Frequency-domain Iterative SIC for SC-MIMO Multiplexing

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Abstract— **Recently, the multi-input multi-output (MIMO) multiplexing technique has been gaining much attention for achieving very high speed data transmissions in a bandlimited wireless channel. However, if single-carrier (SC) transmission is used, the bit error rate (BER) performance significantly degrades due to inter-symbol interference (ISI) resulting from a severe frequency-selective fading channel. Recently, we proposed a frequency-domain iterative parallel interference cancellation (PIC) for SC-MIMO multiplexing to separate signals transmitted from different antennas while achieving frequency and antenna diversity gain. In this paper, we present a frequency-domain iterative successive interference cancellation (SIC) and evaluate, by computer simulation, the BER performance in a frequency-selective Rayleigh fading channel.**

Key words: *MIMO multiplexing, frequency-domain iterative SIC, mobile communication*

1. INTRODUCTION

Recently, there have been tremendous demands for high-speed data transmissions in mobile communications [1]. However, if single-carrier (SC) transmission is used, the bit error rate (BER) performance is severely degraded due to inter-symbol interference (ISI) resulting from a severe frequency-selective channel [2]. It has been shown [3] that the use of frequency-domain equalization (FDE) can significantly improve the SC transmission performance.

For the next generation wireless communication systems, so much higher spectrum efficient transmission technique is required. Multi-input multi-output (MIMO) multiplexing [4] technique has been gaining much attention for achieving very high speed data transmissions in a bandlimited wireless channel. In MIMO multiplexing, a superposition of signals transmitted from different antennas is received. A lot of research attention has been paid to the signal separation method with reduced complexity, which can provide a performance close to maximum likelihood detection (MLD), e.g., V-BLAST [5], MLD using QR decomposition [6] and so on. In a recent work, we proposed a frequency-domain iterative parallel interference cancellation (PIC) scheme for SC-MIMO multiplexing using FDE [7]. Another interesting cancellation scheme is a successive interference cancellation (SIC) scheme. In this paper, we present a frequency-domain iterative SIC scheme. The BER performance of SC-MIMO multiplexing using frequency-domain iterative SIC in a frequency-selective Rayleigh fading channel is evaluated by computer simulation and compared with that using frequency-domain iterative PIC.

The remainder of this paper is organized as follows. Section 2 describes the SC-MIMO multiplexing with the frequency-domain iterative SIC. Section 3 presents the computer simulated BER performances in a frequency-selective Rayleigh fading channel. Section 4 concludes this paper.

2. Frequency-domain iterative SIC

2.1. Transmitted and received signals

Fig.1 shows a transmitter and receiver structure of SC-(N_t,N_r)MIMO multiplexing using frequency-domain iterative SIC, where N_t and N_r denote the number of transmit antennas and that of receive antennas, respectively. At the transmitter, the data-modulated symbol sequence is serial-to-parallel (S/P) converted to N_t parallel symbol sequences, each to be transmitted from a different transmit antenna. In this paper, QPSK data-modulation is considered. As shown in Fig.2, the last N_g symbols in each block are copied and inserted as cyclic prefix into the guard interval (GI) placed at the beginning of each block. N_t parallel blocks are transmitted from N_t transmit antennas using the same carrier frequency. We consider a transmission of N_t parallel blocks $\{d_{n_t}(t);\ t=0\sim(N_c-1) \text{ and } n_t=0\sim(N_t-1)\}$.

