Single Source Optical OFDM Transmitter and Optical FFT Receiver Demonstrated at Line Rates of 5.4 and 10.8 Tbit/s

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Abstract: OFDM data with line rates of 5.4 Tbit/s or 10.8 Tbit/s are generated and decoded with a new real-time all-optical FFT receiver. Each of 75 carriers of a comb source is encoded with 18 Gbd QPSK or 16-QAM.

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1. Introduction

The need for terabit transmission systems with single source Tbit/s transceivers is supposed to arise sooner than anticipated by many in the industry [1]. The question at stake though is if the lower bit-rate tributary information can viably, energy-efficiently and effortlessly be generated and extracted.

Recent record experiments performed by two independent groups have demonstrated the feasibility to generate a 5.1 Tbit/s time-division multiplexing (TDM) single-wavelength signal and to reliably extract the respective 10 Gbit/s tributaries by means of time-division multiplexing methods [2],[3]. Alternatively, OFDM has emerged as a promising technology for ultra-high bit rate transmission [4]. OFDM is attractive as it offers a high spectral efficiency [5], and much better tolerance towards transmission impairments like dispersion. And indeed, the technology has already demonstrated generation of OFDM line rates with up to 1.2 Tbit/s and 1 Tbit/s [6],[7]. While generating a high capacity OFDM signal is straightforward [8], its reception is not. In OFDM, the tributaries or subcarriers are spaced so tightly that their spectra overlap, which makes channel extraction by means of conventional optical filtering impossible. Actually, in OFDM, the subcarrier frequency spacing ∆ω is chosen so that any two subcarriers are orthogonal to each other with respect to integration over the symbol duration. As a consequence, only appropriate receivers will be able to distinguish them. Such receivers exist. They almost exclusively perform the FFT on the time-sampled signal in the electronic domain. Such electronic real-time implementations are currently restricted to OFDM symbol rates of a few Gbd due to speed limitations of the digital signal processor [9],[10]. Higher bit rate OFDM signals are usually processed offline – which was done in the aforementioned Tbit/s OFDM demonstrations [6],[7]. This may be practical for laboratory experiments but not for data transmission. One way to relax the requirements on electronic speed is shifting the FFT into the optical domain with computation speeds beyond the limits of electronics, and with little if no energy consumption [11]. The new all-optical FFT method is based on a direct optical implementation of the FFT [12].

In this paper we demonstrate the power of the new all-optical FFT demodulation technique to generate and demultiplex a 5.4 Tbit/s or 10.8 Tbit/s OFDM signal consisting of 75 spectrally overlapped polarization-division multiplexed (PDM) 18 Gbd QPSK or 16-QAM signals with spectral efficiencies of 2.88 or 5.76 bit/s/Hz, respectively.

2. Experimental setup

The OFDM transmitter and receiver setup is shown in Fig. 1. At the transmitter, the subchannel rate limitations imposed by electronics may be overcome by using a DWDM-like approach, where the possibility to optically generate precisely tuned spectral components in frequency space is exploited to directly generate OFDM subcarriers at the
Fig. 1: OFDM transmitter and receiver setup. A comb generator (mode-locked laser (MLL) with highly nonlinear fiber (HLNF)) provides a broad frequency comb (B). A wavelength selective switch (Wave Shaper) provides disinterleaving and power equalization resulting in 75 subcarriers that are subsequently encoded with 18 Gbd of QPSK or 16-QAM data each. Even and odd channels are then combined and polarization multiplexed to generate the OFDM channel (C). The optical FFT at the receiver consists of a delay interferometer (DI) cascade. The DIs with the shortest delays (largest FSR) have been replaced by narrowband filters, sacrificing some performance.

