A LOW COMPLEXITY HYBRID ALGORITHM FOR ROBUST ITERATIVE MULTIUSER DETECTION

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ABSTRACT

In this paper we consider the problem of joint detection and decoding for CDMA systems that employ forward error control (FEC). The main problems encountered in designing this type of receiver include high complexity and a lack of robustness in impulsive noise and contamination in the prior model. In this paper, we propose that the extrinsic information may not need to be absolutely reliable as we consider impulsive interference. By allowing the judgement of confidence in using this extrinsic information, the proposed M-estimation based soft-in soft-out (SISO) detector exhibits robust performance for a low complexity.

1. INTRODUCTION

Recent years have witnessed a significant amount of research in the area of joint detection and decoding which aims to solve the global optimisation problem in the uplink receiver for coded CDMA systems. By exploiting the extrinsic information passed between the constituent Turbo decoders [4], the detectors can achieve higher performance.

A number of multiuser detectors for coded CDMA systems with different complexities and problem specifications have been developed . In [5], a detailed description of a rate 1/2 convolutionally coded multiuser receiver for additive white Gaussian noise (AWGN) was developed under a maximum likelihood (ML) approach. The complexity of this receiver was $O(2^{K\nu})$ where K is the number of users and ν is the constraint length of the Turbo encoder. A number of suboptimal schemes, mostly for Gaussian noise, have been proposed. These include the soft weighting canceller [1], the cross-entropy minimising technique [7], the decision feedback structure [6], and the MMSE-based soft multiple-access-interference (MAI) canceller [10]. Under a Bayesian approach, a Turbo multiuser receiver was developed in [9] for Gaussian and impulsive noise using Gibbs resampling. By using *noninformative* priors, the performance of this Turbo multiuser receiver is robust, but has a increased computational cost. A recent research [12] has attempted to reduce the complexity when evaluating the conditional mean by approximating the MAI as Gaussian noise.

In this paper, we develop a novel low complexity robust Turbo multiuser receiver which is robust in impulsive noise. It is noted that previous works, when utilising the extrinsic information in the multiuser detection process, often relied heavily on this information. In the traditional Turbo decoder, the extrinsic information is produced upon some measure of channel noise and is refined after each iteration. If the decoder is subjected to unknown and impulsive noise channels, it is likely that there will be some mismatch between the channel noise model given to the decoder and the underlying noise process. Consequently, the extrinsic information may not be absolutely reliable and it may take a considerably larger number of iterations to converge. In such cases, one may wish to employ statistical techniques to minimise the effect of contamination in the prior models. Such a problem was investigated rigorously by statisticians [2, 3]. One advantage of robust detectors in this sense is faster convergence. The structure of our Turbo receiver is simple and based on a geometric interpretation of M-estimation. It is envisaged that this structure allows further development under a robust Bayesian framework.

This paper is organised as follows. In Section II, we give some description of the coded CDMA system model. In Section III, we describe our proposed Turbo multiuser receiver. Section IV gives some simulation results. Finally, Section V concludes the paper.

2. SYSTEM DESCRIPTION

2.1. Signal Model

We consider a Turbo coded synchronous CDMA system with K users. The information bits $d_k(i)$ from the k^{th} user are Turbo coded to produce a code bit stream $b_k(i)$. The code-bits are then modulated and transmitted using a

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spreading sequence $\boldsymbol{s}_k = [s_k^1 \; s_k^2 ... \; s_k^N]^T, k = 1, \ldots, K$. The received signal for the i^{th} bit is the sum of signals from all users and the ambient channel noise,

$$\boldsymbol{r}(i) = \boldsymbol{S}\,\boldsymbol{A}\,\boldsymbol{b}(i) + \boldsymbol{n} = \boldsymbol{S}\,\boldsymbol{\theta} + \boldsymbol{n} \tag{1}$$

where $\boldsymbol{S} = [\boldsymbol{s}_1 \boldsymbol{s}_2 \ldots \boldsymbol{s}_K]$ is the code matrix, $\boldsymbol{A}$ is the diagonal received amplitude matrix, $\boldsymbol{b}(i) = [b_1(i), .., b_K(i)]^T$, $\boldsymbol{\theta} = \boldsymbol{A}\;\boldsymbol{b}(i)$, and $\boldsymbol{n}$ is the vector of i.i.d noise samples. In this work, we consider impulsive noise.

