Optical OFDM as a Promising Technique for Bandwidth-Efficient High-Speed Data Transmission over Optical Fiber

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***Abstract*—Application of the orthogonal frequency-division multiplexing (OFDM) technique for optical high-speed fiber communication is reviewed within this paper. Several choices of implementation are discussed as well as special properties of the optical transmission link affecting the OFDM technique are clarified. Especially, nonlinear properties are taken into account and investigated by simulation. It is shown that transmission of 40Gb/s over 640km of standard single-mode fiber is possible without any dispersion compensation.**

***Index terms*—optical OFDM, optical communications, high-speed data transmission.**

I. Introduction

Optical fiber communications has become a challenging research field for communications and systems engineers. In order to meet the ever-growing demand for transmission capacity, techniques originally known from classical digital communications have entered the field of optical communications, such as forward error correction [1], multilevel digital modulation [2], and maximum likelihood sequence estimation [3].

A very current evolution is the fact that the optical community has paid great attention to OFDM within the past months. While at last year's optical fiber communications conference (OFC, the world's most important forum in this field) only a very few number of contributions were dealing with OFDM, during this year's OFC OFDM was one of the most emerging topics with more than a dozen of presentations.

The main difficulty for transferring classical techniques like OFDM to optical communications is given by the special properties of fiber optic transmission links compared to wireless or copper transmission channels:

First of all, the data throughput desired for an optical link is in the range of some tens of Gb/s up to a few Tb/s. Despite of extensive application of the wavelength division multiplexing (WDM, actually FDM) technique, the single-channel symbol rate is high in the range of 10-40 Gb/s. Hence, even with high-speed electronics and parallel processing only limited complexity of signal processing is realizable.

Secondly, due to nonlinear modulator characteristic, even for arbitrarily low fiber launch power an optical link inherently shows nonlinear behavior. Moreover, the optical fiber as transmission medium is a nonlinear element as soon as the launch power exceeds a certain threshold.

Thirdly, theoretically the channel memory is not limited as the impulse response of the optical fiber is of infinite length, which makes the proper selection of the cyclic prefix very difficult. The actually observable length depends on many parameters, among them signal bandwidth and transmission length. A closed form for the corresponding impulse response is not yet known.

In this contribution, recent development in the field of OFDM for optical communications is reviewed. Different ways how to implement OFDM for optical communications are depicted. Moreover, a couple of results are shown where the focus lies on sensitivity of OFDM towards the special nonlinear impairments of the optical channel.

II. Optical Transmission Link

Optical fiber communication systems are so widely used today because of their exceptionally low loss allowing for long distances between amplifiers or repeaters, and their inherently high-data carrying capacity. As simplest transmission technology, the optical systems employ the Intensity-Modulation Direct-Detection technique (IM/DD) for digital transmission, also known as ON-OFF-Keying (OOK). The block diagram of the basic IM/DD optical system is shown in fig. 1.

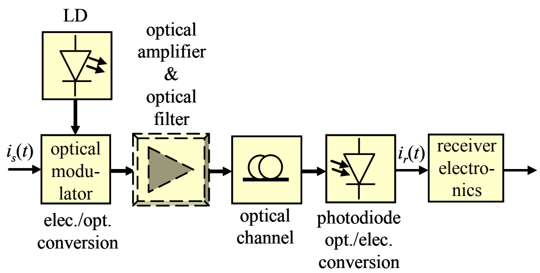

Fig. 1. Block diagram of IM/DD optical system.

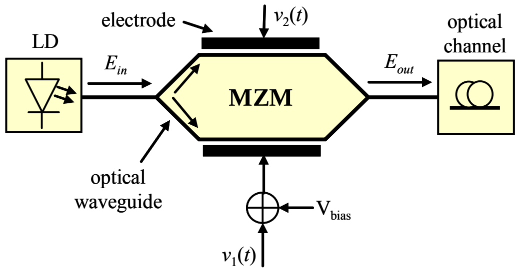

Fig. 2. MZM architecture.

