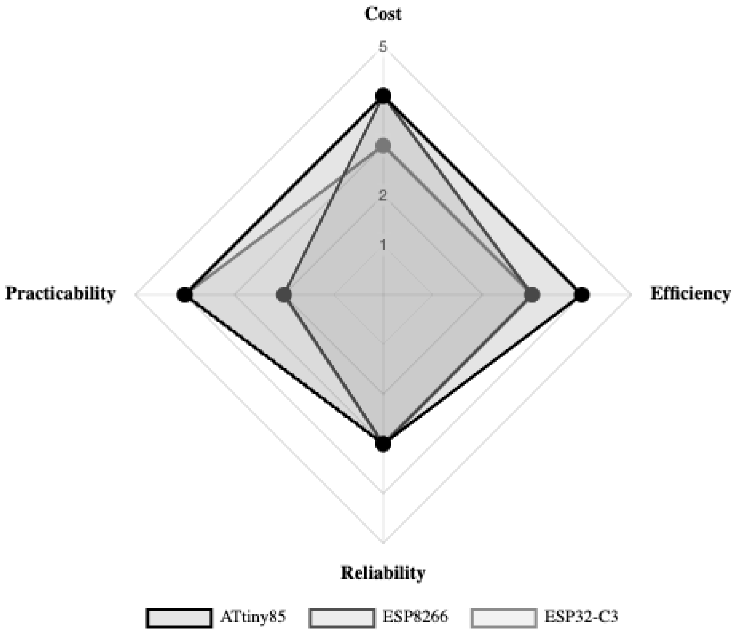

Figure 5.1: MCU comparison across RF technologies

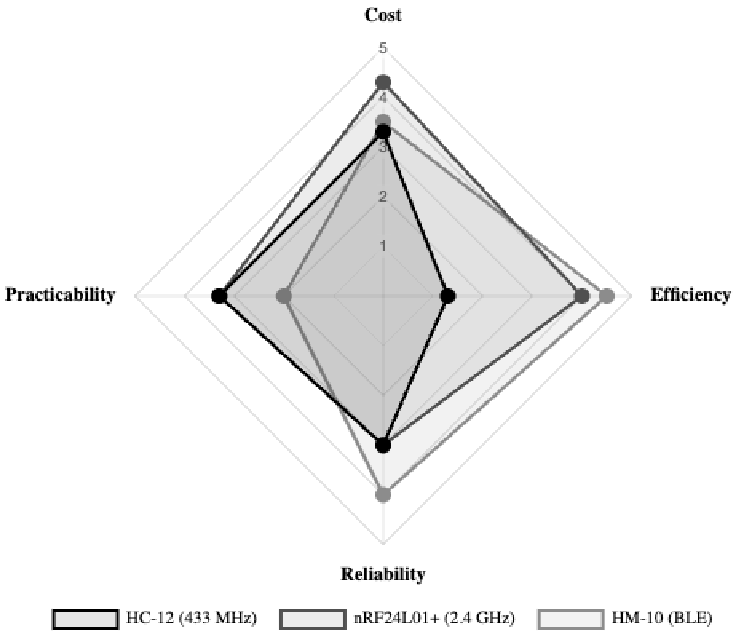

Figure 5.2: RF technology comparison averaged across MCU implementations

However, like backscatter approaches, this solution is also affected by interference problems, which is a limitation for a tracking module in large-scale logistics environments. The theoretical power consumption of 24-28mA, while improved from empirical measurements, also is higher than other compared technologies.

The BLE configurations show promising results, likely due to a more sophisticated protocol. The Bluetooth stack showed good connection behavior and also performed well in multi-device as well. The combination that stands out here is the ATtiny85 with the HM-10, which can theoretically achieve low power consumption compared to backscatter approaches while still maintaining reliable transmissions without interference.

5.7 Discussion

Table 5.7 provides a comprehensive overview of how each hardware configuration performs in relation to the set of functional and non-functional requirements established in 2. The matrix reveals that while all configurations successfully meet the core functional requirements (FR1-FR4), demonstrating basic tracking capabilities, significant variations emerge in meeting non-functional requirements. It is worth noting that the evaluation primarily focuses on the core functional requirements (FR1 to FR4) as well as the non-functional requirements.
The remaining functional requirements regarding onboarding, offboarding, and deactivation were abstracted and not directly evaluated, focusing instead on the core technical and economic constraints of the tracker. The higher-level requirements from FR5 to FR12 also strongly depend on existing backend infrastructure and software processes, which makes them complex to evaluate in this limited scope. In the evaluation, onboarding was simplified to automatic ID assignment by the base station, while backend integration into existing logistics systems was not fully implemented.

