# Distribution of Embedded DWDM Channel Monitors in Pass-Through Node Limited Transmission Links

**Michael Cahill and Glenn Bartolini**
*Aegis Semiconductor, Inc., 78A Olympia Avenue, Woburn, MA 01801*
*mcahill@aegis-semi.com*

**Abstract:** A transmission model is used to derive the requirements for distributing DWDM optical channel monitors in transmission links engineered with ROADM-based architectures, which can require up to 24 transparent pass-through nodes. The model applies random settings of variable parameters to reflect realistic optical transmission link budgets. It is shown that as the number of spans increase, DWDM channel monitors must be distributed more frequently, approaching an economical "tipping point" that may justify integrating channel monitors within optical amplifiers.

**OCIS codes:** (060.0060) Fiber optics and optical communications; (060.2320) Fiber optics amplifiers and oscillators; (060.2360) Fiber optics links and subsystems.

## 1. Introduction

As telecom and cable service providers continue to increase the bandwidth of broadband services to end users, they are also upgrading their metro and regional optical network backbone to support the corresponding increase in traffic. Metro and regional optical architectures are undergoing a fundamental transformation with the deployment of reconfigurable optical add-drop multiplexers (ROADMs). One service provider that serves densely populated regions has set an initial target of traversing 16 to 24 nodes transparently, recognizing the number of nodes as the limiting factor and not the overall reach [1]. ROADMs may be installed at any one of these nodes. The addition of ROADMs adds insertion loss in the optical path and stretches the span budget further. While requiring increased wavelength agility and wider span dynamic range, the same service provider also desires that such equipment retain the simplicity of point-to-point DWDM networks with respect to wavelength engineering and provisioning [1].

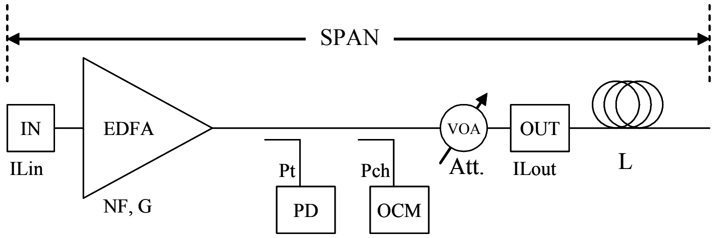
These ROADM network architectures are challenging the design rules for transmission systems more than ever. Extremes in channel loading configuration, span lengths, fiber types and environmental conditions add together with aging budgets to limit the total number of nodes that can be traversed transparently. The fundamental system design challenge is to achieve and maintain an optimal optical amplifier (OA) gain profile at each node of an amplifier chain, under all conditions and over the service life. The use of a combination of optical amplifier aggregate power and optical channel monitoring to improve the OA behavior is widely recognized [2]. For that reason, the International Telecommunications Union (ITU) has specifically carved out Recommendation G.697 for optical channel monitoring within the framework of the Optical Transport Network (OTN) [3].

## 2. Brief Review of EDFA Control Challenges

The erbium-doped fiber amplifier (EDFA) remains the technology of choice for optical amplification in the typical networks considered in this study [1]. As the transmission through increasing numbers of transparent pass-through nodes is considered, DWDM optical link designs must balance the limits in the maximum allowable optical launch power to avoid non-linear impairments in optical fiber and the minimum optical signal-to-noise ratio (OSNR) required to achieve acceptable bit error rates (BER) at the receiver [4]. It has been shown that OSNR penalties increase with increasing tilt in the gain profile [4]. EDFA control systems based only on composite optical power monitoring and look-up tables to determine proper EDFA settings may suffer more OSNR penalties by overestimating the channel power due to the relatively large contribution of amplified spontaneous emission (ASE) noise when few channels are provisioned [5]. One study also shows that stimulated Raman scattering (SRS) in standard single mode fiber alone causes significant wavelength dependent channel performance variation, which if left uncompensated can limit transmission to 18 spans of 80 km [6]. Realistic systems designs however cannot consider each independent variable individually. This study looks statistically at the cumulative effect of many practical parameters that can affect the transmission gain profile as a function of number of pass-through nodes and the distribution of embedded channel monitors used for EDFA feedback and control in a transmission link.

