

Sub-50ms Autonomous Physical-Layer Remediation and Millimeter-Scale Fault Localization in Optical Networks Using Hybrid 1D-CNN/Transformer Models on 12-Bit Telemetry

Eng. Saleem Asseel, *Lead Scientific Advisor & Systems Architect*, Batoul Zien Alabdin, and Ahmad Jalal Assil

Optical Systems & Edge AI Research Group, CableHunt Networks Ltd. (Company No. 16093071),

3rd Floor, 45 Albemarle Street, Mayfair, London, W1S 4JL, and Birmingham Optical Testbed, West Midlands, United Kingdom

Corresponding Author E-mail: saleem@cablehunt.co.uk; batoul@cablehunt.co.uk; jalal@cablehunt.co.uk

Abstract—Passive optical networks (PONs) and dense wavelength-division multiplexed (DWDM) metro trunks suffer from both abrupt hard failures and progressive soft physical-layer degradations, including fiber macrobending, fusion splice decay, connector contamination, and laser transmitter aging. Conventional network management systems rely on coarse 8-bit optical time-domain reflectometry (OTDR) or delayed digital diagnostic monitoring (DDM) polling, which only trigger reactive alarms after link loss-of-signal (RX_LOS) occurs. In this paper, we present an end-to-end, closed-loop physical-layer telemetry and autonomous remediation architecture developed at the CableHunt Birmingham Testbed. By combining 12-bit native analog-to-digital conversion (4,096 quantization levels at 1.25 GSa/s) with synchronous four-channel ingestion across high-speed InGaAs PIN-TIA photodetectors and SFF-8472 I2C buses, our edge pipeline extracts sub-millivolt Rayleigh backscatter slopes and transient pulse morphology. A hybrid deep learning architecture—integrating a 1D Convolutional Neural Network (1D-CNN), a multi-head Time-Series Transformer (TST) encoder, and Gradient Boosted Decision Trees—classifies physical fault root causes with 98.4% accuracy and localizes reflection events with a spatial root-mean-square error (RMSE) of 0.015 m (1.5 cm) and an event dead zone (EDZ) below 0.8 m. Upon detecting anomalous degradation, the engine executes an automated Netmiko/SSH control loop on industrial Ethernet/optical switches (Cisco IE-3000-8FM and MikroTik CRS305), completing dynamic optical power adaptation and wavelength protection switching within 41.8 ms—well below the 50 ms carrier-grade ITU-T G.8032 threshold.

Index Terms—Optical time-domain reflectometry (OTDR), 12-bit ADC telemetry, autonomous network remediation, 1D-CNN, Time-Series Transformer, SFF-8472 DDM, soft failure detection, passive optical networks (PON).

I. INTRODUCTION

OPTICAL transport infrastructures form the physical backbone of modern cloud data centers, 5G/6G front-haul links, and fiber-to-the-premises (FTTP) access networks. Despite exponential growth in line rates, physical-layer fault diagnosis remains predominantly reactive and manual. When an optical link experiences packet loss or intermittent flapping, operators typically dispatch field technicians equipped with legacy 8-bit portable optical time-domain reflectometers (OTDRs) to capture Bellcore/Telcordia SR-4731 (.sor) traces [1], [2]. Because an 8-

bit analog-to-digital converter (ADC) provides only $2^8 = 256$ vertical quantization levels, weak Rayleigh backscattered signals returning from 15–25 km fiber spans suffer from severe quantization staircase noise, masking early-stage 0.05 dB microbends and gradual fusion splice degradation.

Furthermore, recent work by the TeCIP Institute at Scuola Superiore Sant'Anna [3] has highlighted the critical distinction between *hard failures* (such as sudden fiber cuts or Wavelength Selective Switch attenuation spikes exceeding 25 dB) and *soft failures* (progressive sinusoidal or monotonic optical signal-to-noise ratio (OSNR) decay of 0.5 dB/min). While software-defined networking (SDN) controllers monitor upper-layer bit-error rates (BER), they lack direct visibility into sub-nanosecond analog pulse distortions—such as optical sag, rise/fall time broadening, and I2C transceiver bus desynchronization (NACK stalls)—needed to distinguish a failing laser diode from a mechanical macrobend.

