A Block Processing Approach to CMA Equalization of SOQPSK for Aeronautical Telemetry

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***Abstract*— This paper presents the results of using the constant modulus algorithm (CMA) to recover a shaped offset quadrature-phase shift keying (SOQPSK)-TG modulated signal, which has been transmitted over an aeronautical telemetry channel using the iNET data packet structure. The iNET-packet structure contains known data bits (the preamble and asynchronous marker (ASM) bits) within each data packet, which can be used to determine the minimum mean square error (MMSE) and zero-forcing (ZF) equalizer. We present a block processing CMA equalizer which uses either the MMSE or the ZF equalizer for initialization, and compare its performance to the CMA equalizer with the usual method of center-tap initialization. These equalizers are shown to outperform the center-tap initialized CMA at higher SNRs, while providing a performance gain of about 1 dB to 3 dB over the fixed MMSE or ZF equalizer alone.**

Keywords— ZF and MMSE equalizers, Adaptive equalizers, CMA, SOQPSK modulation, iNET, Aeronautical channels

I. Introduction

We investigate the effectiveness of the constant modulus algorithm (CMA) equalizer in recovering an unknown data bit stream that has been transmitted over a frequency selective aeronautical telemetry channel with shaped offset QPSK, version 'TG' (SOQPSK-TG), using the iNET data packet structure. The CMA equalizer has been widely used and is the most popular blind adaptive equalizer in use today because of its relative simplicity, and also its good global convergence properties [1]. It is well studied, and it is known to be effective for signals and constellations that possess the constant modulus property.

Since SOQPSK-TG is a partial response continuous phase modulation (CPM), it should be a perfect candidate for this equalizer, but previous work by Law [2] had noted some difficulties with the use of CMA to equalize SOQPSK-TG over a telemetry channel. We believe that these problems may be due to improper initialization of the CMA equalizer. Here will adopt a block processing approach for CMA, which is similar to that presented in [3, 4] and we will test different methods of initialization for CMA. Note that the iNET-packet structure contains known data bits in the form of the preamble and asynchronous marker (ASM) bits. These known bits can be used to provide an alternative method of initializing the CMA equalizer, and thus decrease convergence time of the adaptation. Using the known data bits, the minimum mean square error (MMSE) equalizer and the zero-forcing (ZF) are computed and used to initialize CMA. The bit error rates achieved after convergence of these alternatively initialized CMA equalizers, are compared to those of the more traditional center-tap initialized CMA equalizer.

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II. Communications System Model

The INET packet structure is made up of the known preamble of length, 128 bits and ASM is of length, 64 bits, together with the actual data of length, 6144 bits. The total packet length is 6336 bits and this packet structure is shown in Fig. 1. The transmitted signal is SOQPSK-TG, a constrained ternary CPM described in [6,7].

Fig. 1: INET Packet structure

The system communication model is shown in Fig. 2. A bit stream formatted as shown in Fig. 1, is modulated using SOQPSK-TG. The SOQPSK-TG signal experiences multipath propagation, in the form of an LTI system with impulse response $h(n)$, and the addition of white Gaussian noise. For cross reference with the channel transfer functions of Fig. 3, the over-the-air bit rate is 10.3125 Mbits/s. The received signal is equalized by an FIR filter with impulse response $w(n)$. The equalizer output is input to a symbol-by-symbol SOQPSK-TG

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demodulator [7] to produce the bit estimates used to assess the performance of the equalizer.

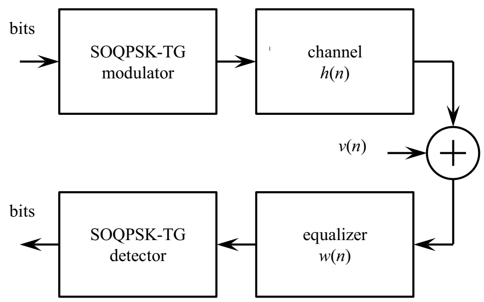

Fig. 2: SOQPSK Communication System Model

Because of the known preamble and ASM bits in the transmitted data packet, it is possible to compute an equalizer based on the minimum mean square error (MMSE) and/or zero-forcing (ZF) equalizer. Since these equalizers are available, they are being used to initialize the CMA equalizer for efficiency. The CMA equalizer is updated by using a single received data block, and bit error rates are determined after convergence of the adaptation.

