

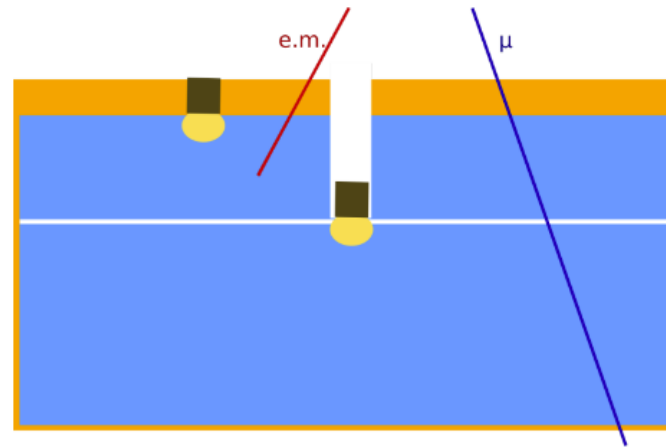
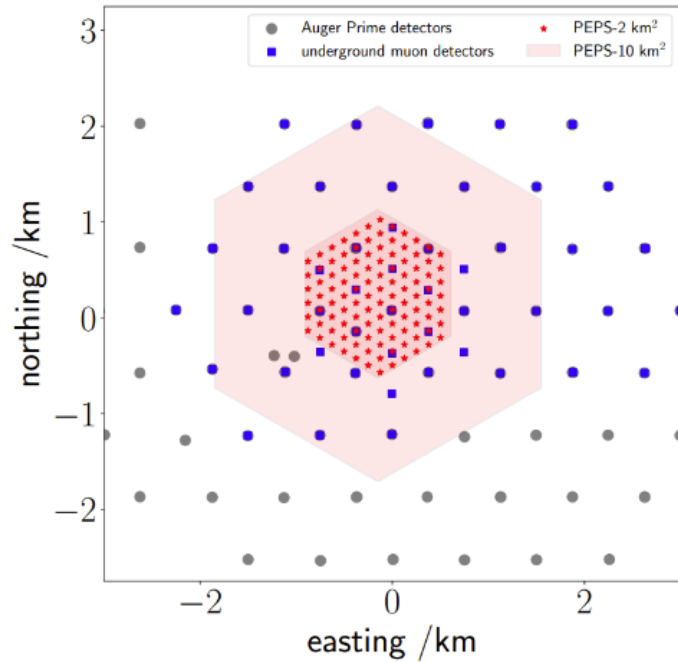
Wireless TDAQ Upgrades for the PEPS Surface Detector Array

Yifan Yang on behalf of PEPS collaboration

Université Libre de Bruxelles

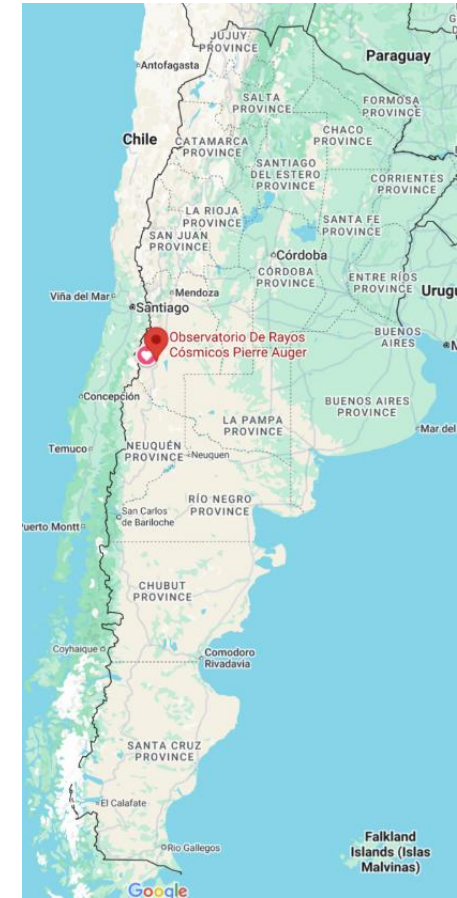


Build PEPS: a 2-km² surface detector at the Pierre Auger Observatory in Malargüe, Argentina

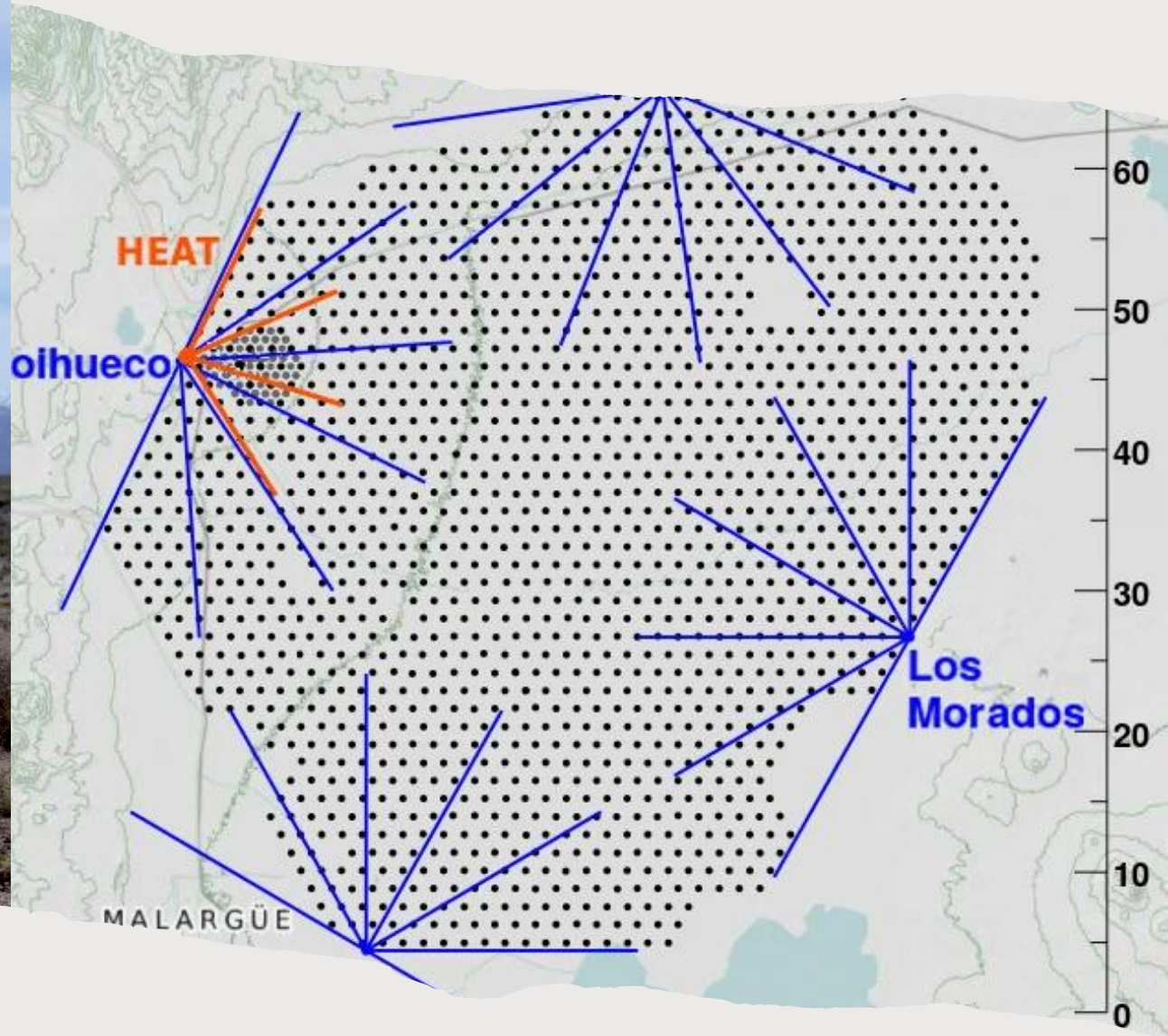


Layered Water Cherenkov detectors optically separated

An array with a spacing of 145 m between the detectors



Probing Extreme PeVatron Sources



Pierre Auger Observatory

PEPS vs AUGER



PEPS has smaller coverage(10km² vs 3000km²) and higher density(55 stations/km² vs 0.5 station/km²)



