107-Gb/s full-ETDM transmission over field installed fiber using vestigial sideband modulation

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Abstract: *107-Gb/s full-ETDM transmission is shown over a 160-km field installed fiber link. A high tolerance towards narrowband optical filtering is demonstrated using vestigial sideband modulation to minimize the spectral width.*

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1. Introduction

Electrical time division multiplexing (ETDM) is the most cost-effective way to increase the capacity of a single wavelength channel. Given the increasing importance of Ethernet-based data traffic there has recently been a strong interest to investigate the feasibility of 107-Gb/s ETDM transmission as a basis for a future 100-Gb/s Ethernet (100GbE) standard [1]. The main challenge to realize 100GbE is the development of cost-effective systems. Full-ETDM based systems that are compatible with today's wavelength division multiplexing (WDM) fiber infrastructure are therefore preferable.

Recently many research groups showed interest in 100GbE and different modulation formats have been proposed, such as NRZ [2, 3], duobinary [2] and DQPSK [4]. The most straightforward implementation for 100GbE that requires the least optical and electrical components is the NRZ modulation format. Many 100GbE papers have been reported using the NRZ modulation format [2, 3, 5], however so far no full 107-Gb/s ETDM transmission experiment has been reported with NRZ.

In this paper we show for the first time full-ETDM 107 Gb/s NRZ transmission. Transmission is reported over 160 km of field installed fiber. The optical bandwidth of the modulator used in this experiment is low compared to the bit rate. Therefore an FIR filter had to be used to compensate for the imperfections of the modulator. The FIR filter used was originally designed for operation at 40-Gb/s and therefore had a small free spectral range of 91 GHz [6]. This put stringent requirements on the available optical bandwidth for the data signal. By using the VSB modulation format, the optical bandwidth of the 107 Gb/s signal is significantly reduced. As a result, the signal becomes extremely tolerant against narrowband optical filtering. Although the VSB modulation format requires a relatively high OSNR, it enables cascaded filtering of the 107-Gb/s data signal with an optical filter having 0.74-nm (92.5 GHz) 3-dB bandwidth.

2. Experimental setup

The experimental setup is depicted in Fig. 1. The data and inverted data outputs of a 53.5-Gb/s pulse pattern generator (PPG, provided by SHF technologies) are fed to a SiGe 2:1 multiplexer (SHF 408). For the experiment a pseudo-random bit sequence (PRBS) with length 2^7-1 is used. The PRBS length is mainly limited by the electrical bandwidth of the receiver. In order to decorrelate the two tributaries, the inverted data output is delayed by 16 bits with respect to the data output. The balanced output of the 107-Gb/s multiplexer provides a peak-to-peak voltage of about 800 mV and is directly fed into a dual-drive Mach-Zehnder modulator with a 3-dB bandwidth of about 30 GHz and V_π = 3 V at 1.5 GHz. A distributed feedback (DFB) laser provides a continuous wave output signal at 1551.64 nm for modulation. Subsequently, the signal is VSB filtered with a tunable bandpass filter (BPF). The center wavelength of the VSB filter is located at 1550.7 nm and the 3-dB and 20-dB filter bandwidths are 1.0 nm and 2.78 nm, respectively.

The optical equalizer used is a finite impulse response (FIR) lattice filter integrated on a SiON planar lightwave circuit. The filter is a six-tap feed forward filter type and has a free spectral range of 91 GHz. A detailed description of the filter can be found in [6, 7]. Comparing the eye diagrams depicted in Fig. 1 it can be seen that the combination of VSB and FIR filter significantly improves the eye opening. However, note that for clarity the eye diagrams shown are for 100 Gb/s, since the precision timebase of the oscilloscope introduced a large jitter when used at the 13.375-GHz base rate required for measurements at 107 Gb/s.

