AN ITERATIVE MAXIMAL RATIO COMBINER FOR USE WITH TURBO ENCODED WAVEFORMS OVER A SIMO RAYLEIGH FADING CHANNEL

J. Todd Reinking (Welkin Sciences, LLC, Colorado Springs, CO, USA, todd.reinking@welkinsciences.com); Blair E. Sawyer (Welkin Sciences, LLC, Colorado Springs, CO, USA); Aaron Corder (Missile Defense Agency, Huntsville, AL, USA); and Teng K. Ooi (Missile Defense Agency, Huntsville, AL, USA)

ABSTRACT

A method is proposed for coherently demodulating and decoding turbo-coded binary phase-shift keyed (BPSK) burst transmissions over a SIMO (single-in, multiple-out) channel. Each individual channel of the overall SIMO channel experiences mutually independent and identically distributed fading. The proposed receiver linearly combines outputs from multiple antennae using a maximal ratio combiner (MRC) with combiner weights determined using a channel estimator. The channel estimator utilizes both pilot symbols and bit decisions from the turbo-decoder to generate the MRC weights. The initial turbo-decoder iteration of the channel estimator uses only pilot symbols. On subsequent turbo-decoder iterations, bit decisions from the turbo-decoder are used for a decision-aided refinement of the channel estimate using all channel symbols. Performance is evaluated using simulation techniques and compared to performance of two variations of the proposed MRC receiver, one using a clairvoyant channel estimator, the other using only pilot symbols for channel estimation.

1. INTRODUCTION

Coherent demodulation in communication systems operating across a flat-fading (non-frequency selective) Rayleigh channel is hampered by the presence of randomly time-varying magnitude and phase in the received signal. Both terrestrial mobile communication systems and natural or nuclear disturbed transionspheric communication systems may experience fading of this type.

Two broad approaches are available to overcome the effects of fading. The first involves the use of channel interleaving and error correction coding. In particular, this work will focus on systems using turbo-coding [1]. The most advanced systems of this type rely on turbo-coding principles to achieve coding gains approaching 40 dB [2]. Achieving gains of this type, however, relies on perfect knowledge of the channel for the design of the channel interleaver and of the channel response for the turbo-decoder.

While perfect channel knowledge is not available, it is possible to add pilot symbols into the transmission, which may be used at the receiver for channel estimation. An example of a turbo-coded BPSK receiver designed using pilot symbols is given in [3].

In the system described above, the use of a channel interleaver aims to assure that the error correction decoder "sees" independent fades for channels where the fading is correlated from symbol-to-symbol. However, if the channel decorrelation time, τ_0, is comparable to the span of the channel interleaver, T_I, then the channel interleaver is no longer effective and the temporal diversity available when $\tau_0 << T_I$ is lost.

For continuous communications it may be possible to increase T_I up to the bounds of acceptable latency and available memory. Even then it may not be possible to assure $\tau_0 << T_I$, especially for nonstationary channels with highly variable decorrelation time, τ_0. For burst communincations, additional constraints may potentially be placed on T_I. Under these design conditions, it is necessary to seek one or more additional sources of diversity. This may include frequency diversity achieved by spectral spreading or spatial diversity achieved by the use of adequately spaced antennae.

In this work we explore the use of a MRC using inputs from multiple antennae [4]. Receivers using the MRC combining method require estimates of the channel response in each diversity channel. The proposed system, described in detail in Section 2, forms channel estimates derived from pilot symbols and codeword symbol decisions (decision-aided feedback) using information from the turbo-decoder. The proposed channel estimation technique is an extension of the approach used in [3] for single path reception. In Section 3 we report on simulation results for the proposed system and compare them to a clairvoyant system using perfect channel estimates.

