Orthogonal Frequency Division Multiplexing over Multimode Optical Fibers

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Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation technique which is already widely employed in both wireless communication systems (WLAN, DVB-T, WiMAX) as well as wireline systems (ADSL, VDSL, PLC). Due to highly increasing speeds and lower costs of electronics, OFDM has recently also gained much interest in optical communication systems. In this paper, we will discuss the use of OFDM to counter the problem of multipath propagation in mutimode fibers (MMF) and the simultaneous use of spectrally efficient modulation schemes such as quadrature amplitude modulation (QAM) to increase the capacity of MMF transmission links.

Introduction

Rapidly increasing data traffic has pushed the demand for high-capacity and low-cost optical fiber-based networks for use in local area networks (LAN), such as enterprise in-building and datacenter backbones. In contrary to long-haul transmission links, multimode fiber (MMF) is used for the vast majority of the optical LAN links [[1]]. Unlike single-mode fiber, the large core diameter (50 - 62.5 µm) of the MMF allows large alignment and dimensional tolerances in transceiver components, thereby lowering installation, maintenance, and component costs. Therefore, high-speed networking standards like Gigabit Ethernet, Fibre Channel, and 10 Gigabit Ethernet all include the MMF as a transmission medium.

With the growth of bandwidth-intensive applications like IPTV, HDTV, as well as data processing in the medical industry, further increase of the capacity in LAN backbones and server interconnects has to be considered. Although investigations on transmission speeds higher than 10 Gb/s over MMF have already been reported [[2]-[4]], these are however either based on novel high-bandwidth components (15-29 GHz) [[2],[3]], external modulation [[3]], or the use of single mode components [[4]], which is not practical and can cause modal noise due to spatial filtering.

With multicarrier transmission techniques, where a high data-rate stream is split into many lower-rate substreams, it has been shown that high-speed data transmission in dispersive channels such as MMF can be possible [[5]-7]. Additionally, by employing higher-order modulation formats like quadrature amplitude modulation (QAM), the available bandwidth can be utilized efficiently, allowing the use of conventional low-bandwidth transceivers.

Orthogonal Frequency Division Multiplexing

An efficient digital implementation of multicarrier modulation is orthogonal frequency division multiplexing (OFDM) [8], which is already widely employed in many wireless communications standards such as WLAN, WiMAX, and DVB-T, and in copper-based xDSL systems such as asynchronous digital subscriber line (ADSL) and very high data rate digital subscriber line (VDSL). Nowadays, analog-to-digital (ADC) and digital-to-analog converters (DAC) with speeds ≥ 10 GS/s are already commercially available. Due to such increasing speeds and lower costs of electronics, OFDM has the potential for low-cost implementation in combination with existing MMF transceivers. It is therefore a promising solution for low-cost, robust and high-capacity MMF LAN links operating at speeds of 10 Gb/s and beyond.

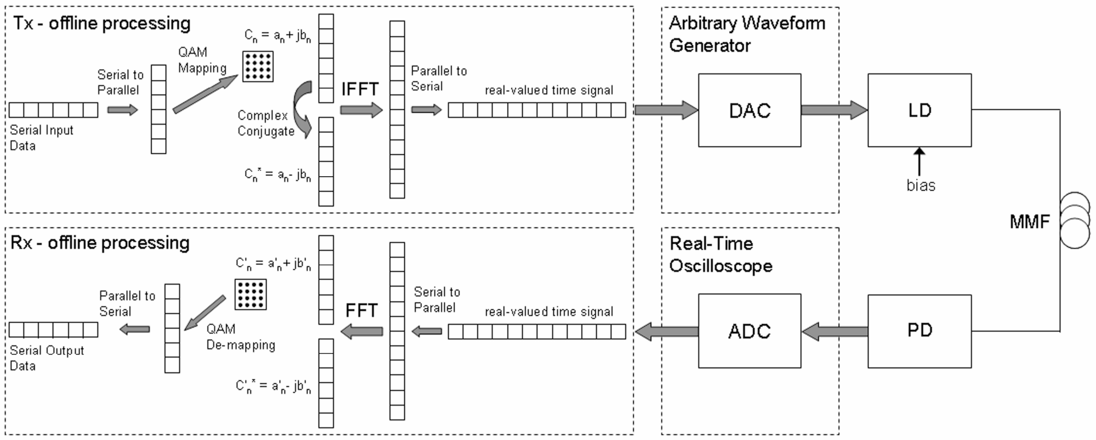

Fig. 1. Schematic representation of OFDM and experimental setup. DAC: digital-to-analog converter; LD: laser diode; PD: photodetector; ADC: analog-to-digital converter.

