Assessment of QoT Penalties Caused by Band Failures in Multi-Band Optical Line Systems

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***Abstract*—Ultra-wideband (UWB) optical transmission systems rely on accurate quality-of-transmission (QoT) estimation to enable automation and reliable lightpath provisioning. While existing physical-layer models typically assume fixed spectral loading conditions, real networks are subject to dynamic changes, including the failure or shutdown of entire spectral bands due to maintenance, reconfiguration, or faults. In this work, we investigate the impact of spectral band failures on the generalized signal-to-noise ratio (GSNR) in multi-band optical networks. Using a numerical propagation framework that accounts for amplified spontaneous emission, nonlinear interference, and stimulated Raman scattering, we analyze single- and multi-band failure scenarios in a five-band UWB system. Our results show that band failures induce significant GSNR redistribution across the remaining spectrum, driven by Raman power transfer and nonlinear effects, leading to both local and global performance variations. These findings highlight the need to explicitly account for spectral failure scenarios in QoT estimation and network design to ensure robust and conservative operation**

***Index Terms*—Ultra-wideband transmission, SRS, GSNR, band failures, QoT estimation**

I. Introduction

An optical network digital twin (ONDT) based on accurate and dynamic quality-of-transmission (QoT) estimation is essential for automation and reliable lightpath provisioning in modern software-defined optical networks [1]. Ultra-wideband (UWB) data transport, spanning multiple spectral bands beyond the C-band, enables large additional capacity [2] but introduce complex frequency-dependent interactions, including Stimlated Raman Scattering (SRS)-induced power redistribution [3][4] modifying the intrinsic fiber loss, and the consequent nonlinear interference (NLI) and ASE noise modifications. Conventional QoT assessments typically assume fixed spectral loading and continuous operation of all channels and bands. However, real networks are dynamic and may experience operational events such as maintenance or failures that lead to the shutdown of individual bands. Band failures modify the spectral power distribution, affecting SRS-induced power transfer as well as the amount of NLI and ASE noise, which can degrade the generalized signal-to-noise ratio (GSNR) [5] of the remaining bands. In UWB scenarios, these effects can be significant; therefore, it is crucial that the ONDT properly accounts for such variations in order to accurately capture the induced GSNR fluctuations and enable effective control counteractions and/or the needed GSNR margin. In this work, we investigate GSNR variations in a five-band ultra-wideband (UWB) line system under both single- and multi-band failure scenarios. Using a numerical propagation framework based on GNPy [6], which accounts for amplified spontaneous emission (ASE) noise, nonlinear interference (NLI), SRS, and the frequency dependence of fiber parameters [7], we analyze how band shutdowns redistribute optical power and impact the performance of the remaining channels. The results quantify the resulting GSNR degradation and highlight the importance of incorporating spectral-failure awareness into the optical network digital twin (ONDT) to ensure robust network operation.

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II. Methodology

In this section, we describe the implemented simulation setup and the adopted methodology for GSNR evaluation. The numerical analysis considers a multi-band WDM system composed of 10 identical 70 km fiber spans. As shown in Fig. 1, the system includes five spectral bands (U, L, C, S, and E), each populated with uniformly spaced WDM channels transmitting 400G dual-polarization 16-QAM signals at 64 GBaud with 75 GHz spacing. At the transmitter, channels are multiplexed and launched using an optimized multi-band power profile that maximizes and equalizes the GSNR across all bands [8]. After each span, channels are demultiplexed and amplified by band-specific optical amplifiers [2], whose noise figures are reported in Tab. II. At the receiver, each wavelength is detected by a coherent receiver for GSNR evaluation.

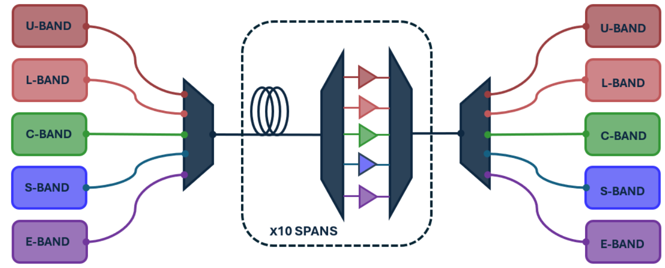

Fig. 1. Simulation setup.

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TABLE I
FREQUENCY BOUNDS AND BANDWIDTH OF EACH BAND COMPOSING THE ENTIRE TRANSMISSION SCENARIO.