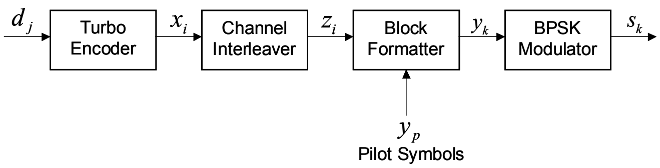

Figure 1 Transmitter Model

2. COMMNUNICATION SYSTEM MODEL

2.1. Transmit Signal

A block diagram of the transmitter model is shown in Figure 1. In the transmitter, a random binary message sequence, $\{d_j\}$, is error correction encoded with a turbo-encoder. The turbo-encoder provides error correction coding using a PCCC (Parallel Concatenated Convolutional Codes) encoder with a near-rate 1/3 code. The convolutional encoders, code interleaver and tail pattern are designed according to the UMTS standard [5]. No code punctuation is used. The turbo-encoder is followed by a 48 by 257 block channel interleaver. The body of the transmission block is formed by turbo-coding 4096 message bits. Embedded in the body of the message are unencoded pilot symbols, where every L^{th} symbol is a pilot symbol. Finally, the channel symbols are modulated using a BPSK modulator.

2.2. Channel Model

The signal path to the receiver is a single-in, multiple-out (SIMO) channel. Physically, the transmitted signal propagates along multiple fading paths to each receive antenna. These channels are modeled as mutually independent, flat-fading channels. The fading is assumed slow with respect to the duration of a transmit channel symbol, so the received complex baseband signal in the m^{th} (out of M) channel after matched filtering is

$$r_{k,m} = c_{k,m} s_k + n_{k,m} \tag{1}$$

In the above equation, the complex-valued receiver noise is assumed mutually independent and identically distributed across channels. The receiver noise is modeled as zero-mean, additive white Gaussian noise.

The complex randomly time-varying channel response, $c_{k,m}$, is modeled as a random process with Rayleigh amplitude statistics, which implies the average channel power response is one. The fading process is assumed to be wide-sense stationary with a power-law spectrum. Specifically, a so-called f^{-4} power-law spectrum is assumed. This particular power-spectrum is often considered a limiting form for transionospheric propagation [6]. For the f^{-4} flat-fading channel, the temporal autocorrelation function of the channel response is given by

$$R_{cc}(k) = (1 + \alpha k T_s / \tau_0) e^{-\alpha k T_s / \tau_0} \tag{2}$$

where α = 2.146193 and T_s is the receiver sampling interval out of the matched filter. The channel decorrelation time, τ_0, is defined so that $R_{cc}(\tau_0 / T_s) = e^{-1}$.

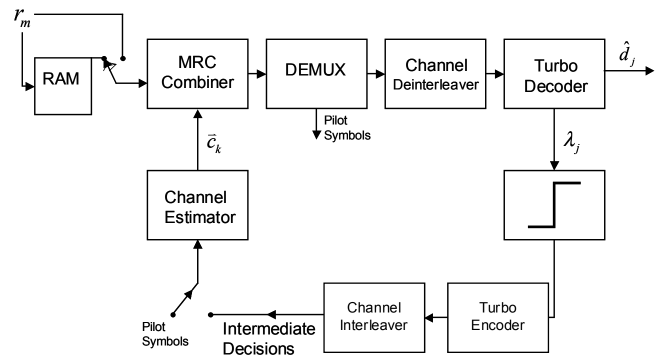

Figure 2 Turbo-Aided Receiver Model

It is important to note that for all results reported in this work the received signal energy is scaled to properly account for the use of error correction coding, the presence of pilot symbols and the distribution of the total receiver aperture over M physical antenna apertures. If the message bit energy is E_b, then the channel symbol energy in the m^{th} channel is $E_s = r\beta E_b / M$, where r is the coding rate, β is the ratio of codeword symbols to transmitted symbols, which includes pilot symbols.

2.3. Proposed Receiver

A block diagram of the receiver model is shown in Figure 2. The signal, $r_{k,m}$, of (1) is combined using the MRC. Ideally, the MRC linearly combines the received signal from each channel using:

$$\sum_{k=0}^{M-1} c_{k,m}^{*} r_{k,m} \tag{3}$$

In an actual receiver the true channel gain, $c_{k,m}$, must be replaced by an estimate, $\hat{c}_{k,m}$. For this work, channel estimates are formed using a moving-average estimator formed using the observed pilot-symbol returns and intermediate hard-decisions based on turbo-decoder symbol likelihoods. The channel estimates formed prior to the first iteration of the turbo-decoder are based solely on the pilot-symbol returns. Specifically, the channel estimates are generated using:

