

100-Gb/s Transmission Using Orthogonal Frequency-Division Multiplexing

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Abstract—The possibility of 100-Gb/s transmission over 25-GHz bandwidth using orthogonal frequency-division multiplexing (OFDM) is demonstrated. It is shown that 100-Gb/s transmission over 3840 km can be achieved using single-sideband quadrature-phase-shift keying OFDM transmission and low-density parity-check codes.

Index Terms—100-G Ethernet, high-speed optical transmission, optical communications, orthogonal frequency-division multiplexing (OFDM).

I. INTRODUCTION

ETHERNET was initially introduced as a communication standard for short-distance connection of hosts in a local area network (LAN) [1]. Due to low cost, high speed, and simplicity compared to other protocols, it has rapidly evolved, and has already been used in campus-size distance connections, and beyond, in metropolitan area networks [1], [2]. The network interface cards for 1- and 10-Gb/s Ethernet are already commercially available [2]. Traditionally, the Ethernet data rates have grown in 10-Gb/s increments, so the data rate of 100 Gb/s is being envisioned as the speed of the next generation of Ethernet [1]–[3]. The 100-Gb/s all-electrically time-division-multiplexed (ETDM) transponders are becoming increasingly important [3]–[6] because they are viewed as a promising technology that may be able to meet speed requirements of the new generation of Ethernet. Despite the recent progress in high-speed electronics [6], ETDM modulators and photodetectors are still not widely available, so that alternative approaches to achieving a 100-Gb/s transmission using commercially available components and differential quadrature-phase-shift keying (QPSK) is of great current interest [4].

In this letter, we propose an alternative technique to QPSK and 100-Gb/s ETDM, which allows us to achieve a 100-Gb/s optical transmission using commercially available components. It is based on the orthogonal frequency-division multiplexing (OFDM) [7]. OFDM is a special case of multicarrier transmission in which a single information-bearing stream is transmitted over many lower rate subchannels. It has been used for digital audio broadcasting [7], high-definition television (HDTV) terrestrial broadcasting [8], in high bit-rate digital subscriber line, asymmetric DSL and very high data rate DSL [7], IEEE 802.11, high-performance LAN type 2 (HIPERLAN/2) and multimedia mobile access communications wireless LANs [7], radio-over-

fiber-based networks [9], and for free-space optics communications [10]. OFDM offers good spectral efficiency and high immunity to chromatic dispersion. Our OFDM system has 64 subcarriers, and a bandwidth of 25 GHz. Fifty of these carriers are used for carrying 2×1 Gb/s Ethernet traffic using either QPSK or 16-quadrature-amplitude modulation (16-QAM), and the remaining 16 subcarriers are used for transmission of pilot signals and for the forward-error correction (FEC) overhead. We show that four pilots are sufficient to mitigate the influence of SPM, which means that an aggregate capacity of 120 Gb/s is possible.

II. 100-Gb/s TRANSMISSION USING OFDM

The basic OFDM transmitter and receiver configurations are given in Fig. 1(a) and (b), respectively. b_i 1-Gb/s data streams are mapped into a two-dimensional signal point from a 2^{b_i} -point signal constellation such as QAM, which is considered in this letter. The complex-valued signal points from all K subchannels are considered as the values of the discrete Fourier transform (DFT) of a multicarrier OFDM signal. The symbol interval length in an OFDM system is $T = KT_s$, where T_s is the symbol-interval length in a single-carrier system. By selecting K , the number of subchannels, sufficiently large, the OFDM symbol interval can be made much larger than the dispersed pulsewidth in a single-carrier system, resulting in an arbitrary small intersymbol interference. The OFDM symbol, shown in Fig. 1(c)–(d), is generated as follows: N_{QAM} input QAM symbols are zero-padded to obtain N_{FFT} input samples for inverse fast Fourier transform (IFFT), the N_{guard} samples are inserted to create the guard interval T_{guard} , and the OFDM symbol is multiplied by the window function (raised cosine function is used in [7], however, the Kaiser, Blackman-Harris, and other window functions are also applicable). The purpose of cyclic extension is to preserve the orthogonality among subcarriers even when the neighboring OFDM symbols partially overlap due to dispersion, and the purpose of the windowing is to reduce the out-of-band spectrum. The cyclic extension, illustrated in Fig. 1(c), is done by repeating the last $N_{\text{guard}}/2$ samples of the effective OFDM symbol part (of duration T_{FFT} with N_{FFT} samples) as the prefix, and repeating the first $N_{\text{guard}}/2$ samples (out of N_{FFT}) as the suffix. (Notice that windowing is more effective for smaller numbers of subcarriers.) For example, for QPSK OFDM transmission $b_i = 2$ 1-Gb/s streams create a QPSK signal constellation point; with 50 subcarriers carrying 2 Gb/s, the aggregate rate of 100 Gb/s is achieved. After a digital-to-analog conversion and RF up-conversion, the OFDM signal is driven to the Mach-Zehnder modulator (MZM) and then transmitted over the fiber. The dc component is inserted to be able to recover the QAM symbols incoherently. It is assumed that 50% of the total launched power (observed in electrical domain) is allocated for the transmission of carrier. To improve the

