Downlink Capacity of Interference-Limited MIMO Systems with Joint Detection[*]

Huaiyu Dai, *Member, IEEE,* Andreas F. Molisch, *Senior Member*, *IEEE* and H. Vincent Poor, *Fellow, IEEE*

Abstract

The capacity of downlink cellular multiple-input multiple-output (MIMO) cellular systems, where co-channel interference is the dominant channel impairment, is investigated in this paper, mainly from a signal-processing perspective. Turbo space-time multiuser detection (ST MUD) is employed for intracell communications, and is shown to closely approach the ultimate capacity limits in Gaussian ambient noise for an isolated cell. Then it is combined with various multiuser detection methods for combating intercell interference. Among various multiuser detection techniques examined, linear minimum-mean-square-error (MMSE) MUD and successive interference cancellation are shown to be feasible and effective. Based on these two multiuser detection schemes, one of which may outperform the other for different settings, an adaptive detection scheme is developed, which together with a Turbo ST MUD structure offers substantial performance gain over the well known V-BLAST techniques with coding in this interference-limited cellular environment. The obtained multiuser capacity is excellent in high to medium signal-to-interference ratio scenario. Nonetheless, numerical results also indicate that a further increase in system complexity, using base-station cooperation, could lead to further significant increases of the system capacity. The asymptotic multicell MIMO capacity with linear MMSE MUD preprocessing is also derived, and this analysis agrees well with the simulation results.

Index Terms: adaptive detection, BLAST, co-channel interference, MIMO systems, multiuser detection, turbo processing

---

[*] This research was supported in part by AT&T Labs – Research, and in part by the National Science Foundation, under Grant 99-80590. H. Dai was with the Department of Electrical Engineering, Princeton University. He is now with the Department of Electrical and Computer Engineering, NC State University, Raleigh, NC 27695-7511. Email: Huaiyu_Dai@ncsu.edu. H. Vincent Poor is with the Department of Electrical Engineering, Princeton University, Princeton, NJ 08544. Email: poor@princeton.edu. A. F. Molisch was with the Wireless Systems Research Division, AT&T Labs – Research, Middletown, NJ 07748. He is now with Mitsubishi Electric Research Labs, Murray Hill, NJ, and with the Department of Electroscience, Lund University, Lund, Sweden. Email: Andreas.Molisch@ieee.org. Part of this work was done while H. Dai was a summer intern with AT&T Labs – Research.

I. Introduction

Recent information theoretic results have indicated the remarkable capacity potential of wireless communication systems with antenna arrays at both the transmitters and receivers. These so-called multiple-input multiple-output (MIMO) systems have been shown to yield remarkable capacity, which grows at least linearly with the minimum of the numbers of transmit and receive antennas [13], [25], when operating on a single link with white Gaussian noise. In a cellular environment, the co-channel interference from other cells becomes the dominating channel impairment. In this paper, we will investigate the capacity of MIMO systems in such interference-limited situations.

Motivation for our work comes from a recent study by Catreux, Driessen and Greenstein [6]. They showed that in an interference-limited environment, the capacity of a MIMO system is hardly larger than when using smart antennas *at the receivers only*. This seems to be related to the fact that an antenna array with N elements can eliminate N-1 interferers, so that the reuse distance (in a time-division multiple-access (TDMA)/frequency-division multiple-access (FDMA) system) can be chosen to be very small. The independent data streams employed by a MIMO system are all different (intracell) interferers, so a receive array has no degrees of freedom with which to cancel the co-channel interferers after it separates the multiple data streams in its own cell. On the other hand, this investigation assumed a certain system structure taken from the noise-limited case, and did not try to optimize the system for interference-limited environments. To be specific, they exploited sub-optimal signal processing techniques (uncoded V-BLAST) at the receivers; no attempt was made to jointly detect desired as well as interfering signals; and no cooperation between base stations was assumed.

Our study investigates whether a more advanced receiver structure can significantly increase the capacity of MIMO systems with adjacent-cell interference. Any BLAST-like receiver (BLAST: Bell-labs space-time layered architecture; see [12], [14]) is by its nature a multiuser detector that separates the data streams from the transmit antennas of the desired base station. It thus seems logical to extend this principle also to the data streams from the interfering base stations. In this paper, turbo space-time multiuser detection (ST MUD) is employed for intracell communications; then, on top of this, various multiuser detection methods are applied to combat intercell interference, thereby hopefully to increase the capacity in this interference-limited scenario. We concentrate here on the downlink, as this is usually the bottleneck for wireless data transmission. Furthermore, we assume that there is no cooperation between base stations during the normal operation status (e.g., no joint transmission as in [2], [22]), and that the base stations have no knowledge of the downlink propagation channel. These assumptions are well fulfilled in typical wireless local area network (LAN) situations. In the end, however, we will address whether it is worth devoting more system resources to these tasks for performance improvement.

The main contributions of our paper are as follows.

1. The downlink capacity of MIMO systems in an interference-limited environment is explored, and advanced signal processing techniques are proposed for enhancing it. Both the advantages over the existing techniques and the limitations of our methods are addressed. While the principles of these techniques are well known, their application to combating intercell interference of MIMO systems has – to our knowledge – not been suggested before.
2. In particular, on top of a turbo space-time multiuser detection structure, various multiuser detection schemes for combating intercell interference are compared, and which ones operate best under which circumstances is shown by simulation. Based on these results, a detector that adaptively uses different multiuser detection algorithms in different interference scenarios is proposed, and its performance in a standard cellular environment is simulated, both for the non-line-of-sight (NLOS) and line-of-sight (LOS) scenario.
3. The asymptotic multicell MIMO capacity with linear minimum-mean-square-error (MMSE) MUD preprocessing is derived, and this capacity is seen to agree well with the simulation results.
4. The similarities and differences of intracell and intercell interference are pointed out, and it is shown that even with ideal coders/decoders, perfect interference cancellation of intercell interference is not

possible. Information theoretic insights on the applicability and limitations of linear MMSE MUD and successive interference cancellation are also given.

This paper is organized in the following way: in Section II, the system model and the assumptions made in the problem formulation are presented. In Section III, turbo space-time multiuser detector structures for intracell communications are illustrated. In Section IV, various potential multiuser detection methods are introduced to combat the intercell interference. Some analytical results of the asymptotic multicell MIMO capacity with linear MMSE MUD preprocessing are also given here. Next, in Section V, these multiuser detection schemes are examined; and an adaptive detection scheme is proposed, which together with an advanced turbo ST MUD structure offers substantial performance gain over the well-known V-BLAST techniques with coding in this interference-limited cellular environment. We also compare our results to the single-cell capacity upper bounds, and show that significant gains can be made by base-station cooperation algorithms. Conclusions and some insights are given in Section VI.

II. Problem Formulation

A. MIMO System Model

For the single-cell interference-free case, Teletar [25] and Foschini [13] have derived exact capacity expressions for MIMO systems, as well as useful approximations and lower bounds. We adopt the same mathematical model here, which is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{1}$$

where $\mathbf{y}$ is the received vector, $\mathbf{x}$ is the transmitted signal, $\mathbf{H}$ is a channel matrix which captures the channel characteristics between transmit and receive antenna arrays, and $\mathbf{n}$ is the background noise. Without loss of generality, we assume an $N \times N$ MIMO system with the transmitted signal vector constrained to have overall power $E\{\mathbf{x}^H\mathbf{x}\} \le P$, and circularly symmetric Gaussian background noise with covariance matrix $\Phi_N = \sigma^2\mathbf{I}$. The entries of the complex matrix $\mathbf{H}$ are independent with uniformly distributed phase and normalized Rayleigh distributed magnitude, modeling a Rayleigh fading channel with sufficient physical separation between transmit and receive antennas. The signal-to-noise ratio (SNR) is given by $\rho = P/\sigma^2$. If the channel matrix $\mathbf{H}$ is unknown at the transmitter, then the capacity for the interference-free (single-cell) case is given by

$$C = \log_2 \det\left[\mathbf{I} + \frac{P}{N}\mathbf{H}^H \Phi_N{}^{-1}\mathbf{H}\right], \tag{2}$$

where the channel state information (CSI) is assumed to be known at the receiver. When $\Phi_N = \sigma^2\mathbf{I}$, Equation (2) can be lower-bounded as

$$C_L = \sum_i \log_2\left(1 + \frac{\rho}{N}\chi_{2i}^2\right), \tag{3}$$

where χ_{2i}^2 is a chi-square distributed random variable with $2i$ degrees of freedom and mean value i[1].

