Communication System Development for TAMBO

Requirements, Candidate Technologies, and Preliminary Results

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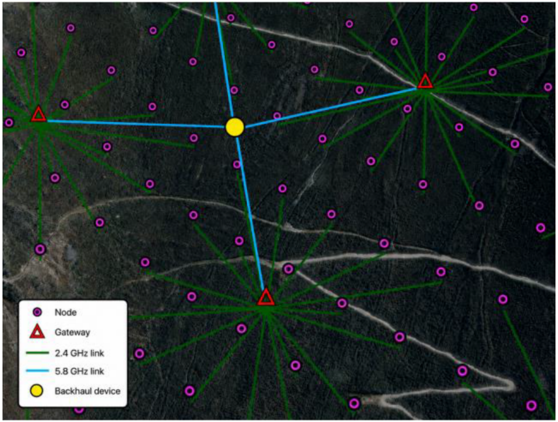
Purpose of the Presentation

- Present the main communication challenges and requirements of TAMBO.
- Describe the proposed communication architecture for distributed detector nodes.
- Compare two candidate technologies for the main data communication link:
  - Conventional Wi-Fi 2.4 GHz, IEEE 802.11n.
  - Sub-GHz Wi-Fi HaLow, IEEE 802.11ah.
- Present preliminary results in terms of:
  - Throughput.
  - Coverage.
  - Energy consumption.

Proposed TAMBO Communication Architecture

- Distributed detector nodes communicate directly with assigned gateways.
- Star topology reduces routing complexity at node level.
- Gateways concentrate local traffic.
- A backhaul device connects multiple gateway areas.
- LoRa is considered as an independent channel for low-rate monitoring and warning messages.



Technologies to be Compared

Feature	Wi-Fi HaLow (802.11ah)	Wi-Fi 2.4 GHz (802.11n)
Frequency	Sub-1 GHz, 915 MHz / 868 MHz	2.4 GHz
Maximum range, line of sight	Excellent, up to ∼1 km with NLOS capability	Medium, ∼100 m with external antenna; could reach 3–5 km using directional antennas and LOS
Ground-level performance, 100 m, PCB antenna	Excellent, high diffraction capability	Poor, connection drops due to attenuation
Theoretical throughput at 100 m	High, ∼1–1.5 MB/s	Very high, ∼150 MB/s; requires elevated antenna
Network stack / protocol	Native TCP/IP	Full TCP/IP, native sockets

Energy Consumption Comparison

Wi-Fi HaLow: Quectel FGH100M-H

- IEEE 802.11ah, 902–928 MHz.
- Two supply lines must be considered:

$$P_{\mathrm{HaLow}} = V_{\mathrm{DD\_FEM}} I_{\mathrm{DD\_FEM}} + V_{\mathrm{BAT}} I_{\mathrm{BAT}}$$

- Transmission power:

$$0.68\ \mathrm{W}\ \text{to}\ 2.20\ \mathrm{W}$$

- Reception power:

$$\approx 0.16\ \mathrm{W}$$

Wi-Fi 2.4 GHz: Hi-Link HLK-RM28E

- IEEE 802.11a/b/g/n/ac.
- Supply voltage:

$$5.0 \pm 0.2\ \mathrm{V}$$

- No-load operation:

$$450 \pm 50\ \mathrm{mA}$$

- Estimated no-load power:

$$2.0\ \mathrm{W}\ \text{to}\ 2.5\ \mathrm{W}$$

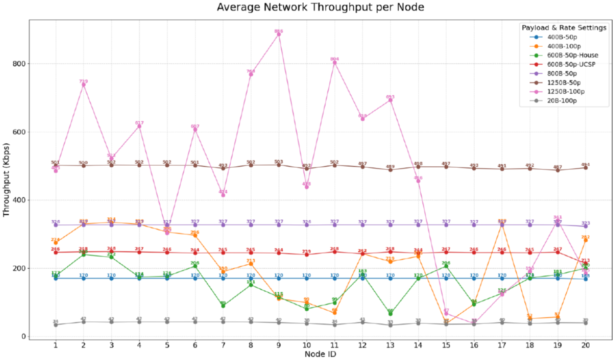
- Recommended supply capacity:

$$\geq 5\ \mathrm{W}$$

First Preliminary Results: UDP Wi-Fi Prototype

Test configuration: 20 nodes, each based on an ESP32 (Wi-Fi 802.11n), simultaneously transmitting image data over UDP.

