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Further Results of Large System Performance of Linear Multistage Parallel Interference Cancellation*

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Abstract: The output signal to interference-plus-noise ratio (SINR) of linear multistage parallel interference cancellation receiver in a random environment is considered. When the number of users and the spreading factors tend to infinity with their ratio fixed, the properties of limiting SINR are studied. Under some weak conditions, the strong consistency and asymptotic normality of the SINR are obtained. the tools of large dimensional random matrices are mainly employed.

Key words: strong consistency; asymptotic normality; large dimensional random matrices

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0 Introduction

Recently, there are a lot of papers concerning the large system performance of code division multiple-access (CDMA). Some popular linear multiuser receiver is usually considered, such as single matched filter (MF) receiver, decorrelator receiver and linear minimum mean square error (MMSE). In [1], a new approach is presented, where the spreading sequence is modelled as random sequences. So one can study the asymptotic limit of a large number of users and a large spreading factor by the tool of large dimensional random matrices. This paper focuses on a linear multistage parallel interference cancellation (IC), which can attain near-MMSE performance with less computational load [2]. Our linear multistage partial parallel IC (PPIC) is based on the first-order stationary linear iterative method[2], which has only one partial cancellation factor. In this paper the performance

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measure for each user is considered as the output signal to interference-plus -to noise ratio (SINR) of the receiver. We show that the limiting SINR is independent of the specific realization of the random spreading sequences. The fluctuations of SINR around the limit is proved to be asymptotically Gaussian. In a related work, Louis et al [2] studied the problem of large system of linear multistage parallel IC. They showed that the SINR converges in probability to a deterministic scalar, and provided a simulation result for mean-squared error (MSE) between SINR and the large system SINR. In contrast to their results, the convergence of the SINR is with probability one in our paper and the asymptotically Gaussian of the SINR is justified by limit theorems.

Our results are asymptotic in nature, with both K and N going to infinity. Throughout this paper, the ratio of K and N is denoted by $y = \lim_{K\to\infty} \frac{N}{K}$, as is the standard[1~6].

1 System Model

We consider the following discrete time model for a synchronous CDMA system. Suppose there are K users in the system when the processing gain is N. The baseband received signal in a symbol interval is

$$r = \sum_{i=1}^{k} \sqrt{P} b_i s_i + w \tag{1}$$

where b_i is the symbol transmitted by user i, $s_i \in R^N$ is the spreading sequence of user i and the noise vector w is Gaussian with zero mean and covariance matrix $\sigma^2 I$. We assume that b_i is independent, $Eb_i = 0$, $Eb_i^2 = 1$ are independent of the noise. Here the received powers of different users are assumed to be the same with common power P.

We shall now focus on the demodulation of user 1. A linear receiver generates an output of the form $b_1^* = c_1^T r$ and the output $SINR$ is defined by

$$SINR_1 \equiv \frac{P\ (c_1^T s_1)^2}{(c_1^T c_1)\sigma^2 + \sum_{i=2}^{K} P(c_1^T s_i)^2}. \tag{2}$$

(refer to [1],[2] and [4]). For performance analysis, we assume that the spreading sequences are as follows:

$$s_i = \frac{1}{\sqrt{N}} (v_{i1}, \cdots, v_{iN})^T,\ i = 1, \cdots, K.$$

For all i and k, the random variables v_{ik}'s are independent and identically distributed (i. i. d.), zero mean and variance 1. Write $S = [s_1, s_2, \cdots, s_K]$ for the $N \times K$ matrix of the spreading sequences and $S_1 = [s_2, s_3, \cdots, s_K]$ for the $N \times (K-1)$ matrix with spreading sequence of user one removed.

The first-order stationary linear iterative method is

$$x_{1,m} = r\tau + \left(I - \tau \left(S_1 S_1^T + \frac{\sigma^2}{P} I\right)\right) x_{1,m-1} \tag{3}$$

and
$$b_{1,m}{}^{*} = s_1^T x_{1,m}$$
where $x_{1,m} \in R^N$ is a measurement vector for user 1 after the mth stage of filtering and cancelling and τ is a partial cancellation factor, which is a scalar. After simple calculation, we have that $c_{1,m} = \tau\Big(\sum_{i=0}^{m}\Big[I-\tau\Big(S_1S_1^T+\frac{\sigma^2}{P}I\Big)\Big]^i\Big)s_1$,

and
$$SINR_1 = \frac{\Big(s_1^T\sum_{i=0}^{m}\Big(I-\tau\Big(S_1S_1^T+\frac{\sigma^2}{P}I\Big)\Big)^i s_1\Big)^2}{s_1^T\Big(\Big(S_1S_1^T+\frac{\sigma^2}{P}I\Big)\sum_{i,j}\Big(I-\tau\Big(S_1S_1^T+\frac{\sigma^2}{P}I\Big)\Big)^{i+j}\Big)s_1} \tag{4}$$