B. Cellular System Model

We consider a TDMA/FDMA multicell system, where each base station (BS) and mobile station (MS) has the same number, *N*, of antennas. Equivalently, the system can also be viewed as an orthogonal code-division multiple-access (CDMA) system. We take into account interference from the first tier of the center-excited cell configuration with reuse factor of one, which is depicted in Fig. 1. Note that we mainly deal with the wireless LAN application with pico-cells, so no sectorization of the cell is intended. We assume a frequency-flat, quasi-static fading environment, and the complex baseband channel gain between the *j*th transmit and the *i*th receive antenna is modeled by

$$h_{ij} = \sqrt{c\frac{1}{d_{ij}^{\gamma}}}\sqrt{s_{ij}}\left[\sqrt{\frac{K}{K+1}}e^{j\Phi_{ij}} + \sqrt{\frac{1}{K+1}}z_{ij}\right], \tag{4}$$

where the three terms embody the path loss, the shadow fading and the multipath fading effect, respectively. In particular, we have the following parameters.

---

[1] That is, χ_{2i}^2 is the sum of the squares of 2*i* real Gaussian variables, each with zero mean and variance 1/2.

- Path loss: d_{ij} is the length of the link and γ is the path loss exponent; c is a propagation constant (e.g., the free distance path loss at the break point [24]);
- Shadow fading: $s_{ij} = 10^{S_{ij}/10}$ is a log-normal shadow fading variable, where S_{ij} is a zero mean Gaussian random variable with standard deviation υ;
- Multipath fading: K is the so-called Ricean K-factor, which denotes the ratio of the direct received power (LOS component) to average scattered power (NLOS component); $\Phi_{ij} = \frac{2\pi d_{ij}}{\lambda}$ is the phase shift of the LOS path (λ is the wavelength); z_{ij} is modeled as a set of normalized complex Gaussian random variables, assumed to be independent for each transmit-receive link.

With these assumptions, the multicell system model is given by

$$\mathbf{y} = \mathbf{H} \cdot \mathbf{x} + \sum_i \mathbf{H}_{ifi} \cdot \mathbf{x}_{ifi} + \mathbf{n}, \tag{5}$$

where the subscript "*if*" denotes interference. The channel matrices $\mathbf{H}$ and $\{\mathbf{H}_{ifi}\}$ are independent with independent and identically distributed (i.i.d.) elements given by (4). The transmitted signals from all users are assumed to be of the same format with $E\{\mathbf{x}^H\mathbf{x}\} = E\{\mathbf{x}_{ifi}{}^H\mathbf{x}_{ifi}\} \le P$, whose codebooks are known to the receivers. As above, the noise is assumed to be white and complex Gaussian with covariance matrix $\mathbf{\Phi}_N = \sigma^2\mathbf{I}$.

In order to make the analysis more tractable, the multicell scenario is usually simplified to a linear array of cells and the interference from the two adjacent cells is characterized by a single attenuation factor [32]. To provide a common framework that is general enough to address multiuser detection across the cell while remaining simple enough for analysis and simulation, we assume such a model that there are four interferers in two groups of two, in which one group is much stronger than the other.[2] Thus, the model (5) is simplified to

---

[2] In Section V, we analyze a more detailed model with a hexagonal cellular structure, which will turn out to be in good agreement with the model described here. We also note that details of the model, like user distribution, number of used tiers, etc., can have an influence on the numerical results.

$$\mathbf{y} = \mathbf{H} \cdot \mathbf{x} + \sum_{i=1}^{2} \mathbf{H}_{ifi} \cdot \mathbf{x}_{ifi} + \sum_{i=3}^{4} \mathbf{H}_{ifi} \cdot \mathbf{x}_{ifi} + \mathbf{n}\,, \tag{6}$$

with $P_{if1} = \alpha P_{if2}$, $P_{if3} = \beta P_{if4}$, and $(P_{if1} + P_{if2}) \big/ (P_{if3} + P_{if4}) = \gamma >> 1$, where $P_{ifi} = E\{\mathbf{x}_{ifi}{}^{H}\mathbf{x}_{ifi}\}$. Different choices of the parameters α, β, and γ define the structure of the interfering signals, as will be addressed in Section V. We use the same assumptions for the channel matrices and noise as (1), while assuming the channel matrices for different cells are independent. The signal-to-noise ratio is given by $\rho = P/\sigma^2$, and the signal-to-interference ratio (SIR) is given by $\eta = P \big/ \sum_i P_{ifi}$.

We will mainly use model (6) for our study. In the end, however, results with model (5) will also be given to test and validate the proposed algorithms with more realistic settings.

III. Turbo Space-Time Multiuser Detection for Intracell Communications

In this section, let us assume a single cell scenario for ease of illustration. We will address the multicell case in the next section.

A. Receiver Structures and Diversity

References [12] and [14] propose two layered space-time architectures, called D-BLAST, and V-BLAST, respectively. Actually, the space-time layered architecture falls into the larger category of *space-time multiuser detection*, which refers to the application of the multiuser detection techniques with the aid of both temporal (e.g. CDMA codes) and spatial (spatial signature) structures of the signals to be detected [31]. The BLAST technique is essentially a decision feedback space-time multiuser detector.

In recent years, iterative processing techniques with soft-in/soft-out (SISO) components have received considerable attention. The basic idea is to break up complex optimum joint signal processing, e.g. concatenated decoding, joint equalization and decoding, or joint decoding and multiuser detection, into simpler separate components, iterating between them with the exchange of probabilities or "soft" information. This approach typically performs almost as well as optimum processing. This so-called turbo principle is exemplified through turbo decoding [15], turbo equalization [10] and *turbo multiuser detection* [19] with application to wireless [30] and wireline [8] communications.

Turbo multiuser detection can be applied to the coded BLAST system, resulting in two *turbo space-time multiuser detection* structures, shown in Fig. 2 and Fig. 3, respectively. One is called coded V-BLAST, where at the transmitter the information bits are first demultiplexed into N substreams, each of which is independently encoded, interleaved, and symbol-mapped. At the receiver, the MMSE criterion is used to decouple the substreams; then for each substream a soft metric is calculated and fed to the SISO maximum *a posteriori* probability (MAP) decoder, which produces soft estimates of information and coded bits, used to refine soft metric calculation in the next iteration. After several iterations within a layer, the estimated bits are good enough to be used as output as well as to be fed to the next layer to assist in detection. The other is called Turbo-BLAST, where at the transmitter the information bits are coded (not necessarily with turbo codes) and interleaved as a whole; then the whole coded stream is demultiplexed into N substreams and symbol-mapped individually. At the receiver, the entire data stream is processed iteratively between a soft metric calculation stage and a decoding stage. Note that in the soft metric calculation stage, either a maximum likelihood (ML) joint detection or a MMSE multistage parallel interference cancellation (PIC) scheme can be used. We will show that these two schemes achieve the same performance, owing to the turbo processing.

For the coded V-BLAST, each substream is tied to a fixed antenna element so no transmit diversity is exploited. On the contrary, Turbo-BLAST, like D-BLAST, introduces inter-substream coding and takes advantage of transmit diversity with transmit antenna arrays. At the receiver end, the first detected substream of the V-BLAST will essentially determine the overall system performance due to error propagation. Unfortunately, it has the least receive diversity degree as a result of interference cancellation. This is also true for D-BLAST. However, for the Turbo-BLAST, either ML MUD or the less-complex MMSE PIC brings in full receive diversity. Therefore, Turbo-BLAST is expected to even outperform the coded D-BLAST, which can theoretically achieve a tight lower bound (3) on the capacity. In Section V, it is shown that the Turbo-BLAST structure essentially approaches the capacity (2) in the interference-free case. The V-BLAST structure serves mainly as a baseline in this study, as it is the first implemented space-time layered architecture and the most promising one to be employed in commercial wireless LAN applications, due to its simplicity. (The study of D-BLAST is mainly for the information-theoretic issues.)

B. Turbo-BLAST Detection

The turbo decoding procedure of coded V-BLAST is exactly analogous to that of the Turbo-BLAST to be discussed and therefore is omitted here. The Turbo-BLAST detection algorithm involves two components: demodulation and decoding. A MAP algorithm is employed in the decoding stage to take in soft metrics from the demodulation stage and produce soft estimates of information and coded data bits. The demodulation stage with ML detection is straightforward. Suppose an $N \times N$ MIMO system is employed by one cell, and each substream adopts *M*-ary quadrature amplitude modulation (*M*-QAM). Then for each symbol interval $B = N \cdot \log_2 M$ bits are jointly detected. The extrinsic information for the *i*th bit, $1 \le i \le B$, is given by

$$L_e(i) = \log \frac{\sum_{\mathbf{x} \in X_i^+} p(\mathbf{y} \mid \mathbf{x}) p(\mathbf{x})}{\sum_{\mathbf{x} \in X_i^-} p(\mathbf{y} \mid \mathbf{x}) p(\mathbf{x})} - L_a(i) \tag{7}$$

where $X_i^+ = \{(x_1, x_2, \ldots, x_N)^T : b_i = 1\}$ and $X_i^- = \{(x_1, x_2, \ldots, x_N)^T : b_i = -1\}$; $p(\mathbf{y} \mid \mathbf{x})$ is a multivariate Gaussian distribution (see (1)); $p(\mathbf{x}) = \prod_{i=1}^{B} p(b_i)$ and $L_a(i) = \log\big(P(b_i = 1)/P(b_i = -1)\big)$ comprise *a priori* information from the decoding stage.