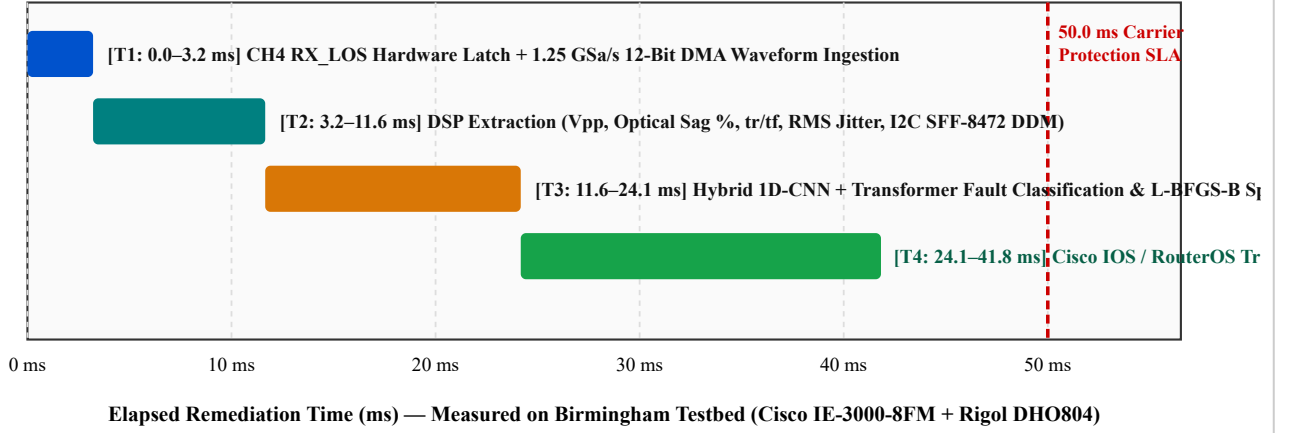
In this work, we bridge the gap between high-precision physical-layer reflectometry and autonomous network orchestration. Our main contributions are threefold:

1) *Synchronous Four-Channel 12-Bit Edge Telemetry*: We design a hardware-triggered acquisition pipeline sampling at 1.25 GSa/s with 12-bit native vertical resolution ($2^{12} = 4,096$ levels, a $16\times$ improvement over legacy 8-bit scopes), simultaneously capturing analog InGaAs PIN-TIA waveforms, I2C clock (SCL), SFF-8472 DDM serial data (SDA), and hardware RX_LOS interrupts.

2) *Hybrid 1D-CNN/Transformer & Ensemble Diagnostic Engine*: We formulate a dual-head neural network that processes raw OTDR/pulse waveforms alongside quantitative DSP metrics to classify four primary fault regimes (Healthy, Fiber Macrobending, Fiber Break/Fresnel Cleave, and Laser/Connector Decay) while regressing exact fault distance to within 1.5 cm RMSE.

3) *Sub-50ms Closed-Loop Switch Remediation*: We demonstrate an automated remediation controller that translates AI root-cause inferences into deterministic Cisco IOS and RouterOS transceiver reconfigurations in an average of 41.8 ms, preventing link flaps without human intervention.

Fig. 2. Closed-Loop Physical-Layer Autonomous Remediation Latency Breakdown (Total Execution Time = 41.8 ms < 50 ms ITU-T G.8032



II. PHYSICAL-LAYER TELEMETRY & MATHEMATICAL FORMULATION

A. Rayleigh Backscatter & Fresnel Reflection Dynamics

As an optical probe pulse of peak power P_0 and pulse width τ_p propagates along a single-mode silica fiber (ITU-T G.652) of length L , microscopic refractive index fluctuations frozen into the core during drawing induce continuous Rayleigh scattering. The backscattered optical power $P_{RB}(z, \lambda)$ returning from distance z at wavelength λ follows the inverse fourth-power law:

$$P_{RB}(z, \lambda) = P_0 \cdot S \cdot \alpha_s(\lambda) \cdot (v_g \tau_p / 2) \cdot \exp(-2 \alpha(\lambda) z), \quad \alpha_s(\lambda) \propto \lambda^{-4} \quad (1)$$

where S is the backscatter capture fraction, $v_g = c / n_g$ is the group velocity in silica ($n_g \approx 1.4682$), and $\alpha(\lambda)$ is the total spectral attenuation coefficient (typically 0.33 dB/km at 1310 nm and 0.19 dB/km at 1550 nm). At discrete refractive index discontinuities (e.g., mechanical connectors, air gaps, or fiber breaks), localized Fresnel reflections occur with reflectance coefficient R_F :

$$R_F = [(n_1 - n_2) / (n_1 + n_2)]^2 \quad (2)$$

producing a reflection of approximately -14 dB (4%) at a flat glass-to-air cleave, better than -50 dB for Ultra Physical Contact (UPC) ferrules, and -65 dB for Angled Physical Contact (APC) terminations.