The channel is a single-input single-output (SISO) system characterized by the input/output relationship:

$$x(n) = \sum_{k=-K_1}^{K_2} h(k)s(n-k) + v(n), \tag{1}$$

where $h(n)$ is the channel impulse response which is non-causal and of length (K_1 +K_2 +1), $s(n)$ are samples of the complex-valued low-pass equivalent signal corresponding to the SOQPSK-TG modulated carrier within the packet structure, and $v(n)$ is AWGN noise. $x(n)$ is a fixed block of received data of length N, which is used to update the CMA equalizer. In our simulations, N consists of at least 12672 samples because the simulation operates at an equivalent sample rate of two samples/bit. For our experiments the equalizer update is done using a single fixed packet of randomly generated data bits, which has been modulated and transmitted over a specified aeronautical telemetry test channel [5]. The equalizer output block is determined by

$$y(n) = \sum_{l=-L_1}^{L_2} w_p(l)\, x(n-l), \tag{2}$$

where $\underline{w}_p = [w_p(-L_1).....w_p(0).......w_p(L_2)]^T$ is the equalizer weight vector at the p^{th} iteration of the CMA adaptation process. The iterative update process for the equalizer will be described in section III.

III. CMA EQUALIZATION ALGORITHM

Because SOQPSK-TG is constant modulus, it is expected that it will be well-suited for equalization using CMA. The zero-forcing equalizer is that filter of length (L_1+L_2+1) which best approximates the inverse of the channel, while the MMSE equalizer is the filter that minimizes the mean square error between the composite channel and the delta function [8]. By initializing CMA with the MMSE or ZF equalizer, there will be no phase ambiguity for the CMA equalized symbols. Note that for center-tap initialization the presence of at least one known symbol is required to resolve the phase ambiguity.

Description of CMA Equalization Algorithm

CMA is a blind equalization algorithm, which provides an adaptation based on a specific cost function. The cost function, $J_{CMA}(y(n))$, which is minimized, is a function of the distance of the equalizer output from a circle of known radius. This radius is determined from the known modulation type, which is used for signal transmission. The CMA cost function is given by

$$J_{CMA}(y(n)) = E\left\{\left(\left|y(n)\right|^2 - R_2\right)^2\right\}, \tag{3}$$

where R_2 is the radius squared of the CMA circle on which the received samples, $x(n)$ lie. This cost function performs equalization by taking into account the distance between the equalizer output symbols and the pre-specified radius of the desired signal. For SOQPSK-TG, the transmitted signal is CPM and of the form: $s(n) = \exp(j\phi(n))$, so the value of CMA radius is $R_2 = 1$. Note that because SOQPSK-TG is a CPM it has constant modulus, and the equalizer operates on samples of the complex-valued low-pass equivalent signal, which are the received samples from a transmitted signal that was constant modulus. This motivates the use of CMA.

The update of the equalizer weights for this cost function is based on a stochastic gradient descent rule given by

$$\underline{w}_{p+1} = \underline{w}_p - \mu_p\ \nabla_w J_{CMA}(y(n)) \tag{4}$$

where μ_p is the algorithm step-size, the equalizer output is a block of data determined by $y(n) = \underline{w}_p{}^T \underline{x}_n$, for equalizer weight vector $\underline{w}_p$, and a received data vector, $\underline{x}_n = [x(n+L_1).....x(n).......x(n-L_2)]^T$.

The gradient vector of the cost function is given as:

$$\nabla_w J_{CMA}(y(n)) = E\left\{4\left(\ \left|y(n)\right|^2 - R_2\right)\ y(n)\ \underline{x}_n{}^*\right\}\ . \tag{5}$$

The * operator denotes the complex conjugate, and for these experiments an adaptive step-size, μ_p was used in (4) which is given by

$$\mu_p = \alpha\,\frac{\left\|\underline{\mathbf{x}}_n{}^T\ \underline{\mathbf{w}}_p\right\|}{\left\|\ \underline{x}_n{}^T\ \nabla_w J\left(y(n)\right)\right\|}, \tag{6}$$

For the simulation results presented below, we have used α=0.4.

The CMA equalizer weight vector is updated starting from an initial vector, $\underline{w}_0$ which is traditionally an all-zeros vector with a single 1 at the center tap. In this paper, we instead use the MMSE or ZF equalizers computed from the channel estimated from the preamble and ASM bits. We will show the improvement in performance of the CMA equalizer when it is initialized using either MMSE or ZF equalizer, since these do converge faster and also achieve a much lower error rate than does the CMA equalizer with center-tap initialization.

IV. Aeronautical Telemetry Channels

Four aeronautical telemetry test channels with impulse responses which have been previously measured from channel sounding experiments at Edwards AFB by Rice [5] were used in our experiments. Characteristics of the four channels used are listed in Table 1. The corresponding frequency responses of the four channels are shown in Fig. 3.

