LETTER

Iterative Adaptive Soft Parallel Interference Canceller for Turbo Coded MIMO Multiplexing

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SUMMARY In this paper, iterative adaptive soft parallel interference canceller (ASPIC) is proposed for turbo coded multiple-input multiple-output (MIMO) multiplexing. ASPIC is applied to transform a MIMO channel into single-input multiple-output (SIMO) channels for maximum ratio diversity combining (MRC). In the ASPIC, replicas of the interference are generated and subtracted from the received signals. For the generation of replicas with higher reliability, iterative ASPIC is proposed. It performs the iterative interference cancellation by feedback of the log-likelihood ratio (LLR) sequence obtained as the turbo decoder output. For iterative ASPIC, at the transmitter, the information sequence and parity sequence are transmitted from different antennas. In this paper, the achievable bit error rate (BER) performance, in a Rayleigh fading channel, for the turbo coded MIMO multiplexing with the proposed iterative ASPIC system is evaluated by computer simulation.

key words: *MIMO multiplexing, parallel interference canceller, mobile communication, Rayleigh fading, turbo coding*

1. Introduction

Recently, there have been tremendous demands for high-speed data transmissions in mobile communications [1]. However, the available bandwidth is limited, so higher spectrum efficiency is required. One of the promising techniques is the multiple-input multiple-output (MIMO) system [2] that uses multiple antennas at transmitter and receiver. Recently, various MIMO systems are being researched. One such technique to provide high speed data rate without requiring additional bandwidth is MIMO multiplexing [3]. In MIMO multiplexing, transmit data sequence is transformed into parallel sequences and each sequence is transmitted from a different transmit antenna at the same time with the same carrier frequency. At the receiver, it is necessary to separate the signals transmitted from different antennas. Various methods for the separation of the transmitted signals are known, e.g., maximum likelihood detection (MLD) [4], minimum mean square error (MMSE) [5], zero forcing (ZF) [6], V-Bell Laboratories layered space-time architecture (V-BLAST) [7] and so on.

In mobile radio communications, channel state is changing every moment. This phenomenon is called multipath fading [8]. In a multipath fading environment, bit error rate (BER) performance degrades drastically. Hence, it is necessary to use MIMO multiplexing together with channel coding. Recently, turbo coding [9], [10] that has powerful error correcting capability is the center of attention. In [11], an MMSE filter followed by successive interference canceller (SIC) is presented for turbo coded MIMO multiplexing for DS-CDMA downlink in mobile radio. Separately turbo coded data sequences are transmitted from different antennas. After carrying out MMSE at a receiver, the best sequence having the highest reliability is selected for turbo decoding. Then, the turbo decoder output information (or systematic) bit sequence is re-encoded to generate the interference replica to be subtracted from the received signal. MMSE is carried out again for separating the remaining data sequences. The above process is repeated until all the data sequences transmitted from all the transmit antennas are decoded.

In this paper, we consider turbo coded MIMO multiplexing. We introduce parallel interference canceller (PIC), instead of SIC, in conjunction with MLD to transform the MIMO channel into the single-input multiple-output (SIMO) channels and perform the maximum ratio diversity combining (MRC) to generate the soft value for turbo decoding. Furthermore, adaptive soft cancellation weight is introduced to reduce the adverse effect of MLD decision error, resulting in an adaptive soft PIC (ASPIC). In the ASPIC, the interference replicas are generated and subtracted from the received signals. For the generation of replicas with higher reliability, iterative ASPIC is introduced. When powerful error correction coding as turbo coding is used, re-encoding spreads the errors in the re-encoded sequence, thereby producing large error propagation, and this prevents reliable generation of interference replica. Therefore, in this paper, to prevent error propagation, only the LLR sequence associated with the information bit sequence is fedback for iterative ASPIC.

In this paper, the achievable bit error rate (BER) performance of the turbo coded MIMO multiplexing with the proposed iterative ASPIC system in a Rayleigh fading channel is evaluated by computer simulation. Another method of soft value generation for turbo decoding is to directly compute the LLR from the received signals [12]. In this paper, the achievable BER performance using iterative ASPIC is compared with that using LLR computation method of [12].

