

Industrial Indoor Positioning: Large-Scale BLE and UWB Deployment Analysis

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Abstract—Indoor positioning system (IPS) remains a challenge due to multipath interference, environmental variability, and high deployment costs. While Bluetooth Low Energy (BLE) and Ultra-Wideband (UWB) solutions are widely studied, most prior works focus on small-scale applications without evidence of industrial-scale feasibility. This paper presents the UNAI Platform, a BLE and UWB tracking system evaluated in 13 real-world deployments across various domains, including warehousing, manufacturing, healthcare, and services domains. Results show BLE enables low-cost, zone-level tracking with long battery life. At the same time, UWB provides sub-meter accuracy for dynamic applications, such as forklift and Automated Guided Vehicle (AGV) monitoring. A key finding is that indirect tracking strategies, using vehicle-mounted UWB tags, reduce infrastructure costs while maintaining operational visibility. Return On Investment (ROI) analysis indicates that most deployments achieved payback within 1–2 years, confirming both technical and economic viability. This study contributes one of the most extensive empirical IPS evaluations to date and provides a practical framework that bridges academic research and industrial adoption. This practical framework will guide and support researchers and industry professionals in their IPS research and decision-making.

Keywords—indoor real-time location tracking, real-world application, RTLS platform

I. INTRODUCTION

Indoor Positioning Systems (IPS) have become increasingly crucial for real-time asset tracking, workflow automation, and intelligent decision-making in smart factories, warehouses, healthcare facilities, and entertainment domains. Unlike GPS, which performs reliably outdoors, IPS solutions must overcome multipath interference, signal attenuation, environmental variability, and high infrastructure costs. Consequently, several wireless localization technologies have been investigated, including Wi-Fi, Bluetooth Low Energy (BLE), Ultra-Wideband (UWB), RFID, acoustic localization, and visible light communication. Each technology offers unique trade-offs in terms of accuracy, scalability, energy efficiency, and deployment feasibility.

A. Related Work and Literature Review

In the past couple of decades, a massive amount of research has been conducted on IPS as a critical application. Alam et al. [1] and Al-Qadami & Kim [2] provide comprehensive reviews of localization methods, including Received Signal Strength Indicator (RSSI), fingerprinting,

Time of Flight (ToF), and Time difference of Arrival (TDoA), highlighting their potential while also addressing the persistent challenges of accuracy, environmental robustness, and cost. Al-Kashoash et al. [4] and Deng et al. [6] focus on UWB-based IPS, demonstrating sub-meter accuracy in controlled conditions, but with limited reports of long-term industrial-scale deployments. Zare [7] discusses IPS in innovative industry applications, while Briffa [3] compares technologies but remains theoretical.

Gerlich et al. [8] argue for in-production benchmarking to bridge the gap between lab research and operational environments, but few empirical reports exist. Moreover, most literature focuses on technical accuracy while neglecting economic metrics such as return on investment (ROI), scalability, and user adoption, which are critical for real-world adoption.

B. Gap in the Literature

Despite extensive algorithmic and technical studies, two gaps remain:

1. **Limited Real-World Deployment Studies** – Most works validate IPS in terms of proof of concept or simulations, but rarely in multi-industry, real production environments.
2. **Lack of Economic Evaluation** – Few studies report ROI or deployment cost-benefit analyses, which are essential for industrial decision-makers.

C. Contribution of This Work

This paper addresses these gaps by presenting the UNAI Platform, a hybrid BLE- and UWB-based IPS, which has been evaluated across 13 industrial and service deployments in Thailand. Our contributions are:

1. **Large-Scale Empirical Study:** One of the most extensive multi-sector IPS evaluations, covering deployment areas from 700 m² to 40,000 m² across warehousing, manufacturing, healthcare, and service domains.
2. **Hybrid Technology Strategy:** A systematic framework for selecting BLE for cost-effective zone-level tracking and UWB for sub-meter precision tracking in dynamic environments.
3. **Economic and ROI Analysis:** Unlike prior studies, we provide ROI evaluations, showing payback

periods of 1–2 years in most cases, validating both technical and economic feasibility.

4. **Bridging Research and Industry:** The UNAI platform demonstrates how IPS can move from laboratory prototypes to industrial-scale, economically sustainable deployments.

