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Adaptive 5G Gateway for Smart Livestock Monitoring

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Abstract

Internet of Things (IoT) systems in smart livestock farming requires resilient real-time or periodic monitoring of animal welfare and farm productivity. This paper presents an implementation of a 5G gateway (Raspberry Pi 5 and Quectel RM520N-GL) that bridges the farm-based anchor sensor mesh network to a cloud server, ensuring reliable cattle health data (pH, temperature, motion) transmission across varying network conditions. The proposed solution features an automatic network detection and adaptation between 5G Standalone (SA), 5G Non-Standalone (NSA), 4G (LTE), and Wi-Fi, a dual layer buffer management with Random Access Memory (RAM) and SQLite storage to ensure no data loss during network outages, and a priority-based message handling for critical health alerts. Comprehensive test results reveal mean latencies of 38.5ms (5G-NSA, 95th percentile: 44.9ms), 34.7ms (4G LTE, P95: 40.0ms), and 24.0ms (Wi-Fi, P95: 26.4ms), all with zero message loss. The gateway maintained stable operation across 47 dB signal range (-65 to -112 dBm), including private 5G-SA infrastructure during our multi-environment testing.

1 Introduction

Smart livestock farming requires continuous monitoring of animal health vitals including body temperature, pH, and activity levels [1]. While IoT sensors like bolus devices can continuously monitor vital parameters, another critical challenge lies in reliable data transmission from the farm locations to cloud-based analytics platforms. Fifth Generation (5G) cellular networks offer promising solutions with their low latency and support for massive Internet of Things (IoT) deployments [2]. Some farm locations (especially, rural areas) often lack consistent 5G coverage, experiencing network degradation or complete disconnection [3]. Some solutions typically rely on LoRaWAN connectivity, which can result in high latency and limited bandwidth for real-time monitoring of large herds [4].

This work presents a 5G gateway that bridges the gap between local sensor networks and cloud infrastructure and focuses on maintaining continuous operation through network adaptation and edge processing capabilities. We provide an empirical validation of the multi-network adaptive gateway architecture developed as part of the Smart Livestock Farming project at Brandenburg University of Technology (BTU) Cottbus-Senftenberg. Our contributions include: (1) A three-layer architecture with adaptive network selection, priority-based Quality of Service (QoS) management, and edge analytics, (2) Comprehensive empirical validation across 60-minute baseline tests on commercial 5G-NSA, 4G LTE, and Wi-Fi networks, (3) Demonstration of operation across a 47 dB signal range from excellent (-65 dBm) to marginal (-112 dBm) conditions, and (4) Dual-layer buffering achieving 100% message recovery during network outages.

2 Related Work

Previous agricultural IoT gateway implementations have primarily focused on single-network solutions. Talavera et al. [5] reviewed IoT applications in agriculture but noted the lack of multi-network resilience. Commercial solutions offer industrial reliability but are limited to LoRaWAN-to-4G bridging without 5G support [4].

2.1 5G for Smart Agriculture

The theoretical benefits of 5G for agriculture have been extensively studied in simulation. Liu et al. [7] discussed potential improvements in precision agriculture, while Meng et al. [8] analyzed low-latency benefits for real-time control.

The distinction between 5G Standalone (SA) and Non-Standalone (NSA) architectures is crucial for rural deployment. As explained by Alnaas and Alhodairy [9], 5G-NSA leverages existing 4G infrastructure as an anchor, making it more readily deployable but potentially compromising latency characteristics.

2.2 Network Resilience in IoT Systems

Resilient data transmission in challenged networks has been addressed through various buffering approaches. Jafri et al. [10] proposed multi-tier buffering for narrowband IoT, but agricultural environments require different optimization strategies due to extended outages and extreme signal variations. Our dual-layer approach extends this work with agricultural-specific adaptations.

3 System Architecture

Figure 1 depicts the system architecture showing the 5G gateway's position as the critical bridge between farm sensors and cloud infrastructure. The gateway consists of a Message Queuing Telemetry Transport (MQTT) broker, dual buffering, QoS management, edge analytics and adaptive network selection features.

The architecture consists of three layers with the gateway implementation as the main focus of our work:

- Farm Layer: Bolus sensors inside the cattle measure temperature, pH, and motion, transmitting data to anchor nodes distributed across grazing areas via Wi-Fi mesh network.