The remainder of this paper is organized as follows. Section 2 describes the turbo coded MIMO multiplexing with the iterative ASPIC system. Section 3 presents the computer simulated BER performance of turbo coded MIMO multiplexing with iterative ASPIC in a Rayleigh fading channel. In addition, the BER performance of MIMO

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multiplexing system using quaternary phase shift keying (QPSK) modulation is compared with that of an Alamouti space time coded transmit diversity (STTD) [13] system using 16 quadrature amplitude modulation (16QAM), which has the same spectrum efficiency as MIMO multiplexing system using two transmit antennas and QPSK modulation. The performance of MIMO multiplexing system using 4 transmit antennas is also presented. Section 4 concludes the paper.

2. System Model of Turbo Coded MIMO Multiplexing with Iterative ASPIC

Figure 1 shows a system model of (N, M)MIMO multiplexing with iterative ASPIC using N transmit antennas and M receive antennas. The binary information bit sequence $\{b_i; i = 0 \sim (I-1)\}$ of length I (for simplicity we assume that I is an even integer) is turbo coded into the coded sequence $\{x_j; j = 0 \sim (I/R-1)\}$ by a rate R turbo encoder. The turbo coded sequence after channel interleaving is transformed into N parallel sequences such that information (systematic) bit sequences and parity bit sequences are transmitted at the same time from different antennas as much as possible. This ensures that the LLR of the information bits at the receiver can be used to increase the reliability of the parity bits transmitted at the same time but from different antennas.

This is further explained in detail here with an R=1/2 turbo code. The turbo coded sequence after interleaving is transformed into $N/2$ information (or systematic) bit sequences and $N/2$ parity bit sequences by serial-to-parallel (S/P) conversion. Each sequence is transformed into QPSK modulated symbol sequence. The information symbol sequences are transmitted from the $0 \sim (N/2-1)$th transmit antennas and the parity symbol sequences are transmitted from the $N/2 \sim (N-1)$th transmit antennas. The symbol transmitted from the nth antenna is denoted as d_n. It is assumed that the signals transmitted from N transmit antennas experience independent Rayleigh fading and are received by M receive antennas.

We assume a square-root Nyquist filter for transmitter and receiver and ideal sampling timing at the receiver. The received signal is sampled at the symbol rate. The received signal r_m on the mth receive antenna can be expressed using the equivalent low-pass representation as

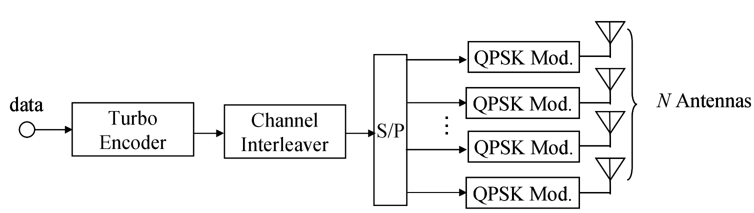
$$r_m = \sqrt{2S}\sum_{n=0}^{N-1}\xi_{n\_m}d_n + n_m \tag{1}$$

for $m = 0 \sim M-1$, where S is the average received signal power on each antenna, ξ_{n_m} is the complex gain of the fading channel between the nth transmit antenna and the mth receive antenna, and n_m is the additive white Gaussian noise (AWGN) process, at the mth receive antenna, and has a zero mean and a variance of $2\sigma^2 = 2N_0/T$, (N_0 is the single sided AWGN power spectrum density and T is the QPSK symbol length). MLD is performed to output the decision values $\{\hat{d}_n; n = 0 \sim N-1\}$ for the N transmitted symbols using the M received signals $\{r_m; m = 0 \sim M-1\}$.

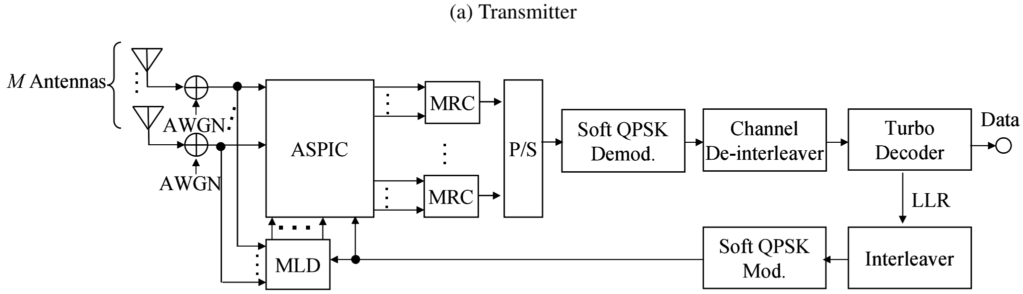
When turbo coding is used, it is necessary to generate soft values for the input to the turbo decoder. In this paper, the soft values are generated by using the iterative ASPIC and MRC.

