

Mitigation of Electrical Bandwidth Limitations using Optical Pre-Sampling

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Abstract: We propose a novel method to improve a system degraded by a low receiver electrical bandwidth. With optical pre-sampling, 4-dB sensitivity improvement at the 7% hard FEC limit is experimentally demonstrated.

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1. Introduction

Spectral efficiency in optical transmission systems can be significantly improved by high-order modulation formats and super-channels, such as orthogonal frequency-division multiplexing (OFDM) and Nyquist wavelength division multiplexing (N-WDM). Nyquist modulation is spectrally efficient due to its near rectangular-spectra, and the corresponding basis function of a single symbol is a long sinc-like waveform. In N-WDM, because each wavelength is well-confined to its own band, the wavelength channel can be routed using optical filters [1, 2].

In Nyquist pulse shaped systems, the peak of one symbol's sinc function is coincident with the nulls of all preceding and following symbols, so the symbols are orthogonal in the time domain. However, bandwidth limitations in the receiver will destroy the orthogonality and cause significant inter-symbol interference, as will jitter of the sampling instant [3]. One possible solution to get around electronic band-limitation is wide-band optical signal processing [4, 5]. In very high baud rate optical time-division multiplexing (OTDM), optical samplers are used to demultiplex temporal tributaries to allow for low bandwidth reception [6, 7], with the sampling done at a rate well below the baud rate.

In this paper, we demonstrate band-limitation mitigation with a single receiver and an optical sampler operating at the baud rate of the incoming signal. We performed a proof of concept experiment with 10 Gbaud Nyquist-OOK signal, showing 4-dB sensitivity improvement at the 7% hard FEC limit ($@ BER= 3.8 \times 10^{-3}$) in a band-limited system. We extend this work to include simulated results, showing reception of a 100-Gbaud OOK signal with a 40-GHz bandlimited receiver, predicting a 3-dB improvement in receiver sensitivity at the 7% hard FEC limit. Since the optical pre-sampler can operate at the baud rate of the incoming signal, our proposed method can be used to process filtered N-WDM subcarriers.

2. Principle

Figure 1 shows three systems transmitting and receiving N-OOK signal. If the receiver's bandwidth is sufficient, the eye diagram is clear, but only during a short timing window. The eye starts to close when the receiver bandwidth is limited. However, with an optical sampler, a wide and clear open eye can be obtained.

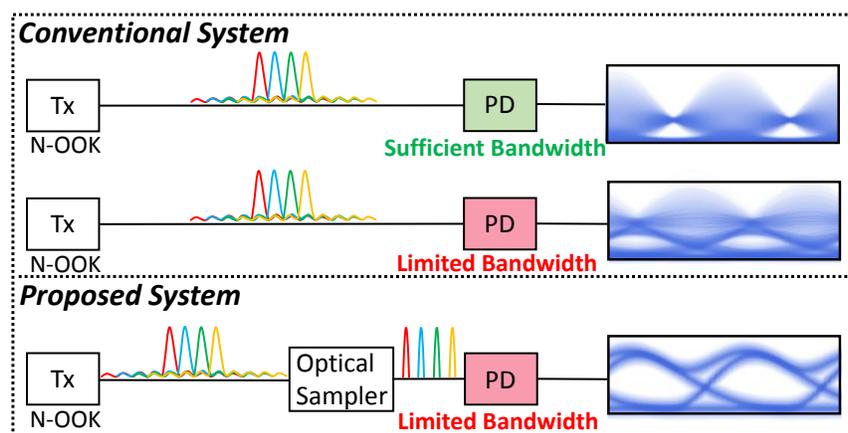


Fig. 1. Principle of band-limited photodiode enhanced by optical pre-sampling.

With a bandlimited receiver, the low-pass transfer function of this system will broaden each symbol and results in inter-symbol interference (ISI). However, with optical pre-sampling, the sinc-like symbol of Nyquist on-off keying (N-OOK) is transformed into a return-to-zero (RZ) symbol, and this signal is more resilient to electrically bandwidth-limited receivers than a sinc-like signal. That is, because the electronic sampler is no longer sampling overlapping sinc functions, the effect of timing jitter is mitigated.

