

Modified MSSNR Based Channel Shortening for UWB Receiver Design Simplification

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Abstract—Ultra wide band (UWB) propagation channels are highly rich in multipaths. A major problem encountered in UWB systems is to capture enough multipaths to maintain a sufficient signal to noise ratio (SNR) for further signal processing. This leads to a RAKE receiver with large number of fingers. Channel shortening can help in simplifying the RAKE receiver architecture by reducing the channel taps. The recent developments in channel shortening mainly deal with time varying wired line scenarios like multicarrier modulation (MCM) systems where it is used to suppress few channel taps outside the cyclic prefix (CP) length. In UWB systems, the problem of channel shortening appears in its extreme form where a large number of channel taps are needed to be suppressed and most of the channel energy should be compressed within just few taps. Hence, the underlying theory and assumptions of most of the existing algorithms are invalidated when applied to UWB.

The algorithm which addresses the channel channel shortening in the most primitive way and can be applied to any system in general is maximum shortening signal to noise ratio (MSSNR) algorithm. In this paper, we modify the MSSNR algorithm to exploit the UWB characteristics and make it capable to handle the extreme nature of channel shortening needed in UWB systems. The proposed algorithm does not need any training or channel estimation and outperforms MSSNR algorithm in terms of different comparative parameters.

Index Terms—Channel shortening, RAKE receiver, ultra wide bandwidth (UWB), MSSNR.

I. INTRODUCTION

Channel shortening equalizers (CSEs) or time domain equalizers (TEQs) are in use in communication systems since early 1970s [1], [2]. Most of the recent applications of CSEs are specifically developed for multicarrier modulation (MCM) systems [3]- [6], [9] to mitigate intersymbol interference (ISI) and intercarrier interference (ICI) produced due to inadequate cyclic prefix (CP). These algorithms exploit some of those parameters explicitly available in MCM systems. A major problem encountered in UWB systems is to capture enough multipaths through a complex RAKE [8] to maintain a sufficient signal to noise ratio (SNR) for further signal processing. CSEs can also greatly simplify UWB receiver structure by reducing the channel delay spread [7], [15]. As UWB systems have entirely different architecture and channel models, new or modified channel shortening algorithms exploiting UWB features are required to address the specific needs of UWB systems.

Remaining of the paper is organized as follows: In section II and III, we briefly discuss the UWB channel models and the signal format used respectively. Section IV describes

the assumed system architecture and associated mathematical model. Section V explains the underlying assumptions and mathematical structure of proposed modified MSSNR algorithm. Simulation results are shown in section VI and section VII concludes the discussion.

II. CHANNEL MODEL

Based on measurement campaigns carried out by different researchers [10]- [12], for a wide variety of propagation scenarios, IEEE 802.15 Study Group 3a has finalized four standard models for UWB channels [11]. In this paper we use these standard channel models, namely CM 1 to CM 4, to develop and evaluate the performance of CSE. These channel models are modified versions of Saleh-Valenzuela (S-V) model [13] and generated to fit different propagation scenarios. They take, in general, the following mathematical form:

$$h(t) = X \sum_{l=0}^L \sum_{k=0}^K \alpha_{k,l} \delta(t - T_l - \tau_{k,l}), \quad (1)$$

where $\alpha_{k,l}$ are the multipath gain coefficients, T_l is the delay of the l^{th} cluster, $\tau_{k,l}$ is the delay of k^{th} multipath component relative to the l^{th} cluster arrival time T_l , L is the number of clusters, K is the number of multipaths within a cluster and X represents the log-normal shadowing.

III. SIGNAL FORMAT

To develop CSE, we assume the first derivative of Gaussian function as the transmitted pulse which is also the most commonly used pulse shape in available UWB literature and hardware [14]. Assuming $g(t)$ is the transmitted pulse shape, for a binary time hopping (TH) UWB signal employing pulse position modulation (PPM), a symbol transmitted by j^{th} user can be given as:

$$s_j(t) = \sum_{i=0}^{N-1} g(t - iT_f - c_{j,i}T_c - a_j\Delta), \quad (2)$$

where $s_j(t)$ is the symbol transmitted by the j^{th} user, T_f is pulse repetition period, N is the number of repetitions, T_c is TH chip period, $c_{j,i}$ is the TH sequence for j^{th} user, $a_j \in \{0, 1\}$ and Δ is the delay to represent a binary symbol.

IV. SYSTEM ARCHITECTURE

The received symbol from j^{th} user is the convolution between (1) and (2), therefore:

$$r_j(t) = \sum_{m=0}^{\infty} \sum_{l=0}^L \sum_{k=0}^K X_j \alpha_{k,l} \delta(t - T_l - \tau_{k,l}) s_j(m - t), \quad (3)$$

where we assumed that the channel impulse response (CIR) does not exist when $t < 0$.

