Semi-Blind Equalization for OFDM using

Space-Time Block Coding and Channel Shortening

Final Report

Multidimensional Digital Signal Processing

Spring 2008

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May 9, 2008

Abstract

Multiple input multiple output (MIMO) communications has become a stalwart in high speed communication systems. By using multiple antennas along with space-time coding, one can leverage spatial diversity gain, or multiple propagation paths, for transmitted signals. This in turn can improve reliability in communication systems. Channel shortening is necessary when the channel impulse response is longer than the cyclic prefix (CP) in a multi-carrier modulation scheme. This precludes low complexity signal recovery, also known as equalization, in the frequency domain. Equalization at the receiver can only be achieved by properly estimating the channel. While known symbols can be transmitted in order to achieve channel shortening and estimation, frequently sending out these pilot symbols may consume precious bandwidth. As an alternative, semi-blind approaches, which use known symbol structure and limited pilot symbols, have been receiving more attention. We propose a cascaded receiver design, which first performs channel shortening with a blind algorithm, using only the structure of the CP, developed by Martin *et al.* in [1]. The receiver then estimates the channel using a semi-blind technique [2], and uses the resulting channel estimate to perform frequency domain equalization. In this paper, we evaluate the combination of a blind channel shortening algorithm and semi-blind channel estimation in a linearly precoded space-time (ST) orthogonal frequency division multiplexing (OFDM) system.

I. Introduction

As the demand to stay constantly connected with the world grows, the necessity for high data rate communication systems has become ubiquitous. Using multiple antennas in a communication system introduces spatial diversity or multiple propagation paths for the transmitted signals, which creates new opportunities to increase the data rate of the system. In multiple input multiple output (MIMO) communication systems, the multiple antennas allow the designer to encode the transmitted signal over space as well as time. This technique, known as space-time coding, is a powerful way to leverage spatial diversity gain and improve transmission reliability with lower bit-error rates.

In most wireless communication systems, we contend with a multipath channel which exhibits inter-symbol interference (ISI). That is, symbols being transmitted at different times can arrive simultaneously at the receiving antenna after traversing different paths. The multipath phenomenon can be attributed to propagation effects on radio frequency signals such as reflection and refraction. Many wireless standards which incorporate MIMO, such as IEEE 802.11n, IEEE 802.16e, 3rd Generation Partnership Project – Long Term Evolution (3GPP LTE), and IEEE 802.20, use orthogonal frequency division multiplexing (OFDM) due to its simplified equalization and resilience in multipath effects [3]. In multi-carrier systems, channel equalization is simplified because we can partition the channel into many narrowband flat-fading sub-channels that can be equalized individually. This is accomplished by pre-pending a cyclic prefix (CP) from the end of the transmitted OFDM symbol to the front of the transmitted OFDM symbol; to ensure that the convolution of the OFDM symbol with a multipath channel can be viewed as pointwise multiplication in frequency.

In this report, we consider a MIMO OFDM system model using space-time coding. We evaluate the combination of a blind channel shortening algorithm proposed in [4] and the subspace based channel estimator in [5] using a realistic model of a time-varying channel. This report is organized as follows. After introducing basic concepts pertinent to our system such as blind channel shortening, and semi-blind channel estimation in Section II, we present our full system model in Section III. Section IV describes the model we used for a slowly time-varying channel, while Section V details the implementation of our project. Section VI provides concluding remarks and insights and summarizes this paper.

II. Background

A. Channel Shortening

Frequency domain channel equalization is a popular technique used in recovering the transmitted signal at the receiver. However, in an OFDM communication system, channel shortening is necessary whenever the channel impulse response is longer than the cyclic prefix. After shortening, a frequency domain equalizer (FEQ), which is composed of a complex-valued gain for each frequency bin, corrects the residual amplitude scaling and phase rotation. The two traditional approaches to channel shortening are training-based and blind, extensively studied by Martin *et al.* in [6] and Melsa *et al.* in [7]. While the training-based approach usually yields faster equalizer convergence, the system can suffer from a decrease in throughput due to the need for frequent transmission of pilot tones in a time-varying channel. Blind methods excel in this regard, but may not converge as quickly as trained equalizers, nor do they provide a straightforward way to compute the optimal FEQ [1].