The principle of OFDM is shown on the left-hand side of Fig. 1. An incoming data sequence is divided into N parallel subcarrier data streams. Each subcarrier stream is then mapped onto complex values C_n according to an M-ary quadrature amplitude modulation (M-QAM) constellation mapping, where $n = 0, 1, \ldots, N-1$ denotes the subcarrier number. The modulator and demodulator of an OFDM system are implemented by use of the Fast Fourier Transform (FFT).

Usually, the inverse FFT (IFFT) is used as the modulator. In the case of OFDM, using the N information symbols C_n ($n = 0, 1, \ldots, N-1$) as input values for an N-point IFFT, the resulting output multicarrier OFDM sequence s_k is

$$s_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} C_n e^{j2\pi k \frac{n}{N}}, \quad k = 0, 1, \ldots, N-1, \tag{1}$$

where s_k is a complex-valued signal consisting of N points. This signal has to be modulated onto an RF carrier prior to transmission, which results in the use of extra analog components.

However, it is also possible to omit the use of an RF carrier by generating a real-valued signal s_k. This is realized by using a $2N$-point IFFT, where the input values must satisfy the Hermitian symmetry property

$$C_{2N-n} = C_n^*, \tag{2}$$

where $n = 1, 2, \ldots, N-1$ and $\mathrm{Im}\{C_0\} = \mathrm{Im}\{C_N\} = 0$. The Im{.} operator denotes the imaginary part. Expressed in words, in order to get a real-valued time-domain multicarrier OFDM sequence for N subcarriers at the output of the IFFT, the transform has to be carried out with $2N$ points with the condition that the second half of the $2N$

IFFT-points has to be the complex conjugate of the first half. Additionally, subcarriers 0 and N must be real-valued. Following this, the output of the $2N$-point IFFT is

$$s_k = \frac{1}{\sqrt{2N}} \sum_{n=0}^{2N-1} C_n e^{j2\pi k \frac{n}{2N}}, \quad k = 0, 1, ..., 2N-1, \tag{3}$$

where s_k is now a real-valued signal consisting of $2N$ points. This kind of real-valued OFDM modulation is also known as discrete multitone modulation [7]. The resulting $2N$-point sequence s_k ($k = 0, 1, \ldots, 2N-1$) corresponds to the discrete time samples of the real-valued multicarrier OFDM time signal $s(k\frac{T}{2N})$, which results from parallel-to-serial conversion after the IFFT:

$$s(k\tfrac{T}{2N}) = \frac{1}{\sqrt{2N}} \sum_{n=0}^{2N-1} C_n e^{j2\pi n \frac{k}{2N} T}, \quad k = 0, 1, ..., 2N-1, \tag{4}$$

where T depicts the time duration of the OFDM signal. This real-valued, $2N$-point time sequence $s(k\frac{T}{2N})$, with $k = 0, 1, \ldots, 2N-1$, which is also called an OFDM frame, results from every $2N$-point IFFT computation. At the receiver, demodulation of the OFDM frames is done by using a $2N$-point FFT. The computation is exactly the inverse of the IFFT. For every received OFDM frame, demodulation results in

$$C_n = \frac{1}{\sqrt{2N}} \sum_{k=0}^{2N-1} s_k e^{-j2\pi k \frac{n}{2N}}, \quad n = 0, 1, ..., 2N-1. \tag{5}$$

It can be seen that the information symbols C_n are recovered after demodulation using the FFT.