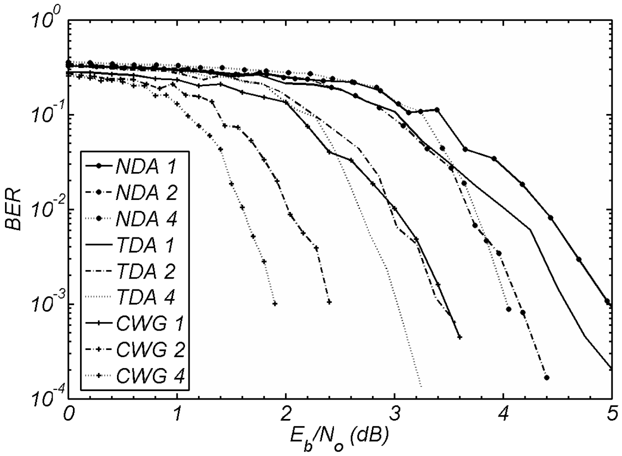

Figure 3 BER for $\tau_0 / T_I = 0.02$ **.**

$$\hat{c}_{k,m} = \frac{1}{K} \sum_{n=-N/2}^{N/2} r_{k,m+n} b_{m+n} \qquad (4)$$

where b_m is either a known pilot-symbol value or a decision based on the most recent iteration of the turbo-decoder. The endpoints of the sum in (4) are properly adjusted at the edge of the received channel symbol block. This decision-aided feedback, which we will refer to as turbo-aided feedback, is formed by generating hard decisions on the message symbol likelihoods, λ_j, after the j^{th} iteration of the turbo-decoder. Prior to the first turbo-decoder iteration, $b_m = 0$ when m corresponds to the index of channel symbol that is not a pilot symbol. On the first iteration, $K = (N+1)/L$, on subsequent iterations, $K = (N+1)$. The value of K is adjusted as needed to account for channel estimates formed near the edge of a receive block. The channel-estimate is reformed after each iteration of the turbo-decoder. The turbo-decoder itself uses a Max-Log-MAP iterative decoder. The decoder uses a fixed number of iterations. For this work, ten iterations are used.

As alluded to above, the data-flow in and out of the turbo-decoder in the proposed receiver differs significantly from that in a standard receiver. In a standard receiver, channel symbol likelihoods are presented to the turbo-decoder. These same likelihoods are used at every stage of the turbo-decoder iteration. After a fixed number of decoder iterations, message bit decisions are output from the decoder. In the proposed receiver, there is data exchange between the turbo-decoder and the channel-estimator after each iteration of the turbo-decoder. This is a significant point for both software and firmware implementations, since standard implementations of turbo-decoders do not: 1) accept updates to the channel symbol likelihoods or 2) provide access to the intermediate message symbol likelihoods.

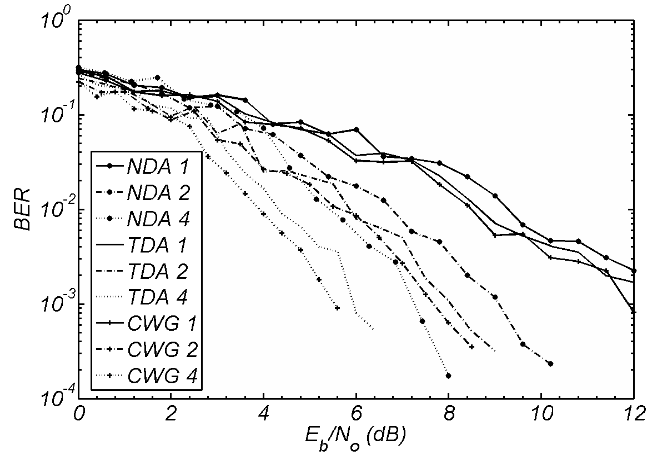

Figure 4 BER for $\tau_0 / T_I = 1.0$ **.**

In addition to estimation of the channel response, the receiver also forms an estimate of the average value of the channel E_s / N_0 to supply the turbo-decoder. For this work, which is dedicated to BPSK channel signaling, the required noise-variance estimate is formed using the quadrature component of the post-MRC signal.

