CHANNEL EQUALIZATION AND SPATIAL DIVERSITY FOR AERONAUTICAL TELEMETRY APPLICATIONS

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ABSTRACT

This work explores aeronautical telemetry communication performance with the SOQPSK-TG ARTM waveforms when frequency-selective multipath corrupts received information symbols. A multi-antenna equalization scheme is presented where each antenna's unique multipath channel is equalized using a pilot-aided optimal linear minimum mean-square error filter. Following independent channel equalization, a maximal ratio combining technique is used to generate a single receiver output for detection. This multi-antenna equalization process is shown to improve detection performance over maximal ratio combining alone.

KEY WORDS

Multipath, minimum mean-square error, equalization, spatial diversity, maximal ratio combining

INTRODUCTION

Aeronautical telemetry range experiments are transforming from single asset tests to complex, networked events with multiple ground and airborne systems that must communicate within scarce frequency allocations and channel interference sources. The demand for high wireless data rate telemetric communication has prompted the development of constant modulus Advanced Range Telemetry (ARTM) waveforms that meet strict bandwidth and waveform properties required by the telemetry community [1, 2]. Frequency selective multipath interference (MPI) from strong single-bounce multipath continues to be the primary obstacle preventing successful communication of telemetry from airborne systems to ground-based receiver systems throughout the entire duration of range experiments [5–8]. Previous research efforts have focused on time-domain equalizers to alleviate channel impairments with limited success [9, 10, 12].

Channel analysis specific to the aeronautical telemetry application presented in [11] revealed the primary contributor to high bit-error-rates (BER) was the nonlinear phase corruption and corresponding abrupt channel group delay associated with the strong single-bounce multipath. This phase corruption destroys the information in the ARTM phase-modulated waveforms and deteriorates performance more so than effective receiver SNR. This analysis prompted an evaluation of optimal linear equalizer performance with the minimum mean-square error (MMSE) equalizer in the frequency domain [13] with notable BER improvements. Following application of the frequency domain MMSE equalizer, BER performance became a function of effective SNR only.

This work explores communication performance with the SOQPSK-TG ARTM waveforms [3, 4] in the presence of strong, frequency-selective multipath interference that regularly occurs within typical test range environments. We present an interference mitigation procedure that first equalizes the channel experienced at a single antenna receiver using the pilot-aided, optimal linear minimum mean-square error frequency domain filter in [13] and subsequently combines equalized signals from multiple antennas using maximal ratio combining (MRC) [14] spatial diversity techniques. Application of multi-antenna spatial combinatorial methods following single antenna optimal linear equalization is shown to improve detection performance over spatial diversity techniques alone.

SYSTEM MODEL

The system model utilized in this work includes the SOQPSK-TG transmit waveforms, the aeronautical telemetry channel model and a multi-antenna receiver system. The ARTM Tier-1 standard waveform SOQPSK-TG [1–4] is a constrained, partial-response, ternary CPM scheme with constant amplitude. The sampled complex low pass equivalent received signal at antenna l within a coherent processing interval (CPI) is given by

$$r_l[n] = s[n] * h_l[n] + w_l[n], \tag{1}$$

where $s[n]$ is the sampled SOQPSK-TG signal, $h_l[n]$ is a realization of the aeronautical telemetry channel for antenna l and $w_l[n]$ is complex white Gaussian noise (CAWGN) at antenna l with zero mean and variance σ_l^2 which is known to the receiver.

The wideband frequency model of the aeronautical telemetry channel depicted in [5] consists of a line-of-sight (LOS) component and single-bounce multipath component. The channel model at antenna l is defined as

$$h_l[n] = \alpha_{0,l}\delta[n] + \alpha_{1,l}\delta[n-\tau], \tag{2}$$

with typical channel parameter values including $|\alpha_{1,l}/\alpha_{0,l}| \in [0.7, 1.0]$, $\angle\alpha_{0,l} \in [0, 2\pi]$, $\angle\alpha_{1,l} \in [0, 2\pi]$ and $\tau \in [1, 5]$samples at 10Mbps transmit rate. The received signal at antenna l is represented in the frequency domain by

$$R_l(\omega) = S(\omega)H_l(\omega) + W_l(\omega), \tag{3}$$

with discrete-time channel

$$H_l(\omega) = \alpha_{0,l} + \alpha_{1,l} \exp(-j\omega\tau), \tag{4}$$

where $S(\omega)$ and $W(\omega)$ are the discrete-time frequency representations of the transmitted signal and the received noise respectively.

