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Monitoring of railcars based on BLE and cellular technologies

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Abstract: This paper examines the architecture of a railcar monitoring system that employs Bluetooth Low Energy (BLE) beacons attached to railcars and gateways equipped with cellular connectivity (GSM, LTE, NB-IoT). A comparative assessment of existing tracking technologies (GPS, RFID, LoRa, etc.) is presented and the rationale for selecting a hybrid BLE + cellular approach is given. The network topology is described (star topology: BLE beacon → gateway → cloud), together with the hardware components (BLE beacons and cellular gateways) and the server infrastructure (MQTT, REST API, buffering, fault tolerance). Options for gateway placement at stations and in depots are considered, operational scenarios (in depot, at station, in transit) are analyzed, and the advantages and limitations of the proposed scheme are discussed. Examples of real-world solutions and technical data are provided.

Keywords: BLE beacons, cellular connectivity, NB-IoT, LTE-M, railcar monitoring, BLE gateways, IoT platform, MQTT, REST API, asset tracking, depot/station monitoring

1. Introduction

Traditionally, railcar tracking has relied on GPS trackers, RFID tags, or LPWAN technologies. GPS positioning provides global visibility and high accuracy in open areas but requires line-of-sight to satellites (it fails in tunnels and covered facilities) and consumes significant energy; GPS modules are relatively expensive and bulky, which complicates installing them on every wagon.

RFID tags (active and passive) make inexpensive marking possible but require powerful readers installed at specific checkpoints (entry gates, depots) and have a limited read range (a few meters). As reported in the literature, passive RFID tags cost approximately $0.10 but require expensive readers (USD 10–20k) and operate only at very close range to the reader. Active RFID trackers are more expensive (~$20 per tag) and have battery lives of 3–5 years and ranges up to ~100 m; however, they tend to be bulkier and harder to integrate with cloud services. Overall, RFID is suitable for checkpoint inventory but does not provide continuous monitoring of rolling stock.

LPWAN technologies such as LoRaWAN provide long range (5–10 km in open terrain) and low energy consumption. LoRaWAN operates in unlicensed spectrum, facilitating private network deployment, but is susceptible to interference and requires deployment of dedicated gateways. NB-IoT and LTE Cat-M1 enable transmission of small packets over existing licensed cellular networks, offering wide coverage (especially in rural areas) and the capacity to support thousands of devices per cell. However, NB-IoT has limitations in mobility: handover between cells can require a relatively long recovery time.

BLE beacons are low-cost, energy-efficient devices that broadcast an identifier and, when equipped, simple telemetry. Compared with RFID, BLE tags provide greater range given the appropriate receiver infrastructure, and inexpensive BLE gateways (consumer and industrial) are widely available. BLE is naturally compatible with consumer devices (smartphones, tablets) and cloud platforms. The main drawback of BLE is its limited coverage (tens of meters) and inability to provide long-range positioning without additional receivers.

Recent studies and reports demonstrate that combining local BLE beacons with cellular communication channels (GSM/LTE/NB-IoT) yields a cost-effective and scalable railcar accounting system: BLE provides inexpensive tagging and local telemetry collection at the "last mile," while cellular networks relay event-driven messages to the cloud and enable integration with IT services [1,3,5]. Comparative reviews note that LPWAN solutions such as LoRaWAN are competitive in terms of energy efficiency and cost but require dedicated infrastructure, whereas NB-IoT/LTE-M benefit from operator-managed coverage and centralized management yet suffer from mobility constraints (notably NB-IoT) [2,4,9]. Experimental studies and industrial pilots validate the use of BLE for local monitoring (station/depot scenarios), while continuous tracking en route typically relies on mobile gateways mounted on locomotives or on hybrid trackers that combine GNSS and cellular connectivity [1,6,10]. Practical cases show that hybrid architectures (BLE + cellular transmission) are optimal for automating acceptance/dispatch and diagnostic monitoring of railcars, but they require careful gateway placement and buffering strategies during connectivity outages [1,5,7]. In summary, the technology choice depends on required update frequency, coverage topology, and economic constraints: BLE is suitable for dense local detection, while LPWAN/NB-IoT/LTE are preferred for backbone transmission and remote sections [2,4,8].

