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Application of H_∞ Control for Suppression of Power Excursions due to Pilot Tones and Network Traffic in Optical Amplifiers

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Abstract— **Conventional Erbium-doped fiber amplfiier (EDFA) control schemes lack a systematic design approach and do not consider the characteristics of system input disturbances. We propose the application of H_∞ control to suppress the cross-gain modulation effects of pilot tones, used for optical monitoring, and packet and burst-switched traffic, commonly found in Optical Burst Switched networks. A detailed design of the H_∞ controller is given, focussing on the characteristics of the input disturbances and desired performance measures. Simulation results under different types of disturbances are presented showing significant improvements in response time and reductions in power excursions.**

I. INTRODUCTION

Erbium-doped fiber amplifiers (EDFAs) form the backbone of todays wavelength division multiplexed (WDM) optical networks by providing fast optical signal amplification directly on the physical layer. Although EDFAs enable increased transmission capacity and network transparency, there remain a number of challenges which must be overcome as WDM optical networks increase in complexity. One challenge exists when incoming signal traffic is subject to intentional disturbances and/or disturbances related to intrinsic network characteristics. In light of these signal disturbances, the control and management of the EDFA response represents an important design problem in the evolution towards a dynamic optical network [15].

The transient response of an EDFA has been extensively examined for the case of a sudden change in the number of channels existing in the network [2]. It has been shown that as channels are added/dropped from the network, the EDFA suffers from cross-gain modulation which induces power transients in surviving channels [3]. Of particular interest is the speed and magnitude at which these power transients propagate through the network. With a natural response time on the order of tens of milliseconds, it has been shown that the rate of power variation increases linearly with the number of EDFAs in the link [4]. As a consequence, the network is vulnerable to large swings in output power which can lead to network service impairments by surpassing thresholds for nonlinear effects and by driving surviving channel power outside of acceptable receiver levels.

In order to overcome these adverse effects, several control configurations have been realized which reduce the effects of these unwanted power transients [1], [5]-[8],[16]. Though effective, these control methods lack a systematic approach for control design as most utilize traditional PID tuning rules. Moreover, there have been no formal attempts to analyze the robustness or optimality of these control methods with respect to different types of disturbances and performance objectives.

In this paper we propose the design and application of H_∞ control to minimize the effects of input signal disturbances in EDFAs. Via H_∞ control we are able to provide a measure of robustness for the EDFA under a range of input conditions while also incorporating what is known of input disturbances in our design. Moreover, the synthesis of H_∞ optimal controllers requires a systematic, yet simple, methodology which is readily available in MATLAB.

II. INPUT SIGNAL DISTURBANCES

The majority of research on EDFA dynamics has focussed primarily on disturbances due to channel addition or removal from the system. However, optical networks are also subject to two other types of known signal disturbances: pilot tones and burst-mode traffic. In this section we review the disturbance models and the EDFA model.

A. Pilot Tones

Pilot tones are used to track and monitor the performance of individual wavelengths in a network [9], by modulating them with a unique pilot tone. The channel can be tracked all-optically by tapping a small portion of the incoming signal. In addition, binary data can be frequency modulated upon the pilot tone, resulting in a simple method to determine signal routing and carry supervisory information. With a pilot tone being used, channels optical power is given as

$$P_i(t) = P_o\ [1 + m_i \sin(2\pi(f_{c,i} + \Delta f d_i(t)\, t)] \qquad (1)$$

where P_0 is the nominal optical power, m_i the modulation depth, $f_{c,i}$ the pilot tone carrier frequency, Δf the peak frequency deviation and $d_i(t)$ is the binary (NRZ) data carried on the pilot tone. Successful utilization of a pilot tone monitoring scheme requires proper selection of carrier frequencies and signal amplitudes. Pilot tone frequencies are typically chosen above the natural slow gain dynamics of the EDFA, and below the high frequency payload of the optical link, i.e., between 10 and 100kHz. By limiting the amplitude of pilot tones to 10% of average optical power, large power penalties and tone corruption can be avoided. However, due to the effects of cross-gain modulation the presence of pilot tones induces ghost tones on surviving channels which may be mistaken as pilot tones at the receiver.

