Multipath Beamforming for UWB: Channel Unknown at the Receiver

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Abstract

We study two adaptive transmission approaches that coherently combine the energy from the first several reflected paths of the ultra-wideband (UWB) channel. Thus, the signal energy at the output of a non-adaptive correlator is enhanced. The two multipath beamforming techniques which are applicable to the DSC-UWB system in a LOS environment, suggest selecting a multilevel spreading sequence based on the signs of the first several multipath coefficients. By employing the beamforming approach, increased fluctuations in the multipath components power, are followed by an increase in the beamforming gain over m-, and single impulse sequences.

1 Introduction

We study an adaptive communications approach which is applicable to time-division duplex (TDD) ultra-wide band (UWB) [1] systems that concentrate most of the receiver complexity at the transmitter side in an attempt to reduce the size and the cost of the receiver. This motivation is quite similar to the one taken when designing portable DS-SS CDMA mobile communication systems. For this purpose, a technique termed pre-RAKE was suggested by Esmailzadeh and Nakagawa [2, 3]. Furthermore, the authors in [4, 5] proposed an optimal weight decision method for pre/post-RAKE. The optimal combing weights derived by employing the principal ratio combining technique can maximize the signal to noise ratio based on perfect channel information presented at both the transmitter and the receiver. However, determining, tracking and conveying the full channel information will increase the complexity of the receiver and require a significant overhead, which runs counter to the original intention. Hence, in this paper, we assume that only the transmitter knows partial information of the channel and adaptively selects the spreading sequence to enhance the energy at the output of the non-adaptive correlator.

Adaptive system's performance based on partial (e.g., the sign or the mean power of several or all multipath components) channel information may be sensitive to the fluctuation of channel coefficients. Thus, we need a robust signaling design when only limited channel information is available.

In this paper, we study two adaptive approaches that exploit the increased phase coherence of ultra-wide band (UWB) channels [6] with a "discrete" number of reflectors relative to narrowband wireless channels. The proposed multipath beamforming technique [7] is applicable to direct sequence phase coded UWB (DSC-UWB) system [8]. Beamforming spreading sequence design assumes that the sign of several reflection coefficients is known, which would be achievable with not too much effort in a TDD system.

We study ternary direct sequence based UWB (TS-UWB) signaling which includes epochs of zero signal amplitude as a natural extension of binary antipodal signaling for this type of technology. Allowing for some of the chips to be 0 enables significant improvement in the autocorrelation properties of the employed signaling.

In the first approach, we arbitrarily select a receiver correlating sequence which is known to the transmitter. Based on the limited channel information, the transmitter constructs the energy based beamforming spreading sequence which maximizes the output energy of the correlator. In this approach, if full channel information is well presented at the transmitter side, we could obtain the optimal energy based beamforming sequence which provides the lower bound of the system BER performance within the systems employing the same correlator sequence, when ISI is neglected.

The second beamforming approach is based on the autocorrelation properties of perfect ternary sequence [9, 10].

Both multilevel beamforming sequences can be quantized to generate ternary beamforming sequences by selecting a threshold.

The paper is organized as follows. In Section 2, a Nakagami fading UWB channel model and the signal model are introduced. In Section 3, we discuss the energy based beamforming spreading sequence which is BER optimal when perfect channel information is available and its quantization. In Section 4, we describe the low-correlation multilevel beamforming approach. Simulation results are presented in Section 5. In Section 6 we draw some concluding remarks.

2 Signal Model

An UWB channel with L resolvable paths is modelled as

$$h(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t - \tau_l) \tag{1}$$

where α_l and τ_l denote the channel gain and the propagation delay of the l_{th} path, respectively.

When sufficient multipath resolution is available, small changes in the propagation time only affect the path delay and path component distortion can be neglected. Under these assumptions, path coefficients α_l can be modelled as independent real valued random variables whose sign is a function of the material properties and, generally, depends on the wave polarization, angle of incidence, and the frequency of the propagating wave [11]. In addition, in slowly changing environments determining, tracking, and conveying the signs of reflection coefficients to the transmitter would require a non-significant overhead. In fact, due to channel symmetry in a UWB TDD system no receiver/transmitter feedback is necessary.

Recent results reveal that the power of individual multipath components is Gamma distributed [12]. The corresponding absolute value of α_l could be modelled as a Nakagami-m random variable. In the special case of $m = 1$, Nakagami reduces to Rayleigh distribution. For $m > 1$, the fluctuations of the signal strength are reduced compared to Rayleigh fading.