At the receiver, a superposition of N_t transmitted blocks is received by N_r antennas. After the removal of the GI from the received signal, N_c-point fast Fourier transform (FFT) is applied to obtain the N_c frequency components. The kth frequency component $R_{n_r}(k)$ of the received signal on the n_rth receive antenna can be expressed as

$$R_{n_r}(k)=\sqrt{2S}\sum_{n_t=0}^{N_t-1}H_{n_r,n_t}(k)D_{n_t}(k)+\Pi_{n_r}(k),\ (1)$$

where S is the received signal power per transmit antenna and $H_{n_r,n_t}(k)$, $D_{n_t}(k)$ and $\Pi_{n_r}(k)$ are respectively the complex channel gain between the n_tth transmit antenna and the n_rth receive antenna, the transmitted signal component associated with the n_tth transmit antenna, and the noise component associated with the n_rth receive antenna. They can be expressed as

$$\begin{cases} H_{n_r,n_t}(k)=\sum_{l=0}^{L-1}h_{n_r,n_t,l}\exp(-j2\pi\tau_l\frac{k}{N_c}) \\ D_{n_t}(k)=\sum_{t=0}^{N_c-1}d_{n_t}(t)\exp(-j2\pi t\frac{k}{N_c}) \\ \Pi_{n_r}(k)=\sum_{t=0}^{N_c-1}n_{n_r}(t)\exp(-j2\pi t\frac{k}{N_c}) \end{cases},\ (2)$$

where $h_{n_r,n_t,l}$ denotes the path gain of the lth path between the n_rth receive antenna and the n_tth transmit antenna, $n_{n_r}(t)$ is a zero-mean complex Gaussian process having variance $2N_0/T$ with N_0 being the one-sided power spectrum density of additive white Gaussian noise (AWGN) and T being the symbol length.

2.2. Frequency-domain iterative SIC

As shown in Fig.1, the frequency-domain iterative SIC is composed of (i) MMSE-FDE and (ii) SIC using (iii) soft symbol decision.

At the i=0th iteration, the transmit signals are detected antenna-by-antenna in the descending order of the channel reliability by using two-dimensional (2D) FDE based on the minimum mean square error (MMSE) criterion and SIC. However, 2D-MMSE-FDE can not suppress the interference from other transmit antennas sufficiently. Therefore, for the i>0 iteration, SIC and one-dimensional (1D) MMSE-FDE are repeated a sufficient number of times.

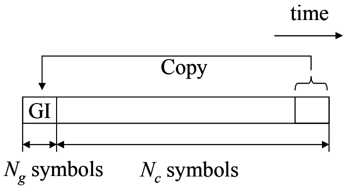


Figure 2 GI insertion.

(i) MMSE-FDE

(a)Initial FDE (*i*=0th iteration)

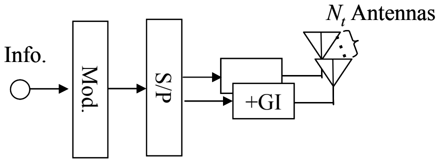
At first, N_t-by-N_r 2D-MMSE-FDE weight matrix $\mathbf{W}^{(0)}(k)$ is computed. It can be derived from [2] as

$$\mathbf{W}^{(0)}(k)=\mathbf{H}^H(k)[\mathbf{H}(k)\mathbf{H}^H(k)+\sigma^2\mathbf{I}]^{-1},\ (3)$$

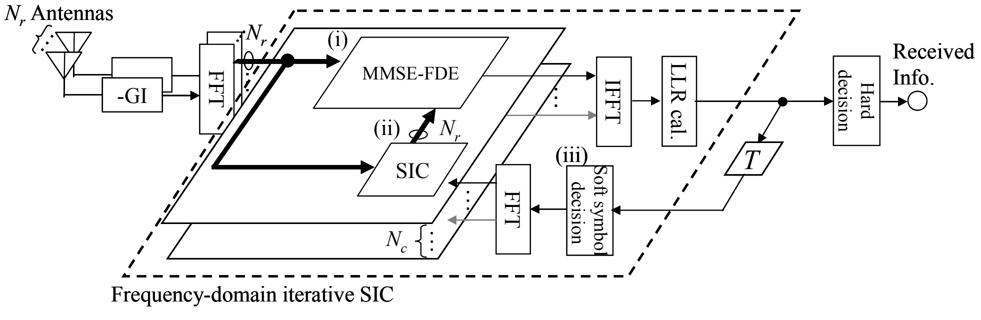
where $(.)^H$ is Hermit transpose operation, $\mathbf{H}(k)$ is an N_r-by-N_t channel gain matrix at the kth frequency and $\mathbf{I}$ is the N_r-by-N_r identity matrix.