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B. Network Traffic

Optical burst switching (OBS) allows for efficient resource sharing amongst numerous users, leading to increased system throughput [10]. Burst-mode traffic is characterized by input channel powers turned ON and OFF for random lengths of time. These input power fluctuations become more problematic due to the nature of today's internet traffic. As input traffic approaches self-similarity, optical burst lengths become comparable to the EFDAs natural response time. As a result the optical link experiences sizable output power swings reaching levels in excess of 9dBm for a chain of five EDFAs [11]. Self-similar traffic can be simulated by the method of Tancevski [11] whereby the input power of each channel is modeled independently as a succession of ON (full power) and OFF (zero power) periods. The duration of each ON-OFF period, T_i, $i \in \{ON, OFF\}$, is a random variable with Pareto distribution, generated by

$$T_i = \frac{1}{U^{1/\psi_i}} \tag{2}$$

where U has uniform distribution on [0,1] and ψ_i is a measure of the variability of the network traffic. This gives the duration of the ON and OFF periods as an integer number of packets or slots, where the packet or slot length is determined by the network protocol and bit rate. The overall network utilization is defined as

$$\rho = \frac{E[T_{ON}]}{E[T_{ON}] + E[T_{OFF}]} \tag{3}$$

By varying the parameters ρ and ψ_i, incoming network traffic can be adjusted for various utilizations and degrees of self-similarity. Thus, $\psi_i >> 2$ translates into relatively smooth traffic, while $1 < \psi_i < 2$ corresponds to self-similar traffic.

III. DYNAMIC EDFA MODEL

The EDFA dynamic behavior is described by the time-dependent gain model of Sun [12], under some simplifying assumptions. The average inversion $\bar{N}_2(t)$ for a forward pumped EDFA is given as in the differential equation

$$\begin{aligned} \frac{d\bar{N}_2(t)}{dt} &= -\frac{\bar{N}_2(t)}{\tau} - \frac{1}{\rho_{Er} S L} \sum_{i=1}^{N} [e^{\bar{g}_i(t)L} - 1]\, p_i^{IN}(t) \\ &\quad - \frac{1}{\rho_{Er} S L} [e^{\bar{g}_p(t)L} - 1]\, p_p(t) \end{aligned} \tag{4}$$

In (4) p_i^{IN} is the input power for channel i and p_p is the EDFAs pump power, while

$$\bar{g}_i(t) = (\gamma_{i,Er} + \alpha_{i,Er})\, \bar{N}_2(t) - \alpha_{i,Er} \tag{5}$$

is the average exponential gain coefficient and τ the EDFAs fluorescence time. Also, ρ_{Er}, S, L, $\gamma_{i,Er}$, $\alpha_{i,Er}$ are fiber specific parameters, [12]. The output channel powers $p_i^{OUT}(t)$ are obtained as

$$p_i^{OUT}(t) = e^{\bar{g}_i(t)L}\, p_i^{IN}(t) \tag{6}$$

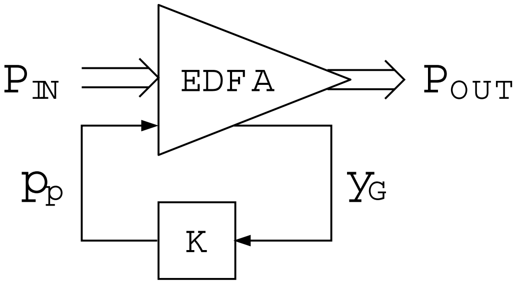

Fig. 1. EDFA Control Configuration

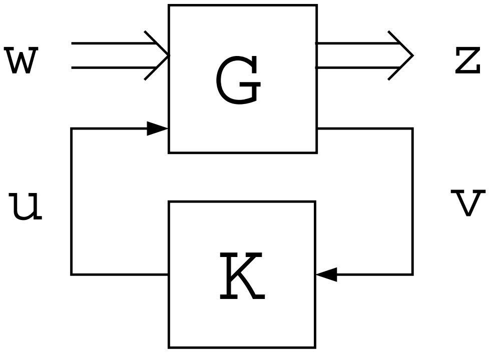

Fig. 2. General Control Configuration

Given the numerical relation between the average inversion level, input power and output power, a measure for the EDFAs average total gain is given by

