LLR OPTIMIZATION FOR ITERATIVE MIMO BICM RECEIVERS

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ABSTRACT

Iterative detection and decoding (IDD) relies on passing useful extrinsic information between the detector and the decoder. Due to the sub-optimality of practical detector and/or decoder, the direct output LLRs from the detector or the decoder may not provide sufficient gains to each other. Proper scaling of the extrinsic LLRs based on certain optimality criteria may improve the performance of the IDD receiver. However, finding optimal scaling function for IDD receiver in general is still an open problem. In this paper, we investigate LLR scaling of the detector and the decoder output based on maximization of generalized mutual information.

Index Terms— iterative receiver, LLR, generalized mutual information

1. INTRODUCTION

Iterative detection and decoding (IDD) can improve receiver performance significantly by exchanging the extrinsic information between detector and decoder [1]. Conventional IDD schemes usually assume that optimal detector/decoder algorithms are applied. Based on that, extrinsic LLRs can be derived as subtraction between a posteriori LLRs and a priori LLRs [1]. In case of sub-optimal detection/decoding, however, the extrinsic information obtained by such subtraction may not work well. For realistic transmissions with various channel estimation errors and detector sub-optimality, how to generate optimal extrinsic information between iterative modules in general is still an open problem. The simplest correction/optimization of extrinsic LLRs is to apply linear scaling factor(s) based on some optimization criteria. For example, based on the consistency condition, extrinsic LLR scaling has been successfully applied within the turbo decoder to improve the max-logMAP (MLM) algorithm [2] [3]. For more sophisticated IDD receivers, various approaches have been investigated in the literature, usually based on certain knowledge of the transmission scenario and more or less rely on numerical solutions, e.g., the methods in [4] [5]. Recently, the concept of generalized mutual information (GMI) has been explored to understand and improve receiver performance of bit interleaved coded modulation (BICM) systems in general [6-8]. For non-IDD BICM receivers, GMI maximization based LLR scaling has been shown as an effective optimization method [7-9]. In this paper, we extend the approach in [9] and investigate LLR optimization for MIMO BICM IDD receivers based on the GMI concept.

2. SYSTEM MODEL

We consider BICM transmission over memoryless multiple-input multiple-output (MIMO) channels. Information bit sequence $\mathbf{u} = [\mathrm{u}_0, \mathrm{u}_1, \dots, \mathrm{u}_{K-1}]$ is encoded to produce coded bit sequence $\mathbf{c} = [\mathrm{c}_0, \mathrm{c}_1, \dots, \mathrm{c}_{K/R-1}]$, where R is the code rate. Coded bits $\mathbf{c}$ are interleaved and possibly scrambled to produce another bit sequence $\mathbf{b} = [\mathrm{b}_0, \mathrm{b}_1, \dots, \mathrm{b}_{K/R-1}]$, which is then mapped into symbols from a M-ary signal constellation χ, producing $\mathbf{x} = [\mathrm{x}_0, \mathrm{x}_1, \dots, \mathrm{x}_{N-1}]$, where $\mathrm{x}_N \in \chi$. The modulated signals are transmitted over the wireless channel via multiple antennas after possible layer mapping and precoding. At the receiver side, following detection of received signal, $\mathbf{y} = [\mathrm{y}_0, \mathrm{y}_1, \dots, \mathrm{y}_{N-1}]$, a general process of descrambling, rate de-matching, and de-interleaving recovers the LLR sequence to match that of the coded bits. The channel decoder then takes these LLRs as input. When the receiver employs an IDD scheme, decoder output LLRs will be passed back to the detector to start another round of detection and decoding. We name a complete cycle of detection followed by channel decoding as a *global iteration*. The system model can be described by Figure 1.

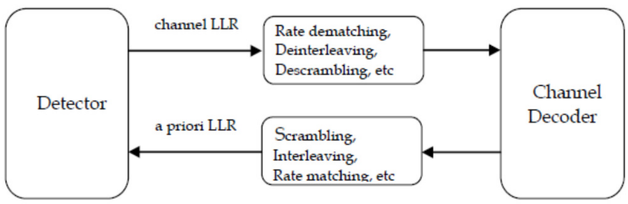

Figure 1 Conventional IDD receiver.