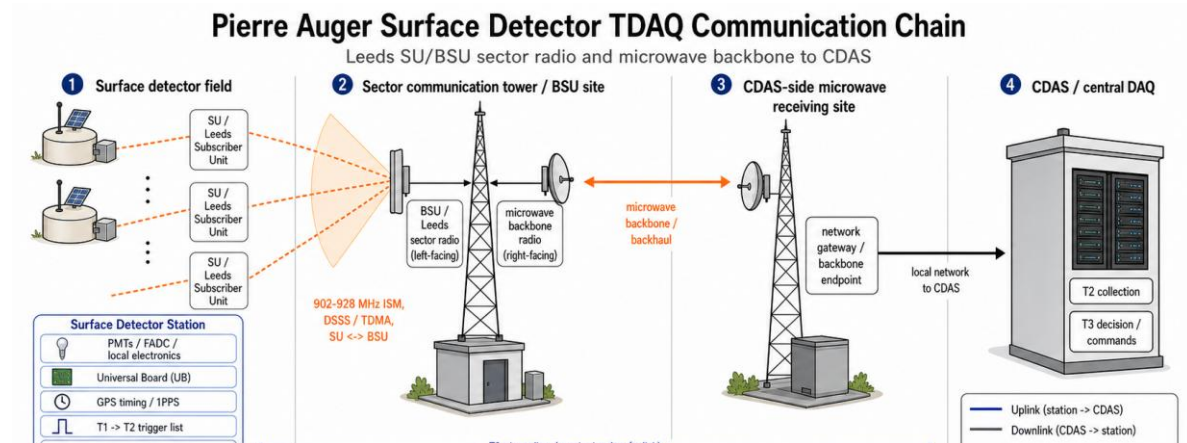
PEPS stations will use the decommissioned electronics from Auger.



The Auger communication system, utilizing the custom 915 MHz "Leeds Radio" for access and a microwave backbone for backhaul, faces challenges regarding spectral congestion and component obsolescence

Key characteristics:

- **Serial Interface Rate:** 38.4 kbps (RS-232 with hardware flow control).
- **Over-the-air Physical Rate:** 200 kbps (DSSS modulation).
- **TDMA Slot Duration:** ~11.76 ms (1-second frame divided into 85 total slots).
- **Effective Payload per Slot:** ~150 Bytes (1200 bits), yielding a net throughput of 1.2 kbps per station.
- **Sector Capacity:** Up to 68 Subscriber Units (detectors) per Base Station Unit



Generated by codex

Interface and protocol

- Designed in 2004
- Customized protocol as well as pinout
- Carrying UART and Power and PPS in the same connector

Electrical and timing boundary

Unified Board (UB)
station firmware endpoint

RS-232 / DB-9

Legacy radio interface role
what the new bridge must emulate

- 38.4 kbps UART, 8N1
- RTS/CTS hardware flow control
- PPS and reset are sideband timing/control signals
- DB-9 mapping is not a generic PC serial cable

Legacy frame carried over the stream

Preamble

Length

Type

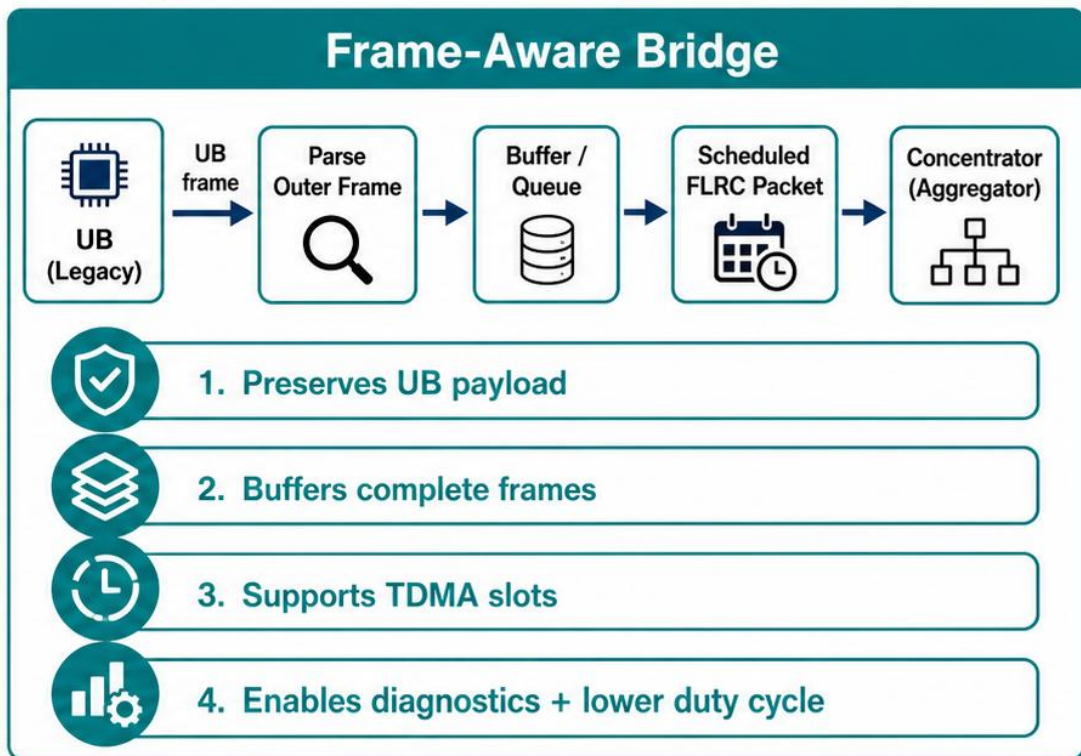
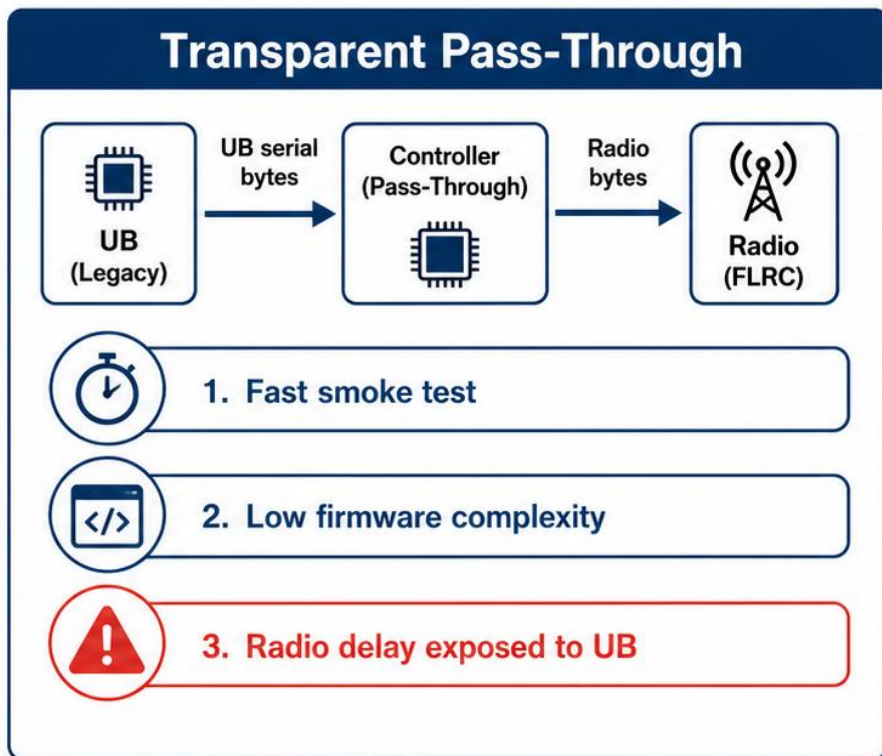
Data

CRC32

- Parser acquisition is based on preamble plus length, CRC and ETX check
- **Type** identifies command/status/data semantics.
- **Data** may contain structured UB payload; default bridge behavior should preserve it byte-for-byte.
- CRC32 and byte order should be confirmed from the primary protocol doc before implementation.