$$y_G(t) = \frac{\sum_{i=1}^{N} p_i^{OUT}(t)}{\sum_{i=1}^{N} p_i^{IN}(t)} \tag{7}$$

The average total gain provides a suitable measurement variable for feedback control, used to adjust the pump power driving the EDFA. It can be shown that by ensuring that the average total gain remains constant, the EDFAs average inversion and hence output power will remain relatively unchanged. Fig. 1 illustrates a typical EDFA with gain feedback, where the average total gain is used to adjust the pump power driving the EDFA.

IV. EDFA H$_\infty$ CONTROL DESIGN

The H$_\infty$ control problem is known to provide simple, reliable and robust control, [13]. Consider a generalized linear plant G with u, v, w, and z as the control, measurement, input disturbance, and performance signals, respectively. Consider the general control configuration shown in Fig. 2.

The H$_\infty$ control objective is to find a feedback stabilizing controller which minimizes the H$_\infty$-norm of the closed-loop transfer function from w to z, $z = T_{zw}\, w$, such that

$$\| \; T_{zw} \; \|_\infty < \gamma_{zw} \tag{8}$$

for some value $\gamma_{zw} > 0$.

A. Mapping the EDFA to the H_∞ Control Problem

We proceed to map the EDFA to the H_∞ control problem by first linearizing the nonlinear equations (4)-(7) around a steady state operating point $(\bar{N}_{2,0}(t), p_{i,0}^{OUT}, p_i^{IN}, p_{p0}, y_{G0})$ and normalizing system variables. Thus the average inversion level is modeled as the internal state, $x \Rightarrow \bar{N}_2 - \bar{N}_{2,0}$, normalized input channel powers are taken as disturbance signasl $w \Rightarrow \hat{p}_i^{IN} = \frac{p^{IN} - p_0^{IN}}{p_0^{IN}}$, measurement signal taken as the average gain $v \Rightarrow \hat{y}_G = \frac{y_G - y_{G0}}{y_{G0}}$, and control signal as the EDFA's pump power $u \Rightarrow \hat{p}_p = \frac{p_p - p_{p0}}{p_{p0}}$.

As performance variable we select $z \Rightarrow x$, such that we minimize the gain from the input signal disturbances upon the EDFA's average inversion.

We obtain an appropriately defined multi-input multi-output state-space realization for the EDFA, with system variables $x, u, v, z \in R$ and $w \in R^N$, given as

$$G : \left\{ \begin{array}{ccccccc} \dot{x} & = & Ax & + & B_1 w & + & B_2 u \\ z & = & C_1 x & + & D_{11} w & + & D_{12} u \\ v & = & C_2 x & + & D_{21} w & + & D_{22} u \end{array} \right. \tag{9}$$

where $C_1 = I$ and $D_{11} = D_{12} = D_{22} = 0$.

B. Plant Augmentation

The original EDFA model is augmented to meet the H_∞ assumptions, [13]. Since D_{12} has to be full column rank, we introduce an augmented

$$\hat{z} = \left[\begin{array}{c} z \\ \tilde{z} \end{array} \right] = \left[\begin{array}{c} x \\ \alpha\, u \end{array} \right] \tag{10}$$

which gives the augmented plant $\hat{G}$ with modified

$$\hat{D}_{11} = \left[\begin{array}{c} D_{11} \\ 0 \end{array} \right], \qquad \hat{D}_{12} = \left[\begin{array}{c} 0 \\ \alpha \end{array} \right] \tag{11}$$

In the above $\alpha > 0$ is a design parameter that represents a control penalty, limiting the control signal to the EDFA. Therefore, the selection of α should reflect the EDFAs pump characteristics, most notably the pump response time and maximum deliverable pump power.

