

Wireless Communication for Trigger and Data Acquisition for the PEPS Surface Detector Array

Yifan Yang, Ioana C. Mariş, Mateo Fernández Alonso, Patrick Stassi on behalf of the PEPS Collaboration

Abstract—The Probing Extreme PeVatron Sources (PEPS) experiment aims to deploy a high-density surface detector array (55 stations/km²) to measure extensive air showers produced by very energetic gamma rays and by cosmic rays. To minimize station-side electronics cost and leverage proven designs, PEPS inherits the Unified Board (UB) electronics from the Pierre Auger Observatory, Malargüe - Argentina. However, its legacy 902–928 MHz “Leeds Radio” link cannot be extended to PEPS: reusing the same sub-GHz band would produce spectral congestion alongside the still-operating Auger system, and the transceivers installed more than 25 years ago are obsolete. A modern wireless Trigger and Data Acquisition (TDAQ) upgrade is therefore required. We present a two-tier wireless readout architecture designed to modernize the telemetry path while preserving the legacy UB serial protocol and electrical boundary. The architecture splits communication into a low-power, center-aggregated 2.4 GHz first-tier access link and a high-capacity 5 GHz commercial backhaul. We describe two readout translators under development: a UB Ethernet bridge built around an ESP32-ETH01 and a MAX3232 converter module, and a custom-designed Pulse Network Unit (PNU) based on the Semtech SX1280 transceiver operated in Fast Long Range Communication (FLRC) mode. Bench tests against the Auger UB board confirm correct acquisition and CRC/ETX validation of the legacy frames. The first tests at a distance of 700 m from the rooftop of our building held the single-link robust counter loss to $\approx 0.5\%$ (statistics-limited, $n \approx 600$) for the 650 kbps, CR 1/2 FLRC configuration in heavy urban interference. These results establish the first-tier access link and define an end-to-end multi-station demonstrator as the next step toward deployment.

Index Terms—Fast Long Range Communication (FLRC), Pulse Network Unit (PNU), Protocol Translator, PEPS, Pierre Auger Observatory, Surface Detector Array, TDAQ, Wireless Readout.

I. INTRODUCTION

THE Probing Extreme PeVatron Sources (PEPS) experiment is being proposed as a ground-based astroparticle physics detector designed to measure particles from the extensive air showers reaching the ground with water-Cherenkov detectors. The air showers are generated by very-high-energy cosmic rays and photons with energies larger than 1 PeV. The science case of PEPS is focused on the search for the most energetic photons in our Galaxy and aims to explore a yet unknown energy range. To separate the photons from the overwhelming cosmic-ray background and to measure the very low expected photon flux (about 10 photons per

square-km per year) PEPS requires a high-density, large-scale surface detector array. The first phase targets a 2-km² coverage area, with a planned expansion to 10 km². The spacing between adjacent detector units is set at 145 m, which yields a deployment density of 55 detector stations per square kilometer.

PEPS will be integrated at the Pierre Auger Observatory, in Malargüe, Argentina. Compared to the Observatory, which covers 3000 km² with stations separated by 1500 m on a triangular grid, the PEPS array represents a significantly denser detector network [1]. PEPS will be interlace with the existing Auger detectors (Fig. 1), sharing the same site, infrastructure, and radio environment. To reduce development cycles and overall hardware cost, PEPS utilizes the decommissioned Unified Board (UB) station electronics and legacy firmware inherited from the Pierre Auger Observatory. The reuse of this heritage electronics ensures that the local PMT (Photomultiplier Tube) readout, analog-to-digital conversion, and trigger generation are managed by a stable, verified hardware baseline.

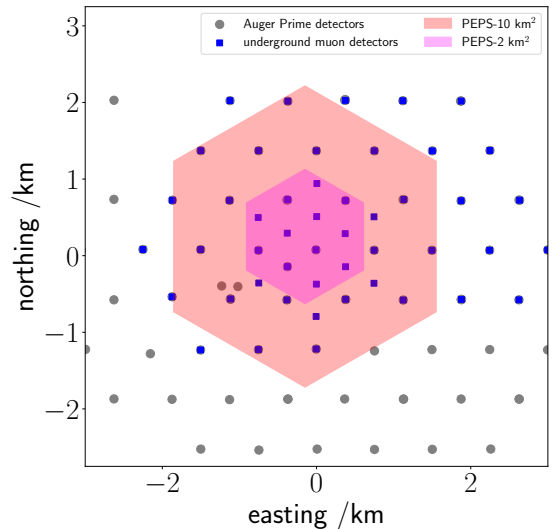


Fig. 1. PEPS surface-detector layout (dense central region) overlaid on the Pierre Auger Observatory array. PEPS is deployed inside the Auger footprint, sharing the same site and sub-GHz radio environment as the still-operating Auger communication system.