B. Semi-blind Channel Estimation

To perform frequency domain equalization, we must still obtain a channel estimate at the receiver. The approaches to this problem are analogous to that of channel shortening. Sending out pilot tones intermittently for a training-based approach may consume precious bandwidth and decrease capacity, while purely blind schemes have trouble resolving an accurate channel estimate. Semi-blind approaches take advantage of the known structure in the transmitted sequence, and combine it with limited pilot tones in order to accurately estimate channels with minimal training overhead.

III. System Model

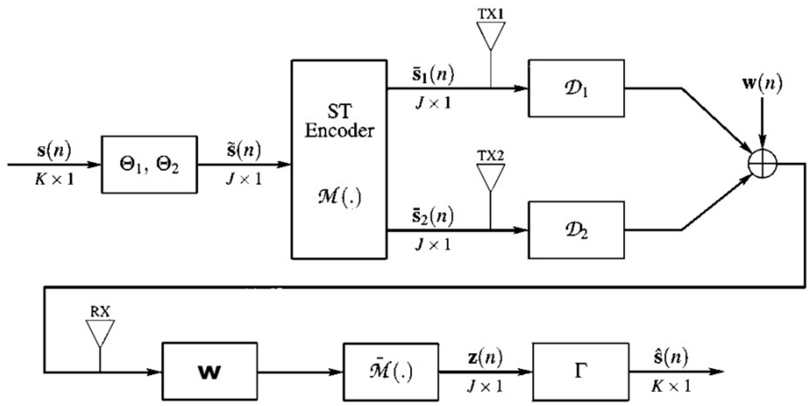

Fig 1. Space-time coded multiple input single output OFDM system model. Precoding is added by Θ_1 and Θ_2, followed by Alamouti space-time coding. The signals are then transmitted in parallel through channels D_1 and D_2, combined with Gaussian noise, and received by a single antenna. The signal is then filtered by the channel shortener, Alamouti decoded, and equalized by M and Γ. [5]

Fig. 1 above illustrates the system model which we used for this project. We assume the use of a 4-QAM (Quadrature Amplitude Modulation) constellation for our symbols sequence *s(n)*. This sequence is grouped into two *K x 1* column vectors which denote the even and odd sequences as *s(2n)* and *s(2n+1)*. These sequences are then linear precoded by pre-multiplying with matrices θ_1 and θ_2 of size *J x K* to create:

$$\tilde{s}(2n) = \theta_1 s(2n) \quad \tilde{s}(2n+1) = \theta_1 s(2n+1) \tag{1}$$

We then feed the resulting *J x 1* length column vectors into an Alamouti block space-time encoder which shape the vectors into the following *2J x 2* matrix:

$$\begin{bmatrix} \bar{s}_1(2n) & \bar{s}_1(2n+1) \\ \bar{s}_2(2n) & \bar{s}_2(2n+1) \end{bmatrix} = \begin{bmatrix} \tilde{s}(2n) & -\tilde{s}^*(2n+1) \\ \tilde{s}(2n+1) & \tilde{s}^*(2n) \end{bmatrix} \tag{2}$$

These vectors are sent through an OFDM modulator, which creates the corresponding transmitted time-domain symbols and then sent out over each of the two transmitters at two OFDM symbol times. We can view the convolution of this symbol sequence with each FIR channel as a multiplication in frequency due to the cyclic convolution property of the Discrete Fourier Transform (DFT). We receive the sum of these convolutions with additive Gaussian noise at the receiver, and process these symbols in an OFDM demodulator. We then remove the effects of Alamouti encoding, and send the sequence through a zero-forcing equalizer to recover the original information-bearing symbols.