The above equation in a multiuser environment having N_u simultaneous active users experiencing same channel length with additive white Gaussian noise (AWGN) can be rewritten as:

$$r_j(t) = \sum_{j=1}^{N_u} \sum_{m=0}^{\infty} \sum_{l=0}^L \sum_{k=0}^K X_j \alpha_{k,l} \delta(t - T_l - \tau_{k,l}) s_j(m - t) + n(t), \quad (4)$$

where $n(t)$ is additive white Gaussian noise.

Since the transmitted pulse $g(t)$ is very narrow in time, it can be approximated to an impulse as compared to the channel delay spread. Thus, if a single pulse is transmitted, the received pulse will quite accurately reveal the CIR. This is a characteristic feature of UWB systems and not available in other systems where pulse/bit duration is comparable to channel delay spread. Hence, a CSE which can shorten the received signal is also capable of shortening the CIR, provided that each user transmits a single pulse in synchronization with others. Assume that the CSE shortens the channel to the $K'th$ multipath of the $L'th$ cluster. In this case, the above equation can be split into two parts with respect to channel taps as follows:

$$r_j(t) = \underbrace{\sum_{j=1}^{N_u} \sum_{m=0}^{\infty} \sum_{l=0}^{L'} \sum_{k=0}^{K'} X_j \alpha_{k,l} \delta(t - T_l - \tau_{k,l}) s_j(m - t)}_{\mathbf{r}_1^{(p,1)}} + \underbrace{\sum_{j=1}^{N_u} \sum_{m=0}^{\infty} \sum_{l=L'+1}^L \sum_{k=K'+1}^K X_j \alpha_{k,l} \delta(t - T_l - \tau_{k,l}) s_j(m - t) + n(t)}_{\mathbf{r}_2^{(q,1)}}. \quad (5)$$

Or alternatively, each part in (5) can be given in matrix form as:

$$\mathbf{r}_1^{(p,1)} \triangleq \sum_{j=1}^{N_u} X_j \mathbf{S}_j^{(p,\varphi)} \mathbf{h}_{1,j}^{(\varphi,1)}$$

and $\mathbf{r}_2^{(q,1)} \triangleq \sum_{j=1}^{N_u} X_j \mathbf{S}_j^{(q,\varphi')} \mathbf{h}_{2,j}^{(\varphi',1)} + \mathbf{n}^{(q,1)}, \quad (6)$

where \mathbf{S}_j is the convolution matrix of appropriate order for j^{th} user transmitted signal vector \mathbf{s}_j , $\mathbf{h}_{1,j}^{(\varphi,1)}$ and $\mathbf{h}_{2,j}^{(\varphi',1)}$ are the splitted parts of channel vector $\mathbf{h}_j^{(L,K,1)}$. The parentheses show the order of each matrix or vector such that $\varphi = (L' - 1)K + K'$, $\varphi' = K(L - L' + 1) - K'$, $p = \varphi + b - 1$, $q = \varphi' + b - 1$, where b is the length of transmitted signal vector \mathbf{s}_j . It is worthy to note that the effective noise component $\mathbf{n}^{(q,1)}$ is added only in $\mathbf{r}_2^{(q,1)}$ to simplify the expression.

V. MODIFIED MSSNR ALGORITHM

Let \mathbf{w} be the CSE such that:

$$\mathbf{w} = [w_0 \quad w_1 \quad w_2 \quad \cdots \quad w_{d-1}]^T, \quad (7)$$

where d is the number of CSE taps.

If the CSE is inserted before the RAKE reception then the received signal applied to the RAKE is:

$$\mathbf{r} = (\mathbf{R}_1^{(\eta,d)} + \mathbf{R}_2^{(\eta',d)})\mathbf{w}, \quad (8)$$

where $\mathbf{R}_1^{(\eta,d)}$ and $\mathbf{R}_2^{(\eta',d)}$ are the convolution matrices of $\mathbf{r}_1^{(p,1)}$ and $\mathbf{r}_2^{(q,1)}$ respectively, $\eta = d + p - 1$ and $\eta' = d + q - 1$.

