Narrowband Filtering Tolerance and Spectral Efficiency of 100GbE PDM-OFDM

Sander L. Jansen, Itsuro Morita, Hideaki Tanaka
KDDI R&D Laboratories, Saitama, Japan
SL-Jansen@ieee.org, Morita@kddilabs.jp, Hide@kddilabs.jp

Abstract—We show that the tolerance of 100GbE PDM-OFDM with respect to narrowband optical filtering is comparable to that of its single-carrier optical counterpart. This translates into a comparable spectral efficiency of OFDM and single-carrier modulated signals.

I. INTRODUCTION
100 Gigabit Ethernet (100 GbE) is considered to become the next generation Ethernet standard for IP networks [1]. For the implementation of this high data rate, the combination of coherent detection and digital signal processing has received significant interest as it can provide virtually unlimited chromatic dispersion and polarization mode dispersion (PMD) tolerance [2-5]. Several modulation formats have been proposed either using a single carrier [2-3], or multiple orthogonal frequency division multiplexed (OFDM) carriers [4-5].

It is often stated that the obtainable spectral efficiency of an OFDM signal is higher than that of its single carrier counterpart [6]. But from information theory we know that this is not per definition true [7]. When we compare the unfiltered spectra directly with each other it indeed seems that the spectrum of OFDM is narrower than that of the single carrier modulated signal. However, there is no clear relation between the unfiltered optical spectrum and the feasible spectral efficiency. In order to determine the feasible spectral efficiency, narrowband filtering tolerance of a signal should be taken into account.

In this paper we investigate the tolerance of polarization-division multiplexed (PDM) OFDM to narrowband optical filtering and compare the obtainable spectral efficiency with that of coherent detected single carrier modulation. It is observed that the tolerance of 100GbE PDM-OFDM with respect to narrowband optical filtering is similar to the filtering tolerance observed for single-carrier 100GbE PDM-QPSK reported in [1-2]. The obtainable spectral efficiency is therefore not significantly higher than single carrier modulation, although the advantage of OFDM is that inherently the linear crosstalk of the neighboring channels is negligible.

II. 100GbE OFDM
Although 100GbE has not been standardized yet, it is foreseen that 7% overhead needs to be allocated for FEC and about 4% for the Ethernet protocol (64B/66B coding). This results in a raw data rate of 111 Gb/s. In an OFDM signal additional overheads are caused by cyclic prefix, training symbols and pilot subcarriers for phase noise compensation. Recently we showed that by using an RF-pilot tone, phase noise compensation can be realized without pilot subcarriers [8] and as such the total OFDM overhead can be reduced to about 8% (see the discussion section in [4]). All overheads combined (7% FEC, 4% protocol and 8% OFDM related), the required nominal data rate for a 100GbE OFDM system is at least 120 Gb/s. The bandwidth of a PDM-OFDM signal can be expressed as

\[ B_d = \frac{D_{\text{Nominal}}}{2 \times \log_2 (M)}, \]

where \( D_{\text{Nominal}} \) is the nominal data rate [b/s], \( M \) is the constellation size and the factor 2 results from the use of PDM. The bandwidth of a 120-Gb/s PDM-OFDM signal with QPSK modulation of the subcarriers is thus 30 GHz. The cyclic prefix required for the mitigation of chromatic dispersion is dependent on the bandwidth of the OFDM signal and the desired transmission distance [8]. A good estimate for the required guard time \( \tau_g \) is:

\[ D \cdot B_d \cdot \frac{c}{f^2} = \tau_g, \]

where \( D \) represents the chromatic dispersion of the desired transmission distance [s/m], \( B_d \) is the effective bandwidth of the modulated OFDM signal [Hz], \( c \) is the speed of light [m/s] and \( f \) the center frequency of the OFDM band [Hz]. For a 1000-km link of SSMF with 16 ps/nm/km chromatic dispersion a cyclic-prefix guardband of \( \tau_g = 3.9 \text{ ns/OFDM symbol} \) is required in this configuration. The FFT of the OFDM system must now be chosen such that the cyclic prefix and training symbol overhead do not exceed the initial estimated 8% OFDM overhead allocated in the nominal data rate. Assuming 20% oversampling at the transmitter and allowing a 4% training symbol overhead, it is easily shown that the FFT size of this system must be at least 4096 [8] so that the OFDM symbol length (excluding cyclic prefix) is 103.1 ns.

For modulation and detection either an electrical [4, 8, 11] or an optical [5, 6, 9] IQ modulation scheme can be used. In both modulator configurations, the DAC and ADC requirements are the same. If the OFDM signal is generated in one single band, the DACs and ADCs require 15 GHz of bandwidth with a sampling rate of at least 36 GHz. For the sampling rate 20% oversampling is included. The oversampling provides in this configuration a 3-GHz guard band between the aliasing products and the OFDM signal so that the aliasing products can be removed with a low-pass filter [8].