3. SIMULATION RESULTS

A computer simulation was used to measure performance of the system shown in Figure 2. Additional simulation runs were made for two variations of the system in Figure 2. The first variation uses a clairvoyant channel estimator. Specifically, this means that MRC combining is performed directly using (3). In the second variation, the channel estimator of (4) uses pilot symbols only; no decision-aided feedback is used. Comparison of the performance of the pilot-symbol only system with the turbo-aided system will indicate whether the use of the non-pilot symbols is an asset or not. Separate simulation runs, not reported on here, indicate that using decision-aided feedback based on hard-decisions formed after the MRC degrade system performance at the low E_b / N_0 operating points achievable when turbo-coding is used.

For simulations of systems using pilot symbols $L = 10$ was used. In addition, the half window-width, N, of the channel estimator is set to 100. Systems with $M = 1, 2,$ and 4 are considered. The stopping criteria for the simulation is 30 message-block errors. Fading is assumed independent from block-to-block. Figure 3 shows the user bit-error rate (BER) performance for a flat-fading environment with $\tau_0 / T_I = 0.02$. The line type indicates the number of receive channels, 1, 2 or 4. The symbols indicate the receiver type, no marking for the turbo-aided feedback, solid-circles for no decision aided feedback and '+' for the clairvoyant receiver.

The results shown in Figure 3 demonstrate that channel estimates obtained using turbo-aided feedback allow a performance improvement of about ½ to 1 dB over channel estimates obtained using only pilot symbols. Performance of the turbo-aided feedback system is roughly about 1 dB poorer than that of the simulated system using the clairvoyant channel estimates. For all receiver types, using additional receive channels yields diversity gain. The use of 4 channels instead of 1 results in about 1.5 dB of diversity gain.

Figure 4 shows the BER performance for a flat-fading environment with $\tau_0 / T_I = 1.0$. Although the performance of the receivers operating in the slow fading environment would have benefited from a larger *N,* the channel estimator window is unchanged from the previous example. Doing otherwise in a fielded receiver would require an estimate of τ_0 / T_I be formed in the receiver. The line-types and markings are the same as discussed for Figure 3. In this example there is a mismatch between the channel interleaver size and the decorrelation time of the channel. The result is an overall loss in performance. (When making comparisons between this figure and the previous figure, take care to note the difference in the range of the E_b / N_0 axis.) The use of multiple channels helps mitigate the loss of performance for all receiver types. The diversity gain achieved in using 4 channels instead of 1 is about 6 dB. As was the case in the previous example, there is some additional performance improvement achieved by using turbo-aided feedback over using only pilot symbols. This performance improvement becomes substantial as *M* increases.

4. CONCLUSION

Using MRC combining of signals received over multiple physical paths allows an extra dimension of diversity for systems that must operate in an environment where there is large uncertainty in the channel decorrelation time. The resulting mismatch between the channel decorrelation time and the width of the channel interleaver can result in a significant increase in the bit-error rate. This work describes a turbo-aided channel estimator to form MRC combining weights for systems using turbo coding. The system proposed in the text uses both pilot symbols and decision-aided feedback based on information gathered from the turbo-decoder to form channel estimates. It was shown that despite the low E_b / N_0 operating point achievable using turbo coding, the quality of the turbo-aided feedback was sufficient to provide additional bit error rate performance improvement beyond the use of pilot symbols alone.

5. REFERENCES

[1] C. Berrou and A. Glavieux, "Near optimum error-correcting coding and decoding: turbo-codes," *IEEE Trans. on Commun.,* Vol. 44, No. 10, pp. 1261-1271, Oct. 1996.

[2] E.K. Hall and S.G. Wilson, "Design and analysis of turbo codes on Rayleigh fading channels," *IEEE J. on Sel. Areas Comm.,* Vol. 16, No. 2, pp. 160-174, Feb. 1998.

[3] M.C. Valenti and B.D. Woerner, "Iterative channel estimation and decoding of pilot symbol assisted turbo codes over flat-fading channels," *IEEE J. on Sel. Areas Comm.,* Vol 19, No. 9, Sept. 2001.

[4] J.G. Proakis, *Digital Communications,* McGraw-Hill; 4th edition, New York, 2000.

[5] 3rd Generation Partnership Project, "Multiplexing and channel coding (FDD)," 3GPP TS 25.212, V4.6.0, 2002.

[6] R.A. Dana, "Effects of ionospheric scintillation on differential demodulation of GPS data," *IEEE Trans. on Aerospace and Electronic Sys.*, Vol. 33, No. 3, pp. 893-902, July 1997.