3. Setup

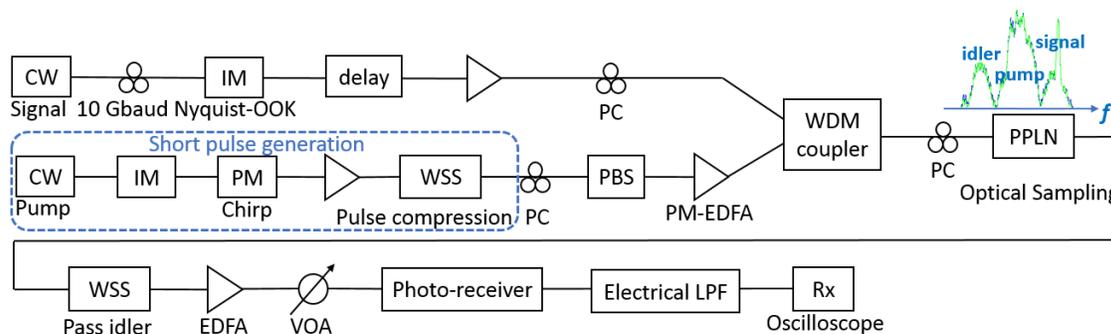


Fig. 2. N-OOK receiver with optical pre-sampling (a) experimental setup (b) simulation setup. CW: constant wave. IM: intensity modulator. PM: phase modulator. EDFA: erbium-doped fiber amplifier. PM-EDFA: polarization maintaining erbium-doped fiber amplifier. WSS: wavelength selective switch. PC: polarization controller. PBS: polarization beam splitter. VOA: variable optical attenuator. LPF: low pass filter. PD: photodiode.

Fig. 2 (a) shows the experimental setup of a Nyquist-OOK system with an optical pre-sampler. The signal that is centered at 193.1 THz is modulated by 10-Gbaud Nyquist-OOK with a 2^{15} bit long random data sequence. A variable optical delay line to temporally align the N-OOK signal with short sampling pulses. The sampling pulses are generated from a CW laser centered at 193.3 THz, whose output is intensity modulated and phase modulated by a 10-GHz sinusoidal RF source [8]. A wavelength selective switch compresses the sinusoid waveform by applying a quadratic phase shift across the spectrum.

The optical sampling gate is a 50-mm long periodically poled lithium niobate (PPLN) waveguide. In the PPLN chip, the optical short pulse train (commonly called ‘pump’) and the N-OOK signal generate the ‘idler’ at a new frequency by difference frequency generation (DFG) [9]. The idler, in this case, is the desired optically sampled signal. Since the PPLN chip is polarization sensitive, polarization controllers are used to maximize the idler power. The WSS filter operates as a 170-GHz band-pass filter centered at 193.5 THz to extract the idler. The EDFA and attenuator control the average power at the photo-receiver to plot BER versus received average optical power. A 3.8-GHz photo-receiver is implemented using a 43-GHz photo-receiver followed by a 3.8-GHz electrical low-pass filter (LPF). The photodiode is a Finisar XPRV 2021(A), and the electrical filter is Minicircuits VLF 3800+.

In the simulation, an ideal intensity modulator driven by short Gaussian pulses mimics the optical sampling gate. To simulate the experiment setup, the 10-Gbaud N-OOK signal is sampled by the intensity modulator, and becomes 12-ps OOK pulses. The electrical low-pass filter is modeled by a 4th-order Bessel filter with a 3.8-GHz bandwidth.

4. Experimental and Simulation Results

Figure 3 compares the simulation results (dashed line) and experimental results (solid line). In each case, represented by different colors, the simulation and experimental results follow the same tendency. Therefore, the simulation is a reasonable estimation of the experiment.

To show the degradation caused by the receiver’s limited electrical bandwidth, the two systems without optical pre-samplers are first compared. The curve with 3.8-GHz electrical filter is slightly better than the one without filter when BER is less than 10^{-3} , since out-of-band noise is reduced. When the BER is close to 10^{-4} , the insufficient receiver bandwidth dominates, and there is little improvement in BER with further increases in optical power.