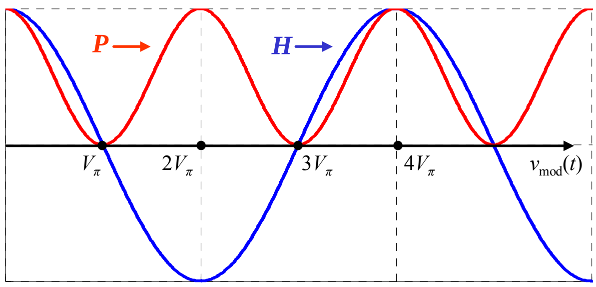

Fig. 3. MZM transfer characteristics.

In the modulator, the data signal $i_s(t)$ is transferred into the optical bandpass domain by modulating intensity of light. Modulation can be implemented directly by modulating the laser diode forward current, or by means of a separate external modulator modulating the output of a constant-intensity optical source. The latter strategy minimizes the chirp effect. Fig. 2 shows the simplified diagram of the most commonly used external modulator called Mach-Zehnder Modulator (MZM). By setting $v_1(t) = -v_2(t)$, the MZM operates in push-pull mode and the electric field transfer characteristic H is equal to

$$H = \frac{E_{out}}{E_{in}} = \cos\left[\frac{\pi}{2V_\pi} v_{\mathrm{mod}}(t)\right], \qquad \textbf{(1)}$$

where V_π is the switching voltage and $v_{\mathrm{mod}}(t)$ represents the data signal. The power transfer characteristic P is equal to

$$P = \frac{|E_{out}|^2}{|E_{in}|^2} = \cos^2\left[\frac{\pi}{2V_\pi} v_{\mathrm{mod}}(t)\right]. \qquad \textbf{(2)}$$

From (1) and (2) we can see that the MZM has a non-linear characteristic as shown in fig. 3. For the photo diode, the output current is proportional to the optical input power. For the cascade of MZM and photo diode, even in case of a linear optical channel an optical transmission link is nonlinear according to the power transfer characteristic.

III. Basics of Optical OFDM (OOFDM)

In order to exploit the optical bandwidth more efficiently, recently optical OFDM as a special case of optical SCM was introduced in the optical domain, and an advanced optical OFDM (OOFDM) modulation technique was proposed [4]. One of the main reasons for suitability of OFDM in optical communications is its ability to deal with large pulse spreads due to chromatic dispersion by dividing the broad optical channel spectrum (for which the dispersion effect is large) into a number of sub-channels N each with a narrow spectrum which decreases the dispersion effect for each sub-channel.

In wireless transmission, the length of the cyclic prefix (CP), also known as Guard Interval, to be added to each OFDM symbol for ISI minimization is equal to the length of the channel impulse response which has a specific length. In optical transmission, the length of the impulse response of dispersive fiber theoretically is infinite. Thus the actually observable length depends on a set of parameters, e.g. signal bandwidth [5]. Fig. 4 shows the impulse response of a fiber channel for a fiber of length L=20km. Apparently, the impulse response is non-causal and does not decay to zero. As an analytical expression of a band-limited version of the impulse response is not available, proper selection of the length of the cyclic prefix is one of the main challenges for OOFDM in the near future. Nevertheless, a main motivation for introducing OFDM in the optical domain is the possibility for high-speed data transmission over dispersive fiber without the need for costly optical dispersion compensation techniques [6].

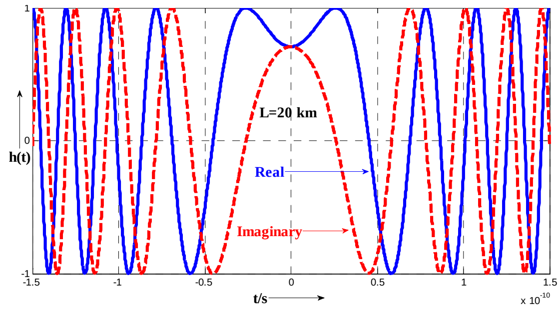

Fig. 4. Impulse response of fiber channel.

