Information Processing Characteristic for Bit Interleaved Coded Space-Time Modulation

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Abstract—Bit interleaved coded space-time modulation with iterative decoding (BICSTM-ID) [1], [2] is an attractive strategy to achieve high power efficiency close to capacity limit by applying turbo principle to multiple-input and multiple-output (MIMO) channels. In this paper, Information Processing Characteristic (IPC) analysis [3] is extended to MIMO systems in order to fully characterize the BICSTM-ID scheme based on a new equivalent model of combined binary input channels. The analysis results show that the IPC analysis offers a unified aspect for BICSTM and BICSTM-ID from an information theoretical point of view and provides a valuable design guideline for BICSTM-ID as well. Moreover, IPC based upper and lower bounds on BER performance [4] are applied to BICSTM-ID, which are confirmed by simulations and seem to be very useful for performance estimation of coding schemes for space-time coded MIMO channels.

I. INTRODUCTION

It was recognized firstly by Zehavi in [6] that the bit-interleaved scheme provides a high diversity order for transmission over Rayleigh fading channels. As this order is equal to the smallest number of distinct bits along any error event (rather than channel symbols), bit-interleaved schemes have attracted much attention. This scheme was later referred to as bit-interleaved coded modulation (BICM) in [7], where no iterative decoding was considered to exploit the dependence that exists between coded bits introduced by the encoder and the interdependence between labeling bits (i.e. interleaved coded bits addressing one modulation symbol) introduced by high order modulation. For such a case, Gray labeling was preferred. Consequently, iterative decoding methods employing hard decision feedback in [8] and employing soft decision feedback cf. [10] were applied to BICM (i.e. BICM-ID) with the result that when the dependence introduced by high order modulation is somewhat exploited, proper designed labeling rule rather than Gray labeling will bring significant benefits.

Later on, this iterative decoding with bit interleaver was further adapted to MIMO systems in several different approaches, cf. [1] and we preferred to denote this by BICSTM-ID in [2], since it can be considered as an extension of BICM-ID to multiple antennas transmission consisting of an outer code and an inner space-time modulation (STM) employing an arbitrary space-time block code (STBC). As a natural consequence, some analysis methods for BICM-ID could be extended to BICSTM-ID such as the harmonic mean of the minimum squared distance $d^2$ in [7]. The modified minimum squared distance in [9] was extended to MIMO systems in [2] by the union bound of bitwise pairwise error probability. An alternative approach with EXIT chart technique proposed by ten Brink in [10], to analyze and design BICM-ID was also extended later to MIMO systems in [12].

Beside EXIT chart analysis, IPC analysis is another attractive tool for analysis and design of the (concatenated) coding scheme with soft output decoding. It was originally proposed in [3] for binary coding over AWGN channel with single antenna and is closely related to EXIT chart analysis, because both of them are based on bitwise mutual information. However, the IPC denotes the bitwise mutual information (between the input bits and the soft outputs, i.e. $a$-posteriori knowledge) versus the capacity of such a transmission scenario, i.e., the IPC is a function mapping the capacity of the underlying channel to the bitwise mutual information between input bits and soft output $a$-posteriori knowledge. Therefore, it offers an entire aspect of the whole system including encoding, channel model and decoding from an information theoretical point of view.

In this work, we extend the IPC analysis to BICSTM-ID scheme over MIMO system to provide a comprehensive insight to BICSTM-ID schemes. In order to obtain the IPC for BICSTM-ID, we propose a new equivalent model for BICSTM-ID with two combined binary input channels, by which $a$-priori information can also be taken into account. With this simple model, IPC is calculated directly from EXIT chart analysis by taking advantage of information combing [13], [15]. The analysis results show that IPC provides the same insight as capacity of BICSTM when assuming no $a$-priori information and gives an interpretation of the superiority of BICSTM-ID with some non-Gray mapping to that with Gray mapping when assuming $a$-priori information being available. Therefore, it offers a unified aspect for BICSTM and BICSTM-ID from some interesting information theoretic point of view. On the other hand, a tight upper and a tight lower bounds on BER performance based on IPC analysis are extended to BICSTM-ID as well, which allow for an analytical performance estimation for an arbitrary choice of the inner STM.