2.2. Turbo Multiuser Receiver

The SISO multiuser detector receives the extrinsic information from the channel decoder and then makes conditional decision about the received signal. The output from the SISO detector can be used as *a priori* knowledge about the code bits for the channel decoder. The detected symbols and the extrinsic information are then passed to the channel decoder. In turn, the channel decoder uses *a priori* knowledge, which is the extrinsic information from the SISO detector, the received symbols, and some measure of channel noise to produce the extrinsic information $\lambda_2[b_k(i)]$ and the *a posteriori* log-likelihood ratio (LLR) $\Lambda_2[b_k(i)]$ for the information bit $b_k(i)$. In the next iteration, $\lambda_2[b_k(i)]$ will be utilised by the SISO detector as *a priori* knowledge. Through this iterative procedure, the information will be refined and converges to the best estimate of the transmitted information bits. The final estimate of the information bit $b_k(i)$ is obtained by taking the sign of the LLR from the channel decoder. A more detailed description of the general mechanism of the Turbo receiver is given in [10]. In this work, the preprocessing concept [8] is also used to simplify the computation of the decoding algorithm and separates the noise problem from the arithmetic decoding problem.

3. LOW COMPLEXITY ROBUST TURBO MULTIUSER RECEIVER

Recall that in M-estimation of the model

$$\boldsymbol{r} = \boldsymbol{S}\,\boldsymbol{\theta} + \boldsymbol{n} \tag{2}$$

the parameter is found by minimising the cost function [11]

$$\hat{\boldsymbol{\theta}} = \arg\min_{\boldsymbol{\theta}} \sum_{n=1}^{N} \rho\left(r_n - \sum_{k=1}^{K} (S)_{nk}\theta_k \right) \tag{3}$$

where $\rho(x)$ is the penalty function. If $\rho(x) = -\log_e f_n(x)$ where $f_n(x)$ is the pdf of the noise, this is the ML estimator. One can consider (3) to be a nonlinear curve fitting problem in the non-Euclidean space $\mathbb{R}^N$ when the noise is

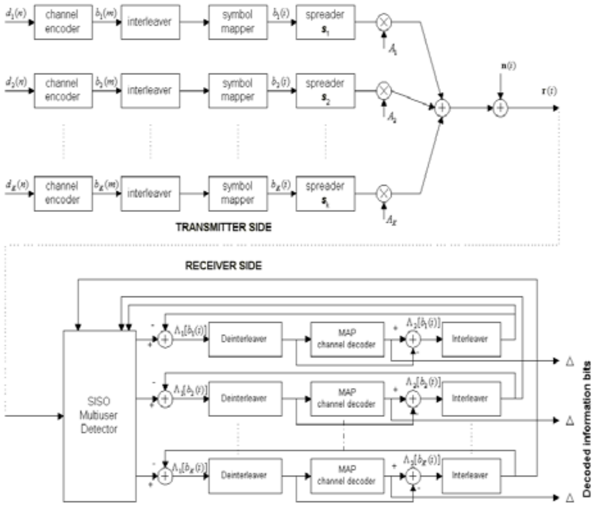

Fig. 1. Block diagram of a Turbo coded CDMA system [10]

non-Gaussian and this is illustrated in Figure 2. We consider a parameter space that involves the true and the estimate of $\boldsymbol{\theta}$ and an observation space that includes the noise $\boldsymbol{n}$ and the received signal $\boldsymbol{r}$. These two spaces are related by a one-to-one mapping defined by $\boldsymbol{S}$. The idea of the proposed algorithm is to represent the influence of the prior as another virtual observeration and to dynamically incorporate it into the conventional M-estimation process. This can be intuitively justified from Bayesian theory that the effective noise variance can be reduced.

Denote $\Lambda[\boldsymbol{\theta}]$ as the prior for $\boldsymbol{\theta}$ and $\tilde{\boldsymbol{\theta}} = [\tilde{\theta_1}, \ldots, \tilde{\theta_K}]^T$ as the soft estimate (or influence parameter) from $\Lambda[\boldsymbol{\theta}]$. A simple way to obtain this soft estimate is $\tilde{\boldsymbol{\theta}} = \tanh(0.5\Lambda[\boldsymbol{\theta}])$ [10]. Denote $\tilde{\boldsymbol{r}}$ as the noise-free observation vector due to the influence parameter $\tilde{\boldsymbol{r}} = \boldsymbol{S}\;\tilde{\boldsymbol{\theta}}$. We define a biased observation vector

$$\boldsymbol{r}^* = \boldsymbol{r} + C\tilde{\boldsymbol{r}} = \boldsymbol{S}(\boldsymbol{\theta} + C\;\tilde{\boldsymbol{\theta}}) + \boldsymbol{n} \tag{4}$$

where C denotes the influence of the prior on the estimate, and is called the *confidence coefficient*. The conditional parameter estimate is the M-estimate from the normalised biased observation vector

$$\boldsymbol{r}^*_{norm} = \boldsymbol{r}^*\,(1 + C||\tilde{\boldsymbol{r}}||/||\boldsymbol{r}||)^{-1} \tag{5}$$