2 Main Results

Obviously, one can observe that a key item is $s_1^T(S_1S_1^T)^i s_1$ in the analysis of the large system SINR. Let $S_{(1)} = \frac{\sqrt{N}S_1}{\sqrt{K}}$ and F_N be the empirical spectral distribution of the eigenvalues of $S_{(1)}S_{(1)}^T$, i. e. , $F_N(x) = \frac{\sum_{i=1}^{N} I(\mu_i \leqslant x)}{N}$. There are plenty of results for the limiting sprectral distribution in the literature[7~11]. The following is a well known result.

Lemma 1 Suppose that $\frac{N}{K} \to y$, and that $Ev_{11}^4 < \infty$, then
$$F_N(x) \to F_y(x) \quad \text{a. s. ,} \quad \text{as} \quad K \to \infty$$
and
$$\lambda_{\max}(S_{(1)}S_{(1)}^T) \to (1+\sqrt{y})^2 \quad \text{a. s. ,as} \quad K \to \infty$$
where $F_y(x)$ is a continuous , deterministic probability distribution function, having a density with support on $((1-\sqrt{y})^2, (1+\sqrt{y})^2)$, and for $y > 1$, $F_y(x)$ places mass $1-\frac{1}{y}$ at 0. The following lemma also plays an important role in our analysis.

Lemma 2[7, Lemma 2. 7] Let $X = (X_1, \cdots, X_n)$ where X_i's are i. i. d. complex random variables with zero mean and unit variance. Let C be a deterministic $n \times n$ complex matrix. Then, for any $p \geqslant 2$, we have
$$E|X^*CX - \mathrm{tr}C|^p \leqslant K_p((E|X_1|^4\mathrm{tr}CC^*)^{\frac{p}{2}} + E|X_1|^{2P}\mathrm{tr}(CC^*)^{\frac{p}{2}}).$$
Now we can set up our lemma.

Lemma 3 Assume that $v_{jk}, j, k = 1, 2, \cdots$, are i. i. d. real random variable with $Ev_{11} = 0$, $Ev_{11}^2 = 1$, for $p > 2$, $Ev_{11}^{2p} < \infty$ and $\lim_{K\to\infty}\frac{N}{K} = y > 0$, then, the random variable $s_1^T(S_1S_1^T)^i s_1$ converges with probability one to the fixed scalar
$$\phi_i(y) = \Big(\frac{1}{y}\Big)^i \int_0^{(1+\sqrt{y})^2} x^i \mathrm{d}F_y(x). \tag{5}$$

Proof Note that s_1 is independent of S_1 and $(S_1S_1^T)^i$ is a symmetric matrix. Hence, by lemma 2, we have that

$$E\left|s_1^T(S_1S_1^T)^i s_1-\frac{1}{N}\mathrm{tr}(S_1S_1^T)^i\right|^p=E\left(E\left(\left|s_1^T(S_1S_1^T)^i s_1-\frac{1}{N}\mathrm{tr}(S_1S_1^T)^i\right|^p\middle|S_1S_1^T\right)\right)\leqslant$$

$$\frac{1}{N^p}C_pE\{[Ev_{11}^4\mathrm{tr}(S_1S_1^T)^i((S_1S_1^T)^i)^T]^{\frac{p}{2}}+Ev_{11}^{2P}\mathrm{tr}((S_1S_1^T)^i((S_1S_1^T)^i)^T)^{\frac{p}{2}}\}\leqslant$$

$$\frac{1}{N^p}C_p((Ev_{11}^4)^{\frac{p}{2}}E(\mathrm{tr}(S_1S_1^T)^{2i})^{\frac{p}{2}}+Ev_{11}^{2P}E\,\mathrm{tr}(S_1S_1^T)^{ip})\leqslant$$

$$\frac{1}{N^{\frac{p}{2}}}C_pE\left(\frac{\mathrm{tr}(S_1S_1^T)^{2i}}{N}\right)^{\frac{p}{2}}\leqslant C_p\frac{1}{N^{\frac{p}{2}}}$$

where the last inequality follows from the proof of [9] and C_p may denote different constants at different positions. By appealing to Borel-Cantelli lemma, we have

$$s_1^T(S_1S_1^T)^i s_1-\frac{1}{N}\mathrm{tr}(S_1S_1^T)^i\to 0 \qquad \text{a. s.} \tag{6}$$