The demodulation stage with PIC is subtler. First, the interference signals are estimated from the soft metric from the decoding stage, and subtracted from the received signal, with which we have for some substream $1 \le k \le N$

$$\tilde{\mathbf{y}}_k = \mathbf{H}(\mathbf{x} - \tilde{\mathbf{x}}_k) + \mathbf{n}, \tag{8}$$

where $\tilde{\mathbf{x}}_k = (\tilde{x}_1, \tilde{x}_2, \ldots, \tilde{x}_{k-1}, \tilde{x}_k = 0, \tilde{x}_{k+1}, \ldots, \tilde{x}_N)^T$ is the estimated interference vector. Then, an MMSE filter is applied to $\tilde{\mathbf{y}}_k$ to further suppress the residual interference plus noise, given by

$$\mathbf{w}_k = E\{\tilde{\mathbf{y}}_k \tilde{\mathbf{y}}_k{}^H\}^{-1} E\{\tilde{\mathbf{y}}_k x_k{}^*\} = \left(\mathbf{h}_k \mathbf{h}_k^H + \mathbf{H}_k \mathbf{Q} \mathbf{H}_k^H + \frac{N}{\rho}\mathbf{I}\right)^{-1} \mathbf{h}_k , \tag{9}$$

where $\mathbf{h}_k$ is the kth column of matrix **H**, $\mathbf{H}_k$ is the complement of $\mathbf{h}_k$ in **H**, and $\mathbf{Q} = \mathrm{diag}[1 - \frac{N}{P} | \tilde{x}_1 |^2, \ldots, 1 - \frac{N}{P} | \tilde{x}_{k-1} |^2, 1 - \frac{N}{P} | \tilde{x}_{k+1} |^2, \ldots, 1 - \frac{N}{P} | \tilde{x}_N |^2]$, which approaches **0** when estimates from the decoding stage are accurate enough for constant-modulus signals. As is shown in [20], the output of the MMSE filter $z_k = \mathbf{w}_k^H \tilde{\mathbf{y}}_k$ can be written as

$$z_k = \mu_k x_k + \eta_k , \tag{10}$$

where $\mu_k = \dfrac{N}{P} E[z_k x_k^*] = \mathbf{w}_k^H \mathbf{h}_k$, and η_k is well-approximated by a Gaussian variable with zero mean and variance $\nu_k^2 = E[| z_k - \mu_k x_k |^2] = E[| z_k |^2] - \frac{P}{N} | \mu_k |^2 = \frac{P}{N}(\mu_k - | \mu_k |^2)$. The extrinsic information is given in the same form as (7), but with **y** replaced by z_k and **x** with x_k, and (1) replaced with (10), and therefore with much lower complexity.

IV. Multiuser Detection to Combat Intercell Interference

We have already discussed various MUD schemes for detection of different substreams within a MIMO system (intracell interference). Here we will focus on exploiting MUD to combat interference of the same format from adjacent cells (intercell interference).

A. Maximum Likelihood MUD

Maximum likelihood multiuser detection is infeasible for most current applications due to its complexity. Suppose an $N \times N$ MIMO system is employed by one cell, and each substream adopts *M*-QAM. If we want to jointly detect all the information bits for users from the desired and *K*-1 interfering cells, then the complexity would be on the order of M^{NK}. Even if we assume the simplest scheme such as $M=4$, $N=2$ and $K=5$ (ignoring the two weakest interfering cells of the first tier), the complexity would be in the order of 2^{20}, which is beyond the capacity of current practical systems.

B. Linear MMSE MUD

We assume knowledge of channel information for the interfering users, which can be obtained either through an initial joint training phase with the coordination of base stations, or through adaptive tracking algorithms from the received signals directly. MMSE MUD, which is generally the most favorable linear MUD, has a detection matrix given by

$$\mathbf{W}=\left(\mathbf{H}\mathbf{H}^{H}+\sum_{i}\frac{P_{ifi}}{P}\mathbf{H}_{ifi}\mathbf{H}_{ifi}{}^{H}+\frac{N}{\rho}\mathbf{I}\right)^{-1}\mathbf{H}\,. \tag{11}$$

Thus, the detection process would be to first apply the weight matrix of (11) to the received signal (5) or (6) to combat co-channel interference; and then to process the modified signal as in Section III. As we mentioned, linear MMSE MUD cannot effectively suppress the intercell interference as the receive antenna array does not have enough degrees of freedom. However, the distribution of the residual interference plus noise at the output of a linear MMSE multiuser detector is well-approximated by a Gaussian distribution [20]. This property will guarantee good performance of the Gaussian-metric-based receivers (e.g. Turbo ST MUD), which would otherwise deteriorate greatly in a multiuser environment. The following proposition gives the multicell MIMO capacity with linear MMSE preprocessing.

Proposition 1: The multicell capacity of the desired MIMO system with the linear MMSE preprocessing is asymptotically (in the sense of large dimensional systems) given by

$$C_{M-mmse}=\log\det\left[\mathbf{I}+\frac{P}{N}\mathbf{H}\mathbf{H}^{H}\mathbf{\Sigma}^{-1}\right], \tag{12}$$

where

$$\mathbf{\Sigma} = \sum_i \frac{P_{ifi}}{N} \mathbf{H}_{ifi} \mathbf{H}_{ifi}{}^H + \sigma^2 \mathbf{I}\,. \tag{13}$$

Proof: After linear MMSE filtering with (11) the system model can be represented as

$$\mathbf{y}' = \mathbf{W}^H \mathbf{H} \cdot \mathbf{x} + \boldsymbol{\eta}\,, \tag{14}$$

where $\boldsymbol{\eta}$ is approximately Gaussian distributed with covariance matrix of $\mathbf{W}^H \mathbf{\Sigma} \mathbf{W}$. This is verified in [33] as $N \to \infty$. The capacity of this model is given by (see (2))

$$C_{M-MMSE} = \log\det\left[\mathbf{I} + \frac{P}{N} \mathbf{H}^H \mathbf{W} (\mathbf{W}^H \mathbf{\Sigma} \mathbf{W})^{-1} \mathbf{W}^H \mathbf{H}\right]. \tag{15}$$

With (11) and (13), it is easy to verify that (note that $\mathbf{W}^H \mathbf{H} = \mathbf{H}^H \mathbf{W}$)

$$\mathbf{W}^H \mathbf{\Sigma} \mathbf{W} = \frac{P}{N} (\mathbf{I} - \mathbf{W}^H \mathbf{H}) \mathbf{H}^H \mathbf{W}\,. \tag{16}$$

On defining $\mathbf{Q} = \frac{P}{N} \mathbf{H}^H \mathbf{\Sigma}^{-1} \mathbf{H}$, it can be shown that the probability that $\mathbf{Q}$ is non-singular goes to 1 as $N \to \infty$ [28]. Then

$$\begin{aligned} \mathbf{W}^H \mathbf{H} &= \mathbf{H}^H \left(\mathbf{H}\mathbf{H}^H + \frac{N}{P} \mathbf{\Sigma} \right)^{-1} \mathbf{H} \\ &= \mathbf{H}^H \left(\frac{P}{N} \mathbf{\Sigma}^{-1} - \left(\frac{P}{N} \mathbf{\Sigma}^{-1} \right) \mathbf{H} \mathbf{\Delta}^{-1} \mathbf{H}^H \left(\frac{P}{N} \mathbf{\Sigma}^{-1} \right) \right) \mathbf{H}, \end{aligned} \tag{17}$$

with

$$\mathbf{\Delta} = \mathbf{I} + \mathbf{H}^H \left(\frac{P}{N} \mathbf{\Sigma}^{-1} \right) \mathbf{H} = \mathbf{I} + \mathbf{Q}\,, \tag{18}$$

by the matrix inversion formula. It then follows that

$$\mathbf{W}^H \mathbf{H} = \mathbf{Q} - \mathbf{Q}(\mathbf{I} + \mathbf{Q})^{-1} \mathbf{Q} = (\mathbf{I} + \mathbf{Q})^{-1} \mathbf{Q}\,, \tag{19}$$

and

$$\mathbf{I} - \mathbf{W}^H \mathbf{H} = \mathbf{I} - (\mathbf{I} + \mathbf{Q})^{-1} \mathbf{Q} = (\mathbf{I} + \mathbf{Q})^{-1}\,, \tag{20}$$

both of which are invertible asymptotically. Therefore

$$\begin{aligned} C_{M-mmse} &= \log\det[\mathbf{I} + (\mathbf{I} - \mathbf{W}^H\mathbf{H})^{-1}\mathbf{W}^H\mathbf{H}] \\ &= \log\det[(\mathbf{I} - \mathbf{W}^H\mathbf{H})^{-1}] \\ &= \log\det[\mathbf{I} + \mathbf{Q}] \\ &= \log\det\left[\mathbf{I} + \frac{P}{N}\mathbf{H}\mathbf{H}^H\mathbf{\Sigma}^{-1}\right]. \end{aligned} \tag{21}$$

