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INTELLIGENT CATTLE MONITORING IN TROPICAL ENVIRONMENTS: INTEGRATING LPWAN AND SATELLITE TECHNOLOGIES AT THE SOGENAC CRAL, KOLO-FUMA (DRC)

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ABSTRACT

In tropical regions, animal traceability is a survival issue for farming families: cattle loss, theft and undetected disease threaten income and food security. This article analyses how satellite positioning, Low-Power Wide-Area Networks (LPWAN, notably LoRaWAN) and cellular networks can be combined for cattle monitoring at the SOGENAC CRAL in Kolo-Fuma (50,000 ha; 16,000 head). Field data come from a survey of 250 staff members (response rate 94%), 15 interviews and a risk analysis: monitoring is entirely manual (digital geolocation 0%) and cattle loss and theft is the most cited problem (36.8%; 95% CI: 31.1–42.9%). A GNSS/GSM collar and a web platform (Firebase, Leaflet) were designed and simulated (Proteus); simulation validated GNSS frame decoding, GSM transmission, GPS-timeout resilience and a 20-position buffer. A Monte-Carlo model shows that at least 85% of alerts arrive within 15 minutes outside white zones, but only 25% in white zones, which motivates a hybrid architecture. We propose a three-layer design in which collars use GNSS for positioning and LoRaWAN for short-range transmission to a few site gateways; gateways forward data over 4G where available and over a satellite IoT link in white zones. Because satellite terminals cost more than €500 per unit and subscriptions more than €100 per year, satellite connectivity is justified at gateway level rather than per animal. An energy model gives about 3.3 days of autonomy for the initial GSM version and about 28 days for an optimized GSM version; the LPWAN gain remains to be measured. Economically, equipping every animal is not profitable (payback of about 14 years), whereas a sentinel strategy (one collar per 20 head) could pay back within

months if its protection hypothesis holds. Operational benefits (theft, health, reproduction) are discussed as hypotheses to be tested. A real deployment plan for the whole domain (16,000 head, 50,000 ha; about ten gateways, enriched collars) is defined, with a conditional business case whose benefits are targets, not measured results. A sensitivity analysis shows that full-herd equipping needs an annual loss rate above about 3.75% to break even, whereas sentinels stay profitable down to about 0.2%. The LPWAN and satellite components are proposed and argued, not simulated or measured; a physical pilot is required.

Keywords: Cattle monitoring; LPWAN; LoRaWAN; Satellite; GNSS; Internet of Things; Tropical environment; Precision livestock farming; SOGENAC.

1 INTRODUCTION

1.1 Context and problem statement

In tropical areas, animal traceability goes far beyond the technical dimension: it is a survival guarantee for farmers and their families. Cattle losses due to theft or disease weaken entire communities and compromise their income, food security and sometimes social cohesion. Developing a robust and affordable solution is therefore a vital need.

Cattle theft, disease (trypanosomiasis in particular), distant pastures and the difficulty of knowing the state of the herd in real time combine to weaken extensive livestock farming. Without a localisation tool, a loss is only discovered at the next count, when it is too late to find the animal or identify the cause; our survey confirms this situation (§ 3.1).

1.2 Limits of existing solutions and opportunities of the IoT

Precision Livestock Farming relies on continuous animal monitoring and automated use of data [1]. Satellite positioning technologies (GNSS) can locate an animal to within a few metres, but do not solve the problem of sending the position to the farmer. Three families of links are then available. Cellular networks (GSM/GPRS, LTE-M) are inexpensive where they are covered. LPWAN networks, notably LoRaWAN, offer low power consumption and a range of several kilometres in rural areas, but their capacity is limited and their efficiency declines with terminal density and signalling overload [2, 3]. Satellite links provide global coverage, but at a high cost and with data-volume restrictions.

Humidity, dense vegetation, large pastures and limited accessibility characterise tropical sites and directly affect the performance of these technologies. At the SOGENAC CRAL in Kolo-Fuma (50,000 ha; 16,000 head), monitoring still relies on paper registers, visual counts and walkie-talkies with a range of 5 to 10 km. Available Congolese studies are mostly limited to a single technology (GSM, ZigBee, health sensors) with neither prior simulation nor a traceability platform [4–6].

Commercial solutions face five obstacles in tropical environments: (i) the lack of reliable mobile coverage, which creates “white zones”; (ii) energy constraints, as access to electricity is limited; (iii) harsh environmental conditions (heat, humidity, dust, dense vegetation); (iv) high costs for both equipment and subscriptions; (v) poor fit with extensive practices, many products being designed for intensive farming in temperate climates. Conversely, the Internet of Things opens two complementary avenues: LPWAN networks, designed for long range and low consumption, and low-Earth-orbit satellite constellations, which bring connectivity even to remote regions [7, 8]. Neither meets all needs on its own: LoRaWAN is frugal and inexpensive but its coverage depends on terrain and vegetation cover, whereas satellite covers everywhere but at a higher cost, with more constrained latency and data volumes.

2 LITERATURE REVIEW

2.1 Field trials

Recent field trials show that the GPS/LoRa pairing is viable for cattle, but with highly variable performance. Jaikaeo et al. [9] report a collar costing about USD 65 per unit, with an average autonomy of 20 days, whose communication depends largely on terrain; Mohapatra [10] reports, on 15 cattle and 30 acres, a range of up to 6.5 km, 97.5% of packets received and 28 days of autonomy; conversely, Nyamuryekung’e et al. [11] observe a reception rate of about 40% in a trial on a 38-ha pasture. On the satellite side, Centenaro et al. [7] stress that low-Earth-orbit constellations offer a good trade-off between coverage and latency for IoT in remote areas. Among the studies reviewed, none combines LPWAN and satellite on a domain of several tens of thousands of hectares in Central Africa.