Furtherly, observe that

$$\frac{1}{N}\mathrm{tr}(S_1S_1^T)^i=\frac{1}{N}\left(\frac{K}{N}\right)^i\mathrm{tr}(S_{(1)}S_{(1)}^T)^i=\frac{1}{N}\left(\frac{K}{N}\right)^i\sum_{j=1}^{N}\mu_j{}^i=$$

$$\left(\frac{K}{N}\right)^i\int x^i\mathrm{d}F_N(x)\to\left(\frac{1}{y}\right)^i\int_0^{(1+\sqrt{y})^2}x^i\,\mathrm{d}F_y(x) \qquad \text{a. s.} \tag{7}$$

which follows from Helly-Bray lemma and lemma 1 or directly from the proof of Theorem 2.1 of [9].

Combing (6) and (7), one can conclude that

$$s_1^T(S_1S_1^T)^i s_1-\left(\frac{1}{y}\right)^i\int_0^{(1+\sqrt{y})^2}x^i\mathrm{d}F_y(x)\to 0 \qquad \text{a. s.}$$

Thus the proof of the lemma is completed.

Theorem 1 Under the conditions of lemma 3, the SINR of the m-stage PPIC receiver converges with probability one to a fixed scalar

$$SINR^*=\frac{\left[\sum_{i=0}^{m}h_i\right]^2}{\sum_{i=0}^{m}[(i+1)g_i+(m-i)g_{m+i+1}]}$$

where

$$h_i=(-\tau)^i\sum_{j=0}^{i}\left(\frac{\sigma^2}{P}-\frac{1}{\tau}\right)^{i-j}\binom{i}{j}\phi_j(y)$$

$$g_i=(-\tau)^i\sum_{j=0}^{i}\left(\frac{\sigma^2}{P}-\frac{1}{\tau}\right)^{i-j}\binom{i}{j}\left(\phi_{j+1}(y)+\frac{\sigma^2}{P}\phi_j(y)\right).$$

Proof Applying lemma 3 and some matrix knowledge, one can obtain theorem 1. For details, refer to [2].

Before moving on, we need some notations and one more lemma.

Let $A_N=S_{(1)}S_{(1)}^T$ and $U_N\Lambda_N U_N^T$ denote the spectral decomposition of A_N.

Let $Y_N=(y_1,y_2,\cdots,y_N)=\sqrt{N}U_N^T s_1$. Define the process

$$X_N(t)=\sqrt{\frac{1}{2N}}\sum_{i=1}^{[Nt]}(y_i^2-1).$$

Lemma 4[3, Theorem A. 1] If the assumptions of lemma 3 are satisfied and v_{11} is symmetrically distributed about 0, then

$$X_N(t)_{t\in[0,1]} \xrightarrow{D} \left[W(t) + \frac{\xi}{\sqrt{2}}t\right]_{t\in[0,1]} \tag{8}$$

where $W(t)$ denotes a Brownian bridge, ξ denotes a Gaussian random variable with zero mean and variance $Ev_{11}^4 - 1$, $W(t)$ and ξ are independent and the convergence is in the sense of distribution in $D[0,1]$, the space of right continuous functions with left limits, equipped with the Skorohod topology. Now we can set up the next result.

Theorem 2 Under the assumptions of lemma 4,

$$\sqrt{N}\,\frac{\left(s_1^T\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i s_1\right)^2-\left(\frac{1}{N}E\,\mathrm{tr}\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i\right)^2}{s_1^T\left(\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\sum_{i,j}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^{i+j}\right)s_1} \xrightarrow{D} N(0,{\sigma_y}^2) \tag{9}$$

where $\sigma_y^2 = \left(\sum_{i=0}^{m}(-\tau)^i\sum_{j=0}^{i}\left(\frac{\sigma^2}{P}-\frac{1}{\tau}\right)^{i-j}\binom{i}{j}\phi_j(y)\right)^2 \times$

$$\frac{\left[2\int_0^{(1+\sqrt{y})^2}\left(\sum_{i=0}^{m}\left(1-\tau\left(\frac{\sigma^2}{P}+\frac{x}{y}\right)\right)^i\right)^2\mathrm{d}F_y(x)+(Ev_{11}^4-3)\left(\int_0^{(1+\sqrt{y})^2}\sum_{i=0}^{m}\left(1-\tau\left(\frac{\sigma^2}{P}+\frac{x}{y}\right)\right)^i\mathrm{d}F_y(x)\right)^2\right]}{\left(\sum_{i=0}^{m}[(i+1)g_i+(m-i)g_{m+i+1}]\right)^2}. \tag{10}$$