The remainder of this paper is structured as follows: Section II reviews localization technologies and deployment challenges; Section III presents the UNAI platform architecture; Section IV describes industrial and service use cases; Section V reports empirical performance and ROI evaluation; and Section VI concludes with contributions, lessons learned, and directions for future research.

II. BACKGROUND ON INDOOR LOCALIZATION TECHNOLOGIES AND CHALLENGES

IPS relies on a range of signal processing techniques and wireless communication technologies to localize objects in environments where GPS is ineffective. This section provides an overview of core localization methods and the standard technologies applied in real-world indoor settings. It also outlines persistent challenges that impact deployment and system performance.

A. Localization Techniques

Several techniques are used to estimate the position of objects indoors, each with specific trade-offs in accuracy, complexity, and infrastructure requirements:

- **RSSI:** Estimates distance based on signal power attenuation. While simple and widely supported, RSSI is susceptible to noise, multipath effects, and environmental variability.
- **Fingerprinting:** Builds a database of RSSI measurements at known locations during an offline phase. During localization, real-time measurements are matched to the database. It offers good accuracy but requires significant calibration and is sensitive to environmental changes.
- **ToF / Time of Arrival (ToA):** Calculates distance by measuring signal travel time. Requires precise clock synchronization and is commonly used in UWB systems for high accuracy.
- **TDoA:** Determines location from the difference in arrival times of a signal at multiple receivers. It reduces the synchronization requirements compared to ToF.
- **Angle of Arrival (AoA):** Uses antenna arrays to estimate the direction of incoming signals. It can achieve good accuracy in line-of-sight conditions but requires specialized hardware.
- **Channel State Information (CSI):** Captures fine-grained signal characteristics across frequencies and antennas. CSI offers better multipath resilience and higher accuracy than RSSI, but it is more complex to process.

B. Wireless Technologies for Indoor Localization

IPS implementations typically utilize one or more of the following wireless technologies:

- **BLE:** Widely used for proximity detection with low power consumption and low cost. BLE is suitable for

zone-based tracking using RSSI. This technology is standard in commercial applications, such as iBeacon and asset monitoring.

- **UWB:** Offers high accuracy (10–30 cm) using ToF or TDoA techniques. UWB performs well even in multipath-rich environments due to its large bandwidth and short pulses. It is preferred for applications requiring continuous, precise object tracking.
- **Wi-Fi:** Leverages existing infrastructure and supports RSSI, CSI, or fingerprinting-based positioning. Accuracy is moderate.
- **RFID:** Enables object detection through short-range interactions with passive or active tags. Used primarily for checkpoint-based asset management, rather than continuous tracking.
- **Visible Light Communication (VLC):** Uses LED light sources for localization via AoA or signal modulation. It requires a line of sight and is limited by the lighting infrastructure.
- **Acoustic Localization:** Uses sound or ultrasound to measure distances. While accurate in quiet environments, it is limited by ambient noise and typically has a short operational range.

C. Key Challenges in Indoor Localization

Despite advances in algorithms and hardware, indoor localization systems face several persistent challenges:

- **Multipath and Signal Interference:** Reflections and obstructions introduce localization errors, particularly in environments with metal structures, machinery, or human movement.
- **Environmental Dynamics:** Changes in layout or object placement can degrade system performance, especially for fingerprinting-based approaches.
- **Energy Consumption:** Battery life is a critical consideration for mobile tags. BLE is often preferred in use cases with long operational cycles, while UWB offers higher accuracy at a higher energy cost.
- **Cost and Scalability:** Infrastructure costs, such as anchor and server installation, can limit scalability. Systems that reuse existing infrastructure (e.g., BLE over Wi-Fi) offer cost advantages.
- **Privacy and Security:** Location data is sensitive, and protecting user or asset movement data is essential. On-premises deployments can address some privacy concerns compared to cloud-based systems.
- **Lack of Standardization:** Interoperability between IPS technologies remains limited, hindering widespread adoption across heterogeneous systems.

