Differential signaling for low optical energy consumption in datacom optical interconnects

I. Roudas (1), B. R. Hemenway (1), M. S. Whiting (1), and R. R. Grzybowski (2)
(1) Corning Inc., Corning, NY 14831, USA; E-mail: {roudasi, hemenwaybr, whitingms }@corning.com
(2) Photonic Controls, 502 IST Ctr., Horseheads, NY 14845, USA; E-mail: rgrzybowski@photoniccontrols.com

Abstract: We propose the use of differential signaling based on parallel transmission of complementary M-ary PAM optical waveforms over fibers of approximately the same length, in conjunction with balanced direct detection, to reduce optical interconnect energy consumption.

1. Introduction

There is a growing consensus among the scientific community that a most important design issue for optical interconnects for high-performance computing and data centers is their overall energy consumption [1]. The purpose of this paper is to investigate the possibility of reducing the optical energy consumption of the aforementioned optical links by using M-ary differential signaling over multiple fibers. This technique is widely used for transmission of electronic signals over twisted pairs and ribbons of copper cables in input/output datacom interfaces, e.g., USB connections. Its optical communications analog was considered in the past for binary intensity modulation (IM)/direct-detection (DD) using differentially-driven VCSELs [2], [3] and analog optical links [4]. We propose here, for the first time, differential signaling using complementary M-ary pulse amplitude modulated (PAM) optical waveforms propagating over SMFs of approximately the same length and detected by balanced photodetectors. A key device for the proposed modulation format is the two-output Mach-Zehnder modulator [5], which lowers the transmitted optical power by 3-dB compared to its single-output counterpart. In the following, we describe alternative differential signaling transceiver architectures for the generation and detection of optical M-PAM waveforms and evaluate their performance.

2. Differential signaling transceiver architectures

Fig. 1(a) shows the block diagram of a representative M-ary differential signaling optical communications system. The transmitter consists of a CW semiconductor laser diode (SLD), followed by an external dual-electrode, two-output, Mach-Zehnder modulator, which is driven by a pseudo-random symbol sequence (PRSS). Either one or both outputs of the Mach-Zehnder modulator are activated depending on the modulating symbol. Two SMFs connect the outputs of the Mach-Zehnder modulator to a pair of balanced photodetectors. The signal at the output of the photodetectors is amplified, filtered, and compared to a zero current threshold in order to make a decision on the received symbol. The two SMFs must have approximately equal length so that the differential group delay between the two lines must be much smaller than the symbol period. Multicore fibers (MCFs) could be used to meet this requirement.

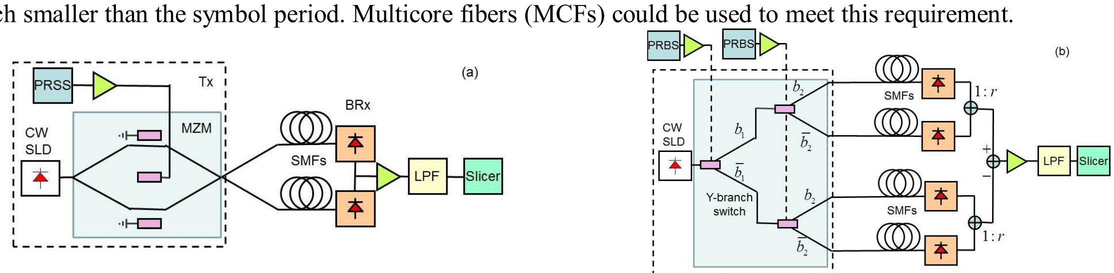

Fig. 1. (a) Short-haul optical link using M-ary PAM differential signaling; (b) Alternative transceiver implementation for differential QPAM based on a 1×4 ultrafast switch fabric as an optical modulator and two balanced receivers.

In Fig. 1(a), the electronic M-ary PRSS ($M = 2^k$ levels) can be synthesized by adding k binary bit-synchronous pseudo-random bit sequences (PRBS's) with bit rate equal to the symbol rate and unequal voltage ratios [6] such that the optical power levels generated at the output of the Mach-Zehnder modulator are equidistant. More specifically, assume that there is a differential phase delay $\phi(t)$ between the two branches of the Mach-Zehnder modulator. The instantaneous optical powers detected by the two photodiodes are $P_1(t) = \cos^2[\phi(t)/2]P_{in}$, $P_2(t) = \sin^2[\phi(t)/2]P_{in}$, respectively, where P_{in} is the average power of the CW optical signal at the input of the Mach-Zehnder modulator. The two balanced photodiodes are assumed to have identical responsivity R. Since the photodiodes are connected back-to-back, the total photocurrent at the output of the balanced receiver is

978-1-4673-5063-1/13/$31.00 ©2013 IEEE

$i_{tot}(t) = R[P_1(t) - P_2(t)] = R\{\cos^2[\phi(t)/2] - \sin^2[\phi(t)/2]\}P_{in} = RP_{in}\cos\phi(t)$. We assume $\phi(t) = \varphi_0 - \pi V(t)/V_\pi$, where V_π is the half-wave voltage of the Mach-Zehnder modulator and we set $\varphi_0=2\kappa\pi$, for simplicity.

For quaternary PAM (QPAM), the total photocurrent at the output of the balanced receiver should take discrete values from the set $RP_{in}\{-1,-1/3,1/3,1\}$. Therefore, $\cos\phi(t)\in\{-1,-1/3,1/3,1\}$. Inverting this trigonometric equation yields $\phi(t)\in\{0,1.23,1.91,\pi\}$rad. Moreover, we assume that the bias voltage $V(t)$ of the Mach-Zehnder modulator is composed of a DC component and the superposition of two synchronous binary bipolar waveforms with amplitudes $\alpha_k,\beta_k \in\{\pm1\}$, pulse shape *g(t)*, bit period *T*, and coefficient ratio *A:B*, i.e., $V(t) = V_\pi/2 + V_\pi/2\left[A\sum_k \alpha_k g(t-kT)+B\sum_k \beta_k g(t-kT)\right]$. Setting $A = 0.61$, $B = 0.39$, yields the desired set of values $\phi(t)\in\{0,1.23,1.91,\pi\}$rad.