2.1 ASPIC and MRC

Figure 2 shows the ASPIC and MRC structure that generates the soft decision values. The sum of signals transmitted by N antennas is received by each of the M receive antennas (see Eq. (1)). In ASPIC, only the symbol transmitted by the nth antenna is extracted from the received signal on each receive antenna. Thus, a MIMO channel is transformed into N SIMO channels. The M signals received by each SIMO channel is equivalent to M antenna diversity reception with single antenna transmission. The M signals received by each



(a) Transmitter



(b) Receiver

Fig. 1 (N, M)MIMO multiplexing transmission system model.

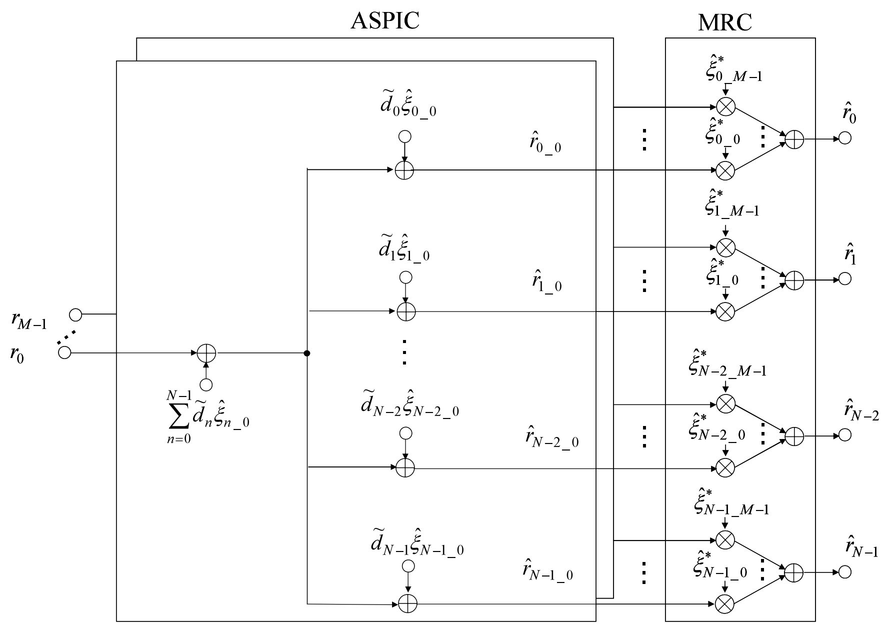


Fig. 2 ASPIC and MRC.

SIMO channel are coherently combined using MRC to generate the soft value needed for turbo decoding. The operation principle of ASPIC is as follows. Using the N hard decision symbol outputs $\{\hat{d}_n;\ n = 0 \sim N-1\}$ of MLD, the ASPIC generates the replicas of interference and performs the parallel interference cancellation. When MLD is incorrect, PIC excessively subtracts the interference, so the use of PIC increases the interference. Therefore, the adaptive soft cancellation weight based on the decision reliability of MLD is introduced (the adaptive soft cancellation weight is explained in Sect. 2.3). The ASPIC output $\hat{r}_{n\_m}$ for the signal transmitted from the nth transmit antenna and received by the mth receive antenna can be expressed as

$$\begin{aligned}\hat{r}_{n\_m} &= r_m - \sqrt{2S}\sum_{\substack{k=0\\ \neq n}}^{N-1}\tilde{d}_k\hat{\xi}_{k\_m}\\ &= \left\{r_m - \sqrt{2S}\sum_{n=0}^{N-1}\tilde{d}_n\hat{\xi}_{n\_m}\right\} + \sqrt{2S}\hat{\xi}_{n\_m}\tilde{d}_n \qquad (2)\end{aligned}$$

for $m = 0 \sim M-1$, where $\hat{\xi}_{n\_m}$ represents the channel gain estimate for ξ_{n_m} and $\tilde{d}_n$ is given by

$$\tilde{d}_n = \lambda_{n\_c}\mathrm{Re}[\hat{d}_n] + j\lambda_{n\_s}\mathrm{Im}[\hat{d}_n], \qquad (3)$$