2.2 Capabilities and limits of LoRaWAN

Adelantado et al. [12] provide an independent analysis: LoRaWAN operates in an unlicensed ISM band, which makes it possible to deploy a private network without a mobile operator, with a maximum raw data rate of 27 kbit/s; a single

gateway can in principle collect data from thousands of terminals located several kilometres away. The same authors insist on the limits of the technology, which must be understood to avoid excessive expectations. In our case, a collar only sends a short frame every 10 minutes, which preserves network capacity; this margin would shrink if the number of terminals per gateway or the sending frequency were increased, which argues for a sentinel-collar strategy.

2.3 GNSS positioning in tropical environments

The error sources of satellite positioning (multipath, attenuation by vegetation, poor satellite geometry) are described in detail by Kaplan and Hegarty [13]; they explain the HDOP and satellite-count filtering used here. In the field, trials on cattle report position errors of the order of 5 m [11], compatible with rangeland management and movement monitoring [9]. For a geofence with a 10 m margin (§ 3.2), this order of magnitude is acceptable, but it does not remove the need to measure accuracy under dense cover.

2.4 Digital adoption in African livestock farming

A recent review of precision dairy farming in Africa [14] identifies recurring barriers: high technology costs, limited access to finance, insufficient infrastructure, low digital literacy and technologies poorly adapted to African conditions. These barriers, which carry over to cattle monitoring, are consistent with our survey results (no digital tool in use) and justify three design choices: a controlled cost per collar, a transmission chain independent of operators where they are absent, and a simple web interface for guards and veterinarians.

Table 1: Summary of the studies reviewed and lessons for the Kolo-Fuma site.

Study	Technology	Main result	Lesson for our site
Jaikaeo et al. [9]	GPS/LoRa, dedicated channel access	≈ USD 65 per unit; 20 days of autonomy; communication depends on terrain	Measure the range according to the site's terrain
Mohapatra [10]	GPS/LoRa, gateways, cloud	Up to 6.5 km; 97.5% of packets; 28 days (15 cattle)	Upper benchmark, small-scale trial
Nyamuryekung'e et al. [11]	LoRaWAN, GPS	≈ 40% of packets received (38-ha pasture)	Lower benchmark: plan for a buffer and measurements
Adelantado et al. [12]	LoRaWAN (analysis)	ISM band, private network possible; limits to be understood	Private network; monitor capacity
Centenaro et al. [7]	Satellite IoT (survey)	Low orbit: good coverage/latency trade-off	Satellite relay at gateway level
Tadele et al. [14]	Precision dairy farming, Africa	Barriers: cost, finance, infrastructure, literacy	Controlled cost; simple interface

2.5 Synthesis and gap

The literature thus establishes (i) the feasibility of the GPS/LoRa pairing for cattle, (ii) the strong variability of link quality with site and terrain, (iii) the value of low-orbit satellites for remote areas, and (iv) the existence of economic and infrastructure barriers in Africa. It says nothing, however, about combining these building blocks on a 50,000-ha domain in a tropical environment, nor about the profitability of shared collars: this is the gap this article seeks to fill.

2.6 Research hypothesis and objectives

This article explores the hypothesis that a hybrid approach, combining the wide coverage of satellite with the frugality and low cost of LoRaWAN, is preferable to any single technology for monitoring cattle in tropical environments. It pursues four objectives: (i) to quantify field needs; (ii) to design and simulate a GNSS/GSM monitoring chain as a baseline; (iii) to compare the GSM, LPWAN and satellite options in terms of coverage, energy and cost, and to analyse the economic viability of deployment; (iv) to propose a reproducible hybrid architecture, a validation plan and the operational benefits to be tested (reduced theft, health monitoring, reproduction management). The originality lies in quantifying needs on a 50,000-ha domain, in the quantified comparison of the three links, and in an economic sensitivity analysis. Terminological note: "satellite" here covers two distinct uses, receiving GNSS signals to compute the position and, possibly, a satellite link to transmit the data.

3 MATERIALS AND METHODS

3.1 Study site and approach

The study took place at the SOGENAC CRAL in Kolo-Fuma (Kongo Central). The design followed a V-cycle with an incremental approach (needs, design, simulation, functional validation). Field data were collected in March 2025 and the simulation was carried out between April and August 2026.

The real deployment is planned over the whole domain (16,000 head, 50,000 ha), made up of wooded savanna (about 75%, i.e. 37,500 ha), gallery forest (15%, 7,500 ha) and open grassland (10%, 5,000 ha); these proportions are indicative and to be confirmed by a topographic survey. The centre has a powered administrative building (solar panels and generator), where the LoRaWAN gateways and the satellite terminal can be installed.