III. UNAI PLATFORM ARCHITECTURE AND TECHNOLOGIES

The UNAI Platform is designed to deliver scalable indoor positioning solutions in industrial environments, supporting multiple wireless technologies to address different localization requirements. This section describes the system architecture, including BLE- and UWB-based deployments, as well as their integration with warehouse management systems (WMS) and Internet of Things (IoT) components.

A. BLE-Based Localization: UNAi-BLE

UNAi-BLE is deployed in scenarios that require cost-effective proximity detection with long battery life and minimal infrastructure, as shown in Fig. 1.

- **Technology:** Operates in the 2.4 GHz ISM band using standard BLE advertisements. The BLE chip that we used is NRF52832.
- **Anchors/Receivers:** BLE anchors are installed indoors and serve as checkpoints. Each anchor covers an area of approximately 20–25 m². They are powered by 5V DC and connected to the server via Wi-Fi.
- **Tags:** Small, battery-powered devices attached to assets or personnel. Configurable transmission intervals support battery life of 1–2 years, depending on use.
- **Localization Method:** Utilizes the RSSI of the anchor to set boundaries, similar to a geofence. When the tag is in the area, the anchor receives the broadcast signal from the tag, and it will be considered in the zone. Suitable for checkpoint-style applications and room-level monitoring.
- **Deployment Example:** Tracking vehicle presence in production areas or asset movement through predefined checkpoints in healthcare or manufacturing environments.



Fig. 1 BLE architecture system with an Anchor and tags.

B. UWB-Based Localization: UNAi-UWB

UNAi-UWB is utilized in applications that require high spatial precision and continuous location updates, as illustrated in Fig. 2.

- **Technology:** Operates in the 3.1–10.6 GHz band (centered around 6.5 GHz) using ToF for distance estimation. The UWB chip that we use is DWM1001C.
- **Anchors/Receivers:** UWB anchors are reference points for trilateration. They are typically spaced to cover Line of Sight (LOS) areas and are powered via a 5V DC supply.
- **Tags:** Rechargeable UWB tags are installed on moving objects (e.g., forklifts, AGVs). Transmission intervals can be adjusted from 100 milliseconds to several seconds, with battery life ranging from 10 hours to 2 weeks.
- **Gateways:** Forward location data from UWB anchors to the UNAi server via Wi-Fi or 4G/5G. This device can be opted out of when using Tag Plus.
- **Tag Plus:** An enhanced tag that integrates both location computation and data transmission via Wi-Fi

or 4G/5G, reducing the need for additional gateways. Requires constant power and is ideal for vehicles.

- **Location method:** We use two-way ranging to detect the tag. However, installing a tag on each pallet is very costly; our team uses indirect tracking by tracking the vehicle, such as a forklift or AGV, instead, and incorporates a QR code to make the system more automated.
- **Deployment Example:** Used in environments with fast-moving equipment or complex workflows, such as forklifts in warehouses or AGVs in factories.



Fig. 2 UWB system architecture with a picture of the Anchor and tags

IV. APPLICATIONS AND USE CASES

The UNAi Platform has been deployed in 13 industrial environments across Thailand, supporting real-time location tracking through either BLE or UWB technology, based on the specific requirements of each scenario. This 13-industrial company has been using our system for at least 6 months, and most of them continue to use our system. This section summarizes selected applications across three primary domains: warehousing, manufacturing, and service environments.

A. Warehousing

1) Vertical Rack Warehouses (UWB-Based)

In high-density storage environments, such as vertical rack warehouses, UNAi-UWB is deployed to enable precise forklift tracking. UWB tags (or UWB tag plus devices) are mounted on vehicles, and their location is used to infer the placement of pallets. Height sensors and pallet detection modules help identify storage levels and movement events. This approach minimizes the need to tag individual pallets while maintaining accurate inventory control.

- **Benefits:** Accurate 2-D location with shelf height detection, reduced infrastructure costs via indirect tracking, and improved automation.
- **Use Case Example:** Automotive parts warehouse with multi-level racking, requiring real-time forklift monitoring.

2) Horizontal Floor Warehouses (UWB-Based)

For goods stored on open floors (e.g., large steel coils or heavy machinery), UWB anchors are installed on ceilings or roof structures, while UWB tags are placed on overhead cranes. UNAi-WMS records the crane's last location to log inventory positions.