A comparison between the systems with and without optical sampling when both are bandlimited shows the advantage of optical sampling. Without optical pre-sampler, the BER hits an error floor at 10^{-4} . However, with an optical pre-sampler, the BER can be well below 10^{-7} . The experimental result shows that the optical power can be decreased by 4 dB, at $\text{BER}=3.8 \times 10^{-3}$, and by more than 9-dB for BERs less than 10^{-4} . The simulations confirm the advantage of the optical pre-sampler. Without a band-limiting filter applied to the receiver, the optically sampled signal also requires much less average received optical power. This is to be expected when sampling a continuous signal with a discrete short optical pulse before reception.

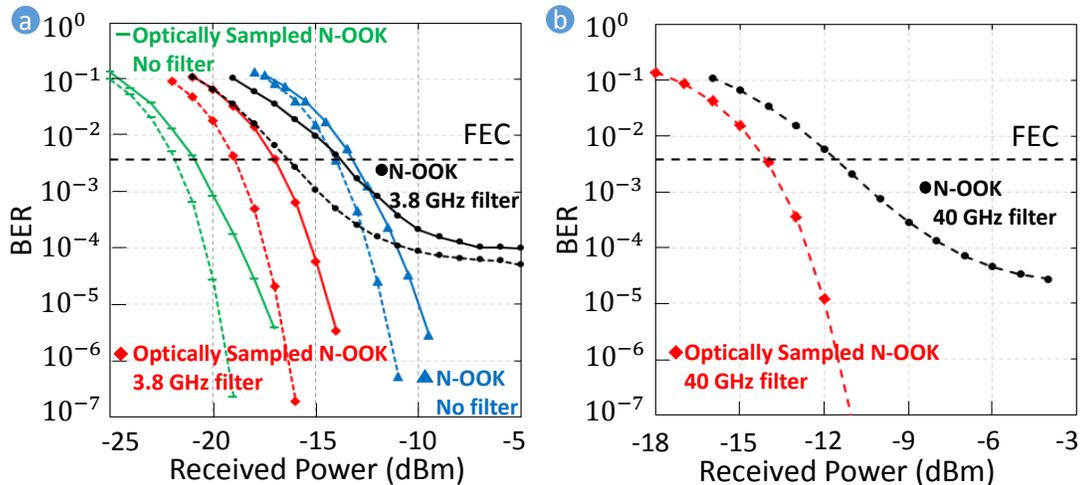


Fig. 3. (a) BER vs. Received Optical Power plot of experiment (solid line) and simulation (dashed line). (b) BER vs. Received Optical Power plot of 100 Gbaud N-OOK received by 40-GHz bandwidth photodiode simulation.

Fig. 3(b) shows the simulation results for a 100-Gbaud N-OOK systems and a 40-GHz photo-receiver. The N-OOK system without an optical sampler has an error floor at about 5×10^{-5} , while the system with optical sampling (1.2 ps pulses) can reach a BER less than 10^{-7} . The similarity between curves for the 10-Gbaud case and 100-Gbaud indicates the result is scalable to other frequencies, if the ratio between the signal and photoreceiver bandwidths is maintained. The difference results in different error floor for N-OOK received by band-limited photodiode.

5. Conclusion

We have experimentally demonstrated that, optical pre-sampling with short optical pulses helps to mitigate the electronic bandwidth limitations. A 4-dB sensitivity improvement was measured at the 7% hard FEC limit.

In our further research, the optical sampling gate will be simplified. Instead of using nonlinear interaction, coherent receiver with optical short pulses can also apply short timing gate to signal [7, 10]. In addition, optical short pulse generation can also be simplified [11, 12].

This method is applicable to real-time N-OOK transmission and it can be used in N-WDM systems to process filtered subcarriers. Besides OOK, other complex modulation formats such as 64 QAM, PAM4 and coherent QPSK could be supported.

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