Configuration	**Functional Requirements**				**Non-Functional Requirements**			
	FR1 ID	**FR2** Beacon	**FR3** Comm.	**FR4** Multi	**NFR1** Battery	**NFR2** Range	**NFR3** Scale	**NFR4** Cost
ATtiny85 + HC-12	✓	✓	✓	✓	×	✓	∼	✓
ATtiny85 + nRF24L01+	✓	✓	✓	✓	×	×	✓	✓
ATtiny85 + HM-10	✓	✓	✓	✓	×	∼	✓	✓
ESP8266 + HC-12	✓	✓	✓	✓	×	✓	∼	✓
ESP8266 + nRF24L01+	✓	✓	✓	✓	×	×	✓	✓
ESP8266 + HM-10	✓	✓	✓	✓	×	∼	✓	×
ESP32-C3 + HC-12	✓	✓	✓	✓	×	✓	∼	×
ESP32-C3 + nRF24L01+	✓	✓	✓	✓	×	×	✓	×
ESP32-C3 (BLE)	✓	✓	✓	✓	×	∼	✓	×

Table 5.7: Compliance Matrix for Requirements of Hardware Configurations

All configurations meet the fundamental tracking functionality requirements specified in Chapter 3, including unique identification (FR1), periodic beacon transmission (FR2), bidirectional communication (FR3), and multi-device support (FR4). This validates the effectiveness of the architectural design across various RF technologies.

However, when examining the non-functional requirements, these reveal critical limitations. Most notably, no configuration fully satisfies the battery life requirement (NFR1) when using CR2032 cells, with theoretical calculations suggesting only 5 to 8 days of operation even under theoretically optimal conditions. This represents the primary barrier to deployment readiness, as increasing battery size would directly affect practicability with larger and bulkier modules. More importantly, larger and longer-lasting batteries also significantly drive up the cost, failing to fulfill the cost requirement.

Range requirements (NFR2) are dependent on the technology used. The 433MHz configurations achieve good results with 15-20m coverage, while nRF24L01+ implementations only achieve 5 to 8m ranges. BLE solutions partially comply at 10 to 12m ranges. Scalability (NFR3) reveals that while nRF24L01+ and BLE handle multiple devices well, 433MHz suffers from interference issues, therefore also only partially fulfilling this requirement.

Cost compliance (NFR4) clearly distinguishes between viable and non-viable configurations. All ATtiny85 variants and ESP8266 configurations (except HM-10) meet the 5 EUR threshold, while ESP32-C3 implementations consistently exceed it, eliminating them from consideration for large-scale deployment.

As a result, the combination of ATtiny85 and nRF24L01+ is the most cost-effective solution despite range limitations, while ATtiny85 + HC-12 offers the best range but with scalability concerns. However, no configuration achieves full compliance across all dimensions, reinforcing the fundamental trade-offs inherent in low-cost tracking system design.

Chapter 6

Final Considerations

6.1 Summary

This thesis investigated the feasibility of developing a low-cost RF-based parcel tracking solution using off-the-shelf components and targeting a cost of at most 5 EUR. Through the design, implementation, and evaluation processes of the different hardware configurations used, the results show that a viable tracking solution is potentially achievable under these cost constraints, although considering limitations in battery performance.

Also, this thesis first analyzed existing tracking technologies, revealing a persistent gap between expensive commercial solutions and the practical requirements of cost-effective logistics tracking. Rather than pursuing custom hardware development or complex protocols, this thesis adopted a pragmatic approach using readily available components. The resulting prototypes successfully demonstrated core tracking functionality, including unique identification, periodic beacon transmission, and multi-device coordination within a mobile base station architecture. The evaluation methodology combined empirical measurements with theoretical calculations, while also acknowledging the substantial gap between prototype performance and production potential. While measured power consumption was often significantly higher than the reported theoretical (e.g., spec sheets) values due to inefficiencies of the development boards, calculations based on datasheet specifications suggest that optimized implementations could achieve an acceptable battery life suited for applications in logistics workflows.

6.2 Conclusions

The results from this thesis confirm that cost-effective RF tracking is achievable with off-the-shelf hardware. Still, they also reveal fundamental trade-offs between the key characteristics of the solution. As seen in the previous Chapter 5, no single evaluated configuration achieved optimal performance across all dimensions, a pattern that was observed in the existing literature in Chapter 2 aswell.