For illustration, in this paper we specifically consider 2x2 MIMO transmissions in an LTE system with open loop spatial multiplexing [10]. The transmitter applies turbo encoding followed by quadrature amplitude modulation (QAM). The detector applies the max-LogMAP detection

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algorithm while the decoder has the option of using either LogMAP (LM) algorithm or scaled max-LogMAP (S-MLM) algorithm [4] [5] for iterative decoding. We note that while the numerical solutions may be specific to the considered system, the methodology is for general cases.

3. GENERALIZED MUTUAL INFORMATION AND BICM-ID

Generalized mutual information (GMI) indicates an achievable rate of BICM receiver [6] [7]. Without loss of generality, we consider M-ary QAM modulation, where there are $m = \log_2 M$ bit channels. For each i-th bit channel, GMI is defined as [6]

$$I_{qB_i,Y}^{gmi} = \max_{s>0} I_{qB_i,Y}(s) \qquad (3.1)$$

where

$$I_{qB_i,Y}(s) = 1 - E_{X,Y}\{\log_2(1 + \exp(-sgn(b_i(X))\Lambda_{qB_i,Y}(Y)s))\}$$
$$\approx 1 - \frac{1}{N}\sum_{n=0}^{N-1} \log_2 (1 + \exp(-sgn(\hat{b}_{i,n})\Lambda_{i,n}s)) \qquad (3.2)$$

and $\Lambda_{qB_i,Y}(Y)$ is the detector output LLR, $b_i(X)$ is the i-th bit from symbol X, $b_{i,n}$ is the i-th bit of the n-th transmitted symbol, and $\hat{b}_{i,n}$ is the decoder hard decision. Following the conventions in [7], we call (3.2) the I-curve of each bit channel. A I-curve is a function of variable $s$that is a uniform scaling value to all LLRs from that bit channel. The total I-curve is the summation of all bit channel I-curves. GMI is the maximum value of the total I-curve.

3.1. Detector output LLR scaling for 1st global iteration

Online LLR scaling based on GMI maximization for non-IDD receiver has been developed in [9]. Conventional extrinsic LLRs of the detector are used. The scaling factor for each bit channel is $s_i = \underset{s>0}{\text{argmax}}\, I_{qB_i,Y}(s)$, i.e., the scaling factor that achieves the peak of a bit channel's I-curve. For IDD receiver, this can be directly applied to the 1st global iterations, i.e., LLRs can be scaled in the same way as in non-IDD case. In this paper, GMI based scaling is applied to each codeword separately so that scaling factors are adapted to each codeword's bit channels. This process is described in Figure 2. One initial turbo decoding iteration is used for finding bit channel scaling factors.

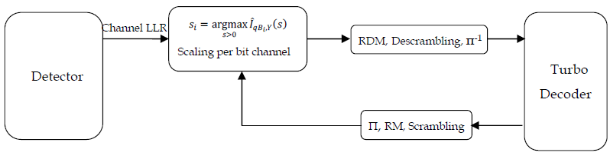

Figure 2 Decoder decision based scaling for detector output LLRs for 1st global iteration.

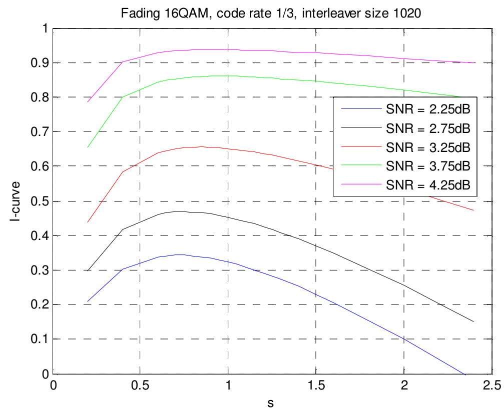

Figure 3 I-curves of decoder output LLR for receiver with ideal channel estimation and max-LogMAP detector.

