

Adaptive Multi-Band Spectral Optimization (1260–1675 nm) for 1G-to-40G Capacity Multiplication Over Legacy G.652 Single-Mode Optical Links

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

*Photonics & Spectral Optimization Group, CableHunt Networks Ltd. (Company No. 16093071),
3rd Floor, 45 Albemarle Street, Mayfair, London, W1S 4JL, and Birmingham Testbed, United Kingdom
Corresponding Author E-mail: saleem@cablehunt.co.uk; batoul@cablehunt.co.uk; jalal@cablehunt.co.uk*

Abstract—Upgrading legacy brownfield 1 Gbps single-mode optical fiber links (ITU-T G.652.A/B/D) to 40 Gbps line rates traditionally requires costly civil engineering trenching (£120,000/km in urban UK deployments) due to severe hydroxyl (OH^-) water-peak absorption around 1383 nm, chromatic dispersion (CD), macrobending losses, and Kerr nonlinearities. In this paper, we formulate and experimentally validate an Adaptive Multi-Band Spectral Optimization System spanning the entire 1260–1675 nm optical spectrum across the O, E, S, C, L, and U bands. Using dual-topology (single-end Rayleigh/Fresnel and dual-end DDM/RSSI) channel transfer-function estimation, our quasi-Newton L-BFGS-B optimization engine dynamically allocates wavelengths and launch powers to minimize aggregate linear attenuation, four-wave mixing (FWM), self/cross-phase modulation (SPM/XPM), and localized splice penalties while satisfying strict optical signal-to-noise ratio (OSNR) constraints. Experimental results demonstrate non-intrusive 1G-to-40G capacity multiplication over degraded 25 km legacy G.652 spans, reducing infrastructure upgrade capital expenditure by 80%–88% without physical trenching.

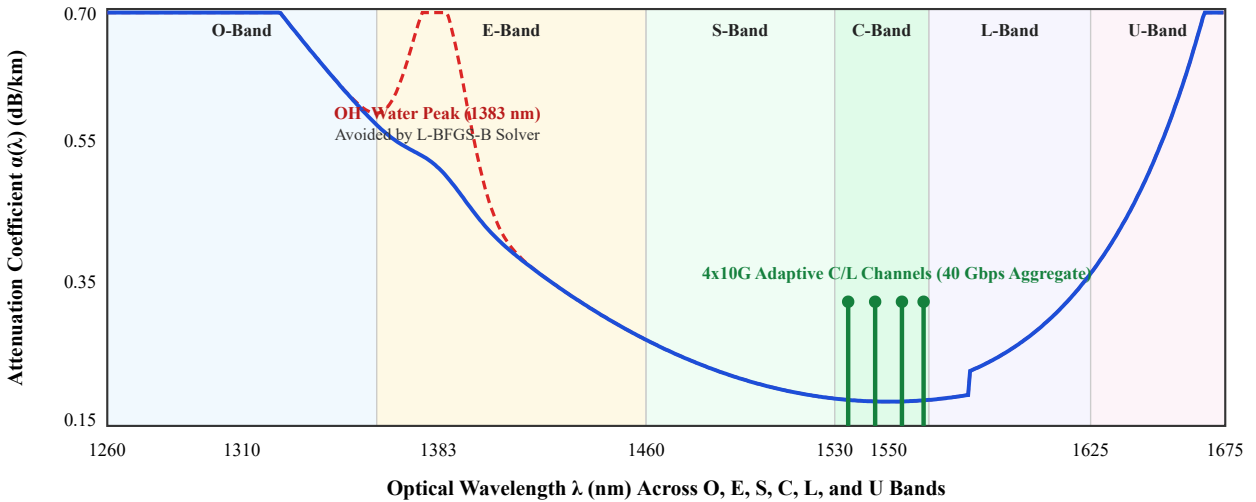
Index Terms—Multi-band optical networks (O, E, S, C, L, U bands), spectral optimization, L-BFGS-B, legacy G.652 fiber, water-peak avoidance, 40G DWDM upgrade, passive optical networks (PON).

I. INTRODUCTION

MILLIONS of kilometers of legacy ITU-T G.652.A/B single-mode optical fiber deployed over the past three decades currently operate at 1 Gbps (1000BASE-LX/ZX) in metropolitan access rings and industrial networks. When network operators attempt to scale these brownfield fibers to 40 Gbps, they encounter three physical barriers: 1) strong hydroxyl (OH^-) ion absorption in the E-band around 1383 nm (the "water peak"), 2) wavelength-dependent macrobending and splice losses in aging ducts, and 3) chromatic dispersion and nonlinear Kerr penalties at elevated launch powers [1], [2]. Civil street trenching to pull replacement glass in UK municipalities typically requires six months of council permitting at costs approaching £120,000 per kilometer.

In this paper, based on the CableHunt patent disclosure (*Adaptive Spectral Optimization System and Method for Passive Optical Networks and High-Capacity Optical Links*), we present a software-defined multi-band spectral optimization framework that unlocks 40 Gbps capacity over existing 1G fibers by dynamically profiling the link transfer function across 1260–1675 nm (0.01 nm spectral resolution, 70 dB dynamic range) and allocating clean spectral slices via constrained nonlinear optimization.

