Discrete Multitone Transmission for Next Generation 400G Data Center Inter-Connections

Annika Dochhan[1], Helmut Grießer[2], Laia Nadal[3], Michael Eiselt[1], Michela Svaluto Moreolo[3], Jörg-Peter Elbers[2]
[1]ADVA Optical Networking SE, Märzenquelle 1-3, 98617 Meiningen, Germany
[2]ADVA Optical Networking SE, Fraunhoferstr. 9a, 82152 Martinsried, Germany
[3]CTTC, Av. Carl Friedrich Gauss 7, Castelldefels, Spain

Paper Summary

Low complexity DMT for inter-connections between data centers is reviewed for an optical noise and chromatic dispersion affected transmission environment, showing 56 Gb/s transmission over up to 200 km of SSMF.

Introduction

DMT is a variant of orthogonal frequency division multiplexing (OFDM) which has attracted attention for the application in optical transmission systems since 2006 [1, 2]. In direct detection OFDM, two major impairments have to be taken into account: While chromatic dispersion (CD) can be easily equalized by a single tap equalizer in the electrical domain, when coherent detection is applied, the detection of a double sided signal by a photodiode leads to the loss of optical phase information and to spectral notches in the received signal (power fading). Conventionally, single sideband modulation (SSB) is applied to overcome this effect. The second impairment are unwanted mixing products between the subcarriers after detection [3]. To reduce this issue, a frequency gap between the data carrying subcarriers and the signal carrier is helpful [4]. Other techniques to overcome these limitations have been proposed recently, including block-wise phase switching [5], carrier interleaving [6] or back-calculation of the mixing interference for known transmission distance [7]. However, in the case of short-reach metro applications, low-cost components and low-complexity setups are mandatory, potentially by decreasing the transmission reach or increasing the required optical signal-to-noise ratio (OSNR). Bit and power loading as simple approach to overcome the effect of power fading was demonstrated by Milion [8]. Paul [9] and Barros [10] showed in simulations that bit and power loading can be an adequate alternative to the SSB and gap approach without including additional hardware. As explained in [3], the effect of the subcarrier mixing strongly depends on the signal carrier power. Tolerating higher carrier power increases the required OSNR to achieve a certain bit error ratio (BER), but reduces the impact of mixing products. A balance between mixing interference, carrier power and the consideration of mixing distortions as noise within the bit and power loading procedure allows double sideband (DSB) gapless DMT generation.

DMT with Bit and Power Loading

While Milion [8] achieved a transmission of 19 Gb/s over a 25 km standard single mode fiber (SSMF) link in a PON system, and Paul's [9] simulations resulted in 42.8 Gb/s over 80 km of SSMF, Yan [11] extended the reach and data rate to 100 Gb/s over 10 km of SSMF and 60 Gb/s over 40 km. All experiments and simulations were performed in the wavelength range of 1550 nm, leading to significant limitations due to CD, as shown in [12] for different types of modulators. Takahara [13] used optical pre-compensation to overcome this effect and achieved 80 km with 2x50 Gb/s. Most recent research focusses on DMT for client side applications in the O-band. Here, with the help of non-linear Volterra equalization, a transmission of 101 Gb/s on a single wavelength over 80 km is possible [14] and 469 Gb/s on four wavelengths have been demonstrated over 30 km [15]. The transmission experiments reported here will focus on the 1550 nm wavelength range, since inter data center connections with 40 to 80 km transmission reach employing DWDM with a high number of channels are also an attractive application for DMT.

DMT System Setup

Fig. 1 shows the system setup. Digital signal processing is performed offline, using python code. The parameters of the DMT system are summarized in Table I. At the transmitter side, the offline generated data is sent through a 64 GS/s DAC. The differential outputs of the DAC are directly connected to a dual-drive 40G-Mach-Zehnder modulator (DD-MZM). This yields a signal swing of ~ 0.2 times the switching voltage. The MZM's bias voltage is set close to the quadrature point of the electrical field. Clipping the signal with an optimized ratio (depending on the maximum constellation size used) and appropriate biasing avoids negative values for the electrical field. Thus, a linear modulation of the field can be performed. In a first experiment, different data rates were transmitted over 81.6 km of SSMF. In this case, only the receiver side included an optical filter to reduce the optical noise. In a second step, the data rate was fixed to 56 Gb/s and the transmission distance was varied up to 200 km. In case of 160 km and 200 km, two spans of fiber were used with an additional EDFA. Tunable optical bandpass filters (BPF) were placed before and after the transmission line to emulate interleavers within a DWDM network. Both filters were set to equal bandwidths, first to 100 GHz and later to