TABLE I. Channel Information

Channel Number	K_1	K_2	Total length
1	1	7	9
2	2	17	20
7	0	4	5
11	3	2	6

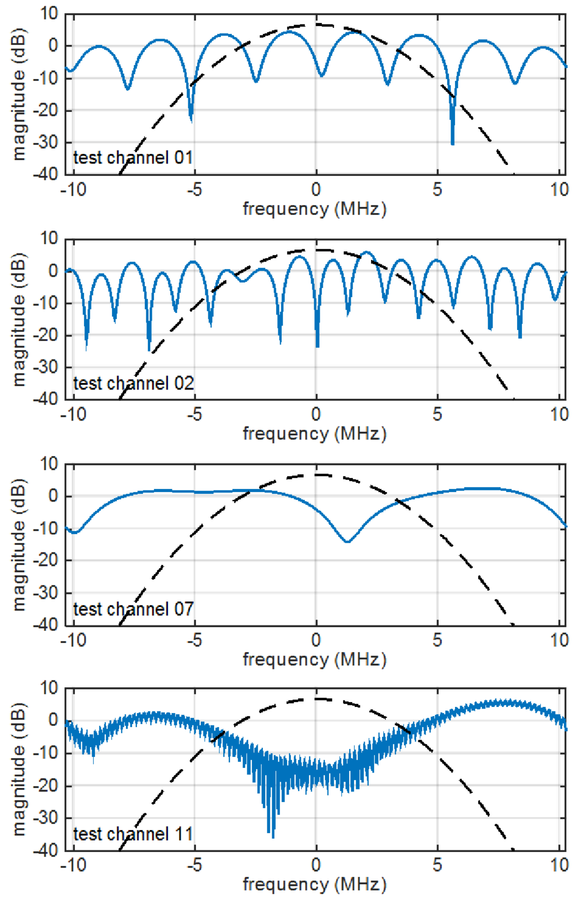

Fig. 3: Frequency Responses of 4 Test channels listed in Table I (solid line) and the spectrum of 10.3125 Mbits/s SOQPSK (dashed line)

These channels represent snapshots of the flight path of an aircraft. Channels 1 and 2 represent the taxiway before take-off, channel 7 is airborne flight, while channel 11 represents final approach and landing of the aircraft.

In Section V below we present results for two experiments which show the performance of the CMA equalizer for the communication system model described in Section II using the four test channels from Table I.

V. Performance Evaluation Results

In the first experiment we consider a single representative data packet, whose data bits have been randomly generated. The results shown in Figs. 4 – 7 are convergence curves of the CMA cost function, as well as the bit error count in the data packet, during the equalizer adaptation for the three different initializations tested over the four channels of Table 1. The top (a) convergence curves of Figs. 4 – 7 show the bit error count in the data packet over iterations as these CMA equalizers are updated. The lower (b) curves of Figs. 4 – 7 show the convergence of the CMA cost function over iterations for the three methods of initialization. The total number of iterations plotted is 200 for all cases. The center-tap initialized CMA takes at least twice as long as the ZF- and MMSE-initialized equalizers to converge. At convergence, the bit error counts for the MMSE-initialized and ZF-initialized CMA equalizers are identical (these final values are 0, 2, 7 and 526 for channels 1, 2, 7 and 11 respectively). In addition the bit error count of the center-tap initialized CMA is consistently higher than those of the MMSE- or ZF-initialized CMA equalizers.

The curves of Figs. 4 - 7 show that the ZF-initialized CMA converges slightly faster than the MMSE-initialized CMA equalizer in general. Based on the results of experiment 1, the total number of iterations required to ensure convergence of the center-tap initialized CMA for experiment 2 was chosen to be 200 for all the channels tested. For channel 11, as shown in Fig. 7(a) the final error count for the center-tap initialized CMA is 1180 out of the 6144 bits in the data packet, so the center-tap initialized CMA equalizer does not provide a satisfactory result for this channel at 20 dB. Further testing showed that this error count does not improve when 500 iterations are used, nor does this improve even in the noise-free case.