Packets /s	Payload Bytes	Theoretical Kbps	Measured Kbps	Efficiency
50	400	173.6	170.0	**97.9%**
100	400	347.2	204.9	**59.01%**
50	600	253.6	244.0	**96.21%**
50	800	333.6	326.8	**97.95%**
50	1250	513.6	496.9	**96.75%**
100	1250	1027.2	465.6	**45.32%**
100	20	43.2	39.04	**90.36%**



Interpretation of the Preliminary Results

- High efficiencies were achieved in several configurations, especially at 50 packets/s.
- The most relevant case for the current TAMBO requirement is:

$$100 \text{ packets/s}, \quad 20 \text{ bytes/payload}$$

$$\eta = 90.36\%$$

- However, no packet recovery mechanism was implemented in these tests.
- Therefore, even in the high-efficiency cases, packet losses still occurred.
- These results validate the basic feasibility of the network, but they do not yet represent final outdoor performance.

The preliminary 802.11n prototype can sustain the required packet rate, but reliability must be improved through packet recovery, power-supply stabilization, and outdoor validation.

20-Node Test with Packet Retransmissions

Test configuration

- Up to **20 ESP32 nodes** connected simultaneously to a central gateway.
- Each node transmits 100 packets/s, with a payload of 20 bytes/packet.
- Unlike the previous tests, a **packet recovery mechanism** was enabled.
- Each lost packet could be retransmitted up to a maximum of 2.
- Nodes were progressively added to the network in order to evaluate the effect of increasing network load.

Performance Metrics

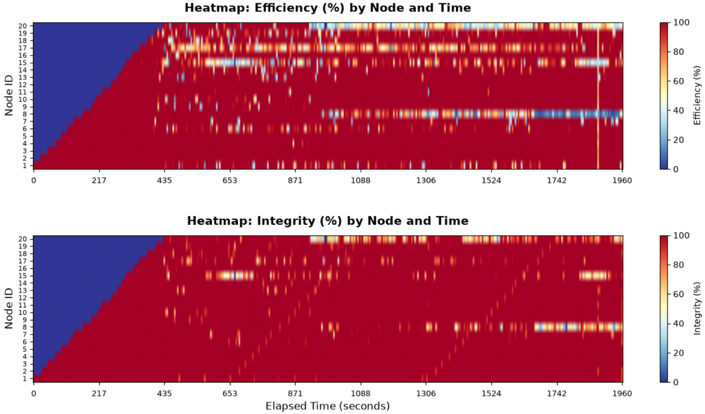
Efficiency

Percentage of transmitted packets successfully received by the gateway.

Integrity

Quality/completeness of the reconstructed image received from each node.

20-Node Performance with Retransmissions



Performance remains high while nodes are progressively added, but a significant degradation appears when the network approaches **18–20 active nodes**, despite allowing up to four retransmissions.

Reducing the Packet Rate while Maintaining the Data Rate

New test configuration

- The total amount of information transmitted by each node was kept unchanged.
- Previous configuration:

$$100 \text{ packets/s} \times 20 \text{ bytes} = 2000 \text{ bytes/s}$$

- New configuration:

$$50 \text{ packets/s} \times 40 \text{ bytes} = 2000 \text{ bytes/s}$$

- Therefore, the application payload remains:

$$\boxed{2 \text{ kB/s} \approx 16 \text{ kbps per node}}$$

- Up to **20 ESP32 nodes** were progressively connected to the gateway.

