Digital livestock management solution for cattle identification, traceability, and real-time monitoring, IoT-based for integrated crop-livestock-forest (ICLF) systems

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Abstract.

Brazil is a global player in the beef industry with the world's largest commercial bovine herd, exceeding 230 million head, and leads the international market, accounting for approximately 25% of the global beef trade, reaching over 170 international markets. The edaphoclimatic diversity, high-performance genetics, rigorous sanitary protocols, and the adoption of a technological framework for tropical livestock, altogether, explain the decoupling of Brazilian ranching from extensive, low-productivity systems toward sustainable intensification. The increasing consumer demand for information on food quality, safety, and production conditions poses a challenge for livestock production, requiring greater control over animal production. Precision livestock farming (PLF) is a potential solution enabling continuous, real-time monitoring of animal health, welfare, and behavior. The "National Bovine Traceability Plan (PNIB)" aims to achieve animal traceability by electronic tags for an individual identification system to track history, location, and movement of the entire Brazilian herd by 2032, enhancing sanitary control and meeting international market demands. The transition toward a digitized livestock production system needs the deployment of a low-latency, cost-competitive cyber-physical architecture capable of autonomous individual identification, high-precision localization, and longitudinal behavioral monitoring. This research implements a scalable Digital Livestock Management Solution (DLMS) that utilizes a multi-layered communication protocol and was conducted at Embrapa Pecuaria Sudeste, São Carlos, SP, Brazil (21°57' S, 47°50' W, 860 m), in both beef and dairy systems. The system employs Taggen Beacon 5.1® (Taggen Industries, Campinas, SP, Brazil), a Bluetooth low energy (BLE) tag affixed to animal collars, with sensor nodes (Taggen Gateway® (Taggen Industries, Campinas, SP, Brazil)) cloud-connected via Long Term Evolution

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(LTE or 4G) or Wi-Fi. Data is integrated into the TG-AGRO® platform, a cloud-based management architecture for real-time access across portable devices (smartphones or tablets). The system operates as follows: the beacon module periodically broadcasts BLE advertising packets that include unique identifiers and telemetry data. The gateway performs active scanning, acquires Received Signal Strength Indicator (RSSI) metrics, and appends temporal metadata (timestamp). In beacon-equipped GNSS (Global Navigation Satellite System) configurations, the gateway correlates these packets with spatial coordinates. DLMS's multi-source power system allows autonomous operation via solar energy, grid connections, or integration with mobile agricultural equipment. For a reliable telemetry transmission over 350 m, the system uses a motion-aware RSSI smoothing algorithm (Log-Distance Path Loss Model) to mitigate multipath fading. The system is fully interoperable with legacy LF and HF-RFID protocols to ensure backward compatibility with the Brazilian Sisbov framework. Evaluation parameters included daily detection rates, report density, and message latency. Field results demonstrated a daily detection rate exceeding 98.5% of the herd, with gateways processing over 500 tags per minute in high-density areas. The system optimizes power consumption by adapting transmission intervals (5 s to 15 min), ensuring data integrity and long-term tag durability in remote settings. The outcome demonstrates a reliable, compatible telemetry system that, despite the logistical limitations of remote settings, ensures data integrity and enables real-time decision-making. This architecture goes beyond limitations of conventional passive tracking by offering a dynamic framework for real-time spatiotemporal management across diverse livestock production systems. Additionally, information flow between on-farm operations and external regulatory or commercial stakeholders is facilitated by the incorporation of user-centric data visualization interfaces.

Keywords.

Precision livestock farming, beef cattle, animal identification, tracking, traceability, IoT, BLE.

1. Introduction

Brazil has the world's largest commercial cattle herd, with around 230 million cattle heads, and is the world's leading exporter of meat, with 3.5 million tons in 2025, representing 25% of the international market. Brazilian meat has reached over 170 countries, generating about US$18 billion in 2025 (ABIEC 2025).

The transition of Brazilian livestock farming from low-productivity extensive systems to sustainable intensification can be explained by a combination of edaphoclimatic diversity, high-performance genetics, strict sanitary protocols, and the adoption of a technological framework for tropical livestock farming (Silva et al. 2017; Pereira et al. 2024).