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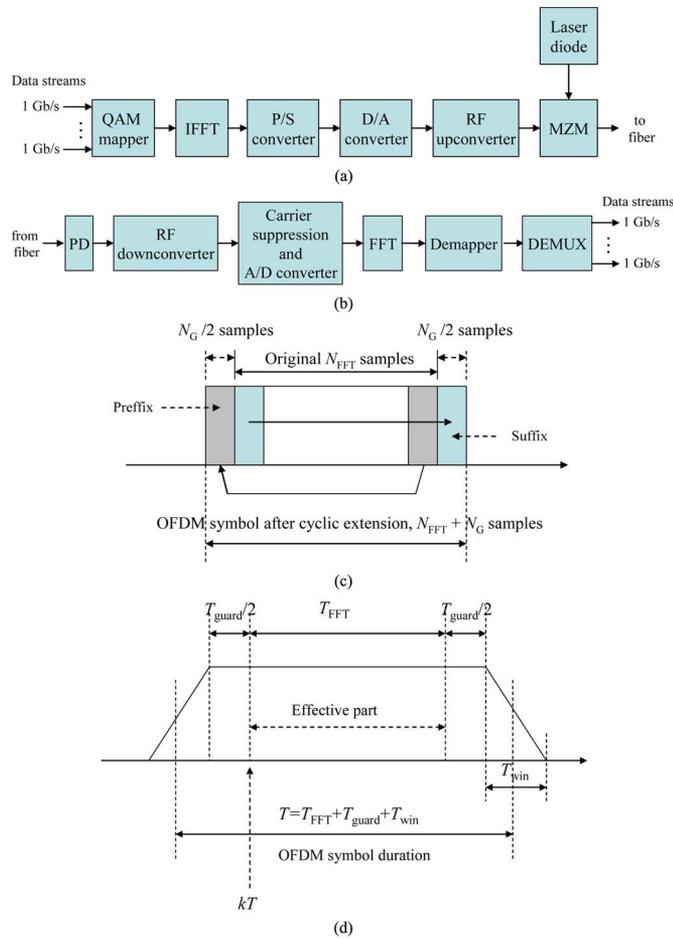


Fig. 1. (a) Transmitter and (b) receiver configurations; (c) OFDM symbol cyclic extension; (d) OFDM symbol after windowing. (Color version available online at <http://ieeexplore.ieee.org>.)

power efficiency a single-sideband (SSB) OFDM transmission is achieved. The information is imposed by modulating the electrical field of continuous-wave laser beam by using the OFDM signal as RF input of an MZM. At the receiver side, after the photodetection (PD), RF down-conversion and carrier suppression, the received signal is demodulated by computing the DFT.

For demonstration purposes, the power spectral densities (PSDs) after MZM are shown in Fig. 2(a) and (b) for double-sideband (DSB) transmission, and SSB transmission, respectively. The PSD at photodetector output for SSB transmission is shown in Fig. 2(c). The in-phase component of RF signal after up-conversion is given in Fig. 2(d), and shows that MZM operates in linear regime. The OFDM signal bandwidth is set to 25 GHz, the number of subchannels is set to $N_{QAM} = 64$, FFT/IFFT is calculated in $N_{FFT} = 128$ points, RF carrier frequency is set to 60 GHz, the bandwidth of optical filter is set to 120 GHz, and the total averaged launched power is set to 0 dBm. One hundred data strings carrying 1-Gb/s Ethernet traffic are QPSK or 16-QAM modulated, and transmitted on 50 subcarriers. The remaining 14 subcarriers are used for the transmission of pilots and FEC overhead. The guard interval is obtained by cyclic extension of $N_{guard} = 2 \times 16$ samples as explained above, and the windowing ($N_{win} = 2 \times 16$ samples) is based on Blackman-Harris windowing function.