C. Linear Channel Shortening MUD

Another linear MUD technique of interest to combat the intercell interference is the so-called channel-shortening multiuser detector [18]. For detecting data originating in the desired cell, the idea is to apply some form of array processing to maximize the signal-to-interference-plus-noise ratio (SINR), where the signal power refers to the power contributions of all the substreams in the cell to be detected, while interference refers to the power contributions of data streams in other cells. Note that this criterion is different from linear MMSE MUD (which also maximizes the SINR) in which the signal refers to the very substream to be detected while all other data streams both in cell and out of cell are treated as interferers. In short, the optimal detection matrix for channel-shortening linear MUD is the collection of the first N principal general eigenvectors of the matrix pencil $\left(\mathbf{H}\mathbf{H}^H, \sum_i \frac{P_{ifi}}{P}\mathbf{H}_{ifi}\mathbf{H}_{ifi}{}^{i} + \frac{N}{\rho}\mathbf{I}\right)$. This scheme also serves as a linear preprocessing stage, often followed by much more complex processing, such as ML processing, within the desired cell.

D. Group IC MUD

Since ML-MUD is highly complex, while linear MUD is limited in its interference cancellation capability, non-linear MUD often provides a tradeoff between performance and complexity. In the context of multicell MIMO systems, group detection techniques naturally call for attention, in which information bits for one group (one cell MIMO) are detected at a time. Following a natural extension from BLAST, we can detect one MIMO system at a time, and feed decisions to other group detectors for interference cancellation. Successive interference cancellation, even though far from the optimal detection scheme, is nonetheless asymptotically optimal under the assumption of perfect interference cancellation [29]. Note that generally, the success of interference cancellation relies on the correct detection of interference. In adverse environment where we cannot get good estimates of interference, IC schemes will worsen the performance instead of improving it. The potential benefit of group IC MUD depends highly on the interference structure, which will be further addressed in the next section.

V. Simulation Results

A. Comparison of Various MUD schemes

In Sections III and IV, various potential advanced techniques have been introduced, the combination of which could yield many detector structures. We now compare them, based on the model (6), to see which one performs best in interference-limited environments. The performance measure we consider is the block-error rate (BLER) over frequency-flat, quasi-static fading channels.

Before conducting simulations, we investigate the distribution of the interference signal strength in a typical scenario. To this end, we set up a simulation scenario for a downlink cellular system with one tier of interferers as shown in Fig. 1. We assume a center-excited pico-cell structure with radius $d = 200$ m. The transmit antenna array sends out signals simultaneously from all elements with a total power of 1W in the 2.45GHz band, which undergo free-space path loss up to a distance of 10m, and then suffers path loss according to a power law with exponent $\eta = 3.7$. The log-normal shadow fading standard deviation υ = 8dB and Ricean *K*-factor = 0. The multipath fading is assumed to be zero-mean complex Gaussian with variance 1/2 per dimension. A mobile is randomly located, according to a uniform distribution over the cell. The cumulative distribution functions (CDF) of the SNR and SIR that a mobile station experiences are shown in Fig. 4 and Fig. 5, respectively. The 90th percentile of SNR is 27 dB while that of SIR is 0 dB, which clearly indicates that the environment is interference-limited. Figure 6 indicates that in most cases the power of the two strongest users dominates. A somewhat surprising phenomenon is shown in Fig. 7, which indicates that the one-dominant-interferer scenario (the power of the strongest interferer is at least 3dB higher than the sum of rest) accounts for one third of all the cases. We also found that for the remaining two-thirds cases, which belongs to the two-dominant-interferer scenario as indicated by Fig. 6, the ratio between the two largest interferer powers varies mostly from 0 – 5 dB. These observations verify in part the effectiveness of model (6), as interference from the two farthest adjacent cells can typically be ignored.

We assume that each cell employs a 4×4 MIMO system, operating at SNR = 30dB. The modulation scheme employed is 4QAM. The coding scheme used is a rate-1/3 64-state convolutional code with generators $(G_1, G_2, G_3) = (155,117,123)_8$ (this code has been proposed for EDGE). It was shown in our simulations that this code achieves better performance than a well-documented turbo-code [3] with two identical 16-state recursive encoders with generators $(G_1, G_2) = (23, 31)_8$, at a considerably lower complexity. We transmit blocks of 384 information bits, and record the block error probability of this system.

The receiver structure is either coded V-BLAST or Turbo-BLAST, combined with various MUD schemes to combat the intercell interference. To be specific, the receivers we study are: 1) Coded V-BLAST (V-BLAST); 2) Coded V-BLAST with linear MMSE MUD preprocessing (V-BLAST+MMSE); 3) Turbo-BLAST with a parallel interference cancellation demodulation stage (T-BLAST (PIC)); 4) Turbo-BLAST with a parallel interference cancellation demodulation stage, with linear MMSE MUD preprocessing (T-BLAST (PIC)+MMSE); 5) Turbo-BLAST with a maximum likelihood demodulation stage (T-BLAST (ML)); 6) Turbo-BLAST with a maximum likelihood demodulation stage, with linear channel shortening MUD preprocessing (T-BLAST (ML)+CS); 7) Turbo-BLAST with a parallel interference cancellation demodulation stage, with full group IC MUD[3] (T-BLAST (PIC)+IC). We study the performance of these receivers in the framework of (6) in

---

[3] This receiver attempts to detect all the interfering signals of interest.

two situations: (A) $P_{if1} = P_{if2} = 4P_{if3} = 4P_{if4}$ and (B) $P_{if1} = 6P_{if2} = 6P_{if3} = 6P_{if4}$.[4] Situation (A) corresponds to a two-equal-power-dominant-interferer scenario, while situation (B) reflects a one-dominant-interferer case.

The simulation results for situation (A) are shown in Fig. 8, from which we can see that: 1) Turbo-BLAST offers both diversity and coding gain over coded V-BLAST; 2) Turbo-BLAST with a PIC demodulation stage performs as well as Turbo-BLAST with an ML stage, while it has much lower complexity; 3) Linear MUD preprocessing offers a considerable performance gain in interference-limited environments; and 4) Full group IC MUD worsens the performance instead of improving it. Note that we attempt to detect all interfering signals in this case. In all, we see that Turbo-BLAST with linear MMSE MUD to combat the intercell interference achieves the best performance, which is about 2 dB and 6 dB over Turbo-BLAST and coded V-BLAST, without MUD, respectively, at 1% BLER.

The failure of the full group IC MUD is owing to the inability to correctly detect the information bits for interfering cells. There are both theoretical and practical reasons for the errors in the detection of the interfering signals. The practical reason is that the codes that we used in this simulation are comparatively simple, and thus cannot correct all the errors that an “ideal” code could eliminate. However, there is also a theoretical limit: with ideal codes, the codes in neighboring cells would be designed to have rates that achieve capacity *in that cell*. However, they suffer more attenuation when propagating to a neighboring cell (where they are interferers). The signal-to-noise-ratios of those signals in a neighboring cell are thus worse, so that the data rate is above the capacity of the link to a neighboring cell. Thus, correct decisions for the symbols of interfering signals might not be possible even theoretically.

Decoding of the data for interfering cells is done with the hope that this can aid in detecting the data for the desired cell. Otherwise, it is a waste of resources to do this. Moreover, incorrect decision feedback can interfere with the iterative processing of the desired user, and actually worsens the performance. Thus, instead of decoding the data for all interfering cells, it makes sense to do it for just one or two strongest interfering signals

---

[4] These values are typical for the hexagonal cell structure used in subsection V.C.

and to ignore the others. The simulation results in Fig. 9 indicate the effectiveness of this approach. However, the performance of group IC MUD is still worse than linear MMSE.

We would expect that when we have only one dominant interfering signal, group IC MUD would outperform linear MMSE MUD. Therefore, it is worth studying the performance of group IC MUD only for the strongest interfering signal when there is one dominant interferer. The simulation results for situation (B) are shown in Fig. 10. We see that group IC MUD only for the strongest interfering signal achieves the best performance, which is about 4dB and 8dB over Turbo-BLAST and coded V-BLAST, without MUD, respectively, and more than 2dB over Turbo-BLAST with linear MMSE preprocessing, at 1% BLER. (Since T-BLAST (ML) offers no advantage over T-BLAST (PIC) while having much higher complexity, we do not consider it further.)

