Homework - Internet Of Things

Professor: Redondi Alessandro - Academic Year: 2024/2025

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Proposed Solution

Implementing an effective tracking system across both outdoor and indoor areas poses challenges in terms of connectivity, localization accuracy, scalability, and cost. We decided to propose a hybrid solution that uses different communication technologies optimized for each environment. Our choices are based on a few assumptions: we have approximately 100 forklifts; we have GPS and cellular (NB-IoT and LTE/5G) coverage outdoors, but not indoor.
For our final decision we decided to prioritize frequency update over cost, but we analyzed various possible solutions.

Outdoor Solution: NB-IoT + GPS

For the outdoor portion of the system, we have chosen to go with GPS for tracking, providing very accurate results, and NB-IoT for communication, for a trade-off between cost and update frequency.
Pros:

- Extensive coverage: Operates over existing cellular infrastructure, covering large areas without requiring additional hardware.
- Good scalability: Supports thousands of simultaneous connections, making it ideal for tracking a fleet of 100+ forklifts.
- Update frequency: Can handle updates every few seconds, making it suitable for near real-time tracking.
- Low energy consumption: Although most power consumption will come from forklift operation, minimizing communication energy usage remains beneficial.

Cons:

- Initial costs: Cost of the module to install on the forklift is pricier compared to other solutions (like LoRa).
- Recurring costs: Given the licenced spectrum, we will need to pay an operator on a subscription/pay-per-use basis

Why not WiFi, LoRa, or LTE/5G outdoors?

Tech	Range	Update Rate	Cost & Complexity	Scalability	Notes
WiFi	~100 m	Very high (<1s)	Very high	Medium	Too expensive

LoRa	2-15 km	Low (10–60s)	Low	Low	Too slow for real-time tracking; High collision with many nodes
LTE/5G	1–10 km	Very high (<1s)	High	High	High cost and energy usage
NB-IoT	1–10 km	Medium-high (every few sec)	Moderate	High	Best trade-off

Indoor Solution: WiFi + BLE

Given that we are underground GPS signals and cellular connectivity are unavailable. To address this, our solution uses Bluetooth Low Energy (BLE) beacons distributed throughout the indoor area for localization (mixed with the data of the movements to improve accuracy) and WiFi for communication.
Pros:

- Low Infrastructure Cost: BLE beacons are inexpensive and WiFi is often already available.
- Leverages Existing Hardware: ESP32 handles both BLE scanning and WiFi communication.
- Human Connectivity: WiFi can also support human operator devices.

Cons:

- Beacon Deployment: Must install and maintain BLE beacons throughout indoor zones.
- RSSI-Based Localization: BLE signal strength can be affected by walls, metal, or interference so it can be noisy (we try to solve this with other sensor data).

Why not Zigbee, 6LoWPAN, RFID or only BLE?

Zigbee and 6LowPAN were not suitable for our usage since their network is not designed to support moving vehicles.
RFID could be used for tracking but only at gateways (for example we could read when a forklift entered a certain zone).
We thought about using only BLE, but we decided not to in favor of other use cases, like human operators having internet connection, or other devices.

Implementation

To realize the proposed hybrid tracking system, the implementation is divided into three main parts: the onboard system installed on each forklift, the infrastructure deployed both indoors and outdoors, and the backend system responsible for collecting, processing, and visualizing data.

Forklift

Each forklift is equipped with an embedded system based on the ESP32 microcontroller (around 10€), which serves as the main processing and communication unit. The ESP32 natively supports both WiFi and BLE but in addition it needs:

- GPS module for outdoor localization (in the range of 5 €)
- NB-IoT communication module to transmit data over the cellular network when outdoors (a bit pricey but around 10–15 €)

- Onboard IMU sensors (accelerometer and gyroscope) to detect movement, impacts and speed (5€ maximum)

The system operates as follows:

- Indoors, the ESP32 scans for nearby BLE beacons, estimates position using RSSI values, and sends data via WiFi.
- Outdoors, GPS data is collected and transmitted through the NB-IoT module.