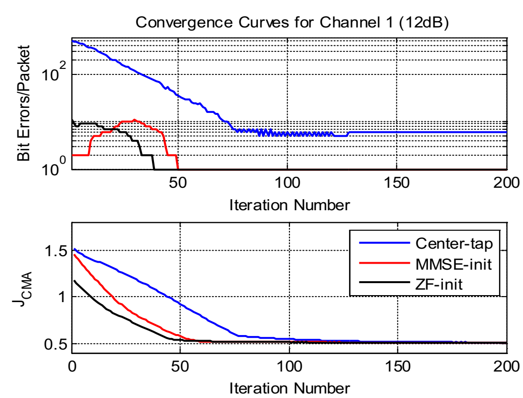

Fig. 4(a): Bit errors vs. Iteration number for channel 1 (top)
Fig. 4(b): J_{CMA} vs. Iteration number for channel 1 (bottom)

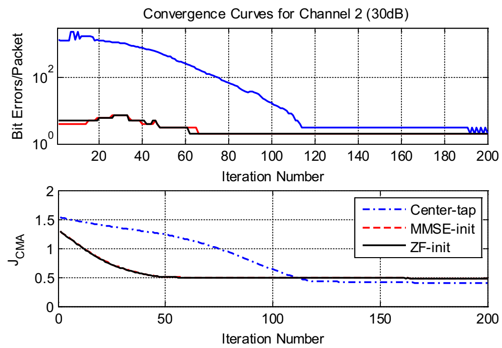

Fig. 5(a): Bit errors vs. Iteration number for channel 2 (top)
Fig. 5(b): J_{CMA} vs. Iteration number for channel 2 (bottom)

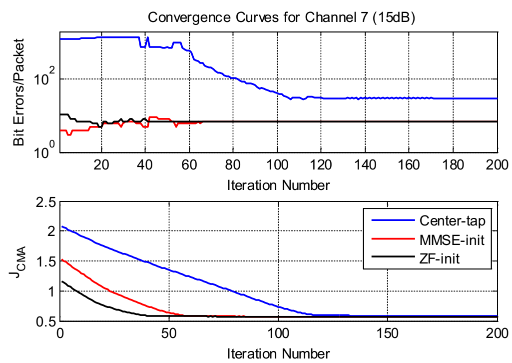

Fig. 6(a): Bit errors vs. Iteration number for channel 7 (top)
Fig. 6(b): J_{CMA} vs. Iteration number for channel 7 (bottom)

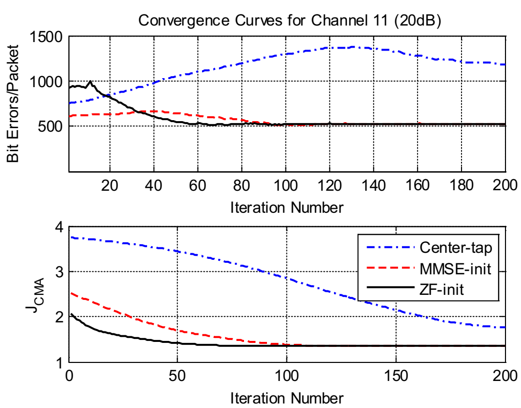

Fig. 7(a): Bit errors vs. Iteration number for channel 11 (top)
Fig. 7(b): J_{CMA} vs. Iteration number for channel 11 (bottom)

For our second experiment, Monte Carlo simulations were run to determine the bit error rates over varying E_b/N_0, for the three different initializations of CMA equalizer. These results are shown in Figs. 8 - 11. Since the new CMA equalizer has been initialized with the MMSE and ZF equalizers, the performance of both these fixed equalizers are included for comparison purposes in all plots. Also included in these plots is the theoretical lower bound curve for the AWGN channel, and the results of using the center-tap initialized CMA. For the center-tap initialized CMA the total number of iterations used is 200, as determined from experiment 1. For the ZF- and MMSE-initialized CMA equalizers, the total number of iterations is fixed at 50. Bit errors are counted after convergence of the CMA equalizers, and these are averaged over a total of 500 Monte Carlo runs (data packets). Each Monte Carlo run involves applying the specified equalizer to a different packet of randomly generated databits. Note that center-tap initialization is the usual method of initialization for CMA [1], and this was previously used for the implementation of the block processing CMA as described in [3]. It is thus provided as a baseline of performance for our experiments.

From the curves of Fig. 8 - 11, we note that at high values of E_b/N_0 the error rates for the alternatively initialized CMA equalizers are almost identical, irrespective of whether MMSE or ZF is used as the initializer, and these outperform the center-tap initialized CMA equalizer. From Fig. 11, we observe that the center-tap initialized CMA equalizer is totally unsuccessful in equalizing channel 11 even at high SNR, and this makes very obvious the superior performance of this alternative method of initialization for CMA equalization. In general, from Figs. 8 – 11 the addition of CMA adaptation provides a performance gain of about 1-3 dB over the use of the MMSE or ZF equalizer alone, while at low SNRs the blind center-tap initialized CMA equalizer performance is either equivalent to, or does outperform, the zero-forcing (ZF) equalizer which uses known pilot data.