We have noticed that group IC MUD (only for the strongest interfering signal) performs the best when one interferer dominates. But when two equal-power interferers dominate, it is no better than the simpler linear MMSE MUD scheme. Figures 11 – 13 show that in the two-dominant-interferer scenario, when the ratio between the two largest interferer powers increases, the gap between the performance of group IC MUD and linear MMSE MUD also increases. In view of this performance, an idea for *adaptive detection* arises: namely, in the case of one dominant interferer (3dB or greater) or in the case of two dominant interferers (4dB or greater) with the ratio between the two largest interferer powers greater than 3dB, group IC MUD could be adopted, otherwise a simple MMSE MUD scheme could be adopted. We will show the advantage of this adaptive receiver over the well known coded V-BLAST in subsection V.C. Please note that the adaptive scheme proposed here is well suited for the corresponding setting. It should be modified when applying to other scenarios, even though the adaptive detection idea is carried on readily.

B. Downlink Capacity of Interference-Limited MIMO

In this subsection, we examine the downlink capacity of interference-limited MIMO systems obtained through the techniques we have developed in the last subsection. Figures 14 and 15 give the outage capacity for interference limited MIMO systems when one and two interferers with equal power dominate, respectively. An upper bound (corresponding to the interference-free situation) is derived from (2), where the block error rate is defined as the probability that the specified spectral efficiency (8/3 bits/s/Hz for a rate-1/3 coded 4QAM-modulated 4×4 MIMO system) is not supported by the randomly generated channels. The Foschini approximation (single link capacity lower bound) is similarly derived from (3). For the one-dominant-interferer case, the Turbo-BLAST with a parallel interference cancellation demodulation stage, with group IC MUD only for the strongest interfering signal (T-BLAST (PIC)+1 IC) is employed, while for the two-equal-power-dominant-interferer case, the Turbo-BLAST with a parallel interference cancellation demodulation stage and with linear MMSE MUD preprocessing (T-BLAST (PIC)+MMSE) is used, as they achieve the best performance in each respective case.

The results are given for five situations: interference-free, SIR = 20, 10, 5 and 0dB. We see that in the noise-dominating scenarios (interference-free, SIR = 20 dB), the obtained MUD capacity is excellent, even better than the Foschini approximation (Turbo-BLAST usually yields better performance than D-BLAST). Even in the medium SIR of 10 dB, the MUD capacity is quite close to the Foschini approximation, which is only 2-3 dB away from the exact interference-free capacity upper bound. However, when the interference gets stronger, the MUD capacity gets worse, and eventually saturates, which indicates the limitations of our methods in strong interference environments and leaves ample room for possible improvement through other techniques. Note that the error floor values of Figs. 14 and 15 when SIR = 0 dB agree well with Figs. 10 and 8.

In Fig. 16, the theoretical results of (12) (upper bounds) are compared with the simulated results for the two-equal-power-dominant-interferer case (cf. Fig. 15). We see that the simulated results are only 2 to 3 dB away from the capacity bound for SIR = 20~5 dB at 1% BLER, and both results exhibit the interference-limited behavior for SIR = 0 dB. The possible reasons for the gap include: 1) Our simulated system is not a large system (4×4 MIMO system); 2) Our Turbo-BLAST structure with the practical convolutional coding already suffers 1 to 2 dB loss in the interference-free scenario (see Fig. 14 and Fig. 15). Therefore, the validity of our simulation results is verified.

C. Simulation Results in Cellular Environments

So far, the performance evaluations have been done in the framework of (6), where we deliberately set the SNR, SIR, and power distributions among the interferers to fixed values that represent some typical cases. In this subsection, we test the performance in the more complete model of (5), where the parameters are set as in V.A. The receivers of interest are 1) Coded V-BLAST treating intercell interference as noise (V-BLAST), which serves as a baseline reference; 2) Turbo-BLAST with a parallel interference cancellation demodulation stage, with linear MMSE MUD (T-BLAST (PIC)+MMSE); 3) Turbo-BLAST with a parallel interference cancellation demodulation stage, with adaptive MUD detection (T-BLAST (PIC)+ADPT); 4) Turbo-BLAST with a parallel interference cancellation demodulation stage, with the better of linear MMSE MUD and Group IC MUD detection (T-BLAST (PIC)+IDEAL).

We again assume a 4QAM-modulated 4×4 MIMO system, with the mobile randomly located within the cell of interest with a uniform distribution. The figure of merit is the CDF of the BLER performance for these four receivers. We collect 1000 points for this CDF profile.

1. NLOS Scenario

The parameters are set as in V.A. The simulation results are shown in Fig. 17, from which we can see that 1) advanced signal processing and coding techniques substantially improve the performance over the well-known V-BLAST technique with coding (roughly 30% more at 1% outage for the linear MMSE); 2) the adaptive scheme affords further gain over linear MMSE (roughly 9% more at 1% outage for the ideal case); 3) the adaptive detection scheme illustrated in V.A approaches the ideal performance at the low BLER area, which is of practical interest. The threshold values of the adaptive detection scheme could be refined to get better performance in practice.

2. LOS Scenario

A mobile is randomly located as before, and the probability for the LOS component seen at the mobile decreases linearly with its distance to a base station, until a "cutoff point", which is set at 300m [24]. If the signal from some base station is NLOS, the same parameters as V.A is used. Otherwise, the signal comprises both the LOS and NLOS components as given in (4). We set the Ricean factor to $K = 13 - 0.03d$ dB, where d is the distance to some base station, and the path loss exponent to 2. Slightly different from model (4), we assume no shadowing for the LOS component; while for the NLOS component, we still assume a log-normal shadow fading with 8 dB standard deviation. Furthermore, we assume that the transmitter and receiver are positioned far apart from each other compared with the antenna spacing, so we get a rank-1 system matrix for the LOS component with energy equally distributed between real and imaginary parts, i.e., $\Phi_{ij} = \pi/4$ for all i and j [9].

The simulation results are shown in Fig. 18. Compared with Fig. 17, we see that the performance of the V-BLAST technique with coding significantly increases due to less signal fading. MUD techniques with the Turbo-BLAST structure still greatly improve the system performance over the V-BLAST. But the advantage of the adaptive scheme over linear MMSE MUD is negligible.

VI. Conclusions

This paper has explored the downlink capacity of interference-limited MIMO cellular systems operating in fading channels. In contrast to the single-cell MIMO system considered in previous studies, where the intercell interference, when accounted for, is added to ambient Gaussian noise, we take the approach of modeling the whole downlink cellular system as a broadcast/interference channel [4], the capacity of which has long been an open question. Upper bounds for this capacity are obtained from the interference-free single-link theoretical formulas. We have primarily addressed the issue of how closely one can approach these bounds without any base station cooperation by implementation and simulation of advanced techniques. After discussing the merit of the turbo space-time multiuser detection, which come remarkably close to the ultimate capacity limits with the Gaussian ambient noise, we have considered multiuser detection for combating intercell interference. Among various multiuser detection techniques examined, linear MMSE MUD and successive interference cancellation have been shown to be feasible and effective. Successive cancellation plays a major role in network information theory from both theoretical and practical points of view. As is known, decoding of the interfering users is not always optimal except in the strong-interference case, nor is treating them as pure ambient noise optimal, except in the very-weak interference case. Based on this phenomenon, we have proposed an adaptive detection idea that offers improved performance. The success of linear MMSE processing arises, in addition to its ability to suppress interference, from its ability of producing Gaussian-like interference [20]. The observations made in [17] indicate that a receiver that uses a Gaussian-based optimal metric (which is true for our study) cannot surpass the Gaussian capacity region in the case of an ergodic additive non-Gaussian channel when Gaussian distributed codewords are selected. On the other hand, transforming the non-Gaussian interference into Gaussian-like interference guarantees the excellent performance of efficient signaling techniques well studied for AWGN channels [5], [11].

We have shown through simulation that advanced signal processing and coding techniques substantially improve interference-limited MIMO system performance over the well-known V-BLAST techniques with coding (6-8 dB in SIR for the simplified model, or 40% more in capacity for the cellular model, at 1% outage). We have also shown that the obtained MUD capacity is excellent in high to medium SIR environments. The asymptotic multicell MIMO capacity with linear MMSE MUD preprocessing is also derived, through which our simulation results are verified. Our proposed techniques might be rather complex for current systems, but will become more practically relevant in the future, as processing power at the mobile increases according to Moore’s law. Furthermore, they are readily applicable today at the base stations for uplink processing.

Finally, numerical results indicate that, due to complexity constraints and adverse environments, there is a significant performance gap between MUD capacity and interference-free capacity, especially in environments with strong interference (SIR of 5 dB or less). This indicates a need to exploit more complex schemes, such as base station cooperation (macrodiversity) with the knowledge of downlink channel state information, to enhance the system throughput.

