# Flexible Optical Modulation Technologies for Data Center Applications

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**ABSTRACT**
Communication equipment for data center applications needs to be low-cost, energy-efficient and flexible in the sense that spectral efficiency, reach and complexity should be adjustable with a high degree of flexibility in the digital signal processing of the transceivers. We present and compare different flexible modulation formats like discrete multi-tone, time domain hybrid pulse amplitude modulation and multidimensional modulation in the environment of data centers. We use vestigial sideband transmission to avoid power fading and minimize the influence of signal-signal-beating interference by optimization of the optical signal to carrier ratio.
**Keywords**: data center interconnects, flexible modulation formats, direct detection, time domain hybrid modulation, multidimensional modulation, discrete multi-tone.

## 1. INTRODUCTION

According to a forecast by Cisco [1], the global data center IP-traffic will increase to 15.3 zettabytes per year in 2020, representing a multiplication with 3 of the 2015 IP-traffic. Additionally, more so called hyperscale data centers will be built to manage the rising amount of cloud based computing. Geographically separated sites may also be integrated into clusters of data centers due to increasing virtualization or to extend existing data centers. Optical data transmission systems with a reach of up to 100 km play a significant role in order to manage the bandwidth demands that are required for these clusters. To keep the system costs low, the research focus lies on simple transmission setups with intensity modulation and direct detection (IM/DD). The deployed data rates for intra-DC links vary between 10 Gb/s for intra rack links, 40 Gb/s between top of the rack (ToR)-switches and aggregation switches and 100 Gb/s to core switches. In the future, an upgrade to higher standards is predicted [2]. Consequently, intra-cluster links must be able to carry at least 400 Gb/s. It has been shown for both discrete multi-tone (DMT) and PAM-4 that a 400 Gb/s-transmission using the 50 GHz grid is possible with a varying number of four to eight carriers [3], [4].

After a brief review of two important impairments of our proposed IM/DD-systems, we describe the three modulation techniques, namely time domain hybrid PAM (TDH-PAM), multidimensional modulation and DMT and show the results of a simulative comparison.

## 2. TRANSMISSION IMPAIRMENTS IN DIRECT DETECTION SYSTEMS

The IM/DD system for intra-cluster connects can be seen in Fig. 1.

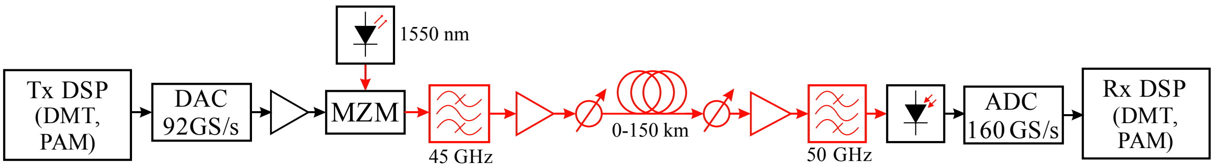


*Figure 1. Optical setup for an intra-cluster connection. The link length is varied between 0 km and 150 km.*

Only one channel is considered, the optical filters represent the optical (de)multiplexers. An intensity-modulated signal suffers from accumulated dispersion of the SSMF, as the photo diode performs a magnitude-square operation. The loss of the signal's phase information results in spectral zeros when lower and upper sideband of the signal interfere destructively. The magnitude transfer function of the IM/DD channel with the dispersion coefficient $D$, and fiber length $L$ can be expressed as [5]:

$$|H_{DD}(f,L)| = \left| cos\left(\frac{\pi D \lambda_c^2 f^2}{c} L\right)\right|. \quad (1)$$

For example, after 5 km transmission over SSMF with $\lambda_c = 1550$ nm as wavelength, the first spectral zeros are located at +/- 27 GHz. Using a dispersion compensating fiber [4] or a precompensation technique in combination with IQ-modulation [6] could be considered, but both approaches add unwanted complexity to the system. Single-sideband transmission is another way to avoid power fading and can be realized in a simple way with vestigial sideband (VSB) transmission [3], [7]. Here, one sideband is partly filtered out with the optical filters. This can be realized by detuning the laser frequency from the center of the filter.