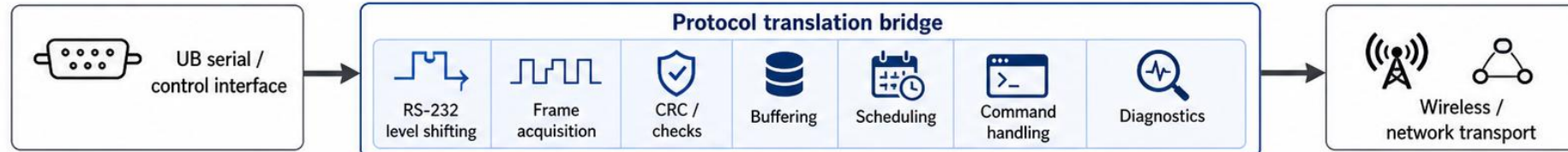
UB Serial Bridge Strategy



Recommended: transparent mode for early tests; **frame-aware, payload-transparent bridge** for production.

i Frame-aware means parsing the outer legacy frame, not interpreting physics payloads.

Implementation : FPGA vs ESP32 Development Board

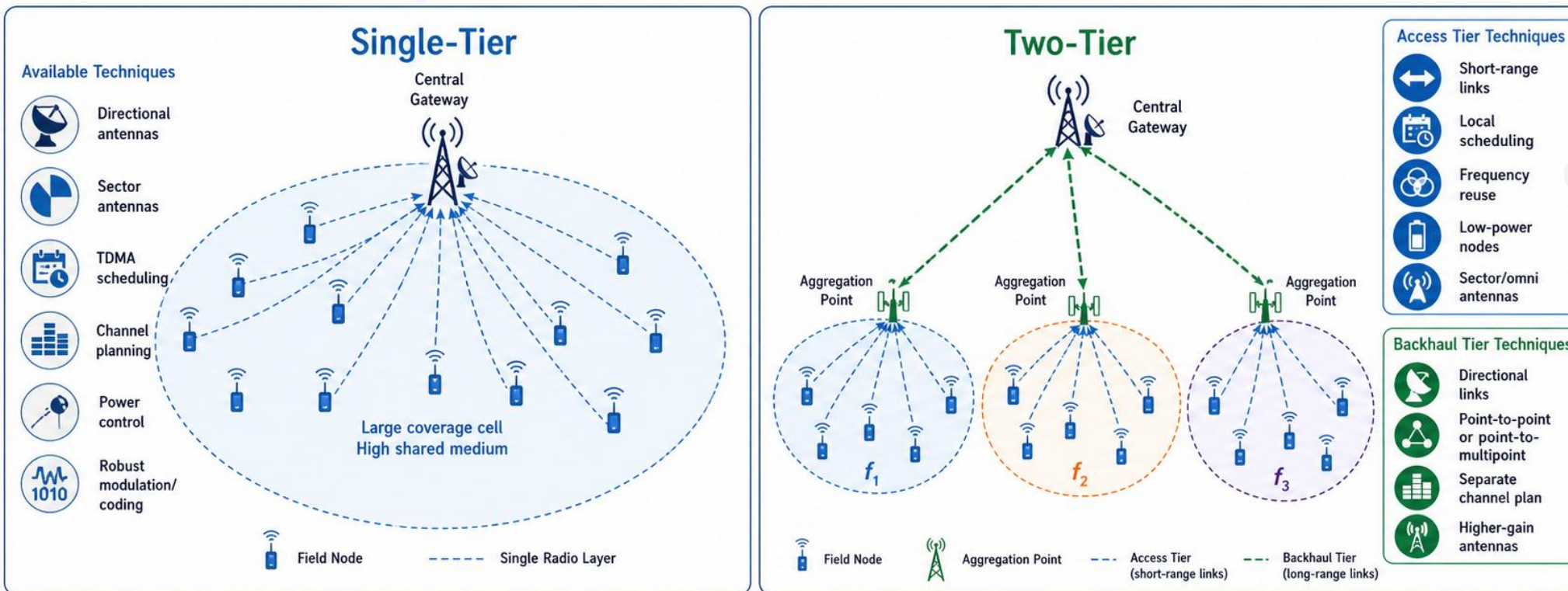


FPGA Implementation	
Timing control	deterministic hardware timing
Parallel I/O	strong for multiple synchronous signals
Latency jitter	very low and predictable
Firmware style	HDL logic design
Development speed	slower iteration, specialized tooling
Debugging	requires logic analyzer / HDL simulation
Power profile	can be efficient, depends on device and clocking
Flexibility	changes require synthesis and reprogramming
Best suited for	hard real-time logic, many precise I/O paths, production hardware integration

ESP32 Development Board	
Timing control	timer/interrupt based software timing
Serial handling	straightforward UART and GPIO integration
Latency jitter	depends on firmware, interrupts, RTOS load
Firmware style	C/C++ embedded software
Development speed	fast iteration, low-cost boards
Debugging	serial logs, JTAG/USB, software instrumentation
Power profile	low-duty operation possible, board overhead varies
Flexibility	easy firmware updates and protocol changes
Best suited for	prototyping, protocol parsing, buffering, diagnostics, early integration tests

Main trade-off: hardware determinism and integration effort vs software flexibility and fast prototyping

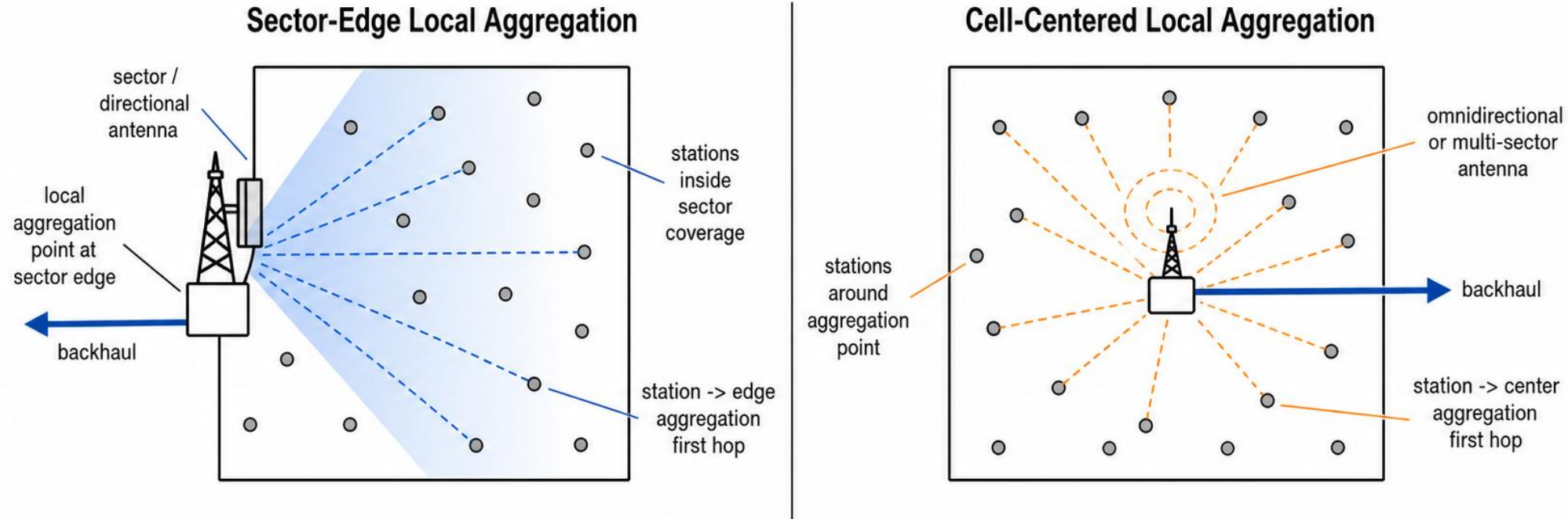
Single-Tier vs Two-Tier Radio Architecture






Coverage domain	one large domain	multiple local domains + backhaul domain
Radio layers	one shared layer	separated access and backhaul layers
Link distance	longer station-to-gateway paths	shorter access paths + longer backhaul paths
Frequency use	shared channel plan over large area	local reuse possible, backhaul separated
Infrastructure	central gateway focus	local aggregation points plus gateway
Antenna options	directional/sector/omni	local omni/sector + backhaul directional

Sector-Edge vs Cell-Centered Local Aggregation









Topology and antenna placement comparison only



	Aggregation point	local node at cell/sector edge	local node near cell center
	Access antenna	directional sector coverage	omni or multi-sector coverage
	First-hop geometry	stations connect toward one edge	stations connect toward center