However, the communication layer of this heritage hardware presents a major engineering bottleneck. The Pierre Auger Observatory communication system relies on the custom 902–928 MHz Leeds radio communication for station-to-base-station access, linked to a central microwave backbone [1], [5]. The Leeds radio system still operates at Auger, but its

Manuscript received June 17, 2026. Yifan Yang, Mateo Fernández Alonso and Ioana C. Mariş are with the Inter-University Institute for High Energies (IIHE), Université libre de Bruxelles, Boulevard du Triomphe, B-1050 Brussels, Belgium (e-mail: yifan.yang@ulb.be).

Patrick Stassi is with Pierre Auger Observatory, Malargüe, Argentina

transceivers are obsolete and difficult to source, so the legacy link cannot be extended to the new PEPS stations. Moreover, because PEPS occupies the same site, adding stations in the same 902–928 MHz allocation would worsen spectral congestion alongside the still-operating Auger communication system. A wireless Trigger and Data Acquisition (TDAQ) design is therefore required.

We propose a two-tier wireless readout architecture that modernizes the radio. The first tier consists of a custom, low-power access link operating in the 2.4 GHz ISM band, while the second tier uses commercial 5 GHz backhaul links (such as Ubiquiti Bullet/Rocket equipment) to forward aggregated data from local aggregation points to the central DAQ. We detail the design and experimental verification of two distinct readout translators:

- 1) A baseline UB protocol converter built from discrete development boards (ESP32-ETH01 and MAX3232 converter modules) to bridge the RS-232 serial stream to TCP/IP.
- 2) A custom Pulse Network Unit (PNU) utilizing the Semtech SX1280 transceiver operated in Fast Long Range Communication (FLRC) mode.

The main contribution is a compatibility-preserving first-tier access architecture: the UB-facing serial, flow-control, timing, and reset constraints remain local to the station bridge, while the radio access and backhaul layers can be modernized independently. The prototype results reported here exercise the UB Ethernet bridge and characterize the SX1280/E28 FLRC first-tier access link at bench and single-link field level.

The paper is structured as follows. Section II defines the legacy UB communication boundary and protocol constraints. Section III describes the two-tier architecture, including TDMA capacity arguments, link budget models, and hardware comparisons. Section IV presents the design, implementation, and functional testing of the protocol translators. Section V details the experimental characterization and channel performance of the PNU. Section VI discusses what the current evidence supports and the remaining open questions, and Section VII concludes with the next prototype path and future work.

II. LEGACY COMMUNICATION BOUNDARY AND CONSTRAINTS

The PEPS wireless upgrade cannot assume any modifications to the heritage UB firmware or its hardware interfaces. Consequently, the upgraded communication system must preserve the UB-visible behavior of the legacy radio interface. This compatibility constraint defines several electrical, serial, and protocol requirements.

A. RS-232 and Electrical Interface

The physical connection between the UB and the legacy radio is established via a non-standard DB-9 connector. Unlike standard PC serial cables, this interface integrates serial data lines, hardware flow control, power supply, and timing signals:

- **Baud Rate and Framing:** The serial interface operates at 38.4 kbps with 8N1 framing (8 data bits, no parity, 1 stop bit).
- **Hardware Flow Control:** The legacy interface specifies RTS/CTS hardware flow control, which a deployable bridge must honor with adequate buffer margin for UART and line-driver latency.
- **Signal Voltages:** The serial lines (TX, RX, RTS, CTS) use standard bipolar RS-232 voltage levels (± 5 V to ± 12 V), whereas the timing and control signals are 3.3 V TTL-level. Connecting RS-232 lines directly to a 3.3 V microcontroller will cause permanent hardware damage, requiring appropriate transceivers (such as the MAX3232).
- **Timing and Reset Pins:** The connector carries a GPS-derived 1PPS (one pulse per second) signal and reset-related control signaling in the TTL-level domain.

B. Legacy Protocol Framing

The serial data stream is framed according to the legacy Leeds radio protocol [5]. The frame fields, in transmission order, are:

Preamble (fixed)	Length (1 B)	Type (1 B)	Data (0–249 B)	CRC32 (4 B)	ETX (1 B)
---------------------	-----------------	---------------	-------------------	----------------	--------------

where:

- **Preamble:** A direction-specific character sequence. For the Link-to-Subscriber Unit (LS→SU) direction, the preamble is " !LS2SU!" (preceded by two spaces). For the Subscriber Unit-to-Link (SU→LS) direction, it is " !SU2LS!".
- **Length:** A 1-byte field specifying the total size of the remaining frame components, which include the Type (1 byte), Data (0 to 249 bytes), CRC32 (4 bytes), and ETX (1 byte).
- **Type:** A 1-byte command or status identifier. Examples include V (Version), G/P/M (GPS status/position/time), U (Station ID), B (Buffer status), and T (UB Reset).
- **Data:** The variable-length payload. In PEPS, this payload carries UB trigger and readout information. The readout translator must treat this field as a transparent payload.
- **CRC32:** A 4-byte check sequence calculated over the Length, Type, and Data fields using the standard Ethernet polynomial (0xEDB88320). The CRC bytes are transmitted in big-endian order.
- **ETX:** An End-of-Text marker fixed at 0xFF. If the received ETX byte does not match, the entire frame is discarded.