## 3. DWDM Transmission Link Performance with Frequency of Embedded Channel Monitors

A more complete picture of the effects of multiple variables on channel power and OSNR can be obtained using a simplified model of an optically amplified span shown in Fig. 1. This model consists of an EDFA launching into a fiber of length *L*. A variable optical attenuator (VOA) is available at the output of the amplifier for power control and at the mid-stage for linear gain tilt control (not shown). The variability of insertion loss through patch panels at the central office is a priori unknown and factored into this model both at the input (IN) and output (OUT) of the amplifier. A photodiode (PD) measures the total optical power (which includes the total channel and the ASE power) and an optical channel monitor (OCM) measures the power in each channel, each through a calibrated optical tap. The amplifier applies a power tilt to compensate for stimulated Raman scattering (SRS) and wavelength-dependent fiber attenuation [7].

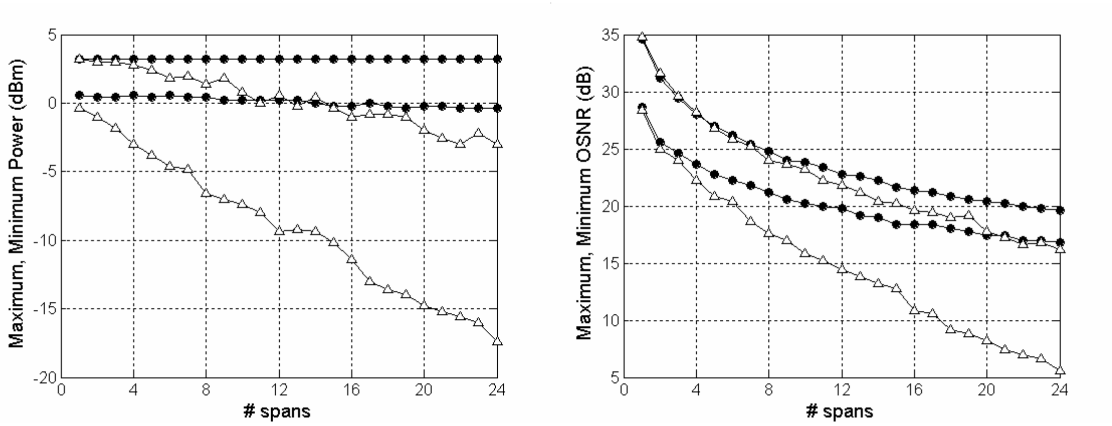


Note: Distributions are obtained by running 100 random variable settings (see table for ranges) and with the following additional assumptions: a) The attenuator (Att.) is increased for span length variations between 50 and 70 km only; b) Gain tilt assumes 85% of full loading SRS and 70 km of fiber; c) A linear tilt is applied at each amplifier output to compensate estimated SRS and fiber attenuation tilt, except at the receiver where no tilt is applied; d) The applied gain is set for maximal output power per channel.

| Variable Parameters | | Min | Max | Units |
|---|---|---|---|---|
| DWDM channels loading | N | 2 | 40 | N/A |
| Nominal channel launch power | $P_{ch}$ | - | 2 | dBm |
| Total launch power | Pt | - | 19 | dBm |
| Total launch power accuracy | | -1 | +1 | dB |
| Noise figure | NF | 5.5 | 6.5 | dB |
| Insertion loss from outside plant to amplifier input | $IL_{in}$ | 1 | 5 | dB |
| Insertion loss from amplifier to outside plant | $IL_{out}$ | 1 | 5 | dB |
| Output attenuation accuracy | Att | -1 | +1 | dB |
| Span length accuracy | L | 50 | 90 | km |
| OCM average absolute accuracy | | -0.4 | +0.4 | dB |
| OCM relative tilt accuracy | | -0.1 | +0.1 | dB |
| OCM relative channel accuracy | | -0.5 | +0.5 | dB |

Fig. 1: Computational model of a transmission span with input variable parameters and assumptions.

The DWDM system is assumed to be turned up with 2 channels in order to determine the required amplifier gain and output attenuation settings, and then loaded with up to 40 channels as more capacity is required. At first we assume that the system turn-up procedure uses the total optical power from the PD to estimate the channel power by dividing the total power by the number of channels present. The relationship between system performance and number of spans is then determined by running 100 simulations for each span using uniformly distributed random variable parameter settings in the ranges listed in Fig. 1 and using the assumptions listed in the same figure.

