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Continuous-Amplitude Modulation for Optical Wireless Channels

Johnny Karout*, Gerhard Kramer†, Frank R. Kschischang‡, and Erik Agrell*
*Department of Signals and Systems, Chalmers University of Technology, SE-412 96 Göteborg, Sweden
†Institute for Communications Engineering, Technische Universität München, D-80290 Munich, Germany
‡Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON M5S 3G4, Canada
Email: johnny.karout@chalmers.se

Abstract

Continuous-amplitude modulation for wireless optical channels is presented. For bandwidth measured as 99% in-band power, its spectral efficiency is 4.57 times that of the same modulation format with discontinuous amplitude for the same power requirement.

I. Introduction

In wireless optical and short-haul fiber links, intensity modulation with direct detection (IM/DD) is prevalent [1]–[4]. IM/DD gives access to only the intensity of light to carry information. As a consequence, conventional quadrature-amplitude modulation (QAM) and spectrally-efficient signaling schemes such as continuous phase modulation [5] cannot be used since they also encode data on the phase of the optical carrier. This makes the design of spectrally-efficient modulation formats for IM/DD channels challenging.

IM/DD systems, in the absence of optical amplification, can be modeled as additive white Gaussian noise (AWGN) channels with nonnegative inputs [1, Ch. 5], [2], [6], [7, Sec. 11.2.3]. One approach to increase spectral efficiency is by using nonnegative M-ary pulse amplitude modulation (M-PAM) [1, Eq. (5.8)]; however, M-PAM is power inefficient for $M > 2$ [8]. Another approach is by using subcarrier modulation (SCM), which enables the use of M-QAM over intensity-modulated channels by adding a direct current (DC) bias to the electrical signal to make it nonnegative [1, Ch. 5]. In [6] and our prior work [9]–[11], SCM formats are optimized to provide a good trade-off between power and spectral efficiency.

In this work, we present a continuous-amplitude modulation (CAM) format for IM/DD systems. In comparison with previously known modulation formats, the presented modulation format offers better spectral characteristics.

II. System Model

In IM/DD systems, an electrical nonnegative waveform $x(t)$ modulates a light source such as a laser diode. At the receiver, the photodetector outputs the electrical signal $y(t)$ which is proportional to the intensity of the incoming light. An equivalent baseband model for IM/DD when the dominating noise is from the receiver itself, and not from optical amplifiers is

$$y(t) = x(t) + n(t), \tag{1}$$

where $x(t) \geq 0$ and $n(t)$ is a zero-mean white Gaussian process with double-sided power spectral density $N_0/2$, under the assumption that the channel is nondistorting [1, Ch. 5], [2], [6], [7, Sec. 11.2.3], [12, p. 155]. The baseband channel input is $x(t) = \sum_{k=-\infty}^{\infty} s_{u(k)}(t - kT)$, where the symbols $u(k)$, for $k = \dots, -1, 0, 1, \dots$, are independent and uniformly mapped to a real and nonnegative waveform belonging to the signal set $S = \{s_0(t), s_1(t), \dots, s_{M-1}(t)\}$, where $s_i(t) = 0$ for $t \notin [0, T)$, $i = 0, 1, \dots, M-1$, and T is the symbol period. The receiver demodulates $y(t)$ using a correlator or matched filter receiver with a minimum-distance detector and puts out $\hat{u}(k)$ as the estimate of $u(k)$.

III. Continuous-Amplitude Modulation

In our prior work, a 4-level modulation format optimized to maximize the minimum distance between constellation points for average and peak optical power constraints was presented [11]. This modulation format was denoted as $\mathscr{T}_4$ and consists of the signaling set

$$\mathscr{T}_4 = \{0, \sqrt{2/T}\ (1 + \cos(\pi t/T))\ p(t), \sqrt{2/T}\ (1 - \cos(\pi t/T))\ p(t), 2\sqrt{2/T}\ p(t)\}, \tag{2}$$

where $p(t) = \mathrm{rect}(t/T) = 1$ for $t \in [0, T)$ and 0 elsewhere. The signals given in the set correspond to the labels $s_0(t)$, $s_1(t)$, $s_2(t)$, and $s_3(t)$. This modulation format is normalized to have unit average optical power. Fig. 1 depicts the baseband waveforms of $\mathscr{T}_4$ over one symbol slot. One drawback of this signaling set is the sharp transitions that could occur between consecutive signals, e.g., if $s_0(t)$ is followed by $s_1(t)$. This leads to spectral broadening and reduces spectral efficiency.