In this work, impulsive noise is modelled by a zero mean M-term Gaussian mixture:

$$f(\boldsymbol{\nu}) = \sum_{m=1}^{M} \alpha_m (2\pi)^{-K/2} |\boldsymbol{R}_m|^{-1/2} \exp\left(-\boldsymbol{\nu}^T\;\boldsymbol{R}_m^{-1}\boldsymbol{\nu}/2\right) \tag{6}$$

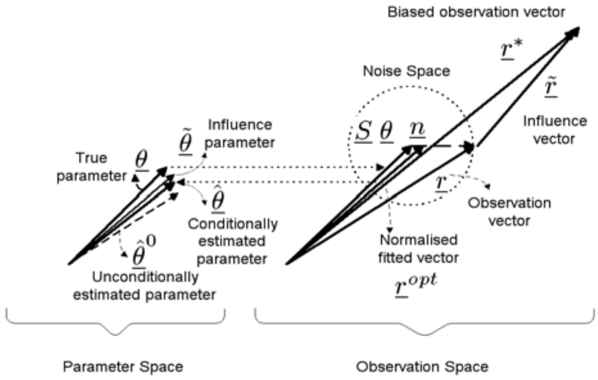

Fig. 2. Estimation with influence of prior

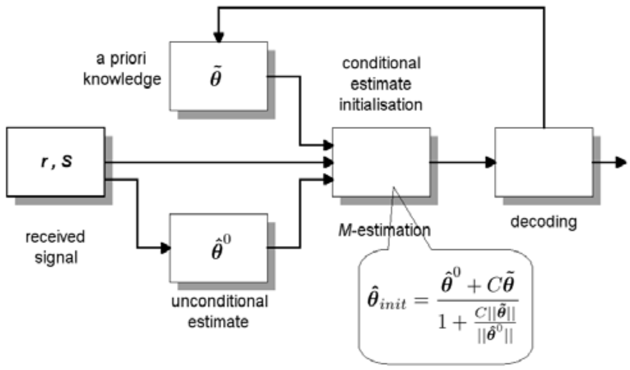

Fig. 3. Block diagram of the proposed receiver

where $\boldsymbol{\nu} \in \mathbb{R}^K$ denotes the K-dimensional correlated noise vector and the cross correlation matrix is $\boldsymbol{R} = \boldsymbol{P}\,\boldsymbol{P}^T$, $\boldsymbol{P} = (\boldsymbol{S}^T\boldsymbol{S})^{-1}\boldsymbol{S}^T$, and $\boldsymbol{R}_m = \sigma_m^2\boldsymbol{R},\ m = 1,\ldots,M$. Suppose that $\boldsymbol{R}$ is isotropically symmetric , using the result in [12], the marginal distribution of ν_j is found to be

$$f_{\nu_j}(\nu_j) = \sum_{m=1}^{M} \alpha_m(\sqrt{2\pi}\sigma_{jm})^{-1}\exp\left(-\nu_j^2/(2\sigma_{jm}^2)\right) \quad (7)$$

where $\sigma_{jm}^2 = \boldsymbol{R}_m(j,j)$ denotes the j^{th} diagonal element of the m^{th} correlation matrix corresponding to the m^{th} component in the mixture. The preprocessed symbol for user k with received amplitude A_k is

$$\frac{1}{2}\log\frac{f_{\nu_k}(\hat{\theta}_k - A_k)}{f_{\nu_k}(\hat{\theta}_k + A_k)} \quad (8)$$

In addition, to achieve faster convergence, we propose to initialise the M-estimation by

$$\hat{\boldsymbol{\theta}}_{init} = \left(\hat{\boldsymbol{\theta}}^0 + C\tilde{\boldsymbol{\theta}}\right)\left(1 + \frac{C||\tilde{\boldsymbol{\theta}}||}{||\hat{\boldsymbol{\theta}}^0||}\right)^{-1} \quad (9)$$

where $\hat{\boldsymbol{\theta}}^0$ is the unconditional M estimate.

The complexity of our proposed Turbo SISO multiuser receiver is very low and at about $O(KI)$ per bit per user per decoding iteration, where I is the number of recursive steps for the estimate in M-estimation to converge. In practice, I is observed to be less than 10. We consider two special cases of the algorithm. The first case is when the prior is zero. In this scenario, the SISO detector produces exactly the same estimate as the unconditional one. Secondly, when the channel decoder produces a large prior, especially at later iterations, the influence of the prior is stronger and the estimate will be statistically closer to the true value. In the next section, we give some simulation results to evaluate the performance of our proposed algorithm.

