

Modeling Cross-channel Interference Caused by Arbitrary Spectral Shaped Signals

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Abstract:

A closed-form, highly accurate model estimates the cross-channel interference for arbitrary spectrum signals in long-haul fiber-optic transmission. It eliminates estimation errors of up to 37% resulting from assuming a rectangular spectrum for RRC signals. © 2022 The Author(s)

1. Introduction

In long-haul fiber-optic networks, precise modeling of the cross-channel interference (XCI) caused by fiber non-linearity is crucial to ensuring adequate transmission quality [1]. In order to accurately estimate the XCI, many mathematical models have been proposed. Among them, the so-called Gaussian noise (GN) model is one of the most accurate and simple enough to use on complex continental-size networks [2]. However, the GN model assumes that the interference can be represented as having a rectangular spectrum, leading to a significant estimation error in typical cases when this assumption is violated. Signals are typically transmitted and received with matched root-raised cosine (RRC) filters to minimize inter-symbol interference [3]. The spectrum is further distorted as it travels through the fiber network due to optical filtering and dispersion effects. We propose an XCI model we call the component-wise Gaussian noise (CWGN) model that can account for arbitrary spectral-shaped interference and is computationally simple enough to use in most network management approaches. We show that it is as accurate as the closed-form expression for XCI given in [4] and avoids significant interference estimation errors resulting from using the GN model that assumes the spectrum is rectangular.

2. CWGN Model of XCI

Assuming the signal of interest is centered at frequency 0, without loss of generality, the GN model for the power spectral density (PSD) of the XCI caused by interferers with rectangular spectra is given by

$$G_{XCI}^{GN} = \mu G_p \sum_{q=1; q \neq p}^M G_q^2 G_{XCI,q}^{GN} = \mu G_p \sum_{q=1; q \neq p}^M G_q^2 \ln \left(\frac{f_q + \Delta_q/2}{f_q - \Delta_q/2} \right), \quad (1)$$

where M represents the number of channels sharing the fiber link with the channel of interest p , f_q is the center frequency of channel q ; Δ_q is the bandwidth of channel q ; and G_q represents the q th channel peak PSD. The constant μ is defined as $\mu = (3\gamma^2)/(2\pi\alpha|\beta_2|)$, where γ is the fiber nonlinear coefficient, β_2 represents the group velocity dispersion parameter, and α is the fiber power attenuation factor.

To account for signals with non-rectangular spectra, we adopt the idea and theorem proposed in [5] to decompose the spectrum along the frequency axis into rectangular components, as a Riemann sum, and then accumulate the overall XCI over these components. Using (1), we write the XCI caused by channel q assuming Δ_q is composed of frequency differentials df , where $\sum df = \Delta_q$. Without violating the assumptions in [4, Eq. (16)], the PSD of the XCI contributed by signal q to the channel of interest p (located at frequency 0) equals the sum over the frequency differentials, written as

$$G_{XCI,q}^{CWGN} = \mu G_p \sum_{i=-\infty}^{\infty} [G_q(f_q + i df)]^2 \ln \left(\frac{f_q + i df + df/2}{f_q + i df - df/2} \right), \quad (2)$$

where $G_q(f_q + i df)$ is a sample of the non-rectangular PSD function $G_q(f)$ at frequency $(f_q + i df)$; the contribution to the overall XCI at this frequency has differential bandwidth df . Therefore, it can itself be modeled as a band-limited signal with rectangular spectrum over the differential df , and thus satisfies the requirements of the GN model listed in [4, 6]. Using the fact that when $dx \rightarrow 0$, $\ln \left(\frac{x+dx/2}{x-dx/2} \right) \approx \frac{1}{x} dx$, the interference PSD in (2) can be further simplified as

$$G_{XCI,q}^{CWGN} = \mu G_p \int_{-\infty}^{\infty} \frac{[G_q(f)]^2}{f} df. \quad (3)$$

The CWGN model of the XCI caused by demands with arbitrary spectral shapes can be obtained by replacing $G_{XCI,q}^{GN}$ with $G_{XCI,q}^{CWGN}$ in (1). We validated the CWGN model by comparing it with the result of the nonlinear Schrödinger model [4, Eq. (3)] that we use as a benchmark, and they give identical results within the accuracy of the numerical integration. However, the CWGN approach has a much lower computational cost because of its closed-form expressions compared to the double-integral needed to compute the benchmark.

3. Numerical Results

In this section, we compare the XCI estimated by the GN and CWGN models to the benchmark given by [4, Eq. (3)] for signals transmitted through a single-mode fiber with parameters listed in Figure 1. While the CWGN model can be applied to any spectral-shaped signal, we restrict our numerical results to signals that use an RRC spectrum. The normalized estimation errors for one fiber span are shown in Figure 1 as percentages.

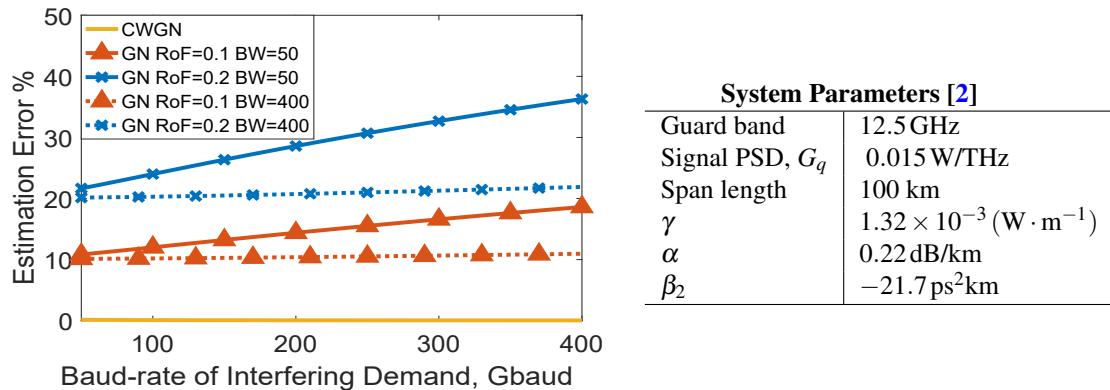


Fig. 1. XCI estimation error by the GN model compared to the CWGN model for an interference with an RRC spectrum, as a function of the RoF, bandwidth of the interfering channel, and bandwidth of the channel of interest, computed using the system parameters given on the right.

In this figure, we show that the GN model has a significant estimation error compared with the proposed CWGN for all interfering channel baud-rates and RRC roll-off factors (RoF) tested. The channel of interest has either a bandwidth of $\Delta_p = 50$ or 400 GHz (labeled “BW” in the figure) and is separated from the interfering signal by a guard band. The GN model estimates the RRC pulse conservatively using its peak PSD and the bandwidth, as is typical. Increasing the RoF strongly increases the estimation error because it makes the transmitted spectrum less rectangular, while the GN model still treats it as a rectangle. The baudrate of the interfering signal has less impact on the estimation error because, when the bandwidth of the interfering channel increases, both the absolute estimation error and the actual XCI increase. The bandwidth of the channel of interest determines how separated the two signals are in frequency; the further away they are, the lower the estimation error because the interfering channel has less impact on the channel of interest.

4. Conclusions

The XCI estimated using the CWGN model is significantly more accurate than using the GN model when the spectrum of the interfering channel is not near-rectangular. In the worst case tested, the GN model results in an estimation error of 37%. The CWGN model has less than a 1% estimation error compared with the benchmark.

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