C. Derived Bridge Requirements

The boundary above implies several implementation requirements. First, the station-side adapter must terminate the electrical interface locally. RS-232 level translation, RTS/CTS handling, PPS input treatment, reset conditioning, and power distribution are station-interface functions; they cannot be delegated to a delayed radio path. Second, the adapter must

parse enough of the Leeds radio protocol frame structure to acquire complete frames and avoid forwarding corrupted or misaligned byte streams into the radio link. The bridge validates frame boundaries and integrity before forwarding, while leaving the UB data field opaque.

Third, the bridge must decouple the UB serial timing from the radio packet timing. The UB transfers bytes at 38.4 kbps, while the wireless access layer works in scheduled packets. The station bridge therefore buffers complete frames on the UB side and queues them on the radio side; merging the traffic of many stations onto the backhaul is a function of the local aggregation node (Section III), not of the per-station bridge.

These requirements motivate the two prototype tracks in this work. The discrete UB protocol converter exercises the electrical and protocol-acquisition part of the problem. The PNU characterizes the SX1280/E28 FLRC first-tier access link. Because the 5 GHz backhaul tier uses commercial Rocket/Bullet equipment already proven in other similar experiments, it is not a TDAQ bottleneck; this study therefore focuses on the station-level design and its verification.

III. TWO-TIER READOUT SYSTEM ARCHITECTURE

To scale the 55 stations/km² array up to 550 stations, PEPS utilizes a two-tier wireless readout architecture, as illustrated in Fig. 2.

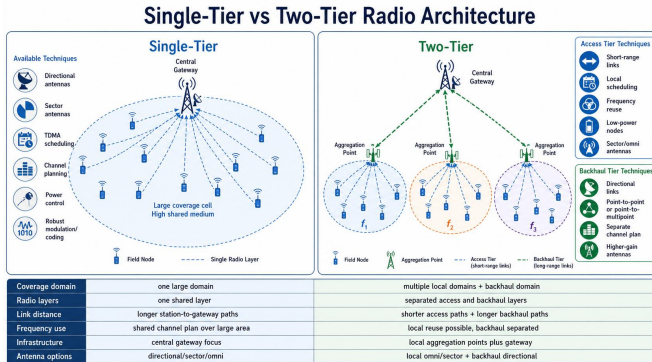


Fig. 2. Single-tier vs. two-tier radio architecture comparison. The PEPS design (right) uses Local Aggregation Points with cell-scale 2.4 GHz first-tier access links and separated 5 GHz backhaul, contrasting with the legacy single-tier approach (left) where all stations share a single large coverage cell.

A. Topology and Geometry

In a single-tier network, every detector station communicates directly with a distant central tower. This asymmetric geometry requires high-power transmitters and directional antennas at each station, which complicates mechanical alignment and raises power requirements.

PEPS resolves this by dividing the array into local cells of 1 km², placing a Local Aggregation Point (LAP) near the center of each cell. Each LAP serves approximately 55 stations. By centering the LAP, the maximum station-to-LAP distance is bounded by:

$$d_{\max} = \sqrt{0.5^2 + 0.5^2} \approx 0.707 \text{ km} \quad (1)$$

Thus, the first-hop access link operates over a cell-scale distance of 600–700 m. This allows both the stations and the LAP to use omnidirectional antennas, reducing mechanical alignment constraints and wind-load vulnerability.

B. TDMA Capacity Rationale

The proposed first-hop access tier intentionally follows the same high-level scheduling principle as the Auger/Leeds system: a deterministic, GPS-referenced, time-division access frame assigns each station a bounded transmission opportunity. The important reuse is not the old RF hardware, but the proven sector abstraction: one base-side radio controller serves a limited set of station-side subscriber units under a fixed schedule.

Two capacity numbers are compatible here. The PEPS cell density is approximately 55 stations per square kilometer, while the legacy TDMA planning supports up to 68 subscriber units per BSU sector. A 1 km² PEPS local cell therefore stays below the legacy sector-count scale, leaving margin for deployment irregularity or modest growth.

The second capacity argument is the air-rate margin. The legacy Auger subscriber-unit over-air rate is reported at 200 kbps, with a much lower effective per-station uplink payload rate after TDMA framing and protocol overhead [1]. The SX1280 FLRC modes evaluated here provide nominal physical rates from 260 kbps to 1.3 Mbps [2]. Even the conservative 650 kbps, CR 1/2 candidate gives a coded physical-layer setting above the legacy over-air rate. Therefore, if PEPS preserves the legacy TDMA structure and uses similar or smaller UB traffic envelopes, the FLRC first hop has a plausible first-order capacity margin for a 55-station cell.