For the SIC operation, the signals transmitted from N_t antennas are ranked by using their equivalent channel gains. The equivalent channel gain $\hat{H}_{n_t}^{(0)}$ associated with the n_tth transmit antenna at the i=0th iteration is given by

$$\hat{H}_{n_t}^{(0)}=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\mathbf{W}_{n_t}^{(0)}(k)\mathbf{H}_{n_t}(k),\ (4)$$



(a) Transmitter



(b) Receiver

Figure 1 Transmitter/receiver structure.

where $\mathbf{W}^{(0)}_{n_t}(k)$ is the 1-by-N_r MMSE-FDE weight vector for the n_tth antenna, which is the n_tth column vector of $\mathbf{W}^{(0)}(k)=[\mathbf{W}^{(0)}_0(k),\cdots,\mathbf{W}^{(0)}_{N_t-1}(k)]^T$ and $\mathbf{H}_{n_t}(k)$ is an N_r-by-1 channel gain vector (the n_tth row vector of $\mathbf{H}(k)$) between the n_tth transmit antenna and N_r receive antennas. In what follows, without loss of generality, the transmit antenna having the highest equivalent channel gain is assumed to be the 0th transmit antenna, followed by the 1st, 2nd, …, (N_t-1)th antennas.

2D-MMSE-FDE is performed to obtain the frequency component $\tilde{R}^{(0)}_0(k)$ associated with the 0th transmit antenna:

$$\tilde{R}^{(0)}_0(k)=\mathbf{W}^{(0)}_0(k)\mathbf{R}(k)\,, \quad (5)$$

where $\mathbf{R}(k)=[R_0(k),\cdots,R_{N_r-1}(k)]^T$ is the received signal vector. Then, soft symbol decision is performed on $\tilde{R}^{(0)}_0(k)$ to generate the replica of the 0th transmitted signal. In SIC, the 0th transmitted signal component using this replica is cancelled from $\mathbf{R}(k)$. The SIC output $\hat{\mathbf{R}}^{(0)}_{n_t}(k)$ corresponds to a superposition of the signals transmitted from the n_t=1~(N_t-1)th transmitted antenna.

Then, the resultant signal is used to detect the signal transmitted from n_t=1st antenna. 2D-MMSE-FDE is performed using Eq.(5), where the weight is computed using Eq.(3) with $\mathbf{H}_0(k)=\mathbf{0}$ and $\mathbf{R}(k)$ is replaced by $\hat{\mathbf{R}}^{(0)}_1(k)$. In SIC, the 1st transmitted signal component is cancelled. The received signal after this cancellation corresponds to a superposition of n_t=2~(N_t-1)th transmitted signals.

The process of 2D-MMSE-FDE and SIC is repeated until the remaining n_t=2~(N_t-1)th transmitted signals are detected.

(b) *i*>0th iteration

Since interference from all the other antennas can be partially removed from the received signals by performing SIC, the resulting signal is close to the case of single antenna transmission. Hence, 1D-MMSE-FDE in the case of signal antenna transmission is carried out in the *i*>0th iteration. Joint 1D-MMSE-FDE and antenna diversity combining are performed to obtain the frequency component $\tilde{R}^{(i)}_{n_t}(k)$ given by

$$\tilde{R}^{(i)}_{n_t}(k)=\mathbf{W}^{(i)}_{n_t}(k)\hat{\mathbf{R}}^{(i)}_{n_t}(k)\,, \quad (6)$$

where

$$\mathbf{W}^{(i)}_{n_t}(k)=\mathbf{H}^H_{n_t}(k)[\mathbf{H}^H_{n_t}(k)\mathbf{H}_{n_t}(k)+\sigma^2]^{-1} \quad (7)$$

is the 1-by-N_r MMSE equalization weight vector for the n_tth transmit antenna [8].