First-Hop Hardware Specs: Bullet AC vs E28/SX1280

Datasheet-level comparison only

	Ubiquiti Bullet AC	Ebyte E28-2G4M27SX / SX1280
 Operating band	2.4 GHz + 5 GHz	2.4 GHz ISM
 Throughput / air rate	160+ Mbps @ 2.4 GHz; 300+ Mbps @ 5 GHz	FLRC: 260 kbps–1.3 Mbps; GFSK up to 2 Mbps; LoRa 0.595–253.9 kbps
 Transmit power	21–22 dBm	up to 27 dBm / 500 mW
 Receive sensitivity	airMAX ac: -93 to -62 dBm depending on modulation	LoRa sensitivity down to -132 dBm; FLRC sensitivity depends on data rate
 Power / supply	7–8 W max; 24 V passive PoE	2.5–3.6 V; TX 580 mA; RX 14.5 mA; sleep 2 μ A
 Antenna interface	N-Type external antenna connector	IPEX / PCB antenna, 50 ohm
 Transmission distance	No single distance number in datasheet; external antenna/ link dependent	Reference distance: 8000 m under ideal open conditions, 5 dBi antenna, 2.5 m height, 1 kbps
 Data interface	Gigabit Ethernet	SPI, pure RF transceiver module

2.4 GHz Link Margin: Distance, Bandwidth, and EIRP

Calculation Model

$$\text{FSPL(dB)} = 32.44 + 20 \log_{10}(d_{\text{km}}) + 20 \log_{10}(f_{\text{MHz}})$$

At $f = 2400$ MHz:

$$\text{FSPL(dB)} = 100.0 + 20 \log_{10}(d_{\text{km}})$$

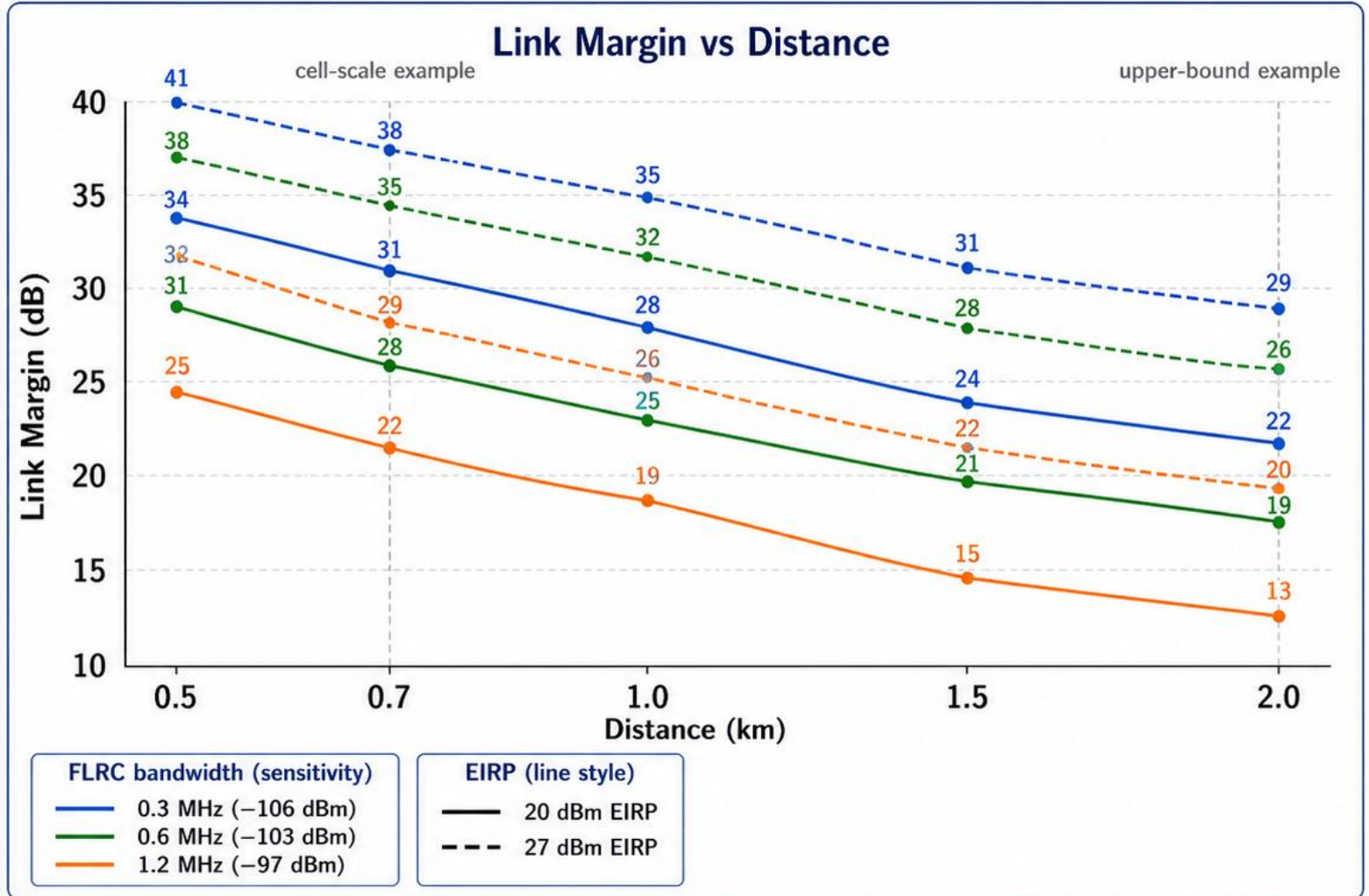
$$P_{\text{rx}}(\text{dBm}) = \text{EIRP} - \text{FSPL} + G_{\text{rx}}$$

$$\text{Margin(dB)} = P_{\text{rx}} - \text{Sensitivity}$$

Assumptions:

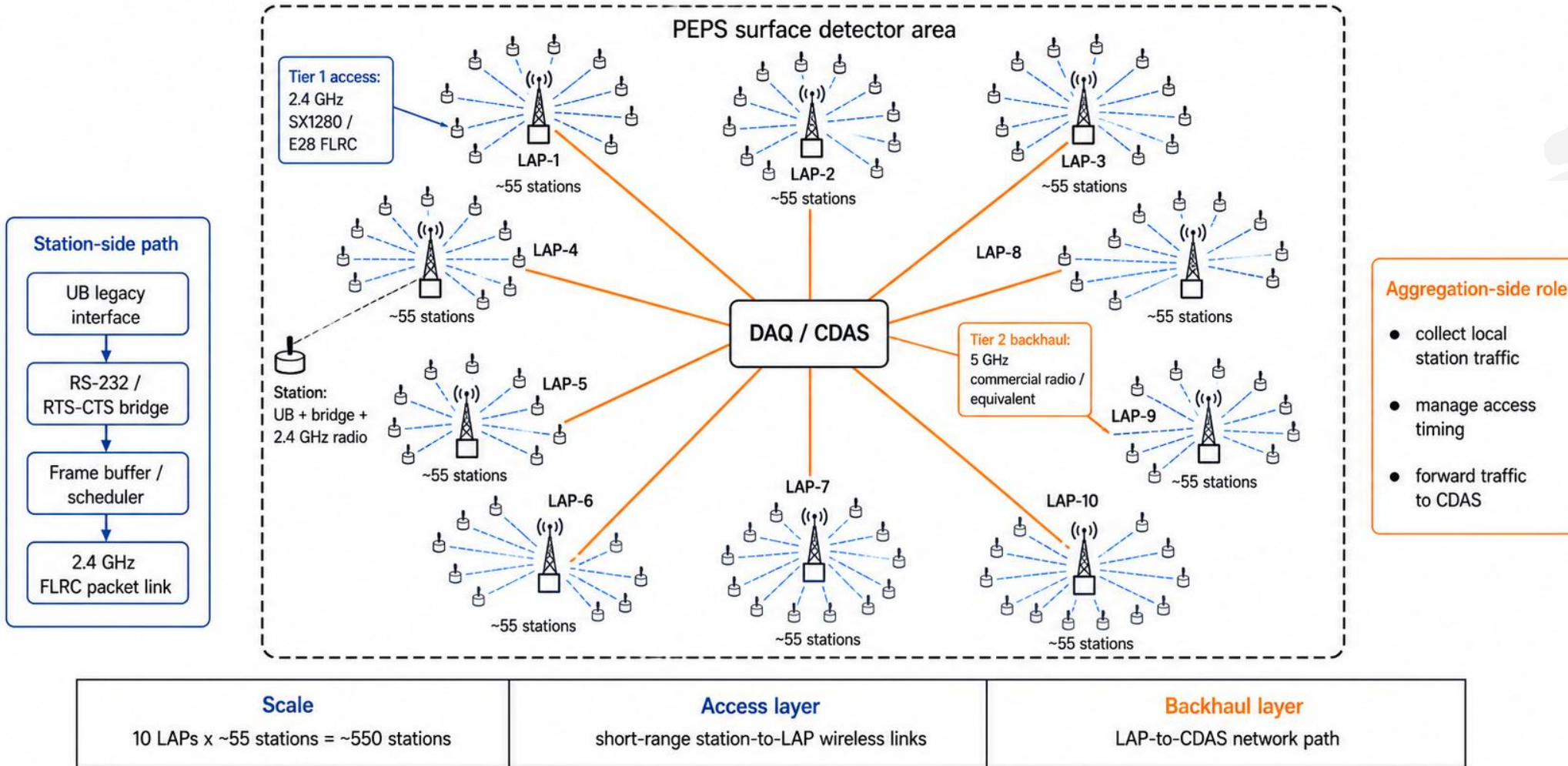
- Frequency: 2400 MHz
- RX antenna gain: +2 dBi
- Cable loss: 0 dB
- EIRP already includes TX antenna gain