Several alternative external modulator designs that utilize all the available power of the CW optical signal could be considered for optical generation of differential M-PAM optical signals. A transmitter setup that avoids the need of multilevel electronic waveforms at the transmitter (albeit at the expense of larger device count at the receiver) uses *m* binary waveforms $(m = \log_2 M)$ to control a 1×m ultrafast switch fabric acting as an optical modulator. The latter is composed of *m* stages of 1×2 Y-branch switches. The schematic shown in Fig. 1(b) is specific to QPAM but can be easily generalized for higher-order M-PAM signals (M>4). Each 1×2 Y-branch switch can stir the optical signal in either its upper or lower arm, depending on if the control signal is a ONE or a ZERO, respectively. The 1×2 Y-branch switches of each stage are controlled by a different binary sequence.

We assume that, at a specific bit interval, the two pseudorandom bit sequences (PRBSs) consist of the bits $b_1, b_2 \in\{0,1\}$, respectively. The complementary bits are denoted by $\bar{b}_1,\bar{b}_2$. Then, the instantaneous optical powers detected by the photodiodes are $P_1(t) = b_1^2 b_2^2 P_{in}/4$, $P_2(t) = b_1^2\bar{b}_2^2 P_{in}/4$, $P_3(t) = \bar{b}_1^2 b_2^2 P_{in}/4$, $P_4(t) = \bar{b}_1^2\bar{b}_2^2 P_{in}/4$. The total photo-current is $i_{tot}(t) = R\left[P_1(t)+rP_2(t)-rP_3(t)-P_4(t)\right]$. Setting $r = 1/3$ yields an ideal QPAM signal.

Next, it is instructive to compare the performance of the proposed M-ary PAM differential signaling, in terms of the required received average optical energy per bit, to the one of conventional M-ary IM/DD [7].

In the absence of noise, the samples of the photocurrent at the receiver output correspond to *M* distinct equidistant levels $I_1 - I_M$, where the distance between adjacent current levels is $2d$. Words of $m = \log_2 M$ bits are assigned to different photocurrent levels using Gray encoding [8]. Decision thresholds are at mid-point between successive levels.

In the absence of intersymbol interference and noise correlation at the sampling instant, it is possible to calculate the bit error probability $P_{e|b}$ of both conventional M-ary IM/DD [7] and M-PAM differential signaling [8] using the analytical expression $P_{e|b}=(M-1)\mathrm{erfc}\left[\sqrt{d^2/(2\sigma_n^2)}\right]/\left(M\sqrt{\log_2 M}\right)$, σ_n^2 is the noise variance, and $\mathrm{erfc}(z) = \left(2/\sqrt{\pi}\right)\int_z^\infty \exp(-t^2)dt$.

For M-PAM differential signaling, the current levels take discrete values from the set $I_m\in\{(2\ell-1-M)d\}$, $\ell=1,2,\ldots,M$, whereas for conventional M-ary IM/DD, the current levels take discrete values from the set $I_m\in\{2\ell d\}$, $\ell=0,2,\ldots,M-1$. The corresponding received average powers are the same in both cases $\bar{P}_{M-PAM}=\bar{P}_{M-IM/DD}=(M-1)d/R$. We conclude that both M-PAM differential signaling and conventional M-ary IM/DD [7] have the same receiver sensitivity. However, in the case of M-PAM differential signaling, the average transmitted power of the CW SLD is 3 dB lower compared to its conventional IM/DD counterpart since the optical power from both branches of the Mach-Zehnder modulator's output coupler is used. Notice that an increase in the number of levels induces an asymptotic optical energy/b penalty at very low error probabilities by $P_d = 10\log\left[(M-1)/\sqrt{\log_2 M}\right]$ compared to the binary case. For instance, the optical energy/b penalty to transition from binary to quaternary PAM is 3.26 dB.

In conclusion, the use of M-ary PAM differential signaling can decrease the optical energy consumption at the transmitter by a factor of 3 dB compared to conventional IM/DD links, while conveniently setting the decision threshold of the DD receiver to zero. For instance, using QPAM differential signaling, it is possible to exchange this 3-dB optical energy advantage in order to halve the symbol rate compared to conventional binary IM/DD. By generalizing the proposed concept, one could further reduce the transmitted optical power using multidimensional signaling [8] based on parallel transmission over multiple fibers. The choice of the most suitable modulation format depends on a trade-off among the transmitted optical power, the energy consumption of the transceiver electronics, and the equipment cost.

3. References

[1] M. Fields, *ECOC,* Torino, Italy, Sept. 2010.

[2] M. C. Olsen et al., *JLT*, Vol. 11, No. 7, pp. 1250–1262, 1993.

[3] P. Gui et al.*, JLT*, vol. 22, no. 9, pp. 2135–2148, 2004.

[4] D.A.I. Marpaung et al., *Intl. Top. Mtg. Micr. Photonics*, 2006.

[5] S. J. Spector et al., *Opt. Expr.*, Vol. 16, pp. 11027–11031, 2008.

[6] M. Seimetz, OFC, NWA4, Anaheim, CA, Mar. 2006.

[7] S. Randel et al., *JSTQE*, vol. 16, no. 5, pp. 1280–1289, 2010.

[8] J. G. Proakis, *Digital Communications*, McGraw-Hill, 2001.