3.2 Survey and interviews

A questionnaire of 37 questions (including 17 five-level Likert items) was administered to 250 people (guards, technicians, veterinarians, managers; response rate 94%). Fifteen semi-structured interviews were analysed by content analysis [15], and three guard rounds were observed. Proportions are given with the Wilson interval [16], equation (1) with z = 1.96; the maximum margin of error (p = 0.5) is given by equation (2). Comparisons between roles rely on the χ^2 test, Cramér's V [17], equation (3), and the Bonferroni correction, equation (4). Risks were ranked by a simplified FMECA (criticality = probability × severity; major-risk threshold: > 12).

$$\hat{p}_W = \frac{\hat{p} + \frac{z^2}{2n} \pm z\sqrt{\frac{\hat{p}(1-\hat{p})}{n} + \frac{z^2}{4n^2}}}{1 + \frac{z^2}{n}} \tag{1}$$

$$e = z\sqrt{\frac{p(1-p)}{n}} = 1.96\sqrt{\frac{0.25}{250}} \approx 6.2\ \% \tag{2}$$

$$\chi^2 = \sum \frac{(O-E)^2}{E}, \qquad V = \sqrt{\frac{\chi^2}{n \min(l-1,\ c-1)}} \tag{3}$$

$$\alpha' = \frac{\alpha}{k} = \frac{0.05}{4} = 0.0125 \tag{4}$$

3.3 Baseline architecture (Rev 1.0, simulated)

The baseline collar combines a NEO-6M GPS receiver, an Arduino UNO and a SIM900 GSM/GPRS module, powered by a 3,400 mAh Li-ion battery. Positions are formatted in JSON and sent to Firebase, then displayed on a web application (HTML, CSS, JavaScript, Leaflet). A zone-exit alert (geofencing) relies on the Haversine distance [18], equation (5), where RT is the Earth's radius: a fix is retained only if HDOP ≤ 2 with at least 5 satellites, and the alert is issued only after three consecutive fixes beyond R − m, R being the radius of the zone and m a safety margin. Component choice relies on the AHP method [19], equation (6).

$$d = 2R_T \arcsin\sqrt{\sin^2\left(\frac{\Delta\varphi}{2}\right) + \cos\varphi_1 \cos\varphi_2 \sin^2\left(\frac{\Delta\lambda}{2}\right)} \tag{5}$$

$$S_j = \sum_i w_i s_{ij}, \qquad CI = \frac{\lambda_{\max} - n}{n-1}, \qquad CR = \frac{CI}{RI} < 0.1 \tag{6}$$

3.4 Simulation and models

The circuit and code (C++) were simulated in Proteus 8 Professional through seven tests (AT commands, NMEA frames, integration, resilience, buffer, geofence, network). Since Proteus does not simulate radio, cellular coverage was modelled by a two-state Markov chain (covered / white zone), whose availability is given by equation (7), where λ is the rate of switching to a white zone and μ the rate of return to coverage. The mean outage is 20 min and one sending attempt takes place every 5 minutes; four coverage qualities were simulated by Monte-Carlo.

$$A = \frac{\mu}{\lambda + \mu} \tag{7}$$

Energy is modelled by equation (8) (Ik and tk: current and duration of phase k; T: period; η: useful efficiency; Cbat: battery capacity), and solar input by equation (9). The avoided annual gain of a deployment and its payback period are given by equation (10) (Nprot: protected animals; p: loss rate; v: value per animal; e: effectiveness; C: annual operating cost; I0: initial investment). Assumptions: 16,000 head, 5% annual loss, USD 500 per animal, collar at USD 70.

$$Q_{cycle} = \sum_k I_k t_k, \qquad I_{avg} = \frac{Q_{cycle}}{T}, \qquad J = \frac{\eta C_{bat}}{24 I_{avg}} \tag{8}$$

$$E_{day} = P_{pv} H_{sun} \eta_{sys} \tag{9}$$

$$G = N_{prot}\, p\, v\, e, \qquad \text{payback} = \frac{I_0}{G - C} \tag{10}$$

3.5 Technologies considered

LoRaWAN. LPWAN protocol operating in unlicensed sub-gigahertz bands, with adaptive data rate and low consumption, which lets the operator run a private network without a mobile operator [12]. Range depends strongly on terrain and vegetation (§ 1.3). **Satellite.** Three families of services were considered for the gateways' backhaul link: a low-rate short messaging service (of the Inmarsat IsatData Pro type), suited to alerts; a medium-rate service (of the Iridium Certus type); and high-speed access (of the Starlink type), oversized for short messages and more power-hungry. The choice of provider and tariff remains to be settled by consultation, as prices vary widely and were not verified here. **Collars.** Rev 2.0 can be offered in an enriched version with a three-axis accelerometer, a body-temperature sensor, an IP68 waterproof case and a small solar panel, at the price of higher consumption and cost; these sensors are not included in the energy and economic balances of this article.

3.6 Comparative analysis of GSM / LPWAN / satellite

The three families of links are compared on five criteria: coverage on the site, consumption, cost per collar and per year, admissible data volume, and longevity. For GSM and satellite, values come from project data (costs, simulated coverage). For LoRaWAN, the comparison is qualitative and based on the literature, as no measurement was made on the site.

3.7 Real deployment plan and validation protocol

Deployment over the domain follows four steps (Table 2 and Figure 7), the 16,000 cattle being equipped progressively, park by park. Data (hourly position, speed, activity, temperature, geofence crossings, alerts) will be stored in a cloud database and analysed with Python (pandas, scikit-learn). The theft rate will be compared with the reference period of the 12 months preceding deployment, taken from the CRAL's security registers. A random-forest classifier will be trained on activity and temperature data and then validated against veterinary diagnoses; heats will be detected by a rise in activity over 6 to 12 hours (initial threshold: +80%), confirmed by veterinary inspection. Staff acceptability will be measured by questionnaire (TAM/UTAUT models) [22, 23].

Table 2: Steps of the real deployment and indicators measured.