IV. Implementation of OOFDM Systems

OOFDM is based on electronic signal processing before the optical modulator and after the photodetector. The optical components are used just for converting the electrical OFDM signal into an optical bandpass signal at the transmitter for transmission through an optical fiber and for converting the received optical signal back into the electrical domain at the receiver. This has a big advantage because the microwave devices are much more mature than their optical counterparts and because the frequency selectivity of microwave filters and the frequency stability of microwave oscillators are significantly better than that of corresponding optical devices [7].

A. IM/DD OOFDM System

IM/DD technology is widely used because of its simplicity. The OOFDM system using IM/DD is shown in fig. 5. After digital modulation (e.g. m-QAM), by means of appropriately feeding the serial data to the input of the IFFT, an OFDM signal centered around an intermediate frequency f_{RF} is created in the electrical domain.

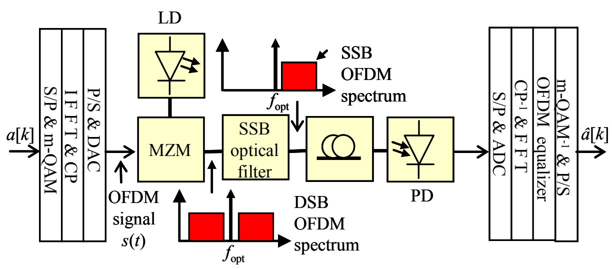

Fig. 5. OOFDM system using IM/DD.

After the MZM, a double sideband OFDM signal is obtained in the optical domain. The optical double-side-band (DSB) transmission suffers from the loss of the phase information of the optical signal after the square law detector, while in optical SSB transmission, the phase information, due to the chromatic dispersion, is preserved even after square-law detection [8]. In addition, SSB transmission reduces the effect of the chromatic dispersion by reducing the optical signal spectral bandwidth.

After propagation through the fiber link, the photodiode produces an electrical waveform. Then, the symbols are converted to frequency domain through FFT. Once in frequency domain, each sub-channel is equalized to compensate for phase and amplitude distortion due to the optical and electrical paths. This is achieved by using a separate complex multiplication for each sub-channel [9]. The output of the equalizer is then digitally demodulated and converted into a single data channel by P/S conversion.

B. Coherent Optical OFDM system (CO-OFDM)

Recently a multi-carrier modulation format called coherent optical OFDM (CO-OFDM) has been proposed [10]. Fig. 6 shows a CO-OFDM system which uses direct up/down conversion at the transmitter and receiver.

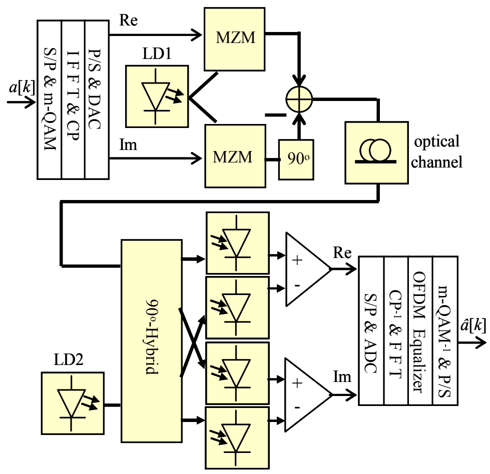

Fig. 6. Homodyne CO-OFDM system.

The OFDM optical transmitter uses the optical I/Q modulator comprising two MZMs to up-convert the real/imaginary parts of the broadband OFDM signal to the optical domain. The OFDM optical receiver (homodyne detection) uses two pairs of balanced receivers to perform I/Q detection optically. In a homodyne system, the phase difference between LD1 and LD2 evolves rapidly which requires narrow line width lasers [11].