Another major impairment that occurs with direct detection is the so-called signal-signal beating interference (SSBI). Let us consider the following SSB-signal $E(t)$ before detection with the photo diode [7]:

$$E(t) = \{1 + \alpha[s(t) + j\hat{s}(t)]\} \cdot e^{j\omega_c t}. \quad (2)$$

The signal consists of a carrier and the analytical signal, where $\hat{s}(t)$ is the Hilbert-transform of the signal $s(t)$. The optical signal to carrier power ratio (OSCR) is determined by $\alpha$ and lies within $0 < \alpha < 0.5$. The OSCR can be controlled with the amplitude of the electrical driving voltage and bias voltage of the MZM. After direct detection, we obtain:

$$|E(t)|^2 \ = 1 + 2\alpha s(t) + \alpha^2[s^2(t) + \hat{s}^2(t)]. \quad (3)$$

The first term represents the signal DC. The second term is the wanted signal and the third term is the nonlinear interference. Iterative compensation techniques have been shown [8], but the influence of the SSBI can also be minimized by using a low $\alpha$. Nevertheless, the resulting strong carrier affects the effective OSNR negatively so that an optimum OSCR for each OSNR needs to be determined.

## 3. FLEXIBLE MODULATION

The data rate of the transceivers can be varied in different ways [9], [10]. Changing the clock rate requires a hardware modification. The FEC-scheme can be changed, if multiple schemes are implemented. Another way is the variation of the modulation cardinality. On the one hand, a higher modulation cardinality increases the data rate, but reduces the system's reach and requires a higher OSNR on the other hand. In flexible networks, it is desirable to have the possibility to change the data rate in the software of the transceivers to adapt the data rate to different reaches or changed transmission characteristics. The Bitloading in the DMT setup offers a fine granularity as the modulation format of each subcarrier can be varied. In contrast, the modulation cardinality of single carrier systems is usually bound to integer values for the number of bits per symbol. Two techniques that allow fractional values for the number of bits per symbol are time domain hybrid modulation (TDHM) and multidimensional modulation.

### 3.1 Time Domain Hybrid PAM

Time domain hybrid modulation (TDHM) is a simple method to increase the flexibility of a transmission system [11]. In TDHM, words of length $N_{\text{Sym}}$ are combined in the time domain out of symbols with different modulation formats. Our approach is limited to modulation formats for direct detection receivers, therefore we use OOK, PAM-4 and PAM-8. The overall data rate is determined by the word length and the relative occurrence of the modulation formats and can be varied between 56 Gb/s and 168 Gb/s for a fixed symbol rate of 56 GBd as can be seen in Table 1.

*Table 1. Word composition and resulting data rates for 56 GBd TDH-PAM and multidimensional modulation.*

| Data rate | Average bits/symbol | TDH-PAM word structure [bits/symbol] | Word length $N_{\text{Sym}}$ [symbols] | Multidimensional amplitude levels | $G_P$ | Channels for 400G |
|---|---|---|---|---|---|---|
| 56 Gb/s | 1 | [1] | 1 | OOK | | 8 |
| 64 Gb/s | 8/7 | [1 1 1 1 1 1 2] | 7 | PAM-3 | 2.5 | 7 |
| 74.67 Gb/s | 4/3 | [1 1 2] | 3 | PAM-3 | 1.1 | 6 |
| 89.6 Gb/s | 8/5 | [1 1 2 2 2] | 5 | PAM-4 | 2.7 | 5 |
| 112 Gb/s | 2 | [2] | 1 | PAM-4 | | 4 |
| 149.33 Gb/s | 8/3 | [2 3 3] | 3 | PAM-7 | 2.9 | 3 |
| 168 Gb/s | 3 | [3] | 1 | PAM-8 | | |

The digital signal processing (DSP) for TDH-PAM is depicted in Fig. 2. As the higher modulation format would dominate the BER, the power ratio between both modulation formats is scaled in the transmitter. The signal is resampled from the symbol rate $f_{\text{Sym}} = 56$ GBd to the DAC rate (92 GS/s). A root raised cosine (RRACOS) filter with a roll-off factor $\beta = 0.3$ is used for pulse shaping. In the receiver the signal is matched filtered after removing the DC portion. A cross correlation is used for synchronization and the signal is resampled from the ADC rate (160 GS/s) to twice the symbol rate for equalization. The channel coefficients for the FFE are estimated using the MMSE-criterion.