Band	Bands parameters				
	f_{min} (THz)	f_{max} (THz)	Bandwidth (THz)	Number of channels	Channel spacing (GHz)
U	180.710	185.510	4.800	64	75
L	186.010	190.810	4.800	64	75
C	191.310	196.110	4.800	64	75
S	196.610	206.210	9.600	128	75
E	206.810	221.210	14.400	192	75

TABLE II
OPTICAL AMPLIFIER NOISE FIGURE VALUES USED IN THE CONSIDERED WIDEBAND SCENARIO.

	Bands				
	U	L	C	S	E
NF [dB]	6.0	6.0	5.5	7.0	7.0

Signal propagation is simulated using the GNPy [9][6] numerical framework that accounts for chromatic dispersion, fiber nonlinearity, and stimulated Raman scattering, enabling accurate modeling of power evolution and spectral tilt across the transmission bandwidth. At the receiver side, the QoT is evaluated in terms of the GSNR [5], defined as the ratio between the received signal power and the total accumulated noise power, including amplified spontaneous emission (ASE) and nonlinear interference (NLI) evaluated encompassing UWB effects [7][3]:

$$GSNR = \frac{P_{ch}}{P_{ASE} + P_{NLI}} \tag{1}$$

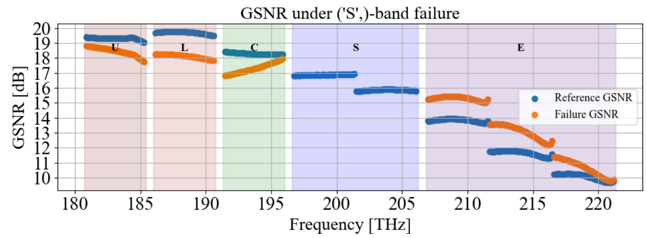
Considering a path (p), the GSNR can be evaluated collecting the GSNR contribution of each link k along the path according to [10]:

$$GSNR = \left(\sum_{k \in (p)} GSNR_k^{-1} \right)^{-1} \tag{2}$$

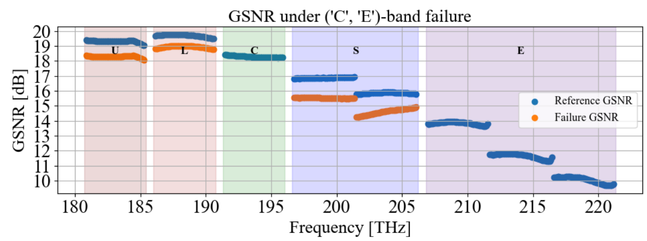
To investigate the impact of spectral band failures, one or more bands are deactivated by setting their transmitted power to zero. The resulting GSNR distribution is evaluated across the remaining channels to quantify power redistribution and performance degradation caused by Raman coupling and non-linear effects.

III. RESULTS

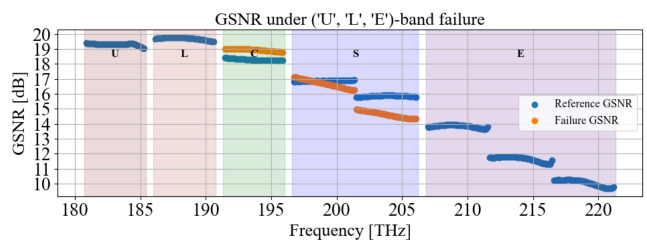
Fig. 2 shows the comparison between the reference GSNR distribution over the entire optical spectrum, with all bands active and Raman amplification enabled, and four representative failure scenarios: (a) single-band failure, (b) two-band failure, (c) three-band failure, and (d) four-band failure. In the single-band failure case, GSNR degradation is mainly confined to the neighboring bands, with limited impact on distant spectral regions. As the number of failed bands increases, GSNR degradation becomes more widespread, affecting multiple bands simultaneously. Due to the Raman effect, the failure of an higher-frequency band causes GSNR degradation for lower-frequency bands, but also a simultaneous increase in higher-frequency bands. To quantitatively assess the impact of failures, the maximum GSNR loss was computed for each band and in each failure scenario. The results are summarized in Fig. 3. Single-band failures lead to maximum GSNR losses up to approximately 2 dB, with the most critical scenarios involving the S and E bands. Two-band and three-band failures produce comparable or slightly higher losses, with peak degradations exceeding 2 dB for combinations involving the C and S bands. Four-band failures generally