Crucially, PEPS reuses the Auger TDMA scheduling without changing the UB firmware. Since it also uses the same UB hardware, the per-station traffic requirements remain the same as in Auger. Therefore, a local cell with fewer stations than the original 68-unit sector, operating at a higher air rate than the legacy link, should have ample capacity headroom. This is only a first-order check. A complete capacity analysis must still consider the scheduler's slot allocation, including guard times, ACK/retry overhead, and downlink control traffic.

C. Link Budget and Margin Calculations

As a first-order check of the 2.4 GHz first-hop link, we calculate the Free Space Path Loss (FSPL):

$$\text{FSPL(dB)} = 32.44 + 20 \log_{10}(d_{\text{km}}) + 20 \log_{10}(f_{\text{MHz}}) \quad (2)$$

At $f = 2400$ MHz, the path loss model simplifies to:

$$\text{FSPL(dB)} = 100.0 + 20 \log_{10}(d_{\text{km}}) \quad (3)$$

For the maximum cell-centered first-hop distance of $d = 0.7$ km, the path loss is:

$$\text{FSPL}(0.7 \text{ km}) = 100.0 + 20 \log_{10}(0.7) \approx 96.9 \text{ dB} \quad (4)$$

The received power P_{rx} is modeled as:

$$P_{\text{rx}}(\text{dBm}) = \text{EIRP}(\text{dBm}) - \text{FSPL}(\text{dB}) + G_{\text{rx}}(\text{dBi}) \quad (5)$$

where G_{rx} is the receiver antenna gain (+2 dBi) and EIRP is the Effective Isotropic Radiated Power. The link margin is:

$$\text{Margin(dB)} = P_{rx}(\text{dBm}) - \text{Sensitivity(dBm)} \quad (6)$$

For European/Belgian operation, the regulatory limit restricts 2.4 GHz EIRP to 20 dBm. In Table I, the link margins at $d = 0.7$ km for the three representative FLRC receiver bandwidths are provided.

TABLE I
2.4 GHz FLRC LINK MARGIN AT 700 M ($G_{rx} = +2$ dBi)

FLRC Bitrate (kbps)	Rx BW (MHz)	Sensitivity (dBm)	Margin at 20 dBm	Margin at 27 dBm
260 / 325	0.3	-106	31.1 dB	38.1 dB
520 / 650	0.6	-103	28.1 dB	35.1 dB
1000 / 1300	1.2	-97	22.1 dB	29.1 dB

The calculations give a free-space margin of at least 22.1 dB at the cell boundary under a 20 dBm EIRP assumption. The 650 kbps, CR 1/2 field configuration corresponds to the 0.6 MHz receiver bandwidth, giving a 28.1 dB free-space margin at 20 dBm EIRP. These are planning margins; antenna height, cable loss, module output, terrain, multipath, and local interference will reduce them in the field.

D. Access and Backhaul Hardware Comparison

The station-side access radio must operate within the solar-powered station's power budget, while the backhaul can be placed at aggregation points with different power and antenna constraints. Table II compares the commercial Ubiquiti Bullet AC backhaul class with the Ebyte E28-2G4M27SX module containing the Semtech SX1280 transceiver for the access tier [2], [4].

TABLE II
ACCESS AND BACKHAUL HARDWARE SPECIFICATIONS COMPARISON

Parameter	Ubiquiti Bullet AC	Ebyte E28 / SX1280
Operating Band	2.4 GHz + 5 GHz	2.4 GHz ISM
Throughput	160+ Mbps (2.4 GHz)	260 kbps - 1.3 Mbps
Transmit Power	21 - 22 dBm	Up to 27 dBm
Rx Sensitivity	-93 to -62 dBm	-132 to -97 dBm
Active Power	7 - 8 W (Max)	TX: 1.9 W / RX: 48 mW
Sleep Power	N/A	6.6 μ W (Sleep mode)
Data Interface	Gigabit Ethernet	SPI

While the Bullet AC offers superior throughput, its 8 W power draw is unattractive for continuous station-side solar operation. The E28 module datasheet reports 48 mW receive power and under 7 μ W sleep power, making it the appropriate candidate for the low-power station access link. The 5 GHz Bullet/Rocket backhaul is a mature commercial solution, briefly verified here and already in service in other detector-array deployments; we therefore treat the backhaul tier as a low-risk integration and focus this paper on the first-tier access link. The transmit-power and sensitivity values in Table II are datasheet specifications rather than calibrated EIRP or measured output power.

E. First-Hop Technology Choice

The 2.4 GHz SX1280 FLRC link was selected for the access tier after comparing candidate low-power technologies. LoRa offers excellent sensitivity but too little bandwidth to sustain the required per-cell air rate. Sub-GHz Wi-Fi HaLow provides good range and throughput, but it operates close to the 900 MHz band of the existing Leeds radio and would reintroduce the spectral-coexistence problem PEPS aims to avoid. FLRC balances bandwidth and sensitivity—offering configurable bitrates up to the 1.3 Mbps class while keeping sensitivity well within the link budget of Table I—and operates in the 2.4 GHz ISM band, cleanly separated from the legacy 902–928 MHz allocation.

