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Railway railcar monitoring system based on BLE and Wi-Fi/PoE

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Abstract: A railway freight car monitoring system is proposed in which BLE beacons mounted on freight cars transmit data to a stationary network built on Wi-Fi and Power over Ethernet (PoE). BLE beacons (Bluetooth Low Energy) continuously broadcast identifiers and basic telemetry from the cars, while gateway devices (Wi-Fi access points powered via PoE) collect these packets and forward them over Ethernet to a central server. This approach provides high throughput and reliable power for the data collection layer and simplifies network installation by eliminating the need for separate mains wiring. The paper describes the methodology, network architecture, hardware components and server infrastructure. Advantages (broadband capacity, centralized power) and limitations (smaller Wi-Fi coverage area, potential interference in the 2.4 GHz band) of the proposed solution are discussed. Application examples for stations, depots and line sections are considered.

Keywords: freight car monitoring, Bluetooth Low Energy (BLE), Wi-Fi/PoE, wireless technologies in transport, Internet of Things (IoT), station and depot solutions, international transport

1. Introduction

The Internet of Things is increasingly used to automate logistics and to monitor rolling stock. Low-power radio methods are applied to track the location and condition of freight cars. A common architecture combines BLE beacons on vehicles with LoRaWAN gateways on masts or contact-line supports. LoRaWAN provides very long range (several kilometers), whereas Wi-Fi is intended for local networks with a radius up to a few hundred meters.

Research on freight car monitoring is rapidly developing due to the adoption of wireless technologies and IoT. BLE networks have shown effectiveness for collecting telemetry from brake-system sensors and wagon subsystems [1][2]. To extend coverage, LoRaWAN is used, enabling service of thousands of tags over large areas [3][4].

Cellular networks (GSM/4G/NB-IoT) are also used: terminals can provide continuous data transmission without deploying a private network [5][11]. However, high connectivity costs and power consumption limit their use in very large deployments.

RFID has long been applied for wagon identification: readers along the track provide accurate tracking, and over 95% of rolling stock in the United States is already equipped with tags [6][7]. For integration with Ethernet, BLE gateways with PoE are often used [8], and onboard Wi-Fi access points are commonly powered by PoE, simplifying equipment installation [9].

Specialized railway communication systems, such as GSM-R, remain in use for voice and certain data services, but trends are shifting towards LTE/5G and next-generation IoT networks [10][11]. Thus, BLE combined with Wi-Fi/PoE appears to be a promising solution for stations and depots, while for line sections and international routes it is reasonable to combine BLE with LoRaWAN or NB-IoT.

Using Wi-Fi as a stationary transport network offers high data rates and reliable device connectivity (thanks to Ethernet backhaul and PoE power), but requires a denser deployment of access points. Bluetooth Low Energy (BLE) provides a low-cost, low-power method to transmit small packets from onboard sensors. BLE beacons continuously broadcast identification and telemetry, and access points (BLE gateways) receive these signals and forward them to the cloud (central server). This work proposes to combine BLE sensors on wagons with a stationary Wi-Fi network powered by PoE and examines its architecture and characteristics.

2. Research methodology

The methodology is based on collecting data at the BLE layer and forwarding it over a stationary IP network. Each freight car is fitted with a BLE beacon equipped with sensors (for example: temperature, shock/impact, door open/close). The beacon periodically transmits a packet (e.g., in iBeacon/Eddystone format) containing measurements and a unique identifier. Base stations (BLE gateways) — implemented as Wi-Fi access points with an integrated BLE receiver — are installed in fixed positions (on platforms, contact-line masts or inside depots) and are powered via PoE switches. A gateway scans for BLE advertisements within its reception area (typically several tens of meters), decodes them and encapsulates them into TCP/IP packets. Data are then forwarded via Ethernet or Wi-Fi backhaul to the server.

This solution allows reuse of existing IT infrastructure: a single Ethernet cable supplies both power and data (PoE according to IEEE 802.3af/at), minimizing additional wiring costs. The network is organized in a “star” layout: BLE devices connect to the nearest access point, while the Wi-Fi/Ethernet layer connects access points to the central control server.

