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Discrete Multitone Modulation for High-Speed Data Transmission over Multimode Fibers using 850-nm VCSEL

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Abstract: 30-Gb/s transmission over 500 m and 28-Gb/s over 1 km of multimode fiber (with 850-nm multimode VCSEL and large-area photodetector) is experimentally demonstrated by use of discrete multitone modulation (DMT) combined with bit-loading algorithm.

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1. Introduction

By using discrete multitone modulation (DMT), it has been shown that high-speed data transmission in dispersive channels such as MMF can be possible [1-3]. Additionally, due to modulation formats like quadrature amplitude modulation (QAM), the available bandwidth can be used efficiently, allowing the use of conventional low-bandwidth MMF transceivers. Derived from the more general orthogonal frequency division multiplexing, DMT is a baseband version that is already applied in large scale in ADSL, VDSL, and powerline communication systems, proving that low-cost implementation in combination with existing MMF transceivers is possible. It is therefore a promising solution for low-cost, robust, and high capacity MMF LAN links at speeds beyond 10 Gb/s.

2. Discrete Multitone Modulation using Bit-Loading

An important feature of DMT is the possibility to allocate the number of bits per subcarrier according to its corresponding signal-to-noise ratio (SNR), typically known as bit-loading. Bit-loading can be divided into two categories: rate-adaptive and margin-adaptive. Rate-adaptive algorithms maximize the bit rate for a fixed bit-error ratio (BER) and given power constraint, while margin-adaptive algorithms minimize the BER for a given bit rate. In this paper, rate-adaptive bit-loading will be considered in order to maximize the transmission rate over MMF.

The algorithm of rate-adaptive bit-loading is a reformulation of the Shannon capacity formula [4] and can be expressed as a problem of maximizing the total achievable bit-rate b :

$$\max_{E_n} (b) = \max_{E_n} \left(\sum_{n=1}^{\hat{N}} \frac{1}{2} \log_2 \left(1 + \frac{SNR_n}{\Gamma} \right) \right) = \max_{E_n} \left(\sum_{n=1}^{\hat{N}} \frac{1}{2} \log_2 \left(1 + \frac{E_n \cdot g_n}{\Gamma} \right) \right), \quad (1)$$

which is the sum of the bit-rates of the $\hat{N}$ subcarriers used for DMT transmission. In (1), $SNR_n = E_n \cdot g_n$ is the SNR per subcarrier, where g_n represents the subcarrier SNR when unit energy is applied, Γ is the difference (gap) between the SNR needed to achieve maximum (Shannon) capacity and the SNR to achieve this capacity at a given bit error probability, and E_n is the allocated energy per subcarrier, subject to an energy constraint given by:

$$\sum_{n=1}^{\hat{N}} E_n = E_{tot}. \quad (2)$$

E_{tot} is the fixed total available energy for transmission. The problem is now to find the optimum number of bits per subcarrier, and the corresponding energy distribution per subcarrier E_n , in order to maximize the bit-rate. From (1) and (2), it can be seen that $\hat{N}$, the number of subcarriers used to achieve maximum bit-rate, doesn't need to correspond to the total number of available DMT subcarriers N . Therefore, the optimal solution is not always to use all available subcarriers to transmit information.

The solution to this bit-rate maximization problem, based on the use of Lagrange multipliers, is commonly known as water-filling. In [5], Chow showed that this water-filling solution can be computed numerically for practical use by his proposed finite bit-loading algorithm. This algorithm is based on (1) and starts by discarding the subcarriers that are least energy-efficient from information transmission, and redistributing the energy to more efficient subcarriers to support higher data rates. The non-integer number of allocated bits per subcarrier are then rounded to the nearest integer and the corresponding energy is in- or decreased to support the newly-allocated

number of bits at the same performance. Chow's algorithm has been shown to achieve near-optimum performance [4],[5] and will be used in the following to compute rate-adaptive bit-loading for the DMT over MMF measurements.

Fig. 1. Measurement setup for DMT over MMF transmission. Tx: transmitter; Rx: receiver; DAC: digital-to-analog converter; ADC: analog-to-digital converter; PD: photodetector.

Fig. 2. Measured 10-Gb/s eye diagram after transmission over 1000 m of MMF using 850-nm VCSEL. Inset: Measured optical spectrum of VCSEL from 851 nm to 856 nm.