Proof

$$\sqrt{N}\left(s_1^T\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i s_1-\frac{1}{N}E\left(\mathrm{tr}\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i\right)\right)=$$
$$\sqrt{N}\left[\left(s_1^T\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i s_1-\frac{1}{N}\mathrm{tr}\left(\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i\right)\right]+$$
$$\sqrt{N}\left[\frac{1}{N}\mathrm{tr}\left(\left(\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i\right)-\frac{1}{N}E\,\mathrm{tr}\left(\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i\right)\right]\triangleq$$
$$S_{N_1}+S_{N_2}. \tag{11}$$

Let $B_N = \mathrm{diag}\left(\sum_{i=0}^{m}\left(1-\tau\left(\frac{\sigma^2}{P}+\frac{K}{N}\mu_1\right)\right)^i,\cdots,\sum_{i=0}^{m}\left(1-\tau\left(\frac{\sigma^2}{P}+\frac{K}{N}\mu_N\right)\right)^i\right)$ and $(B_N)_{jj}$ denote the j-th diagonal element. In the sequel, a^- denotes the value smaller than a. Expanding out the first item on the right side, we obtain

$$S_{N_1}=\sqrt{N}\left(s_1^TU_NB_NU_N^Ts_1-\frac{1}{N}\mathrm{tr}(B_N)\right)=\frac{1}{\sqrt{N}}({Y_N}^TB_NY_N-\mathrm{tr}(B_N))=\frac{1}{\sqrt{N}}\sum_{j=1}^{N}({y_j}^2-1)(B_N)_{jj}=$$
$$\sqrt{2}\sum_{j=1}^{N}(B_N)_{jj}(X_N(F_N((B_N)_{jj}))-X_N(F_N((B_N)_{jj}^-)))=\sqrt{2}\int_0^{\mu_{\max}}\sum_{i=0}^{m}(1-\tau(\frac{\sigma^2}{P}+\frac{K}{N}x))^i\mathrm{d}X_N(F_N(x))=$$
$$-\sqrt{2}\int_0^{\mu_{\max}^-}X_N(F_N(x))\mathrm{d}\left(\sum_{i=0}^{m}\left(1-\tau\left(\frac{\sigma^2}{P}+\frac{K}{N}x\right)\right)^i\right)+\sqrt{2}\sum_{i=0}^{m}\left(1-\tau\left(\frac{\sigma^2}{P}+\frac{K}{N}x\right)\right)^iX_N(F_N(x))\Big|_0^{\mu_{\max}}\xrightarrow{D}$$

$$\sqrt{2}\sum_{i=0}^{m}\left(1-\tau\left(\frac{\sigma^2}{P}+\frac{1+\sqrt{y}}{y}\right)\right)^i\frac{\xi}{\sqrt{2}}-\sqrt{2}\int_0^{(1+\sqrt{y})^2}(W^0(F_y(x))+\frac{\xi}{\sqrt{2}}F_y(x))\mathrm{d}\left[\sum_{i=0}^{m}\left(1-\tau\left(\frac{\sigma^2}{P}+\frac{x}{y}\right)\right)^i\right]=$$

$$\sqrt{2}\int_0^{(1+\sqrt{y})^2}\frac{i\tau}{y}\sum_{i=0}^{m}\left(1-\tau\left(\frac{\sigma^2}{P}+\frac{x}{y}\right)\right)^{i-1}\mathrm{d}(W^0(F_y(x))+\frac{\xi}{\sqrt{2}}F_y(x)) \tag{12}$$

which follows from the lemma 4 and lemma 1 [3~11]. Furthermore, note that

$$\frac{1}{N^2}E\left[\mathrm{tr}\left(\left(\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i\right)-E\,\mathrm{tr}\left(\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i\right)\right]^2\leqslant$$