(ii) SIC operation

At first, $\{\tilde{d}^{(i)}_{n_t}(t)$; t=0~(N_c-1)} is decomposed by FFT into N_c frequency components $\{\tilde{D}^{(i)}_{n_t}(k)$; k=0~(N_c-1)}. Then, the interference replica $\sqrt{2S}\mathbf{H}(k)\{\mathbf{A}^{(i)}_{n_t}(k)+\mathbf{B}^{(i-1)}_{n_t}(k)\}$ is generated, where $\mathbf{A}^{(i)}_{n_t}(k)=[\tilde{D}^{(i)}_0(k),\cdots,\tilde{D}^{(i)}_{n_t-1}(k),0,\cdots,0]^T$ is composed of the current soft decision symbol replicas and $\mathbf{B}^{(i-1)}_{n_t}(k)=[0,\cdots,0,\tilde{D}^{(i-1)}_{n_t+1}(k),\cdots,\tilde{D}^{(i-1)}_{N_t-1}(k)]^T$ is composed of the previous soft decision symbol replicas. Note that when i=0, $\mathbf{B}^{(-1)}_{n_t}(k)=\mathbf{0}$. The SIC operation to obtain the received signal vector $\hat{\mathbf{R}}^{(i)}_{n_t}(k)$ for the detection of the n_tth antenna is expressed as

$$\hat{\mathbf{R}}^{(i)}_{n_t}(k)=\mathbf{R}(k)-\sqrt{2S}\mathbf{H}(k)\{\mathbf{A}^{(i)}_{n_t}(k)+\mathbf{B}^{(i-1)}_{n_t}(k)\}\,. \quad (8)$$

(iii) Soft symbol replica generation

The decision variable $\tilde{r}^{(i)}_{n_t}(t)$ is obtained by performing IFFT on $\{\tilde{R}^{(i)}_{n_t}(k)$; k=0~(N_c-1)}. Then, the loglikelihood ratio (LLR), $LLR^{(i)}_{n_t,\mathrm{b}}(t)$, of the bth bit in the tth symbol transmitted from the n_tth antenna is computed as

$$LLR^{(i)}_{n_t,b}(t)=\frac{1}{2\sigma^2}\left\{\begin{array}{l}|\,\tilde{r}^{(i)}_{n_t}(t)-\sqrt{2S}\hat{H}^{(i)}_{n_t}\bar{d}_{0,\max}\,|^2\\ -\,|\,\tilde{r}^{(i)}_{n_t}(t)-\sqrt{2S}\hat{H}^{(i)}_{n_t}\bar{d}_{1,\max}\,|^2\end{array}\right\}, \quad (9)$$

where $\bar{d}_{0\mathrm{or}1,\max}$ is the most reliable candidate symbol with the bth bit as 0 or 1 and $\hat{H}^{(i)}_{n_t}$ is the equivalent channel gain associated with the n_tth transmit antenna given by

$$\hat{H}^{(i)}_{n_t}=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\mathbf{W}^{(i)}_{n_t}(k)\mathbf{H}_{n_t}(k)\,. \quad (10)$$

The soft QPSK symbol replica $\tilde{d}^{(i)}_{n_t}(t)$ is generated using $\{LLR^{(i)}_{n_t,\mathrm{b}}(t)$; b=0,1} as

$$\tilde{d}_{n_t}^{(i)}(t)=\frac{1}{\sqrt{2}}\tanh(\beta\frac{LLR_{n_t,0}^{(i)}(t)}{2})+\frac{j}{\sqrt{2}}\tanh(\beta\frac{LLR_{n_t,1}^{(i)}(t)}{2}), \tag{11}$$

where β is a parameter that controls the extent to which the decision variable contributes to the replica generation.