In this work it is assumed the airborne asset under test is much farther away from any one antenna than the receiver antennas are from each other so the single-bounce multipath component delay τ in (2) is identical for all receive channels. With this assumption, the magnitude of the complex multipath gain relative to the LOS, $|\alpha_{1,l}/\alpha_{0,l}|$, is also identical for all receive channels. We also assume that receiver antennas are sufficiently spaced apart such that the phase of the complex multipath gains relative to the LOS, $\angle(\alpha_{1,l}/\alpha_{0,l})$, are statistically independent. A symbol-by-symbol detector is used following equalization at each receiver.

SINGLE ANTENNA EQUALIZER

Frequency domain equalization of the aeronautical telemetry channel with the MMSE filter was explored in [13] with noteworthy success. This equalizer first estimates the LOS and multipath complex gain factors as well as the multipath delay parameter in (2) using pilot symbols transmitted within each CPI and subsequently uses these parameters to filter the received data symbols. The MMSE equalizer is applied to length N_{FFT} blocks of received data samples after transformation to the frequency domain using the Fast Fourier Transform operator and is given by

$$F(\omega) = \frac{\Psi(\omega)H(\omega)}{\Psi(\omega)|H(\omega)|^2 + \sigma^2}, \tag{5}$$

where $\omega = (2\pi k/TN_{\text{FFT}})$, $k = 0, 1, \ldots N_{\text{FFT}} - 1$ and T is the sample period. $\Psi(\omega)$ is an approximation to $\mathbb{E}\{|S(\omega)|^2\}$ by the ensemble average spectrum of $|S(\omega)|^2$. The resultant MMSE equalization output in the time domain is

$$r_{\text{MMSE}}(n) = \text{IFFT}\Big\{F^*(\omega)R(\omega)\Big\}. \tag{6}$$

where IFFT is the Inverse Fast Fourier Transform operator.

The superior performance of the MMSE equalizer over the unequalized receive signal is illustrated in Fig. 1 with respect to the phase of the relative multipath gain $\angle(\alpha_{1,l}/\alpha_{0,l})$. This figure indicates that phase corruption of received signals by the multipath (AWGN + MPI) can be as detrimental to detection performance as a reduction of effective SNR (when $\angle(\alpha_{1,l}/\alpha_{0,l}) = \pi$) as described in [11, 13]. Following MMSE equalization (AWGN + MPI + MMSE), performance is now a function of effective SNR or the coherence between LOS and multipath complex gains.

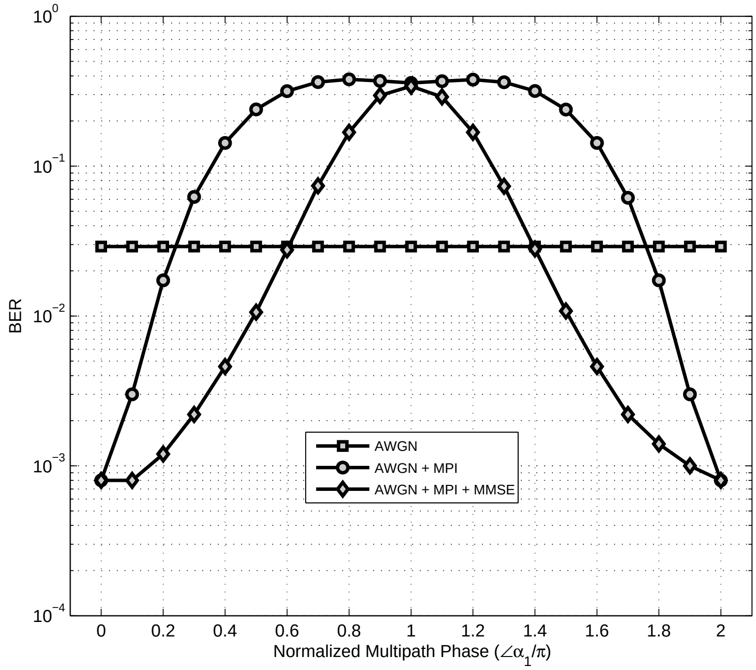

Figure 1: Single antenna BER vs. Channel Multipath Phase before (AWGN + MPI) and after MMSE equalization (AWGN + MPI + MMSE). Simulation parameters include 10Mbps data rate, 10samples/symbol receiver sampling, SNR = 5dB, $\alpha_0 = 1$, $|\alpha_1| = 0.7$, $\tau = 1$ and 20 pilot symbols.

MULTIPLE ANTENNA EQUALIZER

Spatial diversity schemes combine signals from multiple receive antennas to improve BER by exploiting the uncorrelated nature between physically separate receive antennas. Maximal Ratio Combining (MRC) [14] performs the coherent weighted sum of received signals from multiple receive antennas where the gain applied to each channel is determined from the SNR at each channel. The SNR at the MRC output is the sum of SNRs from each receive channel.