II. SYSTEM MODEL OF BICSTM-ID

The system model of BICSTM-ID over MIMO flat Rayleigh fading channels with $n_T$ transmit and $n_R$ receive antennas is shown in Fig. 1. The information bits $u[l]$ are encoded by an outer encoder with rate $R_c$, and the coded bits $e[l]$ are organized to frame of length $N$ and then bitwise interleaved. The interleaved data $c[l]$ are mapped onto signal

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points taken from an $M$-QAM/PSK constellation applying a suitable labeling rule. Then, $Q$ consecutive complex symbols of the sequence of modulation symbols are grouped to form a vector $s[k] = [s_1[k], \ldots, s_Q[k]], \ k \in \{1, \ldots, N/n_c\}$ with $n_c \triangleq Q \log_2(M)$, number of coded bits per STM-codeword. (We assume $N/n_c \in \mathbb{N}$). Finally, these groups of modulation symbols $s[k]$ are the inputs of the encoder of a STBC, which is fully specified by a code matrix $G_{T \times N}(s[k])$. The actual STM-codeword $X[k]$ is given by $X[k] = G(s(k))$. Thus, the overall rate of the concatenated code is

$$R_{\text{overall}} \triangleq R_c \cdot \frac{Q}{T} \cdot \log_2(M)$$

bits per MIMO channel use. Transmission of a matrix STM-codeword $X[k]$ through MIMO channels is modeled by a normalized form

$$Y[k] = \sqrt{E_s \over N_{\text{OFT}}} X[k] \cdot H[k] + N[k], \ k = 1, \ldots, K,$$

where both STM-codewords $X[k]$ and complex additive noise $N[k] \in \mathbb{C}^{T \times n_T}$ are normalized to have unit variance elements. $H[k] \in \mathbb{C}^{n_T \times n_R}$ refers to the complex matrix of spatially independent Rayleigh fading MIMO channels with normalized pdf $\mathcal{CN}(0,1)^{n_T \times n_R}$. This model can be assumed when the transmit and receive antennas are spatially sufficiently separated. Furthermore, the channel coefficients are assumed to be constant in each $k$-th time interval and independent from one time interval to another due to the use of a long bitwise interleaver. In addition, the channel coefficients are further assumed to be perfectly known at the receiver. With the above normalizations, the factor $E_s$ in Eq. (2) can be referred to as the average received energy per MIMO channel use and receive antenna, which is independent of $n_T$.

For the BICSTM scheme, the average received energy per information bit $E_b$ divided by $N_0$ is related to the $E_s/N_0$ by

$$E_b \over N_0 = \frac{E_s \cdot n_R}{N_0 \cdot R_{\text{overall}}}.$$  

At the receive side, the iterative decoder uses decoder module with BCJR algorithm for the outer CC and soft-in and soft-out demapper for inner space-time modulation. The soft demapper can be simply derived from Bayes’ theorem [10]. In order to present the iterative decoding with sufficient clarity, we briefly review the soft demapper for our scheme. We denote $n_c$ consecutive interleaved coded bits $c[p(k-1) \cdot n_c + 1 : n_c \cdot p], \ p \in \{0, \ldots, n_c - 1\}$ as a vector of binary symbols $\{c^0[p(k-1)] \ldots c^{n_c-1}[p]\}$, which are mapped onto one transmit matrix STM-codeword $X[k]$. With the use of long bitwise interleaving and the above notation, the log-likelihood ratio (LLR)-valued a-posteriori information of each interleaved coded bit $c^e[k]$ conditioned on $Y[k]$ is given by

where $X^e_c (\text{resp.} X^0_c)$ is the set of STM-codewords $X$ with the binary symbol 1 (resp. 0) at labeling position $c$. The inequality (7) indicates that the possible capacity loss of BICSTM compared to the STM (defined in Eq. (5)) lies in the inability of exploiting the dependence of labeling bits (i.e. interleaved coded bits) conditioned on $Y$. It further implies, on the one hand, that the uncorrelated labeling rule is preferred.

![Fig. 1. Block diagram of bit-interleaved coded space-time modulation with iterative decoding.](image-url)
for BICSTM without iterative decoding and on the other hand, that when this dependence introduced by STM can be somewhat exploited by iterative decoding, the capacity of BICSTM seems to be unsuitable to measure the BICSTM-ID.

Thus, we need another quantity closely related to the concept of capacity and, at the same time, can cope with the updated a-priori information. Motivated by this, we extend IPC analysis to BICSTM-ID, by which bitwise mutual information combining both updated a-priori information and extrinsic information is calculated versus the capacity of the underlying channel such that it is easy to tell how far/close to the capacity limit BICSTM-ID scheme performs.