A series of SIC and 1D-MMSE-FDE is carried out for n_t=0~(N_t-1) in the ith iteration. After having repeated the above series of operations a sufficient number of times, hard decision is performed.

3. Computer simulation

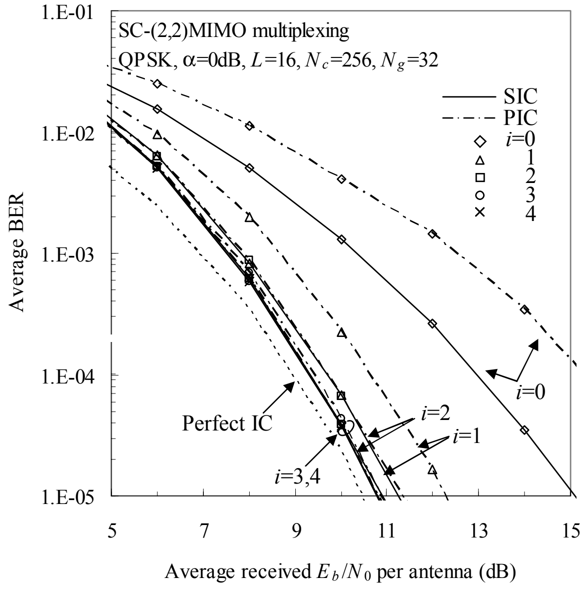
The computer simulation conditions are summarized in Table 1. We assume that N_tN_r channels are independent frequency-selective Rayleigh fading channels having symbol-spaced L=16-path power delay profile with decay factor αdB. Block fading and ideal channel estimation are assumed.

Fig.3 plots the BER performance of SC-(2,2)MIMO multiplexing as a function of the average received energy per bit-to-noise power spectrum density ratio E_b/N_0 per receive antenna. For comparison, the results for perfect IC (i.e., interference from other antennas is perfectly cancelled) and for frequency-domain iterative PIC [7] are also plotted. It can be seen from Fig.3(a) that the BER performance improves as the number of iterations increases. However, almost no additional improvement is obtained by increasing the number of iterations from 2 to 3; therefore, we can conclude that the use of 2 iterations can be sufficient. The E_b/N_0 degradation from perfect IC for the average BER=10^{-4} becomes as small as about 0.35dB. On the other hand, 3 iterations are necessary for frequency-domain iterative PIC. If α=6dB, it can be seen from Fig.3(b) that even without iteration, SIC achieves a degradation of 2.1dB from the perfect IC. For PIC, however 1 iteration is required.

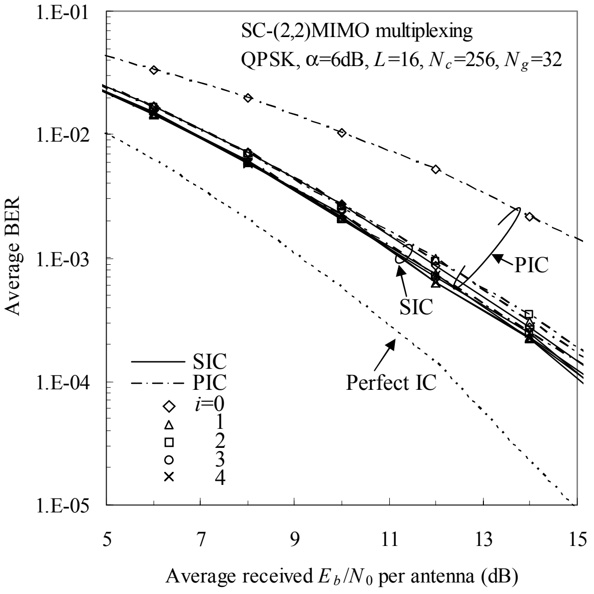
Fig.4 plots the case of (N_t,N_r)=(4,4) as a function of E_b/N_0 per receive antenna. It can be seen from Fig.4 (a) that the trend is the same as when (N_t,N_r)=(2,2). In SIC, when α=0dB, the use of 2 iterations is sufficient and the degradation from perfect IC is 0.4dB. On the other hand, in PIC, 3 iterations are necessary. However, when α=6dB, both SIC and PIC require 3 iterations. The BER performance is better with SIC than with PIC by about 2.8dB.