Consequently, a BLE + cellular approach enables local detection of railcars (BLE beacons) and relays their status to the cloud via the wide coverage provided by GSM/LTE/NB-IoT. BLE beacons are mounted on railcars and fixed or mobile gateways receive their signals and forward them to a central system. This scheme leverages existing cellular infrastructures and supports integration with contemporary IoT platforms.

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2. Research methodology

Network architecture and topology

The monitoring network follows a star-based architecture: BLE beacons attached to railcars broadcast packets containing unique identifiers and, optionally, sensor data. BLE gateways (Bluetooth gateways) are deployed at fixed points (stations, depots) or mounted on mobile units (e.g., locomotives, shunting locomotives). These gateways receive packets from all beacons within their coverage (approximately 10–50 m, depending on environment). The gateway then forwards the collected information via the cellular network to a cloud server.

At the upper level, cellular connectivity (GSM/GPRS, LTE Cat-M1, NB-IoT, etc.) is used to transmit data to the central server. Gateways may support multiple frequency bands and cellular protocols, enabling compatibility with different mobile operators and providing ubiquitous coverage where operator service is available. The topology allows horizontal scaling: as the railcar fleet grows or train lengths increase, additional BLE gateways can be deployed or their coverage extended. Cellular networks provide data transmission capability across railway sections without the need for deploying a dedicated long-range network.

The horizontal data flow is: BLE beacons (edge sensors) → BLE gateways (cellular modem + compute unit) → Internet (MQTT/REST API) → server backend (fig.1). Note that BLE beacons do not directly provide geolocation; the railcar's approximate location is inferred from the gateway(s) that detected its beacon. This approach resembles container or freight truck tracking: a tag in a vehicle is read by a BLE gateway in the vehicle or at a checkpoint, and the gateway relays the information via LTE or NB-IoT.

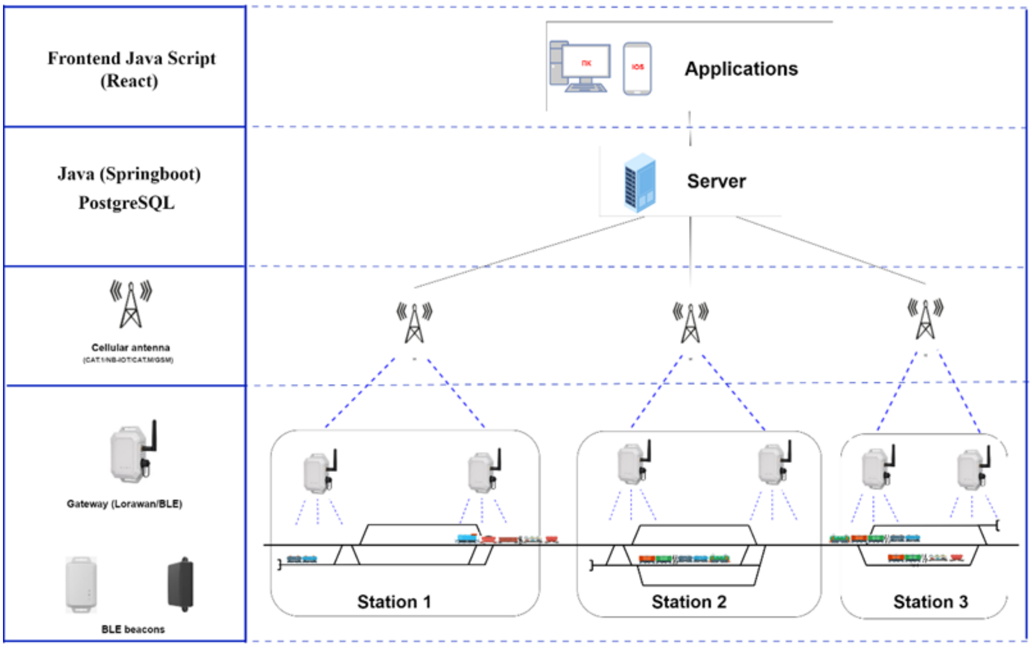

Fig. 1. Network architecture and topology

The number of BLE devices a single gateway can handle depends on hardware capabilities and channel load. Modern BLE 5.0 gateways can process signals from dozens of beacons simultaneously; gateways commonly implement filtering and packet selection at the network edge to reduce load and data consumption. The cellular segment is readily scalable—additional gateways or failover channels can be introduced if needed.