where λ_{n_c} and λ_{n_s} ($0 \leq \lambda_{n\_c}$ and $\lambda_{n\_s} \leq 1$) are the adaptive soft cancellation weights. From Eq. (2), we get M received signals that correspond to the transmitted signal d_n. If $\lambda_{n\_c} = \lambda_{n\_s} = 1$ are used, ASPIC reduces to hard PIC. When channel estimation and MLD detection are ideal (i.e., $\hat{\xi}_{n\_m} = \xi_{n\_m}$, $\tilde{d}_n = d_n$), Eq. (2) reduces to $\hat{r}_{n\_m} = \sqrt{2S}\xi_{n\_m}d_n + n_m$. For diversity combining, we assume MRC. The MRC output is given by

$$\hat{r}_n = \sum_{m=0}^{M-1}\hat{r}_{n\_m}\hat{\xi}^*_{n\_m}, \qquad (4)$$

where * denotes the complex conjugate operation. After MRC, the MRC outputs are parallel-to-serial (P/S) converted into a serial sequence and soft QPSK demodulation is performed for succeeding turbo decoding.

2.2 Adaptive Soft Cancellation Weight

As stated in Sect. 2.1, when decision of MLD detection is incorrect, the use of PIC increases the interference. Hence, adaptive soft cancellation weight is introduced to avoid the increase in the interference.

It is difficult to theoretically find the optimal weight, so we take a heuristic approach based on the decision reliability of MLD. When the decision reliability of MLD is high (otherwise), we use a large (small) cancellation weight. The operation principle is as follows. MLD is carried out to output the hard decision symbol vector $\hat{\mathbf{d}} = [\hat{d}_0, \hat{d}_1, \cdots, \hat{d}_{N-1}]$ that minimizes the log likelihood L:

$$L = \sum_{m=0}^{M-1}\left|r_m - \sqrt{2S}\sum_{n=0}^{N-1}\hat{\xi}_{n\_m}\hat{d}_n\right|^2. \qquad (5)$$

In this paper, MLD finds two candidate symbol vectors, the most reliable symbol vector that has the lowest log likelihood value and the second most reliable symbol vector that has the second lowest log likelihood value, and they are compared bit-by-bit. The adaptive soft cancellation weight is determined as

$$\lambda_{n\_c}(\lambda_{n\_s}) = \begin{cases}1, & \text{if the 1st (2nd) bits in the two symbols are the same}\\ 1-\exp(-\alpha\Delta L), & \text{otherwise,}\end{cases} \qquad (6)$$

where ΔL is the difference of log likelihood between the most reliable candidate vector and the second most reliable one, and α is the adaptivity parameter that controls the extent to which ΔL contributes to the cancellation weight.

2.3 Iterative Process

In an iterative process, the soft decision information symbol sequence is generated from the LLR sequence given by the turbo decoder, and the parity symbols are again detected in MLD using the soft decision information symbols. These information and parity symbol sequences are inputted into the ASPIC again. The ASPIC transforms the MIMO channel into SIMO channels, and MRC combining is performed again. Below, the ith ($i > 0$) iterative process is explained (noted that i=0 corresponds to the initial processing presented in Sect. 2.1).

After the LLR sequence, obtained as the turbo decoder output, is channel-interleaved by an interleaver, the soft decision value $\tilde{d}_n^{(i)}$ of the information symbol sequence transmitted by the nth antenna ($n = 0 \sim N/2 - 1$) is generated as

$$\tilde{d}_n^{(i)} = \frac{1}{\sqrt{2}}\Omega(\beta\Lambda_{n\_c}^{(i-1)}) + j\frac{1}{\sqrt{2}}\Omega(\beta\Lambda_{n\_s}^{(i-1)}), \tag{7}$$

where

$$\Omega(x) = \frac{1-\exp(-x)}{1+\exp(-x)}. \tag{8}$$

In Eq. (7), $\Lambda_{n\_c}^{(i-1)}$ and $\Lambda_{n\_s}^{(i-1)}$ are the LLRs of turbo decoder output, obtained after the $(i-1)$th iteration, that correspond to the 2 bits belonging to an information QPSK symbol transmitted from the nth antenna. β is the parameter which is optimized by computer simulation. Then, MLD is carried out to output the hard decision parity symbols $\{\hat{d}_{n'}^{(i)}; n' = N/2 \sim N-1\}$ that minimizes the log likelihood:

$$L = \sum_{m=0}^{M-1}\left| r_m - \sqrt{2S}\left(\sum_{n=0}^{N/2-1}\hat{\xi}_{n\_m}\tilde{d}_n^{(i)} + \sum_{n'=N/2}^{N-1}\hat{\xi}_{n'\_m}\hat{d}'^{(i)}_{n}\right)\right|^2. \tag{9}$$