Table 1. Simulation conditions

Transmitter	Data Modulation		QPSK
	Number of Tx Antennas		N_t=2,4
	Number of FFT points		N_c=256
	GI		N_g=32
Channel	Frequency-selective block Rayleigh fading		
	Power delay profile	L=16-path exponential power delay profile	
		Decay factor α=0,6dB	
Receiver	Channel estimation		Ideal
	Number of Rx Antennas		N_r=2,4

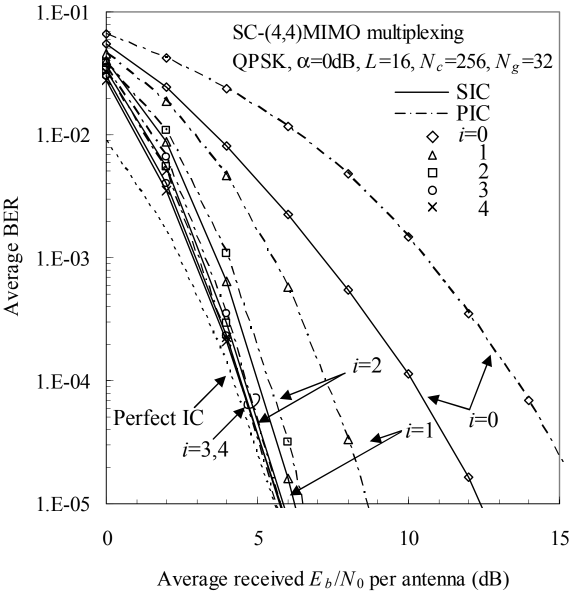


(a) α=0dB

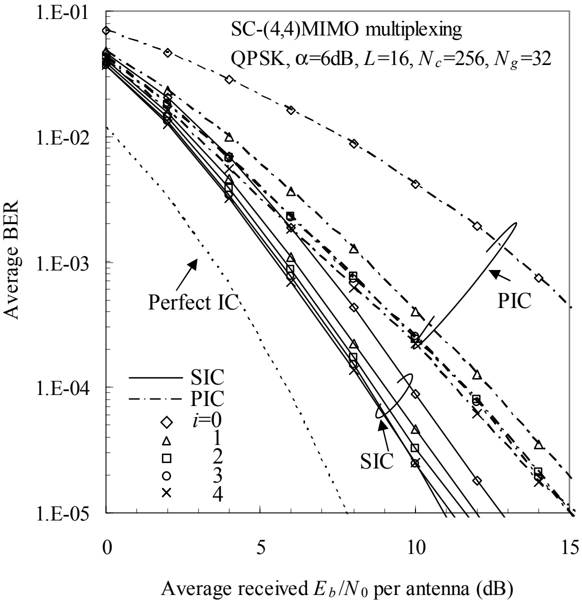


(b) α=6dB

Figure 3 (N_t,N_r)=(2,2)



(a) α=0dB



(b) α=6dB
Figure 4 (N_t,N_r)=(4,4)

4. CONCLUSIONS

In this paper, we presented a frequency-domain iterative SIC scheme for SC-MIMO multiplexing. The BER performance in a frequency-selective Rayleigh fading was evaluated by computer simulation and compared with that using frequency-domain iterative PIC. When (N_t,N_r)=(2,2), the use of 2 iterations is sufficient for SIC. The E_b/N_0 degradation from perfect IC becomes as small as about 0.35dB. On the other hand, PIC requires 3 iterations. When α=6dB, without iteration, the degradation from the perfect IC is about 2.1dB for SIC. However, 1 iteration is required for PIC. The same trend was seen when (N_t,N_r)=(4,4) as when (N_t,N_r)=(2,2).

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