Analysis of WDM and OTDM 256-QAM for 1 Tb/s Transmission Link

Wenzao Li* **and Daniel J. Blumenthal**

University of California, Santa Barbara, Santa Barbara, CA 93106, USA.

**wli@ece.ucsb.edu*

Abstract: We provide feasibility study of building a 1 Tb/s (16×4.375 Gbaud) Pol-Mux 256-QAM, 10 km link using WDM and OTDM. WDM meets the SNR requirement, but OTDM does not and has to reduce tributary count.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation; (060.4230) Multiplexing

1. Introduction

In recent years the fast growth of cloud computing stimulated the growth of datacenters. Larger datacenters can have multiple buildings interconnected. So point-to-point links with multi-terabit per second capacity will be highly desirable. Coherent optical communication systems using quadrature amplitude modulation (QAM) formats can have high data rate on narrow bandwidth. A number of single-channel experiments using 256-QAM [3, 7], 512-QAM [1, 5, 6] and even 1024-QAM [4] formats have been demonstrated.

Although spectrally efficient, the data rate of the high-order QAM experiments are still one order of magnitude lower than 1 Tb/s, limited by the speed of current digital-to-analog converter (DAC) technologies. Therefore, multiplexing in optical domain is still necessary. Historically wavelength division multiplexing (WDM) has been more popular due to easier implementation, while optical time division multiplexing (OTDM) can realize ultra-high speed transmission on a single-carrier. So far there has been no report on either WDM or OTDM link experiments using 256-QAM or higher formats. So in this paper we provide a feasibility study of building a 1 Tb/s (16×4.375 Gbaud) Pol-Mux 256-QAM link using both WDM and OTDM. Based on signal-to-noise ratio (SNR) analysis WDM link meets the SNR requirement and OTDM link does not.

2. 1 Tb/s Link Using 256-QAM Format

One fundamental limit for using high-order QAM formats is the stringent SNR requirement, shown in Fig. 2. Understanding the link SNR penalty provides guideline for system design. In this study, we assume two hypothetical 1 Tb/s links with 12% overhead, using Pol-Mux 256-QAM format, with 16× WDM or OTDM. Each wavelength/tributary is modulated at 4.375 Gbaud, which is currently achievable. To analyze ASE noise limited performance we assume homodyne detection with an optical local oscillator (LO) (CW for WDM link, pulsed for OTDM link) that is phase locked to the signal, therefore the optical phase noise is minimized. The system setups are shown in Fig. 1. The link distance is assumed to be 10 km for inter-building datacenter applications, so fiber impairments such as dispersion are also neglected.

One reason for the need of optical amplification is due to high optical loss at 256-QAM modulation. The 256-QAM signals generated with high speed DACs are modulated onto optical carriers using nested Mach-Zehnder modulators (MZM). Because of the cosine-shape E-O transfer function of MZ interferometer, only a portion of $2V_\pi$ centered at the null point can be used for linear E-O conversion. The linear region is $1.2V_\pi$ out of $2V_\pi$ for $R^2 = 0.99$. Assume equal probability of each symbol, the average-to-peak power ratio is 0.38 for 256-QAM. Taken into account the 5 dB insertion loss for state-of-the-art PM-QPSK MZM, the total minimum loss is 16.7 dB. In our experiment, we use an Agilent M8190A arbitrary waveform generator which has a direct DAC output of V_{pp} = 700 mV, and MZM $V_\pi \approx 2.2$ V. The use of electrical amplifiers is prohibited due to IQ imbalance. In this case, the modulation loss is 28.2 dB. We assume the ideal 16.7 dB case in this analysis.

The WDM channel SNR is similar to that of a single-carrier link, with all carriers being multiplexed and demultiplexed with arrayed waveguide gratings (AWG) and processed in parallel. With proper filtering and pulse shaping at transmitter, filtering effect from AWG, and sufficient guard band, intra-channel signal and noise cross talk can be