After MLD is performed, the $N/2$ soft decision parity symbols $\tilde{d}_{n'}^{(i)}$, $n' = N/2 \sim N-1$, are generated as

$$\tilde{d}_{n'}^{(i)} = |\Omega(\beta\Lambda_{n'\_c}^{(i)})|\mathrm{Re}[\hat{d}_{n'}^{(i)}] + j|\Omega(\beta\Lambda_{n'\_s}^{(i)})|\mathrm{Im}[\hat{d}_{n'}^{(i)}], \tag{10}$$

where $\Lambda_{n'\_c}^{(i)}$ and $\Lambda_{n'\_s}^{(i)}$ are the LLRs of information bits associated with parity bits transmitted from the n'th transmit antenna.

The soft valued information and parity symbols are again input to the ASPIC, which again generates the replicas of interference and performs the parallel interference cancellation. The output $\hat{r}_{n\_m}$ from ASPIC can be expressed as

$$\hat{r}_{n\_m} = \left\{ r_m - \sqrt{2S}\sum_{n=0}^{N-1}\hat{\xi}_{n\_m}\tilde{d}_n^{(i)} \right\} + \sqrt{2S}\hat{\xi}_{n\_m}\tilde{d}_n^{(i)}. \tag{11}$$

Note that when $i = 0$, $\tilde{d}_n^{(0)} = \tilde{d}_n$ given by Eq. (3). Then, MRC and turbo decoding are performed. The repetition of the above process is called iterative ASPIC.

3. Computer Simulation

3.1 Simulation Condition

We assume an (N, M)MIMO multiplexing system using QPSK modulation. Table 1 shows the simulation conditions. The transmission of information bit sequence of length I=996 is considered. A rate-1/3 turbo encoder consisting of two (7, 5) recursive systematic convolutional (RSC) encoders [10] is employed. Figure 3 shows the structure of the turbo encoder. The input to the second RSC encoder is the interleaved version of the information sequence input to the first RSC encoder. The internal interleaver is an S-random ($S = \sqrt{I}$) interleaver [14]. The two parity bit sequences of the two RSC encoders are punctured to increase the coding rate to R=1/2. The turbo coded sequence length is 2000-bit and a 40×50-bit block channel interleaver is used.

Frequency-nonselective Rayleigh fading is assumed with $N \times M$ independent fading channel. The maximum Doppler frequency f_D normalized by the coded bit rate $1/T_b$ is assumed to be $f_D T_b$=0.001, which corresponds to a transmission rate of 64 kbps at a carrier frequency of 2 GHz when the mobile speed is 70 km/h. It is necessary to estimate the $N \times M$ channel gains for performing MLD and ASPIC; in

Table 1 Simulation condition.

Transmitter	Information bit length	I=996
	Turbo encoder	(7,5)RSC component encoder
		Rate 1/2
		S-random interleaver
	Channel interleaver	40x50-bit block interleaver
	Modulation scheme	QPSK
	No. of antennas	N=2,4
Channel Model	Rayleigh fading	
	Normalized maximum Doppler frequency	$f_D T_b$=0.001
Receiver	No. of antennas	M=2,4,8
	Channel estimation	Ideal
	Turbo decoder	Log-MAP
		9 iterations

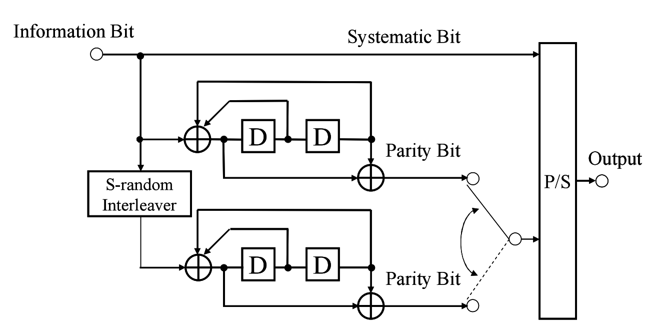


Fig. 3 Turbo encoder.

