Detection and Mitigation of Soft Failure due to Polarization-Mode Dispersion in Optical Networks

J. Zweck[1] **and C.R. Menyuk**[2]

[1] *Department of Mathematics and Statistics*
[2] *Department of Computer Science and Electrical Engineering*
University of Maryland Baltimore County, Baltimore, Maryland 21250
zweck@math.umbc.edu, Phone: (410) 455-2424, Fax: (410) 455-1066

Abstract: A combination of polarization-mode dispersion (PMD) monitoring and network-layer switching managed by the control plane can reduce the outage probability due to PMD to an acceptable level for a link in an optical network, without physical-layer mitigation.

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1. Introduction Until recently, network designers could assume that the physical communications channel was "perfect", in that it always produced a bit-error ratio below some acceptable level. Consequently, network protocols have generally been designed to deal with instantaneous *hard failures* that bring down an entire link, such as those due to equipment breakdowns or fiber cuts. However, communications channels vary over time due to the stochastic nature of some physical-layer impairments, and with recent increases in data rates and transmission distances it is no longer possible to eliminate or bound all these impairments in a cost-effective manner. Failures due to stochastically time-varying physical-layer impairments tend to degrade the system performance over time and can usually be anticipated. Therefore, to distinguish them from hard failures, we call failures of this type *soft failures*. Soft failures are usually not permanent, and often only affect some of the channels in a wavelength-division multiplexed (WDM) network.

A cost effective way to deal with soft failures is to use control plane protection and restoration capabilities in order to switch the traffic to another link, and avoid the cost of physical-layer mitigation. Such an approach is now possible due to the recent and ongoing development of generalized multiprotocol label switching (GMPLS), which allows for the control of all the elements in an optical network [1]. However, because these elements are so diverse, the protocols for controlling and managing them require significant extensions. Optical rerouting using GMPLS has recently been demonstrated with IP routers and photonic cross connects in an installed dense WDM network [2]. In addition, coordination of the GMPLS control, measurement, and data planes has been used to ensure the quality of a 40 Gb/s WDM network that was impaired by residual chromatic dispersion [3].

In this paper, we use a realistic physical-layer model to show that it is possible to combine PMD monitoring and control plane switching to efficiently mitigate soft failures due to polarization-mode dispersion (PMD). The PMD in an optical fiber changes over time due to mechanical vibrations and variations in temperature. Long-term measurements of PMD in installed fiber links have shown that over a period of weeks, the PMD changes only very slightly for buried segments of fiber [4], [5], but that for exposed fiber in amplifier huts or on bridges the PMD can vary significantly [6]. Based on these findings, Boroditsky *et al.* [7] developed the hinge model of PMD and used it to show that each channel has its own outage probability: Some channels remain outage-free as long as the PMD of the buried fiber in the link does not change, while other channels are noncompliant because their outage probability exceeds a target threshold. Compensation of PMD in the physical layer is therefore fundamentally inefficient. Although one must pay for compensation 100% of the time for all channels, it is only needed a small fraction of the time for some channels. For example, if a noncompliant, uncompensated channel undergoes an outage with probability 10^{-3}, compensation is only needed 0.1% of the time. Instead, Kogelnick *et al.* [8] suggest that the noncompliant channels be identified, removed from service, and that protection switching be used to redistribute the traffic in the network.

To protect a network against soft failures, each channel in the data plane must be continually monitored by the measurement plane, and when an impairment is detected this information should be passed to the control plane and used to reconfigure the traffic in the network. Provided that failures have an onset time that is slower than the time required for detection and switching, the only way a failure can occur is if the measurement plane fails to detect an impending outage. In this paper we study the probability of such failures for two simple PMD monitors, namely the 5 GHz RF tone and DOP monitors [9], [10]. These low-cost monitors have been widely used in optical PMD compensators since they have a fast response time and are simple to build and operate [11]. They are effective PMD monitors since their values decrease as the differential group delay (DGD) increases. A key issue is to devise a *PMD outage detection criterion*, which is used to determine when an outage occurs due to PMD. This criterion, which could be incorporated into the link management protocol (LMP), will provide an interface between the GMPLS measurement and control planes. We will show that a detection criterion can be chosen to achieve an acceptable outage probability without requiring excessive switching.

2. Theoretical model In the hinge model of PMD [7], a fiber link with a given root-mean-square (rms) DGD, τ_{rms}, is assumed to consist of N segments of fixed-birefringence fiber connected by $N-1$ "hinges", which are modeled by polarization rotators. The fiber segments model the static long stretches of buried fiber, while the hinges model the active short exposed pieces of fiber. A *fiber realization* for a channel in the link, which is a realization of the static fibers, is obtained by randomly selecting the DGD of each segment from a Maxwellian distribution with an rms DGD of $\tau_{\mathrm{rms}}/\sqrt{N}$. For a given fiber realization, random variations in the hinges result in performance variations that we quantify using an outage probability. The outage probability can be computed using Monte Carlo simulations in which each sample corresponds to a different *hinge realization*, which is a choice of uniformly distributed rotation for each polarization rotator. Consequently, for a given fiber realization, the total DGD of the link depends on the particular hinge realization. In [7], an outage is said to occur in a channel with a given fiber realization when the total DGD exceeds a prescribed maximum value. Since the maximum DGD value is the square root of the sum of the squares of the DGD values of the segments in the link, outages never occur for some fiber realizations. However, for others the outage probability can exceed a target threshold.