Acknowledgements: The authors would like to thank Prof. Larry Greenstein, Prof. Peter Driessen, Dr. Jack Winters, Dr. Yang-Seok Choi, Dr. Martin Clark, Prof. Moe Win, and Dr. Severine Catreux for helpful discussions.

References

[1] S. L. Ariyavisitakul, "Turbo space-time processing to improve wireless channel capacity," *IEEE Trans. Commun*., vol. 48, no. 8, pp. 1347-1359, Aug. 2000.

[2] P. W. Baier, M. Meurer, T. Weber and H. Troeger, "Joint transmission (JT), an alternative rationale for the downlink of time division CDMA using multi-element transmit antennas," *Proc. IEEE 6th Int. Symp. Spread Spectrum Techniques*, vol. 1, pp. 1-5, Parsippany, NJ, Sept. 6-8, 2000.

[3] C. Berrou et al., “Near shannon limit error-correction coding and decoding: Turbo codes,” *Proc. 1993 IEEE International Conf. on Communications*, pp. 1064-1070, Geneva, Switzerland, May 1993.

[4] E. Biglieri, J. Proakis, and S. Shamai, "Fading channels: information-theoretic and communications aspect," *IEEE Trans. Inform. Theory*, vol. 44, no. 6, pp. 2619-2692, Oct. 1998.

[5] A. R. Calderbank, "The art of signaling: fifty years of coding theory," *IEEE Trans. Inform. Theory*, vol. 44, no. 6, pp. 2561-2595, Oct. 1998.

[6] S. Catreux, P. F. Driessen and L. J. Greenstein, “Simulation results for an interference-limited multiple-input multiple-output cellular system,” *IEEE Comm. Lett.*, vol. 4, no. 11, pp. 334-336, Nov. 2000

[7] H. Dai and H. V. Poor, “Iterative space-time processing for multiuser detection in multipath CDMA systems,” *Proc. IEEE 6th Int. Symp. Spread Spectrum Techniques*, vol. 2, pp. 343-347, Parsippany, NJ, Sept. 6-8, 2000.

[8] H. Dai and H. V. Poor, “Turbo multiuser detection for coded DMT VDSL systems,” *IEEE J. Selected Areas Comm.*, vol. 20, no.2, Feb. 2002.

[9] D. F. Driessen and G. J. Foschini, “On the capacity formula for multiple input-multiple output wireless channels: a geometric interpretation,” *IEEE Trans. Commun.*, vol. 47, no. 2, pp. 173-176, Feb. 1999.

[10] C. Douillard et al., “Iterative correction of intersymbol interference: Turbo-equalization,” *European Trans. Telecommun*., vol. 6, no. 5, pp. 507-511, Sept.-Oct. 1995.

[11] G. D. Forney and G. Ungerboeck, "Modulation and coding for linear Gaussian channels," *IEEE Trans. Inform. Theory*, vol. 44, no. 6, pp. 2384-2415, Oct. 1998.

[12] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas, " *Bell Labs Tech. J.*, vol. 2, no. 2, pp. 41-59, Autumn 1996.

[13] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas, " *Wireless Personal Communications*, vol. 6, no. 3, pp. 311-335, Mar. 1998.

[14] G. J. Foschini, G. D. Golden, R. A. Valenzuela and P. W. Wolniansky, "Simplified processing for high spectral efficiency wireless communication employing multi-element arrays," *IEEE J. Selected Areas Comm.*, vol. 17, no. 11, pp. 1841-1852, Nov. 1999.

[15] J. Hagenauer et al., “Iterative decoding of binary block and convolutional codes,” *IEEE Trans. Inform. Theory*, vol. 42, no. 2, pp. 429-445, Mar. 1996.

[16] M. A. Khalighi et al., “On capacity of Ricean MIMO channels,” *Proc. 2001 IEEE 12th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. A150-A154, San Diego, CA, Sep 30-Oct 3. 2001.

[17] A. Lapidoph, "Nearest neighbor decoding for additive non-Gaussian channels," *IEEE Trans. Inform. Theory*, vol. 42, no. 6, pp. 1520-1529, Sept. 1996.

[18] I. Medvedev and V. Tarokh, “A channel-shortening multiuser detector for DS-CDMA systems," *Proc. IEEE VTC 2001 Spring*, May 6-9, Rhodes, Greece, 2001.

[19] H. V. Poor, “Turbo multiuser detection: A primer,” *Journal of Communications and Networks*, vol. 3, no. 3, pp. 196-201, Sept. 2001

[20] H. V. Poor and S. Verdú, "Probability of error in MMSE multiuser detection," *IEEE Trans. Inform. Theory*, vol. 43, no. 3, pp. 858-871, May 1997.

[21] S. Shamai and A. Wyner, "Information theoretic considerations for symmetric, cellular multiple-access fading channels – part I and part II," *IEEE Trans. Inform. Theory*, vol. 43, no. 6, pp. 1877-1911, Nov. 1997.

[22] S. Shamai and B. M. Zaidel, "Enhancing the cellular downlink capacity via co-processing at the transmission end," *Proc. IEEE VTC 2001 Spring*, CDROM, Rhodes, Greece, May 2001.

[23] M. Sellathurai and S. Haykin, "Further results on diagonal-layered space-time architecture," *Proc. VTC 2001 Spring*, CDROM, Rhodes, Greece, May 2001.

[24] M. Steinbauer and A. F. Molisch (eds.), “Directional channel modeling,” in L. Correia (ed.), *Flexible Personalized Wireless Communications*, New York: Wiley, 2001.

[25] E. Telatar, "Capacity of multi-antenna Gaussian channels," *European Trans. Telecomm.*, vol. 10, no. 6, pp. 585-595, Nov.-Dec. 1999.

[26] A. VanZelst, R. VanNee and G. A. Awater, "Turbo-BLAST and its performance, " *Proc. IEEE VTC 2001 Spring*, CDROM, Rhodes, Greece, May 2001.

[27] S. Verdú, *Multiuser Detection*, Cambridge, U.K.: Cambridge Univ. Press, 1998.

[28] S. Verdú and S. Shamai (Shitz), “Spectral efficiency of CDMA with random spreading,” *IEEE Trans. Inform. Theory*, vol. 45, no. 2, pp.622-640, Mar. 1999.

[29] M. Varanasi, “Decision feedback multiuser detection: a systematic approach,” *IEEE Trans. Inform. Theory*, vol. 45, No.1, pp. 219-240, Jan. 1999.

[30] X. Wang and H. V. Poor, “ Iterative (turbo) soft interference cancellation and decoding for coded CDMA”, *IEEE Trans. Commun.*, vol. 47, no. 7, pp. 1046-1061, July 1999.

[31] X. Wang and H. V. Poor, “Space-time multiuser detection in multipath CDMA channels,” *IEEE Trans. Signal Processing*, vol. 47, no. 9, pp. 2356-2374, Sept. 1999.

[32] A. Wyner, "Shannon-theoretic approach to a Gaussian cellular multiple-access channel," *IEEE Trans. Inform. Theory*, vol. 40, no. 6, pp.1713-1727, Nov. 1994.

[33] J. Zhang, E. K. P. Chong and D. Tse, “Output MAI distributions of linear MMSE multiuser receivers in CDMA systems,” *IEEE Trans. Inform. Theory*, vol. 47, no. 3, pp.1128-1144, May 2001.