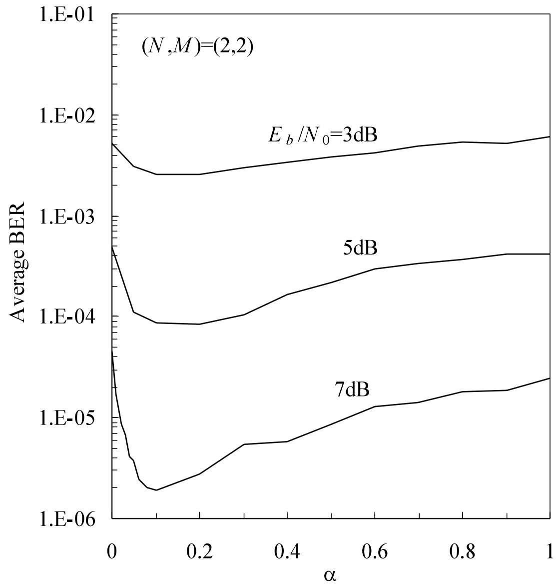


Fig. 4 Impact of the adaptivity parameter α on average BER of turbo coded (2, 2)MIMO multiplexing using ASPIC.

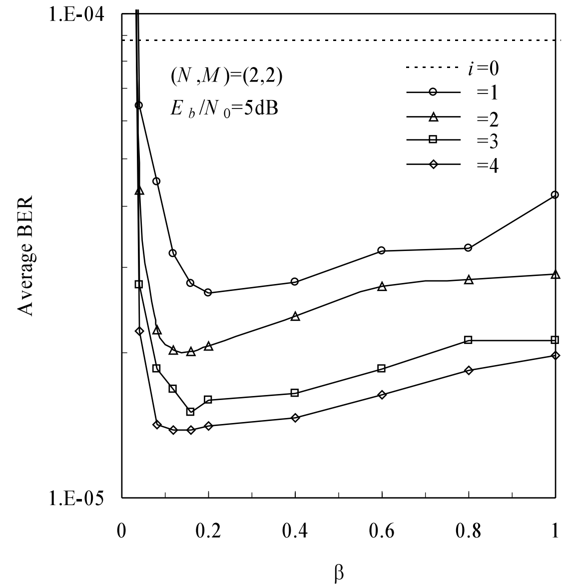


Fig. 5 Impact of the adaptivity parameter β on average BER of turbo coded (2, 2)MIMO multiplexing with iterative ASPIC.

this simulation, channel estimation is assumed to be ideal.

The BER performances of $(2, M)$ and $(4, M)$MIMO multiplexing system are presented. In addition the performance of $(2, M)$MIMO multiplexing is compared with Alamouti space-time transmit diversity system [13] using 16QAM (referred to as 16QAM-STTD system). 16QAM-STTD system has the same spectrum efficiency of 4 bps/Hz as the $(2, M)$MIMO multiplexing system.

3.2 BER Performance

Figure 4 plots the average BER of turbo coded (2, 2)MIMO multiplexing using ASPIC as a function of the adaptivity parameter α. It can be seen from Fig. 4 that there exists an optimum value that minimizes the BER for each average received E_b/N_0 per receive antenna. The optimum value is seen to be α=0.1. Figure 5 plots the average BER of turbo coded (2, 2)MIMO multiplexing with iterative ASPIC as a function of β. It can be seen that the average BER is not so sensitive to β, but the optimum value is seen to be β=0.4. In the following simulations, we use α=0.1 and β=0.4.

Figure 6(a) plots the average BER performances of turbo coded $(2, M)$MIMO multiplexing with iterative ASPIC as a function of the average received E_b/N_0 per receive antenna. Here, perfect $(1, M)$SIMO refers to the condition when PIC is ideal. It can be seen that ASPIC without iteration provides better BER performance than hard PIC and the average required E_b/N_0 for the average BER=10^{-4} is reduced by about 2 dB (0.7 dB) when M=2(4). As the number of iterations increases, the BER performance improves, but almost no additional improvement is obtained after 4 iterations. So, the use of 4 iterations (i=4) is enough. When M=2(4), the average required E_b/N_0 for the average BER=10^{-4} is about 0.7 dB (0.5 dB) less with 4 iterations than without iteration, and the degradation from perfect $(1, M)$SIMO can be reduced by about 2.4 dB (0.7 dB). Figure 6(b) plots the BER performance of $(4, M)$MIMO multiplexing. The trend of improvement by using iterative ASPIC is as same as Fig. 6(a) and the use of 4 iterations (i=4) is enough for the improvement. When M=4(8), the average required E_b/N_0 for the average BER=10^{-4} is about 1 dB (0.6 dB) less with 4 iterations than without iteration and the degradation from perfect $(1, M)$SIMO can be reduced to about 2.3 dB (0.6 dB).