We say that a *physical-layer outage* occurs when the eye-opening penalty due to PMD exceeds a prescribed threshold, such as 2 dB, where we define the *eye-opening penalty* to be the ratio of the eye opening at the end of the link to the back-to-back eye opening. The eye opening of a noise-free signal at the receiver is defined to be the difference between the smallest electrical voltage of a one and the largest electrical voltage of a zero in the low-pass electrically filtered signal at the clock recovery time. The *physical-layer outage probability* of a fiber realization is the probability that such an outage occurs.

For simplicity, we study soft failure due to PMD for the worst case fiber realization which, for a given number of hinges, is the one for which all the fiber segments have the same DGD [12]. In this case, the PMD in the link can be modeled using the standard coarse-step method for PMD with N sections [13]. In addition, to model the low probability hinge realizations that result in outages, we used multiple importance sampling for first- and second-order PMD [14] with a total of 2×10^5 samples. Our results are for a link with an average DGD of 30 ps and $N = 6$ fiber segments. We ignore all other transmission effects, and we do not include noise in our model. We modeled the 10 Gb/s signal in the transmitter as a single-channel, non-return-to-zero (NRZ) signal with a rise time of 30 ps, and we used a 16-bit pseudo-random bit sequence. The receiver consisted of a 60 GHz Gaussian optical filter, a square-law photodetector, and a low-pass fifth-order electrical Bessel filter with a 3 dB bandwidth of 8 GHz.

The criterion we use to detect an outage due to PMD is that the value of the monitored signal falls below a specified threshold. The control plane should reroute the traffic around the link whenever this outage detection criterion is met. We define the value of the RF tone monitor to be the power in the electrical signal after passing a fifth-order electrical Bessel filter with a central frequency of 5 GHz and a full-width-half-maximum of 500 MHz. For the DOP monitor, we calculate the average DOP of the signal. We normalize the values of the monitors relative to their back-to-back values.

3. Results Because of higher-order PMD, the eye-opening is not delta-correlated with the value of the monitor. Consequently, outages and false alarms will both occur. We say that a *network-layer outage* occurs if the eye opening penalty exceeds a prescribed margin but the value of the monitor does not fall below the specified threshold. Similarly, a *false alarm* occurs if the monitor falls below the threshold but the eye opening penalty does not exceed the margin. Our goal is to choose the threshold to achieve a desired outage probability without incurring too many false alarms. In Fig 1, we plot the network-layer outage probability (solid curves), switching probability (dashed curves), and the probability of false alarms (dot-dashed curves) as a function of the normalized threshold. The results for the 5 GHz RF tone and DOP monitors are shown with thick and thin curves, respectively. These results are for an eye opening penalty margin of 2 dB and the worst case fiber realization. For both monitors, as the threshold increases the outage probability decreases sharply at a certain point, while the switching probability increases more gradually. The physical-layer outage probability, which is equal to the network-layer outage probability with a zero threshold, is 2.3×10^{-3}. To guarantee an outage probability of 10^{-6} or less, the RF tone threshold should be 0.41, which gives a switching probability of 6.3×10^{-3}, whereas the DOP threshold should be 0.79 for a switching probability of 1.5×10^{-2}. At these threshold values, 62% of the switches occur as a result of false alarms for the RF tone, and 83% for the DOP monitor. Although the 5 GHz RF tone is a better monitor for this worst case fiber realization, a statistical study of all fiber realizations is needed before any definitive conclusions can be reached.

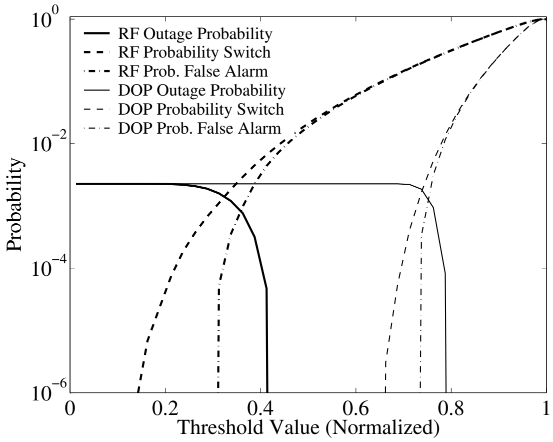

Fig. 1. Network-layer outage, switching, and false alarm probabilities as functions of the monitor threshold for the 5 GHz RF tone and DOP monitors with the worst-case fiber realization with $N = 6$ fiber segments.

4. Conclusions Using a realistic physical-layer model, we showed that PMD monitoring combined with network-layer switching reduces the occurrence of soft failures due to PMD, without physical-layer mitigation.

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