The growing demand of consumers and markets for food safety and socio-environmental transparency requires individual and continuous monitoring systems. This is the challenge facing national livestock farming, which necessitates greater control over production processes. Precision livestock farming (PLF) is a promising solution that enables the management of individual animals through continuous real-time monitoring of health, welfare, behavior, production, reproduction, and environmental impact (Berckmans, 2017). PLF has advanced in the instrumentation of animal behavior in intensive systems (Bernardi et al. 2024). Silvipastoril systems and Integrated Crop-Livestock-Forestry (ICLF) systems impose specific physical challenges that limit conventional tracking technologies.

The National Bovine Traceability Plan (PNIB) aims for the individual identification of the entire Brazilian herd by 2032 (Brazil 2024). Current systems based on batches and documents (Animal Transit Guide - GTA and CAR) or by individual identification, using the SISBOV Brazilian System for Individual Identification of Bovines and Buffaloes (Brazil 2017), are vulnerable to fraud and insufficient to monitor producers in areas with a higher risk of deforestation.

The transition from the current SISBOV (Sistema Brasileiro de Identificação Individual de Bovinos e Búfalos) to the PNIB (Plano Nacional de Identificação Individual de Bovinos e Búfalos) is a paradigm shift from a voluntary market system to a national mandatory infrastructure. This transition affects the technical and logistical protocols of the Brazilian beef exporters' supply chains.

The oldest technology used in livestock farming is RFID, which is the basis for individual traceability and automated data management (Barioni et al. 2024a 2024b). Other monitoring systems that use GPS (Global Positioning System) technology face problems such as high prices, high energy consumption, and signal attenuation in wooded systems such as ICLF, where dense eucalyptus canopies cause signal losses of -15 to -25 dBm, making satellite tracking costly for the herd scale and unreliable. Low-cost, low-latency cyber-physical architectures that function under forest canopies are therefore desperately needed.

The present study aims to develop and implement a scalable Internet of Things (IoT)-based digital livestock management solution (DLMS) for individual cattle identification, routine herd management, security, traceability, and real-time longitudinal behavioral monitoring.

2. Material & Methods

2.1. Study area and system characterization

The experiment was conducted at Embrapa Pecuária Sudeste, in São Carlos, SP (21°58'23.9"S 47°51'03.1"W, 860 m), in the experimental area of an Integrated Crop-Livestock-Forestry (ICLF) system for beef cattle (Bernardi et al. 2026; Pezzopane et al. 2026).

2.2. Sensing architecture and wearable devices

For data collection, the digital livestock management solution (DLMS), a cyber-physical architecture based on the Internet of Things (IoT), was used. The animals were instrumented with smart collars (Taggen Beacon 5.1®). These devices operate on ultra-low-power Bluetooth Low Energy (BLE 5.0) technology (~0.8 µA in standby) and integrate a triaxial MEMS accelerometer (3D). The project opted to exclude GPS modules from the collars to optimize energy autonomy and reduce operating costs. The transmission interval was configured adaptively (between 5 seconds and 15 minutes), depending on the level of activity detected in the animal.

2.3. Network infrastructure and data flow

Signal reception was performed by a mesh of 15 solar gateways (Taggen Gateway®), equipped with 5-W panels and batteries with 72 hours of autonomy, strategically distributed to ensure area coverage. The data flow followed the following hierarchy:

1. The beacons transmit BLE advertising packets containing unique identifiers (IDs) and telemetry.
2. The gateways perform active scanning, capturing the signal strength indicator (RSSI) and inserting temporal metadata (timestamp).
3. The data is sent via LTE (4G) or Wi-Fi network to the AWS IoT Core service in the cloud.
4. Final processing and visualization take place on the TG-AGRO® management platform.

2.4. Behavioral Location and Classification Algorithms

The animals' location was estimated using weighted least squares (WLS) trilateration, processed whenever a collar was detected simultaneously by three or more gateways. To mitigate the effect of multipath fading and signal noise, a log-distance path loss model (Log-Distance Path Loss Model, n = 2.2) was applied.
Behavioral monitoring (digital ethogram) was performed using the "CowPhysics" algorithm. The framework processes the normalized vector magnitude of three-dimensional acceleration to classify the animal's motion status into active (moving) or inactive (stationary) states, while the fine-grained classification into five functional states (grazing, walking, running, standing, and alert) is currently under validation and development.

