Statistical Method for ROADM Cascade Penalty

Biplab Pal, Lei Zong, Emily Burmeister and Harshad P. Sardesai
Ciena Corporation, 920 Elkridge Landing Road, Linthicum, MD 21090
bpal@ciena.com

Abstract: ROADM elements in DWDM optical networks exhibit variations in pass-band amplitude response due to manufacturing variations and supplier diversity. We present a novel statistical approach for ROADM cascade penalty allocation, which reduces OSNR penalty with negligible impact to the worst case penalty estimate.

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1. Introduction

Transmission penalty due to ROADM cascades has been identified as one of the most critical limiting factors in high bit rate, 50GHz-spaced DWDM systems [1,2,3]. In 10Gbps systems, the ROADM cascade penalty was generally modeled using worst case manufacturing specifications and statistical models did not yield lower penalties. However, in 40Gbps systems modeling ROADM cascade penalties using worst case manufacturing specifications will lead to very high penalties [2], which would decrease reach and increase network deployment cost. In this work, we present a statistical method of modeling ROADM cascade penalty which is both realistic and does not compromise performance as compared with the worst case ROADM design.

2. Method

The manufacturing statistics of ROADM filters are implemented assuming a truncated Gaussian distribution where the truncation point indicates specification values for the ROADM filter. There are two major statistics of ROADM filters; center frequency (Fig.1a) and 3-dB bandwidth (Fig.1b), but the analytical shape of the filter remains almost the same over manufacturing variations and supplier diversity. The phase response of the ROADM filter elements tends to contribute negligibly as the number of cascades increases because it leads to the reduction of phase ripple variance. Phase response is therefore neglected. The equivalent transfer function (TF) of N cascaded SuperGaussian filters of order m is computed as:

$$H_{eq}(f)=\prod_{i=1}^{N} e^{-2^{2(m-1)}\ln(2)\left(\frac{f-f_c^{(i)}}{f_{3dB}^{(i)}}\right)^{2m}}, \qquad (1)$$

where $f^{(i)}{}_c$ and $f_{3dB}{}^{(i)}$ are the center frequency and 3-dB bandwidth of the individual filter respectively. Both are generated as random variables according to manufacturing statistics. The formula also assumes the worst-case condition as this is the equivalent filter for a channel expressed through all of the ROADMs while its immediate neighbors are added and dropped such that the effective pass-band for the channel under consideration gets narrowed with each successive ROADM traversal. This enables estimation of the equivalent filter shape of the cascaded ROADM for any given number of ROADM cascades with 99 or 99.5 percentile worst-case bandwidth. This worst-case bandwidth is found by obtaining a histogram of equivalent 3-dB bandwidths for 10,000 or more combinations for a given N-cascade. By comparing with experimental data, an empirically deterministic simulation model of ROADM cascading generated by the Monte-Carlo method can be obtained to provide a predictor of OSNR penalty for a given bandwidth which can be used to estimate the penalty for equivalent cascaded ROADMs with 99 or 99.5 percentile cut-off.

3. Simulation and Experiment

The ROADM element passband used in simulations has a mean 3-dB value at 42.5GHz, a cut-off spec. at 37.5GHz and a variance of 3.2GHz (Fig 1A/B), based on real supplier data. These data points were obtained by measuring 88 ITU channels of approximately 100 commercial devices. Narrowing of this passband has been simulated with 100,000 combinations where each combination yielded multivariate distributions of 3-dB bandwidth as in Fig. 2A in which a resulting distribution of 3-dB bandwidth for 10 cascaded ROADM is shown. An AWG filter combination has been assumed to emulate channel ingress-egress filtering effects on 44 Gbps RZ-DQPSK systems. Figure 2B shows reduced bandwidth obtained from the histogram for 95, 99 and 99.5 percentile in which the 95 percentile bandwidth involves an optimistic estimate, whereas only a small difference exists between 99 and 99.5 percentile bandwidth. This suggests 99.5 percentile bandwidth would be a suitable measure to use for the reduced bandwidth in cascaded ROADM systems.