The channel coefficients α_l form a channel vector $\mathbf{h} = [\alpha_0, \alpha_1 \ldots, \alpha_{L-1}]^T$ such that $E\{\|\mathbf{h}\|^2\} = E\{\mathbf{h}^T\mathbf{h}\} = 1$, where $(.)^T$ denotes the matrix transpose operator. We assume $\tau_l = lT_c$, where T_c is the chip duration time. The corresponding received signal model is:

$$r(t) = \sum_{l=0}^{L-1}\sum_{k=0}^{K-1} \alpha_l b_k p(t - kT - lT_c) + n(t) \tag{2}$$

where

$$p(t) = \sum_{n=0}^{N-1} c_n \psi(t - nT_c) \ , \tag{3}$$

b_k are binary antipodal symbols, $T = NT_c$ is the symbol period, K is the number of symbols and N is the length of the spreading sequence $\{c_n\}$. $\psi(t)$ is the unit energy signaling pulse assumed here to be equal to zero outside an interval which is equal to or smaller to the chip interval $[0, T_c]$ and assumed known to the receiver. We normalize the symbol energy to unit energy, that is

$$\int_0^T [p(t)]^2 dt = \int_0^T [\sum_{n=0}^{N-1} c_n \psi(t - nT_c)]^2 dt = 1 \tag{4}$$

which implies

$$\|\mathbf{c}\|^2 = 1 \tag{5}$$

where $\mathbf{c} = [c_0, c_1 \ldots, c_{N-1}]^T$ denotes the spreading sequence vector.

For both energy based and low-autocorrelation multipath beamforming UWB signal design, we assume only that the transmitter knows the sign of the first L_c paths. In the former case, the correlator arbitrarily chooses a sequence and the transmitter attempts to employ a different spreading sequence so that the energy is enhanced at the output of the correlator. In both cases, by selecting the beamforming sequence at the transmitter side, the resulting effect is that the first L_c paths are combined coherently in a beamforming manner.

3 Energy Based Beamforming Sequence Design

Based on the preceding signal model, when a spreading sequence $\{c_n\}$ is transmitted and a same length receiver correlator sequence $\{d_n\}$ (either binary or ternary sequence) is employed at the receiver side, in order to maximize the energy at the output of the correlator, the optimal spreading sequence is obtained by:

$$\hat{\mathbf{c}} = arg \max_{\|c\|=1} \{\mathbf{d}^T\mathbf{H}\mathbf{c}\} \tag{6}$$

where $\mathbf{d} = [d_0, d_1 \ldots, d_{N-1}]^T$ denotes the receiver correlator sequence vector. $\mathbf{H}$ is the equivalent $N \times N$ channel matrix given by,

$$\begin{pmatrix} \alpha_0 & 0 & 0 & \cdots & & & 0 \\ \alpha_1 & \alpha_0 & 0 & \cdots & & & 0 \\ \vdots & \ddots & \ddots & & & & \vdots \\ \alpha_{L_c-1} & & \ddots & \ddots & & & \\ 0 & \ddots & & \ddots & \ddots & & \\ \vdots & & \ddots & & \ddots & \ddots & \\ 0 & \cdots & & \alpha_{L_c-1} & \cdots & \alpha_1 & \alpha_0 \end{pmatrix}.$$

Thus, the solution for energy based spreading sequence vector is $\hat{\mathbf{c}} = \mathbf{H}^T\mathbf{d}/\|\mathbf{H}^T\mathbf{d}\|$. We observe that the spreading sequence is a multilevel sequence when only the coefficient sign information is provided in the channel matrix $\mathbf{H}$ instead of true channel coefficient values. Under the assumption that only the sign information and dummy correlator sequence are known at the transmitter side, the more signs that we could evaluate from the channel, the better BER performance that we could achieve.

The multilevel sequence can be quantized into ternary beamforming sequence $\mathbf{c}^*$ by setting proper threshold k,

$$\mathbf{c}^* = sign(\lfloor \frac{\mathbf{H}^T\mathbf{d}}{k} \rfloor) \tag{7}$$

where $\lfloor \mathbf{x} \rfloor$ denotes rounding the elements of $\mathbf{x}$ to the nearest integers towards zero and k is an positive integer.

When k is chosen to be 1, the quantized ternary beamforming sequence is $\mathbf{c}^* = sign(\mathbf{H}^T\mathbf{d})$, which contains the least number of zeros in elements of $\mathbf{c}^*$ for all thresholds k. This quantization method is also suitable for the low correlation beamforming sequence discussed in the next section.