Several CSE designs formulate a single Rayleigh quotient to be optimized and in general take the following mathematical form:

$$\mathbf{w}_{opt} = \arg \max_{\mathbf{w}} \frac{\mathbf{w}^H \mathbf{B} \mathbf{w}}{\mathbf{w}^H \mathbf{A} \mathbf{w}}, \quad (9)$$

The solution to this problem is to maximize the numerator keeping denominator constant or minimize the denominator with constrained numerator. Thus, an optimum CSE is the generalized eigenvector corresponding to largest or smallest generalized eigenvalue respectively of appropriate matrix pairs. Constrained are applied to avoid some trivial solutions. The algorithm which deals channel shortening in a very primitive sense is maximum shortening signal to noise ratio (MSSNR) [16]. In this algorithm, the channel energy outside the shortened window is minimized keeping the energy within the window constant. This solution assumes that $d < \varphi$, violation of this assumption results in a situation where \mathbf{B} can not be decomposed through Cholesky factorization. In case of UWB channels, we need a comparatively larger d which could efficiently shorten the dense multipath channel. This makes $d > \varphi$ and thus normal solution does not work. A variant of [16] is [17] which works the other way round and hence a CSE with $d > \varphi$ is possible. Here, we modify [17] to work in UWB scenarios.

In the proposed algorithm, we define a unique Rayleigh quotient be maximized. From (8), the signal energy within the shortened channel window and outside can be given as:

$$\lambda_{win} \triangleq \mathbf{w}^T [\mathbf{R}_1^{(\eta,d)}]^T \mathbf{R}_1^{(\eta,d)} \mathbf{w} \quad (10)$$

$$\lambda_{wall} \triangleq \mathbf{w}^T [\mathbf{R}_2^{(\eta',d)}]^T \mathbf{R}_2^{(\eta',d)} \mathbf{w}. \quad (11)$$

To efficiently shorten the channel, an optimum \mathbf{w} will maximize λ_{win} keeping λ_{wall} constant.

Since UWB CIRs exhibit a sort of exponentially decaying profile, therefore the signal amplitude is larger in beginning and reduces with time. As we assumed the shortened channel window is spanning over first $(L' - 1)K + K'$ multipaths, therefore some statistical parameters associated to shortened channel window and the rest of the CIR can be optimized to improve CSE performance. Hence we define and include the following parameters in the optimization problem:

The second moment of $\mathbf{r}_1^{(p,1)}$ about the mean of $\mathbf{r}_2^{(q,1)}$ is:

$$\boldsymbol{\theta}^{(p,1)} \triangleq E[\text{diag}(\gamma\gamma^T)], \quad (12)$$

where

$$\gamma \triangleq \mathbf{r}_1^{(p,1)} - \mu_{\mathbf{r}_2} \mathbf{u}^{(p,1)}, \quad (13)$$

in which $\mu_{\mathbf{r}_2} = E[\mathbf{r}_2^{(q,1)}]$ and $\mathbf{u}^{(p,1)}$ contains all elements equal to 1.

The additional parameter to be included in optimization is ψ :

$$\psi \triangleq \mathbf{w}^T [\Theta^{(\eta,d)}]^T \Theta^{(\eta,d)} \mathbf{w}, \quad (14)$$

where $\Theta^{(\eta,d)}$ is the convolutional matrix of $\theta^{(p,1)}$.

This parameter basically addresses the signal amplitude level difference within and outside the shortened channel window. This can be optimized to force the channel taps in a certain region to their minimum or maximum.

The second parameter is the gradient of $\mathbf{r}_1^{(p,1)}$:

$$\xi^{(p,1)} \triangleq \nabla \mathbf{r}_1^{(p,1)}, \quad (15)$$

where ∇ is gradient operator. Hence, the other optimization parameter is:

$$\zeta \triangleq \mathbf{w}^T [\Xi^{(\eta,d)}]^T \Xi^{(\eta,d)} \mathbf{w}, \quad (16)$$

where $\Xi^{(\eta,d)}$ is the convolutional matrix of $\xi^{(p,1)}$.

This parameter exploits the decaying characteristics of the CIR and can be optimized to increase or decrease the decaying factor within or outside the shortened channel window.

Therefore, based on (10), (11), (14) and (16) we define the following optimization problem for the proposed algorithm:

$$\mathbf{w}_{opt} = \arg \max_{\mathbf{w}} \frac{\lambda_{win}}{\lambda_{wall} + \psi + \zeta}. \quad (17)$$

Replacing the values:

$$\mathbf{w}_{opt} = \arg \max_{\mathbf{w}} \frac{\mathbf{w}^T (\mathbf{R}_1^T \mathbf{R}_1) \mathbf{w}}{\mathbf{w}^T (\mathbf{R}_2^T \mathbf{R}_2 + \Theta^T \Theta + \Xi^T \Xi) \mathbf{w}}. \quad (18)$$

where parentheses depicting the order of each matrix has been removed for concise representation.