$$\frac{m}{N^2}\sum_{i=0}^{m}E\left(\mathrm{tr}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i-E\,\mathrm{tr}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i\right)^2\leqslant$$

$$\frac{m}{N^2}\sum_{i=0}^{m}E\left[(-\tau)^i\sum_{j=0}^{i}\left(\frac{\sigma^2}{P}-\frac{1}{\tau}\right)^{i-j}\binom{i}{j}(\mathrm{tr}(S_1S_1^T)^j-E\,\mathrm{tr}(S_1S_1^T)^j)\right]^2\leqslant$$

$$\frac{m}{N^2}\sum_{i=0}^{m}i\,\tau^{2i}\sum_{j=0}^{i}\left(\frac{\sigma^2}{P}-\frac{1}{\tau}\right)^{2(i-j)}\binom{i}{j}^2E(\mathrm{tr}(S_1S_1^T)^j-E\,\mathrm{tr}(S_1S_1^T)^j)^2 \tag{13}$$

which follows from C_r inequality. Define $R_N=\int x^j\mathrm{d}F_N(x)=\frac{\mathrm{tr}(S_1S_1^T)^j}{N}$, then, we have

$$E(R_N-ER_N)^2=O\left(\frac{(\log N)^{4j}}{N^2}\right) \tag{14}$$

(one may see [9], P 67). Based on (16) and (17),

$$S_{N_2}\to 0 \qquad \text{in probability.} \tag{15}$$

Hence

$$S_{N_1}+S_{N_2}\xrightarrow{D}N(o,\sigma_{y_1}^2) \tag{16}$$

where

$$\sigma_{y_1}{}^2=2\int_0^{(1+\sqrt{y})^2}\left(\sum_{i=0}^{m}\left(1-\tau\left(\frac{\sigma^2}{P}+\frac{x}{y}\right)\right)^i\right)^2\mathrm{d}F_y(x)+$$

$$(Ev_{11}^4-3)\left(\int_0^{(1+\sqrt{y})^2}\sum_{i=0}^{m}\left(1-\tau\left(\frac{\sigma^2}{P}+\frac{x}{y}\right)\right)^i\mathrm{d}F_y(x)\right)^2.$$

Next, observe that

$$\frac{1}{N}\left(E\,\mathrm{tr}\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i\right)=\sum_{i=0}^{m}(-\tau)^i\sum_{j=0}^{i}\left(\frac{\sigma^2}{P}-\frac{1}{\tau}\right)^{i-j}\binom{i}{j}\frac{1}{N}E\,\mathrm{tr}(S_1S_1^T)^j=$$

$$\sum_{i=0}^{m}(-\tau)^i\sum_{j=0}^{i}\left(\frac{\sigma^2}{P}-\frac{1}{\tau}\right)^{i-j}\binom{i}{j}\left(\frac{k}{N}\right)^iE\int x^j\,\mathrm{d}F_N(x)\to$$

$$\sum_{i=0}^{m}(-\tau)^i\sum_{j=0}^{i}\left(\frac{\sigma^2}{P}-\frac{1}{\tau}\right)^{i-j}\binom{i}{j}\phi_j(y) \tag{17}$$

which follows from Lemma 3.

Applying Theorem 2.5.2[12] and Slutsky's Theorem, with (19) and (20), one can conclude that

$$\sqrt{N}\left[\left(s_1^T\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^is_1\right)^2-\left(\frac{1}{N}E\,\mathrm{tr}\sum_{i=0}^{m}\left(I-\tau\left(S_1S_1^T+\frac{\sigma^2}{P}I\right)\right)^i\right)^2\right]\xrightarrow{D}$$

$$N\left(0,\left(\sum_{i=0}^{m}(-\tau)^i\sum_{j=0}^{i}\left(\frac{\sigma^2}{P}-\frac{1}{\tau}\right)^{i-j}\binom{i}{j}\phi_j(y)\right)^2\sigma_{y_1}{}^2\right). \tag{18}$$

Thus the final result follows from Slutsky's theorem and lemma 3.

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线性多阶段平行干扰取消的大系统性能的进一步结果

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摘要：研究了随机环境下的线性多阶段平行干扰取消接收器的输出信干比.在很弱的条件下，当用户的个数和扩频因子都趋近无穷大，而它们的比保持不变时，信干比的强相合性，渐近正态等结果被证明.本文主要采用了高维随机矩阵的工具.

关键词：强相合；渐近正态；高维随机矩阵.