FLRC bandwidth	Representative sensitivity
0.3 MHz	-106 dBm
0.6 MHz	-103 dBm
1.2 MHz	-97 dBm



Proposed PEPS Radio Readout Structure

10 local aggregation points, about 55 stations per aggregation point



Test consideration

Ubiquiti Bullet
and Rocket
communication

UB and protocol
translator
communication

SX1280 tx and rx
communication

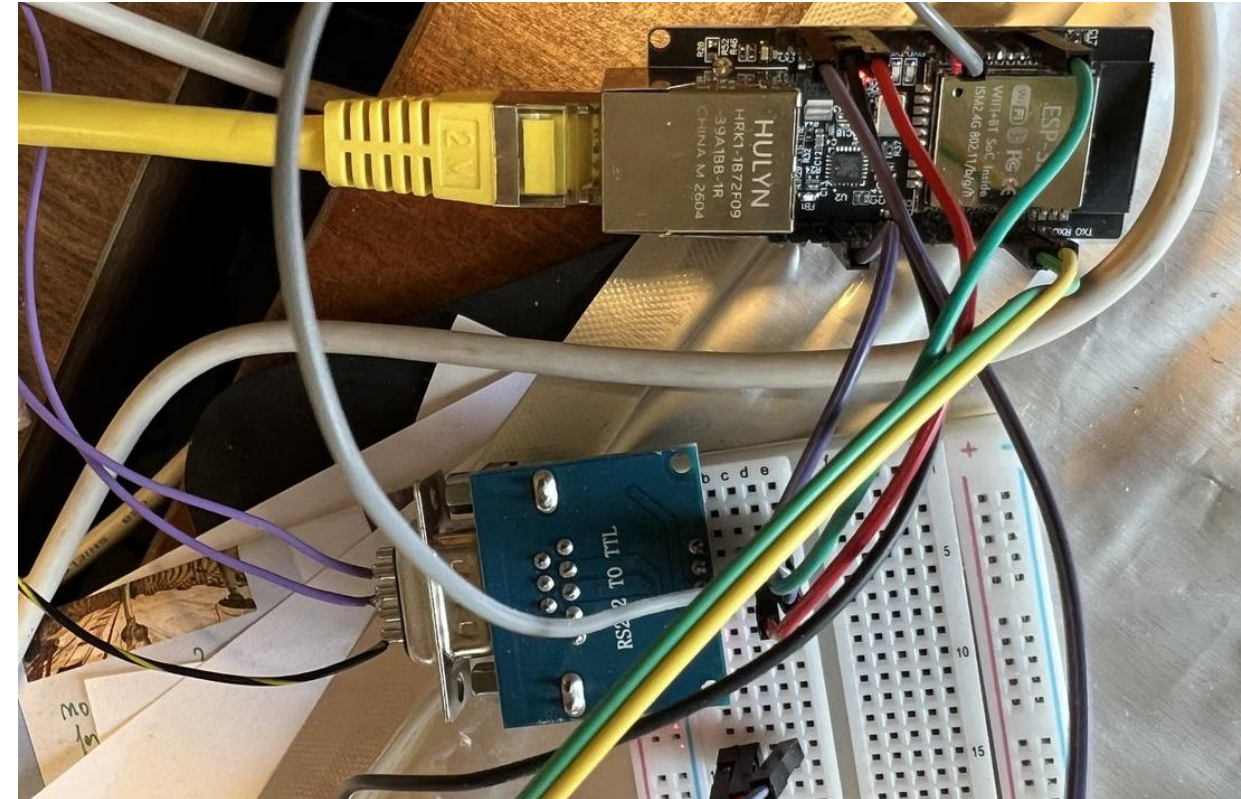


Bullet and rocket communication

UB and protocol translator communication



5/26/2026



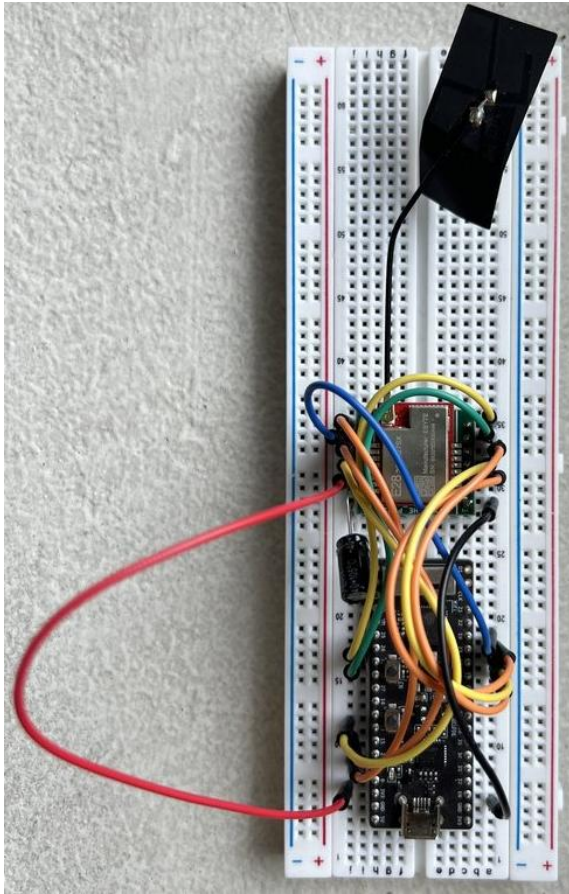
Realtime Conference

16

UB Ethernet bridge prototype

- Embedded web server for command control and diagnostics
- Auger/UB UART frame encoder and parser
- Predefined command templates
- Raw UART logging and validated-frame monitoring

The screenshot displays the 'UB Ethernet Bridge' web interface. At the top, there are several navigation buttons: 'Version', 'GPS Status', 'GPS Position', 'GPS Time', 'Station ID', 'Refresh', and 'Clear Logs'. Below these is an input field for 'Echo payload (ASCII)' with a 'Send Echo' button. A status bar shows 'Device IP: 10.248.1.132 | Raw RX chunks: 0 | Valid frames: 0'. A message 'Logs updated.' is visible. The main content area is split into two panels: 'Raw RX Bytes' and 'Valid Frames'. The 'Raw RX Bytes' panel shows 'No raw RX bytes yet.' and the 'Valid Frames' panel shows 'No valid frames yet.'.