The above equation poses a traditional optimization problem as in (9) with:

$$\mathbf{B} = \mathbf{R}_1^T \mathbf{R}_1 \quad (19)$$

$$\text{and } \mathbf{A} = \mathbf{R}_2^T \mathbf{R}_2 + \Theta^T \Theta + \Xi^T \Xi. \quad (20)$$

Hence:

$$\mathbf{w}_{opt} = (\sqrt{\mathbf{A}}^T)^{-1} \hat{\mathbf{a}}_{max} \quad (21)$$

where $\hat{\mathbf{a}}_{max}$ is the eigenvector corresponding to maximum eigenvalue of $(\sqrt{\mathbf{A}})^{-1} \mathbf{B} (\sqrt{\mathbf{A}}^T)^{-1}$ and $\sqrt{\mathbf{A}}$ is the Cholesky factor of \mathbf{A} .

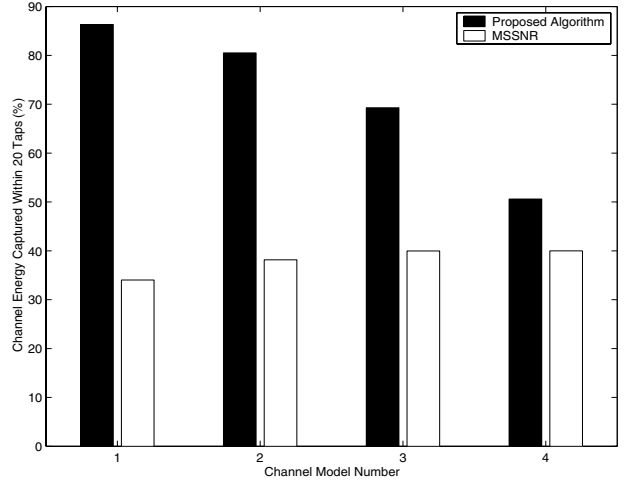


Fig. 1. Channel energy captured within 20 taps of shortened window in a single user and noise free environment. For CM1 and CM2 $d=50$ and for CM3 and CM4 $d=75$.

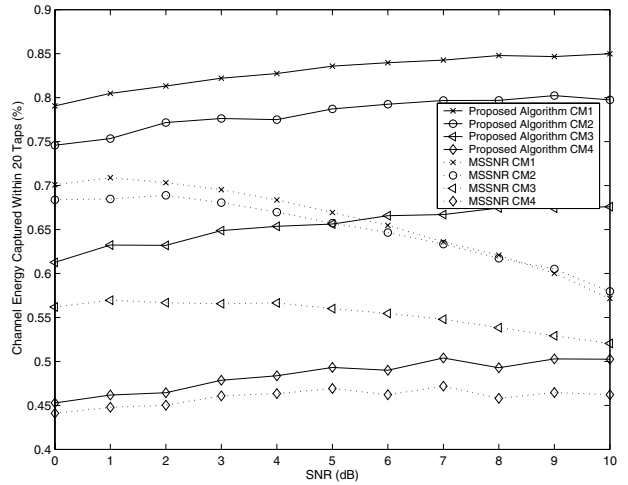


Fig. 2. Channel energy captured within 20 taps of shortened window in a multiuser AWGN environment with $N_u=10$. For CM1 and CM2 $d=50$ and for CM3 and CM4 $d=75$.

VI. SIMULATION RESULTS

Extensive simulations are performed to obtain a fair comparison between the proposed algorithm and MSSNR algorithm in standard UWB channel models. Figure 1 shows the channel captured energy within a shortened channel window of first 20 multipaths in a single user and noise free environment. The value of $d = 50$ for CM 1 and CM 2, and $d = 75$ for CM 3 and CM 4. CSE length is chosen Figure 2 depicts the comparative performance of both algorithms in a multiuser AWGN environment with $N_u = 10$. Remaining of the factors remain same as in previous case.

Both figures clearly indicate that the proposed algorithm outperforms the MSSNR algorithm in terms of energy capture. It is observed that MSSNR algorithm's performance gradually decreases with increasing SNR in a multiuser environment

whereas the proposed algorithm performs gradually better. The performance enhancement is a result of inclusion channel statistics in the optimization problem.

VII. CONCLUSION

In this paper, we presented a modified version of MSSNR algorithm which exploits characteristic features of UWB communications systems and useful channel statistics for performance improvement. It is shown through simulations that these modifications enhance the performance of algorithm in UWB environment. Hence, this algorithm enables a simplified RAKE structure with less of number fingers but still capturing good percentage of channel energy. Receiver's front end simplification simplifies the whole receiver structure and the further signal processing involved. Such a RAKE incurs less manufacturing cost from hardware implementation point of view.

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