To determine the penalty predictor, a commercially available simulation package, Optsim, is used to simulate the relationship of OSNR penalty and ROADM bandwidth. At first, four ROADM filters are modeled based on the measured amplitude and group delay data from real samples. In the simulation, the four filters are cascaded between a pair of 44 Gb/s RZ-DQPSK transceivers. BER and Q-factor are estimated in both back-to-back configuration and after the concatenation with Karhunen-Loeve techniques in a direct-detection receiver. At the same time, experiments are done with those WSS samples to validate the accuracy of the simulation models. As shown in Fig. 3a, modeling and experiment results are in good agreement for both back-to-back and WSS cascading configurations.

After experimental validation, eight filters from another WSS sample set are modeled and cascaded in the simulation, and it yields a clear-concatenation-bandwidth versus penalty curve as shown in Fig.3b. The clear bandwidth is defined as the measured raw bandwidth minus twice of the center frequency shift, and the filter concatenation bandwidth is calculated based on individual filter passband bandwidth and center frequency shift. The results in Fig.3b have subsequently been used to estimate the penalty of ROADM cascading for 99.5 percentile reduced bandwidth (Fig. 4). Percentile bandwidth is obtained from parametric kernel fitting of the resulting histograms in (Fig. 2A/B) for all the combinations.