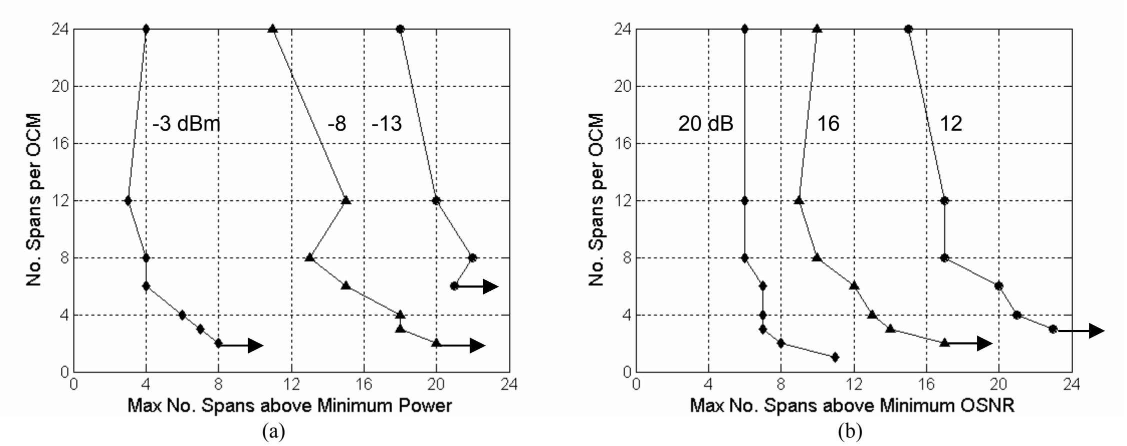


(a) (b)

Fig. 2: (a) Channel power degradation and (b) OSNR degradation with increasing number of spans for a fully-loaded system. Solid points represents the use of OCMs at each span, hollow points represent no DWDM channel monitoring.

The 95th percentile minimum and maximum channel power over all channels and all runs is calculated versus the number of spans and these are plotted in Fig. 2(a) with hollow triangles (i.e. there is a 95% probability that the maximum (minimum) channel power is less (greater) than the value shown in the graph). The 95th percentile minimum and maximum OSNR is plotted in Fig. 2(b) with hollow triangles. The same simulation is then run with OCMs present at each amplifier output, where the OCM provides an accurate measure of channel power that is then used by the amplifier to adjust its gain and linear gain tilt in order to optimize the channels' launch power. The 95th percentile results for power and OSNR are shown with solid circles in Fig. 2(a) and (b), respectively. The results show that if OCMs are not employed the channel power and OSNR degrade rapidly due to accumulated power tilt and accumulated amplified spontaneous emission (ASE). If, however, OCMs are present at every amplifier site, the channel power is maintained, power tilt degradation is minimized and the OSNR is maximized.

The calculation is repeated assuming that OCMs are available at equal intervals of number of spans to measure the channel power. The channel power and OSNR across the band increase as OCMs are more frequently available throughout the link as the OCM provides more accurate information on channel power at each amplifier output than a photodiode alone. Assuming that the link budget can sustain a channel power of greater than -3, -8 or -13 dBm at the receiver amplifier output or an OSNR of greater than 20, 16 or 12 dB at the receiver, we show in Fig. 3 an engineering requirement for the minimum availability of OCMs in the link as a function of spans (the arrows indicate greater than 24 spans for the next data point). If the link can support received powers as low as -13 dBm, then placement of an OCM at every 4th span is required in order to reach 24 spans, however, if the minimum received channel power is increased to -3 dBm an OCM is required every span. If the link budget requires a minimum OSNR of 20 dB, then placement of an OCM at every 4th span or less is required for links with more than 8 spans. As the required OSNR decreases the achievable number of spans increases, however, in order to maximize the system reach for minimum OSNR of 16 or 12 dB it is necessary to place an OCM at every span.



