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Imperfect narrow filtering in optical links with phase modulation

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A R T I C L E I N F O

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A B S T R A C T

In order to reveal the pattern effect in the optical signal transmission it is studied as a random complex process. The different sources of detection error are studied for quadrature phase-shift keying in the absence of nonlinearity: the error in the rectangular filter width, the finite duration of the initial pulses, the deviation of detection point from the bit interval center. The dispersion and diameter of cloud in the constellation diagram are calculated and shown to be less for longer initial pulses. The error of imperfect optical system is proved to be important at a noise level of 11 dB and more. The result is also applicable for 8-PSK, 16-PSK and higher formats.

1. Introduction

Exploiting the coherence detection and phase-shift keying formats [1] is a very promising way to increase the capacity of fiber communication networks [2]. Nyquist (sinc) pulse shaping provides spectral efficiency close to the theoretical limit [3]. Perfect Nyquist pulses have the rectangular shape in the frequency domain. It allows one to arrange the frequency channels as dense as possible. In time domain the shape of Nyquist pulses is sinc(πbt), where $2\pi b$ is the channel bandwidth. Sinc-like pulses are extended to neighbor bit intervals to the left and to the right. Since they turn to zero in the centers of bit intervals, it is possible to detect each bit separately when we choose the detection point exactly in the center. Nyquist pulses are well-known in electronics, but relatively new in optics.

From a mathematical point of view the Nyquist pulse can be obtained by passing very short pulse (close to δ-function) through the rectangular optical filter of the width $2\pi b$ in concordance with the bit interval $T=1/b$. The application of rectangular filter corresponds to mixing of an optical pulse with Nyquist signal and integration over time, because the product of Fourier transforms is equivalent to the convolution of functions in the time domain. Then it is impossible to get the perfect sinc-like signal, since theoretically it spreads out along the whole time axis, and then all the pulses influence each other. Similarly it is impossible to realize a perfect rectangular filter, since the delay of a pulse passing through the filter must be infinite [4]. The Nyquist signals in a non-ideal optical system are one of the urgent problems of optical communications [5].

In the present paper we consider an optical communication link where the short pulses are passing through the rectangular filter at the transmitter end in order to form the Nyquist shape. The identical rectangular optical filters is applied at the receiver end. In a linear system, in the context of pulse shapes, the signal passing through two rectangular filters is equivalent to passing through one filter with the minimal bandwidth. In the frequency domain the filtering means multiplication by the transfer function, then only the less width enters the result. Then one can consider the line with identical input and output rectangular filters with minimal width. The following parameters influencing the pulse shape are treated: the finite duration of pulses at start, the variation of rectangular filter bandwidth at the receiver end, and the deviation of the detecting point from the center of bit interval. We analyze the contribution of each factor into the coordinates in the constellation diagram. We compare the effects of noise and imperfect optical system. We find the signal-to-noise ratio (SNR) for which the effect of imperfect optical system occurs greater than that of the noise.

The filter decreases the noise of amplifiers and splits the link bandwidth by individual channels. At the same time the narrow filter changes the shape of pulses broadening them in the time

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domain [4,6]. The pulses overlap, and then the nearest (adjacent) pulses and more distant pulses influence the signal. The result depends on the realization of the bit sequence. This effect (the pattern effect) is a serious problem in high-speed all-optical communications [7].

To include all the possible patterns the sequence has to be modeled as a random process. For the amplitude modulation (on/off keying format) the statistical approach is applied in paper [8]. Here we consider the quadrature phase-shift keying (QPSK) format. The coordinate of given pulse on complex plane can also be considered as a random complex number. The aim of present paper is to find the domain of values and dispersion of this random number. In Section 2 we introduce the possible sources of the error, describe the constellation diagram, the Nyquist signal and the optical system. Section 3 presents the results of simulation: root-mean-square and marginal errors on the complex plane.

2. Sources of error

2.1. Duration of initial pulse

In phase-shift keying QPSK format four values are used for coding, placed equidistantly in the unit circle. We chose the values 0, $\pi/2$, π, $3\pi/2$, a bit pair corresponds to each value. We assume pairs "00", "01", "10", "11", respectively. The sequence of optical pulses is defined by formula $\sum_n c_n E_n(t)$, where $E_n(t) = E(t-nT)e^{-i\omega_c t}$ is complex electric field, n is the number of bits, t is the time, T is the duration of a bit interval, ω_c is the carrier optical frequency, $E(t)$ is the profile of an individual pulse. For pulses with profile $E(t) = A\exp(-t^2/2T_0^2)$, where T_0 is the pulse width parameter, A is a coefficient, the duration is determined relation $W = 1.67T_0$. For QPSK format the coefficients c_n possess the values $c_n \in \{1, i, -1, -i\}$, $i = \sqrt{-1}$.