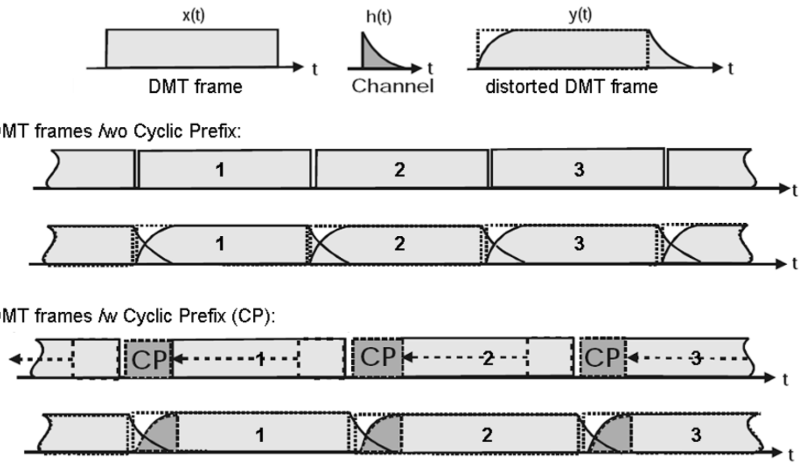

Fig. 2. Combating multipath dispersion using cyclic prefix (CP).

Multipath propagation in MMF

One important reason to use OFDM is the advantage to counter multipath delay spread with the cyclic prefix (CP). Due to the large number of propagating modes, the MMF channel is analogous to a multipath wireless channel. Therefore, in the case of optical OFDM transmission over MMF, the CP can be used to counter the effects of modal dispersion [6,7]. The CP is essentially a copy of the last fraction of a DMT frame which is inserted in front of the frame (see Fig. 2). Usually, its length is chosen to be larger than the largest delay spread expected from a transmission channel such that dispersion will not affect the actual DMT frame to be received. This property is schematically illustrated in Fig. 2. It therefore guards against intersymbol interference between two consecutive DMT frames and ensures the cyclic convolution nature of a DMT frame, so that demodulation with the FFT doesn't result in intercarrier interference. However, this comes at an expense of additional redundancy.

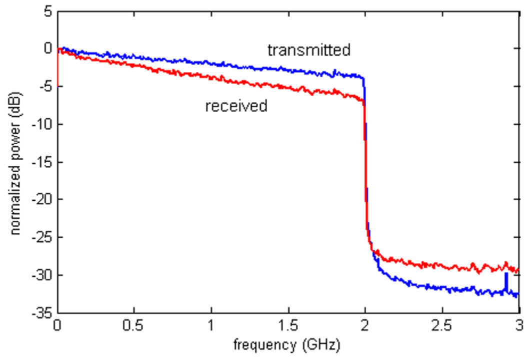

Fig. 3. Transmitted and received electrical OFDM signal spectra.

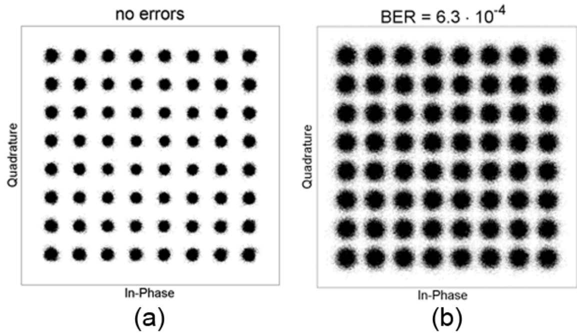

Fig. 4. Received constellation diagrams of all 508 carriers together (a) electrical back-to-back (b) after transmission over 100 m of POF

Experimental results

Fig. 3 and 4 show some experimental results of an OFDM system over 100 m of polymer optical fiber (perflourinated, graded-index, 120-µm core-diameter) at a transmission bit-rate of 11.9 Gb/s. The experimental setup is depicted in Fig. 1. Due to modal dispersion, the -3dB-bandwidth of the system is about 1 GHz. 508 out of a total of 512 subcarriers are used for data transmission, all with 64-QAM mapping. The used transmission bandwidth is only 2 GHz, resulting in a spectral efficiency of 5.3 bit/s/Hz. 10-Gb/s transmission is impossible using standard on-off-keying modulation. Such results demonstrate the potential of OFDM over optical fibers, especially for MMF.

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