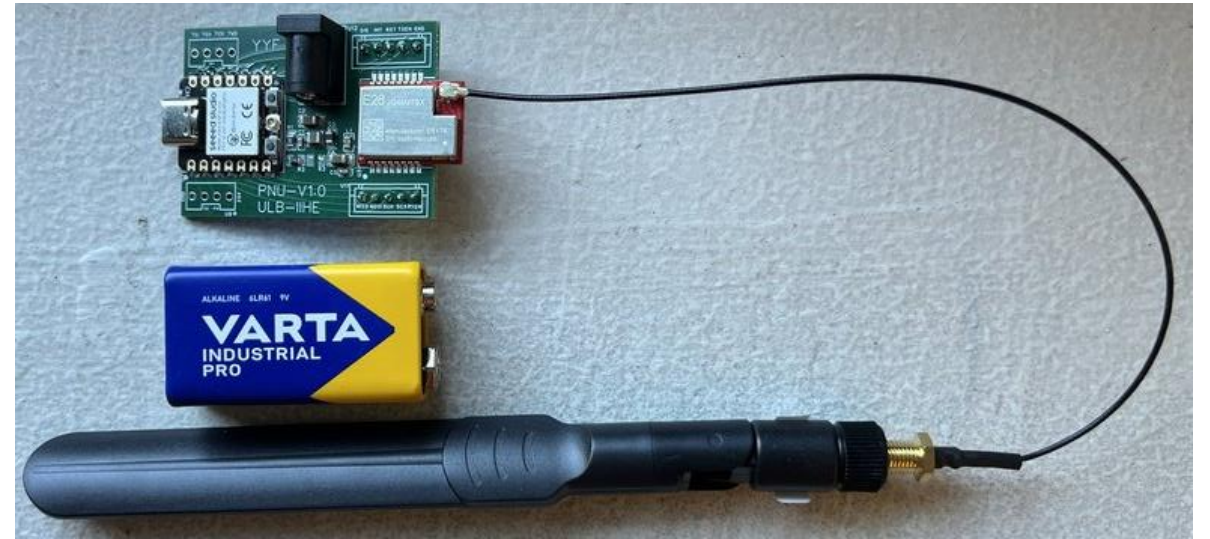
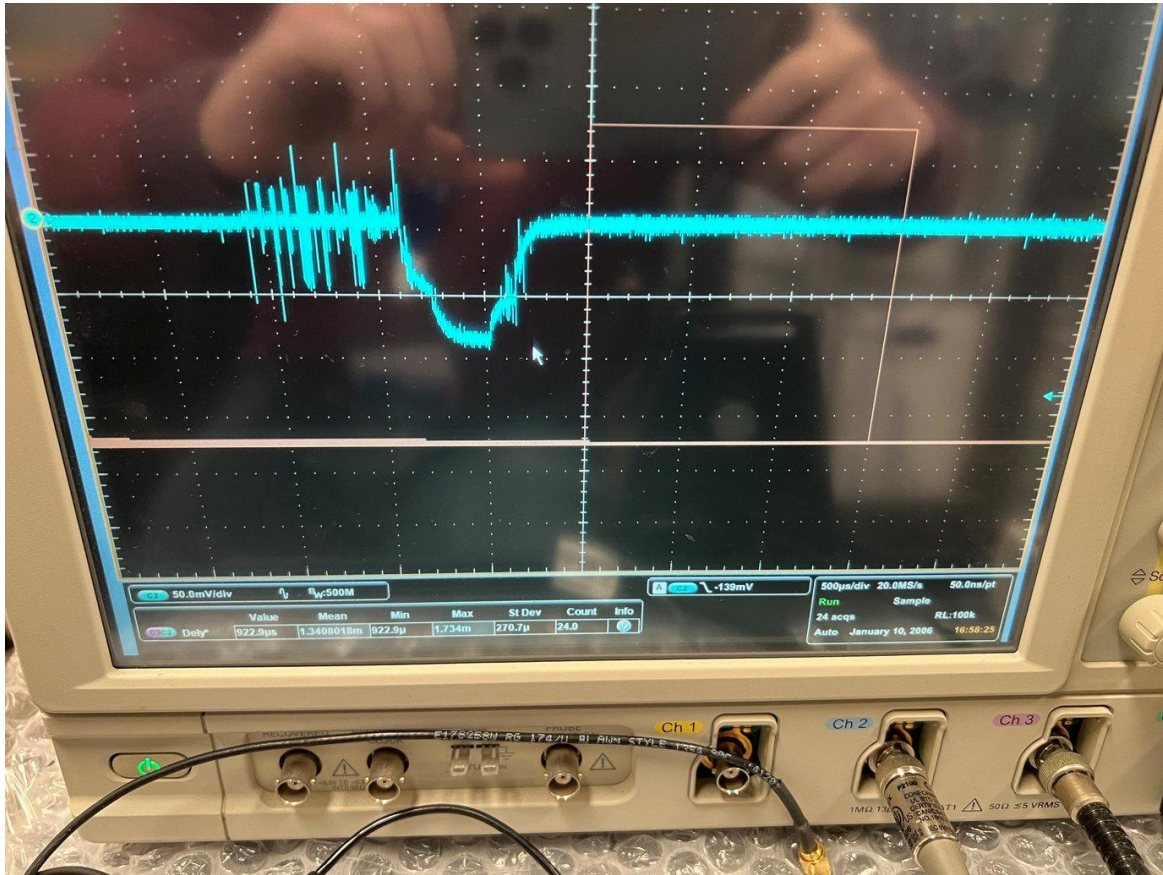
Mode: SX1280 FLRC packet mode
Frequency: usually 2449.5 MHz
Bitrates tested: 260, 325, 520, 650, 1000,
1300 kbps
Coding rate index:
2 -> CR 1/2
3 -> CR 3/4
4 -> CR 1/1
Preamble: usually 16
CRC: RadioLib default 2-byte CRC
Whitening: disabled in current notes
Packet length: fixed 6-byte payload

valid row = tail == 0xAA55

CRC failure count = receiver-
side integrity rejection
tail-bad count = payload
marker corruption