C. Disturbance Weightings

In addition, weighting functions are designed to shape the desired frequency response: $W_w(s)$, to describe the input signal disturbances, and $W_y(s)$, to impose integral control for minimum steady state error.

Thus from the augmented plant $\hat{G}$, a weighted augmented plant G_p is created using the weighting function $W_w(s)$ and $W_y(s)$ (see Fig. 3). The selection of the disturbance weighting W_w is based on characteristics of the input disturbances. Assume that the disturbance signals reside in a specified bandwidth $[f_{min}, f_{max}]$ where f_{max} is less than the transmission bit rate, which is typically on the order of Gb/s to Tb/s. Further, the disturbance signals have a maximum modulation index m_{max}, and the system has a maximum allowable optical signal deviation ϵ.

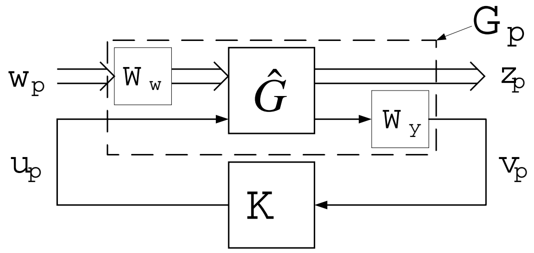

Fig. 3. Weighted augmented EDFA for H_∞ controller synthesis

A bandpass filter is used to describe the frequency content of the input signal disturbances

$$W_w = \frac{k_w\, w_H\, s}{(s + w_L)(s + w_H)} + \alpha_w \tag{12}$$

with parameters selected such as: w_L and w_H describe the frequency bandwidth (rad/s) of disturbances, i.e., $w_L = 2\pi f_{min}$, $w_H = 2\pi f_{max}$; α_w describes the maximum amplitude of input disturbances, $\alpha_w = 1 + m_{max}$, and $k_w < 1$ to describe the amount of cross gain modulation within the disturbances. Initially we set $k_w = 0.1$.

D. Integral Control

A desired performance objective is to minimize the steady state error of channels' output power, which can be achieved by maintaining the average total gain relatively constant.

This can be done by imposing approximate integral control on the resulting H_∞ controller. In turn this is realized by using a biproper weighting function W_y (in order to meet the H_∞ assumptions),

$$W_y = \frac{\beta_y s + k_y}{s + \alpha_y} \tag{13}$$

with the following parameters: $k_y = 1$ as the pre-designed controller gain; $\beta_y << \frac{1}{f_{max}}$ and $\alpha_y << f_{min}$ such that integral control is imposed over the same bandwidth as the input disturbances.

From the augmented plant $\hat{G}$ and W_w and W_y we obtain a weighted augmented plant G_p (see Fig. 3). Given G_p, the design objective is to find a stabilizing controller K_∞ such that the H_∞ norm is minimized, that is

$$\| T_{z_p w_p} \|_\infty < \gamma_\infty \tag{14}$$

This K_∞ can be synthesized following the H_∞ algorithm in [13].

For this we need to select γ_{min} and γ_{max}. Based on the EDFA model and specified performance objectives we choose: $\gamma_{min} = \sigma(D_{11})$, $\gamma_{max} = \sigma(D_{11}) + \epsilon$. Here σ denotes the maximum singular value and ϵ is the maximum allowable optical signal power deviation at the receiver. Typically $\epsilon \approx 0.1$ or -10dB.

Combining the resulting controller with the imposed measurement weighting W_y, we get the desired controller $K = K_\infty\, W_y$ to be used on the original EDFA plant G, (Fig. 4).