Data sent includes timestamp, position, movement metrics, and status indicators. Messages are published over MQTT, enabling a lightweight and scalable communication layer.
Based on a rough estimate, this setup will cost around 35€ per forklift.

Pseudocode

```
// SYSTEM SETUP
initializeSensors() // GPS, IMU (accelerometer + gyro)
connectToWiFi() // Attempt WiFi connection (indoor)
initializeNBIoTModule() // Initialize NB-IoT (outdoor)
connectToMQTTBroker() // MQTT configuration

initializeState() // speed = 0, lastAccel = [0,0,0]

// LOOP EVERY 10 SECONDS
loop:
    timestamp = getCurrentTime()

    // Detect if outdoor or indoor
    if gpsFixAvailable():
        mode = "outdoor"
        gpsData = readGPS()
        lat = gpsData.latitude
        lon = gpsData.longitude
    else:
        mode = "indoor"
        beaconData = scanBLEBeacons() // List of (ID, RSSI)
        lat, lon = estimatePositionFromBLE(beaconData)

    // Read IMU data
    acc_x, acc_y, acc_z = readAccelerometer()
    speed = calculateSpeed(acc_x, acc_y, acc_z)

    // Detect impact (e.g., sudden acceleration spike)
    impact = detectImpact(acc_x, acc_y, acc_z)

    // Create payload
    payload = {
        "timestamp": timestamp,
        "lat": lat,
        "lon": lon,
        "speed": speed,
        "acc_x": acc_x,
        "acc_y": acc_y,
        "acc_z": acc_z,
        "impact": impact
    }

    // Send data via MQTT over correct interface
    if mode == "indoor" and isWiFiConnected():
        mqttPublish("forklifts/X", payload)
    else if mode == "outdoor" and isNBIoTConnected():
        mqttPublish("forklifts/X", payload)

    delay(10)
```

Infrastructure

To support both indoor and outdoor tracking, the following infrastructure components are deployed:

- NB-IoT network: Connectivity is provided by a mobile operator so no custom hardware is needed aside from NB-IoT SIM cards, which incur a recurring cost per device (around 0.5–1 €/month per forklift).
- BLE beacons: Simple battery-powered beacons are installed throughout the facility to act as location anchors. Beacons are low-cost (around 5–10 € each), and their density is planned to ensure consistent coverage (at least 3–4 beacons in range at any point).
- WiFi Access Points: Existing WiFi infrastructure is used when possible. If needed, additional access points can be installed to ensure seamless coverage for both forklifts and human operators (around 50-100 € each).

Initial costs will be around 700€ for beacons and APs and recurring costs will be in the 50€/month range for the IoT subscription.