The first key characteristic is that cost viability is achievable but requires careful selection of hardware, with the need to keep other hardware restrictions and trade-offs in mind. Of the nine tested configuration five met our 5 EUR budget constraint. The results also show that the selection of the MCU platform directly restricts the remaining choices for RF modules due to the cost of the MCU itself.

Continuing, the next big deployment barrier is the battery life constraints. While theoretical calculations based on specifications from the manufacturer's datasheet indicate that longer operational periods are possible, empirical measurements reveal that all the off-the-shelf boards selected in this thesis have significantly higher power consumption in reality than indicated on paper. This gap between the theoretical calculations and empirical measurements suggests that more optimized hardware is necessary to achieve the desired extended battery life. Specifically, the use of low-capacity batteries, such as the tested CR2032 batteries, is challenging and may also require larger capacities in general. This would, however, have an impact on cost and practicability characteristics.

Additionally, the choice of RF technology depends on the operational scenario and real-world environment. The tested hardware configurations exhibited different operational ranges, and in the case of the 433 MHz solutions, also encountered interference issues, suggesting that further investigation into a suitable RF technology is necessary to determine the best solution for the given operational scenario. The simplified onboarding, off-boarding, and data management implementation in this thesis also represents incomplete solutions for real-world production environments and can be used for further investigation and development.
Returning to the central question posed by this thesis: *Are We There Yet?*, the answer is: almost. This thesis has shown that a low-cost RF-based parcel tracking system is technically feasible with several configurations meeting the 5 EUR budget while still providing functional tracking capabilities. Battery life remains the primary barrier to a production deployment as the current power consumption of the prototypes does not reach the desired time span of multiple weeks.

However, when considering these results within the broader context of tracking solutions in general, we can see that being "almost there" with commercially available off-the-shelf hardware is still far from the vision of research in smart printables and labels. The future of parcel tracking solutions is pointed in the direction of using thin, printable devices combining sensing, communication, and display logic into a paper-thin form factor, as can be seen in industry goals and academic research. But these solutions are still in the future, as the required technologies like printed batteries still need to be more reliable and are currently also too expensive for the scale required in logistics [9, 10]. Consequently, in the near term, the best approach is to continue researching both smart printable technologies and simultaneously optimize traditional RF-based tracking solutions, such as those tested in this thesis. The findings presented here can provide logistics providers with a baseline against which future printed solutions can be compared, while also serving as a stepping stone for the evolution of printable smart labels.

6.3 Future Work

Based on the findings in this thesis, we can see that further development and research into this topic can bring promising results. By moving away from off-the-shelf development boards and designing custom integrated circuits, an implementation could achieve better battery performance and power consumption. These implementations could potentially yield results closer to the theoretical calculations presented in this thesis. Furthermore, research into alternative battery options or energy harvesting methods could prove a viable option for increasing battery life as well.

Additionally, given a longer time to evaluate all the solutions in real-world logistics scenarios over extended periods, this could provide valuable empirical data that can serve as a basis for further research. This could involve more rigorous power consumption measurement, as well as testing the reliability of implemented solutions on a production scale with hundreds or thousands of parcels equipped with tracking modules.

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Abbreviations

RF	Radio Frequency
RFID	Radio Frequency Idenditfication
LF	Low Frequency
HF	High Frequency
UHF	Ultra High Frequency
TDM	Time Division Multiplexing
SPI	Serial Peripheral Interface
MHz	Mega Hertz
GHz	Giga Hertz
EM	Electromagnetic
UART	Universal Asynchronous Receiver Transmitter
BT	Bluetooth
LAN	Local Area Network
LoRaWAN	Long Range Wide Area Network
WLAN	Wireless Local Area Network
RP5	Raspberry Pi 5
BOM	Bill of Materials
FR	Functional Requirement
NRF	Non Functional Requirement
RSSI	Received Signal Strength Indication

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Appendix A

Contents of the GitHub Repository

The complete source code, documentation, and evaluation data for this thesis are available in a public GitHub repository at:

`https://github.com/davidcoita/rf-based-parcel-tracker`

A.1 Repository Structure

The repository is organized into three main directories, based on the elements implemented:

- **transmitter/** — tracking module implementations for hardware configurations
- **basestation/** — Raspberry Pi receiver scripts
- **evaluation/** — analysis scripts