IV. Modeling

The multipath channel can be modeled in several ways, such as with a multi-tap FIR filter or a Rayleigh random process which is comprehensively examined in [8, 9]. A FIR filter can simulate the effect of discrete signals transmitted at different times arriving simultaneously, while a Rayleigh random process is a good model when there is no dominant direct-path component in the channel impulse response. We examine channels which vary slowly in time due to a mobile transmitter at pedestrian speeds, which requires the receiver to track the evolving channel.

In [5], the authors test the channel estimation algorithm over slowly time-varying FIR channels in which each tap varies according to Jakes' model [10]. Since this model was originally developed in 1975, we evaluate the performance of the algorithms using the more modern 3GPP spatial channel model specified in [11], shown in figure 2 below.

$$h_{u,s,n}(t) = \sqrt{\frac{P_n \sigma_{SF}}{M}} \sum_{m=1}^{M} \left(\begin{array}{l} \sqrt{G_{BS}(\theta_{n,m,AoD})} \exp\left(j\left[kd_s \sin(\theta_{n,m,AoD}) + \Phi_{n,m}\right]\right) \times \\ \sqrt{G_{MS}(\theta_{n,m,AoA})} \exp\left(jkd_u \sin(\theta_{n,m,AoA})\right) \times \\ \exp\left(jk\|\mathbf{v}\| \cos(\theta_{n,m,AoA} - \theta_v) t\right) \end{array} \right)$$

Fig. 2. P_n is the power of the nth path, j is the square root of -1
σ_{SF} is the lognormal shadow fading , not used, M is the number of subpaths per-path (20)
$\theta_{n,m,AoD}$, $\theta_{n,m,AoA}$ is the Angle of Departure and Angle of Arrival for the mth subpath of the nth path
$G_{BS}(\theta_{n,m,AoD})$, $G_{MS}(\theta_{n,m,AoA})$ is the base station and mobile station antenna gain
k is the wave number $2\pi/\lambda$ where λ is the carrier wavelength in meters, d_s, d_u is antenna spacing in meters at base station and mobile station, $\Phi_{n,m}$ is the phase of the mth subpath of the nth path
$\|\mathbf{v}\|$, θ_v is the magnitude and angle of the MS velocity vector

V. Implementation and Results

A. Implementation

We developed a simulation of our two transmitters by one receiver system model using MATLAB. We grouped the input sequence into column vectors of length $K = 48$. For the system transmitter, we generated the linear precoders offline using columns from a *JxJ* Walsh-Hadamard matrix where $J = 64$. The linear precoding is then followed by an Alamouti block encoder, and two OFDM modulators, corresponding to the two transmit antennas, that create a time domain waveform for convolution with the channel. We generated 500 pairs of OFDM symbols and convolved each pair with one of 500 realizations of the 3GPP channel model. At the receiver, the two channel output sequences are summed and combined with an additive Gaussian noise sequence with mean of 0 and variance of .005. At the receiver, we removed the cyclic prefix from every OFDM symbol, transformed the symbols back to the frequency domain using an FFT, and passed pairs of symbols into an Alamouti decoder. In order to perform Alamouti decoding, we first take a running correlation matrix R_{yy} of the received data and perform the subspace algorithm detailed in [5] to obtain a channel estimate. It should be noted that the resulting channel estimate $[h_3^T, h_4^H]$ contains an unresolved scalar ambiguity α. That is:

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \alpha\mathbf{I} & 0 \\ 0 & \alpha^*\mathbf{I} \end{bmatrix} \begin{bmatrix} h_3 \\ h_4 \end{bmatrix} \qquad (3)$$

We then multiply the received vector by the Hermitian, denoted by superscript $\mathcal{H}$, of the channel estimates and obtain:

$$\check{z}(n) = \begin{bmatrix} \overline{D}_{12}\theta_1 & 0 \\ 0 & \overline{D}_{12}\theta_2 \end{bmatrix} + \check{s}(n) + D^{\mathcal{H}}\breve{w}(n) \qquad (4)$$

It is easily shown that we can resolve the sent symbols up to a scalar ambiguity, by pre-multiplying $\check{z}(n)$ with the pseudo-inverse of $\overline{D}_{12}\theta_1$ and $\overline{D}_{12}\theta_1$. Our linear precoders were chosen to be distinct, permitting the scalar ambiguity can be resolved using a single pilot tone placed in the same position of the vectors *s(2n)* and *s(2n+1)*. We can then resolve α using the equation:

$$\alpha = ({p_1}^*\grave{s}_1 + p_2{\grave{s}_2}^*)/(|p_1|^2 + |p_2|^2) \qquad (5)$$

where p_1,p_2 stand for the sent pilot symbols and $\grave{s}_1$,$\grave{s}_2$ stand for the received symbols.