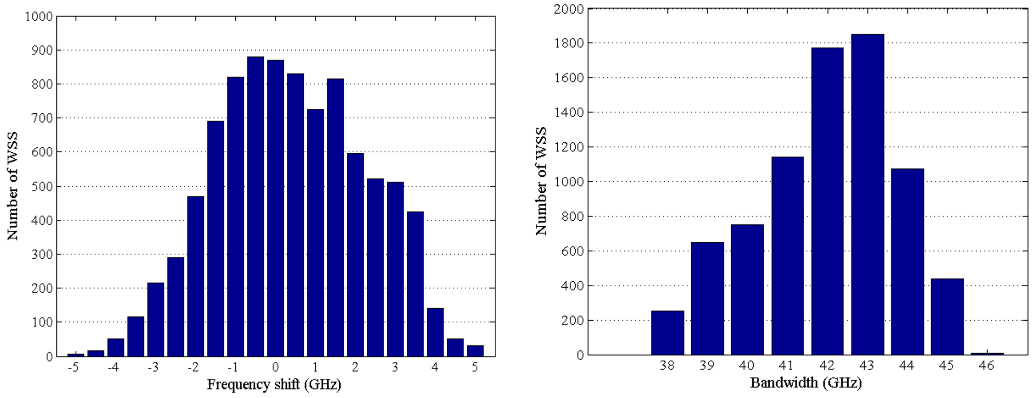

Fig.1.(a) Histogram of center frequency shift. (b.) Histogram of 3-dB bandwidth

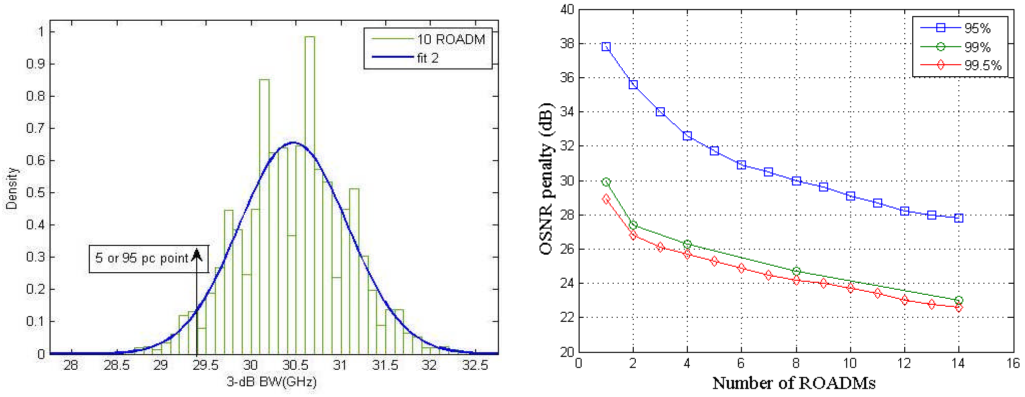

Fig.2. (a.)_Histogram of 3-dB statistics after 10 cascaded filter. (b.) Reduced bandwidth with different percentile from histograms.

4. Discussion

Fig 4 shows the difference between ROADM penalties using the worst case specified values of the filter versus the present method. The results indicate up to 0.5dB of OSNR margin can be saved by statistical design without compromising the robustness in design methodology. Further reduction of penalty is possible if we accept 95 instead of 99.5 percentile, but since a network may have more than hundreds of light-paths, underestimation of penalty for 5% of the light-paths is not advisable. In reality, such probability is likely still low because most light-paths will transmit through much wider pass-bands due to the presence of express through-path neighbors. Since manufacturing specifications are generally done at 0.01 or 0.05 rejection probability, having N such worst case cascades in a system gives a probability of $(0.01)^N$ or $(0.05)^N$. When N>5, this leads to unrealistically low probabilities and wastage of network margin. The described method yields a more realistic estimate of ROADM cascading penalties, without compromising system margin.

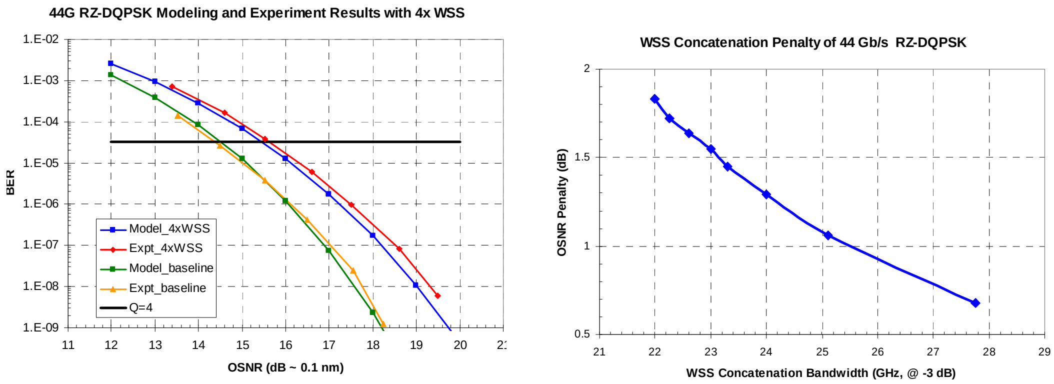

Fig.3. (a.) Experiment and modeling results for ROADM cascading penalty. (b.)Optsim simulated penalty from deterministic model.

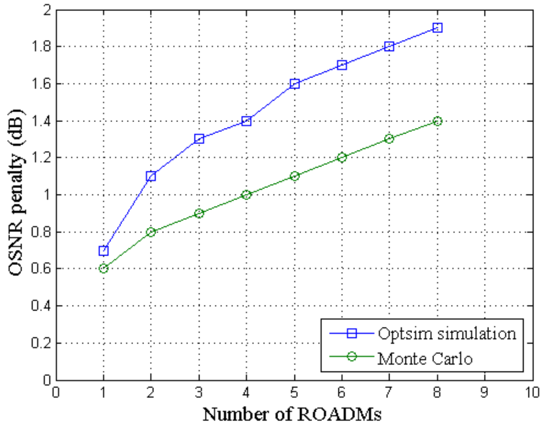

Fig.4. Difference between ROADM cascade penalty from specification-based simulation and statistical approach

5. **References**

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