Network architecture and topology

The network comprises BLE beacons, Wi-Fi gateways with PoE and a central server. BLE beacons on wagons operate in the 2.4 GHz band and are optimized for low-power transmission. A BLE→Wi-Fi gateway integrates a Bluetooth radio and a Wi-Fi/Ethernet client. A single access point may collect BLE data from several dozen beacons concurrently. The Ethernet network is typically arranged according to the enterprise wired network topology

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(gateway-to-server links over cable or Wi-Fi backhaul). Access points are PoE-powered and can be mounted on poles, depot walls or platform supports. Standards such as IEEE 802.11 (e.g., 802.11n/ac for 2.4 and 5 GHz) and IEEE 802.3af/at (PoE) are applied. Each access point acts as a bridge between the BLE device "star" and the Ethernet "star" of the network (fig.1). The topology may be complemented by redundant channels (for example, secondary radio backhaul or a redundant Ethernet ring).

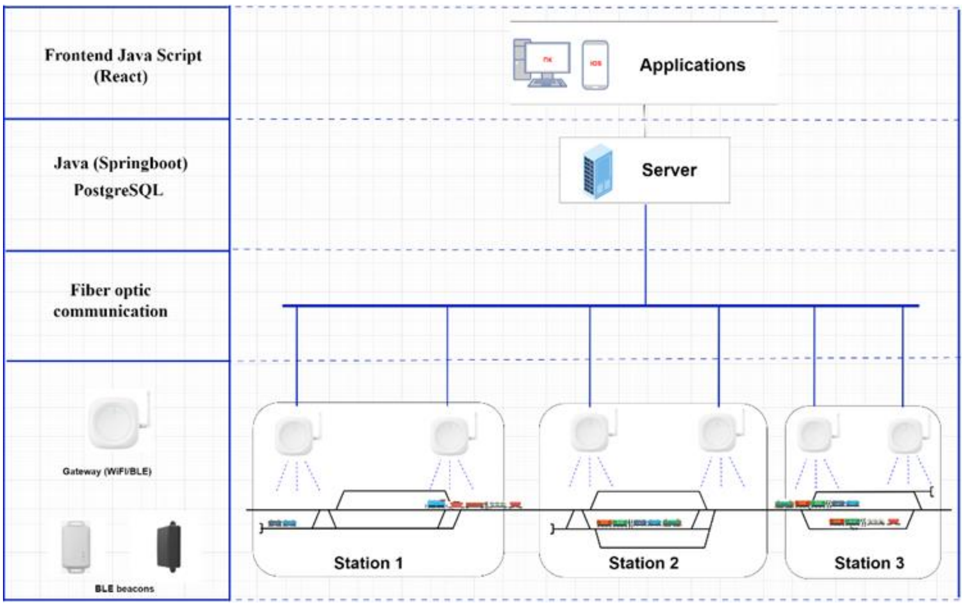

Fig. 1. Network architecture and topology

Hardware components

Main system components:

- BLE beacons on wagons. Autonomous battery-powered transmitters that send condition data from the wagon (e.g., temperature, door status, shock events) along with a unique identifier. BLE modules use Bluetooth Low Energy and are designed for low power consumption. Practical detection range varies (roughly 20–300 m depending on transmit power and environment). Beacons require minimal maintenance (battery replacement every few years under typical settings).
- Wi-Fi/BLE gateways with PoE. Wi-Fi access points (e.g., dual-band 2.4/5 GHz IEEE 802.11n/ac) augmented with a BLE module that scans BLE advertisements in the surrounding area. These devices are powered via PoE (IEEE 802.3af/at), simplifying installation since a single Ethernet cable provides both power and connectivity. Separate antennas or integrated modules provide Wi-Fi and Bluetooth radio functions. Outdoor units are housed in weather-resistant enclosures.
- Network equipment. An Ethernet LAN interconnects gateways. PoE switches, routers and access switches are used for aggregation. Where necessary, access points can operate over a configured Wi-Fi backhaul. Routers provide routing to the central server, which may be located on-premises or in the cloud.
- Server and software. The server ingests packets from gateways, stores data, visualizes telemetry and performs analytics. Standard protocols (MQTT, HTTP/REST, etc.) are used to deliver data to the management system. The server infrastructure can be deployed in a transportation control center or in the operator's cloud environment.