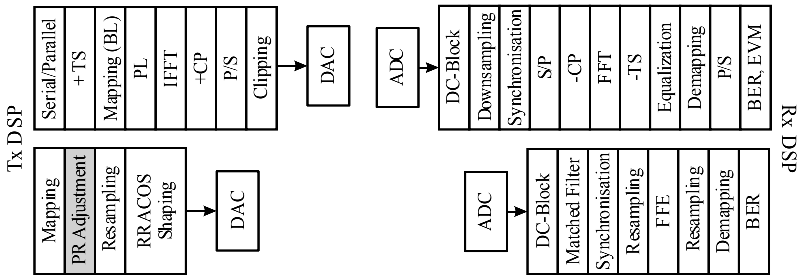


*Figure 2: DSP for the DMT setup (top) and both single carrier approaches (bottom). The PR-Adjustment is only performed in the TDH-PAM configuration. The DAC rate is 92 GS/s and the ADC rate is 160 GS/s.*

### 3.2 Multidimensional Modulation

Multidimensional modulation can also be used to obtain flexible data rates [12]. Again, $N_\mathrm{B}$ bits are combined to words of length $N_\mathrm{Sym}$, resulting in $N_\mathrm{Sym}$-dimensional constellations for PAM. Different to TDH-PAM, the modulation format is constant within the word. The number of PAM-levels $M$ must fulfill the following condition:

$$M^{N_{Sym}} \geq 2^{N_B}. \tag{4}$$

For example, in case of $N_\mathrm{B} = 4$ and $N_\mathrm{Sym} = 3$, PAM-3 is chosen as modulation format. Since the number of possible constellation points $M^{N_\mathrm{Sym}}$ can be higher than required, the combinations with maximum power are excluded from the labeling. In general, gray coding is not possible for multidimensional modulation, resulting in a gray penalty $G_P > 1$ [12]. Thus, an optimum labeling has to be determined and stored in a lookup-table for the (de-)mapping procedure. This is a pre-implementation task whose complexity strongly depends on $N_\mathrm{B}$, as $(2^{N_\mathrm{B}})!$ different mapping possibilities exist. Consequently, the gray penalty for 74.67 Gb/s transmission is an optimum, for the other data rates a suboptimal mapping is used. Except for the mapping procedure, the DSP in the transceivers is identical to the TDH-PAM setup.

### 3.3 Discrete Multi-tone

Another modulation technique with high research activities in the field of data center applications is DMT [3], [13]. The corresponding DSP can be seen in Fig. 2. The signal is constructed in the frequency domain after training symbols for synchronization and channel estimation have been inserted in the data stream. To obtain a real valued signal after modulation, the signal must have Hermitian symmetry, meaning that only one half of the subcarriers carries data. The data rate $R$ can be changed in the Bitloading (BL) procedure by variation of the number of bits $N_\mathrm{BpS}$ that are assigned to one DMT-symbol:

$$R = f_{Sym} \cdot \frac{N_{BpS}}{N_{FFT}} \cdot \frac{1}{1+{N_{TS}}/{N_{Data}}} \cdot \frac{1}{1+{N_{CP}}/{N_{FFT}}}\,, \tag{5}$$

where $N_\mathrm{FFT}$ is the FFT-size, $N_\mathrm{TS}$ and $N_\mathrm{Data}$ denote the number of training (TS) and data symbols, respectively and $N_\mathrm{CP}$ is the length of the cyclic prefix (CP) that is inserted after the IFFT. The BL and Powerloading (PL) also allows an optimum adaptation of the signal to channel impairments like the DAC roll-off or other bandwidth limitations. As the individual subcarrier-SNR must be known for the BL/PL procedure, the channel is estimated with a uniformly loaded DMT-signal at the beginning of the transmission. In our approach we use the Fischer-Huber algorithm for BL/PL [14]. The signal is symmetrically clipped to reduce the peak-to-average power ratio before D/A-conversion. In the receiver, the signal is downsampled to the symbol rate and the DMT-frame is synchronized using cross-correlation with a TS. The equalization is performed in the frequency domain with a zero-forcing equalizer.

## 4. SIMULATION RESULTS

We designed a simulation model according to the setup from Fig. 1. The component characteristics are in accordance with commercially available products. The DAC resolution is 8 bits. The bandwidths of DAC, electrical amplifier and MZM are modelled with 32 GHz, 38 GHz and 31.7 GHz, respectively. The optical filter bandwidths would allow D-WDM transmission and the laser frequency is detuned 20 GHz from the channel center for VSB-filtering. We use a linear SSMF with a maximum reach of 150 km. Detection is performed with a photo diode with 50 GHz bandwidth. The ADC is running with 160 GS/s and has a bandwidth of 63 GHz. The MZM-driving voltage and bias point have been optimized for each OSNR value for the single carrier approaches and the number of FFE-taps is adjusted to the fiber length, resulting in 12 taps in B2B transmission and 64 taps at 150 km. In case of DMT-transmission, one frame consists of 4 TS and 120 data symbols, the FFT-size is chosen to be 2048. The cyclic prefix lies within 12 (back-to-back) and 48 samples (150 km). The clipping PAPR is 7 dB for 56 Gb/s up to 11 dB for 168 Gb/s transmission. For the DMT-setup, a fixed bias point $(0.4 \cdot V_\pi)$ close to the quadrature point is chosen.