4 Low Correlation Beamforming Sequence Design

The construction of low-correlation multilevel beamforming sequences is based on the properties of perfect ternary sequence, the idea of pre-RAKE [2] and Lüke's approach to the construction of binary Alexis sequences [13].

In [13], Lüke suggested an approach to the construction of binary Alexis sequences [14] for various length. The aperiodic autocorrelation function (ACF) of Alexis sequences vanishes in a broad window. This approach achieves beamforming gain in a multipath environment by employing a perfect correlation multilevel beamforming sequence pair at the transmitter and the receiver. Note that, the only knowledge we need to construct the beamforming sequence is the same as in the previous approach, the signs of several multipath coefficients.

A mother perfect ternary sequence $\{c_0, c_1, ...c_{N-1}\}$, for which

$$\sum_{i=0}^{N-1} c_i c_{i+k} = \begin{cases} M & \text{if } (k \bmod N) \equiv 0 \\ 0 & \text{if } (k \bmod N) \neq 0 \end{cases} \tag{8}$$

where M is the number of non-zero elements in the sequence, is linearly combined with its first $L_c - 1$ left cyclic shifts where the combining coefficients are the signs of the first L_c paths. Thus, the multilevel beamforming sequence $\{\tilde{c}_0, \tilde{c}_1, ..., \tilde{c}_{N+\tilde{L}-1}\}$ is obtained by appending $\tilde{L} < L - 1$ zero guard chips to

$$\tilde{c_i} = \sum_{l=0}^{L_c-1} \text{sign}(\alpha_l) c_{(i+l)modN}, i = 0, 1, ...N - 1 \tag{9}$$

By periodically extending the mother perfect ternary sequence up to length $N + \tilde{L}$, we obtain the receiver correlation sequence. By employing this pair of sequences and a simple correlation receiver, the signal replicas corresponding to the first L_c paths are coherently combined at the output of the correlator.

For example, assume that the multipath number is 11, that the signs of the first three paths (including the direct path) are {+, -, +} respectively, and that the mother sequence is the Hoholdt's perfect ternary sequence {+ + + + + - + 0 + 0 - + + - 0 0 + - 0 - -} [9]. Then, the transmitter beamforming sequence of length 31 is {1 1 1 -1 3 -2 2 -1 0 2 -1 -1 2 -1 1 -2 2 -2 0 1 -1 0 0 0 0 0 0 0 0 0 0 } and the received correlation sequence is {+ + + + + - + 0 + 0 - + + - 0 0 + - 0 - - + + + + + - + 0 + 0}. The transmitter beamforming sequence is a multilevel signal with a number of levels no larger than $2L_c + 1$, while the received correlation sequence is ternary. In this example, the energy from the first, second, and third path are coherently combined. The multipath interference from other paths will be suppressed due to the perfect ACF properties of the mother perfect ternary sequence.

5 Analysis

The mean power of multipath component is chosen to be equal to average value given in [15], which is based on the indoor line of sight (LOS) measurements performed in 23 homes. In [15], it is observed that the line of sight component and the first 10 paths account for 33% and 75% of the total power, respectively. The sign of the reflected path coefficient is modelled as a uniformly distributed random variable [16].

The path power is quantized into 0.4 nanosecond bins corresponding to a chip duration T_c. We assume each bin contains exactly one multipath component (emulating a dense multipath environment) and the delay spread was restricted to be less than 4 nanosecond. The effects of interchip interference has been assumed negligible.

We study correlator receiver performance for a beamforming, m- and single impulse sequence. The m-sequence we use here is $[- - - - + - - + - + + - - + + + + + - - - + + - + + + - + - +]$. Bit energy for all signaling schemes is normalized. The employed multipath beamforming approaches are based on the sign of first L_c path coefficients. For each simulation block, one of 2^{L_c} beamforming sequences was selected based on the sign of the first L_c reflected path coefficients. In almost all cases of this experiment, we choose $L_c = 2$ and denote it as beamforming 2 or energy based sequence 2" in the plots. The construction of low-correlation beamforming sequence is based on a Hoholdt's perfect ternary sequence which has been introduced in Section 4.

In Figure 1, we choose the shape factor of the Nakagami distribution to be 5. Thus, the fluctuations of the strength of channel coefficients is much weaker than that in a Rayleigh fading channel. For the energy based spreading sequence design, the receiver correlation sequence is the same as what we used for the low-correlation based beamforming sequence design. Figure 1 depicts that more than $2-3$ dB multipath beamforming gain can be achieved by employing beamforming sequences over m- and single pulse sequences.

