Digital Back-Propagation of a Superchannel: Achievable Rates and Adaption of the GN Model

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Abstract *The impact of back-propagating an entire superchannel and sub-channels thereof is quantified by evaluating mutual information. We report a 50 Gb/s per channel increase in data rate. Additionally, the Gaussian Noise model is adapted to take into account back-propagation.*

Introduction

The increasing demand for high data rates in optical fiber communications has lead to high-order modulation formats such as 16-state quadrature amplitude modulation (QAM) being used for long-haul links. Simultaneously, wavelength-division multiplexing (WDM) channels are spaced almost at the Nyquist rate to increase the spectral efficiency. Superchannels are a logical evolution of this trend[1] as they are generated, routed, and finally processed in a joint manner such that information about co-propagating signals is available at the receiver. As high-order modulation schemes are more susceptible to noise and the sub-channels of a superchannel experience stronger nonlinear signal-signal interference due to the decreased WDM spacing, steps must be taken to ensure a sufficiently small post-forward error correction (FEC) bit error rate (BER).

A powerful method to mitigate these nonlinear effects is digital back-propagation (DBP)[2]. The gain by DBP is increased when more than one WDM channel is back-propagated[3,4]. In this work, we focus on the potential gain by DBP in terms of data rate rather than on the challenging task of decreasing the DBP complexity while maintaining its performance[5,6]. For the first time, the increase in data rate is presented when more than one channel is back-propagated.

Mutual Information

Mutual information (MI) is a fundamental quantity of information theory that describes how much information about the channel input is contained in the channel output after transmission. It is also the achievable rate of transmission, i.e. it states the maximum amount of information that can be transmitted per symbol while achieving an arbitrarily small post-FEC BER. MI is estimated with histograms for which the correct bin number is determined with a blind algorithm. More details on MI as a figure of merit for optical fiber systems are given in prior work[7]. The maximum data rate for the considered system is found by determining MI at the receiver. This analysis inherently assumes an ideal FEC scheme. For a non-ideal FEC, a larger coding overhead is required.

GN Model

The Gaussian noise (GN) model[8] has proven to provide an accurate estimate of the signal-to-noise ratio (SNR) of Nyquist-WDM systems with high baud rate and no inline chromatic dispersion (CD) compensation[9]. As it takes into account only fiber parameters, adaptations must be made for it to reflect the performance increase by DBP. By changing the nonlinear fiber para-meter γ to a reduced *effective* γ_{eff}, we show that the GN model produces a good estimate for single-channel (SC) and multi-channel (MC) DBP.

Simulation Setup

A system with 15 dual-polarization (DP) co-propagating (quasi)-Nyquist WDM channels forming a superchannel is simulated. The setup for one WDM channel is depicted in Fig. 1. All other sub-channels are decorrelated copies of this center channel of interest. Many components and algorithms at transmitter and receiver are taken to be ideal as we are interested in maximum data rates over transoceanic legacy fiber rather than quantifying the impact that practical devices and algorithms have on the achievable rate.

The bandwidth of each channel is 29.4 GHz and the 15 channels are located on a 30 GHz WDM grid, resulting in a total bandwidth of 450 GHz. Each channel consists of 2^{18} bits per polarization that are mapped onto 16-QAM symbols at a symbol rate of 28 GBd. The symbols are upsampled to 32 samples per symbol (SpS). The pulses are

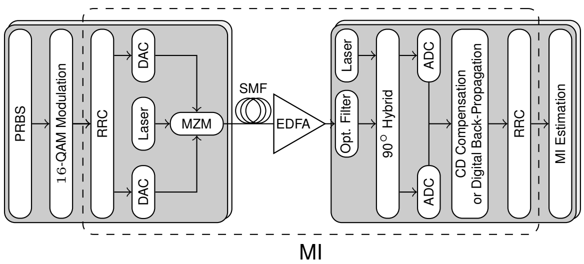

Fig. 1: Simulation setup of one DP WDM channel. The dashed box includes all components and subsystems that influence MI.

digitally shaped with a root-raised cosine (RRC) filter with 5% roll-off. The resulting signal is converted into the analog electrical and into optical domain at 1550 nm with an ideal digital-to-analog converter (DAC) and ideal Mach-Zehnder modulator (MZM), respectively. The y-polarization is created the same way and added to the x polarization to generate the transmit signal.