The simulation results can be seen in Fig. 3. The back-to-back curves show that the gaps between the conventional modulation formats (56 Gb/s, 112 Gb/s and 168 Gb/s) are filled with the flexible modulation formats. The BER of the multidimensional approach is directly connected to the gray-penalty, that is why the 74.67 Gb/s transmission performs best. For TDH-PAM, a penalty compared to multidimensional modulation of 1.6 dB OSNR can be seen at the HD-FEC limit for that data rate. Except for the 149.33 Gb/s transmission, even the data rates with a high $G_P$ show a similar performance as the TDH-PAM setup. Due to the clipping noise and the lower OSCR in the DMT setup, the DMT curves show a penalty of around 4 dB that decreases with increasing data rates. In the lower figures, the required OSNR for the HD-FEC limit is plotted. In the single carrier approaches, the required OSNR increases over the first kilometers because of the remaining power fading from the vestigial sideband, resulting in too high required OSNR values for 168 Gb/s transmission. The required OSNR for the DMT-transmission increases with the fiber length, as $N_\mathrm{BpS}$ is increased due to the longer CP.

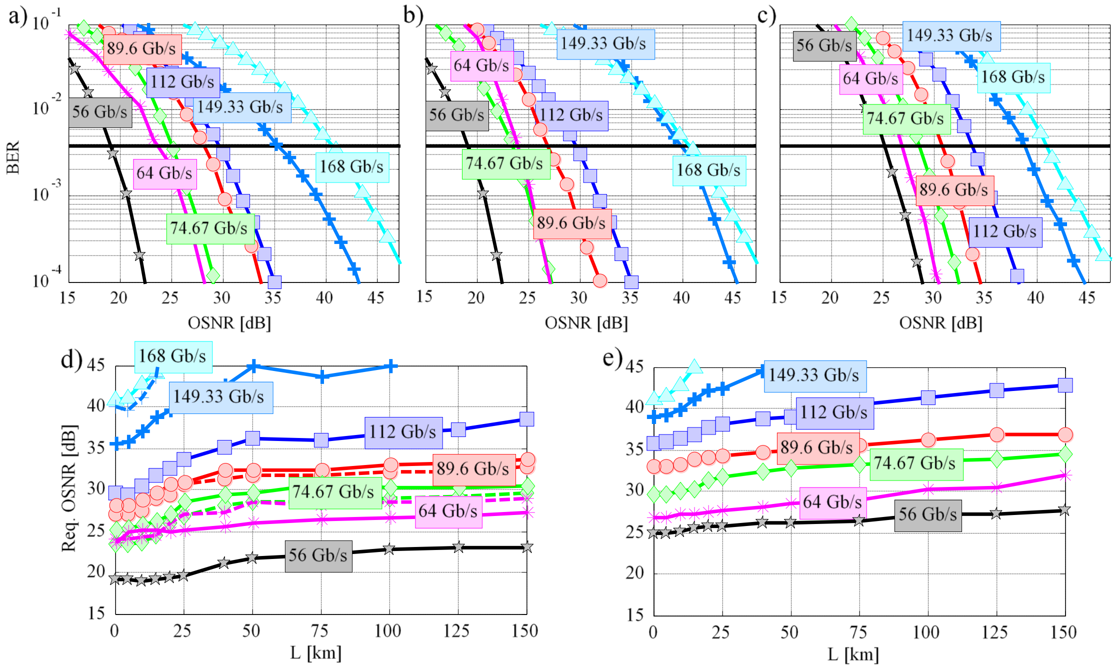


*Figure 3. Simulation results. Back-to-back performance for: a) TDH-PAM, b) multidimensional modulation and c) DMT. The HD-FEC limit (BER = 3.8e-3) is marked as a reference. The OOK, PAM-4 and PAM-8 curves are also included in a) and b). The required OSNR for the HD-FEC limit at varying fiber lengths is depicted in d) for TDH-PAM and multidimensional modulation (dashed curves) and in e) for the DMT setup.*

## 5. CONCLUSIONS

We show three different techniques for a higher resolution of possible data rates at a fixed symbol rate for intra-cluster links between data centers. All modulation techniques can be applied in the DSP of the transceivers so that a high flexibility is achieved. The discussed impairments that arise with IM/DD-transmission can be circumvented with vestigial-sideband transmission (power fading) or a proper OSCR (SSBI). The single-carrier approaches require less OSNR at the FEC limit than the DMT setup. Nevertheless, the suboptimal mapping schemes affect the multidimensional modulation so that we expect an improvement if a lower gray penalty could be found.


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