3.2. Decoder feedback LLR scaling based on GMI

As stated earlier, extrinsic information as subtraction of a posteriori and a priori LLRs is effective when ideal channel knowledge and optimal iterative modules are assumed [1]. Furthermore, with ideal channel knowledge, either optimal Log-MAP or max-LogMAP detector can produce near optimal demodulated LLRs. For example, Figure 3 shows I-curves of S-MLM decoder output LLRs of the receiver with ideal channel estimation and max-LogMAP detector. The SNRs are corresponding to FER range of 1 to 0.001. The decoder output LLRs are collected after finishing the 1st global iteration (after 4 turbo decoding iterations). In fact, as SNR become medium to high, I-curves of this scenario achieves maximum around 1 and therefore GMI based scaling for decoder feedback is unnecessary.

In real systems, however, due to channel estimation errors, etc., the most appropriate information to be exchanged may vary case by case [4] [5], and certain scaling factors may improve IDD receiver performance considerably. Consider LTE downlink transmission as an example, we found the performance by using conventional decoder extrinsic LLRs and a posteriori LLRs are very close to each other. (In fact, decoder output LLRs are significantly larger than decoder input LLRs, thus a posteriori and extrinsic LLRs do not differ significantly at least numerically.) In order to find appropriate scaling factor(s) for either of them, we investigated both types of feedback LLRs.

Specifically, when GMI based scaling is already applied to detector output in the 1st global iteration to improve the subsequent channel decoding, the input LLRs to the decoder are linearly optimized. In order to determine whether what scaling factor should be used as feedback to the detector, we first examine the I-curves in different scenarios.

In Figure 4, I-curves of the decoder output a posteriori LLRs from transmissions over EVA70 (Extended Vehicular A channel profile with Doppler frequency 70 Hz) and ETU300 (Extended Typical Urban channel profile with

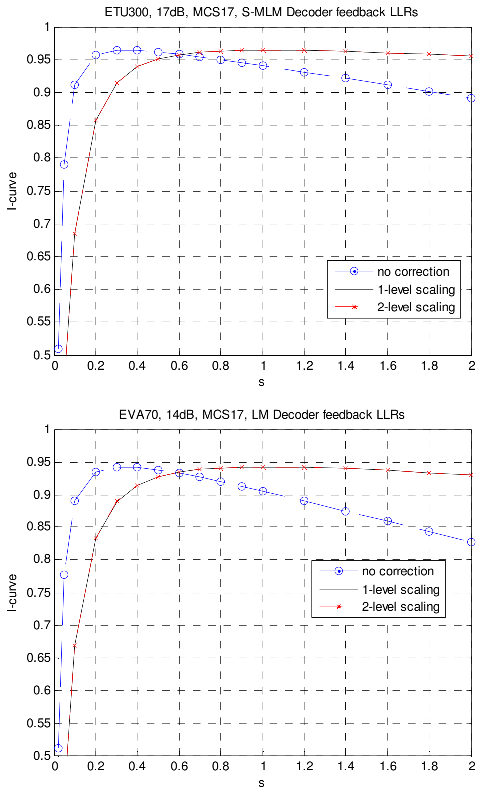

Figure 4 I-curves of decoder extrinsic output LLR after applying online GMI scaling to detector output

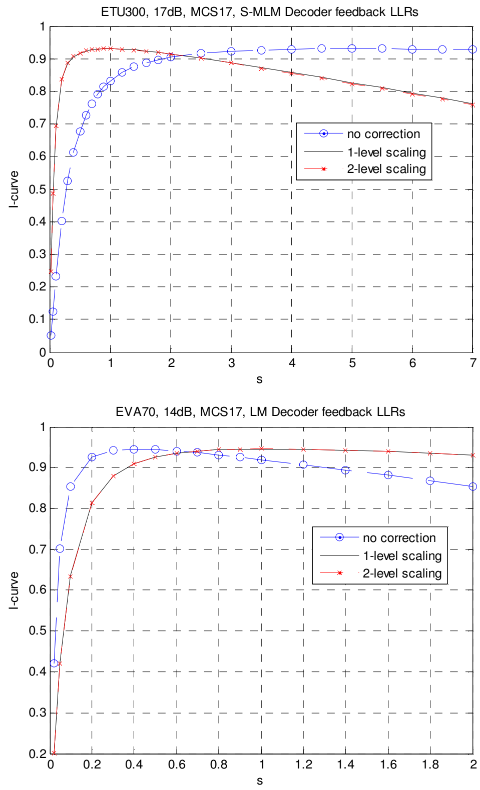

Figure 5 I-curves of decoder extrinsic output LLR without applying online GMI scaling to detector output