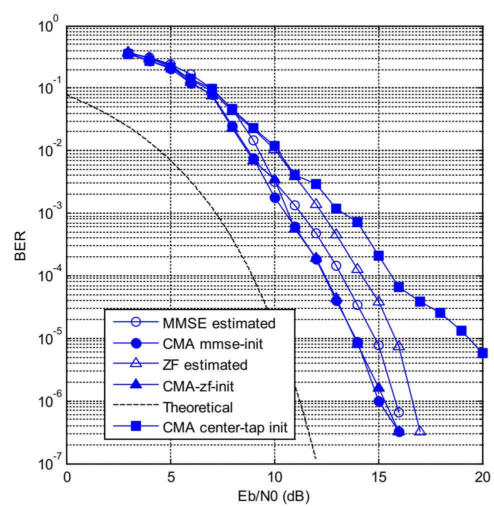

Fig. 8: BER vs. E_b/N_0 for channel 1

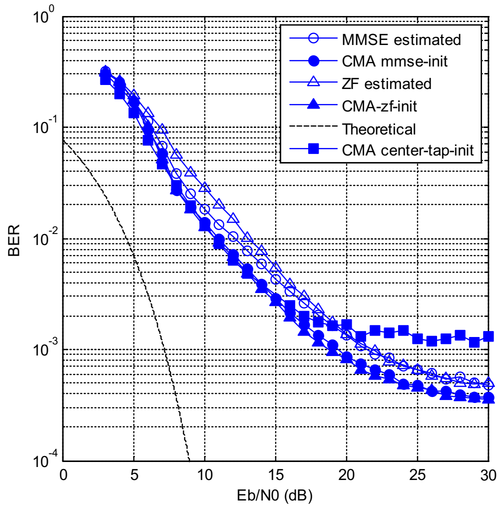

Fig. 9: BER vs. E_b/N_0 for channel 2

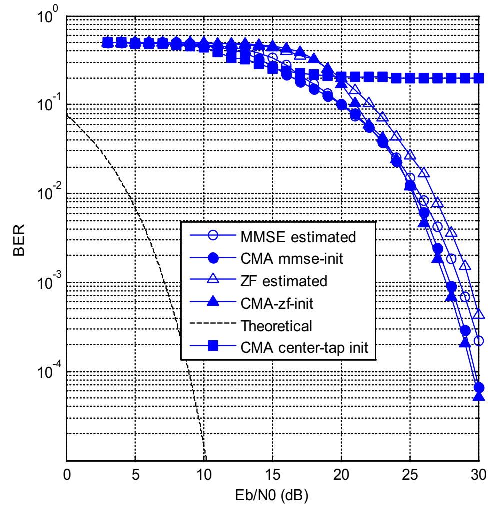

Fig. 11: BER vs. E_b/N_0 for channel 11

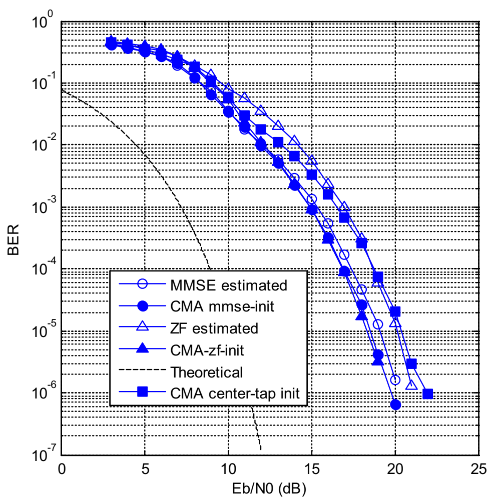

Fig. 10: BER vs. E_b/N_0 for channel 7

VI. Conclusions

In this work, we have presented a block-processing CMA equalization scheme for SOQPSK-TG modulated data, which has been transmitted over an aeronautical telemetry channel. Since the transmitted data packets contain known data for this application (iNET data packet structure), the MMSE and ZF equalizers can be used as initializers for CMA. The described MMSE-initialized and ZF-initialized CMA equalizers are shown to have superior performance to the center-tap initialized CMA equalizer for this application. For all the channels tested, these CMA equalizers are always able to successfully equalize the received data, using fewer iterations than the center-tap initialized CMA (i.e. 50 compared to 200), while also producing a lower final error rate. In addition the MMSE- and ZF-initialized CMA equalizers produce a gain of about 1-3 dB over the use of either the fixed MMSE or fixed ZF equalizer alone.

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