4. SIMULATION RESULTS

We consider a synchronous coded CDMA system with $K = 4$ users using the same Turbo code (31,27) at a code rate of 1/3. The frame size is 128 and the Turbo code interleaver is cyclic with a cyclic shift of 16, the number of iterations for decoding is 4. All users have the same power and the processing gain is $N = 15$. Impulsive noise is modelled by a two-term Gaussian mixture with $\alpha_1 = 0.9, \alpha_2 = 0.1$ and $\sigma_2^2 = 100\sigma_1^2$. The performance of the proposed algorithm is investigated with some confidence coefficients C = 0.1, 0.5, 1.0, 2.0, and 5.

The plot of average bit error rate (BER) in impulsive noise is given in Figure 4. The performance of the matched filter and the linear decorrelator followed by a channel decoder is also included. It is observed that when the confidence coefficient is large (i.e. $C = 2, 5$) the receiver produces higher BERs. At low SNRs, the performance for $C = 0.1$ and $C = 0.5$ is similar, but is better for $C = 0.5$ at higher SNRs. A possible explanation is that at higher SNRs, $C = 0.5$ exploits the prior better than $C = 0.1$, but if C is too large, especially at the first or second iteration, inaccuracies may make the algorithm diverge. Performance in Gaussian noise is given in Figure 5. It is observed that when the SNR is low, small values of the confident coefficients can lead to performance approximately equivalent to that of the linear decorrelator, which is optimal in the unconditional case and for Gaussian noise. However, when the SNR is large, it is clear that there are values of the confident coefficents (i.e. C = 0.1 in this case) that can significantly outperform the linear decorrelator.

Observations of performance in impulsive and Gaussian noise indicate that there exists a choice of static confidence coefficient that can lead to desirable performance in both cases. Future work includes an analytical investigation of

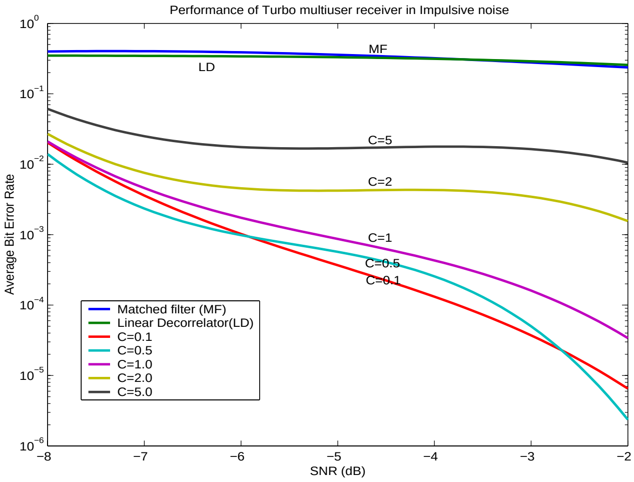

Fig. 4. Performance of the proposed robust Turbo multiuser receiver in impulsive noise

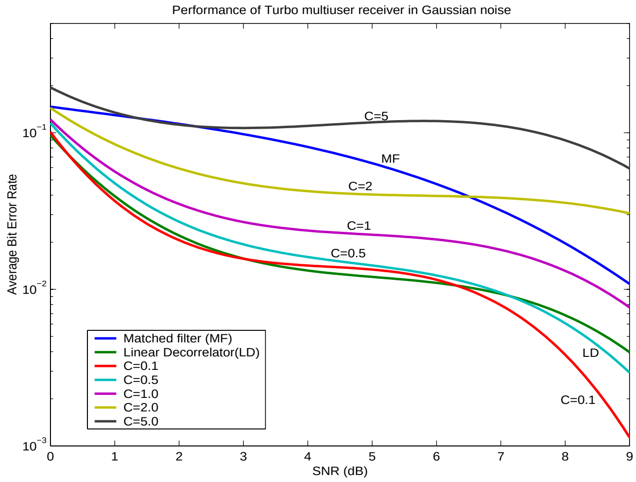

Fig. 5. Performance of the proposed robust Turbo multiuser receiver in Gaussian noise

the choice of dynamic confidence coefficients by building statistical models for the priors and will be presented elsewhere.

5. CONCLUSION

We have described a novel robust Turbo multiuser receiver in impulsive noise at a very low complexity from a simple geometric approach. The performance of the proposed receiver has been investigated in heavily impulsive noise and Gaussian noise and its robustness has been confirmed. Extensions of this work are being investigated to make the receiver more robust.

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