The optical signal travels over 6000 km of single-mode fiber (SMF) divided into 60 spans, each of length 100 km and each followed by an Erbium-doped fiber amplifier (EDFA) with 4 dB noise figure fully compensating for the fiber loss of 0.2 dB/km. Further fiber parameters are a CD of 17 ps/nm/km, a fiber nonlinear parameter $\gamma = 1.3\ \frac{1}{\mathrm{W\cdot km}}$, and no polarization-mode dispersion (PMD). The propagation is simulated using the split-step Fourier method (SSFM) with 32 SpS and a step size of 0.1 km.

At the receiver, the signal is filtered with an ideal band-pass whose bandwidth equals the number of channels to be processed times the WDM spacing. The filtered signal is input into a $90°$ optical hybrid where it is mixed with an ideal coherent laser that has no frequency offset. After ideal analog-to-digital conversion, CD is fully compensated when no DBP is performed. When DBP is employed, deterministic DBP is performed with identical SpS and step size as for the SSFM. Next, matched filtering with an RRC filter and downsampling to 1 SpS is done. For the center channel, MI is estimated per polarization and averaged over both polarizations. The MI of non-center sub-channels is not evaluated. Note that equalization is not necessary because the first Nyquist criterion is fulfilled by the RRC filtering and the absence of PMD. Due to the ideal lasers, carrier phase recovery is not required either.

Simulation Results

The effect of varying the number of back-propagated channels is analyzed in simulations with MI as figure of merit. The solid curves in Fig. 2 depict the MI for a launch power P_{tx} from -8 dBm to 8 dBm in increments of 1 dBm. The number in each circle is located next to the maximum MI obtained for the respective optimum launch power $P_{\text{tx,opt}}$ and states how many channels are back-propagated, with zero denoting CD compensation only. In this case, a maximum MI of 2.9 bits/symbol is achievable for the considered transmission system. This means that $4 - 2.9 = 1.1$ bits/symbol must be used for FEC redundancy while the remaining 2.9 bits/symbol are available to convey information. The assumed ideal FEC overhead must be at least $\frac{4}{2.9} - 1 \simeq 38\%$ to reach an arbitrarily small post-FEC BER. The net DP data rate per channel is 162.4 Gb/s. When DBP is employed, both $P_{\text{tx,opt}}$ and MI increase. For SC DBP, MI grows by 0.2 bits/symbol compared to CD compensation only, increasing the net data rate per channel to 173.6 Gb/s. This trend qualitatively continues with the number of back-propagated channels. For full MC DBP, i.e. when all WDM sub-channels are processed, more than 3.8 bits/symbol are achievable. This corresponds to a net data rate of 212.8 Gb/s per channel, which is a gain of almost 40 Gb/s and more than 50 Gb/s compared to SC DBP and no DBP, respectively. The trend of MI growing for a higher number of back-propagated channels is depicted in the inset of Fig. 2. Going from no DBP to full MC DBP, $P_{\text{tx,opt}}$ increases from -2 dBm to 3 dBm. Note that the maximum MI of 3.8 bits/symbol is only 0.2 bits/symbol from the maximum MI of 4 bits/symbol of 16-QAM. This gap cannot be closed by deterministic DBP as it is due to nonlinear signal-noise interactions. When 16-QAM, which is shown to be the optimal modulation format for the considered simulation setup yet without DBP[7], is replaced with 64-QAM, a higher MI is achievable. For full MC DBP and a setup identical to the one described above except that 64-QAM is used as modulation scheme, simulations show that a MI of more than 4.2 bits/symbol is achievable.

Comparison to an Adapted GN Model

The dashed curves in Fig. 2 show a comparison between the DBP simulations and the GN model evaluated with MI as figure of merit. The GN MI is determined by calculating the GN SNR estimate of a multi-span Nyquist-WDM system and looking up the corresponding MI for the considered modulation format, i.e. 16-QAM, and an additive white Gaussian noise (AWGN) channel. When only CD is compensated, the match be-