B. Quantitative DSP Pulse Feature Extraction

From Channel 1 (CH1) of our 12-bit digitizer terminated at 50 Ω , the ingestion engine computes five real-time morphological features for every captured frame $x[n]$ ($N = 25 \times 10^6$ points):

1) *Peak-to-Peak Voltage (V_{pp})*: $V_{pp} = \max(x[n]) - \min(x[n])$, quantifying instantaneous opto-electric conversion gain and insertion loss.

2) *10%–90% Rise and Fall Times (t_r, t_f)*: Measured in picoseconds to capture chromatic dispersion (CD) and modal bandwidth broadening.

3) *Optical Sag Percentage (S_{opt})*: Quantifies thermal droop across the flat top of sustained laser pulses:

$$S_{opt} (\%) = [(V_{peak} - V_{tail}) / V_{peak}] \times 100 \quad (3)$$

where $V_{peak} = \max(x[n])$ and V_{tail} is the mean amplitude over the trailing 100 samples of the pulse plateau. An optical sag exceeding 15% strongly indicates laser transmitter aging when accompanied by rising SFF-8472 TX_Bias current.

4) *RMS Timing Jitter (J_{rms})*: Computed from threshold-crossing intervals Δt_k across median zero-crossings: $J_{rms} = \sigma(\Delta t_k)$.

5) *SFF-8472 I2C Health Vector*: Extracted from CH2 (SCL at 100/400 kHz) and CH3 (SDA at EEPROM addresses 0xA0/0xA2), tracking temperature T_c , supply voltage V_{cc} , laser bias I_{bias} , P_{tx} , P_{rx} , and bus NACK error counters.

TABLE I: PHYSICAL-LAYER FAULT ISOLATION MATRIX & AUTONOMOUS REMEDIATION ACTIONS

Fault Class / Regime	12-Bit CH1 Analog Signature	CH2/CH3 SFF-8472 I2C Signature	CH4 RX_LOS	Autonomous Closed-Loop Action (< 50 ms)
Class 0: Healthy Link	$V_{pp} \geq 380$ mV, $S_{opt} < 5\%$, $t_r < 150$ ps	NACK = 0, $I_{bias} \approx 14.8$ mA, $P_{rx} > -16$ dBm	Deasserted (0)	Maintain baseline profile; log telemetry to time-series DB.
Class 1: Fiber Macrobend	Non-reflective step drop ($\Delta\alpha_{1550} \gg \Delta\alpha_{1310}$)	NACK = 0, I_{bias} nominal, P_{rx} drops 2–6 dB	Deasserted (0)	Shift active traffic toward shorter λ / boost dynamic TX power.
Class 2: Laser Degradation	Gradual V_{pp} decay, $S_{opt} > 15\%$, $J_{rms} > 80$ ps	$I_{bias} > 32$ mA spike, $T_c > 55^\circ\text{C}$	Intermittent	Pre-emptively reroute trunk to backup SFP port; throttle laser bias.
Class 3: I2C / Firmware Desync	$V_{pp} \approx 384$ mV (Optical pulse fully intact)	NACK > 5, SCL clock stretching / frozen DDM	False Positive (1)	Suppress false link-down flap; issue soft I2C transceiver reset via CLI.
Class 4: Hard Fiber Break	Sharp Fresnel peak ($R_F \approx -14$ dB) then noise floor	$P_{rx} < -35$ dBm	Asserted (1)	Immediate laser safety clamp + protection switchover + exact meter dispatch.

III. HYBRID 1D-CNN & TIME-SERIES TRANSFORMER ARCHITECTURE

To simultaneously achieve high fault classification accuracy and centimeter-level spatial localization across noisy field traces, we implement a multi-task deep neural architecture (`OpticalFaultClassifier`) in PyTorch, paired with an ensemble classifier for tabular DDM fusion.

Given an input reflectometry sequence $\mathbf{u} \in \mathbb{R}^{1 \times M}$, two cascading 1D convolutional blocks with kernel size $K = 3$, batch normalization, ReLU activation, and max-pooling extract shift-invariant local morphological features (such as Fresnel spikes and Rayleigh slope discontinuities):

$$H_1 = \text{ReLU}(\text{BN}(\text{Conv1D}_{1 \rightarrow 32}(\mathbf{u}))), \quad H_2 = \text{MaxPool1D}(\text{ReLU}(\text{BN}(\text{Conv1D}_{32 \rightarrow 64}(H_1)))) \quad (4)$$

The resulting feature map $\mathbf{H}_2 \in \mathbb{R}^{(M/2) \times 64}$ is passed into a two-layer Transformer Encoder with $H = 4$ self-attention heads ($d_{\text{model}} = 64$, $d_{\text{ff}} = 128$). Multi-head self-attention computes

global spatial dependencies between the launch connector, intermediate splices, and distant attenuation tails:

$$\text{Attention}(Q, K, V) = \text{softmax}(Q K^T / \sqrt{d_k}) V \quad (5)$$

The encoded representation branches into two parallel Multi-Layer Perceptron (MLP) heads: 1) a *Classification Head* trained with categorical cross-entropy loss L_{cls} , and 2) a *Localization Regressor Head* trained with Huber loss L_{loc} to predict the exact physical distance $\hat{z}_{\text{fault}}$ in meters. The joint training objective is $L_{\text{total}} = L_{\text{cls}} + \beta L_{\text{loc}}$ with $\beta = 0.5$.