- **Benefits:** Efficient tracking in large open spaces without line-of-sight constraints to individual pallets.
- **Use Case Example:** A steel manufacturing plant utilizes cranes to move and place coils in a grid layout.

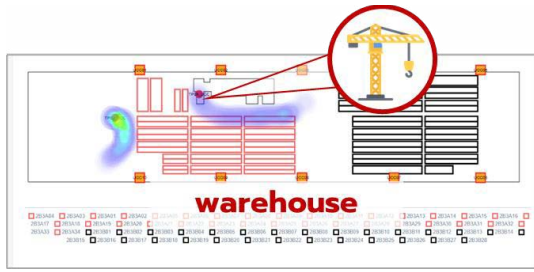


Fig. 3 web-view of the horizontal floor warehouse use case

B. Manufacturing

1) In-Process Goods Tracking (UWB-Based)

UNAi-UWB is used to track parts or work-in-progress (WIP) items as they move along production lines. Tags attached to carriers or carts allow monitoring of station dwell time and material flow between processes.

- Benefits: Enables time-motion analysis, production balancing, and WIP visibility.
- Use Case Example: A large-item assembly line (e.g., automotive parts) where real-time visibility of item status is required.

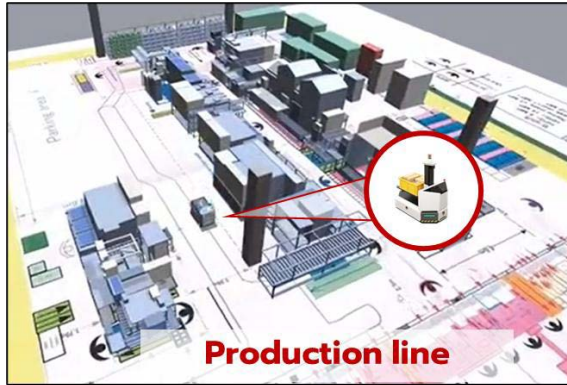


Fig. 4 web-view of the manufacturing use case

2) Material Handling Vehicle Monitoring (BLE or UWB)

Both BLE and UWB technologies are used to monitor the movement of materials in vehicles such as trolleys, forklifts, or AGVs.

- BLE Use Case: When the scenario of the use case is like a checkpoint, BLE provides a cost-effective solution with longer battery life.
- UWB Use Case: For applications requiring continuous 2-D tracking (e.g., safety zones, dynamic routing), UWB is the preferred choice.
- Use Case Example: A factory floor with mixed vehicle types; BLE tags on trolleys for checkpoint detection, or UWB tags on AGVs for continuous navigation.

C. Service and Other Domains

Beyond industrial operations, the UNAi Platform's flexibility supports various service-sector use cases:

- Healthcare: BLE tags attached to medical equipment or patient beds enable hospital staff to locate assets in real time across wards.

- Emergency Management: UWB tags may be used for personnel tracking in safety-critical indoor environments, supporting evacuation or rescue operations.
- Intelligent Environments: Both BLE and UWB can be deployed in museums, shopping centers, or corporate buildings to enable location-aware services, such as proximity-based content delivery or behavioral analytics.



Fig. 5 web-view from the service use case

The 13 cases comprise five from the warehouse category, four from the manufacturing category, and four from the services category.

V. PERFORMANCE EVALUATION AND DISCUSSION

This section evaluates the performance of BLE and UWB deployments within the UNAi Platform based on operational data and deployment feedback from 13 use cases across different industries. Evaluation focuses on key metrics, including accuracy, cost, energy efficiency, scalability, latency, and the system's effectiveness in addressing everyday challenges in indoor localization. We implemented a proof of concept in 13 use cases, covering an implementation area ranging from 700 sq m to 40,000 sq m.

A. Accuracy and Precision

- UNAi-UWB: In industrial deployments with precise anchor placement, UWB achieved sub-meter accuracy, with average errors typically below 0.8 ± 0.5 m. in 2-D tracking scenarios. This level of precision proved sufficient for forklift navigation, AGV tracking, and fine-grained asset positioning.
- UNAi-BLE: BLE-based localization offers zone-level granularity, typically within a range of 5 ± 2.5 m. Proximity detection (e.g., "zone entry/exit") was accurate and stable under standard indoor interference conditions; however, BLE was not utilized for continuous coordinate tracking due to RSSI variability.
- Discussion: UWB is superior for applications requiring real-time, continuous tracking. BLE performs well for simpler proximity-based scenarios or checkpoint systems, particularly when cost and power consumption are key constraints.