Important Difference

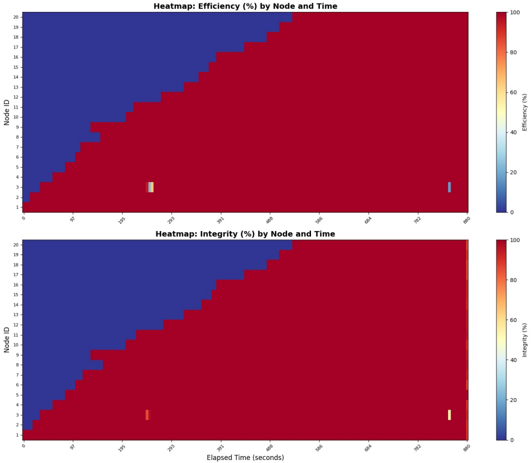
For this first test with the new packet configuration:

Packet retransmissions were disabled.

Objective

Evaluate whether reducing the number of packets per second improves network performance while maintaining the same information rate.

Performance with 50 Packets/s and 40-Byte Payload



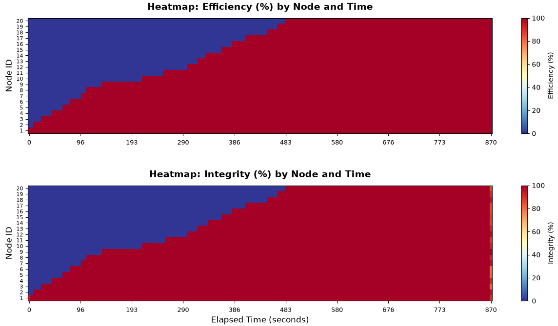
Key observation: Despite disabling packet retransmissions, both **efficiency and data integrity remain close to 100%** for almost all active nodes, including the 20-node configuration.

Test configuration

- Up to **20 ESP32 nodes**.
- Packet rate: 50 packets/s
- Payload 40 bytes/packet
- Data rate per node: 2 kB/s
- Maximum number of retransmissions: 2

Results:

- Efficiency: **100%**
- Integrity: **100%**



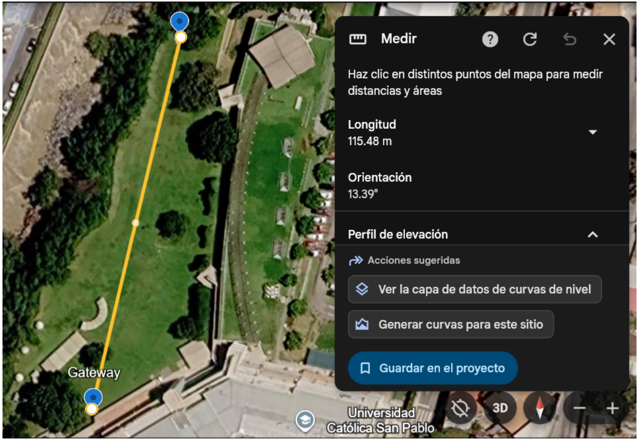
Outdoor test at the UCSP campus

- The **gateway** was placed at a fixed location.
- A single ESP32 node was progressively moved away from the gateway.
- The objective was to evaluate the communication link under outdoor line-of-sight conditions.
- Maximum tested separation:

$$\boxed{\approx 115 \text{ m}}$$

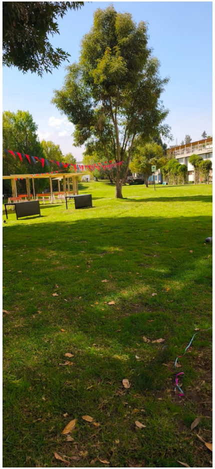
- Communication technology:

Wi-Fi 2.4 GHz (802.11n)



Gateway–node separation measured using Google Earth.

Coverage Test: Line-of-Sight Conditions



Node viewed from the Gateway

Gateway viewed from the Node

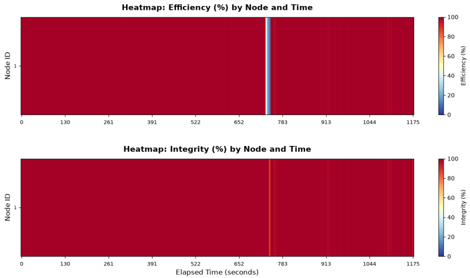
Coverage Test Results at UCSP Campus

Test condition

- One ESP32 node was moved progressively away from the gateway.
- Maximum tested distance 115 m.
- Outdoor line-of-sight condition.
- Each lost packet could be retransmitted up to a maximum of 4.