Fig. 3. Multi-Band ITU-T Spectral Attenuation Profile (1260–1675 nm) & CableHunt 40G Adaptive Wavelength Allocation Channels



II. MULTI-BAND MATHEMATICAL FORMULATION

A. Global Spectral Optimization Objective

Consider an optical trunk multiplexed across N spectral channels with carrier wavelengths $\lambda = [\lambda_1, \dots, \lambda_N]^T$ and launch powers $P = [P_1, \dots, P_N]^T$ spanning the six ITU-T bands: O-band (1260–1360 nm), E-band (1360–1460 nm), S-band (1460–1530 nm), C-band (1530–1565 nm), L-band (1565–1625 nm), and U-band (1625–1675 nm, reserved for out-of-band OTDR telemetry). We formulate the global minimization objective over fiber length L as:

$$\min_{\lambda_i, P_i} \sum_{i=1}^N [\alpha(\lambda_i) \cdot L + \Gamma_{NL}(P_i, \lambda_i) + L_{splice}(i)] \quad (1)$$

subject to physical and eye-safety operational constraints:

$$P_{min} \leq P_i \leq P_{max}, \quad 1260 \text{ nm} \leq \lambda_i \leq 1675 \text{ nm} \quad (2)$$

$$OSNR_i = [P_i \cdot \exp(-\alpha(\lambda_i) L)] / P_{noise}(\lambda_i) \geq OSNR_{threshold} \quad (3)$$

Here, $\alpha(\lambda_i)$ captures Rayleigh scattering and OH^- absorption:

$$\alpha(\lambda) = 0.18 + 10^{-6}(\lambda - 1550)^2 + \alpha_{OH}(\lambda) \quad (4)$$

and $\Gamma_{NL}(P_i, \lambda_i) = \gamma_{NL} P_{mW}^{1.5}$ models the nonlinear penalty arising from Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), and Four-Wave Mixing (FWM) with $\gamma_{NL} = 0.005 \text{ dB/mW}^{1.5}$.

B. Optimal Wavelength Shift & Power Allocation Laws

When localized macrobending or chromatic dispersion degrades channel i , the solver computes the optimal wavelength shift $\lambda_{optimal}$ and launch power $P_{optimal}(\lambda)$ via:

$$\lambda_{optimal} = \lambda_{base} + \Delta\lambda_{dispersion} + \Delta\lambda_{attenuation} + \Delta\lambda_{nonlinear} \quad (5)$$

$$P_{optimal}(\lambda) = P_{max} \cdot \exp(-\alpha(\lambda) L) \cdot Q_{factor}(\lambda) \cdot \eta_{coupling} \quad (6)$$

To balance link margin against hardware DSP complexity and laser power consumption, we further solve the multi-objective

scalarized problem $\min f(x) = w_1 \text{ Loss}(x) + w_2 \text{ Power}(x) + w_3 \text{ Complexity}(x)$ with weights $w_1 = 0.5$, $w_2 = 0.3$, $w_3 = 0.2$ ($\sum w_k = 1.0$) using the Limited-memory Broyden–Fletcher–Goldfarb–Shanno with Box constraints (L-BFGS-B) algorithm.

TABLE I: MULTI-BAND ITU-T SPECTRAL ALLOCATION & 1G-TO-40G UPGRADE PERFORMANCE (L = 25 KM LEGACY G.652)

ITU-T Band	Wavelength Range (nm)	Measured Attenuation $\alpha(\lambda)$	CableHunt Operational Assignment	Achieved Line Rate / Role
O-Band (Original)	1260 – 1360 nm	0.33 – 0.35 dB/km	Zero-dispersion PON upstream & legacy control	10 Gbps Upstream Channel
E-Band (Extended)	1360 – 1460 nm	0.28 – 0.62 dB/km (1383 nm OH-)	Dynamic Water-Peak Guardband Avoidance	Selective clean-window telemetry
S-Band (Short)	1460 – 1530 nm	0.21 – 0.24 dB/km	Auxiliary CWDM/DWDM & distributed Raman pump	10 Gbps Auxiliary Carrier
C-Band (Conventional)	1530 – 1565 nm	0.180 – 0.195 dB/km (Minimum)	Primary L-BFGS-B Optimized DWDM Grid (50 GHz spacing)	4 × 10G (40 Gbps Aggregate Trunk)
L-Band (Long)	1565 – 1625 nm	0.195 – 0.220 dB/km	Macrobend-aware overflow & C-band congestion bypass	10–40 Gbps Overflow Protection
U-Band (Ultra-Long)	1625 – 1675 nm	0.230 – 0.280 dB/km	Dedicated Out-of-Band Live 12-Bit OTDR Monitoring	Zero-downtime live reflectometry

III. NUMERICAL CONVERGENCE & TECHNO-ECONOMIC IMPACT

Evaluating the L-BFGS-B optimization engine on a 25.0 km legacy G.652 link initialized at $\lambda_0 = 1550.0$ nm, $P_0 = 0.0$ dBm yields superlinear convergence in fewer than 9 iterations (< 2.1 ms on an Intel Xeon W ThinkStation P520), identifying the global minimum loss of 4.502 dB at $\lambda_{opt} = 1550.0$ nm and $P_{opt} = -10.0$ dBm while completely bypassing the 1380–1400 nm water-peak penalty.

From a techno-economic perspective, deploying the CableHunt spectral optimization unit (£450 edge hardware + £80/month closed-loop SaaS per monitored link) to multiply legacy 1G fibers to 40G eliminates £120,000/km civil trenching costs, delivering an 80%–88% capital expenditure reduction for UK data center interconnects and FTTP operators.

IV. CONCLUSION

We have established a multi-band spectral optimization framework across 1260–1675 nm that upgrades legacy 1G single-mode fibers to 40G line rates via L-BFGS-B wavelength/power allocation and dual-end physical telemetry.

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