B. Cost and Infrastructure Investment

- UWB: Requires investment in specialized anchors, gateways, and rechargeable tags. Costs are higher

per square meter, especially in large-scale coverage. However, indirect tracking via vehicles instead of pallets or products significantly reduced the number of tags needed—only forklifts or cranes require UWB tags, not individual assets.

- BLE: Anchors and tags are low-cost, and BLE can often leverage existing Wi-Fi for connectivity. BLE tags are disposable and suitable for large-scale, low-priority tracking environments.
- Trade-offs: Cost-effectiveness is maximized when the tracking precision is matched to the application's needs. For example, BLE was used for trolley tracking in factories as a checkpoint.

C. Energy Efficiency

- BLE Tags: Achieved battery life up to 1–2 years with configurable transmission intervals. Ideal for long-term deployments where manual recharging is impractical.
- UWB Tags: Rechargeable tags last 10 hours to 2 weeks per charge, depending on update frequency. UWB tag plus devices, intended for use on powered vehicles, require continuous power.
- Summary: BLE is significantly more energy-efficient for low-bandwidth applications. UWB offers high-performance tracking with acceptable power consumption when power sources (e.g., forklifts) are available.

D. Scalability and System Availability

- UNAi-WMS + BLE: Highly scalable due to indirect tracking strategies and use of low-cost tags. Suitable for environments with many moving objects but limited need for high-resolution tracking.
- UNAi-UWB: Scalable with proper anchor planning and infrastructure availability. On-cloud and on-premise deployment options support factories with different IT requirements.
- Discussion: UNAi's flexible architecture supports gradual system expansion, and mixed deployments (BLE in some zones, UWB in others) can be managed centrally, although the technologies are used independently.

E. Latency and Update Frequency

- UWB Tags: Configurable to transmit data as often as every 100 milliseconds, enabling responsive tracking of fast-moving equipment.
- BLE Tags: Typically used with 1–5 second intervals to balance energy efficiency and detection needs.
- Observation: UWB provided near-real-time feedback for operational decisions (e.g., AGV collision avoidance), while BLE was sufficient for periodic presence detection.

F. Addressing Deployment Challenges

UWB and BLE face distinct challenges due to their unique characteristics, as outlined in Table 1.

TABLE 1: DEPLOYMENT CHALLENGES

Challenge	UNAi-BLE	UNAi-UWB
Multipath/NLOS	Performs well for proximity detection	Robust due to short pulses and wide bandwidth
Environmental Variability	Stable under most industrial conditions	Anchor calibration helps maintain performance
Battery Life	Long-lasting, low-maintenance	Rechargeable, continuous power via vehicles
Privacy and Security	On-premise deployment supports data control	Same; factory server options available
Deployment Cost	Low infrastructure investment	Offset by indirect tracking and flexible tagging

Note: App. A = Warehousing, B = Manufacturing, C = Services in Tables 2 and 3. According to Tables 2 and 3, if the solution applies to the correct problem, such as the bottleneck in the production line or the time wasted searching for a product, it is considered a success. This indoor location helps significantly in both time savings and equipment usage. We evaluate the feedback from the 13 use cases. However, some of the use cases did not provide feedback to our team; therefore, we use N/A for the absence of information.

TABLE 2: FEEDBACK AND IMPACT OF 13 USE CASES

Use case	App.	Impact (Quality)	Quantity	Return \$/year
1	C	Received attention from the e-sports community	N/A	N/A
2	A	Reduce product search time	30 mins/day	480
		Reduce forklift energy usage	1 \$/day/unit	1,400
3	A	Reduce product search time	1hr./month	1,110
		Reduce checking stock time	50% /day 2 hr./day	190
		Reduce the misdistribution of material in the production line	2\$/ day/car	2,145
		Reduce packing the wrong SKU	30 mins/day	340
4	c	Reduce asset tracking time	N/A	N/A
		Preventing lost assets	N/A	N/A
5	c	Reduce the time spent finding a wheelchair time	0 (5 times/day or 50 mins/day)	570
		Distribute work quickly	100%	N/A
		Service faster (from 200 users)	Serve customer 80% within 5 mins (previous 60%)	2,300
		Customer satisfaction (208 customers)	99.1% (previous 80%)	N/A
6	B	Reduce forklift rental	1 car	6,550
		Reduce energy	2\$/day/car	2,145