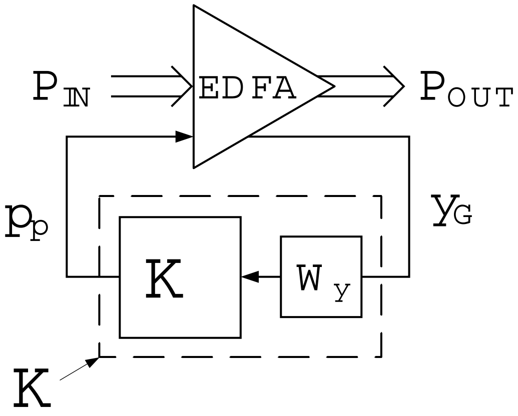

Fig. 4. Application of H_∞ controller to original EDFA model

TABLE I

EDFA PHYSICAL SPECIFICATIONS

Parameter	Expression	Value	Unit
Fluorescence Time		0.0105	s
Length of Erbium Fiber	L	10.5	m
Erbium Ion Density	$_{Er}$	6.1506×10^{24}	ions/m^3
Er effective core radius	r_{Er}	1.80	μm

TABLE II

CONTROLLER SYNTHESIS PARAMETERS

Parameter	Expression	Value	Unit
Max Acceptable Power Excursion		10	%
Min Frequency Disturbance	f_{min}	100	Hz
Max Frequency Disturbance	f_{max}	10×10^6	Hz
Max modulation depth	m_{max}	0.1	-
Control Signal Penalty		0.001	-

V. SIMULATION RESULTS

We consider a single stage, 16 channel C-Band EDFA with an average gain of 14dB. Under nominal operating conditions all input channels are ON and operate with an average optical power of 0.1995mW. The nominal average inversion is taken as 0.6. The 16 channels are evenly spaced from 1544 to 1559nm, with the EDFA pumped at 980nm with a nominal pump power of p_{p0}= 150mW. Additional EDFA parameters are given in Table I. Controller parameters were chosen based on EDFA and disturbance properties (see Table II).

A. Channel Add/Drop

We generate the weighted plant G_p and synthesize a 5^{th} order H_∞ controller K_∞ via MATLAB. The response of the closed loop EDFA with the controller $K = K_\infty W_y$ is observed under channel add/drop, pilot tones and network traffic disturbances for three different control cases: uncontrolled case ($u = 0$); PID controller as in [1] (K_{PID}), H_∞ Controller (K_{II}). Fig. 5 shows the results of applying a channel drop on channel #2 while channel #1 is taken as the surviving channel. When applying the standard test case of channel drop, the transient response shows significant improvements of the H_∞ controller versus the PID controller: a response time of 4.2 μs compared to a response time of 0.1ms, and a maximum power excursion reduced by approximately 80%.

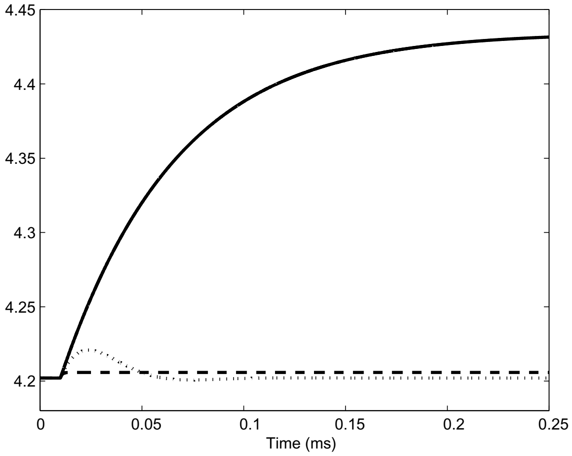

Fig. 5. Power excursion on surviving channel #1 for drop on channel #2 under three different control cases: Uncontrolled case (Solid Line), K_{PID} Controller (Dotted line), K_{II} Controller (Dashed Line)

This performance is achieved by a fast control response: the PID controller requires a 8mW change in pump power within 30 μs, while the K_{II} controller demands 7mW within 5.4 μs.