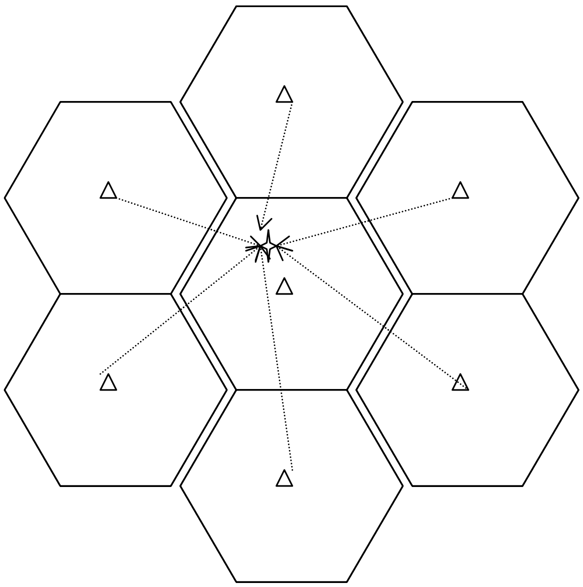

Fig. 1 Cellular system with one tier of interferers in the downlink case

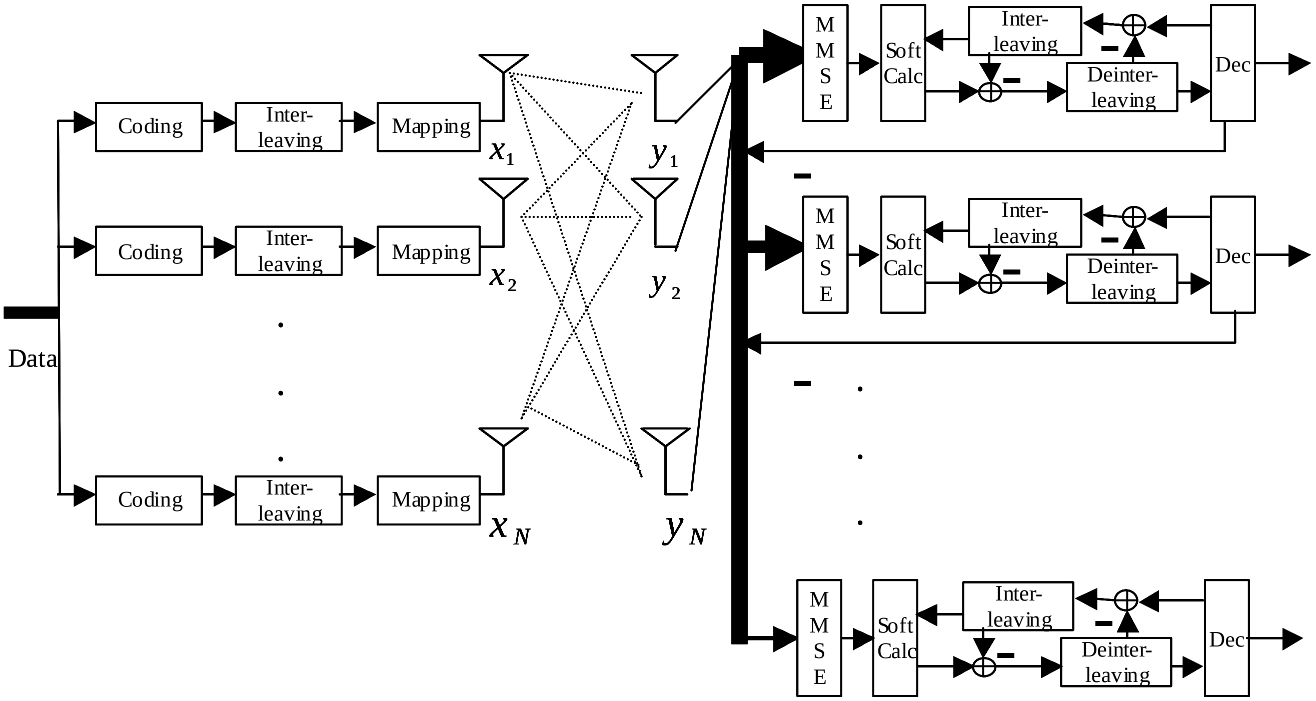

Fig. 2 Structure of coded V-BLAST

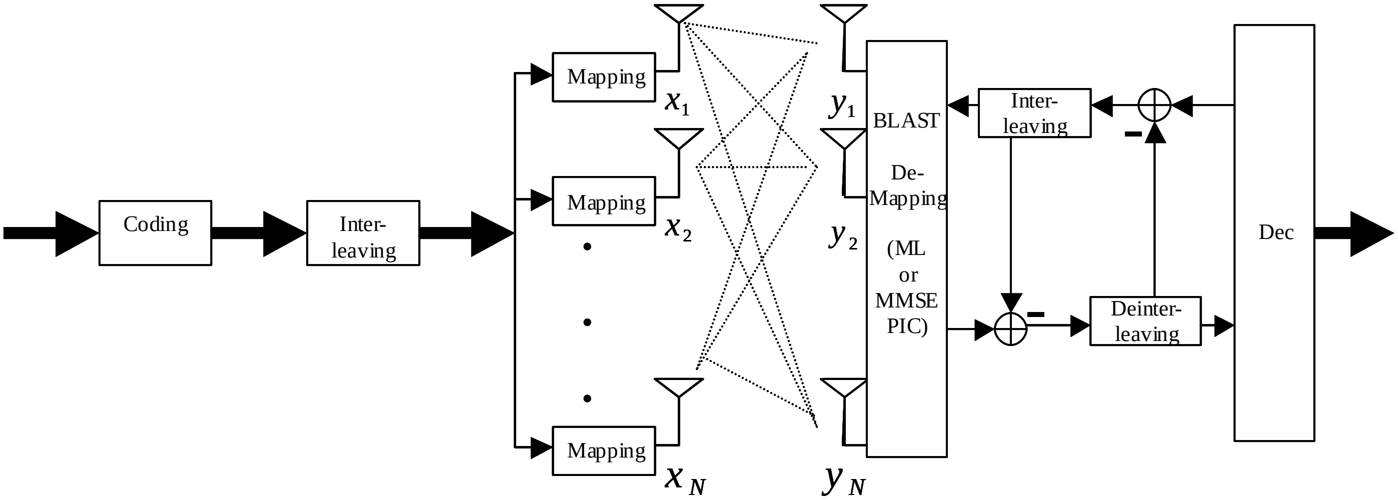

Fig. 3 Structure of Turbo-BLAST

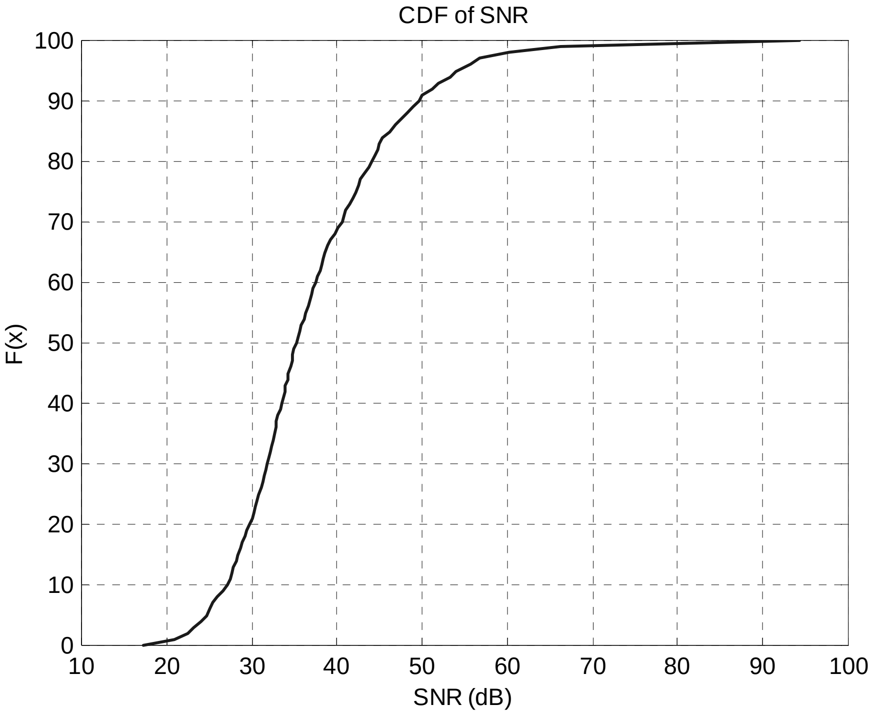

Fig. 4 CDF of SNR experienced by a mobile in the setting of Fig. 1

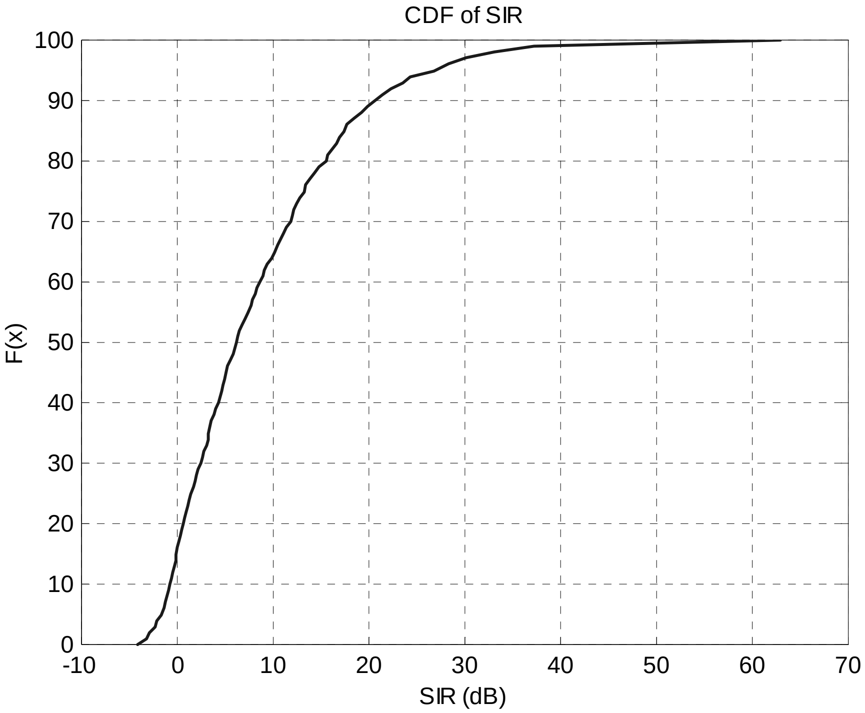

Fig. 5 CDF of SIR experienced by a mobile in the setting of Fig. 1

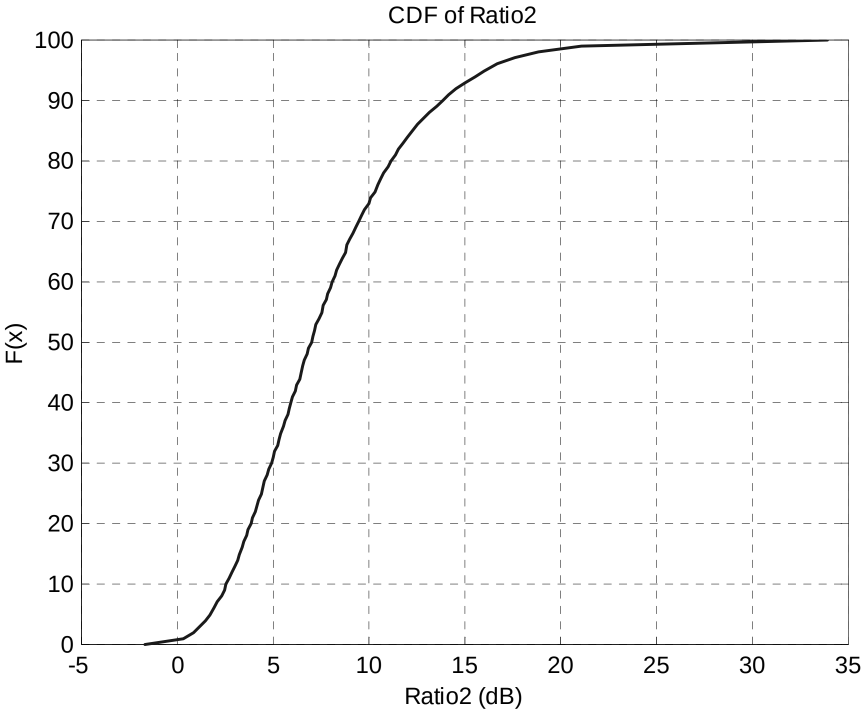