IV. DESIGN AND IMPLEMENTATION OF READOUT TRANSLATORS

To integrate the legacy serial interface with the upgraded networks, we developed and verified two translation units.

A. UB Protocol Converter (Discrete Boards)

The baseline UB protocol converter is designed to bridge the RS-232 serial stream to standard TCP/IP. The hardware implementation is constructed from discrete COTS (Commercial Off-The-Shelf) development modules:

- **Processing and Ethernet Unit:** An ESP32-ETH01 module running custom C++ firmware.
- **Serial Interface:** A MAX3232 converter module to translate the RS-232 data and flow-control lines to the ESP32 logic domain.

The converter implements a frame-aware bridge strategy, following a general design principle of decoupling functions across the link: rather than passing raw bytes straight through, the bridge acquires and validates complete legacy frames locally, so that the serial-side timing is isolated from the variable latency of the packet-radio path. Incoming bytes are accumulated in a ring buffer, and an active parser tracks the Leeds radio protocol frame structure. Once a complete frame is validated (correct preamble, length, CRC32, and ETX), it is encapsulated and transmitted over a TCP socket to the aggregation node. The UB payload remains opaque to the bridge.

Additionally, the firmware runs an embedded HTTP web server on the ESP32. This server hosts a diagnostics page displaying active device IP addresses, cumulative GPS status (capturing GPS Status, Position, and Time frames), raw received serial bytes, and a counter of validated frames.

B. UB Protocol Converter Functional Verification

The protocol converter was verified by connecting it directly to a real Auger UB board over RS-232 (38.4 kbps, 8N1, through a MAX3232 level translator).

Using the predefined command templates exposed by the diagnostics interface (Fig. 3), the bridge issued UB queries and acquired the UB response frames. The parser locked onto the Leeds radio protocol preamble and validated each returned frame against its length, CRC32, and ETX fields. For example,

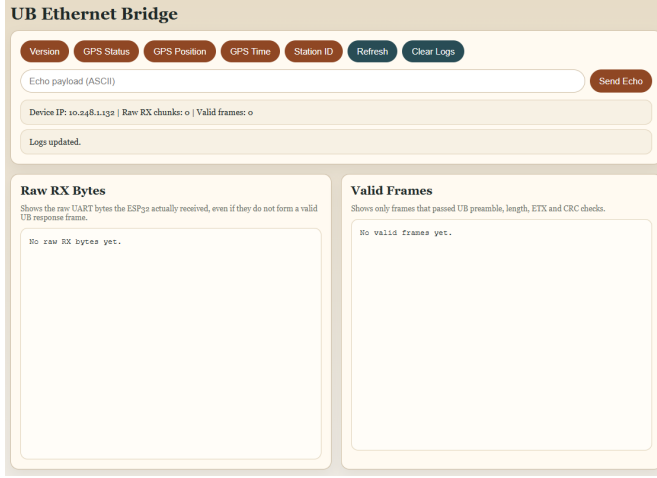


Fig. 3. Web diagnostics interface of the UB protocol converter (“UB Ethernet Bridge”). The dashboard displays device IP, command buttons for GPS Status/Position/Time queries, and two panels showing raw received UART bytes and validated Leads frames.



Fig. 4. PNU V1.0 hardware prototype (marked “PNU-V1.0 ULB-IIHE”). The custom PCB integrates the Ebyte E28 module and Seesee Studio XIAO ESP32, powered by a 9 V VARTA industrial battery through a regulated power rail. An external 2.4 GHz SMA antenna is attached.

a Version query returned the ASCII firmware string V02.01 with a valid CRC, and GPS status and position frames were received and validated; spontaneous UB status frames were also captured during idle. These exchanges confirm correct frame acquisition and integrity checking on live UB traffic.

C. Pulse Network Unit (PNU)

For the custom wireless access path, we developed the Pulse Network Unit (PNU), named for its per-time-slot (pulsed) enabling of the station radio. Early link tests used a discrete prototype built around an ESP32-PICO controller and a separately designed E28 daughterboard. This prototype showed significant packet corruption and elevated loss (around 5%) at high transmit power; oscilloscope measurements traced the cause to voltage droops of up to 400 mV on the 3.3 V rail at the onset of each E28 transmission, driven by the 580 mA transmit-current peak. This motivated an integrated redesign. The PNU V1.0 board combines the Ebyte E28 module with a compact Seesee Studio XIAO ESP32 (S3 or C3 variant) on a custom PCB, with an improved RF power rail and local low-ESR decoupling adjacent to the E28 supply pins. With this board, the droop-induced failure mode of the discrete prototype was no longer observed during bring-up, and the received-signal stability improved markedly.