Mathematically the pulse transmission through the rectangular filter is realized by multiplication of its Fourier transform by rectangular function:

$$B(\omega) = \begin{cases} 1, & |\omega| < \pi b, \\ 0, & |\omega| > \pi b, \end{cases}$$

where b is the spectral width of filter. For the Gaussian pulse with zero phase the profile after the rectangular filtering is given by the formula:

$$\tilde{E}(t) = Ae^{-t^2/2T_0^2}\,\mathrm{Re}\left[\mathrm{erf}\left(\frac{\pi T_0 b}{\sqrt{2}} + \frac{it}{T_0\sqrt{2}}\right)\right]. \quad (1)$$

Here $\mathrm{erf}(x) = 2\int_0^x e^{-t^2}\,dt/\sqrt{\pi}$ is the error function [9]. To study the effect of neighbor pulses let us use value $\tilde{E}(\delta_0)$ as a normalization factor, where δ_0 is the deviation of detecting point from the center of bit interval, then the single pulse is located in point (1,0).

Let us calculate the influence of a remote pulse that is separated by l bit intervals from the pulse with $n=0$. The normalized distortion is

$$\varepsilon_l = \frac{e^{-\tau^2/2T_0^2}\,\mathrm{Re}\left[\mathrm{erf}\left(\dfrac{\pi T_0 b}{\sqrt{2}} + \dfrac{i\tau}{T_0\sqrt{2}}\right)\right]}{\mathrm{Re}\left[\mathrm{erf}\left(\dfrac{\pi T_0 b}{\sqrt{2}} + \dfrac{i\delta_0}{T_0\sqrt{2}}\right)\right]}, \quad (2)$$

where b is the bandwidth of filter, $\tau = lT + \delta_0$. The effect of $2k$ neighbor pulses is given by the sum

$$\xi(k) = 1 + \sum_{l=1}^{k} (\varepsilon_l c_l + \varepsilon_{-l} c_{-l}). \quad (3)$$

where c_l and c_{-l} are statistically independent values. Coefficient c_l posses values $\{1, i, -1, -i\}$ with probability 1/4. If $\delta_0 = 0$, then $\varepsilon_l = \varepsilon_{-l}$.

After filtering the coordinate of a pulse is a complex random number. The coordinates depend on the neighbor pulses. If we take into account k neighbor pulses to the left and k to the right,

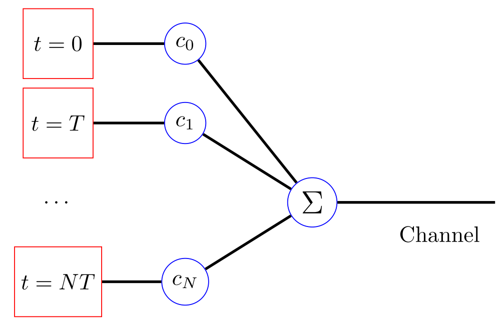

Fig. 1. Schematic diagram of the transmitter end of optical system.

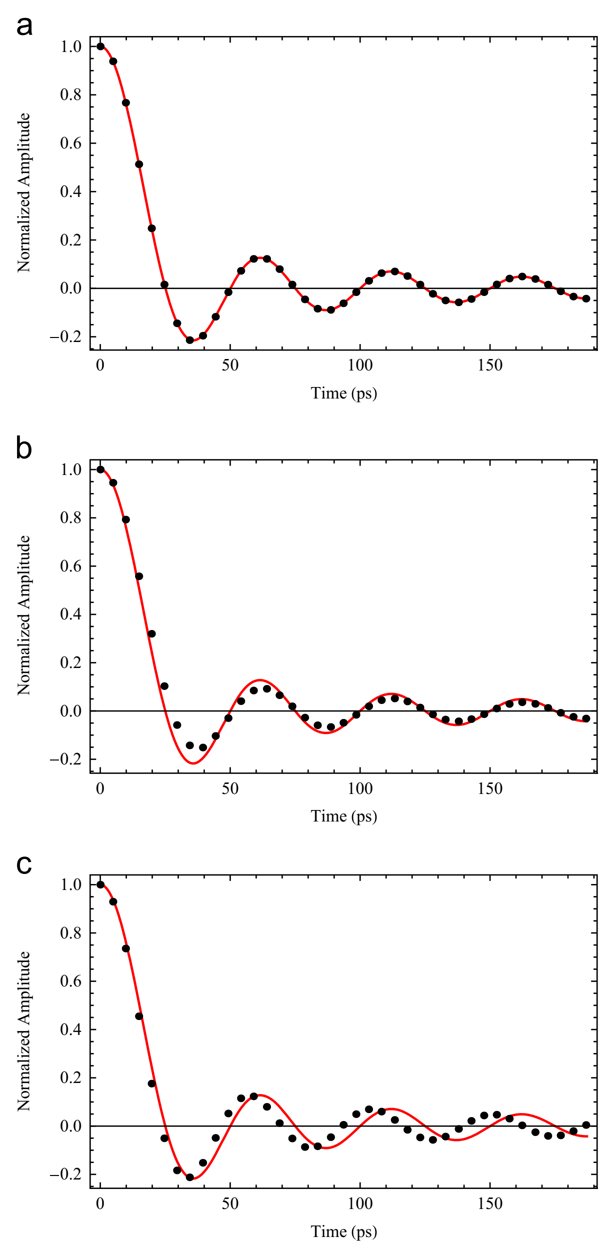

Fig. 2. Comparison of signal obtained from narrow pulse (pulse duration is W=2.5 ps) with the help of rectangular filter (with bandwidth b=40 GHz) (filled circles) with pure Nyquist pulse (solid line) (a). The same for longer pulse (pulse duration W=12.5 ps) (b) and for wider filter (bandwidth b=43 GHz) (c).