B. Pilot Tones

Fig. 6 show results for pilot tones test case. Pilot tones are modulated onto channels 2, 3 and 4, selected such that they coincide with current frequencies used for optical monitoring, with the following parameters: $f_{c,i} = \{20, 10, 100\}kHz$, $m_i = \{0.1, 0.05, 0.08\}$, $i = 2, 3, 4$ and $\Delta f = 1kHz$. Also, random binary data is generated to be frequency modulated onto the pilot tones. In order to gauge the performance of the different control cases we are interested in minimizing the cross response on surviving channels. In Fig. 6 we observe significant improvements in performance when the H_∞ controller is used. When controller K_{II} is used, the maximum power excursion on the selected surviving channel #1 is reduced by approximately 20dB and 15dB, as compared to the uncontrolled and to PID controlled EDFA, respectively.

C. Network Traffic

For the network traffic simulation we assume that the burst-mode channels (# 2,6,10,14) are transmitting optical bursts over a 1.0 Gbps optical fiber with all optical burst lengths chosen as a multiple of 53 bytes, corresponding to one ATM cell. This amounts to a cell length of $\approx 0.4\mu s$. We use a sampling rate to plot 100 points per cell, resulting in a time resolution of 4ns, which is fast enough to capture the power excursions for all control schemes, as shown by the response times in Fig. 7-10. The responses are simulated for

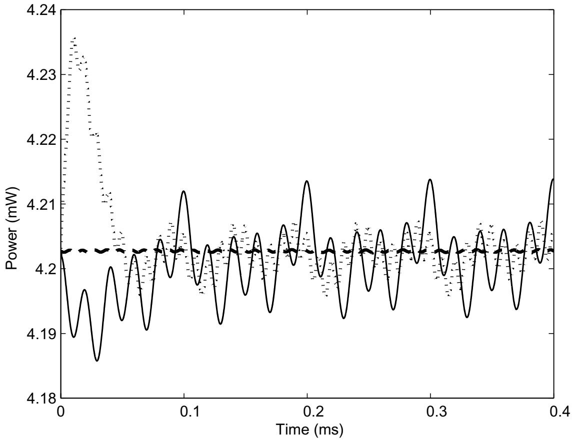

Fig. 6. Response to 3 pilot tones (ch 2,3,4) under different control cases: Uncontrolled case (Solid Line), K_{PID} Controller (Dotted line), K_{II} Controller (Dashed)

1000 cells, i.e., a simulation time of 0.4ms or 0.1 million samples.

We analyze the effects of cross gain modulation on a channel which is left at a constant power (ch. #1). As traffic parameters, all burst mode channels have 50% utilization (ρ= 0.5); $\psi_{ON} = \psi_{OFF} = 1.2$ for self-similar traffic, and $\psi_{ON} = \psi_{OFF} = 5.0$ for smooth traffic. We use the probability distribution function (PDF) of the resulting output power on channel #1, to measure these dynamic power swings for both the PID and H_∞ controller.

As the nominal traffic case, we use 4 OBS channels with self-similar traffic in a 1.0 Gbps link (25 % load). Fig. 7 shows the PDF results for the nominal case.

The H_∞ controller significantly maintains the size of surviving channel power swings to under 0.02mW at a probability of 1×10^{-3}. In comparison the PID controller experiences power swings in excess of 0.085mW.

In addition, to test the robustness of the control design, we simulate different traffic schemes and observe how the power swings vary with the disturbance characteristics. Thus, Fig. 8, 9 show results for simulations in a high speed 25 Gbps link, and a link where all channels are streaming OBS traffic (100% load).

Smooth traffic (Fig. 10) produces the smallest power swings on the EDFA, as in [11], [14]. The full load case (Fig. 9), results in large power swings under uncontrolled and PID controlled EDFA schemes, due to the choice of nominal operating condition. In the full load case for OBS traffic, all channels are allowed to turn off, thus the total input power is expected to have larger variations compared to a 25% loaded case. In the case of the 25 Gbps link, cell sizes are approximately $0.016\mu s$ in length; the gain of the EDFA is unable to respond sufficiently fast, leading to smaller power swings under both controlled and uncontrolled schemes.