correct frequency separation $\Delta \omega = 2\pi/T$ [8]. An optical comb generator provides these subcarriers which can then be modulated individually. The comb generator comprises a single mode-locked laser (ERGO-XG MLL) with a repetition rate of 25 GHz, followed by a booster amplifier and a highly nonlinear fiber (HNLF) to generate new frequency components by means of Kerr nonlinearity. An optical equalizer is used to adjust the output power of all spectral lines to the same value and separate them into even and odd subcarriers using a wavelength selective switch (Wave-Shaper). Both sets of frequency-locked subcarriers are then individually modulated with independent QPSK or 16 QAM signals (PRBS 2$^{15}$-1), respectively, and combined to form the OFDM signal. This transmitter can be considered as performing the Fourier transform in analog form, equivalent to the discrete transform performed (electronically) by the IFFT. In such a transmitter, bandwidth limitations of the modulator will cause subchannel crosstalk which can be mitigated by insertion of a guard interval (corresponding to the cyclic prefix) between symbols [11]. This guard interval, however, reduces the OFDM symbol rate. We have used a guard interval of 15.6 ps, resulting in a usable OFDM symbol rate of 18 Gbd. To obtain a polarization-multiplexed output, the OFDM signal is split in a 3 dB coupler, one of the data streams is delayed by 5.3 ns to decorrelate both streams, and then both streams are recombined in a polarization beam combiner.

The receiver comprises the all-optical FFT circuit and an optical modulation analyzer (Agilent N4391A) which performs real-time coherent detection and an EVM analysis. The optical FFT circuit [11] consists of a cascade of one to three DIs (where a trade-off between complexity and quality can be made), followed by a 1nm bandpass filter (actually a cascade of two such filters) to suppress crosstalk from spectrally distant subcarriers. The final element of the OFFT is the EAM sampling gate. A tunable polarization filter to perform polarization demultiplexing is inserted before the optical FFT circuit to avoid residual polarization dependence of the DIs.

3. Results
To evaluate the transceiver performance, we plotted the error vector magnitudes (EVMs) for both polarizations in all 75 subchannels as measured with the Agilent modulation analyzer. Each measurement comprises $2^{10}$ received symbols. The results are shown in Fig. 2(a) at top and bottom for the 5.4 Tbit/s OFDM signal with QPSK.
subcarriers and 10.8 Tbit/s OFDM signal with its 16-QAM subcarriers, respectively. Typical constellation diagrams are depicted in Fig. 1(b). The symbols have a clear and distinct shape. To get a feel for the quality of the received signals we have performed bit-error rate (BER) estimations as derived in Ref. [13] and renormalized them to be compatible with the Agilent EVM definitions. It can be seen that all QPSK subcarriers have BERs in the order of $1 \times 10^{-6}$. BER measurements with the Agilent modulation analyzer provided error free operation even after long measurement durations. EVM for the 16-QAM signals were found to be in the order of 12% and 14%. Estimations by Ref. [13] indicate that all 75 subcarriers are well below the $1.9 \times 10^{-3}$ third generation FEC limit [14] but slightly above the $2.3 \times 10^{-3}$ FEC limit with 7% overhead. These BER values are also close to the BER that have been derived for some representative points with the Agilent modulation analyzer.

![Fig. 2](PDPC1.pdf)

**Fig. 2**: (a) Measured error vector magnitude (EVM) and spectrum (right axis) of 75 subcarriers. The upper graph shows the EVM of the QPSK OFDM data. The dashed horizontal lines indicate estimated BER. The lower graph shows the corresponding results for the 16-QAM OFDM data. The horizontal line indicates BER below the third generation FEC limit $1.9 \times 10^{-3}$. (b) Comparison of performance of new all-optical FFT OFDM receiver types with alternative OFDM receivers.

Finally, we have tested the performance of the all-optical FFT receiver concept against allegedly more simple OFDM receiver concepts. Performance comparisons for various types of OFDM receivers and for a representative QPSK subcarrier are shown in Fig. 2(b). If the all-optical FFT filter with the three delay interferometer cascades is replaced by a bandwidth tuneable bandpass filter (XTRACT Anritsu) and adjusted to optimally extract a single subcarrier we get EVMs in the order of 41%. If the Agilent coherent detector with built in equalization filter is used we get EVMs of 30%. The all-optical FFT receiver with the ideally matched filter [11] however provides EVMs of 14.9%, clearly showing the strength of the new concept.

### 4. Conclusions

We demonstrated, to the best of our knowledge, a record high-speed single-source transmitter and receiver. Real time processing of 5.4 Tbit/s and 10.8 Tbit/s line rate data was enabled by means of an optical FFT. BERs below state-of-the-art FEC thresholds were achieved.

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### 5. References