Step	Schedule	Equipment	Measurements and criteria
1. Validation	Months 1–2	10 then 50 collars; first gateway	Settings and training; RSSI/SNR mapping at 500 points; first fix < 30 s; packet loss < 5% (gate 1)
2. Deployment	Months 3–8	16,000 cattle; 10 gateways on high points; satellite backhaul terminals	Coverage by zone type (gate 2: coverage ≥ 85%); add gateways if needed
3. Operation	Months 9–20	Real-conditions operation for 12 months	Battery voltage monitored daily; response times on alerts; damaged or lost collars
4. Evaluation	Month 21	Full review	Theft compared with the reference; classifier sensitivity and specificity; confirmed heats; 3-year cost-benefit analysis (gate 3: losses cut by more than 50%, payback ≤ 3 years)

4 RESULTS

4.1 Field needs

None of the 250 respondents had a digital monitoring tool (0%; Wilson CI: 0–1.5%): 56.8% relied on the paper register, 31.2% on direct observation, 12.0% on ear tags. Table 3 and Figure 1 rank the problems (403 citations, i.e. 1.6 problems per respondent).

Table 3: Main problems cited (N = 250, multiple answers).

Problem	Citations	%	95% CI
Cattle loss / theft	92	36.8	31.1–42.9
Health monitoring difficulty	68	27.2	22.1–33.0
Poor pasture management	51	20.4	15.9–25.8
Counting errors	39	15.6	11.6–20.6
Lack of traceability	38	15.2	11.3–20.2
Locating sick animals	35	14.0	10.2–18.8
Ineffective communication	30	12.0	8.5–16.6

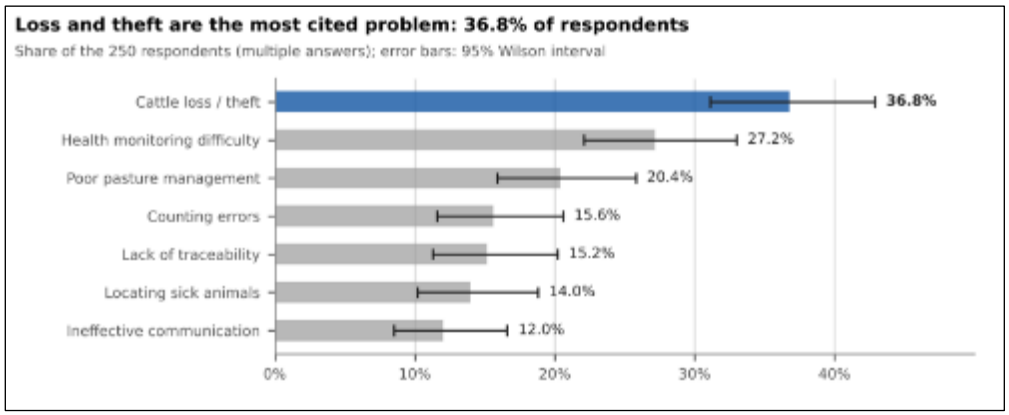


Figure 1: Problems cited, drawn from Table 3 (March 2025 survey, N = 250).

Loss and theft are perceived uniformly across all roles ($\chi^2 = 2.45$; $p = 0.29$). Only health monitoring differs significantly by role after Bonferroni correction ($\chi^2 = 18.72$; $p = 0.0001$; $V = 0.27$): veterinarians must find the animal before treating

it. The FMECA ranks loss/theft first (criticality 20), ahead of delayed care and overgrazing (15 each). A technician reports losing 15 animals in a month without being able to establish the cause: “without GPS, it’s a black box”.

4.2 Validation of the GNSS/GSM chain (simulation)

The five tests carried out in Proteus were validated: correct responses to AT commands, valid NMEA frames, sending of an SMS containing the coordinates, sleep triggered when there is no fix, and 20 positions kept during a network outage. The hysteresis rule brings the probability of a false alert down to about 6×10^{-8} (σ = 3 m; margin of 10 m). Figure 2 presents the collar algorithm: a position is stored only if the fix is valid, and transmission is attempted only if the network responds.

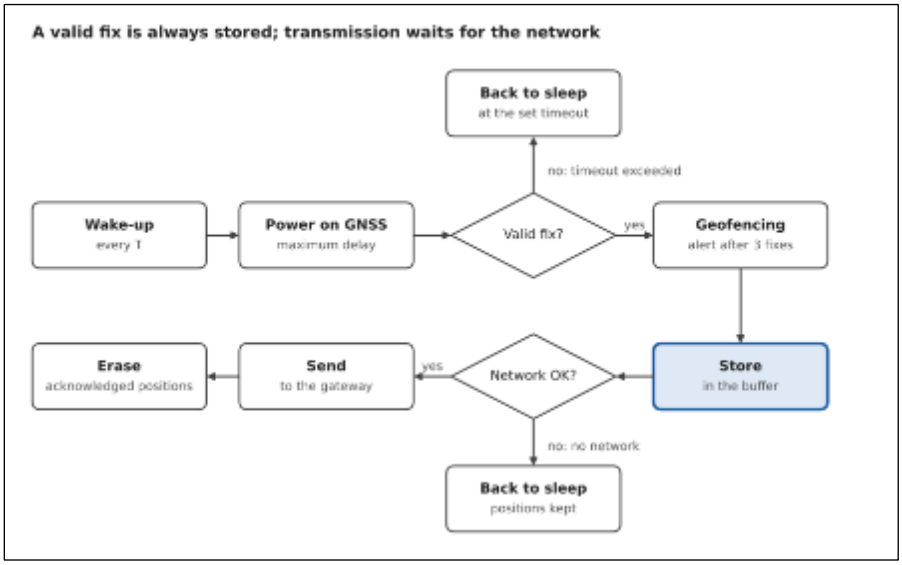


Figure 2: General collar algorithm (Rev 2.0).