The PNU pin mapping is defined as: SCK (D2), MOSI (D3), MISO (D4), NSS (D5), RXEN (D6), NRST (D7), TXEN (D8), DIO1 (D9), and BUSY (D10).

Crucially, the RXEN and TXEN pins are connected to the ESP32 and handed to the RadioLib driver: `radio.setRfSwitchPins(RXEN, TXEN)`. This allows the library to automatically switch the E28 module’s external PA and LNA RF switches between transmit and receive states.

The PNU runs a specialized Fast Long Range Communication (FLRC) test firmware. The transceiver is configured in FLRC packet mode with a 2-byte CRC, whitening disabled,

and a fixed payload size [2]. The link is managed using a serial configuration command:

CFG <freq_MHz> <br_kbps> <cr> <pwr_dBm> <preamble>

where the coding rate parameter maps to the physical coding rate (2 → CR 1/2, 3 → CR 3/4, 4 → CR 1/1). The `pwr_dBm` field is a RadioLib/SX1280 configuration setting used for repeatable tests [3]; it should not be interpreted as calibrated module output power or final EIRP without independent RF output, cable-loss, and antenna-gain measurements.

The current test firmware utilizes a fixed 6-byte packet format containing: a 1-byte reinitialization counter (`reinitCount`) to track radio power-ups, a 3-byte low-24-bit packet counter, and a 2-byte fixed tail marker (0xAA55).

A known technical debt exists where the receiver-side parser reconstructs a 32-bit counter from the first 4 bytes, so a power-up that increments `reinitCount` produces a large, characteristic counter jump. The analysis distinguishes such a reinit jump from a genuine loss—which appears as a unit-step gap in the 24-bit counter with `reinitCount` unchanged—and computes loss as the number of missing counter indices across the observed span, so real losses are counted rather than discarded.

V. PNU EXPERIMENTAL CHARACTERIZATION AND LINK RESULTS

We conducted parametric characterization and field tests to evaluate the PNU wireless link.

A. Measurement Definitions

The PNU test firmware sends a small diagnostic packet once per second. Each valid test payload contains a reinitialization counter, a 24-bit packet counter, and a fixed `0xAA55` tail marker. This deliberately simple payload makes it possible to distinguish several error classes:

- **Accepted payload row:** a received packet whose tail marker is valid and whose counter can be placed into a plausible monotonic sequence.
- **Robust counter loss:** the fraction of counter values missing across the observed span of accepted rows. A genuine loss appears as a missing index and is counted; CRC failures and tail-bad receptions are excluded before this count. This is the loss metric used for the candidate-link comparison.
- **CRC failure:** a packet-like reception rejected by the radio or driver integrity check. In a noisy 2.4 GHz environment, such events can include corrupted packets or background activity that briefly resembles a valid reception.
- **Tail-bad event:** a received payload whose final marker is not `0xAA55`, indicating payload corruption or parser misalignment.

These categories are intentionally not merged into one “packet loss” number. For evaluating a final TDAQ service, rejected CRC events and malformed payloads matter because they consume receiver attention and may indicate interference. For evaluating whether the delivered valid stream has sequence gaps, robust counter loss is the more stable metric. Both views are reported where available.

The uncertainty in the short run is dominated by the finite packet count and by the definition of the denominator. At 1 Hz, a ten-minute run contains only about 600 transmitted opportunities, so a difference of a few packets changes the percentage visibly. Accordingly, we report the 700-m result as an $\approx 0.5\%$, statistics-limited robust counter-loss observation rather than a high-precision packet-error figure.

B. Indoor Parametric Sweeps

To characterize FLRC behavior across its operating modes, we performed automated parametric sweeps in an indoor line-of-sight setup. The transmitter sent packets at 1 Hz, while

the receiver recorded RSSI, background noise, CRC failures, and tail-bad events over 3600 s per setting. The loss metric in Table III is a robust counter-loss estimate computed from valid rows with the expected `0xAA55` tail and plausible monotonic counter behavior. CRC failures and tail-bad events are reported separately because they represent rejected or malformed candidate receptions, not accepted payload packets.

TABLE III
1-HOUR PARAMETRIC SWEEP RESULTS (RSSI AVG: -37 TO -41 DBM)

Bitrate (kbps)	CR	Loss %	CRC Fails	Tail Bad
260	3/4	0.000%	124	5
260	1/1	0.056%	129	5
325	1/2	0.028%	139	9
325	3/4	0.028%	132	1
325	1/1	0.056%	145	4
520	1/2	0.111%	265	13
650	1/2	0.056%	288	10
1000	3/4	0.000%	433	18
1300	1/2	0.000%	410	23

The sweeps show low robust counter loss ($\approx 0.1\%$ or below, worst case 0.11%) across the tested configurations. However, the number of CRC failures and tail-corrupted packets increases at higher bitrates (1000–1300 kbps), indicating that the robust counter-loss metric alone is not sufficient to choose the operating point. For deployment-oriented configuration selection, rejected candidate packets, airtime, coding rate, payload size, and scheduler overhead must be considered together.

