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Bandlimited Power-Efficient Signaling for Intensity Modulation

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Abstract *A new, power-efficient signaling method for intersymbol interference-free transmission over the bandlimited intensity-modulation direct-detection channel is proposed. The method utilizes pulse-amplitude modulation with a sinusoidal bias function and is more power-efficient than previously known methods.*

Introduction

Intensity-modulation direct-detection (IM/DD) systems are a potential solution for low-cost, low-complexity optical communication links. In such systems, the information is encoded on the intensity of the transmitted optical signal by varying the driving current of a vertical-cavity surface-emitting laser, a laser diode, or a light-emitting diode at the transmitter. Direct detection is performed at the receiver by using a photodetector that generates an electrical current, proportional to the received optical power[1]. Applications of IM/DD systems include short-range optical links such as fiber-to-the-home, optical interconnects[2], and diffuse indoor wireless optical links[1]. An IM/DD system implies two major constraints on the transmitted electrical signal; it must be nonnegative, and for safety and energy consumption purposes, both average and peak optical power have to be within certain limitations[1].

Hranilovic investigated[3] intersymbol interference (ISI)-free transmission over a strictly bandlimited IM/DD channel for the first time. Pulse-amplitude modulation (PAM) schemes were designed using bandlimited ISI-free nonnegative Nyquist pulses such as the squared sinc (S2) pulse, which requires a bandwidth equal to the symbol rate. It was also shown that nonnegative bandlimited ISI-free root-Nyquist pulses do not exist. As an extension, new nonnegative Nyquist pulses were introduced[4], which provide a trade-off between the required optical power and the bandwidth. In 2012[5], a new modulation scheme for bandlimited ISI-free IM/DD systems was proposed, where a direct-current (DC) bias signal is added to the transmitted waveform in order to make it nonnegative. This approach improves the bandwidth efficiency, by reducing the required bandwidth below the symbol rate, and it also allows the usage of root-Nyquist pulses.

In this paper, we propose a more power-efficient signaling scheme by means of adding a time-varying bias to the transmitted PAM signal. The introduced bias is strictly bandlimited and it consists of a sinusoidal and a DC signal with optimized coefficients. The sinusoidal component of the bias can be used at the receiver to improve the symbol time recovery. By this scheme, up to 0.91 dB gains can be achieved in signal-to-noise ratio (SNR) compared to the previously best known signaling scheme at the same spectral efficiency, which is based on S2.

System Model

In the absence of optical amplification, the dominating noise sources are thermal noise and shot noise in the photodetector[6]. The IM/DD link can in this case be accurately modeled as a baseband additive white Gaussian noise (AWGN) channel with a nonnegative input signal[1]. Fig. 1 shows the passband model of a IM/DD system (top) and the corresponding baseband channel (middle). We construct the nonnegative transmitted intensity as a modified PAM signal

$$x^{+}(t) = f(t) + \sum_{k=-\infty}^{\infty} a_k p(t-kT), \tag{1}$$

where $a_k \in \{0,1\}$ is the kth transmitted bit, T is the bit time, and $p(t)$ is an arbitrary pulse with bandwidth $B \leq 1/T$. ISI-free transmission is achieved by considering only Nyquist or root-Nyquist pulses $p(t)$, for sampling or matched-filter (MF) receiver designs, respectively[7]. The nonnegativity constraint is satisfied by adding a proper signal bias $f(t)$ to the PAM signal.

The average transmitted optical power can be computed as[1,4]

$$P_{\text{opt}} = \frac{1}{T}\int_0^T \mathbb{E}\{x^{+}(t)\}\mathrm{d}t, \tag{2}$$

where $\mathbb{E}\{\cdot\}$ denotes the statistical expectation. In order to ensure eye and skin safeties, and to optimize the energy consumption, the average optical power has to be kept within certain limitations.

The Bias Signal

The bias signal $f(t)$ can be any waveform, as long as it is strictly bandlimited and achieves the nonnegativity of the transmitted signal. We consider

$$f(t) = \mu_0 + \mu_1 \cos\left(\frac{2\pi t}{T} + \phi\right), \tag{3}$$

which is in the form of the Fourier series of any waveform of bandwidth $1/T$ and period T. The coefficients μ_0, μ_1 and the phase ϕ are constant. For any given μ_1, the DC component μ_0 can be chosen to ensure $x^{+}(t) \geq 0$. From the average optical power perspective, the cosine component of the bias does not require any extra optical power since its integral in (2) is equal to zero. The extra power is consumed only by the DC bias. However, compared to using only a DC bias[5], the