Comparing with the LLR computation [12], the iterative ASPIC provides almost identical or slightly better performance when more than two receive antennas are used (i.e., $M \geq 4$). It can be seen from Fig. 6 that although the performance of iterative ASPIC (i=4) is inferior by about 0.5 dB to that of LLR computation for (N, M)=(2, 2), it is better by about 0.3 dB, 0.2 dB, and 0.4 dB for (N, M)=(2, 4), (4, 4), and (4, 8), respectively. In this paper, the adaptive weight is computed by using a heuristic approach. If the optimum weight function can be found, the iterative ASPIC could be more superior to LLR computation, at the cost of increase in complexity, and closer to the perfect $(1, M)$SIMO.

For comparison, the BER performance for 16QAM-$(2, M)$STTD using two transmit antennas is also plotted in Fig. 6(a). The performance of (2, 2)MIMO multiplexing with ASPIC is about 0.2 dB inferior to that of (2, 2)STTD. However, (2, 4)MIMO multiplexing provides about 1.9 dB better performance than (2, 4)STTD. Possible reason for this is discussed below. $(2, M)$MIMO multiplexing has M-branch MRC antenna diversity gain if MLD decision is perfect, while $(2, M)$STTD has $2M$-branch MRC antenna diversity gain. Therefore the comparison between $(2, M)$MIMO multiplexing and $(2, M)$STTD is equivalent to the performance comparison between QPSK using M-branch MRC

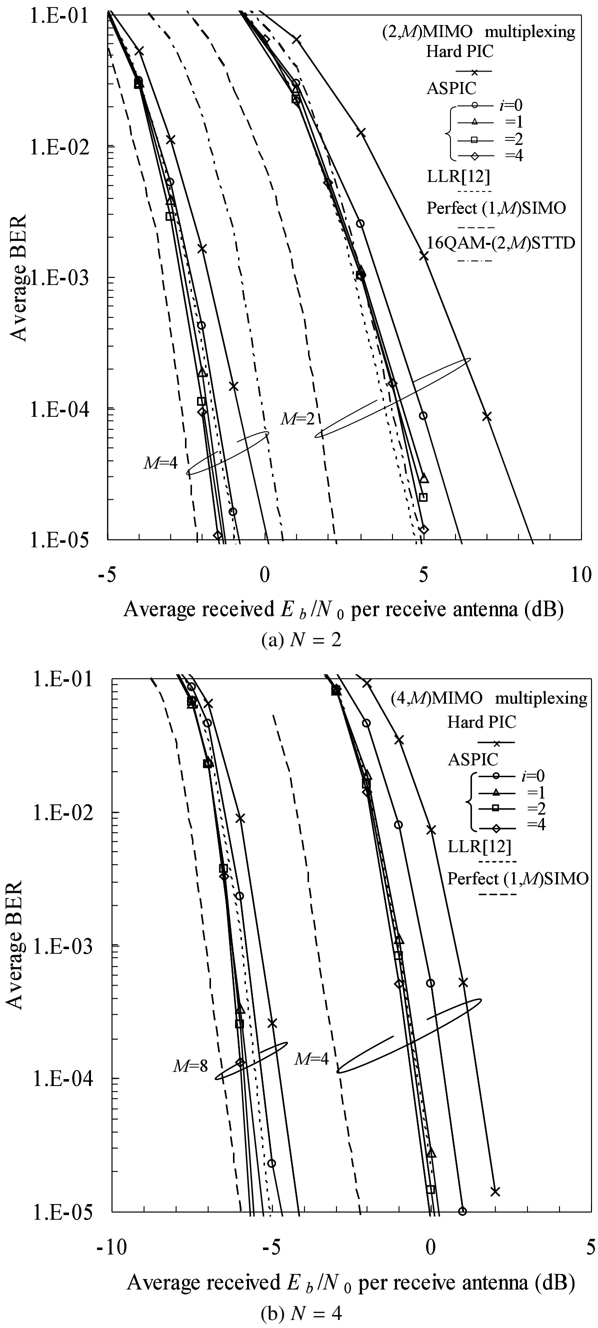


Fig. 6 Average BER performances of turbo coded (N, M)MIMO multiplexing with iterative ASPIC.