4.3 Limit of cellular coverage: motivation for the hybrid

Table 4: Alert reception delay by coverage level (Monte-Carlo).

Coverage	Availability	Median delay (min)	5–95% range (min)	Received within ≤ 15 min
Excellent	99.9%	2.5	0.3–4.7	99.9%
Fair	95%	2.6	0.3–5.0	97.1%
Intermittent	75%	3.4	0.3–38.2	85.0%
White zone	10%	36.4	2.4–157.2	25.0%

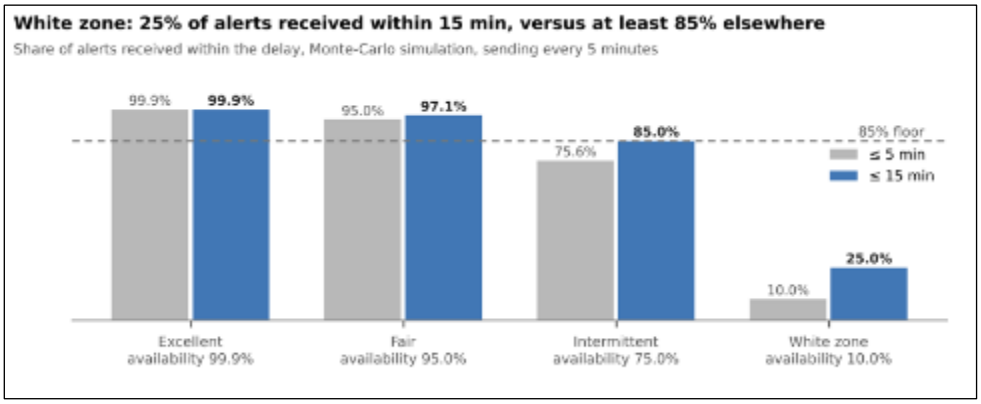


Figure 3: Alerts received within the delay, drawn from Table 4 (Monte-Carlo simulation).

The degradation in white zones is the result that directly justifies the use of a complementary link (local LPWAN and satellite as backup).

4.4 Energy

For the initial GSM version (Rev 1.0), the 5-minute cycle consumes 10,950 mAs, i.e. a mean current of 36.5 mA and an autonomy of about 3.3 days; the Arduino in sleep mode accounts for nearly half of the energy. The optimised GSM version (ESP32, NEO-M8N, SIM7000, 10-minute cycle, assumptions to be validated) gives a mean current of 5.3 mA and about 28 days with a 4,000 mAh LiFePO4 battery (90% efficiency). GSM transmission then represents 60% of the cycle energy (1,900 mAs out of 3,180), against 22% for the GNSS fix (700 mAs). A 0.5 W panel (about 1.1 Wh/day under the assumptions used) would cover more than twice the daily consumption of 127 mAh. Figure 4 shows that spacing out transmissions benefits Rev 2.0 above all: from 15.6 days at 5 min to 87.4 days at 60 min, whereas Rev 1.0 levels off at 5.6 days.

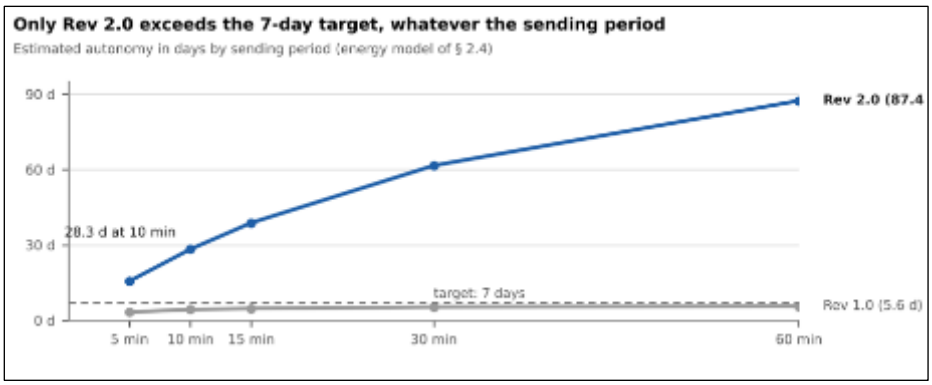


Figure 4: Autonomy computed with the currents and durations of § 3.4 (assumptions to be validated).

4.5 Comparison of links

Table 5: Comparison of transmission options for cattle monitoring.

Criterion	GSM / LTE-M	LPWAN (LoRaWAN)	Satellite IoT
Coverage	Depends on operators; white zones (§ 3.3)	To be built: a few gateways on the site	Global
Collar consumption	High (transmission = 60% of the cycle)	Lower (to be measured)	High to very high (terminal needs sky view)
Cost per collar	≈ USD 70 (complete collar)	Same order; gateways extra (to be costed)	> €500 per terminal
Recurring cost	SIM subscription	No operator if private network	> €100 per year per terminal
Data volume	Sufficient	Low (short frames)	Restricted
Longevity	2G being phased out; 4G preferred	Open standard	Depends on the provider

GSM alone leaves white zones without a fast alert. Satellite per animal is ruled out by its cost: for 16,000 head, more than €500 per collar is prohibitive. LPWAN reduces the collar's long-distance transmission, but requires gateways to be deployed and powered.

4.6 Proposed hybrid architecture

The architecture has three layers (Figure 5). **Animal layer:** the collar computes its position by GNSS (NEO-M8N), applies geofencing locally and sends a short LoRaWAN frame; if the link is unavailable, it stores its positions in a buffer (20 positions validated in simulation). **Gateway layer:** a few gateways spread over the site receive the collars' frames and forward them to Firebase over 4G/LTE-M when the network is available, or over a satellite IoT link when it is not. **Supervision layer:** Firebase and the Leaflet web application display positions, history and alerts, with a veterinary view (animal location and history). The cost of the satellite is thus borne by a few gateways, not by 16,000 animals.