C. Preliminary 700-m Long-Range Rooftop Field Test

To probe the cell-boundary distance of the PEPS geometry, we conducted a preliminary 700-m rooftop line-of-sight test in Brussels. The environment presented severe urban radio noise in the 2.4 GHz band from co-located Wi-Fi networks.

The test was conducted using the following parameters: Frequency = 2449.5 MHz, Bitrate = 650 kbps, CR = 1/2, Preamble = 16, and a RadioLib transmitter power setting of -8 dBm. Because the rooftop site did not provide long-duration local power, this run was limited to an approximately 10-minute field window rather than a full one-hour scan.

The link telemetry is shown in Fig. 5. The key results are:

- **Signal Strength:** The average packet RSSI was approximately -68 to -70 dBm for the antenna and front-end configuration used.
- **Noise Floor:** The background noise floor fluctuated between -85 dBm and -95 dBm.
- **Link Quality:** Robust counter-loss analysis gave $\approx 0.5\%$ for the 650 kbps, CR 1/2 setting. The receiver also recorded 296 CRC failures and 8 tail-bad events, which are treated as rejected or malformed candidate receptions rather than valid payload packets.

Because robust counter loss is computed from counter values missing across the observed span, a CRC-failed reception that corresponded to a genuinely transmitted packet would leave its counter value missing and so appear as counter loss. That robust counter loss stays near 0.5% while CRC

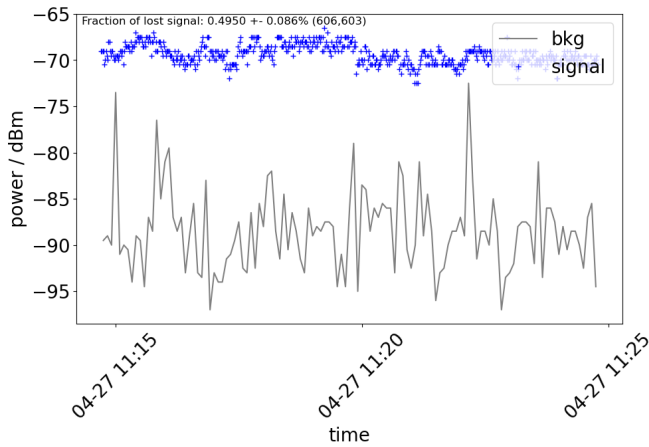


Fig. 5. Received signal strength and background noise during the 700-m Brussels rooftop field test (04-27, 650 kbps FLRC, CR 1/2). Blue markers show per-packet RSSI (≈ -68 to -70 dBm); the gray trace shows the 2.4 GHz background noise floor (-85 to -95 dBm). Robust counter loss for this run is $\approx 0.5\%$, which the manuscript treats as a counter-loss indicator rather than a total packet-error rate.

failures number in the hundreds, therefore indicates these CRC events are overwhelmingly noise-triggered false detections in the busy 2.4 GHz band, not lost payload packets.

The measured average RSSI of approximately -69 dBm is about 34 dB above the -103 dBm sensitivity of the 0.6 MHz FLRC mode, indicating that the 700 m link maintained a substantial link margin even in the presence of significant urban interference. The -8 dBm RadioLib power setting was chosen conservatively to respect the Belgian 2.4 GHz EIRP limit, with the actual radiated power left uncalibrated. With this margin and the -85 to -95 dBm noise floor, the residual losses are dominated by bursty Wi-Fi interference rather than path loss: the link is interference-limited, not range-limited. At the Argentine site, both the quieter spectrum and the headroom to raise transmit power are therefore expected to improve performance relative to this Brussels measurement. Cell-level operation with many stations and operational UB frames is addressed in Section VI and Table IV.

VI. DISCUSSION

Three results establish the basis for a compatibility-preserving two-tier readout. At the architecture level, the PEPS geometry decomposes into local 1 km^2 cells with a 600–700 m first hop. At the capacity level, the ~ 55 stations per cell stay below the 68-subscriber-sector scale of the legacy TDMA planning. At the physical-link level, the measured FLRC modes deliver nominal air rates above the legacy 200 kbps subscriber-unit rate. Together these justify continued development of the two-tier readout.

The experiments also identify useful design constraints. The 650 kbps, CR 1/2 mode is a conservative candidate because it trades peak bitrate for coding robustness while remaining above the legacy over-air rate. The lower-rate 260–325 kbps cases remain useful alternatives if site conditions require more margin. The highest rates should be treated as exploratory until

longer and geometry-matched measurements show comparable robustness.

A. Limitations and Open Questions

The present PNU tests use a synthetic 6-byte counter payload, not a full UB data frame. Therefore, the results characterize the radio link and analysis chain, not a complete PEPS TDAQ path. A deployable station bridge must still encapsulate legacy UB frames, preserve RTS/CTS behavior, handle reset and PPS sideband signals, schedule multiple stations, support downlink/control traffic, and expose operational diagnostics.