III. NARROWBAND FILTERING AND SPECTRAL EFFICIENCY
Fig. 1 shows the simulated tolerance with respect to narrowband filtering of the QPSK-modulated 120-Gb/s PDM-OFDM configuration described in Section II. In this simulation the optical signal-to-noise ratio (OSNR) is...
fixed to 10.6-dB, resulting in a BER of $1 \times 10^{-5}$ when a sufficiently broad optical filter is used. A fourth order Gaussian filter is used in this simulation as optical filter. Because of the confined spectrum of the OFDM signal a negligible BER penalty is observed as long as the optical filter is broader than the OFDM band (30-GHz for 120-Gb/s PDM-OFDM). At narrower bandwidths the subcarriers located on the sides of the OFDM signal are attenuated and thereby the SNRs of the subcarriers located at these frequencies is severely degraded. As a result, a steep increase in BER is observed when the filter bandwidth is lower than 30 GHz. The 30-GHz filter tolerance is comparable to that observed for single carrier 100GbE [2-3]. It can thus be concluded that even though the unfiltered spectrum of PDM-OFDM is significantly smaller, it has a similar tolerance towards narrowband optical filtering compared to single carrier PDM-modulated signals with coherent detection (given that the constellation size is the same).

The comparable tolerance with respect to narrowband optical filtering suggests that the obtainable spectral efficiency is similar as well. We look into this in more detail by comparing two recently reported 100GbE measurements with constellation size $M=8$, namely narrowband filtered 114-Gb/s PDM-RZ-8PSK [10] and 121.9-Gb/s PDM-OFDM-8QAM [11]. The spectra of both modulation formats at 0.01-nm spectral resolution bandwidth are shown in Fig. 2. Note that in the OFDM spectrum the residual of the suppressed optical carrier can be observed at 17-GHz. The optical carrier is not part of the OFDM signal and can be further suppressed by using optical modulators with a lower $V_{pi}$ to increase the extinction ratio or by employing a different modulation technique [5, 6, 9]. The 3-dB and 20-dB spectral widths of the 100GbE signals are summarized in Table 1. In [10] a spectral efficiency of 4.2 b/s/Hz was obtained by multiplexing 114-Gb/s PDM-RZ-8PSK channels at 25-GHz channel spacing. Even though the 20-dB spectral width of the narrowband-filtered 114-Gb/s PDM-RZ-8PSK signal (32.6 GHz) is broader than the channel spacing, the penalties measured due to the 25-GHz multiplexing and demultiplexing were relatively low: 0.5-dB penalty due to linear crosstalk and 0.7-dB penalty for narrowband filtering was observed.

As shown in Fig. 2, the OFDM spectrum has a more rectangular-like optical spectrum and can therefore be packed closely together with avoiding linear crosstalk. However, as discussed in Section II, OFDM inherently requires a higher overhead due to training symbols and cyclic prefix. For a 100GbE PDM-OFDM signal with a nominal data rate of 120-Gb/s, the maximum obtainable spectral efficiency (without guard band between the WDM channels) is 5.2 b/s/Hz. However, any practical realization will require a guard band between individual WDM channels to cope with laser drifts and to enable adding and dropping individual WDM channels. The obtainable spectral efficiency of OFDM systems is therefore not significantly higher than that of single carrier systems.

Finally we note that by coherently modulating WDM channels the guard band between the WDM channels can be removed [6, 12]. This coherent WDM method can be applied to both single carrier and OFDM transmission systems. In such case, the WDM channel spacing is the same for single-carrier or OFDM modulation. Because of the higher overhead that is required in OFDM systems for channel estimation, the spectral efficiency of the single carrier coherent WDM system will then be slightly higher.

![Figure 2. Optical spectrum of narrowband filtered 114-Gb/s PDM-RZ-8PSK (adopted from [10]) and 121.9-Gb/s PDM-OFDM. RB = 0.01 nm.](image)

### Table I.

<table>
<thead>
<tr>
<th>Spectral width</th>
<th>PDM-RZ-8PSK</th>
<th>PDM-OFDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-dB</td>
<td>19.9 GHz</td>
<td>22.6 GHz</td>
</tr>
<tr>
<td>20-dB</td>
<td>32.6 GHz</td>
<td>25 GHz</td>
</tr>
</tbody>
</table>

### IV. Conclusion

In this paper we showed that the narrowband optical filtering tolerance of 100GbE PDM-OFDM is comparable to that of its single carrier counterpart. This translates into a comparable spectral efficiency although the advantage of OFDM is that inherently the linear crosstalk of the neighboring channels is negligible.

### Acknowledgment

We would like to thank Dr. X. Zhou from AT&T for providing the optical spectrum of 114-Gb/s PDM-RZ-8PSK. Furthermore the authors are grateful to Dr. S. Randel, Dr. T.C.W. Schenk, Dr. D. van den Borne, Dr. S. Akiba and Dr. M. Suzuki for the support. This work was partly supported by a project of the National Institute of Information and Communications Technology of Japan.

### References

[1] M. Duelk, in proc. ECOC 2005, Tu. 3.1.2