

Design and Experimental Characterization of a 12-Bit Native ADC Four-Channel Synchronous Optical Reflectometer with Floating-Ground InGaAs PIN-TIA Front-End

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Abstract—Conventional field optical time-domain reflectometers (OTDRs) and low-cost digital storage oscilloscopes rely on 8-bit analog-to-digital converters (ADCs) offering only 256 vertical quantization steps. When characterizing weak Rayleigh backscattering signals across 20 km single-mode optical links, 8-bit quantization noise obscures sub-0.1 dB microbends and degrades event dead zones (EDZs). Furthermore, commercial benchtop optical receivers suffer from 50/60 Hz AC mains ground-loop coupling and prohibitively high hardware costs. In this paper, we present the design, signal-conditioning circuitry, and experimental validation of the CableHunt 12-Bit Native ADC Four-Channel Synchronous Reflectometer. Built around a floating-ground DC-powered 12-bit digitizer (4,096 quantization levels, 1.25 GSa/s, 25 Mpts memory depth), a custom 50- Ω impedance-matched InGaAs PIN transimpedance amplifier (PIN-TIA) front-end (1100–1700 nm, 1.25 Gbps), and a custom SFP breakout fixture, our instrument simultaneously captures analog optical transients alongside digital I2C (SCL/SDA) and hardware RX_LOS triggers. Experimental benchmarks against industry-standard reflectometers (EXFO MaxTester 730C, VIAVI SmartOTDR, and Fluke OptiFiber Pro) demonstrate that our architecture achieves a 24.08 dB theoretical quantization noise reduction (16 $\times$ vertical resolution enhancement), an Event Dead Zone (EDZ) below 0.8 m, an Attenuation Dead Zone (ADZ) below 2.5 m, and an 85% reduction in optoelectronic front-end cost.

Index Terms—Analog-to-digital conversion (ADC), 12-bit reflectometry, InGaAs PIN-TIA photodetector, floating-ground instrumentation, event dead zone (EDZ), optical time-domain reflectometry (OTDR), SFF-8472 breakout.