Doppler frequency 300 Hz) are plotted [11]. The transport block length is 15264 for each sub-frame [12]. The legend "1-level scaling" refers to using (3.2) for all bits, while "2-level scaling" refers to using (3.2) for bits with positive LLRs and negative LLRs separately, whereby producing 2 different scaling factors, one for positive LLRs and another for negative LLRs. Both LM and S-MLM decoders are tested. It is interesting to observe that in all cases the desired scaling factor (the peak of the blue curve) is approximately 0.3. It also indicates that 1-level scaling is sufficient. While an analytical explanation is lacking, for the considered LTE down link receiver, this value may be considered as similar to the 0.7 value found for scaling extrinsic LLRs by S-MLM turbo decoder [2] [3]. In fact, simulations with different scenarios have shown that the same 0.3 scaling factor on decoder feedback (either a posteriori or extrinsic LLRs) performs almost equally well.

In Figure 5, I-curves of the decoder feedback LLRs from same transmission conditions, but without applying online GMI based scaling in the 1st global iteration, are plotted. We observe that in these cases the desired scaling factor changes significantly with different channel conditions, with around 5 for the ETU300 case while about 0.4 for the EVA70 case. As a result, a single scaling factor for decoder output LLRs for all transmission scenarios is not available. For this reason, we found that applying scaling method as in [9] for 1st global iteration is necessary for further optimization of decoder feedback LLRs.

To summarize, when linear optimization is applied to detector output LLRs in the 1st global iteration, we may expect that a constant 0.3 scaling on decoder feedback LLRs as feedback will be helpful. Applying this value, in the following we further consider designing scaling factor(s) for detector output LLRs in the next global iteration.

3.2. Detector output LLR scaling for later global iterations

For the 2nd global iteration, we note that at medium to high SNR, hard decisions of detector output by 2nd global iteration mostly agree with those by the next decoding iteration. If (3.2) is applied again for 2nd global iteration, numerical search of scaling factors may be instable due to short block lengths (e.g., $I_{qB_i,Y}(s)$ monotonically increases with s). Therefore, the scaling factors found from 1st global iteration may be further utilized. Consider the metric calculated by the detector function for i-th bit:

$$\mathrm{D}_{i,k} = \left(-\frac{\|Y-HX_k\|^2}{N_o} + \sum_{j=0}^{M_c-1} c_j L_{j,a}\right)$$

where H is the channel matrix, N_o is the noise variance, M_c is the number of bits per transmitted symbol vector. Note that for the 1st global iteration no a priori LLRs are available. Assume that by online GMI based search a scaling factor s_i is found for i-th bit channel, then desired detection with a priori LLRs will be

$$\mathrm{D}'_{i,k} = (-s_i \frac{\|Y-HX_k\|^2}{N_O} + \sum_{j=0}^{M_c-1} c_j L_{j,a}) \qquad (3.3)$$

for the next global iteration, so that both the Euclidean and a priors are scaled properly. This requires non-trivial modification of the detector in presence of a priori LLRs.

For simple implementation, an averaged scaling $\bar{s} = \frac{1}{m}\sum_{i=0}^{m-1} s_i$ may be used for all bit LLR calculations so that the detector calculates the following metric

$$\mathrm{D}''_{i,k} = (-\bar{s} \frac{\|Y-HX_k\|^2}{N_O} + \sum_{j=0}^{M_c-1} c_j L_{j,a}) \qquad (3.4)$$

By this simplification, the detector function can remain unchanged for all global iterations. In fact, if the input a priori LLRs to the detector is scaled by $0.3/\bar{s}$ instead of 0.3, then in the next global iteration, scaling detector output LLRs uniformly by $\bar{s}$ will produce channel LLRs by (3.4). (Online scaling factor search is not performed again.) The corresponding receiver structure is shown in Figure 6.