Results:

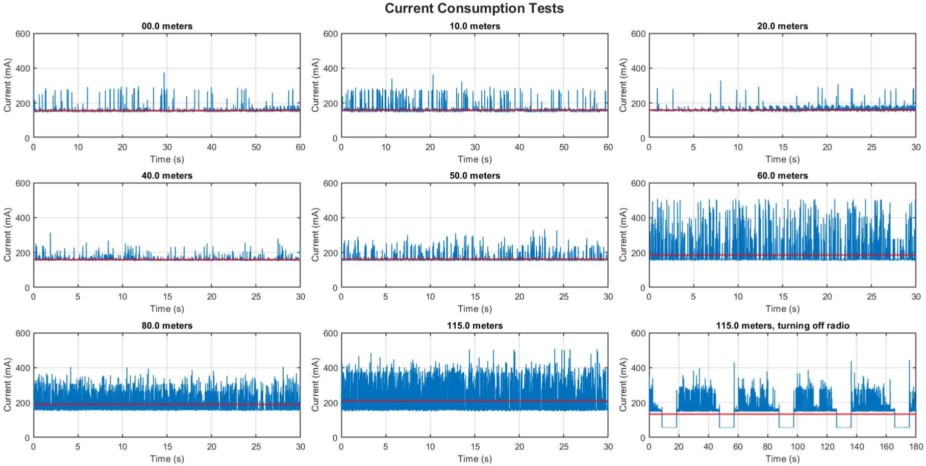
- Efficiency = 100%
- Integrity = 100%



Current monitoring system

- The communication node was connected to a dedicated current data logger.
- The data logger was implemented using:
  - an ARM STM32F4 microcontroller, and
  - a Texas Instruments INA228 current and power monitor.
- Current consumption was continuously recorded while the node communicated with the gateway.
- Measurements were repeated for different node–gateway distances during the outdoor coverage test.

Current Consumption at Different Distances



Blue: measured instantaneous current **Red:** mean current for each test

Current Consumption Summary

Test condition	Mean (mA)	Min (mA)	Max (mA)	Std. (mA)
0 m	157.36	145.57	375.06	12.30
10 m	159.44	146.33	363.71	16.58
20 m	160.17	146.56	329.36	12.49
40 m	160.21	150.62	313.38	11.57
50 m	163.05	151.06	333.19	20.79
60 m	184.47	152.44	507.01	70.95
80 m	188.72	151.23	403.86	53.23
115 m	208.41	148.96	508.14	84.55
115 m, radio off	132.82	55.18	442.94	51.22

The average current increases as the node–gateway distance becomes larger, rising from approximately 157 mA at 0 m to 208 mA at 115 m. With a 5V Supply, power consumption remains below 2.5 Watts on average.

Conclusions

- A star-based communication architecture has been defined for TAMBO, with Wi-Fi 2.4 GHz and Wi-Fi HaLow considered for the main data link, while LoRa is reserved for low-rate monitoring and warning messages.
- Preliminary 802.11n tests showed that packet rate strongly affects network performance. With the same application data rate of 2 kB/s per node, reducing the traffic from 100 packets/s $\times$ 20 bytes to 50 packets/s $\times$ 40 bytes significantly improved communication reliability.
- With 20 simultaneously active nodes, using 50 packets/s, 40-byte payloads, and up to two retransmissions, the prototype achieved an Efficiency $=$ 100% and an Integrity $=$ 100%.
- Outdoor line-of-sight tests demonstrated reliable 802.11n communication up to the maximum evaluated distance of approximately 115 m, maintaining 100% efficiency and data integrity.
- Current measurements showed an increase in average consumption with distance, from approximately 157 mA at 0 m to 208 mA at 115 m. This trend requires further experimental validation.

Thank you!

Gracias

Questions?