antenna diversity reception and 16QAM using $2M$-branch MRC antenna diversity reception, but with 3 dB power penalty (this power penalty in STTD is due to the fact that the same signal is transmitted from two antennas. Referring to Ref. [15, chaps. 5 and 7], the average BER of QPSK and 16QAM using L-branch MRC diversity can be derived as follows:

$$\begin{cases} P_{QPSK} = \\ \dfrac{1}{2}\left[1 - \dfrac{1}{\sqrt{1+1/E_b/N_0}}\left\{1 + \displaystyle\sum_{l=1}^{L-1} \dfrac{(2l-1)!!/(2l)!!}{(1+E_b/N_0)^l}\right\}\right] \\ P_{16QAM} = \\ \dfrac{3}{8}\left[1 - \dfrac{1}{\sqrt{1+5/(2E_b/N_0)}}\left\{1 + \displaystyle\sum_{l=1}^{L-1} \dfrac{(2l-1)!!/(2l)!!}{(1+(2E_b/N_0)/5)^l}\right\}\right] \end{cases} . \tag{12}$$

Roughly speaking, sufficient coding gain can be obtained uncoded average BER less than 10^{-2}. Using Eq. (12), we computed the required E_b/N_0's for the uncoded average BER=10^{-2} for $(2, M)$MIMO multiplexing and $(2, M)$STTD, taking into account the 3 dB power penalty in STTD. We found that $(2, M)$MIMO multiplexing provides smaller E_b/N_0 than $(2, M)$STTD by about 1 dB for M=2 and by about 2 dB for M=4. Note that the above estimation is based on the assumption of ideal MLD. However, when M=2, since the diversity gain is not sufficient, MLD decision is far from perfect, inter-symbol interference from different transmit antennas remains and therefore, (2, 2)MIMO multiplexing provides worse performance than (2, 2)STTD. However, when M=4, as larger diversity gain is obtained, MLD approaches the perfect detection and hence, (2, 4)MIMO multiplexing provides better performance than (2, 4)STTD, as was estimated. This is a possible reason for better performance with $(2, M)$MIMO multiplexing than with $(2, M)$STTD when M=4.

4. Conclusion

In this paper, MIMO multiplexing with iterative ASPIC was proposed. The soft values needed for turbo decoding is generated by using the ASPIC, which transforms the MIMO channel into SIMO channels, and performing diversity combining using the MRC scheme. The achievable turbo coded BER performance of MIMO multiplexing using iterative ASPIC was evaluated by computer simulation assuming a Rayleigh fading channel. The results of the computer simulation can be summarized as follows.

(a) Improvement effect of iterative ASPIC: when N=2 and M=2(4), the iterative ASPIC with 4 iterations provides an improvement of 0.7 dB(0.5 dB) at BER=10^{-4} and the degradation from the perfect $(1, M)$SIMO is about 2.4 dB(0.7 dB). Similar improvement is also obtained when N=4 and M=4(8) with 4 iterations.

(b) Comparison to LLR computation method of [12]: although the iterative ASPIC is inferior to the LLR computation method by about 0.5 dB for (N, M)=(2, 2), it becomes better by about 0.3 dB, 0.2 dB, and 0.4 dB for (N, M)=(2, 4), (4, 4), and (4, 8), respectively.

(c) Comparison to 16QAM-$(2, M)$STTD: (2, 2)MIMO multiplexing is inferior to 16QAM-(2, 2)STTD by about 0.2 dB. However, (2, 4)MIMO multiplexing becomes about 1.9 dB better than 16QAM-(2, 4)STTD.

The separation method of transmit signals considered in this paper was MLD. However, the computational complexity of MLD grows exponentially as the number of transmit antennas increases. To reduce the computational complexity, MMSE, ZF, and simplified MLD can be applied. This is left as an interesting future study. In this paper, we have assumed turbo coding MIMO multiplexing with the code rate R=1/2. For $R > 1/2$, since the number of parity bits is less than the number of systematic bits, transmission of only parity bits from all the antennas does not happen. Therefore, the reliability of all parity bits can be improved in iterative ASPIC by using LLRs obtained from the turbo decoder. However, for $R < 1/2$, the number of parity bits is more and the reliability for such parity bits becomes lower. This may affect the achievable BER performance. The performance investigation for various code rates is also an important future work.

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