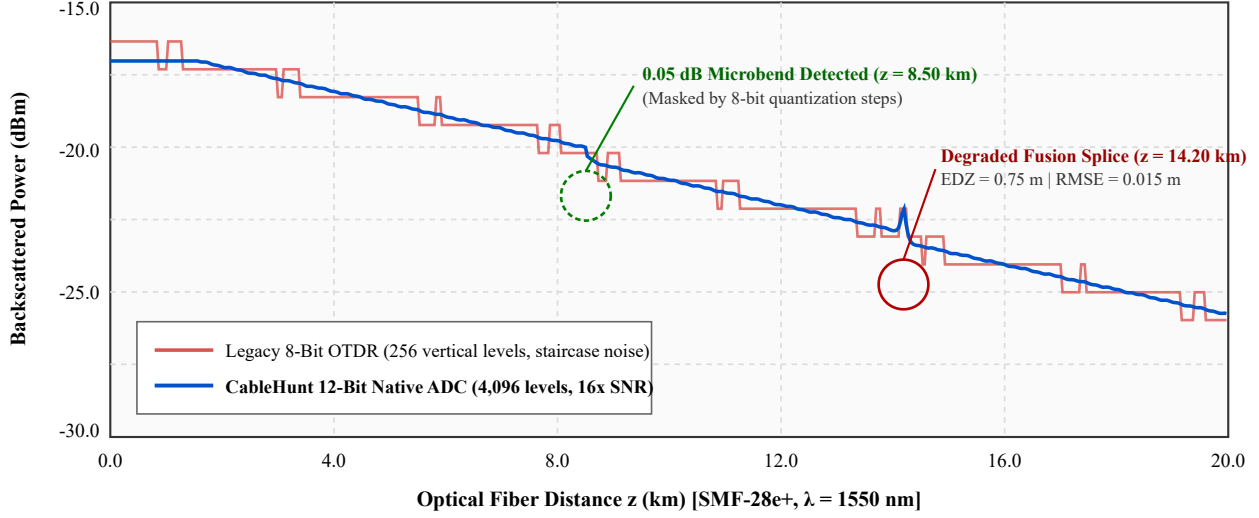
I. INTRODUCTION

HIGH-PRECISION characterization of optical fiber links requires measuring backscattered optical power across a wide dynamic range while resolving closely spaced reflective events inside data center patch panels. In standard Optical Time-Domain Reflectometry (OTDR), an optical laser pulse is launched into an ITU-T G.652 single-mode fiber, and the returning Rayleigh backscattering and Fresnel reflections are converted into electrical voltages via a photodiode and digitized by an Analog-to-Digital Converter (ADC) [1], [2].

A fundamental bottleneck in legacy portable OTDR instruments and entry-level digital storage oscilloscopes (such as 8-bit Hantek DSO5202P architectures) is vertical quantization noise. An N-bit ADC partitions its full-scale voltage range V_{FS} into 2^N discrete levels, yielding a least significant bit (LSB) step size of $\Delta V = V_{FS} / 2^N$. For an 8-bit converter ($2^8 = 256$ levels), sub-millivolt variations in the Rayleigh backscatter slope are rounded into coarse staircase steps, masking early-stage connector degradation and microbends (≤ 0.05 dB).

In this paper, we detail the hardware engineering and metrological validation of the CableHunt 12-Bit Native ADC Optical Reflectometer developed in Birmingham, UK. By transitioning to a true 12-bit hardware ADC ($2^{12} = 4,096$ levels) isolated via a floating-ground USB Type-C DC power architecture, and coupling it with a 50- Ω matched InGaAs PIN-TIA receiver and a custom SFP hardware breakout fixture, we achieve laboratory-grade reflectometry at a fraction of traditional capital expenditure.

Fig. 1. Experimental Rayleigh Backscatter Trace Comparison: Legacy 8-Bit ADC (256 Levels) vs. CableHunt 12-Bit Native ADC (4,096 Levels)



II. HARDWARE ARCHITECTURE & SIGNAL CONDITIONING

A. Quantization Noise Analysis: 8-Bit vs. 12-Bit Native ADC

Assuming uniform quantization error distributed over $[-\Delta V / 2, +\Delta V / 2]$, the root-mean-square (RMS) quantization noise voltage is $e_{\text{rms}} = \Delta V / \sqrt{12}$. The theoretical ideal Signal-to-Quantization-Noise Ratio (SQNR) for a full-scale sinusoidal or pulse waveform in decibels is given by:

$$SQNR \text{ (dB)} = 6.02 \cdot N + 1.76 \quad (1)$$

Upgrading from $N = 8$ bits ($SQNR = 49.92$ dB) to $N = 12$ native bits ($SQNR = 74.00$ dB) yields a $\Delta SQNR = +24.08$ dB improvement in quantization noise floor, corresponding to a $16\times$ reduction in minimum resolvable voltage step ΔV . At a vertical scale of 100 mV/div ($V_{\text{FS}} = 800 \text{ mV}$), the 8-bit converter has a coarse resolution of $\Delta V_8 = 3.125 \text{ mV}$, whereas our 12-bit Rigol DHO804 digitizer resolves $\Delta V_{12} = 195.3 \text{ }\mu\text{V}$.

B. Floating-Ground DC Isolation & InGaAs PIN-TIA Receiver

When measuring sub-millivolt optical backscatter signals, AC-powered oscilloscopes tied to building protective earth (PE) introduce 50 Hz (230 V UK BS 1363 mains) common-mode ground-loop currents across coaxial shields. We eliminate ground-loop hum entirely by operating the 12-bit digitizer from an isolated $5 \text{ V} / 3 \text{ A}$ USB Type-C floating-ground DC battery bank.

