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Improving the power efficiency of SOA-based UWB over fiber systems via pulse shape randomization

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A B S T R A C T

A simple pulse shape randomization scheme is considered in this paper for improving the performance of ultra wide band (UWB) communication systems using On Off Keying (OOK) or pulse position modulation (PPM) formats. The advantage of the proposed scheme, which can be either employed for impulse radio (IR) or for carrier-based systems, is first theoretically studied based on closed-form derivations of power spectral densities. Then, we investigate an application to an IR-UWB over optical fiber system, by utilizing the 4th and 5th orders of Gaussian derivatives. Our approach proves to be effective for 1 Gbps-PPM and 2 Gbps-OOK transmissions, with an advantage in terms of power efficiency for short distances. We also examine the performance for a system employing an in-line Semiconductor Optical Amplifier (SOA) with the view to achieve a reach extension, while limiting the cost and system complexity.

1. Introduction

As there is a growing demand for high speed and low power transmission systems nowadays, ultra wide band (UWB) radio technology becomes an important technique to be used in the new generation of short-range broadband wireless communications [1,2]. The main advantages offered by UWB are the high data rate, immunity to multipath propagation, flexibility in reconfiguring data rate and power, very good time domain resolution, accurate mobile user location, and easy data protection. UWB applications include local and wide area networks, sensor networks, emergency communications, radar, remote sensing, and military applications [3]. Widening UWB system coverage via optical access networks has become an important research topic over the past few years [4–8]. Such UWB-over-fiber infrastructures require direct optical pulse generation [9,10] or electro-optical conversion utilizing intensity modulators [11]. IR-UWB technique has shown a great interest to be used due to its low complexity and cost transceiver architectures [12,13]. In 2002, the Federal Communication Commission (FCC) allowed UWB devices to operate within a particular spectral mask in order to avoid dangerous interference with other narrow band communication systems [14]. According to this regulation the transmitted power spectral density of UWB has to stay below the limit of −41.3 dBm/MHz in the frequency range of [3.1,10.6] GHz [15]. This power limitation has raised the need for highly efficient IR-UWB signals [16], hence pulse shaping and spectrum smoothing are mandatory to increase the transmitted power without violation of FCC regular limit [17]. A special effort has recently been made by Abraha et al. [18–20] for improving the power efficiency of Gaussian pulses with a lower order of complexity, by using a combination of monocycles and delayed doublets. Pulse shaping can improve the envelope of the overall spectrum, but has no influence on the discrete spectral peaks resulting from modulation patterns. Hence smoothing the spectrum of modulated signal requires a change in the statistical properties of the pulse train, time randomization being important so as to reduce the intensity of frequency comb lines. Direct sequence (DS) and time hopping (TH) are the mostly utilized randomization techniques, based on varying the pulse amplitude or time position respectively [21–23]. The main drawback for DS is the complexity associated with multi-level generation, and randomizing in terms of polarity [24] is not suitable for unipolar encoding like OOK or PPM. Hopping the pulse position between different chips in case of TH requires a larger symbol duration, which consequently lowers the data rate and may not be pertinent for high speed applications. In this work, a simple randomization technique is adopted for improving the system performance; it consists in changing the pulse waveform over time while keeping the same time location and scaling factor. The energy per bit is

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conserved for all transmitted frames/symbols, in order to fit the requirement of non-coherent energy-detection based UWB systems [25]. The proposed multi-waveform OOK (MWOOK) and multi-waveform PPM (MWPPM) modulation schemes have been applied to a radio over fiber (RoF) system. Our scheme has proved a better power efficiency at short distances of fiber, which can be extended into several kilometers using a Semiconductor Optical Amplifier (SOA) for in-line amplification purpose.

2. Proposed multi-waveform OOK/PPM modulation formats

Conventional OOK and PPM impulse radio signals correspond to a stream of modulated pulses via amplitude or position, respectively. The same pulse is systematically repeated along different transmitted frames, leading to a periodicity in time domain and hence to high spectral spikes. Our approach aims to alleviate this undesirable properties by changing the pulse shape over time while conserving the digital modulation format principle. Adjusting the pulse waveform is not new in UWB communications [26], but here it is for randomization purpose and not for modulation. In case of an OOK-modulated signal, the proposed multi-waveform OOK scheme consists in transmitting different pulse shapes for the bit ‘1’, each pulse being selected randomly from a particular set $\mathcal{P}$ containing N candidate waveforms, and no transmission is done for bit ‘0’ as in the conventional scheme. The transmitted signal is then expressed as

$$w_{MWOOK}(t) = \sum_k \sum_{j=1}^{N} b_{j,k} d_k p_j(t - kT) \quad (1)$$

where $d_k \in \{0, 1\}$ denotes the binary data to transmit, T is the frame duration, and $b_{j,k} \in \{0, 1\}$ stands for the j^{th} bit of the N-bits coded number $B_k = (2^{R(k)})_2$, with $R(k)$ being a random integer from the uniform distribution on the interval $[0, N-1]$. Hence, $\sum_{j=1}^{N} b_{j,k} = 1$ which means that only one pulse p_j is triggered in the set $\mathcal{P}$.