2.5. Interoperability and regulatory compliance

The integration with the official traceability systems of the Ministry of Agriculture and Livestock (MAPA) was ensured by devices adopting the numbering prefix 076 (ISO Brazil standard) under the management. The architecture maintains technical compatibility with low-frequency (LF) and high-frequency (HF) RFID protocols, ensuring interoperability with the Brazilian Individual Identification System for Cattle and Buffaloes—Sisbov (Brazil 2017) and the National Plan for Individual Identification of Cattle and Buffaloes—PNIB (Brazil 2024).

Behavioral classification “CowPhysics” algorithm processes the vector magnitude of three-dimensional acceleration, eliminating dependence on collar orientation. The Normalized Vector Magnitude (ΔG) was calculated as:

$$\Delta G = \left| \sqrt{(X^2 + Y^2 + Z^2)} - 1.0G \right|$$

where,

ΔG = normalized acceleration vector magnitude;
X = acceleration on the x-axis;
Y = acceleration on the y-axis;
Z = acceleration on the z-axis;
G = acceleration gravity unit (9.81 m/s²).

3. Results & Discussion

The implementation of the Digital Livestock Management Solution (DLMS) in the Integrated Crop-Livestock-Forestry (ICLF) system proved to be a robust cyber-physical architecture that overcame critical limitations of conventional technologies in tropical environments. Unlike the GPS-based identification and location system, which faces severe signal attenuation (between -15 and -25 dBm) under the tree canopy, the tested network solution based on Bluetooth Low Energy (BLE 5.0) and WLS trilateration geolocation by Weighted Least Squares (WLS) maintained tracking integrity without dependence on satellite signals. Thus, the actual architecture integrating real-time physical monitoring with cloud-based analytical processing enables herd management to shift from reactive to proactive and individualized approaches (Dao et al. 2026).

Table 1: Operational metrics for reception and transmission volume from gateways in different sectors of the ICLF system in São Carlos, SP, Brazil.

Gateway	Location	RSSI (dBm)			N	Transmissions
		Mean	Min.	Max.		
08ED313AF9FA	ICLF 07/08	-86.7	-102	-42	24	401,087
1929C17929B0	ICLF 09	-87.7	-100	-36	24	158,970

1F77C9B8A5B5	ICLF 10	-93.4	-107	-42	25	847,299

Regarding operational performance and scalability, the field results revealed a daily detection rate exceeding 98.5% of the herd, indicating high observational availability and reducing the risk of bias from the systematic loss of individuals in the data stream. Field results indicate that the proposed architecture achieved performance compatible with continuous traceability and precision monitoring applications.

In addition, the processing capacity of over 500 beacons per minute in high-density areas demonstrates that the system maintains stability even under higher communication loads, reinforcing its scalability for commercial scenarios (Table 1). The median range (181 m) associated with the design of a 200 m radius indicates consistency between empirical performance and the sizing of the coverage grid. Maximum ranges (P95) up to 754 meters were observed, which may allow the network density to be approximately one gateway every 12.6 hectares (Table 2). This performance is fundamental, as discussed by Silva et al. (2017) and Pereira et al. (2024) for this DLMS to boost the transition from extensive systems to sustainable intensification. Results also demonstrate that, even in an environment with high electromagnetic challenge, the system preserved the capacity to capture spatiotemporal patterns useful for management.

The integration of triaxial accelerometers and the "CowPhysics" algorithm for behavioral and animal welfare monitoring has enabled the digital solution to expand beyond simple identification to include functional characterization of behavior. The "CowPhysics" algorithm captures kinematic signatures that differentiate active from inactive behaviors. Preliminary tests indicate that the framework achieves up to 70% accuracy in identifying food intake (grazing) under experimental conditions. Although this fine-grained classification is still undergoing validation to improve its precision in diverse grazing environments, it demonstrates the system's sensitivity in capturing animal-specific kinematic profiles. These advances align with Berckmans’ (2017) statements on precision livestock farming's role in individualized animal management of health and welfare. Monitoring space and behavior without human interference is a significant advancement for animal welfare management under modern protocols (Hofstra et al. 2022). It also indicates that the behavioral data generated by the system has value not only for management but also for scientific purposes, as they allow investigation of how environmental structure interferes with the expression of behavior in pasture-managed herds.