loss estimate = counter
discontinuity after filtering
corrupt rows

SX1280 tx and rx communication

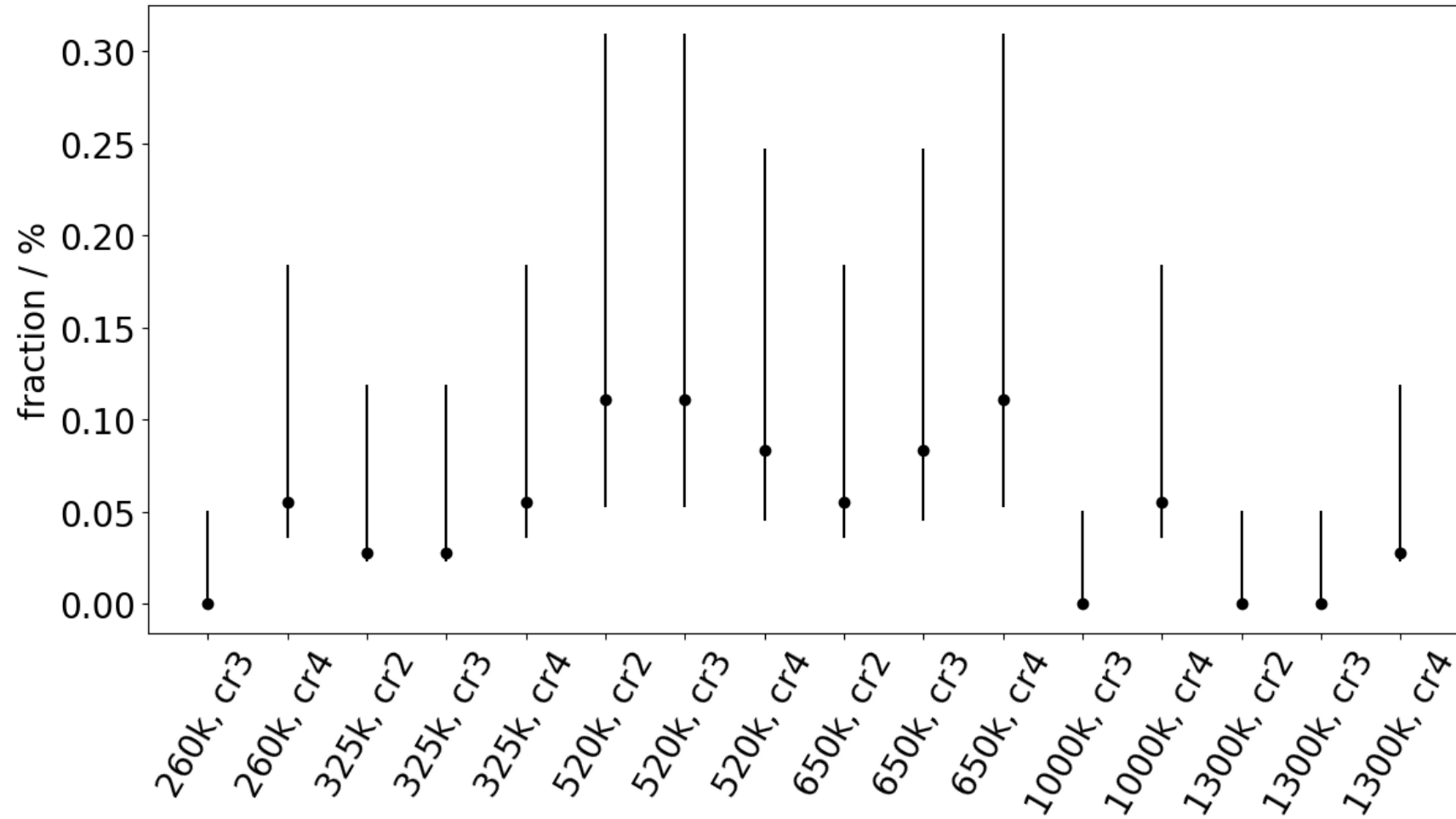


E28+ESP32XIAO
Optimized power distribution system

段	时间	counter	valid RX	expected	lost	loss rate
Segment 1	10:50:45 - 10:53:44	1492 - 1670	169	179	10	5.59%
Segment 2	10:55:37 - 10:57:33	0 - 116	113	117	4	3.42%
合并, 剔除分段影响	-	-	282	296	14	4.73%

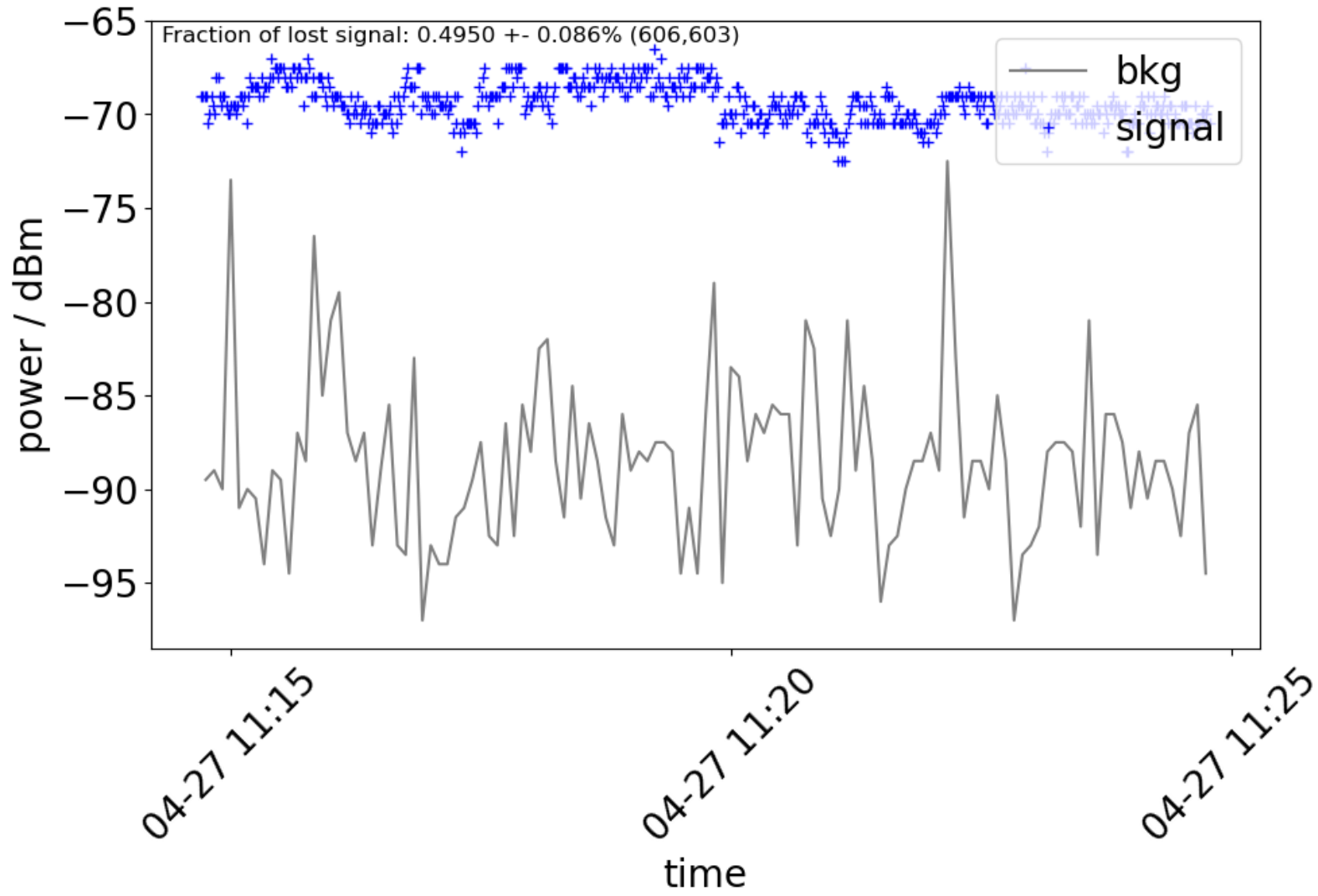
V1 vs V2

Short distance test results



Preliminary long distance test(700 m)





700 meters
results

Summary and Outlook

- **Summary**

- A 2.4 GHz two tier system based on omnidirectional antennas is proposed for the communication of PEPS
- A very low power consumption can be achieved (important for the remote location in La Pampa Amarilla)
- Initial tests show that the system is stable a short distance with a data loss of less than 0.1%, depending on the configuration
- Long range tests in Brussels limited for now by the large city noise and by the time of the data taking
- Full functional hardware firmware is under development

- **Outlook**

- Perform tests at different distances, also by raising the antennas from the ground
- Test the system on site in Argentina (lower background noise)



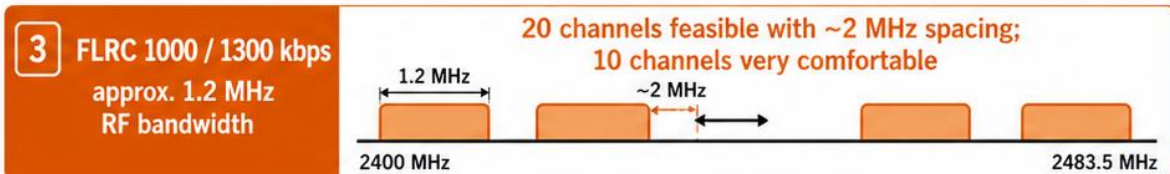
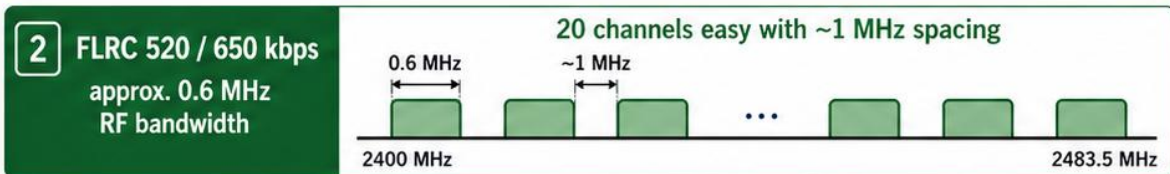
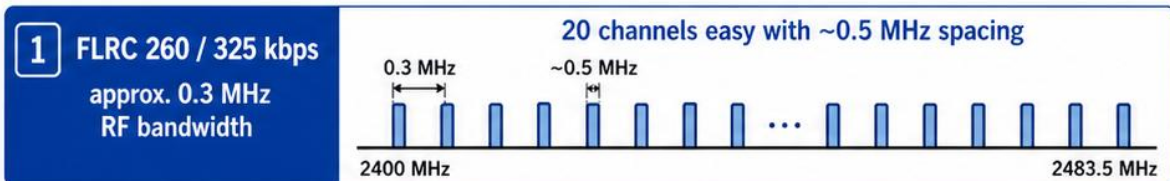
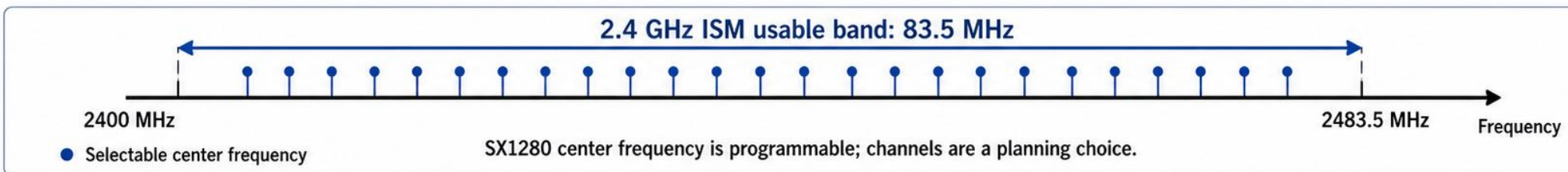
- Thank you!



