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Cluster-head based feedback for simplified time reversal prefiltering in ultra-wideband systems

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ABSTRACT

Time-reversal prefiltering (TRP) technique for impulse radio (IR) ultra wide-band (UWB) systems requires a large amount of feedback to transmit the channel impulse response from the receiver to the transmitter. In this paper, we propose a new feedback design based on vector quantization. We use a machine learning algorithm to cluster the estimated channels into several groups and to select the channel cluster heads (CCHs) for feedback. In particular, CCHs and their labels are recorded at both side of the UWB transceivers and the label of the most similar CCH to the estimated channel is fed back to the transmitter. Finally, the TRP is applied using the feedback CCH. The proposed digital feedback provides three main advantages: (1) it significantly reduces the dedicated bandwidth required for feedback; (2) it considerably improves the speed of transceivers; and, (3) it is robust to noise in the feedback channel since few bytes are required to send the codes that can be heavily error protected. Numerical results on standard UWB channel models are discussed, showing the advantage of the proposed solution.

1. Introduction

In wireless communications, multipath is the propagation phenomenon causing multiple replicas of each transmitted signal to arrive at the receiver with different time delays and attenuations. The phenomenon is particularly relevant in impulse radio ultra-wideband (IR-UWB) systems due to the extremely short duration of pulses involved in the communication process [1]. The RAKE receiver is the optimum receiver in absence of interference [2], which is capable of recovering the waveform associated with different Channel Impulse Response (CIR) taps [3]. A long CIR delay spread [4–6] may lead to high complexity in RAKE receiver design [7], due to the need of coping with substantial Inter-Symbol Interference (ISI) [8] and Multiuser Interference (MUI) [9,10], especially in high data rate scenarios. Design and implementation of the UWB RAKE receiver are, therefore, extremely challenging [11]. Transmit prefiltering techniques have been proposed to reduce the RAKE receiver complexity, by moving part of complexity into the transmitter. For example, the so called *Pre-RAKE diversity combination* technique [12,13], is able to reduce both complexity and cost of the RAKE receiver. A different approach is Time Reversal prefiltering (TRP), a technique originally applied in acoustics [14], ultrasonic multi-user communications [15], underwater acoustics [16], and more recently in wireless communications in general [17], and UWB [18–20].

In TRP, the receiver estimates the CIR, and sends the estimate back to the transmitter, periodically, with a period equal to the coherence time, that is, the time interval during which channel characteristics can be supposed to be invariant. Then, the transmitter applies the time-reversed conjugate of CIR to transmitted pulses, leading to the temporal focusing of transmitted signals that, in turn, reduces both ISI and MUI, since the received power concentrates within the strongest taps [21]. Hence, TRP simplifies the RAKE receiver structure and improves the performance of UWB systems because a few channel taps carry most of the energy of the transmitted signals. TRP can also positively impact the performance of positioning systems using Direction of Arrival (DOA) [22].

The main disadvantage of TRP technique is the requirement to estimate and send back the channel state information (CSI) as a quantized versions of CIRs. The CSI accuracy increases with the number of quantization levels, and requires a larger bandwidth since more information has to be transmitted on the feedback channel [23]. Over the last few years, several methods have been proposed to overcome TRP problems by decreasing the amount of feedback information. One simple method is to quantize the CIR with a small number of quantization levels. When brought to the

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extreme, this approach leads to the use of only 1 bit per sample, typically converting the sign of the channel tap [8,24,25]. The information loss in one-bit quantization and its effect on the quantization error are investigated in [26,27], while the main drawback of one bit quantization approach is the increased perceived delay spread of the channel [25]. One solution is the phase compensation method [28] in which signals are prefiltered with the channel taps phases. This approach reduces the ISI because the amplitude of the side lobes of the transmitting signals is decreased with respect to the side lobes of the TRP. In [27] the impact of the number of quantization levels for the channel taps phases is evaluated. In parallel, a technique for optimizing the vector quantization of the CIR is proposed in [29] in order to reduce information transmission in the feedback channel.

In this paper, we propose a new feedback design based on vector quantization for time reversal prefiltering impulse radio UWB using a machine learning algorithm to reduce the amount of feedback information. The use of machine learning has been proposed in the past in UWB communication systems, for example, as a way to recognize UWB signals [30] and reduce the ranging error in localization [31]. Instead, we use a machine learning algorithm to cluster the estimated channels into several groups and to select the channel cluster heads (CCHs) for feedback. In particular, CCHs and their labels are recorded at both side of the UWB transceivers and the label of the most similar CCH to the estimated channel is fed back to the transmitter. Finally, the TRP is applied using the feedback CCH.

Two scenarios can be envisaged for the learning phase: when CIR statistics are unknown, CIRs estimates are collected during a set-up phase and used to obtain clusters and CCHs. When instead CIR statistics are known a priori, e.g., from standard IEEE 802.15.3a channel model [32], then off-line generated CIRs can be used for the learning phase.