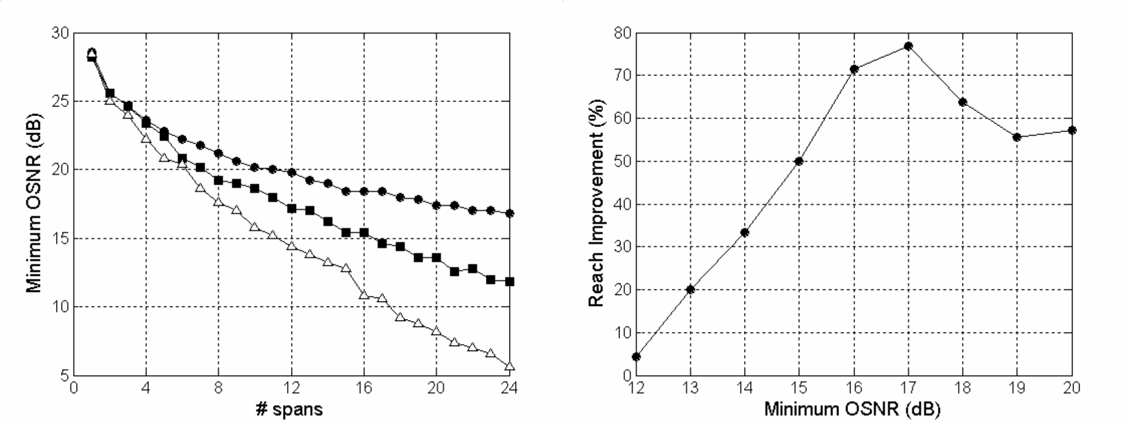
(a) (b)

Fig. 3: Number of spans (a) above minimum channel power of (-3, -8, -13) dBm and (b) above minimum OSNR of (20, 16, 12) dB versus number of spans per OCM.

## 4. Economic Considerations for Embedded Channel Monitoring

DWDM channel monitors are typically embedded in repeater systems on a separate line card for the flexibility of optional provisioning. This flexibility comes with the technical limitations of inter-card communication bandwidth. Measurement inaccuracies due to patch cords and connectors between monitoring and measurement points must be factored in as well. A separate line card also consumes valuable space on the system shelf and requires additional sparing in the field. Still, many systems designers have resisted the integration of channel monitoring on the amplifier line card to avoid the cost penalty of deploying a channel monitor at every repeater node.

Technologies are now available at a cost and size that greatly facilitate the integration of channel monitoring within the EDFA module [8]. The cost premium of this so-called self-managed EDFA can be shown to be approximately less than a third of the cost of a DWDM channel monitor on a line card. The savings include the DWDM channel monitor line card host electronics and associated hardware. The EDFA processor resources are applied to spectral computations to achieve increased computing efficiencies and eliminating the need for a separate channel monitoring processor. The added cost of a DWDM channel monitor card for every three repeater nodes is approximately equivalent to the incremental cost of embedding optical monitors into three self-managed EDFAs. Increasing the number of OCMs from every third node to every node also improves system performance. Fig. 4(a) shows the relationship between the minimum OSNR and the number of spans traversed for a system with OCMs used every span (solid circles), every third span (solid squares) and not at all (hollow triangles). Depending on the minimum OSNR required, an improvement in system reach of greater than 50% is achievable if the numbers of OCMs is increased from every three spans to every span, and this is shown in Fig 4(b) which plots the percentage improvement in reach versus the minimum OSNR required at the receiver. The improvement is small for low values of minimum OSNR since placement of OCMs every third span allows a system reach of just less than 24 spans which is the maximum reach modeled. In this scenario the placement of OCMs every span provides significant increase in OSNR margin after the 24 spans.



(a) (b)

Fig. 4: (a) minimum OSNR versus number of spans for a system with OCMs used every span (solid circles), every third span (solid squares) and not at all (hollow triangles) and (b) percentage improvement in system reach (up to 24 spans) versus minimum required OSNR for a system with OCMs used every span compared to one using OCMs every third span.

## 5. Conclusion

A computational model of a multi-span optical link was analyzed statistically using a random distribution of variable parameters representative of realistic DWDM systems and turn-up conditions. This model applies well to pass-through node limited transmission links which are growing more frequent due to the increased deployment of ROADM architectures. The calculations show that the increased distribution of channel monitors in the transmission link increases the number of achievable spans and pass-through nodes. Economical considerations imply that if the number of spans is large enough to require at least one channel monitor for every three spans, then a self-managed amplifier at every span may be considered at little or no cost penalty that will also improve the system reach.

## 6. References

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