An order of magnitude for the number of gateways follows from equation (11), where S is the area of the domain, r the useful range and k an overlap factor for redundancy and terrain. The ranges used are assumptions: 6.5 km corresponds to a trial in open terrain (Mohapatra, 2025) and 2 km to an unfavourable case under dense cover (Table 6). The actual range on the site is precisely what the pilot must measure.

$$N = \left\lceil \frac{k\,S}{\pi r^2} \right\rceil, \qquad k = 1.5, \quad S = 500\ \text{km}^2 \tag{11}$$

Table 6: Indicative number of gateways for 500 km² (k = 1.5, range assumptions).

Useful range r (km)	Area covered per gateway (km²)	Gateways required
2.0 (dense cover)	12.6	60
5.0	78.5	10
6.5 (open terrain)	132.7	6

For the deployment plan, a calculation by zone type (equation 11) with assumed ranges of 8.2 km in wooded savanna, 3.5 km in gallery forest and 12.5 km in open grassland gives 3 + 3 + 1 = 7 gateways for 375, 75 and 50 km² respectively. We retain 10 gateways to keep a margin; these ranges are assumptions that the RSSI/SNR survey of step 1 will have to confirm or correct.

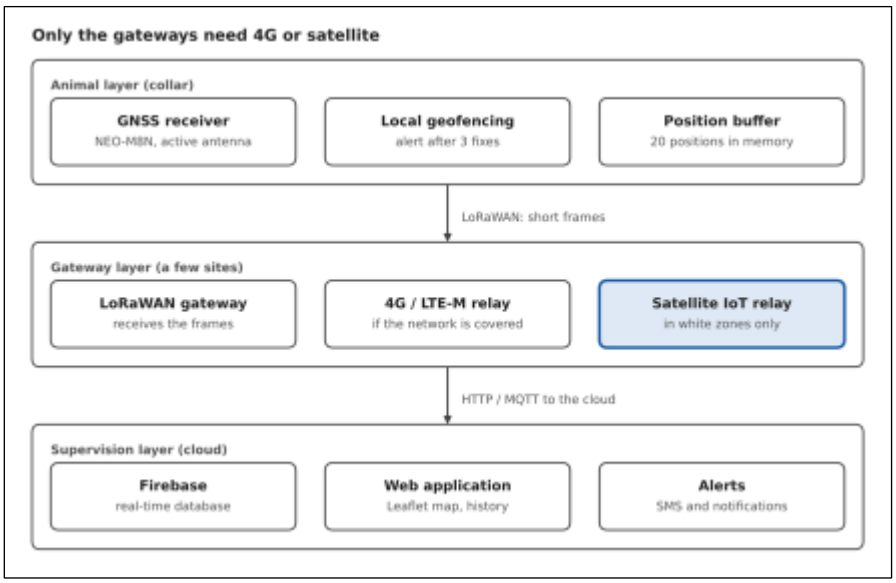


Figure 5: Three-layer hybrid architecture.

4.7 Economic analysis

Table 7: Deployment scenarios (GSM technology, assumptions of § 2.4).

Scenario	Collars	Invest. (USD)	Operation (USD/yr)	Avoided loss (USD/yr)	Net (USD/yr)	Payback
Whole herd	16,000	1,120,000	240,000	320,000	80,000	14 years
Pilot (equipped animals only)	500	35,000	7,500	10,000	2,500	14 years
Sentinels (1 per 20), e = 80%	800	56,000	12,000	320,000	308,000	2.2 months

Equipping every animal is not profitable. The sentinel strategy exploits the herd behaviour of cattle, but rests on the untested assumption that one collar protects about 20 animals; with an effectiveness of 20%, payback is still 10 months.

These figures include neither the LoRaWAN gateways nor the satellite subscription: adding them is a necessary step of the costing.

Table 8 tests sensitivity to the loss rate p (assumption from the thesis, not measured; e = 80%). Equipping the whole herd only becomes profitable if p exceeds about 3.75% (condition G = C), whereas sentinels remain so down to rates of about 0.19%: the sentinel strategy is therefore robust to an error on the loss rate, which is not the case for full equipping.

Table 8: Sensitivity to the annual loss rate p (e = 80%).

p	Avoided loss (USD/yr)	Sentinels net (USD/yr)	Sentinels payback	Whole herd net (USD/yr)	Whole herd payback
1%	64,000	52,000	12.9 months	−176,000	never
2%	128,000	116,000	5.8 months	−112,000	never
5%	320,000	308,000	2.2 months	80,000	14 years
8%	512,000	500,000	1.3 months	272,000	4.1 years