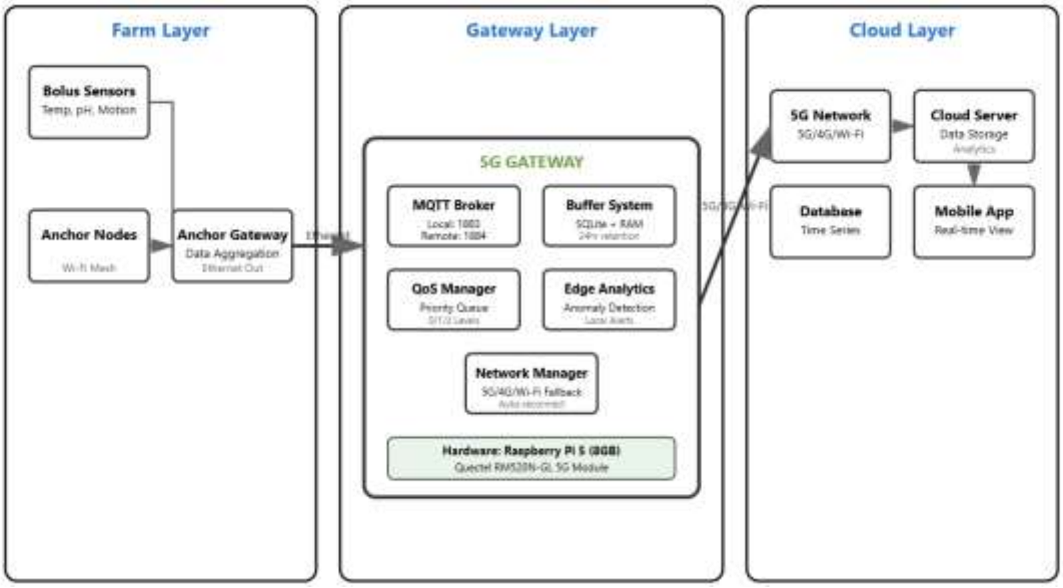

Figure 1 Proposed Sytem Architecture

- Gateway Layer: The adaptive 5G gateway receives aggregated data from the anchor node via Ethernet, implementing dual buffering, network selection, and edge analytics.
- Cloud Layer: Receives processed data for storage, analysis, and mobile app distribution.

3.1 Hardware Platform

The gateway hardware consists of a Raspberry Pi 5 (8 GB RAM)) with ARM Cortex-A76 processor at 2.4 GHz, providing sufficient computational capacity while maintaining low power consumption [11]. It is connected to a Quectel RM520N-GL 5G modem via USB-to-M.2 B-Key adapter. The RM520N-GL supports 5G New Radio (NR) Sub-6 GHz bands including n1, n3, n28, n41, n77, n78, and n79, as well as LTE bands B1, B3, B7, B8, B20, B28, B38, B40, and B41 [12]. The network status is monitored through Attention (AT) commands over a serial interface (/dev/ttyUSB2 at 115200 baud).

3.2 MQTT Bridge Architecture

The gateway implements a dual-client MQTT bridge [6]. A local Mosquito broker (port 1883) receives telemetry from the anchor node, while a dual-client system subscribes locally and publishes to the cloud broker (port 1884). This separation enables local buffering during cloud disconnection. All livestock/# topics are automatically forwarded with source validation and format checking, and ensures message persistence during cloud disconnections.

3.3 Quality of Service Manager

The QoS Manager implements priority-based message handling across three MQTT QoS levels. Critical health alerts such as fever detection or abnormal pH readings use QoS 2 (exactly one delivery) ensuring guaranteed transmission with duplicate message detection. Regular health telemetry including periodic temperature and activity readings use QoS 1 (at least one delivery) providing reliable transmission with potential duplicates. Location updates and non-critical status messages use QoS 0 (best effort delivery) minimizing overhead for high-frequency, loss-tolerant data. The edge analytics feature performs local anomaly detection for temperature deviations exceeding 2°C from baseline, generating immediate alerts without cloud dependency.

Network	Signal Threshold	Transmission Strategy	Message Batching
5G NR	> -70 dBm	Real-time streaming	None (immediate)
4G LTE (strong)	> -85 dBm	Light compression	10 messages
4G LTE (weak)	> -100 dBm	Heavy compression	50 messages
Wi-Fi (strong)	> -60 dBm	Real-time streaming	None (immediate)
Wi-Fi (moderate)	> -75 dBm	Light compression	10 messages
Wi-Fi (weak)	> -85 dBm	Heavy compression	50 messages
Offline	No signal	Local buffering only	Unlimited (to buffer)

Table 1: Adaptive Network Manager Thresholds and Strategies.

3.4 Adaptive Network Manager

The Network Manager continuously monitors signal quality through AT commands (including AT+QRSRP for cellular Reference Signal Received Power (RSRP), AT+QENG for serving cell information) and adapts transmission strategy based on current conditions. Table 1 presents the adaptive thresholds and corresponding strategies for each network type.

3.5 Dual-Layer Buffer System

A two-tier buffering architecture ensures zero message loss during network outages. The primary buffer uses a Python collections.deque structure in Random Access Memory (RAM) with a capacity of 10,000 messages. When RAM buffer utilization exceeds 80%, messages automatically overflow to the secondary SQLite database, providing persistent storage for extended outages. Upon network recovery, messages are transmitted in First-In-First-Out (FIFO) order with configurable batch sizes (default: 50 messages) to prevent network congestion during buffer flush operations.