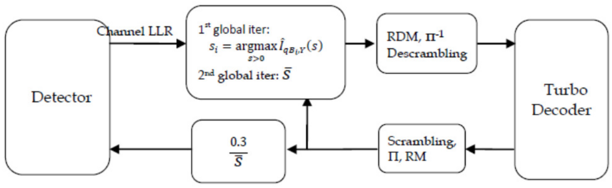

Figure 6 Online GMI based forward scaling and uniform backward scaling for IDD.

3.3. Complexity Analysis

The proposed scheme requires searching of s_i by repeated computation of (3.2) in the 1st global iteration. For each candidate s_i, 2 additions, 2 multiplications, and 2 look-up table operations, are needed per coded bit. Based on s_i, LLR scaling will be performed 3 times in 2 global iterations. For moderate s_i, searching can be finished within a few candidates. The total operations are much less than a LM or S-MLM turbo decoding iteration [13]. When s_i value is far from 1, although more repetitions of (3.2) are needed, a larger gain is expected and can justify the cost.

4. SIMULATIONS

We test the proposed scheme with an LTE link level simulator. The results are shown in Figure 7. Simulation parameters include: 2x2 MIMO, transmission mode 3 as open loop spatial multiplexing, bandwidth 10 MHz, normal cyclic prefix. Channel profiles include EVA70, and ETU300

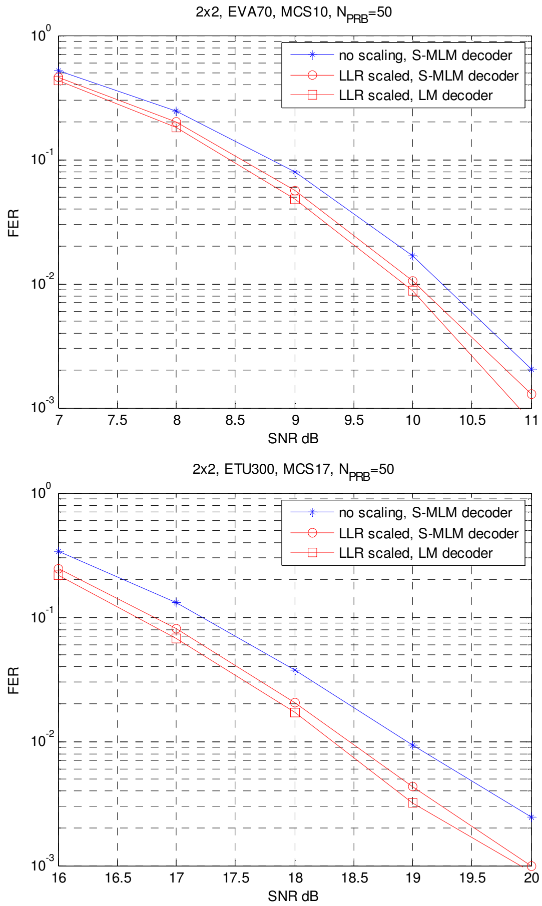

Figure 7 FER performance comparisons.

[11]. Tested modulation and code set (MCS) levels [12] include:

MCS level	Modulation	Code rate	Subframe length
10	16-QAM	0.31~0.33	7992
17	64-QAM	0.39~0.41	15264

The receiver performs 2 global iterations where each global iteration includes 4 turbo decoding iterations.

5. CONCLUSIONS

LLR optimization based on GMI maximization for MIMO BICM IDD receiver is investigated. In the forward direction, for 1st global iteration, LLR scaling is based on online GMI maximization per bit channel as for non-IDD receiver. In the backward direction, decoder feedback LLRs are scaled by a constant $0.3/\bar{s}$, where $\bar{s}$ is the average of the scaling factors of all bit channels for 1st global iteration. Detector output LLRs by later global iterations are uniformly scaled by $\bar{s}$. No bit-channel wise scaling is further applied since the 2nd global iteration. From simulations in a link level simulator, we found the proposed scaling methods for IDD receivers improves performance to substantial extents depending on channel conditions.

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