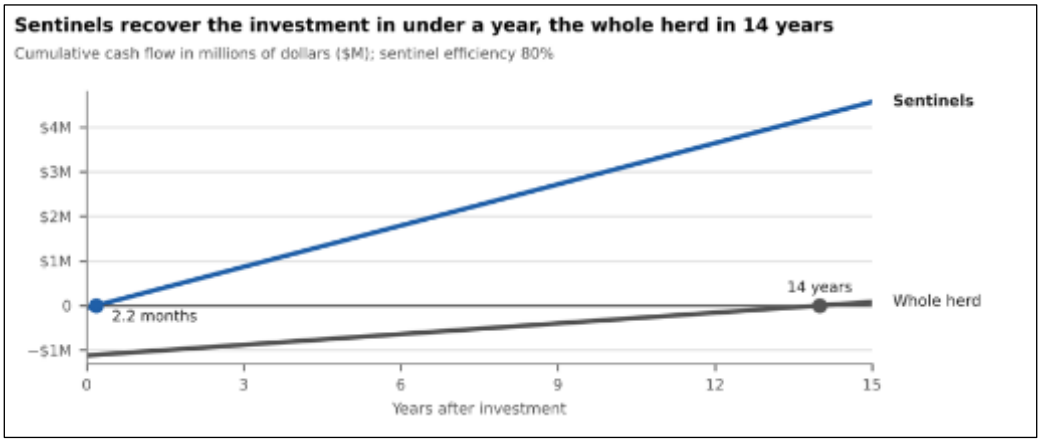


Figure 6: Cumulative cash flow computed from Table 7. The 500-collar pilot, not plotted, follows an almost flat trajectory (14 years).

Figure 7 divides deployment into four phases, from 10 collars to extension to other CRALs; three criteria govern the move from one phase to the next.

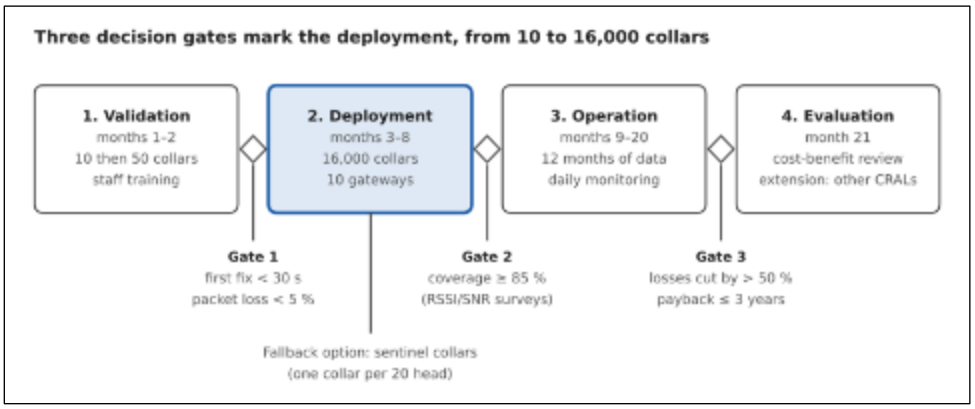


Figure 7: Progressive deployment plan in four phases.

4.8 Economic projection of deployment at domain scale

Table 9 projects, in dollars and over 3 years, the deployment of enriched collars (GNSS, accelerometer, temperature; about USD 100 per unit) across the domain's 16,000 cattle. It is a target scenario: the targeted effects (theft reduced by 75%, mortality reduced by 40%, conception rate from 55% to 78%) are objectives, not measured results, and the

baseline values (5% losses to theft, 5% mortality, conception rate of 55%, 50% breeding females) are assumptions to be confirmed from the CRAL registers. Unit values are USD 500 per animal and USD 300 per calf. Labour savings and the traceability premium sometimes put forward for other sites are not counted, as a precaution.

Table 9: Target deployment scenario over 3 years, 16,000 cattle (assumptions, to be validated).

Item	Amount (USD)
Investment (3 years)	
16,000 enriched collars (USD 100 each)	1,600,000
10 LoRaWAN gateways (USD 500 each)	5,000
Satellite terminals and subscriptions (10 × USD 5,000)	50,000
Training and maintenance (USD 12.5 per animal)	200,000
Total investment	1,855,000
Targeted annual benefits	
Thefts avoided (800 → 200 animals: 600 × USD 500)	300,000
Mortality avoided (800 → 480 animals: 320 × USD 500)	160,000
Improved conception (8,000 females: +1,840 calves × USD 300)	552,000
Total targeted annual benefits	1,012,000

If the targeted benefits were fully achieved, the investment would be paid back in about 22 months (1,855,000 / 1,012,000). The scenario is nevertheless sensitive: over three years, cumulative benefit reaches USD 3,036,000 at 100% of targets and only covers the investment from 61% of targets onward; at 50%, the deployment would run at a deficit of USD 337,000. Without any reproduction gain, annual benefit falls to USD 460,000 and payback exceeds 4 years: reproduction accounts for 55% of the targeted benefits. By comparison, the sentinel strategy of § 3.7 targets only loss and theft but requires only USD 56,000 of investment; it is the fallback option if health and reproduction uses are not exploited.

5 DISCUSSION

5.1 What is established and what is not

The need (traceability, fighting loss and theft), the logical feasibility of the GNSS/GSM chain and the degradation of delays in white zones rest on collected or simulated data. By contrast, the gains attributed to LPWAN (autonomy, range under vegetation cover) and the operation of the satellite-relay gateway come from the literature and reasoning, not from measurements on the site. Some sources mention an autonomy of several years for LPWAN sensors, but a GNSS collar cannot reach it so simply: the GNSS fix consumes energy at each position (700 mAs per cycle in our balance) and autonomy depends on sending frequency. This value must be measured, not assumed.

5.2 Positioning relative to the literature

The 20 to 28 days of autonomy reported by Jaikaeo et al. [9] and Mohapatra [10] are of the same order as our estimate of 28 days for Rev 2.0, which makes it plausible without proving it; their cost of about USD 65 is close to our USD 70 per collar. By contrast, the gap between 97.5% and 40% of packets received across trials [10, 11] shows that LoRa link quality depends strongly on the site, hence the need to measure range on site (gate 1) before any sizing. For satellite, the literature on low-orbit constellations [7] supports the choice of a relay at gateway level.