A. From EXIT Chart to IPC Analysis

In EXIT chart analysis [11], the bitwise mutual information is introduced to measure the information content of a-priori knowledge and of extrinsic knowledge for soft decoder. For the inner soft demapper in our work, the bitwise mutual information w.r.t. a-priori and extrinsic knowledge is denoted by \( I(c; L_0(c)) \) and \( I(c; L_e(c)) \), respectively. The conditional pdf \( p_L(c|c) \), required for the calculation of \( I(c; L_e(c)) \) is assumed to be Gaussian distributed and the conditional pdf for the calculation of \( I(c; L_0(c)) \) is measured by simulation of a single frame of length \( N = 120000 \). Based on the notation of bitwise mutual information, we define the IPC of BICSTM-ID as

\[
IPC_{\text{BICSTM-ID}}(\text{CSTM}) \triangleq \frac{n_u}{T} I(u; L(u)), \tag{9}
\]

where

\[
n_u \triangleq n_c R_c \tag{10}
\]

is the number of information bits transmitted per one STM-codeword (i.e. \( T \) MIMO channel uses). This definition of IPC denotes that the information contents of the soft output \( L(u) \) can be calculated via an end-to-end bitwise channel. In the following, we study the two examples of BICSTM-ID schemes, both with the same rate 1/2 (i.e. \( R_c = 1/2 \)) systematic recursive convolutional code with generator \((G_r = 7, G_1 = 7, G_2 = 5)\) in octal form as the outer code and Alamouti’s STBC with 16QAM symbols as the inner STM, but one with Gray labeling and the other with modified set partitioning (SP) labeling as shown in Fig. 2, since for the latter case, the labeling bits are more interdependent as analyzed in [2] and thus can be used as a typical example in opposition to the Gray labeling rule. In order to figure out where the superscript 0 denotes 0 iteration is performed, with which BICSTM-ID is equivalent to BICSTM, such that \( c \) and \( L(c) \) instead of \( u \) and \( L(u) \) are used compared to Eq. (9).

Furthermore, because a-priori information are assumed to be 0 and hence \( L(c) = L_0(c) \). Recall the soft demapper algorithm in Eq. (4), we see that with no a-priori information, the mutual information of \( I(c'; L_0(c')); |H| \) obtained by simulation with a single frame of length \( N = 120000 \) will be a good approximation of \( I(c'; Y|H) \), with which \( C_{\text{BICSTM}} \) in Eq. (7) can be approximately linked to \( IPC_{\text{BICSTM-ID}}^0 \) as

\[
C_{\text{BICSTM}} \approx \frac{1}{N} \left[ I(c^0; L_0(c^0)) + \cdots + I(c^{n_e-1}; L_0(c^{n_e-1})) \right]
\]

\[
\approx \frac{1}{n_c} I(c; L_0(c)) = IPC_{\text{BICSTM-ID}}^0. \tag{12}
\]

This relationship is confirmed by the numerical calculation given in Fig. 3. It is shown that \( C_{\text{BICSTM}} \) is well approximated by \( IPC_{\text{BICSTM-ID}}^0 \) with the both examples employing Gray and modified SP labeling. Like \( C_{\text{BICSTM}} \), \( IPC_{\text{BICSTM-ID}}^0 \) also confirms the propriety of the Gray labeling for BICSTM-ID scheme without a-priori information and therefore, \( IPC_{\text{BICSTM-ID}}^0 \) can provide almost the same insight as \( C_{\text{BICSTM}} \) for BICSTM. Moreover, the calculation of \( IPC_{\text{BICSTM-ID}}^0 \) is significantly simpler than that of \( C_{\text{BICSTM}} \), because for \( IPC_{\text{BICSTM-ID}}^0 \), we don’t have to simulate \( p_L(c|c) \) for different \( \nu \in \{0, \ldots, n_e-1\} \), but only need measure \( p_L(c|c) \) regardless which index \( \nu \) they belong to.

C. IPC analysis of BICSTM-ID w.r.t. sufficiently many iterations

In this case, we discuss the calculation of the IPC for BICSTM-ID with sufficiently many iterations yielding convergence. It is worth mentioning that the convergence here indicates that the transfer characteristics (TC) curves of outer decoder and inner demapper intersect at one point for a fixed \( E_b/N_0 \), (which is not necessarily to be (1,1) in an EXIT chart), such that more iterations can not reduce BER further. In fact, for non-recursive inner system like STM, its TC curve can not always go to (1,1) point as the constraint length is relatively short. Next, we study how to obtain the IPC defined in Eq. (9) directly from EXIT chart when convergence occurs. According to the BCJR algorithm used in the outer soft decoder, for systematic recursive convolutional code, the bitwise mutual information between information bits \( u \) and the soft outputs \( L(u) \) can be well approximated by the bitwise mutual information of coded bits \( c' \) and the soft outputs \( L(c') \), i.e.,