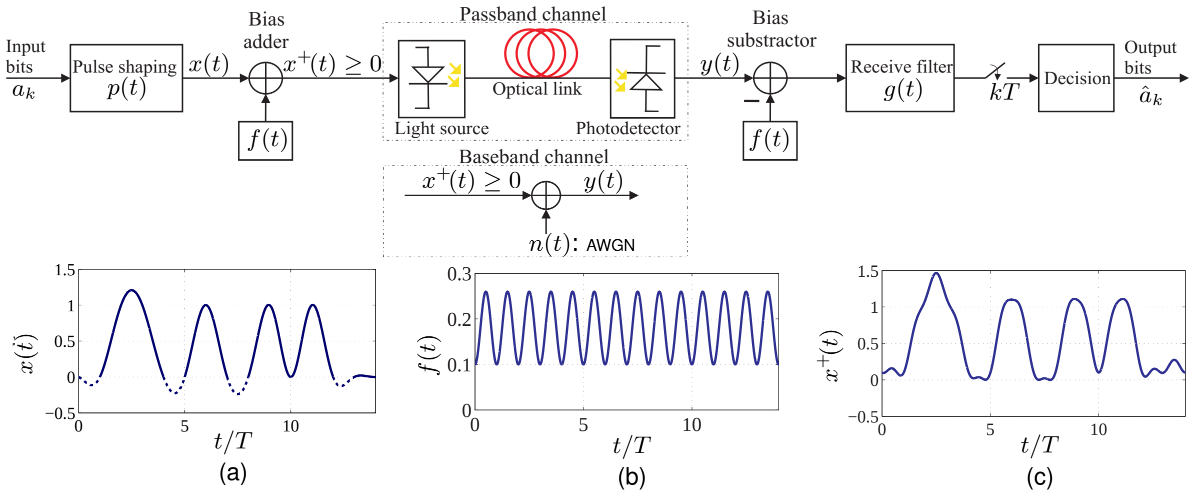

Fig. 1: The passband IM/DD system model (top). The baseband IM/DD channel (middle). The negative PAM waveform before adding the bias (bottom (a)), where the dashed part represents the negative values; the added bias (bottom (b)); the resultant nonnegative waveform (bottom (c)).

transmission is more power-efficient because less DC bias is required after adding a suitably scaled cosine term. If $\mu_1 \neq 0$, the bandwidth of $x^+(t)$ is $\max(B, 1/T) = 1/T$, where $B \leq 1/T$ is the bandwidth of $p(t)$. The receiver does not need any extra synchronization for the time-varying bias, since the cosine term has the same period as the bit clock. Moreover, the cosine-tone added to the spectrum can be used at the receiver in the clock-recovery circuit, analogously to detecting the return-to-zero modulation format which has a similar spectral component at $1/T$.[6]

Fig. 2 shows the normalized spectrum of a signal $x^+(t)$ formed using the proposed modulation format and the root-raised-cosine pulse with a roll-off factor $\alpha = 1$ (see Results Sec.). It can be noticed that the spectrum is strictly bandlimited and exhibits a spectral component at $f = 1/T$ which corresponds to the cosine term in (3). A narrow-bandpass filter or a phase-locked loop can easily isolate this component for further use in the clock-recovery circuit.

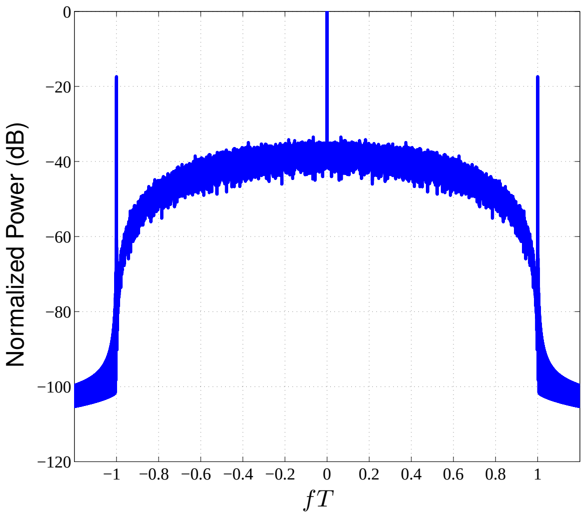

Fig. 2: Frequency spectrum of the proposed signaling method using a root-raised-cosine pulse with $\alpha = 1$.

By finding an expression for the global minimum of $x^+(t)$ that is independent of the instantaneous transmitted data bits a_k, an optimization similar to Tavan[5] is formed and numerically solved to obtain the μ_0, μ_1, and ϕ that maximize the optical power efficiency.

Results

Tab. 1 presents the achievable optical gains obtained by using the proposed signaling method for different pulse shapes $p(t)$ in terms of asymptotic power efficiency (APE) defined as

$$\text{APE} = \frac{P_{\text{opt}}^{\text{ref}}}{P_{\text{opt}}}, \tag{4}$$

where $P_{\text{opt}}^{\text{ref}}$ is the average optical power of the benchmark signaling method[3], employing a sampling receiver and the S2 pulse, which does not require any bias signal. The S2 pulse is the most power-efficient pulse previously known for the bandlimited IM/DD channel[3] and requires the same bandwidth as our proposed signaling scheme, i.e., $B = 1/T$, which leads to a fair comparison. Results are given for the raised-cosine (RC)[7], the first-order parametric linear (PL)[8], the better than Nyquist (BTN)[9], and the first-order Xia[10] pulses. When the MF receiver is used, the root-Nyquist pulses are obtained from the Nyquist pulses by taking the square root in the frequency domain[7]. The excess bandwidth for each pulse is controlled by the roll-off factor parameter $\alpha \in [0, 1]$. The optimal APE for different pulses is obtained at $\alpha = 1$, except for PL $(\alpha = 0.992)$ and BTN $(\alpha = 0.976)$ in case of using the MF receiver. Except the Xia pulse, which is the only nonsymmetrical pulse in the time domain, the optimal phase of the cosine term is $\phi = 0$.

