MC1.2 (Invited)
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Advances in Modeling Optical Fiber Transmission Systems

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SUMMARY

In the past five years, the complexity and cost of optical fiber transmission systems has grown substantially. The greatly increased complexity of modern-day systems has led to a need for modeling methods that will allow engineers to design and optimize their systems in parallel with laboratory testbeds. A number of commercial enterprises now offer modeling tools that partially fulfill this need; however, current modeling methods are not equal to the task of accurately calculating bit error rates. Of course, there is much that current methods can do. They can be used to accurately optimize dispersion maps, modulation formats, channel spacings, and receiver bandwidths. Recently, my own group demonstrated an unprecedented agreement between theory and experiment over a distance of 24,000 km in calculating amplitude margins [1]. In this experiment, we observed voltage margins above which the error rate is greater than 10^{-6} due to marks being counted as spaces and below which the error rate is greater than 10^{-6} due to spaces being counted as marks. This achievement required us to use highly accurate models of both the receiver and gain saturation in the amplifiers.

At the same time, the holy grail of finding methods to accurately calculate bit error rates in real-world systems remains elusive. We have made important progress in this quest during the past year, and we will present those results here.

Before describing our recent progress, we note our view that this quest is not only of evident practical importance but is also a highly rewarding area of intellectual endeavor. The task of reconciling theoretical and experimental results, so that they agree to within the accuracy of both, more often than not yields unexpected insights into what is really important in the experiments. The great 19-th century mathematician, Henri Poincaré stated it best when he wrote (slightly abbreviated here), "Il est inutile de demander plus de précision (des calculs théoriques) qu'aux observations; mais on ne doit pas en demander moins." (There is no point in asking for more accuracy from theory than from the observations, but one should not ask for less.) [2].

The first advance that I will describe is the application of importance sampling to polarization problems in optical fiber transmission. In particular, we have addressed the problem of determining the outage probability of an ideal first-order compensator. In practical system design, the usual practice is to allocate some system margin for a particular

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effect, *e.g.*, 2 dB of margin for polarization mode dispersion (PMD), with an assurance that the power penalty will be less than that margin with some low probability, *e.g.*, 10^{-6}. The challenge has been that it is impossible in practice to directly simulate the billions of fiber realizations that would be needed to show that the outage probability is less than 10^{-6}. Thus, workers in this field have resorted to stopgap procedures like demonstrating that the average differential group delay (DGD) is reduced as much as possible. Using importance sampling [3], we have found ways to bias the distributions of the DGD so that with 10^5 realizations or even less, we can accurately calculate the outage probability.

The second advance, which we call linearization, is based on the observation that noise beating with itself during the transmission through the optical fiber is normally quite small. One must, of course, take into account the noise beating with itself in the receiver. If noise beating with itself is small during transmission, then the noise components at the end of the transmission line will obey a multivariate Gaussian distribution [4]. We have applied this approach to our experimental dispersion managed soliton system over 24,000 km [1]. This application is a stringent test of our approach because the system is highly nonlinear. The noise components that we use are the Fourier components with phase and timing jitter removed, as is appropriate in a soliton system. The phase jitter has no effect on the received signal, but the timing jitter must be restored at the receiver. We have directly calculated the covariance matrix from Monte Carlo simulations, and we have validated the linearization assumption by computation of the timing jitter and the marginal distributions of the Fourier components. We note that this approach not only allows us to accurately calculate the probability distribution function of the receiver voltage for the marks and the spaces, but it also allows to calculate the probability contour plots for the entire eye diagram.

In conclusion, good modeling of optical fiber transmission systems has become critical to design them efficiently. Much has been accomplished in recent years, and my own group has contributed in important ways to this development. In the past year, we have applied importance sampling to calculating the outage probability of PMD compensators, and we have shown that it is possible to accurately calculate the probability distribution functions of the receiver voltage for the marks and the spaces. While much remains to be done to achieve the ultimate goal of accurately modeling bit error rates, much has been accomplished.

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