4 Experimental Methodology

4.1 Test Environments

Comprehensive testing was conducted across different network types:

- 5G-NSA: Deutsche Telekom network with EN-DC (LTE Band 3 + NR Band n78)
- 4G LTE: Deutsche Telekom Band 3 (1800 MHz)
- Campus Wi-Fi: Eduroam
- Private Campus 5G-SA: BTU campus network Band n78

4.2 Test Protocols

We implemented a livestock sensor data simulator which generated health telemetry including temperature (38-40°C), rumen pH (6.2-7.0), and activity levels (0-100) for 72 to 200 virtual cattle. Each simulated cow transmitted data every 60 seconds via MQTT QoS 1. Three test categories were performed: (1) 60-minute baseline tests measuring latency via Internet Control Message Protocol (ICMP) ping to Google DNS (8.8.8.8), sampled every 10 seconds which yielded 360 samples per test; (2) throughput stress tests with 200 cows (double baseline load), and (3) buffer tests using a three-phase protocol: normal operation, simulated outage via remote broker termination, and recovery monitoring.

5 Results

Network	Latency (ms)	Std Dev	P95 (ms)	RSRP (dBm)	Msg Loss
5G-NSA (n78/B3)	38.5	±5.7	44.9	-86.7	0%
4G LTE (B3)	34.7	±4.9	40.0	-85.2	0%
Wi-Fi (2.4 GHz)	24.0	±1.2	26.4	-65*	0%

** Wi-Fi signal measured as RSSI (Received Signal Strength Indicator)*

Table 2: Network Performance (60-minute baseline tests)

5.1 Network Latency Comparison

Table 2 summarizes network performance across 60-minute baseline tests on Deutsche Telekom's commercial network. All networks achieved sub-50ms 95th percentile latency, meeting requirements for real-time livestock monitoring where sub-minute alert delivery is acceptable. Notably, 4G LTE (34.7ms mean) outperformed 5G-NSA (38.5ms mean), which could be attributed to dual-connectivity coordination overhead in NSA mode where the device must coordinate between LTE anchor and NR secondary cells. Wi-Fi achieved the lowest latency (24.0ms) with exceptional stability (±1.2ms standard deviation) due to local network proximity.

5.2 Signal Range Validation

Our testing across multiple environments validated gateway operation across 47 dB signal range. Table 3 summarizes results from BTU campus tests, demonstrating successful operation from good signal conditions in the 5G-SA laboratory (-66 dBm RSRP) to marginal commercial cellular coverage outdoors (-112 dBm RSRP).

Network	RSRP (dBm)	Duration	Status
5G-SA (n78)	-66	~10 min	Operational
Wi-Fi (Eduroam)	-75*	~7 min	Operational
5G-NSA (n78/B3)	-110	~3 min	Operational
4G LTE (B3)	-112	~9 min	Operational

Table 3: Signal Range Validation

5.3 Throughput Scalability

Baseline tests achieved approximately 62 messages per minute (3,720 messages per hour) across all network types. Stress testing with 200 simulated cattle (double the baseline load) showed the gateway achieved sustained throughput of 121.4 messages per minute over a 5-minute test period with zero message loss. Mean latency during stress testing was 36.2ms (±4.0ms), demonstrating no degradation under increased load.

Signal Quality	RSRP (dBm)	Throughput (msg/hr)
Excellent (BTU 5G)*	-66	1,167
Good (Wi-Fi)	-65	3,714
Fair (4G LTE)	-85	3,714
Poor (5G-NSA)	-87	3,720
Marginal (5G-NSA)*	-110	1,101

**Short duration tests, extended validation pending*

Table 4: Performance Across Signal Strength Range

5.4 Buffer Resilience

Buffer resilience was validated using the dual-broker architecture with a 60-second simulated cloud outage. During the 60-second outage, the gateway continued receiving telemetry via the local broker and buffered 51 messages in RAM. Upon broker restoration, the gateway automatically reconnected and flushed all buffered messages within 2 seconds, achieving 100% message delivery with no data loss. The SQLite overflow mechanism provides additional resilience for extended outages exceeding RAM buffer capacity.

6 Conclusion

This paper presented an adaptive 5G gateway for smart livestock monitoring. Key findings from our tests include obtaining sub-50ms P95 latency across all network types (5G-NSA: 44.9 ms, 4G LTE: 40.0 ms, WiFi: 26.4 ms), with 4G LTE outperforming 5G-NSA possibly due to dual-connectivity overhead. We observed 47 dB operational signal range (-65 to -112 dBm), 121.4 msg/min throughput with 200 cattle and zero message loss, and 100% message recovery within 2 seconds. The results demonstrate that existing 4G/Wi-Fi infrastructure effectively supports livestock IoT, while multi-network adaptability ensures reliable operation across diverse conditions. Future work will include extended 5G-SA and Wi-Fi validation and field trials with real data from bolus sensors.

Acknowledgments

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