The results in Tab. 1 show that using the proposed bias signal, the MF receiver is more power-efficient than the sampling receiver, in contrast to previous results[3–5]. The best APE is obtained by either the RC or Xia pulse using a MF receiver. They have the same

Tab. 1: The achievable APE (dB) of the proposed method for various pulses and their corresponding bias coefficients. The highlighted cells have the best APE.

	$f(t)$	RC	PL	BTN	Xia
Sampling receiver	μ_0	$\mathrm{APE} = -0.277$ $\mu_0 = 0.033$	$\mathrm{APE} = 0$ $\mu_0 = 0$	$\mathrm{APE} = -0.039$ $\mu_0 = 0.005$	$\mathrm{APE} = -1.893$ $\mu_0 = 0.273$
	$\mu_0 + \mu_1 \cos(\frac{2\pi t}{T} + \phi)$	$\mathrm{APE} = -0.257$ $\mu_0 = 0.031$ $\mu_1 = 0.011$	$\mathrm{APE} = 0$ $\mu_0 = 0$ $\mu_1 = 0$	$\mathrm{APE} = -0.032$ $\mu_0 = 0.004$ $\mu_1 = 0.004$	$\mathrm{APE} = -1.051$ $\mu_0 = 0.137$ $\mu_1 = 0.136$
Matched filter receiver	μ_0	$\mathrm{APE} = -0.388$ $\mu_0 = 0.273$	$\mathrm{APE} = -0.771$ $\mu_0 = 0.345$	$\mathrm{APE} = -0.905$ $\mu_0 = 0.371$	$\mathrm{APE} = -0.388$ $\mu_0 = 0.273$
	$\mu_0 + \mu_1 \cos(\frac{2\pi t}{T} + \phi)$	$\mathrm{APE} = 0.454$ $\mu_0 = 0.137$ $\mu_1 = 0.136$	$\mathrm{APE} = 0.171$ $\mu_0 = 0.180$ $\mu_1 = 0.166$	$\mathrm{APE} = 0.010$ $\mu_0 = 0.205$ $\mu_1 = 0.169$	$\mathrm{APE} = 0.454$ $\mu_0 = 0.137$ $\mu_1 = 0.136$

optimal bias because at $\alpha = 1$, the Xia pulse is a time-shifted version of the root-RC pulse by $-T/4$. Hence, with a $\phi = -\pi/2$-radian shift in the cosine term, the same APE can be achieved for both of the pulses.

Fig. 3 illustrates the bit error rate (BER) of the system for the S2 and RC pulses as a function of the required SNR defined as[1] $\mathrm{SNR} = P_{\mathrm{opt}}^2/(N_0 R_b)$, where $R_b = 1/T$ is the bit rate and $N_0 R_b = N_0 B$ the in-band noise power. A gain of 0.91 dB can be noticed, which is twice the APE gain, between our proposed signaling method compared to the previously best known scheme.

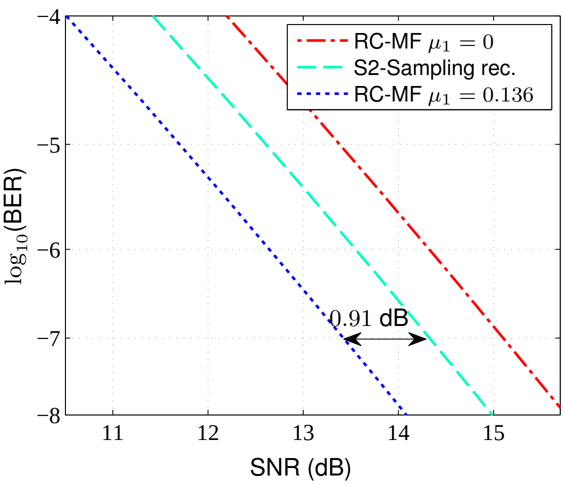

Fig. 3: BER as a function of SNR.

Conclusion

This paper presents a power-efficient signaling method for bandlimited optical intensity transmission. A time-varying but bandlimited bias signal, consisting of a DC and a cosine term, is added to the transmitted signal to make it nonnegative. The proposed method can simplify the symbol time recovery at the receiver and enables power-efficient use of root-Nyquist pulses and the matched-filter receiver design. The evaluation of the proposed modulation format is done by computing the asymptotic power efficiency and the BER of the system. The results show that gains up to 0.91 dB can be achieved in SNR compared to the best previously known signaling method at the same bandwidth.

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