Similarly, as illustrated in Fig. 1, a multi-waveform PPM can be expressed as

$$w_{MWPPM}(t) = \sum_k \sum_{j=1}^{N} b_{j,k} p_j(t - kT - d_k\Gamma) \quad (2)$$

where Γ denotes the modulation index.

As different pulses are involved in the randomization process, no correlation must appear between any 2 waveforms from the set $\mathcal{P}$ over the pulse interval T, (notice that frame duration is considered to be equal to the pulse period in this work):

$$\int_0^T p_m(t) p_n(t) \mathrm{d}t = 0 \quad \forall m \neq n \quad (3)$$

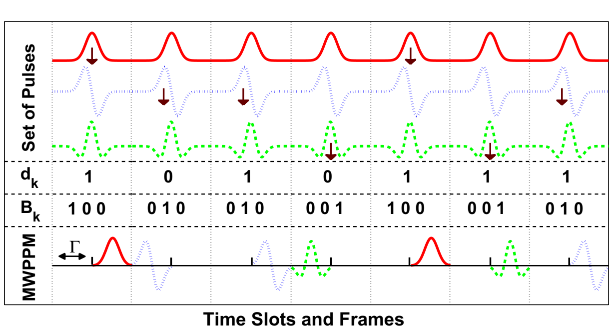

Fig. 1. A simple description for multi-waveform PPM transmission, where each frame consists of 2 time slots.

Following a similar approach than that used in [27], closed-form expressions of the power spectral densities (PSDs) can be easily derived for the proposed MWOOK/MWPPM formats (see Appendix A for an outline of the proof). For MWOOK, we get the following PSD expression:

$$S_{MWOOK}(f) = \left| \sum_{j=1}^{N} P_j(f) \right|^2 \left[\frac{\mu_d^2}{T} \left(\frac{2}{N} - \frac{1}{N^2} \right) + \frac{\mu_d^2}{N^2 T^2} \sum_k \delta\left(f - \frac{k}{T} \right) \right] \quad (4)$$

where μ_d stands for the expectation of the binary data d_k and $P_j(f)$ is the spectrum of pulse $p_j(t)$. For the MWPPM format, the PSD takes the form

$$S_{MWPPM}(f) = \left| \sum_{j=1}^{N} P_j(f) \right|^2 \left[\frac{1}{T} \left(\frac{1}{N} - \frac{|\mu_m|^2}{N^2} \right) + \frac{|\mu_m|^2}{N^2 T^2} \sum_k \delta\left(f - \frac{k}{T} \right) \right] \quad (5)$$

where $\mu_m = cos(\pi f \Gamma)$ is the expectation of the random process $m_k = e^{-j2\pi f \varepsilon_k}$ in the spectral domain, with $\varepsilon_k = d_k \Gamma$. With the view to characterize the spectrum smoothness, we define the Discrete to Continuous Spectral Ratio (*DCSR*) as the factor multiplying the series of frequency comb lines divided by the continuous part of the spectrum. For the MWOOK scheme we obtain the following expression

$$DCSR_{MWOOK} = \frac{1}{T(2N - 1)} \quad (6)$$

whereas for MWPPM the ratio takes the form

$$DCSR_{MWPPM} = \frac{|\mu_m|^2}{T(N - |\mu_m|^2)} \quad (7)$$

The DCSR criterion has been established based on theoretical PSD expressions; so, this criterion will no longer be suited to spectral estimates. In the sequel, we will adopt a complementary principle for assessing the benefits of randomization, the Peak-to-Average Spectral Ratio (*PASR*), corresponding to be the mean of discrete lines intensity divided by the average of the overall power spectral density.

We will also consider the important criterion of power efficiency, defined as

$$\eta = \frac{P_{\mathcal{F}}}{max(\overline{P_{\mathcal{F}}})} \quad (8)$$

where $P_{\mathcal{F}}$ stands for the power collected over a frequency band of interest $\mathcal{F}$ (typically the [3.1–10.6] GHz band) for the electrical signal at antenna input, and $max(\overline{P_{\mathcal{F}}})$ denoting the total power evaluated over the same band for an OOK or PPM modulated signal based on the *sinc* pulse, which is optimal in the sense that it corresponds to a 100% spectrum use (full coverage of the spectral mask).

From Eqs. (6) and (7), it can be clearly seen that increasing the number N of pulses tends to decrease the DCSR, which can result in a better power efficiency as will be illustrated in the next section. Note also that for a unit processing gain transmission, the data rate is $R_b = 1/T$, so the DCSRs are linear with R_b. A critical step for taking advantage of the randomized signals is the design of the set of candidate pulses $\mathcal{P}$. One obvious constraint is to conserve energy per bit for all transmitted frames. In addition, we must ensure that the pulses are all mutually uncorrelated (Eq. (3)). There are mainly two approaches to achieve this goal, either the transmitter relies on sine and cosine waves with use of local oscillators, or the transmitter directly operates in baseband (impulse radio system). The two solutions are investigated in the next section.