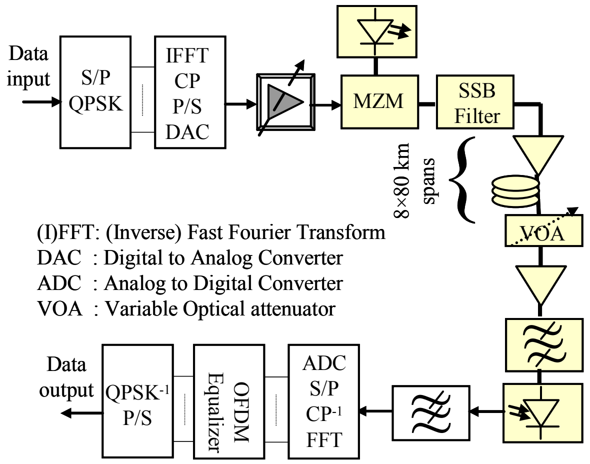

Fig. 7. OOFDM simulation setup.

V. Simulation Results

The OOFDM system setup based on the IM/DD strategy that was used for simulation is shown in fig. 7. The bandwidth of the generated OOFDM signal is set to B_{OFDM} =21.4 GHz. This is equal to the minimum bandwidth required for 40 Gb/s (D)QPSK with 7% overhead for FEC.

First, the serial high speed data channel is parallelized into N low speed parallel data sub-channels. Each path is mapped using QPSK and presented to the input of an IFFT processor. A real-valued waveform, up-sampling and up-conversion to a frequency of $f_{RF} = 1.5 \cdot B_{OFDM} = 32.1$ GHz are generated by appropriate zero-padding and complex conjugate extension. Finally, the cyclic prefix is added. The resulting signal is modulated onto an optical carrier by a MZM. A SSB optical filter of B_{OSSB} =70 GHz bandwidth is used to suppress the lower sideband. The optical transmission line consists of 8 spans of 80 km of standard single-mode fiber with a dispersion coefficient of 17 ps/(nm km). Span loss is compensated for by means of inline amplifiers. For the receiver, a variable optical attenuator (VAO) in front of the optical preamplifier allows for optical signal-to-noise ratio (OSNR) tuning. The noise of the optical amplifier is limited in bandwidth by means of an optical filter with bandwidth B_{OSSB}. An electrical filter with B_e=60 GHz models the bandwidth of the electrical circuit. OFDM demodulation is performed including the removing of CP, S/P conversion, FFT, post detection OFDM equalization, symbol de-mapping and P/S conversion.

A. Cyclic Prefix and Raw Data rate

The length of the CP is chosen long enough such that there is no dispersion-induced interference from one OFDM symbol to the next one. By simulation, a value of T_{CP} =12 ns is found. A raw data rate (after FEC decoding) of 20 Gb/s, 26.7 Gb/s, 30 Gb/s and 32 Gb/s is obtained for N=256, 512, 1024 and 2048, respectively. However, accepting slight interference between the OFDM symbols will allow for decreasing the length of CP and the raw data rate will approach 40 Gb/s without significant degradation.

B. MZM Nonlinearity

The MZM is biased at quadrature point where the power transfer characteristic is linearizable (see fig. 3). By means of low modulation depth, the nonlinear distortions due to the MZM can be made arbitrarily small. This results in low ratio of useful power to carrier power, i.e. the sensitivity is low. Hence, modulation depth is a compromise between these constraints. Fig. 8 shows results for back-to-back transmission obtained by Monte-Carlo simulation.