The 700-m Brussels test ran in urban 2.4 GHz noise, expected to be harsher than the Malargüe site, so the link is encouraging. A full field campaign—calibrated antennas, measured module output, legal EIRP settings, ground-level mounting, multipath assessment, and multiple simultaneous stations—remains required.

Table IV summarizes the present evidence boundary and the validation targets for the next prototype.

VII. CONCLUSION AND OUTLOOK

We presented the design and experimental characterization of a wireless TDAQ upgrade path for the PEPS surface detector array. The system is designed to preserve compatibility with heritage Auger Unified Board electronics by implementing a two-tier architecture, localizing the low-power station links to a 700-m cell radius.

We developed and tested two translation prototypes. The discrete UB protocol converter performed payload-transparent, frame-aware RS-232 to Ethernet bridging in laboratory tests against a real UB board. The integrated PNU V1.0, using the SX1280 transceiver in 2.4 GHz FLRC mode, added power-supply improvements that eliminated the transmit-droop failure mode. Field testing over a 700-m urban link held robust counter loss to $\approx 0.5\%$ for the FLRC 650 kbps, CR 1/2 configuration with about 34 dB of measured RSSI margin, establishing the first-tier access link.

The next milestone is not a higher peak bitrate but an end-to-end cell demonstrator that connects the UB protocol converter to the PNU access link, assigns deterministic slots to multiple stations, and delivers reconstructed UB traffic through the aggregation point to the DAQ. Its acceptance criteria are frame-level delivery, bounded queue residence, controlled retry behavior, flow-control correctness, and duty-cycle power.

Future work will focus on:

- Deploying and testing PNU units on site near Malargüe, Argentina, to evaluate performance in the target deployment environment.
- Characterizing the link budget and path loss as a function of antenna height and terrain topology.
- Developing a GPS-disciplined TDMA schedule in the PNU firmware to arbitrate channel access within each first-tier cell.
- Integrating the UB Ethernet bridge, first-tier FLRC access link, and aggregation/backhaul interface in an end-to-end demonstrator.

TABLE IV
CURRENT EVIDENCE BOUNDARY AND REQUIRED NEXT VALIDATION

Requirement	Evidence in this work	Required next validation
UB electrical compatibility	RS-232 level shifting and basic UB frame parsing were exercised against a real UB board.	Integrated station-side bridge with DB-9 power, PPS, reset, RTS/CTS, and long-duration UB command sequences.
Payload transparency	Parser checks Leeds framing while preserving the data field as opaque payload.	End-to-end transfer of representative UB frames and waveform-like payloads through the radio access layer.
First-hop range	700-m rooftop FLRC test supports the selected cell-edge distance scale under a noisy urban single-link condition.	Site-representative tests at several antenna heights, legal EIRP settings, ground conditions, and deployment geometries.
Cell capacity	Legacy sector planning supports 68 subscriber units, while the PEPS local cell target is about 55 stations. FLRC nominal air rates exceed the legacy over-air benchmark.	Multi-station TDMA test with slot assignment, guard time, ACK/retry behavior, queueing, downlink control, and burst traffic.
Power suitability	E28 receive and sleep power are much lower than commercial backhaul radios; integrated PNU V1.0 reduced the observed RF supply droop in bench tests.	Duty-cycle power measurement over operational schedules, including wakeup, transmit, receive, sleep, and diagnostics.
Backhaul separation	Architecture separates low-power 2.4 GHz access from 5 GHz or equivalent aggregation backhaul.	Aggregation-node test that forwards reconstructed station traffic to DAQ-side software over the selected backhaul.

Funding is available to deploy a small array of 8 detectors at the site of the Pierre Auger Observatory; this will allow for an end-to-end test in data-taking conditions of this wireless communication system.

Acknowledgements: We would like to thank the Pierre Auger Collaboration for the valuable information on the Leeds radio communication system, for providing us with the UB and for the constant and excellent support for PEPS.

REFERENCES

- [1] Pierre Auger Collaboration, "Properties and performance of the prototype instrument for the Pierre Auger Observatory," *Nucl. Instrum. Methods Phys. Res. A*, vol. 523, no. 1-2, pp. 50–95, May 2004.
- [2] Semtech Corporation, *SX1280/SX1281 2.4 GHz Transceiver Datasheet*, Rev. 3.2, Nov. 2020.
- [3] RadioLib Library, *Universal wireless communication library for Arduino*, [Online]. Available: <https://github.com/jgromes/RadioLib>
- [4] Ebyte, *E28-2G4M27SX 2.4 GHz SX1280 Wireless Module Datasheet*, v1.2, 2022.
- [5] L. Leeds, "RS-232 Protocol Specifications for Auger Subscriber Units," Leeds Comms Tech Report LLC-2004-12, Aug. 2004.