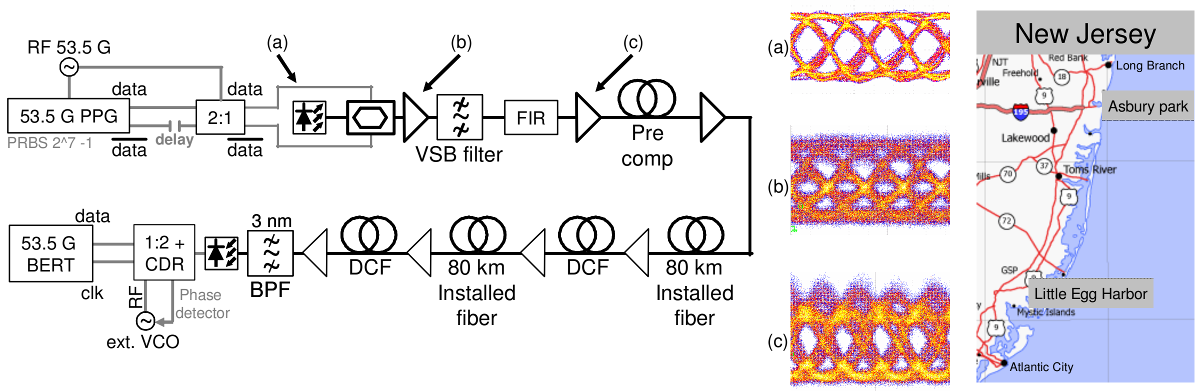


Fig. 1: Experimental setup, map and eye diagrams for (a) Electric back-to-back, (b) After optical modulator and (c) After VSB and FIR filter.

Before transmission, a dispersion compensating module (DCM) with -40 ps/nm is used for pre-compensation. The transmission link consists of two spans of 80-km non-zero dispersion shifted fiber (NZDSF) installed between Asbury Park and Little Egg Harbor (as depicted in the map of Fig. 1). These fibers have an average span loss of 19.7 dB and a dispersion of approximately 4.3 ps/nm/km at 1551.64 nm. After each span a DCM is used to compensate the chromatic dispersion. In front of the receiver the residual dispersion is optimized with additional fiber to obtain the best bit-error ratio (BER) performance. The input power levels into the transmission fiber and DCMs are 7 dBm and 0 dBm, respectively.

The 107-Gb/s signal is detected with a high-speed photodiode (provided by u2t photonics). Subsequently, the electrical 107-Gb/s signal is fed directly into the integrated ETDM receiver chip [3], which consists a 1:2-demultiplexer (DEMUX) and the clock and data recovery (CDR). An external voltage controlled oscillator (VCO, provided by Agilent Technologies) is used, which is controlled by the phase-detector signal generated in the receiver chip. The demultiplexed 53.5-Gb/s tributaries are subsequently detected with a BER tester (provided by SHF technologies) synchronized by the recovered 53.5-GHz clock signal from the receiver chip.

2. Experimental results

Table 1 summarizes the observed Q-factors and optical signal-to-noise ratios (OSNR) before and after transmission over the 160-km installed fiber link. After transmission the Q-factors are about 0.5 dB above the correction limit of a concatenated FEC code with a 7% overhead (Q-factor 9.0 dB). Both the electrical and optical signals are severely band-limited and the amplitude and phase response of the optical equalizer and of the VSB filter have a strong influence on the transmission performance.

	Q-factor Tributary 1 / 2	**OSNR**
Back-to-back	10.4 dB / 10.5 dB	42 dB
After 160 km	9.6 dB / 9.7 dB	35.6 dB

Table 1: Performance and OSNR before and after transmission.

The amplitude responses of the FIR, VSB and BPF filters are depicted in Fig. 2a, as well as the cumulative amplitude response. An advantage of the VSB filtered signal is the increased resistance to narrowband optical filtering [8], although it requires a higher OSNR. We measured the resistance of the 107-Gb/s signal to narrowband optical filtering using a flat-top narrowband BPF, with a 3-dB bandwidth of 0.74 nm and 20-dB bandwidth of 0.89 nm (shown in Fig. 2a). Fig. 2b depicts the optical spectrum of the 107-Gb/s NRZ signal as well as the VSB signal before and after the narrowband filter. After filtering the 107-Gb/s signal with the narrowband BPF, a negligible increase of the BER was seen. Even for two (identical) cascaded narrowband BPFs no noticeable penalty with respect to back-to-back was observed. Hence it can be concluded that the 107-Gb/s VSB modulated data signal is sufficiently tolerant towards narrowband optical filtering to be used in an existing 100-GHz WDM infrastructure. In order to avoid possible penalties resulting from linear and nonlinear crosstalk from neighboring channels 200-GHz spaced 107-Gb/s channels can be interleaved with 40/10-Gb/s traffic.