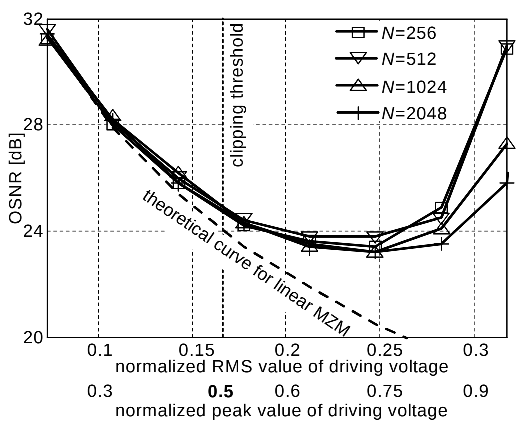

Fig. 8. Required OSNR for BER=10^{-3} as function of driving voltage swing.

The OSNR for BER=10^{-3} is plotted vs. normalized driving voltage. The normalization is performed such that minimum and maximum optical output power are obtained for instantaneous input voltages of -0.5 and 0.5, respectively. Beyond these values, clipping occurs due to MZM characteristic. The OFDM signal is an analog signal having nearly Gaussian amplitude distribution [12]. In good approximation, the peak voltage is within an interval from plus to minus the triple of the RMS voltage. This relation is used to create the lower from the upper of the two horizontal axes. The clipping threshold obtained for a peak voltage of ±0.5 is given in the figure, too. Finally, the impact of MZM nonlinearity, which within the range of acceptable sensitivity obviously does not depend significantly on *N*, is identified by means of the dashed line.

C. *Fiber Nonlinearity*

Fig. 9 depicts the nonlinear performance of the fiber link. To investigate only one impairment at a time, the MZM is driven in the quasi-linear range with a normalized effective voltage swing of ≈0.15 resulting in a back-to-back sensitivity of ≈25.5 dB. For low values of launch power, figure 3 shows the robustness of OOFDM towards fiber dispersion, as the OSNR penalty achieved with ≈11000 ps/nm accumulated dispersion is negligible. In the nonlinear regime, however, penalty increases rapidly. Beyond 8 dBm fiber launch power, the BER does not fall below 10^{-3} due to strong signal distortion.

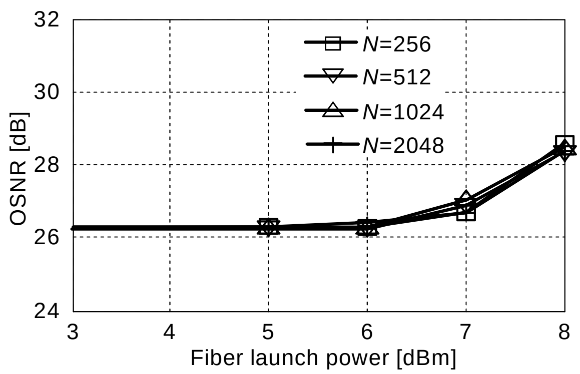

Fig. 9. Required OSNR for BER=10^{-3} as function of fiber launch power.

The optical power consists of a strong DC component and a weaker AC component carrying the OFDM-signal. Since only the AC component results in signal distortion [13], the acceptable launch power found in this contribution is higher than for CO-OFDM. Nevertheless, for CO-OFDM this is made up by higher sensitivity such that lower launch power is sufficient.

Obviously, the result does not depend on *N*, although increasing *N* decreases the separation between the sub channels, and fiber nonlinearity is expected to cause stronger intermodulation products known as Cross-Phase Modulation and Four-Wave-Mixing. However, with increasing *N* the power per subchannel is decreased. Apparently, both aspects cancel out each other to result in equal performance for all *N*.

VI. CONCLUSION

OOFDM is shown to be an efficient modulation format for long-haul optical transmission systems. Obviously, OOFDM is quite robust towards the specific nonlinear impairments in fiber-optic transmission systems and therefore it seems as if in contrast to mobile communications there is no upper limit for *N* from point of view of system performance. Nevertheless, OFDM is still a very young research field for optical transmission engineering. Well known techniques like channel estimation and peak power reduction are just awaiting to be implemented and adapted to the requirements of the optical channel.

VII. REFERENCES

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