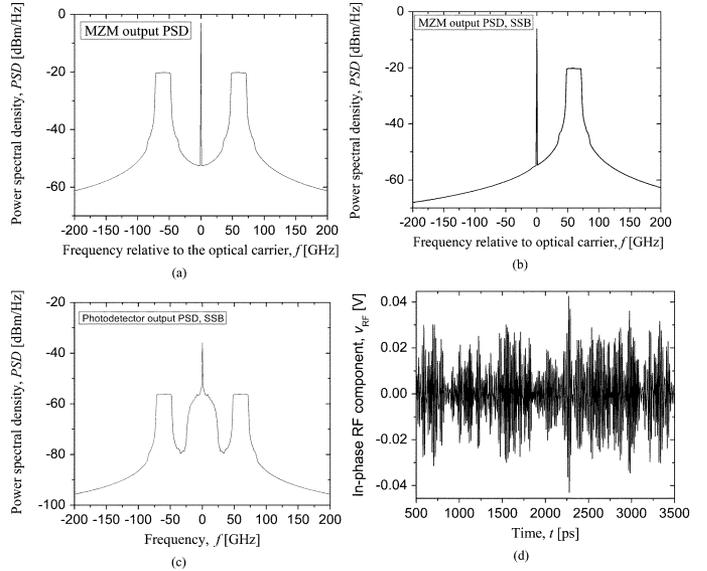


Fig. 2. PSD for (a) DSB and (b) SSB transmission. (c) PD output PSD for SSB transmission. (d) In-phase RF up-conversion waveform.

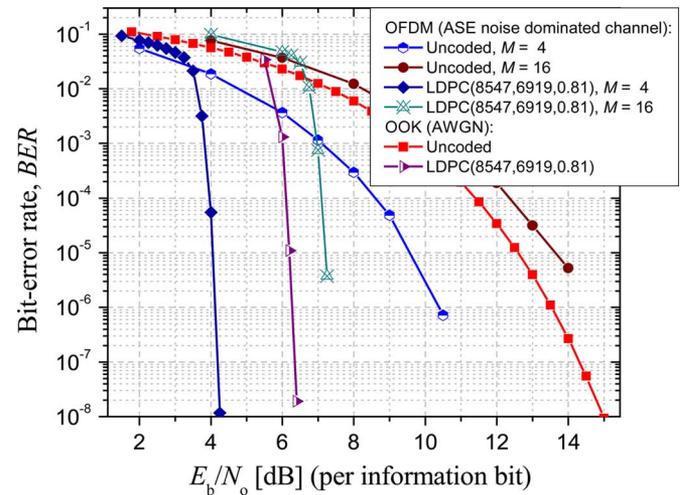


Fig. 3. BER of OFDM system versus OOK for ASE noise dominated channel. (Color version available online at <http://ieeexplore.ieee.org>.)

Fig. 3 shows the comparison of the bit-error-rate (BER) performances of the ON-OFF keying (OOK) system and the OFDM transmission over the amplified spontaneous emission (ASE) noise dominated channel. Because the OFDM is essentially an RF coherent scheme, it provides an initial 3-dB improvement compared to OOK. However, an initial 3-dB advantage is lost due to transmission of dc bias. Moreover, for the same launched powers (into fiber), the energy per bit for return-to-zero (RZ)-OOK is significantly larger than that of OFDM. This is the only way to keep fiber nonlinearities reasonably low, and to allow MZM and RF amplifier to operate in the linear regime. The comparison is done in the electrical domain (see [7] for definition of signal-to-noise ratio) because the concept of optical signal-to-noise ratio is not straightforward to define for OFDM waveforms [see Fig. 2(d)]. The FEC is based on the low-density parity-check (LDPC) (8547, 6919) code of code rate 0.81 proposed by the authors in [11]. As it has been shown in [11], the employed LDPC code does

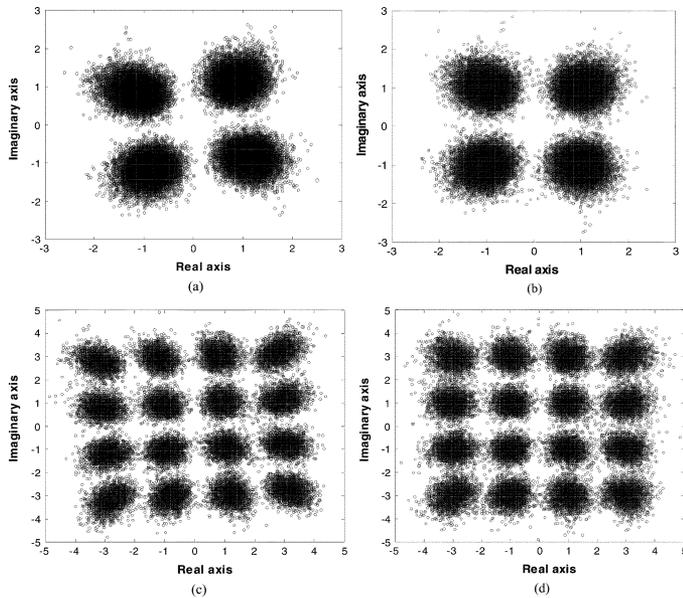


Fig. 4. Received signal constellation for QPSK SSB transmission after 20 spans: (a) before phase correction, (b) after phase correction. The received signal constellation for 16-QAM SSB transmission after 10 spans: (c) before phase correction, (d) after phase correction. Average launched power is set to -3 dBm, and erbium-doped fiber amplifier noise figure to 6 dB.

