BLIND MULTIUSER DETECTION FOR IMPULSE RADIO UWB SYSTEMS

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ABSTRACT

The minimum variance (MV) technique minimizes output variance of a receiver subject to a constraint which guarantees no cancellation of the desired signal while interference is mitigated. It has been successfully applied to multiuser detection for a direct sequence code-division multiple access (CDMA) system even when multipath channel is unknown. Its applicability in multiple access ultra-wideband (UWB) systems is investigated in this paper. First, similarities between a time-hopping (TH) UWB system using pulse position modulation (PPM) and a multirate CDMA system are explored where a code matrix for each user can be defined based on its unique TH sequence, similar to a spreading code matrix in a CDMA system. Meanwhile, modulation delays are transformed to amplitudes of pulses, yielding a virtually linear model. After following MV optimization procedures, the desired signal can be detected from outputs of a bank of receivers.

1. INTRODUCTION

Recently there emerges considerable interest in studying and deploying time-hopping (TH) ultra-wideband (UWB) communication systems due to their appealing features [1] and recent release of the spectral mask from the Federal Communications Commission. An UWB system communicates by short-duration pulses and can lead to low-cost implementation. Meanwhile, its low probability of interception and detection property is of extreme importance for secure communication links.

With on-going widespread deployment of UWB systems, reliable signal detection is desirable. Most existing approaches employ correlators to correlate received signal with a template signal [2]. This technique appears very powerful, but not so satisfactory in a multipath and multiple access channel. Therefore, both unknown multiple access interference (MAI) and multipath distortion need to be mitigated. Although multiuser detection (MUD) techniques can be directly applied to a direct sequence (DS) code-division multiple access (CDMA) based UWB system [3], their applicability is not trivial to an UWB system employing pulse position modulation (PPM). Some work has appeared for perfect channel [4] or multipath but known channel [5], [6]. However no MUD method exists to tackle those unknown interference. Since modulation delay causes non-linearity of the system and not easy for signal processing, we thus first transform the UWB channel input/output model to a linearly modulated system following [5] sampling at a pulse rate. The TH sequence uniquely specifies a "code" matrix for each user that only contains zeros and ones to indicate whether contribution of the channel exists or not. Then data model is in a tri-linear form. If we treat "code" matrix to be in a similar role as code matrix in a CDMA system [7], then the model resembles a multi-code multirate CDMA system [8], leading to application of the MV technique [7]. By using "code" matrices to distinguish users, multirate receivers can be designed for the desired user without a need to know its channel parameters.

2. DISCRETE-TIME UWB SYSTEM MODEL

Assume there are K users simultaneously sharing the spectrum in a multiple access (MA) TH UWB system. The transmitted baseband UWB signal from user k can be described by [6]

$$\alpha_k(t) = \sqrt{\mathcal{P}_k} \sum_{i=-\infty}^{\infty} w(t - iT_f - c_k(i)T_c - \tau_{I_k(\lfloor i/N_f \rfloor)}) \quad (1)$$

where $\mathcal{P}_k$ is the kth user's transmission power, $w(t)$ is the baseband monopulse, T_f is the frame duration, N_f is the number of frames over which an M-ary PPM symbol repeats, $c_k(i) \in [0, N_c - 1]$ is a periodic hopping sequence with period equal to one symbol period. Each chip has duration T_c. $I_k(\lfloor i/N_f \rfloor) \in [0, M-1]$ is the kth user's information bearing symbol during the ith frame, $\tau_{I_k(\lfloor i/N_f \rfloor)} = I_k(\lfloor i/N_f \rfloor)\sigma$ is the corresponding modulation delay in a multiples of σ seconds. Assume $T_f = N_c T_c$ and $T_c = M\sigma$. If we define $w_m(t) \triangleq w(t - m\sigma)$ where $m = 0, \cdots, M-1$ and $s_{k,m}(\lfloor i/N_f \rfloor) = \delta\Big(I_k(\lfloor i/N_f \rfloor) - m\Big)$, then (1) may be expressed by linear modulation in a chip rate as [6]

$$\alpha_k(t) = \sqrt{\mathcal{P}_k} \sum_{i=-\infty}^{\infty} \sum_{m=0}^{M-1} u_{k,m}(i) w_m(t - iT_c) \quad (2)$$

where chip index has replaced frame index in (1),

$$u_{k,m}(i) = s_{k,m}\Big(\lfloor i/(N_c N_f) \rfloor\Big) \widetilde{c}_k(i),$$

$$\widetilde{c}_k(i) = \delta\Big(\lfloor i/N_c \rfloor N_c + c_k(\lfloor i/N_c \rfloor) - i\Big).$$

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It is clear according to (2) that input $u_{k,m}(i)$ is modulated by waveform $w_m(t)$ at a chip rate. The transmitted signal $\alpha_k(t)$ propagates through a linear channel with channel $\bar{g}_k(t)$. At the receiver, the channel output is first passed through a matched filter matched to the monopulse $w(t)$. We can define a front-end effective channel including effects from modulated pulse at the transmitter, propagation channel and matched filter at the receiver by $g_{k,m}(t) = w_m(t) \star \bar{g}_k(t) \star w(-t)$ where $\star$ denotes convolution. Considering additive white Gaussion noise (AWGN) $v(t)$, the output of the matched filter becomes

$$y(t) = \sum_{k,i_1,m} \sqrt{\mathcal{P}_k} u_{k,m}(i_1) g_{k,m}(t - i_1 T_c) + v(t). \quad (3)$$

