10x121.9-Gb/s PDM-OFDM Transmission with 2-b/s/Hz Spectral Efficiency over 1,000 km of SSMF

S.L. Jansen, I. Morita, H. Tanaka.

KDDI R&D Laboratories, Saitama, Japan, email: SL-Jansen@kddilabs.jp.

Abstract: PDM-OFDM transmission of 10x121.9-Gb/s (112.6-Gb/s without OFDM overhead) at 50-GHz channel spacing is demonstrated over 1,000-km SSMF without any inline dispersion compensation. 8-QAM subcarrier modulation allows transmission of 121.9 Gb/s within a 22.8-GHz optical bandwidth.

©2007 Optical Society of America

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

1. Introduction

Optical networks are currently shifting towards a data-centric configuration, in which the transport of internet protocol (IP) traffic is expected to play a more dominant role. 100 Gigabit Ethernet (100 GbE) is considered to become the next generation Ethernet standard for IP networks [1]. Consequently, research has recently accelerated into finding appropriate long-haul Ethernet transport solutions for the physical layer [2-5]. In the short term, multi-wavelength transport might provide a solution for 100-Gb/s Ethernet, but in the long run a single-wavelength solution will be the most cost-effective approach.

Different modulation formats such as OOK and DQPSK have been proposed for the realization of 100GbE. On a 100-GHz grid, 107-Gb/s VSB-OOK transmission has been realized over 510 km [2], 107-Gb/s NRZ-DQPSK over 1,200 km [3], and 100-Gb/s DQPSK-modulated coherent-WDM over 1,300 km [4]. However, in these experiments direct detection is employed, resulting in a limited chromatic dispersion and PMD tolerance. This can be alleviated through optical compensation, but this is not suitable for cost-sensitive applications. The tolerance towards these linear impairments can be increased significantly through the use of coherent detection. In combination with digital signal processing, coherent receivers can provide a superior tolerance towards chromatic dispersion and PMD [5]. In [6] 111-Gb/s transmission has been reported over 2,375 km of SSMF on a 50-GHz WDM grid.

Orthogonal frequency division multiplexing (OFDM) is a digital multicarrier technique, which offers significant advantages for long-haul optical transport. It offers the same advantages as a single-carrier coherent receiver (i.e. a virtually unlimited chromatic dispersion and PMD tolerance [7]), but is furthermore easier scalable to higher level modulation formats [8-10]. However, the data rate of fiber-optic OFDM experiments reported so far has been limited to 52.5 Gb/s because of limitations of the electrical bandwidth at the transmitter [7]. In this paper we report for the first time transmission of 121.9-Gb/s (112.6-Gb/s without OFDM overhead) polarization-division-multiplexed OFDM (PDM-OFDM) over 1,000 km of SSMF, without inline chromatic dispersion compensation. In this WDM experiment 10x121.9-Gb/s channels are transmitted at 50 GHz channel spacing, providing a spectral efficiency of 2 b/s/Hz. The subcarriers are modulated with 8 QAM, allowing transmission of 121.9 Gb/s within an optical bandwidth of 22.8 GHz.

2. Experimental setup

The experimental setup is shown in Fig. 1. Two Tektronix AWG7102 arbitrary waveform generators (AWG) are used to produce two independent 15.2-Gb/s OFDM baseband signals. The 121.9-Gb/s OFDM signal consists of two polarization-multiplexed signals with four subcarrier-multiplexed OFDM bands each. The 121.9-Gb/s signal has therefore a total of eight 15.2-Gb/s tributaries. In order to create this subcarrier multiplexed signal, the two OFDM baseband signals are upconverted to four intermediate frequencies (IF), present at 8.7 GHz, 14.4 GHz, 20.4 GHz and 26.1 GHz. Inset 2 of Fig. 1 illustrates the electrical OFDM channel allocation after upconversion. For decorrelation, AWG 1 is used for the first (8.7 GHz) and third OFDM (20.4 GHz) bands and AWG 2 for the second (14.4 GHz) and fourth (26.1 GHz). The OFDM baseband waveforms that are produced by the AWGs have been calculated offline and are outputted continuously. The FFT size is 1024, from which 520 subcarriers are effectively used for the transport of data and the cyclic prefix length is 22 samples (2.2 ns) per OFDM symbol. Together with the cyclic prefix, the OFDM symbol length is 104.6 ns and the OFDM symbol rate 9.6 MHz. A non-rectangular 8-QAM constellation is used for symbol mapping, which provides the maximum symbol distance [10]. For some specific subcarriers, the electrical SNR was not sufficient to support 8-QAM modulation. The SNR at these subcarriers is impaired by for instance side-modes of the local oscillator laser or the roll-off of electrical components (at high frequencies). Therefore 5% extra OFDM channels had to be allocated at the transmitter which are omitted at the...
receiver. In a practical system one could signal this back to the transmitter and transmit the data on these subcarriers using a lower constellation size, such as BPSK or QPSK. This is known as adaptive coding and is used extensively in radio communications. Such an adaptive modulation technique would allow for an increased data rate. However, in this experiment this was not possible as each AWG was driving two IQ mixers at different intermediate frequencies. More details about the OFDM baseband generation and IQ-mixing can be found in [11]. For this WDM experiment, 10 external cavity lasers (ECLs) with an approximate linewidth of 100 kHz are aligned on a 50-GHz ITU grid between 1553.7 nm and 1557.4 nm. Two parallel Mach-Zehnder modulators are used in this setup for separate modulation of the even and odd channels. The optical modulators are single-ended Mach-Zehnder modulators designed for analog applications (with a high linearity). In order to suppress the carrier of the OFDM signal the modulator is biased in its minimum. After modulation, the even and odd WDM channels are combined using a 50-GHz interleave. As described in [7] the interleaver is aligned such that the image band of the OFDM signal is rejected. Polarization multiplexing is emulated by splitting the signal with a 3-dB coupler and combining it with a polarization beam combiner. As shown in inset 1 of Fig. 1, one arm is delayed by exactly one OFDM symbol, LSPS = loop-synchronous polarization scrambler, DGE = dynamic gain equalizer, ADC = analogue-to-digital converter. The re-circulating loop consists of 4 spans of 82-km SSMF without optical dispersion compensation. After every span, amplification is provided by a Raman/EDFA structure with an average on/off Raman gain of ~10 dB. A dynamic gain equalizer (DGE) is used for power equalization and a loop-synchronous polarization scrambler (LSPS) is employed to reduce loop-induced polarization effects. After transmission, 25 km of SSMF is inserted, resulting in a total transmission distance of 1,009 km. At the receiver, the signal is split in two random polarizations and is detected with a polarization-divergent 90 degrees optical hybrid. An ECL with ~100-kHz linewidth is used as free running local oscillator (LO) and four single-ended 20-GHz Pin/TIA modules (Discovery DSC-R401HG) are used for detection. A real-time digital storage oscilloscope (Tektronix DPO72004) is used to sample the four outputs of the optical hybrid. The bandwidth of the oscilloscope is 16 GHz, the sampling frequency is 50 GHz and the effective number of bits is approximately 5.5 bits. After detection, the data is post-processed off-line. Fig. 2b shows the computed electrical spectrum after coherent detection. The LO is located in the middle of the OFDM signal, in between the second and third OFDM bands.