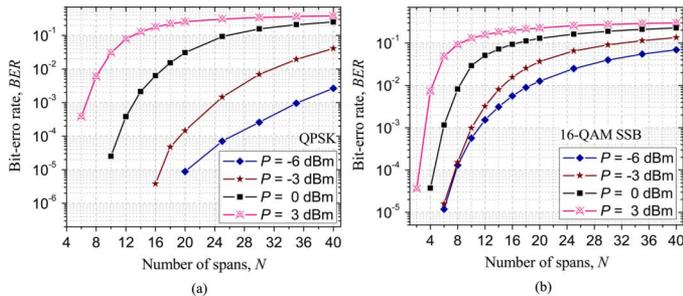


Fig. 5. Uncoded BER versus number of spans for SSB OFDM transmission and (a) QPSK, (b) 16-QAM modulation, for different launched powers (P). (Color version available online at <http://ieeexplore.ieee.org>.)

not exhibit error-floor in the region of interest for 100-Gb/s Ethernet (below 10^{-12}). The QPSK OFDM combined with LDPC coding provides the coding gain improvement of more than 2 dB over the LDPC coded RZ-OOK at BER of 10^{-8} .

III. PERFORMANCE ANALYSIS AND CONCLUSION

The results of simulation in the presence of Kerr nonlinearities and ASE noise are given in Figs. 4 and 5. The dispersion map is composed of N spans of length $L = 120$ km, consisting of $2L/3$ km of D_+ fiber followed by $L/3$ km of D_- fiber, with precompensation of -1600 ps/nm and corresponding post-compensation. D_+ fiber has a dispersion of 20 ps/(nm·km), a dispersion slope of 0.06 ps/(nm²·km), an effective area equal to 110 μm^2 , and loss equal to 0.19 dB/km. D_- fiber has a dispersion of -40 ps/(nm·km), a dispersion slope of -0.12 ps/(nm²·km), an effective area equal to 30 μm^2 , and loss equal to 0.25 dB/km. The nonlinear Kerr coefficient is set

to 2.6×10^{-20} m²/W in both types of fibers. The dispersion map is chosen in such a way to increase the total transmission distance. For terrestrial applications, the total transmission distance is determined as $N \times 80$ km, since the dispersion compensating fiber is already included in the optical repeater.

The influence of Kerr nonlinearities is illustrated in Fig. 4 for QPSK SSB transmission [Fig. 4(a) and (b)], and 16-QAM SSB transmission [Fig. 4(c) and (d)]. The phase noise introduced by the self-phase modulation (SPM) causes the rotation of the constellation diagram [Fig. 4(a) and (c)]. By using the phase correction based on four pilot tones, the phase rotation due to SPM can be completely eliminated, as shown in Fig. 4(b) and (d). For worse dispersion maps, the larger number of pilot tones is required. Notice that after 20 spans (2400 km), the received constellation diagram for QPSK SSB transmission is still clear.

The BER curves for the uncoded 100-Gb/s OFDM SSB transmission using QPSK or 16-QAM are shown in Fig. 5(a) and (b), respectively. From Fig. 5(a) (for launched power of -3 dBm) it can be concluded that 100-Gb/s transmission over 3840 km is possible using OFDM and LDPC codes [11] with threshold BER of 10^{-2} , which cannot be achieved using the state-of-the-art ETDM high-speed electronics operating at 100 Gb/s [5].

In conclusion, we demonstrated that 100-Gb/s transmission may be realized by using the SSB OFDM with 64 subcarriers and the 25-GHz bandwidth. OFDM is shown to be an efficient modulation format for long-haul transmission systems that provides a number of advantages: 1) increasing the transmission distance, 2) improvement of spectral efficiency, and 3) simplification of the dispersion compensation engineering. It is demonstrated by simulations that 100-Gb/s transmission over 3840 km can be achieved using single-sideband QPSK OFDM transmission, supplemented with LDPC codes, and commercially available components.

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