In Figure 2, we decrease the shape factor of the Nakagami distribution to 1 modeling a Rayleigh fading channel. The result demonstrates that the performance of all the signaling schemes degrade significantly, while the beamforming gain is increased another $3 - 4$ dB over what we have achieved in a Nakagami fading channel with the shape factor 5. Hence, the experiment shows that the two adaptive transmitting signaling schemes are more robust than m- and single pulse sequence signaling.

Figure 3 demonstrates the achievable BER performance when full sign information is available at the transmitter side. Larger number of signs the transmitter knows, larger the beamforming gain is expected. In the Rayleigh fading channel, by evaluating two signs of the multipath coefficients at the transmitter side, $BER = 10^{-3}$ can be achieved with $SNR = 15dB$, while m-sequences require a much larger SNR.

Figure 4 depicts the loss of beamforming gain after quantization. Energy based beamforming sequence with full sign information of the channel has large number of levels, which provides more options for choosing quantization threshold k. The quantized beamforming sequence which has the smallest number of zeros is obtained by setting $k = 1$. It has a less than 1dB beamforming gain loss compared to quantized ternary beamforming sequences with $k > 1$.

6 Conclusions

The proposed multipath beamforming signaling are applicable to the DSC-UWB system in a LOS environment. The experiment shows that, in a Nakagami fading multipath channel, increase in fluctuations in the multipath component power, is followed by an increase in the beamforming gain over m-, and single impulse sequences.

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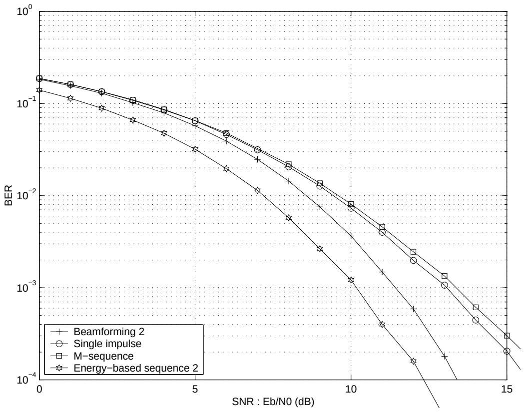

Figure 1: Nakagami fading channel with $m = 5$

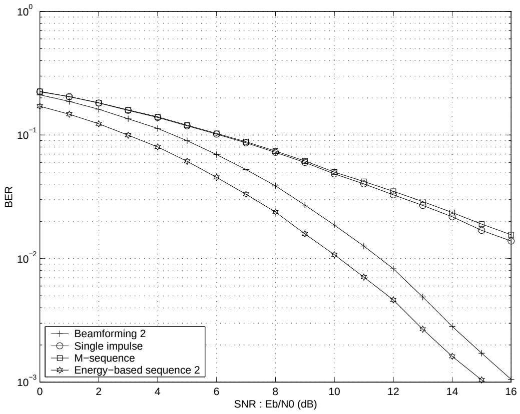

Figure 2: Nakagami fading channel with $m = 1$

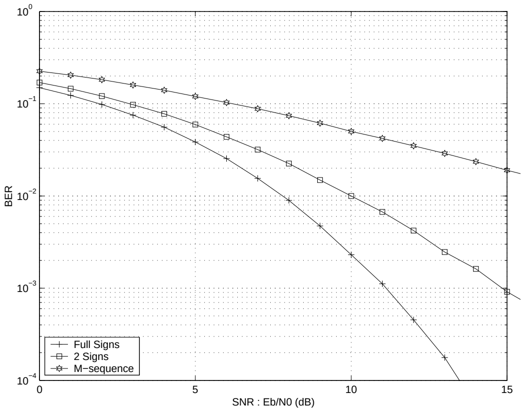

Figure 3: Rayleigh fading, the receiver correlation sequence is the m-sequence

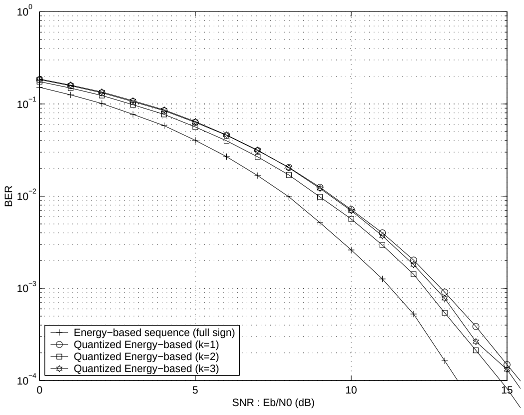

Figure 4: Rayleigh fading, Energy based sequence with full sign information of the channel compared with its quantized version for various thresholds k