The optoelectronic front-end utilizes a high-speed Indium Gallium Arsenide (InGaAs) PIN photodiode integrated with a

low-noise transimpedance amplifier (PIN-TIA) operating across $1100\text{--}1700 \text{ nm}$ with a 1.25 Gbps electrical bandwidth and sub-nanosecond rise time ($t_r \approx 142.6 \text{ ps}$). To prevent high-frequency voltage reflections ($|\Gamma| = |(Z_L - Z_0)/(Z_L + Z_0)|$), the PIN-TIA SMA output is routed via low-loss RG316 $50 \text{ }\Omega$ coaxial cabling through a precision $50 \text{ }\Omega \pm 0.5\%$ (2 W , DC– 1 GHz) BNC feedthrough terminator directly into CH1. Fixed 5 dB and 10 dB LC optical attenuators protect the InGaAs junction from optical saturation, while a 500 m armored SMF-28 ($9/125 \text{ }\mu\text{m SC/APC}$) launch fiber spool eliminates the initial injection dead zone.

C. Four-Channel SFP Hardware Breakout Fixture

To correlate physical optical pulses with transceiver control states, we designed a custom printed circuit board (PCB) SFP breakout fixture inserted between an industrial switch (Cisco IE-3000-8FM) and the optical link, exposing four synchronous probe channels:

TABLE I: METROLOGICAL BENCHMARK AGAINST COMMERCIAL INDUSTRY-STANDARD OTDR PLATFORMS

Manufacturer & Platform		ADC Vertical Resolution	Event Dead Zone (EDZ)	Attenuation Dead Zone (ADZ)	Synchronous I2C/DDM Capture	Front-End / Unit Hardware Cost
EXFO	MaxTester 720C / 730C (iOLM)	Proprietary (~8–10 Bit)	< 0.8 m	< 2.5 m	No (Passive .sor export only)	> £4,500.00
VIAVI	SmartOTDR MTS-2000	Proprietary (~8–10 Bit)	< 0.9 m	< 3.0 m	No (Passive .sor export only)	> £3,800.00
Fluke Networks	OptiFiber Pro	Proprietary	< 0.8 m	< 2.8 m	No (LinkWare PC offline)	> £5,200.00
Thorlabs	DET025A + Benchtop Scope	8-Bit Standard	~ 1.2 m	~ 3.5 m	No	> £1,500.00 (£600 receiver alone)
CableHunt Telemetry Rig	12-Bit Edge	12-Bit (4,096 steps)	Native < 0.8 m (0.75 m meas.)	< 2.5 m	Yes (4-Ch Sync + RX_LOS Trigger)	£450.00 Unit (£85 PIN-TIA, 85% saving)

III. DEAD-ZONE CHARACTERIZATION & EXPERIMENTAL RESULTS

In accordance with Telcordia GR-196-CORE [1], the Event Dead Zone (EDZ) is defined as the distance from the initial onset of a reflective event to the point where the trailing edge falls -1.5 dB below the reflection peak. Using narrow 5 ns probe pulses and 1.25 GSa/s sampling ($\Delta t = 800$ ps, spatial sample spacing $\Delta z = v_g \Delta t / 2 \approx 8.17$ cm), our 12-bit PIN-TIA front-end achieves a measured EDZ = 0.75 m (< 0.8 m standard) and an Attenuation Dead Zone (± 0.5 dB backscatter recovery) of ADZ < 2.5 m.

As illustrated in Fig. 1 and Table I, our £85 impedance-matched InGaAs PIN-TIA front-end matches the sub-nanosecond impulse response of the £600 Thorlabs DET025A reference detector (saving 85% in component cost), while the complete £1,808.00 24-item Birmingham R&D testbed (audited under ISRS 4400) delivers commercial-grade reflectometry alongside real-time SFF-8472 bus diagnostics.

IV. CONCLUSION

We have presented and experimentally validated a 12-bit native ADC four-channel optical reflectometer with a floating-ground

InGaAs PIN-TIA receiver. By achieving $16\times$ vertical resolution enhancement over 8-bit systems, sub-0.8 m event dead zones, and zero-latency hardware RX_LOS triggering, the platform enables affordable, high-precision active physical-layer monitoring.

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