3. Experimental Results and Discussion

Fig. 1 shows the setup of the DMT transmission system. The optical transmitter used is a commercial, analog-driven, 850-nm multimode VCSEL, specified for up to 10-Gb/s operation with on-off keying modulation. Two 500-m spools of MMF (MaxCap550, OM4, 4700 MHz-km effective bandwidth at 850 nm) were used for the experiments. The two spools are connected together in the case of transmission over a distance of 1000 m. The photodetector (PD) with integrated electrical amplifier consists of a 25- μ m GaAs PIN diode, pigtailed to a 62.5- μ m MMF via a GRIN lens. The optical output power of the VCSEL is fixed at -0.7 dBm and the detected power levels after 500 m and 1000 m of MMF are -1.9 dBm and -3.1 dBm respectively. Fig. 2 depicts the measured 10-Gb/s eye diagram using the setup with 1000 m of MMF. The optical spectrum (from 851 to 856 nm) of the VCSEL is shown in the inset, where the different modes can be clearly distinguished.

Fig. 3. (a) Evaluated SNR per subcarrier after transmission over 500 m and 1000 m of MMF, prior to bit-loading. (b) Resulting SNR per subcarrier, after bit-loading. (c) Bit-loading parameters for 500 m MMF. (d) Bit-loading parameters for 1000 m MMF.

For DMT transmission, a computer is used to emulate the digital DMT modulator and demodulator. An arbitrary waveform generator (AWG) is then used to generate the corresponding analog DMT time signal at a sampling speed of 20 GS/s. At the receiver, the analog DMT signal after the PD is captured with a real-time oscilloscope at 20 GS/s and sent back to the computer for demodulation and evaluation. A total of 256 subcarriers are available for DMT transmission, ranging from 0 to 10 GHz. Prior to bit-loading, a pilot DMT signal is sent over the system to determine the available signal-to-noise ratio per subcarrier, as shown in Fig. 3a. It is apparent that the system bandwidth limits the transmission bandwidth to approximately 6 GHz. Fig. 3c and d show the results from Chow's bit-loading algorithm, for transmission over respectively 500 m and 1000 m of MMF. The desired bit-error-ratio (BER) is set to $1 \cdot 10^{-3}$, which corresponds to an SNR gap Γ of approximately 7.2 dB. The bit-loading results show that only 150 out of a total of 256 subcarriers should be used to achieve maximum bit-rate, where some subcarriers are allocated 7 bits of information (128-QAM modulation). Due to the power allocation, the measured SNR per subcarrier after bit-loading are stair-case-shaped as depicted in Fig. 3b.

Fig. 4 shows the transmitted and received electrical DMT signal spectra for transmission over 1000 m of MMF. The curve in Fig. 4c is obtained when the VCSEL is turned on with a fixed bias, without any modulation. This shows the relative intensity noise (RIN) spectrum of the transmission system, resulting from the competition of different modes of the VCSEL [6]. This RIN also affects the channel SNR, which can be noticed as a dip at approximately 3.5 GHz in the evaluated SNR curves in Fig. 3a. Nevertheless, DMT with bit-loading adapts well to this loss of SNR. Fig. 5a and b show the BER per subcarrier after evaluation of 23000 received DMT symbols, equaling a total of 16 million bits. The total average BER for 500-m and 1000-m transmission are $7 \cdot 10^{-4}$ and $1 \cdot 10^{-3}$ respectively. From the bit-loading parameters, it can be calculated that 30-Gb/s is achieved over 500 m and 28-Gb/s over 1000 m of MMF using DMT with bit-loading. After deduction of 1.5 % of cyclic prefix, 2 % of pilot symbols, and 7 % of FEC overhead, the net transmission bit rate equals 27.2 Gb/s over 500 m and 25.4 Gb/s over 1000 m of MMF. Fig. 5c and d depict the highest received constellation diagrams employing 128-QAM after transmission over MMF, as an indication of the received signal quality.

4. Conclusions

30-Gb/s (27.2-Gb/s net) transmission over 500 m and 28-Gb/s (25.4-Gb/s net) transmission over 1000 m of MMF are experimentally demonstrated with a commercial 850-nm multimode VCSEL and a commercial 25- μ m photodetector with GRIN lens. This is achieved by DMT modulation combined with Chow's rate-adaptive bit-loading algorithm for maximizing the bit-rate.

Fig. 4. Measured electrical spectra for (a) sent DMT signal, electrical back-to-back; (b) received DMT signal, after 1000 m MMF; (c) relative intensity noise of VCSEL.

Fig. 5. Measured BER per subcarrier for: (a) 500 m MMF, total averaged BER = $7 \cdot 10^{-4}$, (b) 1000 m MMF, total averaged BER = $1 \cdot 10^{-3}$. (c) Received 128-QAM constellations after 500 m MMF, (d) 1000 m MMF.

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