Backend

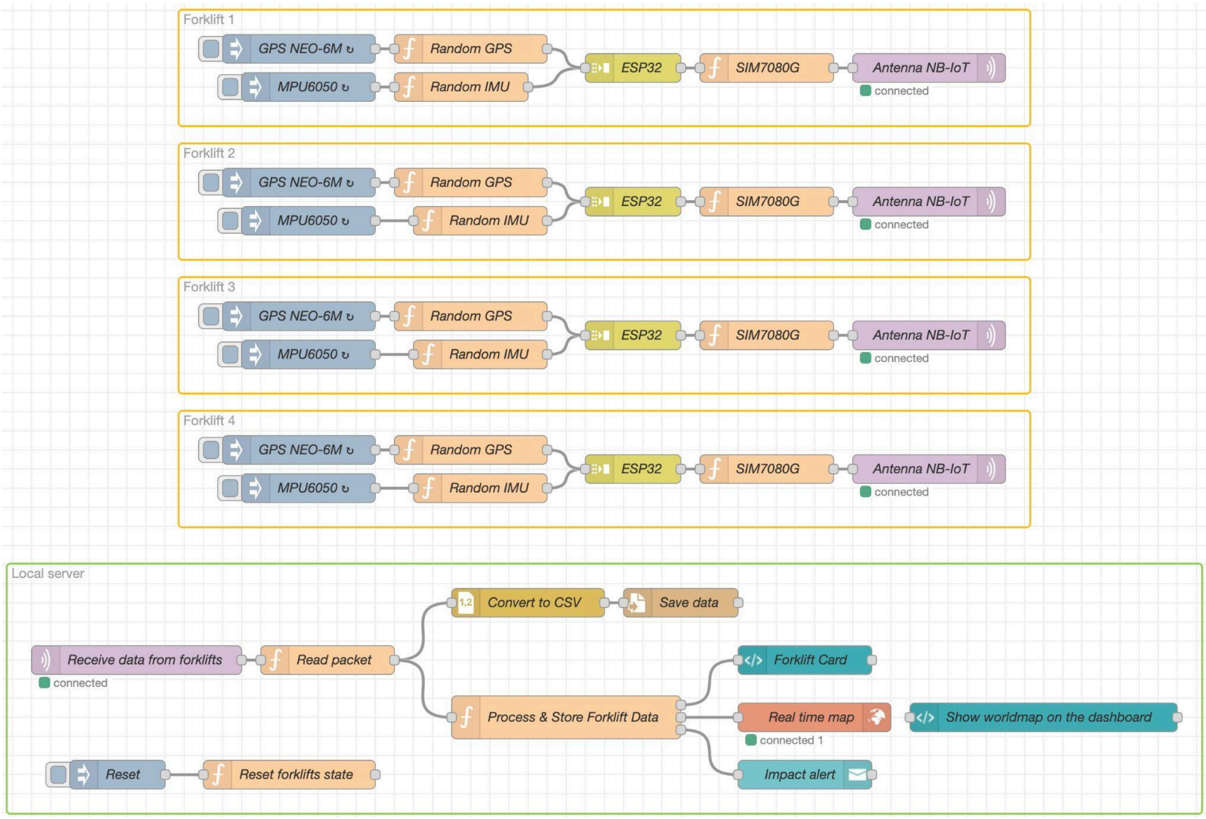
Since data is not complex and could be easily managed we decided to opt for a low-cost on-premise server, such as a Raspberry Pi 4 or mini-PC (around 100€), and install the following softwares:

- MQTT broker (e.g. Mosquitto): Handles message delivery from the forklifts.
- Database (e.g. PostgreSQL): Stores position, movement, and status data.
- Dashboard (e.g. Node-Red or a custom web interface): Visualizes forklift locations, alerts, and statistics in real-time.

Conclusions

The proposed solution offers a balanced and modular architecture for tracking forklifts in both indoor and outdoor environments, leveraging technologies that are well-suited to the specific constraints of each context. By combining communication, localization, and data processing layers in a unified system, we achieve reliable, near real-time tracking with low hardware and infrastructure costs.
But it is important to note that the final solution reflects a balance between performance and cost, based on our specific assumptions and priorities. However, as outlined in our technology comparison, different design choices may be preferable depending on budget constraints, update frequency requirements, or infrastructure availability. For example, in a scenario with fewer mobile units or more tolerance for delayed updates, a LoRa-based solution could eliminate recurring costs; conversely, for higher precision and instant updates, LTE/5G could be considered despite higher operational expenses.
To validate our design, we developed a simulation using Node-RED, where some virtual forklifts publish telemetry data via MQTT. This data is then parsed and stored in a CSV file, while simultaneously being visualized in a real-time dashboard within Node-RED, where we show telemetry and location for each forklift and alerts in case of impact. This prototype demonstrates the end-to-end workflow of data generation, transmission, storage, and visualization, confirming the feasibility and responsiveness of our proposed architecture.

Node-RED Flow



Node-RED Dashboard