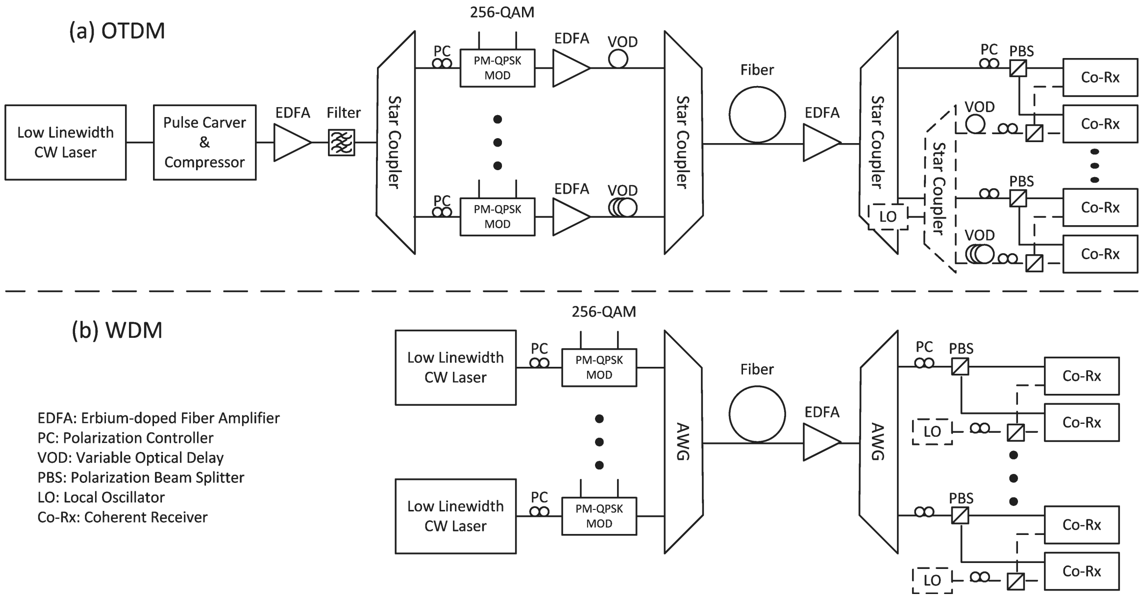

Fig. 1. Hypothetical 1 Tb/s links using Pol-MUX 256-QAM format, with (a)OTDM and (b)WDM.

neglected. In the link we assume 20 dBm laser power, no booster amplifier, and one pre-amplifier. Therefore ASE-introduced OSNR penalty will be the same as a single-carrier link, and the link performance degradation will mainly due to other fiber impairments such as four-wave mixing (FWM) and cross-phase modulation (XPM), which is not in the scope of this paper.

On the other hand, OTDM is a serial approach where all tributaries share a single optical carrier. For the pulsed light source, due to the superior phase noise performance over mode-locked lasers (MLL), QAM OTDM systems usually use a low-linewidth CW laser followed by a pulse carver and a pulse compressor, which usually consists of cascaded MZMs and dispersive fibers. The process of pulse carving is inherently lossy. For an n-tributary link, the minimum loss is $1/n$ plus the insertion loss of cascaded MZMs. The loss is then compensated by the first EDFA. The pulse source then splits into n tributaries using a 1xn star-coupler, interleaved in T/n symbol slots, and combined for transmission. At the receiver the OTDM signal is split spatially and then demultiplexed with pulse LO during coherent detection. Each splitting and combining process has a minimum loss of $1/n$, resulting in a total loss of $1/n^3$ (36 dB for $n = 16$). We assume the loss from the first splitter and modulator is compensated by the second EDFA, and loss from multiplexer, demultiplexer and fiber is compensated by the third EDFA.

Aside from high loss, there is also a direct SNR penalty during time domain multiplexing. For the i-th OTDM tributary, we model the modulated optical signal amplitude in each polarization before the multiplexer as

$$y_i(t) = s_i(t) + n_i(t) = \sum_k u_k p\left(t - (k + \frac{i}{n})T\right) + n_i(t) \tag{1}$$

where T is the symbol period, u_k is the k-th symbol, $p(t)$ is the pulse shape function, and $n_i(t)$ is the ASE noise amplitude. For this analysis we assume ideal Nyquist pulse shape [2] with roll-off factor $\alpha = 0$, so $p(t) = A_0\,\mathrm{sinc}(nt/T)$. In this case there is no inter-symbol interference (ISI) between tributaries and the bandwidth is minimum ($B = n/T$). Therefore, the multiplexed signal (in each polarization) is

$$y(t) = \sum_{i=1}^{n} \frac{y_i(t)}{\sqrt{n}} = \frac{1}{\sqrt{n}} \left\{ \sum_{i=1}^{n} \sum_k u_k A_0\,\mathrm{sinc}\left[\left(t - (k + \frac{i}{n})T\right)\frac{n}{T}\right] + \sum_{i=1}^{n} n_i(t) \right\} \tag{2}$$