Table III summarizes the results of the histograms in Fig. 7-10. Under all traffic schemes the H_∞ controller provides the largest reduction in power swings, whereas both the PID controlled and uncontrolled EDFA exhibit power swings dependent upon the network traffic characteristics.

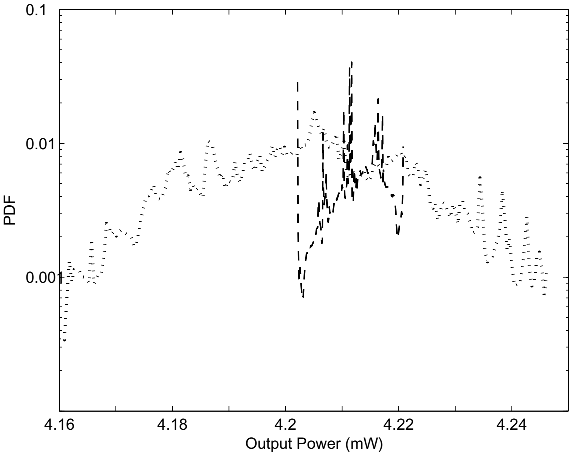

Fig. 7. 25% Load, 1Gbps, Bursty traffic: K_{PID} Controller (Dotted line), K_{II} Controller (Dashed Line).

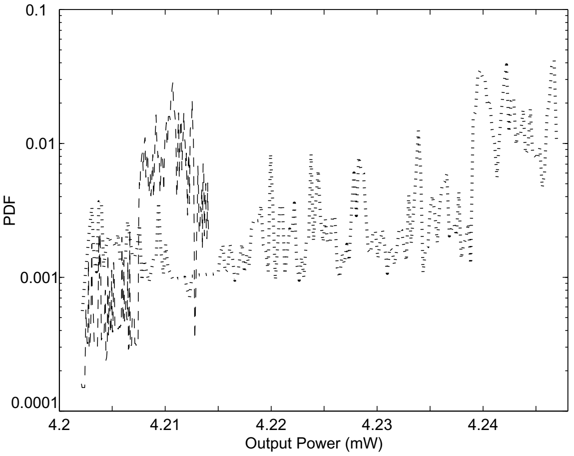

Fig. 8. 25% Load, 25Gbps, Bursty traffic: K_{PID} Controller (Dotted line), K_{II} Controller (Dashed Line).

Table III
POWER SWINGS AT 0.1% PROBABILITY

	$u = 0$	K_{PID}	K_{II}
25% Load, 1.0 Gbps, Bursty	1.06	0.085	0.02
25% Load, 25.0 Gbps, Bursty	0.18	0.045	0.011
Full Load, 1.0 Gbps, Bursty	0.75	0.185	0.012
25% Load, 1.0 Gbps, Smooth	0.25	0.018	0.009

D. EDFA Cascade

In order to simulate an optical link, we place 5 EDFAs in series, operating under identical conditions, with constant fiber loss of 14dB between each EDFA. The response to a

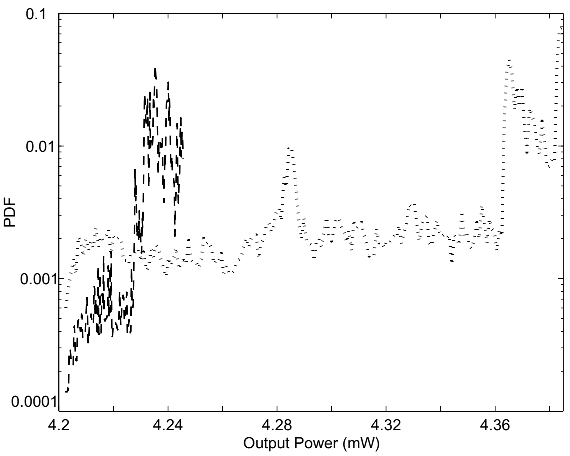

Fig. 9. 100% Load, 1Gbps, Bursty traffic: K_{PID} Controller (Dotted line), K_{II} Controller (Dashed Line).