B. Results

Simulations from [1] showed the convergence of their channel shortening algorithm after iterating over thousands of samples. We found that iterating over several hundred OFDM symbols was not enough to yield the same results. Also, the cost function used in FRODO is designed to minimize the energy of the channel impulse response outside a set window of length

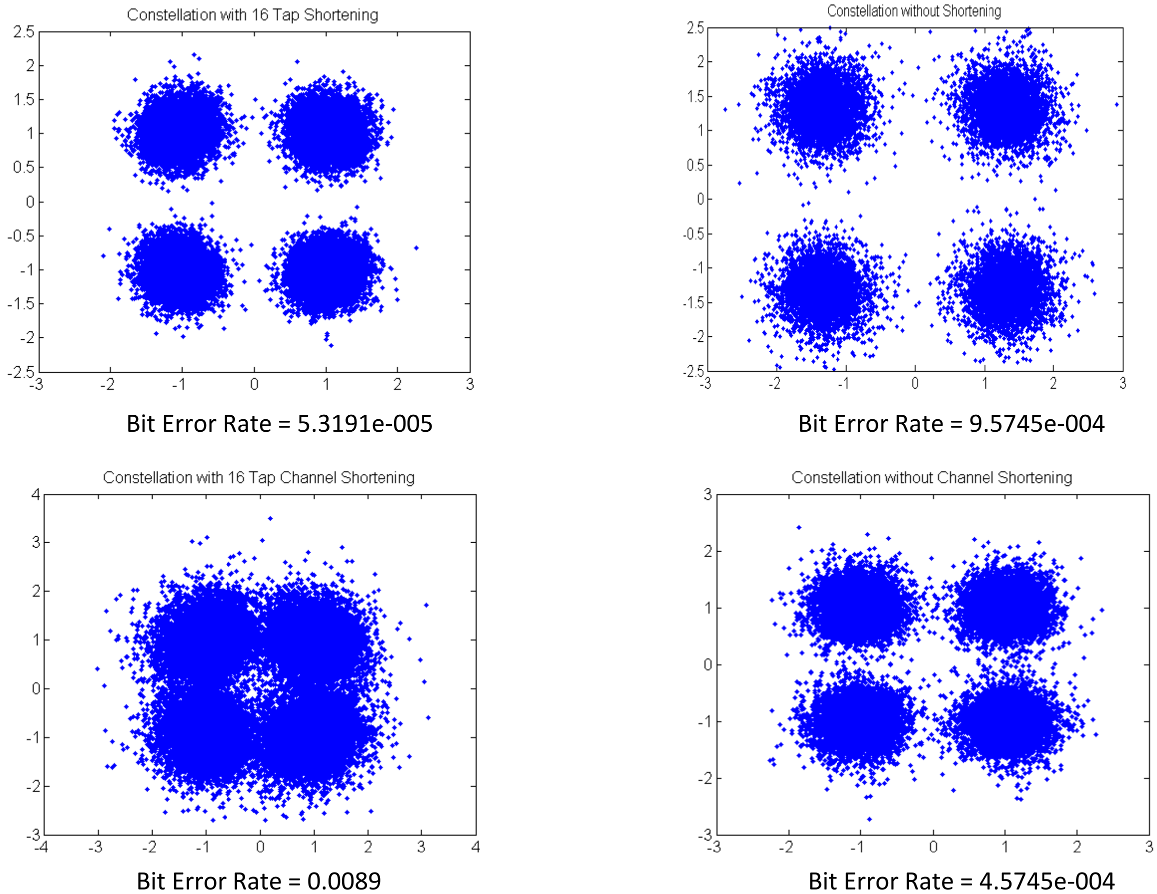

Fig 3. Comparison of constellation plot with and without channel shortening for different trials

