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A closed-form derivation of self and multi-user interference for time-reversed UWB communications

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ABSTRACT

Multipath degradation is a significant consideration for all wireless communication systems. A time-reversed UWB system harnesses the multipath channel to achieve temporal and spatial focusing through signal pre-filtering at the transmitter side. In cases where the RMS delay spread of a channel is larger than a user's transmitted pulse separation, inter-pulse, -frame, and -symbol interference may occur. Of even more concern is multi-user interference, which significantly reduces system performance. This paper presents closed-form expressions for self and multi-user interference for a UWB system utilizing a time-reversed approach. The influence of user multiplexing codes is taken to account through incorporation of a 'separation probability', which characterizes a family of hopping sequences. The standardized IEEE 802.15.3a channel model is applied, and the derived performances are compared with that of a simulated time hopped time-reversed UWB system.

1. Introduction

Ultra Wideband (UWB), or impulse radio, has seen significant attention since its release for commercial applications in early 2002 [1]. The possibility of use in home entertainment led to the development of a UWB based wireless video system by Freescale Semiconductor [2]. It is characterized by having a fractional bandwidth of more than 20%, or bandwidth occupancy greater than 500 MHz [3]. The two main competitors for the UWB standard are direct sequence based and orthogonal frequency division multiplexing based schemes, supported by the 'UWB Forum' and 'WiMedia Alliance', respectively [4].

This paper is focused on an extension to time hopped UWB (TH-UWB) [5], similar in implementation to direct sequence UWB. Within TH-UWB, pulses transmitted are either delayed in time (pulse position modulation (PPM)) or changed in amplitude (pulse amplitude modulation (PAM)) for encoding data. Users are multiplexed through code division multiple access based upon a family of orthogonal time hopping codes.

The aforementioned 'extension' is a channel equalization scheme herein referred to as the 'time-reversed' (TR) approach, which has its origins in underwater acoustics [6]. This scheme has also been referred to as 'pre-rake' [7]. While a conventional system would operate with the transmission of sub-nanosecond width Gaussian waveforms, a TR-UWB system uses the channel impulse response from the transmitter to the receiver as a transmit pre-filter. With the channel being estimated through the use of a pilot test signal, a time-reversed signal retraces its path through the channel, resulting in an autocorrelation of the response being received [8].

A notable benefit of pulse-based UWB is that multipath components are fully resolvable, provided that the duration of each pulse is shorter than the difference between propagation delays of different multipath components [9]. Unfortunately,

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typical UWB indoor channel responses have a delay spread of approximately 80 to 200 ns, with 60 to 200 paths [10]. The overlap of transmissions for consecutive symbols hence leads to the effect of inter-pulse, inter-frame, and inter-symbol interference, herein collectively referred to as inter-symbol interference (ISI). Multi-user interference presents a more severe degradation than ISI, with large delay spreads of transmissions causing interference by other transmitters in close proximity.

Consideration for hopping sequences is generally conducted through partial cross correlation equations [11] or traditional Hamming correlations [12]. This paper presents a unique approach to the sequence based performance analysis, developing a set of state probabilities for pulse separations within a TR-UWB system, specific to a family of hopping codes. It develops closed-form expressions for the self and multi-user interference present for a given set of communication parameters, taking into consideration channel degradations. Derivations presented are based upon core interference equations introduced in [13], adopting similar channel and system parameters.

This paper is organized as follows: Section 2 outlines a TR-UWB system, together with the channel model and BER calculation method applied; Section 3 overviews the time hopping code analysis used to account for a multi-user system, together with closed-form solutions for the ISI and MUI present in downlink UWB communications; and Section 4 compares the performance of derived formulas to simulated results. Finally, Section 5 gives all concluding statements and remarks.

2. System description

2.1. Signal equations

The signal $s^{(u)}(t)$ transmitted for the uth user in a time hopped UWB system, with equiprobable data $b_m^{(u)} \in \{-1, 1\}$ mapped through binary PPM with the time shift ε set to equal the pulse width, is given by [14]:

$$s^{(u)}(t) = \sqrt{E_{TX}(u)} \sum_{m=-\infty}^{\infty} w(t - mT_f - c_m^{(u)} T_c - \varepsilon b_m^{(u)}), \tag{1}$$

where $E_{TX}(u)$ is the user signal energy, $w(t)$ is the base transmitted waveform of width T_w seconds, and m is the frame number. T_f is a single frame length, which is segmented into equally spaced intervals called ‘chips’ of duration T_c, such that $T_f = N_h T_c$. $c_m^{(u)}$ denotes the position within the particular frame (the chip number) that is occupied by the uth user’s signal in accordance with a time hopping sequence. For the purpose of this paper the pulse shape was set as the second derivative of the Gaussian pulse, with center frequency f_0, defined as [15]:

$$w(t) = [1 - 2(\pi t f_0)^2] \exp\{-(\pi t f_0)^2\}, \tag{2}$$

with energy:

$$E_{w(t)} = \frac{3}{\sqrt{32\pi \cdot f_o^2}}, \tag{3}$$

and energy normalized Fourier transform of:

$$\widetilde{W}(f) = \sqrt{\frac{\sqrt{32\pi \cdot f_o^2}}{3} \frac{2}{\sqrt{\pi \cdot f_o^2}} \left(\frac{f}{f_0}\right)^2 \exp\left\{-\frac{f^2}{f_0^2}\right\}}. \tag{4}$$

A center frequency of 3.9 GHz was used, which results in a monocycle width of $T_w = 0.5$ ns.

If two users simultaneously occupy the same chip, a collision or ‘hit’ occurs. The characterizing parameters of these time hopping codes are the cardinality (N_h), which specifies the alphabet size; and the periodicity (N_p), which indicates the length of the code before it is repeated.

With the data shift ε, and the pulse duration T_w, the remaining duration of a chip is the guard time T_g, given as:

$$T_g = T_c - (\varepsilon + T_w). \tag{5}$$

Defining the data rate as R, and the number of transmissions per symbol N_s, the frame duration T_f and chip duration T_c are:

$$T_f = \frac{1}{N_s R},$$

$$T_c = \frac{1}{N_h N_s R}.$$

TR-UWB differs to UWB in that it shifts the design complexity from the receiver to the transmitter, with the received signal focused both in time (temporal focusing) and in space (spatial focusing) at the intended receiver [8]. Since the transmitter requires channel state information, TR-UWB is suitable for time-division duplexing schemes, where uplink and downlink radio paths are similar. This information is used to pre-filter the transmit signal using the time-reversed complex conjugate of the forward link channel response, modeled as a discrete linear filter. As the channel applied here is real, the pre-filter reduces to the time-reversed response.