Hardware components

BLE beacons on railcars. Each railcar is equipped with a compact battery-powered BLE beacon. Typical beacons may implement standard payloads (e.g., iBeacon/Eddystone) and may include auxiliary sensors (temperature, shock/acceleration, door open/close, etc.). BLE beacons are ultra-low power, operate in the 2.4 GHz band, and have an effective range in open areas from a few tens up to about 100 m; range is reduced in enclosed or heavily shielded metallic environments.

BLE gateways with cellular modems. A gateway integrates a BLE receiver and a cellular modem (GSM/3G/LTE Cat-M1/NB-IoT). Gateways are available in portable small-form factors with modest batteries for temporary or mobile deployments, and in ruggedized stationary variants with larger batteries or mains power intended for long-term outdoor installation (wide temperature range, high ingress protection). Mobile gateway installations on locomotives provide the capability to collect beacon signals while in transit and transmit them via LTE Cat-M1 or NB-IoT. Many gateways also implement local buffering to store messages when connectivity is lost (for example, in tunnels) and to forward them when the link is restored. There are also hybrid trackers that combine BLE interfaces, cellular modems and sometimes GNSS receivers, enabling the device to function as both a local beacon and an autonomous cellular tracker when required.

Server infrastructure (MQTT, REST API, buffering, fault tolerance)

The central component of the system is an IoT platform or cloud server that ingests messages from gateways and makes data available to users. Lightweight protocols such as MQTT and HTTP/REST are commonly used. MQTT is particularly suited to IoT use cases due to its low overhead, support for quality of service (QoS) levels, persistent sessions and straightforward integration with brokers and cloud services. In some deployments, MQTT is used as the primary transport, ensuring reliable delivery and secure transmission.

On the server side, message queues and data stores (time-series databases, NoSQL or SQL stores) are configured, and APIs are provided for external systems. Buffering at the gateway level is essential: when a gateway loses connection, messages are cached locally and forwarded later (store-and-forward). MQTT brokers support session persistence and QoS which help to avoid data loss during transient connectivity disruptions.

For reliability, the platform can employ redundant MQTT brokers, geo-distributed database clusters and cellular channel redundancy. Integration with enterprise IT is typically provided through standard interfaces: the monitoring platform exposes REST APIs, webhooks or a message bus. Standardized interfaces enable automated data exchange with customer systems, facilitating integration into existing operational ecosystems.

3. Results

Gateway placement at stations and in depots

BLE gateways are positioned where railcars can be reliably detected. At stations, typical locations include entry/exit tracks, departure platforms and nearby tracks used for parking. In depots, gateways are placed at yard gates and along formation tracks where locomotives couple and uncouple cars. The objective is to ensure that each car passes through the capture zone of at least one gateway during entry/exit operations. Where mains power is available, stationary gateways are connected to permanent power; in field sites, autonomous gateways with large battery packs or solar panels can be used.

Inside depots or facilities lacking cellular coverage, local wired transmission (Ethernet) to a central server can be arranged. More commonly, however, LTE/NB-IoT gateways are mounted on technical huts or masts to obtain mobile operator channels. Mobile gateways can be installed on locomotives or service vehicles to capture beacon signals while the train is moving and forward them via GSM/LTE.

Operational scenarios

At a station during arrival/departure. When a train arrives and stops, wagons enter the coverage area of station BLE gateways (fig.2). Gateways automatically read IDs of beacons within range (up to ~50–100 m in open conditions) and forward the information to the cloud. This yields an accurate manifest of wagons in the consist. If integrated with an ERP/WMS system, wagon entries and exits are recorded automatically, reducing manual checks and speeding cargo processing.