Assume each effective channel has maximum delay spread $q\sigma$. Then $y(t)$ is sampled very σ seconds to yield a discrete-time output $y(n) = y(t)|_{t=n\sigma}$. Using the discrete-time version of the effective channel and invoking $T_c = M\sigma$, we obtain a pulse-rate model

$$y(n) = \sum_{k,m} \sum_{i_2=0}^{q} \sqrt{\mathcal{P}_k} u_{k,m}(\lfloor \frac{n - i_2}{M} \rfloor) g_{k,m}(i_2) + v(n). \quad (4)$$

Consider P symbol intervals of data samples with coppresponding time instants $nMN_cN_f + p$ for $p = 1, \cdots, MPN_cN_f$ and collect them in a big vector $\boldsymbol{y}_n$ of length $\nu = MPN_cN_f$, a vector form model follows

$$\boldsymbol{y}_n = \sum_{k,m,l} \sqrt{\mathcal{P}_k} \boldsymbol{C}_{k,l} \boldsymbol{T}_m \boldsymbol{g}_k s_{k,m}(n+l) + \boldsymbol{v}_n \quad (5)$$

where symbol index l takes all integers $-\lceil q/(MN_cN_f) \rceil, \cdots, P-1$, $\boldsymbol{g}_k$ is an unknown channel vector for user k, $\boldsymbol{T}_m = [\boldsymbol{0}, \boldsymbol{I}, \boldsymbol{0}]^T$ is a tall selection matrix, $\boldsymbol{C}_{k,l}$ is a matrix constructed from corresponding $\widetilde{c}_k(i)$ and is uniquely determined by the TH sequence. If we treat $\boldsymbol{S}_{k,m,l} = \boldsymbol{C}_{k,l} \boldsymbol{T}_m$ as a code matrix for new input $s_{k,m}(n+l)$, then (5) resembles a multi-rate CDMA system with M low-rate inputs [8]. Then MV technique can be applied to detect $s_{k,m}(n+l)$ and finally decode information symbols.

3. BLIND MULTIUSER DETECTION IN UNKNOWN MULTIPATH CHANNEL

From our model (5), each time there are M virtual inputs $s_{k,m}(n)$ ($l = 0$) to be detected. Therefore, we need to design M receivers $\boldsymbol{f}_{k,m}, m = 0, \cdots, M-1$ for user k. Denote the auto-correlation of $\boldsymbol{y}_n$ by $\boldsymbol{R}$. To apply the MV idea, we minimize the total output power of all receivers subject to a common unknown constraint vector $\bar{\boldsymbol{g}}_k$ [8]

$$\min \sum_m \boldsymbol{f}_{k,m}^H \boldsymbol{R} \boldsymbol{f}_{k,m}^H, \text{subject to } \boldsymbol{S}_{k,m,0}^H \boldsymbol{f}_{k,m} = \bar{\boldsymbol{g}}_k. \quad (6)$$

The solution to (6) becomes

$$\boldsymbol{f}_{k,m} = \boldsymbol{R}^{-1} \boldsymbol{S}_{k,m,0} (\boldsymbol{S}_{k,m,0}^H \boldsymbol{R}^{-1} \boldsymbol{S}_{k,m,0})^{-1} \bar{\boldsymbol{g}}_k, \quad (7)$$

and the total output power parameterized by a common unknown constraint vector $\bar{\boldsymbol{g}}_k$ becomes

$$MOE = \bar{\boldsymbol{g}}_k^H [\sum_{m=0}^{M-1} (\boldsymbol{S}_{k,m,0}^H \boldsymbol{R}^{-1} \boldsymbol{S}_{k,m,0})^{-1}] \bar{\boldsymbol{g}}_k. \quad (8)$$

Since (8) is the resulting power after interference has been suppressed, the optimal constraint vector can be obtained by further maximizing this output power with respect to the constraint vector under constraint $||\bar{\boldsymbol{g}}_k|| = 1$ to avoid trivial solutions. Once $\bar{\boldsymbol{g}}_k$ is obtained, our detectors can be easily derived based on (7). It is noticed that among all M virtual inputs $s_{k,m}(n)$, only one takes value "1" while all others are zeros according to our definition. We then consider the absolute values of all receivers' outputs to determine the index $\bar{m}$ of the receiver which produces the largest output. Accordingly, modulation delay is determined to be $\bar{m}\sigma$ and user's information is decoded.

Compared with MUD techniques [5], [6], our method does not require channel state information. Meanwhile, our receiver is to detect $s_{k,m}(n)$ directly based on effective channel including effects of both propagation channel and hopping code, while [5], [6] involve a two-step procedure which inverts the propagation channel first and then despreads the resulting signal. In a case when channel delay spread is small, it is unnecessary to collect all ν samples to process because of low duty cycle of the UWB signal. Only $q + M$ pulse-rate samples in each frame using the time hopping code as a time reference are relevant to the desired signal. Therefore, totally $(q + M)PN_f$ samples are collected, resulting in a reduced dimension of the data vector and consequently reduced complexity.

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