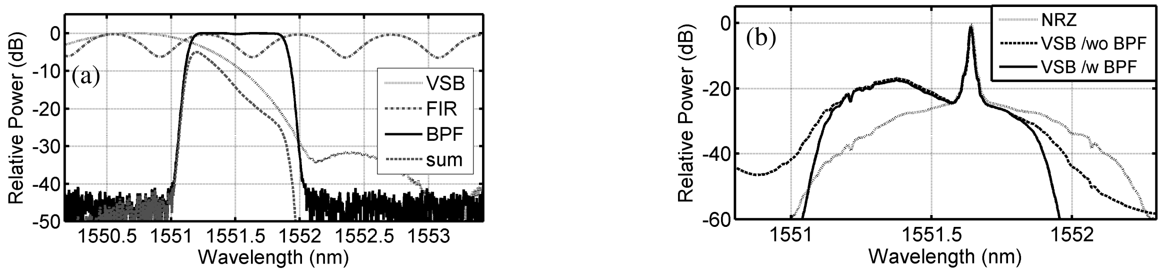
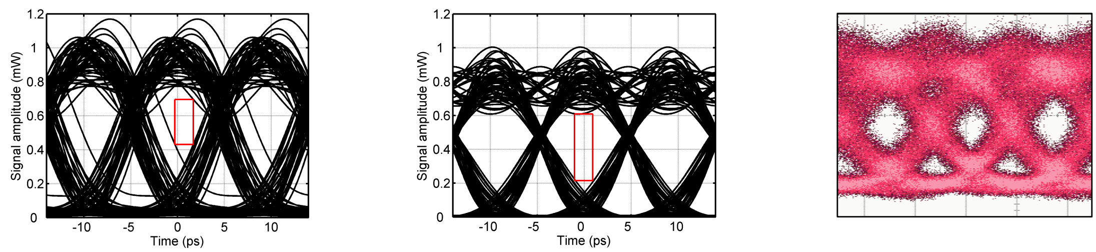


Fig. 2: Optical spectra (0.01-nm resolution bandwidth). a) Filter curves, b) 107-Gb/s NRZ and VSB with and without BPF.



(a) (b) (c)

Fig. 3: Eye diagrams at 107-Gb/s after filtering with the narrowband BPF, a) simulation without the VSB filter, b) simulation with the VSB filter, c) experiment with VSB filter.

The VSB filter plays a crucial role in increasing the tolerance of the 107-Gb/s optical signal with respect to narrowband optical filtering. Fig. 3a and 3b show simulated eye diagrams for an ideal 107-Gb/s optically modulated signal after filtering with the narrowband BPF without and with VSB filter, respectively. The center frequency of the narrowband BPF is in both configurations optimized to obtain the smallest eye opening penalty (EOP). The obtained EOP with and without VSB filter is 2.3 dB and 3.8 dB, respectively. Therefore it can be concluded that the resistance to narrowband optical filtering is significantly increased by the VSB filter. The 2.3-dB penalty in the simulation for narrowband BPF and VSB filter was not observed in the experiment. We attribute this to the modulator impairments in combination with the small FSR of the FIR filter, which already reduce the effective optical bandwidth of the signal. Therefore a further bandpass filtering by BPF and VSB, as done in the experiment, did no significantly affect the data signal. Fig. 3c shows the obtained experimental eye diagram of the 107-Gb/s VSB signal after the narrowband BPF. Please note that extra jitter is present in this eye diagram, caused by the precision timebase in the oscilloscope. Simulation and experiment show a similar eye diagram after narrowband filtering.

4. Conclusions

We demonstrated for the first time 107-Gb/s full-ETDM transmission over 160-km field installed fiber. Furthermore, we show a high tolerance towards narrowband optical filtering by using 107-Gb/s vestigial sideband modulation.

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5. References

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