Server infrastructure

The server subsystem aggregates incoming data from BLE gateways and performs processing and storage. Gateways send data in real time over secured channels (Ethernet/Wi-Fi) through the local network or a VPN to the central server. Communication may use MQTT or HTTPS to ensure reliable delivery of small messages. On the server, a database stores wagon telemetry, and analytics and visualization services (web or SCADA interface) are deployed. The server can aggregate data across multiple stations or depots, providing centralized control. With PoE-powered gateways, a unified network of numerous BLE sensors is supported: sensors transmit signals which gateways capture and forward to the cloud/on-premise server. This scheme enables near-real-time tracking of wagon locations on yards (by associating a beacon with a specific gateway) and recording of onboard condition changes, plus long-term archival for analytics.

3. Results

A modeling study and pilot testing of the proposed architecture were conducted. BLE beacons produce small packets on the order of tens of bytes (ID and sensor state), and their practical reception radius is typically tens of meters. In depot or station environments, a single access point can cover several tracks. Wi-Fi coverage from one access point (depending on output power and obstacles) usually spans several tens of meters radius. For example, IEEE 802.11n/ac equipment can maintain stable links at distances up to 50–100 m in open areas. At shunting speeds up to 10–20 km/h, BLE advertisements can be captured sequentially by several gateways. Tests showed that with an advertisement interval of approximately 1 s, stations received over 90% of messages for consists moving at speeds up to about 15 km/h. The use of PoE-mounted wall

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or ceiling access points demonstrated reliable powering and straightforward installation without the need to run separate mains cabling.

Solution for the classification (sorting) yard

On a classification yard the system operates as a simple chain: beacons → receivers → server. Each wagon carries a compact wireless beacon that periodically transmits its identifier and basic telemetry (temperature, sensor alarms, etc.). Stationary receivers, mounted along tracks and powered via the Ethernet network, capture these transmissions and forward them over the local network to a central processing point.

Coverage planning ensures overlap between receiver footprints so a wagon is typically observed multiple times, enabling accurate localization. Receivers are placed more densely in areas of intensive shunting and on the hump, and more sparsely in less active zones.

To ensure fast and reliable operation, receivers perform simple edge preprocessing: they discard irrelevant signals, compress repeated messages and timestamp each record together with the receiver identifier. If the connection to the server is temporarily lost, a receiver buffers data locally and forwards it when the link is restored.

At the server, raw records are merged into events such as wagon arrival, departure, track transfer and prolonged stoppage. A practical rule is used: several detections within a short time window constitute a confirmed event. These events are used to automatically produce an electronic consist manifest — a list of wagons with timestamps and location of detection, together with available telemetry.

Operational best practices include synchronized time across all devices (to properly order events), coverage calibration (measuring signal level along tracks) and battery status monitoring for beacons. For robustness, zones are overlapped by multiple receivers and a redundant data path is provided in case of primary network failure.

Integration with enterprise systems is supported via simple interfaces: the server provides data in commonly used formats (for example, JSON) and offers dispatchers a station map, wagon processing times and key operational metrics. Implementation typically begins with a pilot sector: testing, adjustment of receiver density, and then progressive scaling across the station.

The key outcome is automation of recordkeeping and acceleration of processing: reduced manual input, faster generation of consist manifests, improved inventory accuracy and faster detection of deviations in train handling.

4. Discussion

The proposed approach offers high throughput and integration with existing IT infrastructure. Wi-Fi provides significant data rates (megabits per second and higher) and a bidirectional channel, unlike long-range low-power networks such as LoRaWAN. PoE simplifies access point installation because separate power sources are not required. Using BLE beacons conserves energy onboard and does not require complex onboard equipment.

However, limitations exist. The range of Wi-Fi is notably smaller than that of LoRaWAN, so a denser network of access points is required. Both BLE and Wi-Fi operate in the 2.4 GHz band, which can cause mutual interference. It is recommended to avoid overlapping Wi-Fi channel allocations with BLE advertising where possible — e.g., configure Wi-Fi to non-overlapping channels (1, 6, 11) while BLE uses its own channel scheme. Applicability varies by environment: at stations and in depots (bounded areas with stable power and cabling) Wi-Fi + PoE is a good fit — access points can be installed under canopies or on platform posts. On long line sections, the system is effective mainly for short control zones (for example, at weigh stations or at localized track sensors). For extended line coverage, LTE or LoRaWAN remain preferable. Overall, BLE + Wi-Fi/PoE is most useful where a wired network exists and a large volume of near-real-time data is required (for example, centralized monitoring of wagon stock in depots and around stations).