Use case	App.	Impact (Quality)	Quantity	Return \$/year
		Reduce forklift drivers	1 person	5,455
7	A	Real-time tracking of forklift usage	N/A	N/A
8	A	Reduce energy (2 forklifts)	7\$/day/car	4,245
		Reduce searching time	1person	5,455
		traceability	100%	N/A
9	C	Reduce the work process	1 process	685
		Increase the accuracy of stock	25%	N/A
		Reduce searching time	3.40 mins faster	120
		On-time delivery to the customer	N/A	N/A
10	B	Reduce wrong delivery	0%	N/A
		Reduce workload	N/A	N/A
		Reduce waiting time	N/A	N/A
11	B	Real-time locate and time spent in each location	N/A	N/A
		Real-time detection of anomalies.	1 car detected	N/A
12	B	Reduce distribution time	40% /day	220
		Reduce finding employee	8 mins faster	100
		Balance workload	12%	655
		Adjust the workforce according to the workload	1 person	5,455
13	A	Reduce human error	1 hr./day	685
		Reduce crane usage	9\$/day/crane	2,890

We calculated the ROI from

$$ROI (\%) = \frac{Total\ Benefits - Total\ costs}{Total\ costs} \times 100 \quad (1)$$

The total benefits are derived from the return/year from Table 3, and the total costs include the cost of implementing the platform, which encompasses both hardware, software, and installation, ranging from \$3,000 to \$11,000, depending on the installation area. The average annual labor cost is approximately \$180. The average yearly forklift rental cost is roughly \$8,500. However, we cannot evaluate every use case in terms of ROI due to several reasons: the company did not provide feedback information, or it has a service-based nature, which makes it challenging to evaluate. Those who can determine ROI typically show that the results yield a return in 1-2 years, which is acceptable in most real-world situations.

TABLE 3: ROI OF 8 USE CASES

Use case	App.	cost	Area Sq.m.	Benefit	Payback period	
1	C	5,500	1,800	N/A	N/A	N/A
2	A	8,500	720	1,880	-80%	5 yr.
3	A	7,700	1,600	3,785	-54%	2yr 2 mo.
4	C	3,000	1,600	N/A	N/A	N/A

Use case	App.	cost	Area Sq.m.	Benefit	Payback period	
5	C	6,000	8,000	2,870	-56%	2 yrs 3 mo.
6	B	4,800	5,200	14,150	179%	4 mo.
7	A	5,000	6,300	N/A	N/A	N/A
8	A	11,000	40,000	9,700	-16%	1yr. 2 mo.
9	C	4,700	1,080	805	-84%	6 yr. 2 mo.
10	B	4,300	2,100	N/A	N/A	N/A
11	B	5,400	2,000	N/A	N/A	N/A
12	B	8,600	9,600	6,430	-7%	1 yr 1mo.
13	A	4,900	5,000	3,575	-31%	1 yr. 5 mo.

VI. CONCLUSION AND FUTURE DIRECTIONS

This paper evaluated the UNAI Platform across 13 real-world deployments in warehousing, manufacturing, healthcare, and service domains. Unlike prior studies that focus on laboratory accuracy, our work demonstrates both the technical performance and economic feasibility of hybrid BLE-UWB indoor positioning in industrial settings.

Results confirm that BLE offers low-cost, zone-level tracking with long battery life, while UWB delivers sub-meter accuracy for dynamic applications such as forklift and AGV monitoring. A key contribution is the use of indirect tracking (vehicle-mounted tags), which reduces infrastructure cost while maintaining visibility. ROI analysis showed that most deployments achieved payback within 1–2 years, confirming practical viability.

Future work will focus on BLE-UWB fusion algorithms, predictive analytics for workflow optimization, seamless indoor-outdoor continuity, and enhanced privacy and interoperability standards.

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