\[
I(u; L(u)) \approx I(c'; L(c')). \tag{13}
\]
where \( L(c') \) is a-posteriori information of coded bits and equals to the sum of \( \Lambda_0(c') \) and \( \Lambda_e(c') \), i.e. \( L(c') = \Lambda_0(c') + \Lambda_e(c') \). Thus, inserting Eq. (10) and Eq. (13) into Eq. (9), the \( \text{IPC}_{\text{BICSTM-ID}} \) can be rewritten as

\[
\text{IPC}_{\text{BICSTM-ID}}(C_{\text{STM}}) = R_e \frac{n_e}{T} I(c'; L(c')) - R_e \frac{n_e}{T} I\left(c'; (\Lambda_0(c') + \Lambda_e(c'))\right) \tag{14}
\]

To approach \( I\left(c'; (\Lambda_0(c') + \Lambda_e(c'))\right) \) without measuring the pdf again for \( \hat{L}(c') \) (i.e. \( \hat{L}(c') = \hat{L}_0(c') + \hat{L}_e(c') \)), information combining [13] is applied by the approximation

\[
I\left(c'; (\Lambda_0(c') + \Lambda_e(c'))\right) \approx 1 - \left(1 - I(c'; \Lambda_0(c'))\right) \left(1 - I(c'; \Lambda_e(c'))\right) \tag{15}
\]

which is indeed a tight upper bound. Furthermore, the convergence of iterative decoding implies that both \( I(c'; \Lambda_0(c')) = I(c; \Lambda_0(c)) \) and \( I(c'; \Lambda_e(c')) = I(c; \Lambda_e(c)) \) hold, as they label the same intersection point. Therefore, \( \text{IPC}_{\text{BICSTM-ID}}(C_{\text{STM}}) \) can be finally defined and expressed by the bitwise mutual information w.r.t. coded interleaved bits \( c \) instead of \( c' \) by

\[
\text{IPC}_{\text{BICSTM-ID}}^{\text{conv}}(C_{\text{STM}}) \triangleq \frac{R_e n_e}{T} \left[ 1 - \left(1 - I(c; \Lambda_0(c))\right) \left(1 - I(c; \Lambda_e(c))\right) \right]. \tag{16}
\]

where the superscript \( \text{conv} \) denotes that convergence is arrived by performing sufficiently many iterations. In such a way, the IPC which initially denotes the mutual information between information bits \( u \) and their corresponding soft outputs \( L(u) \) via an end-to-end binary input channel can further be calculated by the combined mutual information of two effective binary input channels, one is between \( c \) and \( \Lambda_0(c) \) and another one between \( c \) and \( \Lambda_e(c) \), which is depicted in Fig. 4. Thus, IPC curve can be directly obtained from EXIT chart and fully characterize the asymptotical behavior of the concatenated coding scheme without simulating the iterative decoding process. Below, EXIT chart curves for the two BICSTM-ID schemes with Gray labeled and modified SP labeled 16QAM symbols are plotted for some \( E_b/N_0 \) and the intersection points are emphasized by markers labeled by their respective \( E_b/N_0 \). For Gray labeling with orthogonal STBC shown in Fig. 5 (a), the TC curve of soft demapper is almost horizontal so that there is almost no benefit gained by iterative decoding. However, when modified SP labeled 16QAM symbols are employed, the labeling bits of STM-codeword are more correlated, which results in increasing TC curves for varied \( E_b/N_0 \) illustrated in Fig. 5 (b). At only \( E_b/N_0 = 4.02 \text{ dB} \), a narrow tunnel is opened to allow an iterative decoding towards low BER and this small channel in EXIT predicts a turbo cliff in BER chart.

Upon the values of \( I(c; \Lambda_0(c)) \) and \( I(c; \Lambda_e(c)) \) labeled the intersection points in EXIT chart, IPC curves are directly calculated based on Eq. (16) and drawn in Fig. 6. The theoretical limit is also plotted for reference.

It is interesting to see that an “upward cliff” occurs in the IPC curve as well. At \( E_b/N_0 = 4.02 \text{ dB} \), the mutual information between input and soft output of the whole coding scheme with modified SP labeled symbols increases sharply to about 2 bits per MIMO-channel use and hence at \( E_b/N_0 = 4.4965 \text{ dB} \), the IPC of the scheme with modified SP labeling is obviously larger than that with Gray labeling, which indicates that the scheme with modified SP labeled symbols will outperform that with Gray labeled symbols. In order to verify this superiority, a useful estimation of BER performance based on IPC [4] is given in the next subsection.