5.3 Why a hybrid model

The results converge: GSM alone is insufficient in white zones (25% of alerts received within 15 minutes), satellite per animal is unaffordable, and LPWAN alone requires a gateway infrastructure which, in an isolated area, itself needs a backhaul link. The combination distributes the constraints: frugal energy on the animal side, coverage ensured by the gateways, satellite cost shared. Its relevance contrasts with the Congolese studies cited, which rely on a single technology.

5.4 Adoption by staff

The barriers of digital literacy and poorly adapted tools reported by Tadele et al. [14] make training of guards and veterinarians inseparable from deployment: a simplified view, SMS alerts and hands-on field practice during the pilot condition adoption, which the acceptability measurement (TAM/UTAUT models) [22, 23] will make it possible to assess.

5.5 Risks specific to LPWAN in tropical environments

Dense vegetation and humidity attenuate radio signals [20], terrain can create shadow zones, and the capacity of a LoRaWAN network declines with the number of terminals and the transmission rate. Only an indicative number of gateways has been computed (§ 3.6); the actual number for 50,000 ha is an expected result of the pilot.

5.6 Expected operational benefits

Beyond localisation, an enriched collar could support three uses that this study has not evaluated: (i) fighting theft, through geofencing alerts and rapid intervention by the security team; (ii) health monitoring, by spotting animals with abnormal behaviour through the accelerometer and temperature, which addresses the difficulty of health monitoring (27.2% of citations); (iii) reproduction management, by detecting activity peaks associated with heats. These benefits remain hypotheses: measuring them requires a pilot with a reference period, precise indicators (theft rate, time to detect sick animals, conception rate, herd-management time) and, for (ii) and (iii), a learning model (for example a random forest) trained on local veterinary diagnoses.

5.7 Durability of the equipment

A deployment report from a large Australian property showed the feasibility of a private LoRaWAN network, but also collar losses (broken buckles, collar slippage) [21]: the rate of damaged or lost collars is an indicator to monitor from the pilot onward.

5.8 Localisation only or enriched collar?

The analyses of § 3.7 and § 3.8 reach different conclusions because they do not value the same uses. Based on localisation alone, the economics support only the sentinel strategy; with an enriched collar on every animal, the investment is only justified if health and reproduction uses are actually exploited by the staff, hence the importance of training and of integration with veterinary services.

5.9 Direct satellite on a few collars

A direct satellite module on sentinel collars or on animals in transhumance could double the LoRaWAN link for emergency alerts (theft, serious illness), at the extra cost noted in § 3.5. The latency of a short satellite messaging service, of the order of ten seconds, remains compatible with alerts but less so with strict real time; low-orbit constellations could reduce it [8].

5.10 Data governance and social acceptability

Collecting high-resolution position and activity data raises questions of ownership, confidentiality and data security, and some farmers may perceive the system as surveillance. Participatory design, transparency on data use and clear access rules are success conditions on a par with technical performance.

5.11 Limits

(i) Simulation results, no physical prototype; (ii) LPWAN and satellite components neither simulated nor measured; (iii) autonomy of the optimised version based on hypothetical currents; (iv) survey measuring perceptions rather than actual losses, the 5% loss rate being an assumption; (v) staff acceptability not yet measured (TAM/UTAUT models) [22, 23]; (vi) the economic analysis of § 3.7 includes neither gateway nor satellite costs, and that of § 3.8 rests on target effects and unverified baseline values.

6 CONCLUSION

This study shows that at the SOGENAC CRAL in Kolo-Fuma, cattle monitoring is entirely manual and that loss and theft are the priority problem. A GNSS/GSM chain validated in simulation provides a baseline, but its transmission degrades sharply in white zones. We propose a hybrid architecture, with GNSS positioning, LoRaWAN transmission to gateways and a 4G or satellite relay, which concentrates the satellite cost on a few gateways. A sentinel-collar strategy, subject to validation, is the only economically plausible route at herd scale. For the CRAL management, the decision is therefore less about whether to monitor the herd by GPS than about the number of sentinel collars and gateways to finance for a pilot.

Perspectives: (1) measure on site the range and reception rate of LoRaWAN under vegetation cover and in the rainy season, to size the number of gateways; (2) build 10 collars to measure time to first fix (target < 30 s), packet loss (< 5%) and real autonomy; (3) cost gateways and the satellite link to complete the economic analysis; (4) carry out the real deployment over the whole domain (16,000 head) and test the sentinel hypothesis on a subset of collars (target: loss reduction > 50%); (5) measure staff acceptability (TAM/UTAUT regression) [22, 23]; (6) develop behavioural anomaly detection (isolation index, Kalman filter, random forest) for health monitoring and heat detection; (7) study energy harvesting (solar, kinetic) and the social impact of the technology.

Recommendations for deployment: (a) start with a pilot limited in number of animals; (b) involve farmers and staff in design and training; (c) plan regular maintenance; (d) mobilise funding, for example through public-private partnerships; (e) integrate data into veterinary services; (f) develop mobile interfaces adapted to local languages. In the longer term, research could explore drones, blockchain for traceability, scaling to other tropical contexts and fusion of collar data with Earth observation from satellites.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflict of interest regarding this manuscript.

Statement of ethical approval

The study was conducted with the authorisation of the SOGENAC CRAL management. No experiment was carried out on animals: the data collected concern staff perceptions and herd-management practices.

Statement of informed consent

Informed consent was obtained from all individual participants included in the survey and in the interviews.

Data availability

The survey data and the simulation parameters used in this article are available from the corresponding author on reasonable request.

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