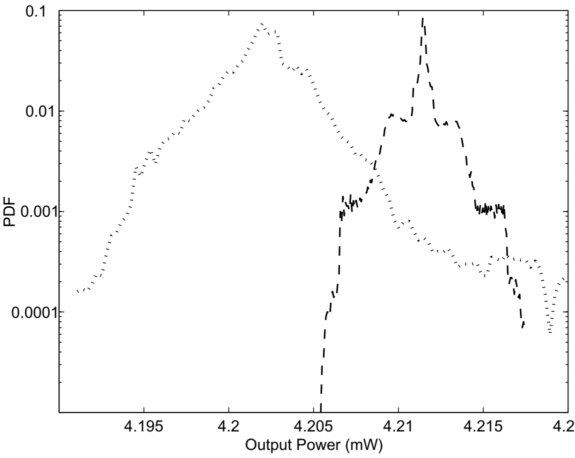

Fig. 10. 25% Load, 1Gbps, Smooth traffic: K_{PID} Controller (Dotted line), K_{II} Controller (Dashed Line).

channel drop within a cascade of EDFAs is expected to be similar to that of a single stage EDFA with a gain shift. This gain shift can be explained by the non-uniform gain profile inherent within the Erbium fiber. We synthesize an H$_\infty$ controller for each EDFA span within the link. Note that the time plots have been time shifted to compensate for expected transport delay between each EDFA span.

In Fig. 11 we observe this gain shift as the optical signal travels across the link. In addition, we notice that the speed of the transients increases as the signal propagates through the cascade of EDFAs. However, in the H$_\infty$ control case, these fast transients are significantly reduced.

VI. CONCLUSIONS

We proposed an optimal H$_\infty$ controller to reduce the effects of cross-gain modulation within EDFAs. Specifically, we modeled input disturbances due to pilot tones and OBS network traffic, in addition to channel add/drops in the network. We incorporated knowledge of the input disturbances and performance objectives into a systematic design. We synthesized the H$_\infty$ controller using tools available in MATLAB. Via simulations, we demonstrated significant reductions in output power swings on surviving channels upon application of the H$_\infty$ controller. In particular, for pilot tone disturbances, the appearance of ghost tones on surviving channels is reduced by 80% when compared against a nominal PID controller. Under a variety of network traffic characteristics, the H$_\infty$ controller reduces power swings by 95%, and by more than 50%, when compared against the uncontrolled EDFA, and PID controlled EDFA, respectively. Furthermore, the performance of the H$_\infty$ controller is maintained when simulated for a optical link of 5 EDFAs.

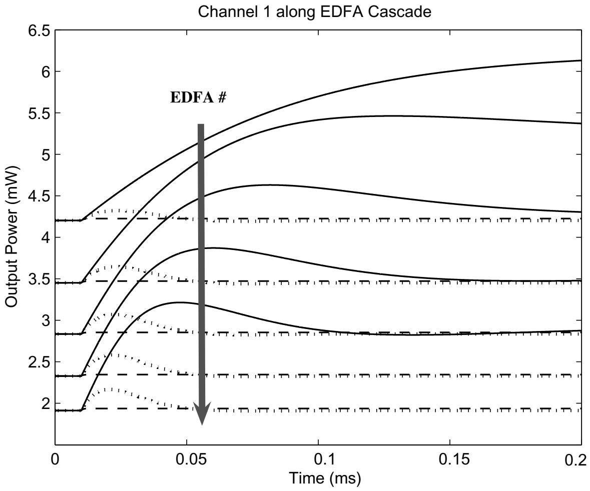

Fig. 11. Output power on Channel #1 due to a 5 channel drop along optical link. Uncontrolled case (Solid Line), K_{PID} Controller (Dotted line), K_{II} Controller (Dashed Line).

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