5. Conclusion

This study has presented and analyzed a monitoring system for freight railcars based on the integration of Bluetooth Low Energy beacons and a Wi-Fi/PoE backbone infrastructure. The proposed architecture demonstrates that the combination of energy-efficient short-range wireless communication and high-capacity wired transport channels can effectively address the operational challenges of wagon monitoring in stations and depots. BLE beacons provide a low-maintenance and long-lasting mechanism for transmitting identifiers and telemetry, while Wi-Fi access points powered over Ethernet ensure reliable data collection, centralized power distribution, and straightforward installation without the need for additional cabling.

The results of pilot tests and model evaluations confirm the applicability of the approach in environments with dense wagon flows, such as sorting yards, where overlapping coverage zones and redundant gateways enable reliable data reception even during intensive shunting operations. Data aggregation on the server side allows the system to automatically generate electronic consist manifests, detect wagon movements, and record telemetric events such as temperature changes or impacts. This contributes directly to the automation of logistics processes, improved data accuracy, and reduced reliance on manual input.

When compared to alternative technologies, the proposed solution has both advantages and constraints. In contrast to LoRaWAN, which supports communication over several kilometers [3][4], Wi-Fi offers significantly higher throughput and supports real-time data exchange, but requires denser deployment of access points. Unlike GSM/LTE or NB-IoT solutions [5][11], Wi-Fi/PoE avoids recurring operational costs and dependence on public networks, but it is limited to areas with available wired infrastructure. Similarly, while RFID provides robust identification [6][7], it does not inherently support continuous telemetry. Therefore, BLE combined with Wi-Fi/PoE is best positioned as a station- and depot-focused solution, where it can complement rather than replace wide-area technologies.

Overall, the integration of BLE and Wi-Fi/PoE contributes to the ongoing digital transformation of railway transport, enabling more efficient rolling stock management, increased transparency in freight operations, and the foundation for advanced predictive analytics [1][2][10]. Future research should focus on hybrid system architectures that leverage the strengths of different technologies — BLE/Wi-Fi/PoE for localized high-resolution monitoring and LoRaWAN or NB-IoT for long-haul tracking. Such convergence would enable a truly scalable and resilient monitoring framework capable of supporting both domestic and international freight corridors in line with the broader vision of smart rail transport.

References

[1] Zanelli F., Mauri M., Castelli-Dezza F., et al. Energy autonomous wireless sensor nodes for freight train braking systems monitoring // Sensors. 2022. Vol.22, no.5. P.1876.

[2] GAO Tek Inc. Railway and Infrastructure Monitoring – Predictive Maintenance IoT [Electronic resource]. Available at: https://www.gaotek.com/railway-and-infrastructure-monitoring-predictive-maintenance-iot.

[3] Actility. SNCF Implements LoRaWAN IoT Solutions to Monitor Railway Assets and Rolling Stock [Electronic resource]. Available at: https://www.actility.com/sncf-blog.

[4] Tang H., Kong L.J., Du Z.B., et al. Sustainable and smart rail transit based on advanced self-powered sensing technology // iScience. 2024. Vol.27, 104283.

[5] Artmatica LLC. Freight container monitoring device [Electronic resource]. Available at: https://www.artmatica.ru/product/seti/iot-modemy/ustroystvo-monitoringa-zhd-konteynerov.

[6] GAO RFID Inc. RFID Railway Management System [Electronic resource]. Available at: https://gaorfid.com/gao-railway-management-system.

[7] Smiley S. RFID & Railways [Electronic resource]. Available at: https://www.atlasrfidstore.com/rfid-insider/rfid-railways

[8] GAO RFID Inc. PoE BLE Gateways [Electronic resource]. Available at: https://gaorfid.com/devices/ble/ble-gateways/poe-ble-gateways.

[9] Westermo AB. Rail Approved Onboard Wi-Fi Solutions [Electronic resource]. Available at: https://www.westermo.com/us/industries/train-networks/wireless-solutions/onboard-wifi.

[10] Hossain A., Fraga-Lamas P., Fernández-Caramés T.M., Castedo L. Toward the Internet of Smart Trains: A Review on Industrial IoT-Connected Railways // Sensors. 2017. Vol.17, no.6. P.1457.

[11] Tinu O. Application of sensors and wireless technologies for IIoT // Wireless Technologies. 2021. No.3-4.

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