36 GHz. In all cases, the input power into the fiber was 5 dBm. The signal was detected by a broadband PIN photo diode and captured by a real-time oscilloscope with 80 GS/s sampling rate and 29.4 GHz bandwidth. As the photo diode current is proportional to the power of the optical signal, the square root of the detected signal was calculated in software to obtain the transmitted signal. Demodulation was performed by applying resampling, Schmidl-Cox [16] like synchronization, FFT, removal of all overhead, and one-tap equalization with decision-directed channel estimation. After de-mapping the signals, the bit errors were counted.

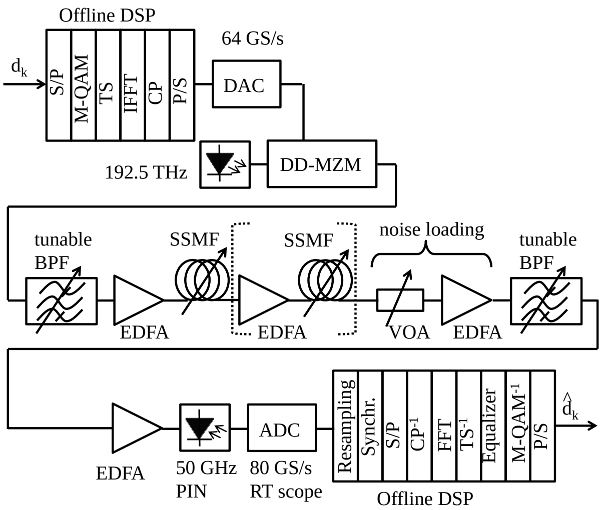

Fig. 1. System Setup. Offline generated DMT frames were transmitted over up to 200 km. Data rates were varied from 56 Gb/s to 112 Gb/s.

Bit and power loading were used in all the experiments. In an initial step, 16QAM modulation was loaded onto all subcarriers and transmitted. From the received signal, the signal-to-noise ratio (SNR) was calculated, and the number of bits necessary to achieve a certain data rate was distributed over the available subcarriers. Power loading for the fine adjustment to achieve similar performance for all subcarriers completed this procedure. Different margin adaptive algorithms were considered [17, 18], showing only slight differences in the bit distributions and almost equal performance in terms of bit error ratio (BER).

Experimental Results

The most interesting data rates for enabling 400 Gb/s are 112 Gb/s (using 4 wavelengths) and 56 Gb/s (using 8 wavelengths). However, to better evaluate how the performance degrades with increasing rate, we also considered 76 Gb/s, 86 Gb/s and 96 Gb/s. Fig. 2 shows BER vs. the OSNR in the back-to-back (b2b) case. It can be seen that all data rates reach the hard decision forward error correction (HD-FEC) limit of $4{\cdot}10^{-3}$ [19]. We also took into account a possible soft decision (SD) limit of $1.9{\cdot}10^{-2}$. For b2b, all data rates reach the HD-FEC limit. Transmission over 81.6 km increases the OSNR requirement, e.g. for 56 Gb/s at the HD-FEC limit from 23.5 dB to 27.7 dB by ~ 4 dB. However, the SD-FEC limit is still reachable up to 96 Gb/s after transmission.

Tab. 1. DMT Parameters.

Modulation formats	BPSK to 512-QAM
Frame length (data symbols)	119
Training symbols	5
FFT length	2048
Usable carriers	1023 (max. used 974)
Cyclic prefix (CP)	1/64
Clipping Ratio	9-10 dB
Equalizer	Decision directed, 1 tap

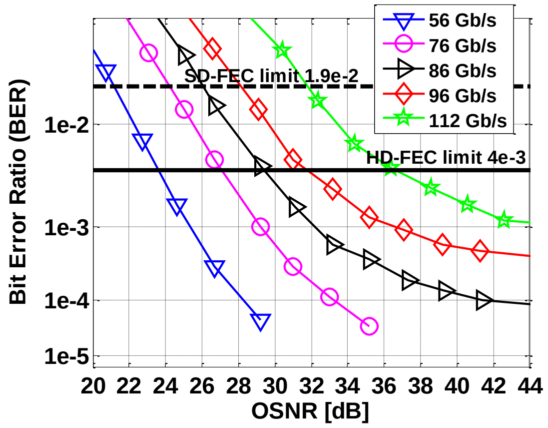

Fig. 2. BER vs. OSNR for different data rates b2b, DSB.