We propose a new modulation format $\mathscr{T}_4^c$ which is constructed using $\mathscr{T}_4$. The general idea is that at every time interval, two symbols can be selected from $\mathscr{T}_4$ in order to keep the signal amplitude continuous. Thus, if $s_0(t)$ or $s_1(t)$ are sent in time interval k, then either $s_0(t)$ or $s_2(t)$ can be sent in time interval $k+1$ (see Fig. 2). Further, if $s_2(t)$ or $s_3(t)$ are sent in

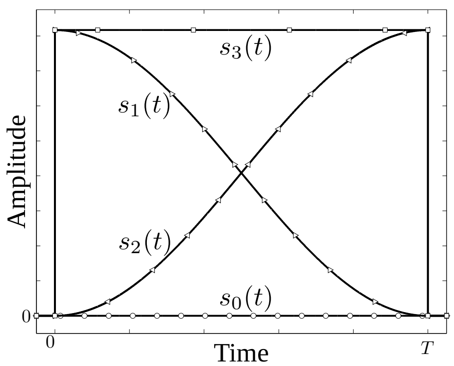

Fig. 1. The baseband waveforms of $\mathscr{T}_4$ over one symbol slot. $\mathscr{T}_4^c$ is a subset of $\mathscr{T}_4$ at every time interval.

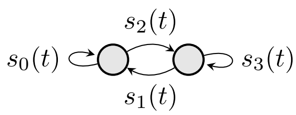

Fig. 2. A two-state Markov chain describing $\mathscr{T}_4^c$ signaling.

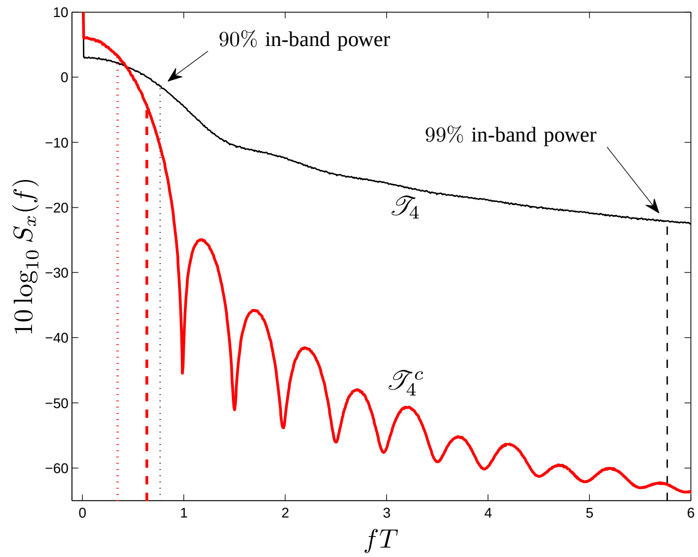

Fig. 3. Spectra of $\mathscr{T}_4$ and $\mathscr{T}_4^c$. Dotted lines indicate the normalized frequency for 90% in-band power and dashed lines for 99% in-band power.

time interval k, then either $s_1(t)$ or $s_3(t)$ can be sent in time interval $k+1$. This reduces the modulation rate but can improve spectral efficiency. The generated signal is continuous, and so is the first derivative, which also helps in producing a rapid roll-off of the power spectral density. For $\mathscr{T}_4^c$, the demodulator should use a detector that takes the memory into account, e.g., a maximum-likelihood sequence detector, rather than making decisions based on one output symbol only.

IV. Performance Analysis

To evaluate the performance of the above modulation formats, we use the spectral efficiency defined as $\eta = R_b/W$ [bit/s/Hz], where $R_b = R_s \log_2 M$ is the bit rate in bits per second, $R_s = 1/T$ is the symbol rate in symbols per second, and W is the baseband bandwidth of $x(t)$. To measure spectral efficiency, we use the fractional power bandwidth W defined as the width of the smallest frequency interval carrying a certain fraction of the total power as in [11, Eq. (10)]. Fig. 3 depicts the spectra $S_x(f)$ of $\mathscr{T}_4$ and $\mathscr{T}_4^c$, and the normalized frequencies fT corresponding to 90% and 99% in-band power. If the bandwidth is measured as 90% in-band power then $\mathscr{T}_4^c$ has $\eta = 2.87$ bits/s/Hz, which is 1.1 times that of $\mathscr{T}_4$ ($\eta = 2.61$ bits/s/Hz) for the same average and peak optical power requirement. Further, $\eta = 2.87$ bits/s/Hz is 1.53 times that of OOK ($\eta = 1.88$ bits/s/Hz) for a 0.62 dB degradation in average and peak optical power. However, if the bandwidth is measured as 99% in-band power, $\mathscr{T}_4^c$ has $\eta = 1.58$ bits/s/Hz which is 4.57 times that of $\mathscr{T}_4$ ($\eta = 0.35$ bits/s/Hz) for the same power requirement, and 8.25 times that of OOK ($\eta = 0.19$ bits/s/Hz) for a 0.62 dB degradation in average and peak optical power.

V. Conclusions

We presented a continuous-amplitude modulation for intensity-modulated channels. This modulation format achieves high spectral efficiency which makes it suitable for low-cost systems.

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