- backup



SX1280 FLRC Channel Planning: Channel Count vs Bandwidth



Example non-overlapping plans

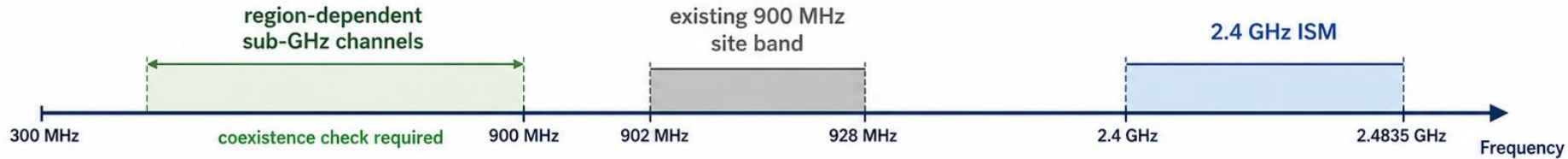
FLRC bandwidth	example center spacing	span for 10 channels	span for 20 channels	fits in 83.5 MHz?
0.3 MHz	0.5 MHz	4.5 MHz	9.5 MHz	Yes
0.6 MHz	1.0 MHz	9 MHz	19 MHz	Yes
1.2 MHz	2.0 MHz	18 MHz	38 MHz	Yes

Approx. occupied span = (N - 1) x spacing + channel bandwidth

- Practical constraints:**
- guard bands
 - Wi-Fi avoidance
 - local interference scan
 - adjacent-channel leakage
 - antenna / filter behavior
 - regulatory limits

✓ Answer: 10 channels is straightforward; 20 channels is technically feasible in 2.4 GHz FLRC if spacing and site interference are managed.

Candidate First-Hop Technologies: Wi-Fi HaLow vs 2.4 GHz FLRC

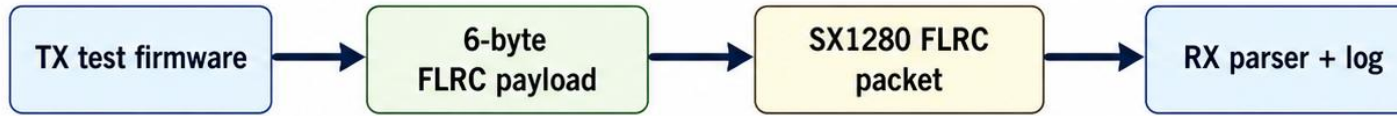


		Wi-Fi HaLow	2.4 GHz FLRC
1	Operating band	sub-GHz; channel availability depends on region	2.4 GHz ISM band
2	Coexistence context	closer to existing 900 MHz site radios; requires site-specific coexistence study	frequency-separated from existing 900 MHz site radios
3	Channel / bandwidth model	Wi-Fi style channels; PHY/MAC profile dependent	packet-radio bandwidth options: approx. 0.3, 0.6, 1.2 MHz
4	Data-rate range	Mbps-class possible depending on channel and MCS	260 kbps to 1.3 Mbps configurable FLRC bitrates
5	MAC and timing control	standard Wi-Fi MAC; less direct low-level slot control	custom packet timing and TDMA-style control possible
6	Power profile	device and Wi-Fi stack dependent	simple duty-cycle control around scheduled packets
7	Antenna size	larger sub-GHz antennas for similar gain	smaller antennas for similar gain
8	Integration focus	regulatory channel availability, coexistence, stack behavior	link budget, interference, custom firmware validation



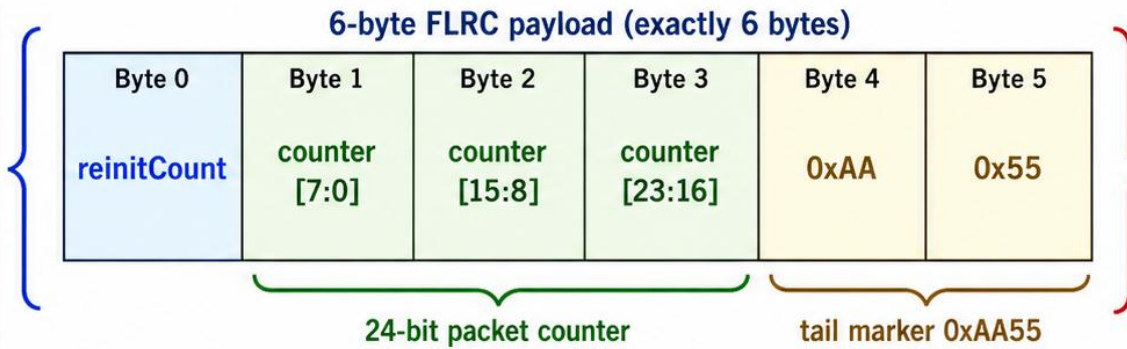
Selection depends on site coexistence, regulation, timing control, power budget, and validation effort.

Current SX1280 FLRC Test Firmware Data Format



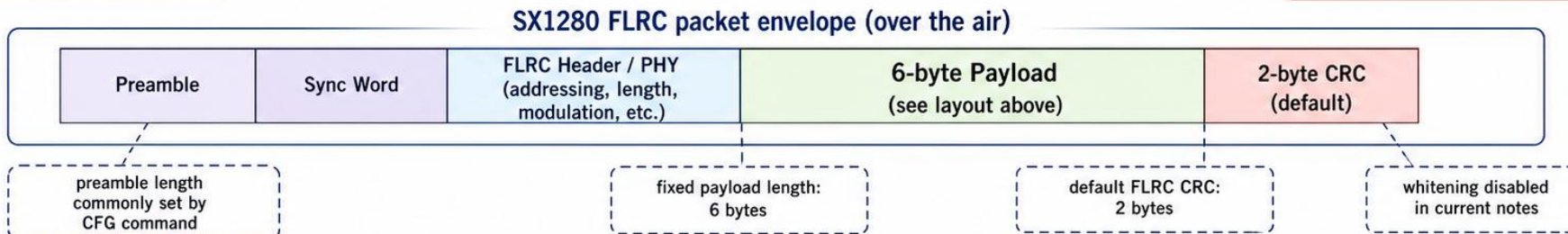
TX-side meaning

- reinitCount:** increments after radio re-initialization
- counter:** monotonic low 24 bits
- tail:** fixed integrity marker



RX-side diagnostics

- packet counter discontinuity -> **loss estimate**
- tail != 0xAA55 -> **corrupted payload / tail-bad event**
- RadioLib CRC mismatch (-7) -> **packet rejected** before payload use
- RSSI** recorded for valid packets



Runtime configuration command

CFG <freq_MHz> <bitrate_kbps> <CR_index> <power_setting_dBm> <preamble>

Example candidates: 2449.5 MHz 650 kbps CR = 2 pwr = -8 dBm preamble = 16

CAUTION

Current parser caveat: some RX logs still reconstruct a 32-bit counter from bytes 0-3, so **reinitCount** may affect the printed counter.

V1 rx vs V2 rx