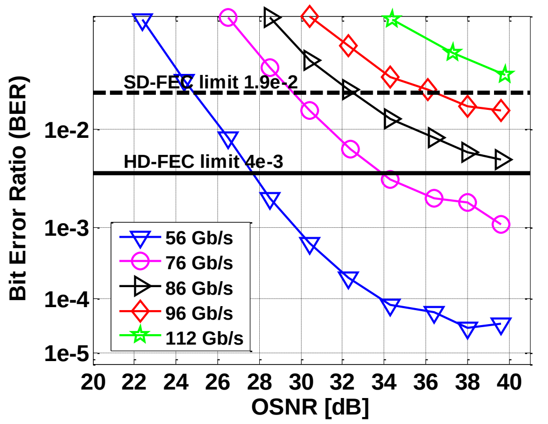

Fig. 3. BER vs. OSNR for different data rates, 81.6 km, DSB.

To further investigate the influence of CD, we increased the CD stepwise and measured the required OSNR for a BER of $4{\cdot}10^{-3}$ and 56 Gb/s. The result is shown in Fig. 4. It can be seen that the highest penalty occurs for the first 20 km. This is due to the fact that in this dispersion range notches start to occur within the optical spectrum. For higher amounts of CD, the notches move closer together, but also have steeper edges so that the usable bandwidth is not significantly further decreased. This effect is illustrated by Fig. 5 where the estimated SNR for b2b, 10 km and 80.5 km of SSMF is depicted. Consequently, 56 Gb/s could be transmitted over up to 200 km of SSMF. The results of Fig. 4 and 5 were obtained with two 100 GHz filters, one before and one after the transmission link. In a DWDM system, interleavers will be used. E.g. if the channel spacing is

50 GHz, the pass band width of these filters might be 36 GHz. Decreasing the filter bandwidth significantly decreases the transmission reach, as can also be seen in Fig. 4.

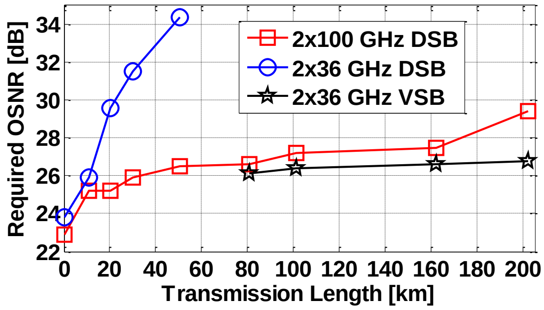

Fig. 4. Required OSNR @ BER $4 \cdot 10^{-3}$ vs. reach, 56 Gb/s.

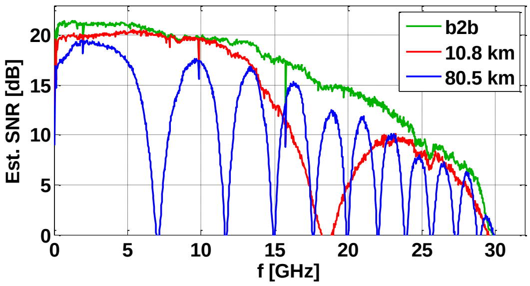

Fig. 5. Estimated SNR for various SSMF lengths and 2x100 GHz filters.

As described before, SSB transmission mitigates the power fading effect. We tried to partly filter out one sideband by detuning the 36-GHz filters. We tuned the filters in 1-GHz steps, finding an optimum detuning of 10 GHz in case of 80.5 km transmission and 12 GHz in case of 162.1 km reach. With these vestigial sideband (VSB) signals the OSNR performance is even better than for the 100-GHz centralized filtering (see Fig. 4). In a practical DWDM system, the VSB filtering could simply be realized by detuning the laser and keeping the interleaver filters fixed.

Conclusions

We reviewed the research on DMT transmission for short-reach and metro applications and presented our recent results with up to 96 Gb/s over 81.6 km of SSMF for a double sideband signal and 56 Gb/s over 202 km in only 36 GHz bandwidth by vestigial sideband filtering.

Acknowledgements

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