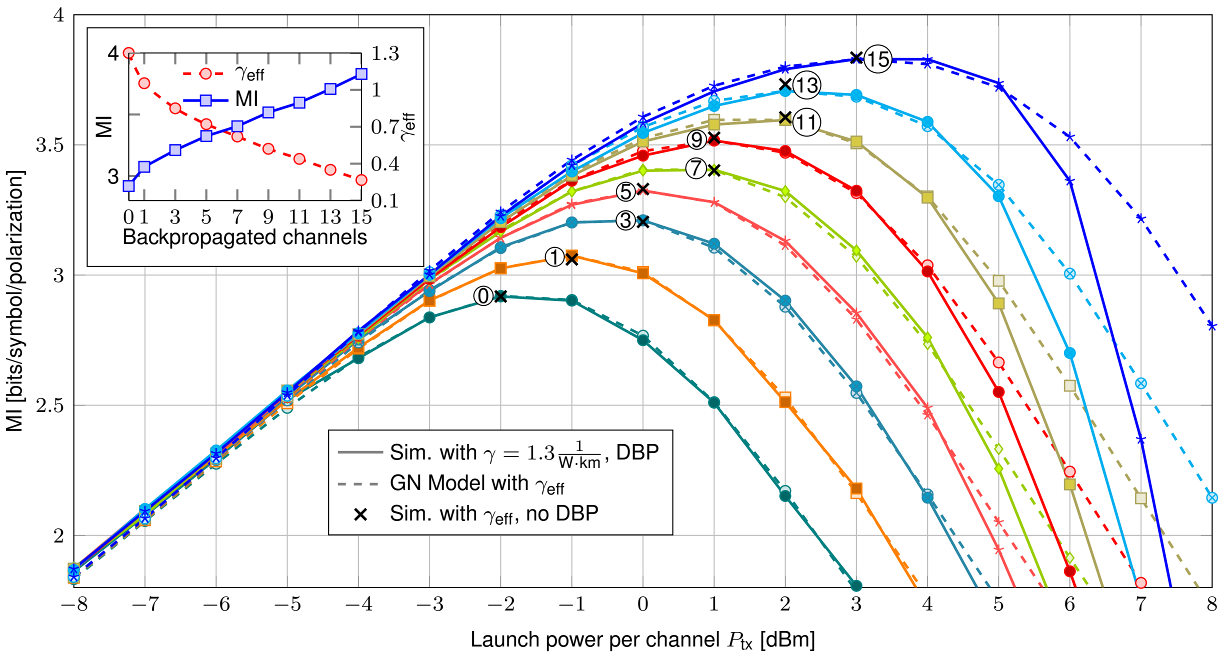

Fig. 2: MI in bits/symbol/polarization over launch power per channel P_{tx} in dBm. Solid lines: Simulations with $\gamma = 1.3\ \frac{1}{\text{W·km}}$ and DBP with the numbers in the circles denoting how many channels are back-propagated. Dashed lines: GN model for the respective γ_{eff}. Black crosses: Simulations of an SMF with γ_{eff} and CD compensation only. Inset: γ_{eff} (dots) in $\frac{1}{\text{W·km}}$ and MI (squares) in bits/symbol/polarization over the number of back-propagated channels.

tween GN model and simulations is excellent over the entire range of P_{tx}, validating the GN model for the first time in the information-theoretic context of MI. For SC and MC DBP, the nonlinear fiber parameter of the GN model is adapted such that the GN MI matches the MI of the DBP simulations at the $P_{tx,opt}$ that corresponds to the number of back-propagated channels. Accordingly, γ_{eff} is varied from the initial $1.3\ \frac{1}{\text{W·km}}$ when no DBP is performed to $1.05\ \frac{1}{\text{W·km}}$ and $0.27\ \frac{1}{\text{W·km}}$ for SC and full MC DBP, respectively. This trend is in detail shown in the inset of Fig. 2. For SC DBP, the GN MI calculated with γ_{eff} accurately describes the MI over all simulated powers. For MC DBP, the adapted GN model is accurate up to high powers, yet a gap that increases with the number of back-propagated channels and the launch power is present. By using a γ_{eff} that is smaller than γ of the fiber, the actual nonlinearities in the high-power regime are underestimated by the GN model and MI is overestimated because deterministic DBP is not capable of undoing nonlinear signal-noise interactions that are the dominant source of distortions in this regime.

The black crosses in Fig. 2 show MI obtained in simulations for which the fiber nonlinearity is set to γ_{eff}, the signal power to $P_{tx,opt}$, and no DBP is performed. The excellent match of the results and the DBP MI shows the validity and accuracy of our approach.

Conclusion

For the first time, the gain in data rate by back-propagating a fraction of sub-channels of a superchannel as well as an entire superchannel is shown. The net DP data rate is increased by more than 50 Gb/s per WDM channel when all channels are back-propagated. The GN model is validated with MI as figure of merit. By adapting the fiber nonlinear parameter to account for DBP, the GN model provides an accurate estimate for SC DBP and MC DBP for reasonably high launch powers.

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