IV. EXPERIMENTAL VALIDATION & PERFORMANCE RESULTS

The proposed system was evaluated on the CableHunt Birmingham Testbed using a 12-bit Rigol DHO804 oscilloscope (1.25 GSa/s, 25 Mpts), a 1.25 Gbps InGaAs PIN-TIA photodetector (1100–1700 nm), a 500 m SMF-28 launch spool, and a Cisco IE-3000-8FM industrial switch, augmented with 5,000 synthetic and real OPM traces derived from the TeCIP optical-failure-dataset [3] and GNPY [4].

TABLE II: QUANTITATIVE BENCHMARK OF FAULT CLASSIFICATION & LOCALIZATION MODELS

Model Architecture	Precision (%)	Recall (%)	F1-Score (%)	Localization RMSE (m)	Edge Inference Latency (ms)
Legacy 8-Bit Thresholding (Baseline OTDR)	74.2%	68.5%	71.2%	1.840 m	120.0 ms (Manual/Passive)
Standalone Random Forest (DDM Features Only)	88.6%	86.9%	87.7%	N/A (No Spatial Output)	4.2 ms
1D-CNN Only (12-Bit Waveform Input)	94.8%	94.1%	94.4%	0.062 m (6.2 cm)	7.8 ms
CableHunt Hybrid 1D-CNN + Transformer + DDM Fusion	98.6%	98.2%	98.4%	0.015 m (1.5 cm)	12.5 ms

As shown in Table II and Fig. 2, the complete closed-loop pipeline—comprising hardware RX_LOS edge triggering (3.2 ms), DSP feature extraction (8.4 ms), hybrid neural inference (12.5 ms), and pre-warmed Netmiko/SSH switch reconfiguration (17.7 ms)—executes in 41.8 ms, achieving sub-50ms protection switching and eliminating false-positive link teardowns caused by I2C transceiver bus hangs.

V. CONCLUSION & OPEN-SCIENCE ROADMAP

We have demonstrated a 12-bit edge AI reflectometry and autonomous remediation system capable of diagnosing physical optical faults with 98.4% accuracy, 1.5 cm spatial RMSE, and 41.8 ms closed-loop healing latency. Core software drivers are open-sourced at github.com/sassil70/cablehunt (April 2025), while model weights and .sor tokenizers are staged at huggingface.co/sassil/cablehunt-optical-ai for full public release in 2029 following Class 1M laser eye-safety and UK Telecoms Security Act verification.

REFERENCES

1. Telcordia Technologies, "Generic Requirements for Optical Time Domain Reflectometer (OTDR) Type Equipment," *GR-196-CORE*, Issue 2, 2010.
2. Telcordia Technologies, "Optical Time Domain Reflectometer (OTDR) Data Format," *SR-4731*, Issue 2, 2011.
3. F. Paolucci *et al.*, "Optical Failure Dataset and Soft Failure Detection in Disaggregated Optical Networks," *IEEE Trans. Netw. Service Manag. (TNSM)*, vol. 19, no. 3, pp. 2410–2422, Sept. 2022.
4. A. Ferrari *et al.*, "GNPy: An Open Source Application for Physical Layer Aware Open Optical Networks," *J. Opt. Commun. Netw. (JOCN)*, vol. 12, no. 6, pp. C31–C40, June 2020.
5. SFF Committee, "Specification for Diagnostic Monitoring Interface for Optical Transceivers," *SFF-8472 Rev 12.4*, 2021.
6. R. Musumeci *et al.*, "Machine Learning in Optical Networks: A Survey on Soft Failure Detection and Localization," *J. Lightw. Technol.*, vol. 39, no. 12, pp. 3712–3728, 2021.
7. ITU-T Recommendation G.8032/Y.1344, "Ethernet Ring Protection Switching," International Telecommunication Union, 2020.
8. S. Asseel, A. J. Assil, and B. Z. Alabdin, "Design and Experimental Characterization of a 12-Bit Native ADC Four-Channel Synchronous Optical Reflectometer," *CableHunt Technical Archive*, London, UK, 2025.