We use the pilot-aided channel parameter estimation procedure in [13] to estimate $\alpha_{0,l}$ and $\alpha_{1,l}$ for the received signal at antenna l. Because the multipath delay τ is less than a symbol, the complex amplitude of the received signal at antenna l may be approximated by the sum of the LOS and multipath complex gains. The MRC weight at antenna l is therefore

$$a_l = \frac{(\alpha_{0,l} + \alpha_{1,l})^*}{N}, \tag{7}$$

where N is the number of receiver channels so the MRC output is

$$r_{\text{MRC}}[n] = \sum_{l=1}^{N} a_l r_l[n]. \tag{8}$$

We propose a multi-antenna equalizer generated from the weighted sum of received signals that have been independently equalized with the aforementioned single-antenna MMSE equalizer. Because the received signals from each equalized channel are co-phased by their independent MMSE equalizer, the channel weights for the signals combined using MRC are

$$b_l = \frac{|\alpha_{0,l} + \alpha_{1,l}|}{N}, \tag{9}$$

so the proposed multi-antenna equalizer output is

$$r_{\text{MMSE,MRC}}[n] = \sum_{l=1}^{N} b_l r_{l,\text{MMSE}}[n]. \tag{10}$$

Fig. 2 illustrates the performance improvements using the single-antenna MMSE equalizer in (5) as a function of SNR with relative multipath phase as a uniformly distributed random variable $\angle(\alpha_1/\alpha_0) \in [0, \pi)$. Fig. 2 also depicts BER for multi-antenna MRC and (MMSE + MRC) techniques in (8) and (10) respectively for 2 and 3 antenna systems. Multipath channel phase for each branch of the multi-antenna receiver was constructed as a uniformly distributed random variable so that $\angle(\alpha_{1,l}/\alpha_{0,l}) \in [0, \pi)$. BER performance for the (MMSE + MRC) technique was improved over MRC-only for 2 and 3 antenna systems when the multipath delay was half a symbol ($\tau = 5$). No performance improvement was observed for systems with more than 3 antennas.

CONCLUSIONS

This work explored multi-antenna equalization techniques to improve aeronautical telemetry communication performance. Simulated BER with ARTM SOQPSK-TG waveforms were evaluated with strong, single-bounce, frequency-selective multipath that is characteristic of many aeronautical telemetry experiments. A single-antenna equalization scheme that applies the optimal linear MMSE filter received data after estimation of key channel parameters was revisited. Utilizing MMSE equalizers for each receive channel branch, a multi-antenna receiver scheme was presented that applies maximal ratio combining following independent channel equalization. Simulations illustrated that this multi-antenna equalization process can improve detection performance over maximal ratio combining without independent channel MMSE equalization.

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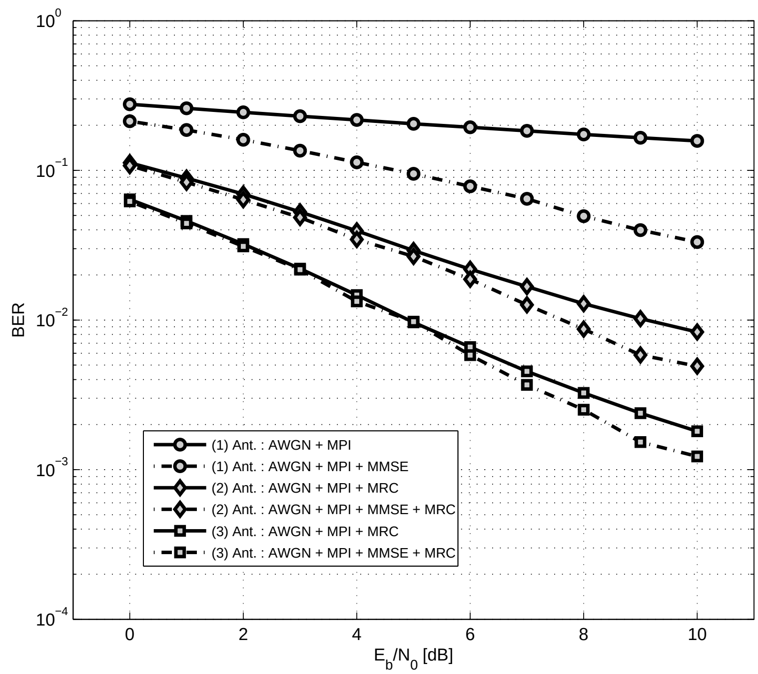

Figure 2: Multi-antenna equalizer with MRC BER vs. Channel Multipath Phase. Simulation parameters include $\alpha_{0,l} = 1$ and $|\alpha_{1,l}| = 0.7$ for all channels, $\tau = 5$ and 20 pilot symbols.

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