**Fig. 5.** EXIT chart for the BICSTM-ID schemes with (a) Gray labeled and (b) modified SP labeled 16QAM symbols.

**Fig. 6.** \( \text{IPC}_{\text{BICSTM-ID}}^{\text{conv}} \) for the BICSTM schemes with Gray and modified SP labeled 16QAM symbols.

**IV. PERFORMANCE ESTIMATION AND SIMULATION RESULTS**

Since IPC analysis has been extended to BICSTM-ID, the IPC based upper and lower bounds [4] can also be applied to BICSTM-ID. In particular, because the traditional analytical upper union bound on the BER performance is valid only for linear code with BPSK symbols [5], these IPC based bounds are of significant interest for the concatenated coding scheme over MIMO channels with a general and usually nonlinear inner system.

**A. Upper and Lower Bounds on BER performance of BICSTM-ID by IPC analysis**

It was derived in [4], [15] that if \( u \rightarrow L(u) \rightarrow \tilde{u} \) (\( \tilde{u} \) is the hard decision based on the soft output \( L(u) \)) forms a Markov
chain, an upper and a lower bound on $p_0$ can be obtained with

$$p_0 \geq 2^{-1}(1 - I(u; L(u)))$$

(17)

and

$$p_0 \leq \frac{1}{2}(1 - I(u; L(u)))$$

(18)

respectively. Here $e_2(x) = -e^{\log_2(x) - (1 - x)\log_2(1 - x)}$, $x \in (0, 1)$ and $e_2^{-1}(x)$ is the inverse function of $e_2(x)$ with $x \in (0, \frac{1}{2})$. Moreover, since the equation in (17) can be achieved for binary symmetric channel (BSC) channel and the equation in (18) holds for binary erasure channel (BEC) channel [4], [15], they turn out to be tight bounds. Comparing to another BER estimation method in [11], where the relation between $p_0$ and $I(u; L(u))$ was based on the assumption of $L(u)$ being distributed as if $u$ had been transmitted over an AWGN channel, these bounds provide analytical limits of $p_0$.

B. Simulation Results

The BER performance curves of the two BICSTM-ID schemes employing Gray and modified SP labeled 16QAM symbols with corresponding upper and lower bounds are depicted in Fig. 7 (a) and Fig. 7 (b), respectively. The interleaver length is of $N = 120000$ coded bits and sufficiently many iterations that yield convergence are performed for the both cases (here 2 iterations for the case with Gray labeled symbols and 20 iterations for the case with modified SP labeled symbols). We see that in Fig. 7 (a), the BER curve is well estimated by the lower and upper bounds derived in Eq. (17) and Eq. (18), respectively. Moreover, since the Gray labeling cannot gain from the iterative decoding and hence its BER curve goes slowly down to about $2.4 \cdot 10^{-2}$ at $E_b/N_0=5$ dB. On the contrary, when modified SP labeled symbols are used, the BER performance shown in Fig. 7 (b) is significantly improved and as predicted by IPC and EXIT chart, a cliff occurs in BER chart at about 4.2 dB, which results in a BER blow $10^{-4}$ at that $E_b/N_0$, only 1.5 dB away from the theoretical limits of $(E_b/N_0)_{\text{min}} \approx 2.7$ dB for this setup. In particular, these upper and lower bounds based on IPC analysis are also confirmed by this scheme with modified SP labeling, although the simulation curve for this case is slightly larger than the upper bound in the cliff region. It is due to the fact that in the cliff region, much more iterations are required and hence, very lager interleaver (much larger than $N = 120000$) is consequently needed to ensure the assumed independence of a-priori and extrinsic information. However, in spite of this little deficiency of the upper bound in the cliff region, these upper and lower bounds are still very useful for the performance estimation of the BICSTM-ID scheme.

V. CONCLUSIONS

In this paper we extend the IPC analysis to BICSTM-ID scheme to provide a comprehensive understanding of iterative decoding over MIMO systems. In particular, we analyze two cases of BICSTM-ID with 0 iteration and with sufficiently many iterations resulting convergence. It is shown that the IPC can provide the same insight as capacity of BICSTM and can fully characterize the information processing of BICSTM-ID with large number of iterations as well by simplifying the BICSTM-ID scheme to an equivalent model consisting of two combined binary input channels. Hence, the IPC analysis provides a unified aspect for both BICSTM and BICSTM-ID scheme. Moreover, an upper and a lower bound on BER performance based on IPC analysis are applied to BICSTM-ID to render an efficient estimation of BER performance without simulating the BICSTM-ID scheme with high complexity.

REFERENCES