Since the ASE noise are independent random process, the noise variance is the sum of the noise variance of all tributaries. Therefore, the sampled SNR at $y\left((k + \frac{i}{n})T\right)$ is decreased by a factor of $1/n$. Note that OSNR does not decrease in this process. Another way to understand this is that while signal pulses are interleaved, the noise is not. A third way to understand this is the frequency domain picture. Because all tributaries share the same wavelength, although OSNR remains the same after multiplexing, the actual performance related *real* OSNR for the tributary is $1/n$ of the measured OSNR. This SNR degradation is fundamentally different from WDM, where intra-channel noise is automatically suppressed by the filtering effect of an AWG. A way to suppress this SNR penalty due to time division multiplexing is to use fast optical gating to clean up noise outside of the optical pulses before multiplexing. However this will also modify the sinc pulse shape and is not included in this analysis.

At the homodyne receiver, we assume a phase-locked pulsed LO is used for simultaneous demultiplexing and detection. Electrical signal is linearly proportional to the optical field amplitude. In OTDM systems, the high baud rate pulses have large optical bandwidth that is usually larger than the photodetector (PD) bandwidth. In this analysis we assume the PD RF bandwidth to be $2/T$. Therefore, due to filtering effect, the received signal peak amplitude is reduced by a factor of $1/n$, while the noise power is also reduced by $1/n$. As a result, the SNR of the sampled output is reduced by $1/n$. This penalty could be eliminated if high bandwidth ($2n/T$) PDs are used to fully retrieve the short pulse, but other penalties such as timing jitter may rise.

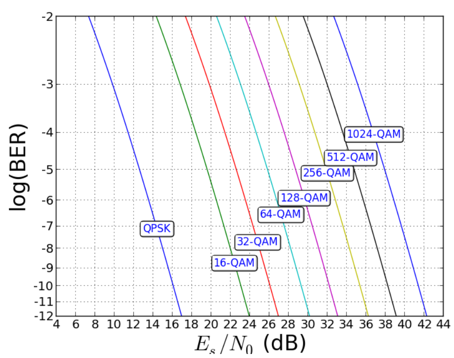

Fig. 2. BER as a function of SNR for QAM formats.

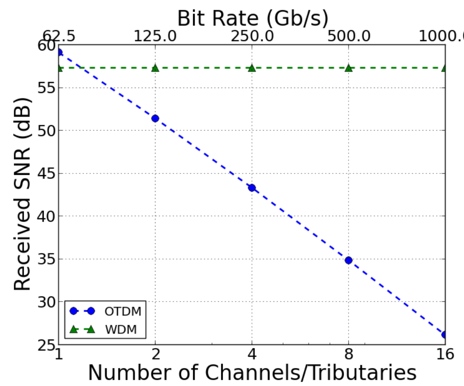

Fig. 3. Received SNR as a function of wavelength/tributary count.

For both the OTDM and WDM links, we assume 20 dBm laser power and 6 dB typical EDFA noise figure, and the calculated received SNR as a function of the number of wavelength/tributaries is shown in Fig. 3. For 256-QAM format, at the FEC limit of BER = 2×10^{-3}, the required SNR is 27.7 dB. The OTDM link only has SNR of 26.1 dB at $n = 16$ or 1 Tb/s. To meet the requirement one has to increase baud rate and reduce n. Note that many other penalties such as pulse extinction ratio, fiber impairments and laser noise have not been included, so real performance will be worse and the difference between OTDM and WDM can be even larger.

3. Conclusion

We compared two 1 Tb/s (16×4.375 Gbaud) links using OTDM and WDM, with Pol-Mux 256-QAM modulation format. The analysis showed that OTDM has higher SNR penalty due to high loss, noise cross talk in multiplexing, and receiver filtering effect. The SNR is not sufficient to support 1 Tb/s under current assumption, but can be improved by increasing baud rate and reducing the number of tributaries.

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