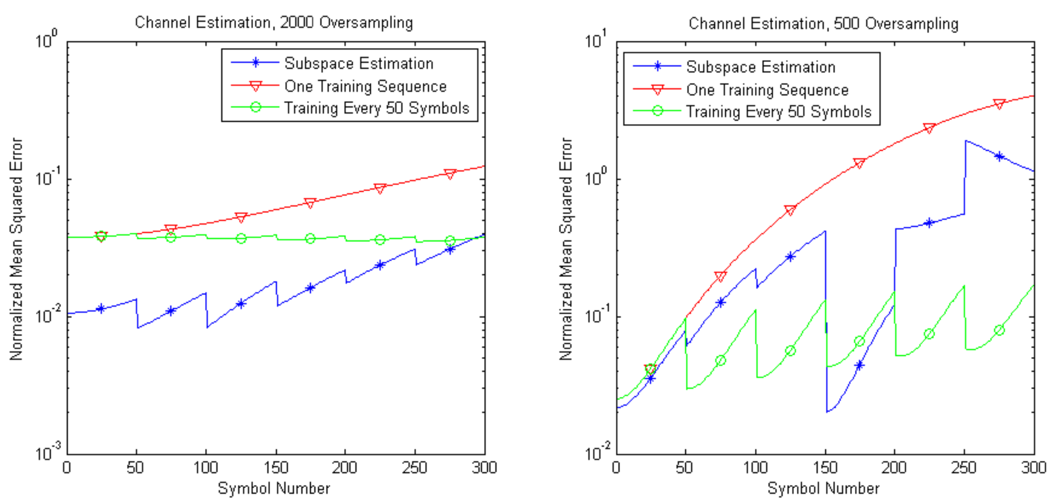

Fig. 4. Channel NMSE with subspace estimation once every 50 symbols over 4-tap FIR channel assuming 2GHz carrier frequency oversampled at 2000 samples (left) and 500 samples (right) per half wavelength v.

While the algorithm could perform joint channel shortening for a MIMO system, minimizing the energy did not translate into lower bit error rate in our OFDM simulations. Figure 3 illustrates our results when running our simulation with and without channel shortening. Including channel shortening did not consistently yield lower bit error rates for our system.

In order to match the slow time variations of normalized mean square error (NMSE) shown in figure 4 of [5], we set the oversampling factor in the 3GPP-LTE channel to 2000 samples per half wavelength at 2 GHz. We approximated the estimation error of a training based approach by adding Gaussian noise with mean zero and variance 0.005 to the actual channel, matching the channel NMSE of the training based approach in figure 4 of [5]. At this unrealistic sampling rate, the channel varies slowly enough for the subspace method to track it, outperforming the training based approximation. However, when we reduce the channel sampling rate to 500, the channel varies too quickly and frequent training outperforms the semi-blind method as seen in figure 4. In practice, communications systems would have an oversampling factor of less than 50, and this subspace-based channel estimation algorithm would not be a good choice to achieve channel equalization. As a consequence, the cascade of blind channel shortening and semi-blind channel estimation also did not perform reliably.

VI. Conclusion

In this paper, we have evaluated the bit error rate performance of Martin *et al.*'s blind channel shortening algorithm and the NMSE performance of Zhou *et al.*'s semi-blind channel estimation technique in a MIMO OFDM system over a modern channel model. The cost function used to calculate the channel shortening filter was designed to maximize the channel energy within a window but our simulations show that this did not reliably translate into reduced bit error rates for space-time coded OFDM. This disconnect could be addressed in future work by altering the cost function to create a direct link between channel shortening and reduced bit error rate, perhaps in a single carrier cyclic prefixed system. In addition, the semi-blind channel estimation algorithm was unable to track a moderately time varying channel and the combination of the two algorithms performed poorly. The authors would like to thank Prof. R. Martin for sharing the MATLAB code implemented in [1].

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