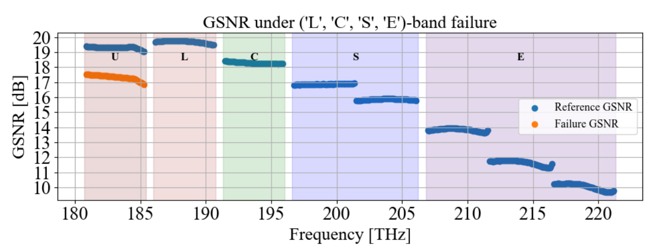
(a) One-band failure example



(b) Two-band failure example

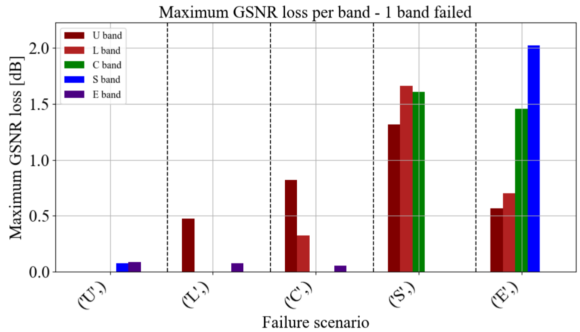


(c) Three-band failure example

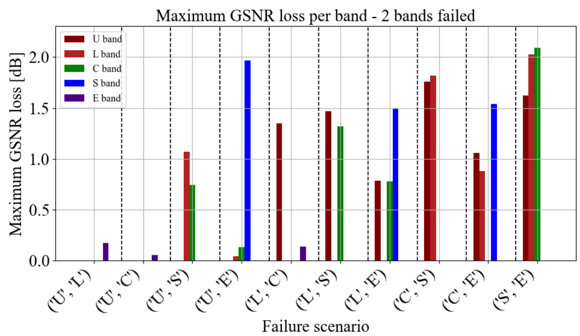


(d) Four-band failure example

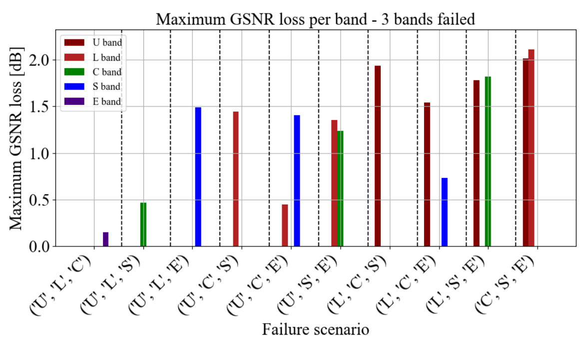
Fig. 2. GSNR spectra under different band failure scenarios: (a) one-band, (b) two-band, (c) three-band, and (d) four-band failures.



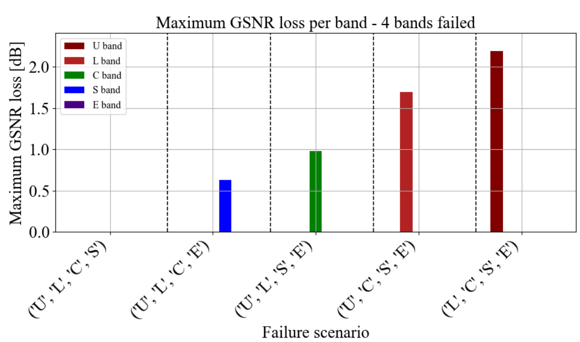
(a) One-band failure



(b) Two-band failure



(c) Three-band failure



(d) Four-band failure

Fig. 3. Maximum GSNR loss under different band failure scenarios: (a) one-band, (b) two-band, (c) three-band, and (d) four-band failures.

exhibit smaller incremental losses, as only a limited portion of the spectrum remains active. These results indicate that a GSNR design margin of approximately 2–2.5 dB is required to ensure robustness against realistic band failure scenarios in ultra-wideband Raman-amplified optical networks.

IV. Conclusion

This work analyzed the impact of spectral band failures on GSNR performance in ultra-wideband optical systems. Numerical results for a five-band UWB line system show that band shutdowns significantly modify the spectral power distribution through stimulated Raman scattering, causing non-negligible GSNR variations in the remaining bands. Even single-band failures can induce GSNR penalties of up to about 2 dB, mainly affecting adjacent bands, while multi-band failures lead to more widespread degradations. In particular, failures of higher-frequency bands penalize lower-frequency bands and partially benefit higher-frequency ones, reflecting the asymmetric nature of Raman-induced power transfer. Overall, a GSNR margin of approximately 2–2.5 dB is required to ensure robustness against realistic band failure scenarios.

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