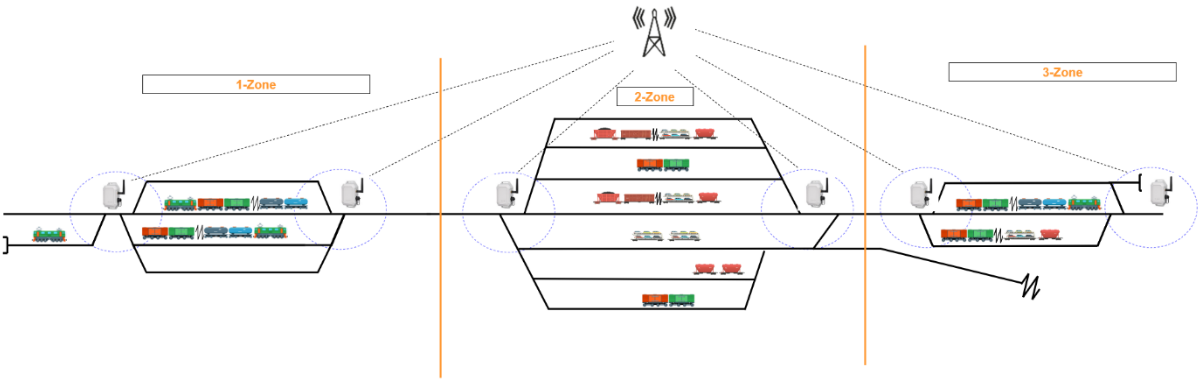

Fig. 2. Operational scenario at a station

In the depot (repair and formation tracks). In depots, gateways track wagon presence and status. If a wagon enters a maintenance bay, the system records that it has left the departure line. Movement within the depot can be monitored; for parked wagons, scanning intervals can be reduced (for example, hourly). The key requirement is that the system can confirm all wagons intended for dispatch have been read before departure.

4. Discussion

Advantages:

- *Energy efficiency and cost of beacons:* BLE beacons are highly energy efficient and can operate for several years on a single battery. They are cheaper than active RFID or GPS trackers, reducing maintenance frequency.
- *Ease of deployment:* The approach leverages existing wireless infrastructures—BLE for the local segment and public cellular networks for backbone transmission—eliminating the need to deploy a dedicated long-range network. Gateways are easy to mount on walls, poles or rolling stock.
- *Scalability:* Adding a new railcar requires only mounting a new beacon. The gateway network can be extended incrementally as the fleet grows. BLE receivers are inexpensive and easy to integrate (e.g., via a smartphone app or a compact IoT gateway).
- *IoT integration:* BLE gateways commonly support MQTT and REST APIs and JSON payloads, facilitating integration with operational systems. The architecture is compatible with industrial IoT platforms and enterprise SCADA.
- *Versatility:* BLE payloads may carry not only an ID but also sensor data (temperature, shock, door status), enabling richer monitoring functionality.

Limitations:

- *Limited BLE range:* Typical BLE coverage is on the order of 10–50 m, necessitating a sufficient density of gateways in large yards. In open countryside between stations, BLE coverage is impractical without mobile gateways.
- *Deployment density and cost:* Ensuring reliable reads for all wagons requires careful gateway placement; the cost of installing many gateways can offset some of the beacon cost savings.

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- *Cellular coverage reliability:* Cellular networks may be unreliable in remote areas. NB-IoT offers good coverage at major nodes but presents challenges for moving objects due to limited handover capabilities; migration away from legacy 2G/GSM also requires adoption of LTE/NB-IoT.
- *Lack of precise geolocation from BLE:* BLE only indicates proximity to a gateway, not precise coordinates. Unlike GNSS, it cannot provide continuous geolocation; for continuous tracking, combination with other methods is needed.
- *Dependence on infrastructure:* If a gateway fails (power loss or modem failure), data about wagons in its zone will not be available until the gateway is repaired; thus, redundancy and uninterruptible power supplies are advisable.

5. Conclusion

A hybrid architecture combining BLE beacons and cellular connectivity enables cost-effective railcar accounting and monitoring. BLE beacons provide inexpensive marking and long battery life, while cellular gateways (GSM/LTE/NB-IoT) ensure wide-area transmission and integration with cloud platforms. The system is well suited to automating acceptance/dispatch operations and diagnostic monitoring in stations and depots, reducing manual labor and increasing operational transparency. Limitations related to BLE range and cellular coverage can be mitigated by careful gateway placement, the use of mobile receivers, and buffering strategies. Overall, combining BLE and modern LPWAN/cellular technologies represents a promising direction for digitizing railway logistics.

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