Table 2: BLE signal range statistics and coverage grid sizing parameters under an ICLF system in São Carlos, SP, Brazil.

Reach statistics (Gateway ICLF 09 — GPS Cruzado)	**Value (m)**	**Interpretation**
Median (P50)	181.1	Modal reach — conservative basis of the network design
Mean	325.5	Influenced by readings in clearings and high points
95th percentile (P95)	754.2	Maximum reach
Design Radius Adopted	200.0	P50 + safety margin ensures coverage redundancy

The absorption of 2.4 GHz waves by animal tissues can lead to instability in the RSSI, which can induce errors in algorithms. Therefore, “body shadowing” is still a technical challenge to overcome. Taggen mitigated this physical attenuation by implementing a Motion-Aware RSSI Smoothing algorithm at the backend, which dynamically adjusts filter coefficients using a Log-Distance Path Loss Model (n = 2.2). Crucially, the positioning framework incorporates accelerometer-derived movement state flags within its cloud processing pipeline. When the animal is identified as stationary, the backend algorithm dynamically adjusts the smoothing weights of the path-loss model, effectively dampening high-frequency RSSI fluctuations and preventing artificial location drift (anti-drift filtering) caused by body shadowing.

Another challenge concerns energy autonomy, which remains a bottleneck to scalability. However, the use of ultra-low-power BLE and adaptive transmission mitigates the need for invasive battery replacement. The analysis of 22 units after 100 days showed that battery and firmware failures still affect the persistence of data series. Although the use of ultra-low power BLE and adaptive transmission mitigates the need for invasive handling to change batteries, analysis of the 22 units after 100 days revealed that battery and firmware failures continue to cause gaps in the continuous data collected

From an operational perspective, energy consumption is one of the main determinants of the viability of wearable systems for cattle. For a digital solution to be viable in livestock farming, energy autonomy and data integrity are fundamental requirements.

In livestock systems, the need for frequent battery replacement compromises the technology's scalability, increases maintenance costs, and disrupts the herd's routine which can also affect animal performance. Therefore, the adoption of adaptive transmission, in which intervals between 5 s and 15 min are adjusted according to activity, and the use of ultra-low-power BLE ensure the temporal persistence of data series, which is essential for longitudinal behavioral analyses. Thus, the adoption of adaptive transmission, combined with ultra-low-power BLE devices and solar-powered gateways, represents a digital solution that enhances the temporal persistence of data series. This characteristic is particularly relevant to traceability, since it depends on the continuity of monitoring and the reduction of sampling gaps throughout the diurnal and seasonal cycles.

The system minimizes observational biases with a high daily detection rate (> 98.5%), ensuring an "observational availability" that is indispensable for precision livestock farming. Furthermore, Edge-AI or TinyML (local processing on the wearable device, such as future ear tags) strategies emerge as future possibilities to reduce dependence on constant transmissions and to save battery power (Dao et al. 2026; Patrick et al. 2026).

From a regulatory compliance and international market perspective, adopting the 076 prefix (ISO Brazil standard) ensures interoperability with the National Plan for Individual Identification of Cattle and Buffaloes (PNIB). This compliance is strategic for Brazilian production to meet the food safety and traceability requirements of rigorous markets such as the European Union and China, ensuring that the animal's health and socio-environmental history are verifiable in real time. In summary, the proposed architecture enhances the current SISBOV (Brazilian System for Bovine Identification and Traceability) technologically and positions the sector to meet the goal of total herd traceability by 2032.

In this context, the obtained indicators confirm the functionality of the BLE network and its ability to support zootechnical inferences and management decisions under environmental conditions known to be averse to wireless communication, such as structural heterogeneity of vegetation, attenuation by biomass, multipath, and body shading.

From a regulatory perspective, compliance with the 076 numbering and compatibility with legacy RFID protocols give the system a strategic advantage since its adoption does not require a break with the already consolidated institutional infrastructure but rather a technological qualification. This interoperability is central to the transition between the model historically based on batch records and the individual identification logic foreseen in the PNIB (National Program for Identification of Bovine Identification).

Thus, this study suggests that the proposed solution brings together essential technical attributes for large-scale applications, such as low energy consumption, high detection rate, ability to operate in field environments, and integration with digital platforms. This position is a concrete alternative to support sanitary traceability, transparency in the production chain, and the generation of objective evidence for increasingly demanding markets, as well as a fundamental tool for real-time decision-making by the farmer.