Training symbols are periodically inserted into the OFDM signal so that at the receiver, polarization de-rotation can be realized through MIMO processing. The processing algorithm is described in detail in [7]. In order to distinguish between the training symbols of the PDM tributaries the training symbols should be received one after the other. The delay of the PDM emulator is exactly one OFDM symbol, thus training is realized in this experiment by inserting an empty OFDM symbol before and after the training symbol (see inset 1 of Fig. 1). In order to compensate for the phase noise of the local oscillator, RF-aided phase noise compensation is implemented (for the
In order to mitigate the influence of amplified spontaneous emission (ASE) noise on the channel estimation, a moving average over 12 training symbols was used for MIMO processing at the receiver. For all reported BERs five sets with each 2.4 million bits have been evaluated, each set with different polarization state settings in the LSPS.

3. Measurement results

Fig. 3a shows the measured back-to-back sensitivities for 60.9 Gb/s (single polarization) and 121.9 Gb/s (PDM). Additionally, the simulated sensitivity for 121.9 Gb/s is shown as well. The required optical signal-to-noise ratio (OSNR) for a BER of $1 \times 10^{-3}$ is 14 dB/0.1 nm and 17.8 dB/0.1 nm for 60.9 Gb/s and 121.9 Gb/s, respectively. Apart from the 3-dB expected penalty, a 0.8-dB excess penalty is observed for PDM. This penalty is most likely caused by a less effective phase noise compensation scheme. Because of the one symbol delay in the PDM emulator at the transmitter, there is a 105-ns delay between the RF-pilot tones of the two polarizations. At the receiver, the sum of these RF-pilot tones is used for phase noise compensation and thus the delay between the polarizations reduces the effectiveness of the phase noise compensation scheme. We note that this penalty only applies for our emulated PDM setup and that in a convention PDM setup with a modulator per polarization such a penalty has not been observed [7].

Taking this difference into account, the 17.8-dB sensitivity for 121.9-Gb/s PDM-OFDM with 8-QAM modulation is similar to previously reported 100-Gb/s sensitivity measurements with coherent detection [12]. Compared to the simulated sensitivity of 121.9 Gb/s, a penalty of about 2 dB at a BER of $1 \times 10^{-3}$ is present. For lower BER values an increase in performance penalty between the simulated and experimental curve is observed. This penalty increase is most likely caused by the fact that at lower BER values the residual carrier frequency offset and phase noise after compensation start influencing the system performance [13]. Additionally, the performance of the fourth OFDM band is limited by nonlinearities of the amplifiers and frequency mixer. As a result, a BER floor is observed for this OFDM band, limiting the BER of the 121.9-Gb/s configuration to about $5 \times 10^{-6}$.

The fiber launch power optimization for channel 3 (located at 1554.5 nm) after 680-km transmission is shown in Fig. 3b. The BER performance shows little variation over a wide launch power range (from -9 dBm to -5 dBm). The nonlinear tolerance could be increased by reducing the constellation size to QPSK, however, this would require a larger electrical bandwidth (which was not available for this experiment). Fig. 3c shows the performance of the 10 WDM channels after 1,000-km transmission (with -7-dBm/channel launch power). The average OSNR after transmission is ~21.5 dB and the average BER per channel varies between $3.9 \times 10^{-4}$ and $1.3 \times 10^{-3}$. The channels on the red side of the spectrum slightly outperform the other channels as the noise figure of the EDFA/Raman amplifiers is slightly lower for these wavelengths, which results in a ~0.4-dB higher OSNR. The obtained BER values are well below the threshold of a concatenated FEC code with 7% overhead ($2.3 \times 10^{-3}$).

4. Conclusion

In this paper, we demonstrated for the first time WDM transmission of 10x121.9-Gb/s polarization-division multiplexed OFDM at 2-b/s/Hz spectral efficiency. Transmission over 1,000 km of SSMF was achieved without any inline chromatic dispersion compensation.

This work was partly supported by a project of the National Institute of Information and Communications Technology of Japan.

References

[1] M. Duelk, ECOC 2005, Tu. 3.1.2
[9] X. Yi, et al., ECOC 2007, Tu. 2.5.3