The proposed digital feedback provides *three* main advantages: (1) it *significantly* reduces the dedicated bandwidth required for feedback; (2) it *considerably* improves the speed of transceivers; and, (3) it is *robust* to noise in the feedback channel since few bytes are required to send the codes that can be heavily error protected.

The rest of the paper is organized as follows; in Section 2 we describe the system model and review the TRP approach. Also, we review the IEEE 802.15.3a channel model which is used for the generation of CIRs and for performance evaluation. In Section 3 we introduce the idea of using CCHs for reduction of number of bits in the feedback system and then discus how to select CCHs. Next, in Section 4 we examine the performance of the proposed algorithm in terms of bit-error-rate (BER) and we investigate the amount of information to send back. We compare performance of the CCHs with benchmark methods in Section 4.3 before concluding the paper in Section 5.

2. System model

We consider a point-to-point IR-UWB system that uses either pulse amplitude modulation (PAM) or pulse position modulation (PPM) schemes to transmit information from the transmitter (Tx) to the receiver (Rx) [2,33]. The IR-UWB encodes data symbols with either Time Hopping (TH) or Direct Sequence Spread Spectrum (DS-SS) methods to avoid collision in multiple access [2]. The time hopping PAM scheme encodes a data sequences b_i into the continuous signal at time t is

$$S_{Tx}(t) = \sqrt{E_s/N_s} \sum_{i=1}^{p} b_i \sum_{n=0}^{N_s-1} w(t-(iN_s+n)T_f - C_{(iN_s+n)}T_c) \tag{1}$$

where b_i is the binary sequence $(-1, 1)$ in the 2-PAM case for the ith transmitted symbol that is repeated N_s times, T_f is a frame time interval, T_c is a chip time interval, $\sqrt{E_s/N_s}$ is the amplitude of a transmitted symbol, where E_s is the signal energy per pulse [2]. The TH sequence $(C_i)_{i\in Z}$ is generated from a pseudo-random code [1] and $w(t)$ is the transmitted mono-cycle waveform [34], i.e. the energy normalized second derivative of a Gaussian pulse

$$w(t) = \left[1 - 4\pi\left(\frac{t}{\alpha}\right)^2\right] \exp\left[-2\pi\left(\frac{t}{\alpha}\right)^2\right] \tag{2}$$

where α is the shape factor.

The received signal can be written as

$$S_{Rx}(t) = S_{Tx}(t) \otimes h(t) + n(t) \tag{3}$$

where $\otimes$ is the convolution operation , $n(t)$ is the additive white Gaussian noise (AWGN) and $h(t)$ is the CIR.

2.1. Transmitter and receiver model using TRP

Transmitting the signal defined in (1) without any additional operation poses several problems because of the long channel delay spread. Therefore, the TRP technique was proposed to address such issues and is adopted in this work. TRP provides better performance, higher achievable data rates and more secure data transmission with respect to traditional (no TRP) UWB transceiver while reducing the complexity at the receiver.

We assume that both of Tx and Rx are perfectly synchronized, and for TRP, we need the perfect channel knowledge. TRP is implemented by the following procedure performed once every coherence time [15]:

1. Tx sends a training signal enabling Rx to obtain the CIR estimate $\hat{h}(t)$;
2. Rx sends back the $\hat{h}(t)$ to Tx, using a feedback channel;
3. Tx prefilters $S_{Tx}(t)$ with the time-reversed conjugate of $\hat{h}(t)$ i.e.

$$T_x(t) = \sqrt{E_{Tx}}\left[S_{Tx}(t) \otimes \hat{h}^*(-t)\right], \tag{4}$$

   where $E_{Tx} = \frac{E_s}{\int_{-\infty}^{\infty} |w(t)\otimes\hat{h}^*(-t)|^2 dt}$ normalizes the transmitted pulse $w(t)$ to power E_s and $*$ denotes complex conjugate operation.
4. The received signal becomes

$$S_{Rx}(t) = T_x(t) \otimes h(t) + n(t). \tag{5}$$

   The optimum multipath receiver in absence of interference is a RAKE receiver that uses a bank of single user matched filters (SUMFs) to improve the pulse detection performance and minimizes the probability of error [2]. The signal after the matched filter is

$$v(t) = S_{Rx}(t) \otimes \Psi_i(t), \tag{6}$$

   where $\Psi_i(t) = M_i(t)\otimes\hat{h}^*(-t)\otimes h(t)$ is the matched filter for ith pulse detection and

$$M_i(t) = \sum_{n=0}^{N_s-1}(w(t-(iN_s+n)T_f) - C_{(iN_s+n)}T_c). \tag{7}$$

   Then $v(t)$ is sampled at time $\tau + iT_f$, with τ being a suitable delay and a hard decision is taken to obtain $\hat{b}_i$, [35] (see Fig. 1).