The analysis regarding the performance of 22 BLE collar units after 100 days of continuous use reveals critical challenges to the viability and scalability of cyber-physical architectures in field environments (Table 3). The data show that only 36.4% (8 units) of the devices remained functional at the end of the 100-day cycle. Even these units showed low battery voltages (2.8V to 2.85V), indicating they were nearing the end of their useful life. Battery failure was the direct cause of inoperability in 22.7% of the units, even resulting in firmware locking in DFU mode. As battery replacement is an invasive and costly operation, these results reinforce the need for adaptive transmission strategies and the use of ultra-low-power components to ensure the persistence of data series and reduce maintenance costs. It was also observed that 13.6% of the devices failed due to firmware problems, despite having sufficient battery charge (≥ 2.56V). In addition, the intermittent failure due to probable internal damage (4.5%) indicates that almost one-fifth of the sample exhibited electronic instabilities independent of energy autonomy. This suggests that the reliability of a Precision Livestock Farming (PLF) system depends not only on the hardware but also on the maturity of the embedded software to handle the dynamic conditions of the field. The pasture-based production environment and the animals' social behavior impose severe physical stress on the sensors. Failures due to damage to the physical structure (straps/fasteners) and catastrophic damage (compromised plate and carcass) totaled 22.7% of the sample.

Table 3: Analysis of the electronic and mechanical integrity of bovine IoT sensors (BLE devices) after 100 days of continuous field monitoring in an ICLF system in São Carlos, SP, Brazil.

Results	N	%	Observation
Functional (end of cycle)	8	36.4	They were operational, but with battery voltage indicating the end of their useful life (between 2.8 V and 2.85 V).
Failure due to battery depletion	5	22.7	became inoperative due to complete battery depletion (voltage ≤ 2.3 V), leading to firmware locking in DFU mode.
Firmware failure (battery functional)	3	13.6	They presented a critical firmware failure, rendering it inoperable even with the battery showing a usable charge (≥ 2.56V).
Mechanical failure (functional electronics)	2	9.1	failed due to damage to the physical structure (strap or fastener), while the electronic module remained functional.
Catastrophic failure (mechanical and electronic damage)	3	13.6	suffered severe physical damage that compromised both the external structure and the internal electronic board.
Intermittent failure (internal damage)	1	4. 5	exhibited intermittent operation, probably due to internal physical damage (e.g., cold solder joint), despite the battery being functional.
Total beacons analyzed			22

These indicators show that the shielding of the devices must be able to withstand the heterogeneity of the silvipastoril environment and physical contact between animals otherwise the "observational availability" of the herd will be compromised. To address these specific limitations, Taggen Industries systematically evolved the beacon design and firmware during the project. Specifically, the mechanical housing was redesigned into a ruggedized IP68 casing with reinforced fasteners to withstand physical animal-to-animal contact and environmental friction. On the firmware side, low-voltage management protocols were implemented to prevent DFU-mode locking and flash memory corruption under critical power states, alongside optimized sleep routines to extend battery life well beyond the initial pilot phase.

Although the daily detection rate reported in other sections exceeds 98.5%, demonstrating the efficiency of the gateway network, the durability of the wearable devices (beacons) is the factor currently limiting uninterrupted longitudinal monitoring. Overcoming these bottlenecks will be essential for the system to continuously generate objective evidence of animal welfare and space use.

From a commercial and regulatory point of view, physical and electronic robustness is what will ensure that electronic identification remains intact throughout the animal's life, meeting the goals of the Brazilian National Individual Identification Plan (PNIB) by 2032.

Conclusion

The implementation of an IoT network based on BLE 5.0 and WLS trilateration is technically viable and a robust solution for individual cattle identification and continuous monitoring, overcoming the signal and cost limitations of traditional GPS systems in complex environments such as ICLF (Integrated Crop-Livestock-Forestry Systems). The detection rate of 98.5% and the generation of real-time digital ethograms provided a precision management tool ensuring data integrity. The system enables quantification of animal welfare and space use without observational bias. This architecture is interoperable with the requirements of the National Animal Identification Plan (PNIB), positioning Brazil to meet the stringent traceability requirements of the international market by 2032.

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