Fig. 6 CDF of the ratio between the power sum of the two strongest interferers and the power sum of the rest interferers experienced by a mobile in the setting of Fig. 1

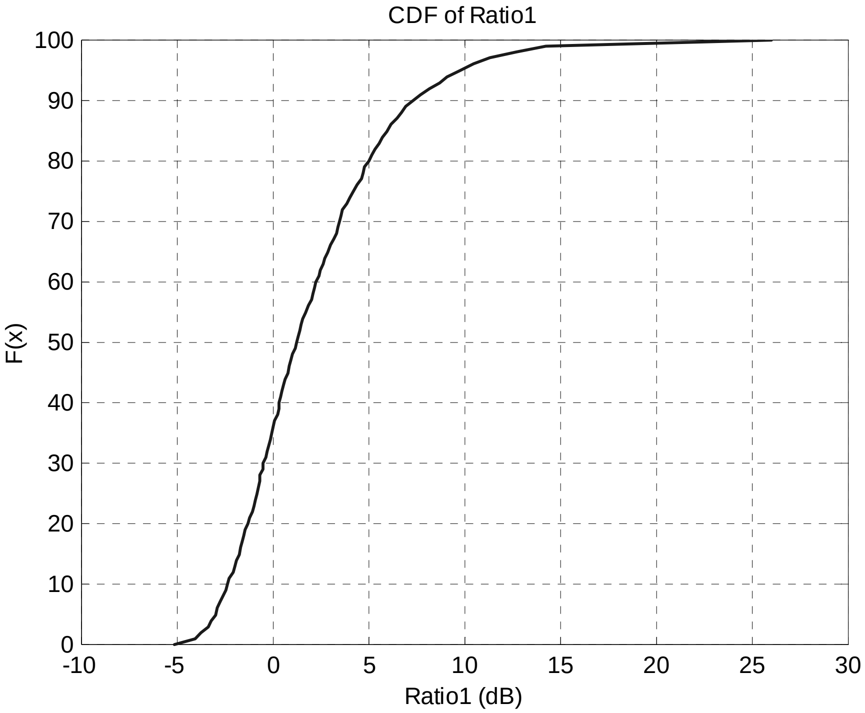

Fig. 7 CDF of the ratio between the power of the strongest interferer and the power sum of the rest interferers experienced by a mobile in the setting of Fig. 1

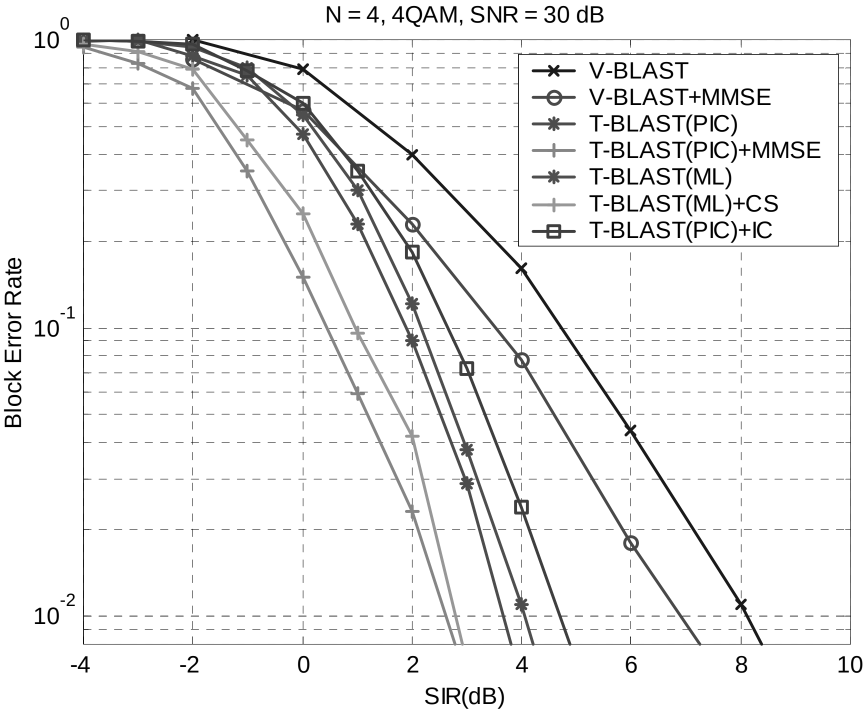

Fig. 8 Performance comparison of various MIMO receivers when two equal-power interferers dominate

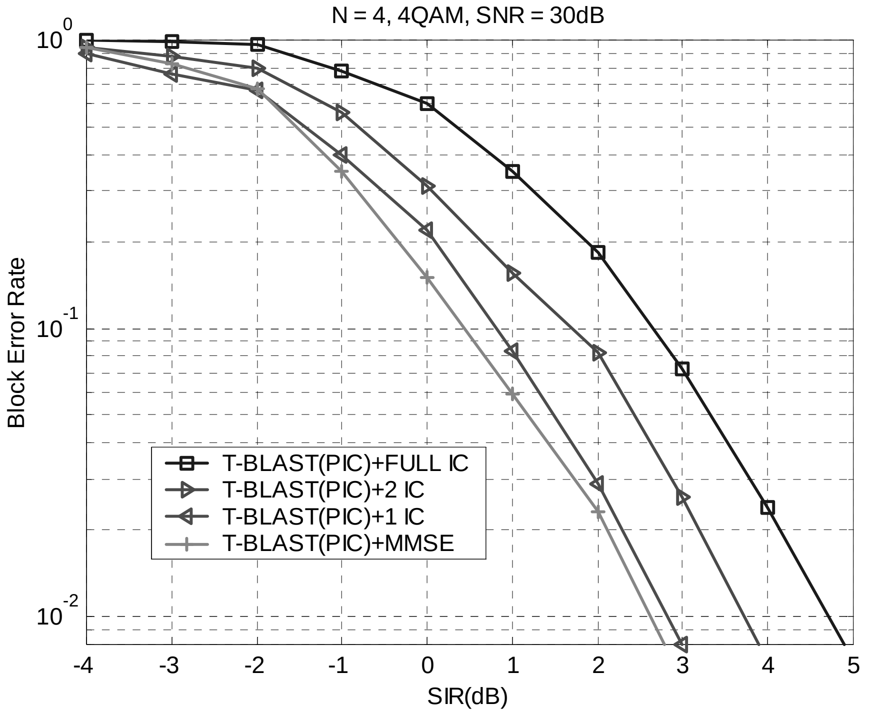

Fig. 9 Performance comparison of various versions of group IC MUD when two equal-power interferers dominate

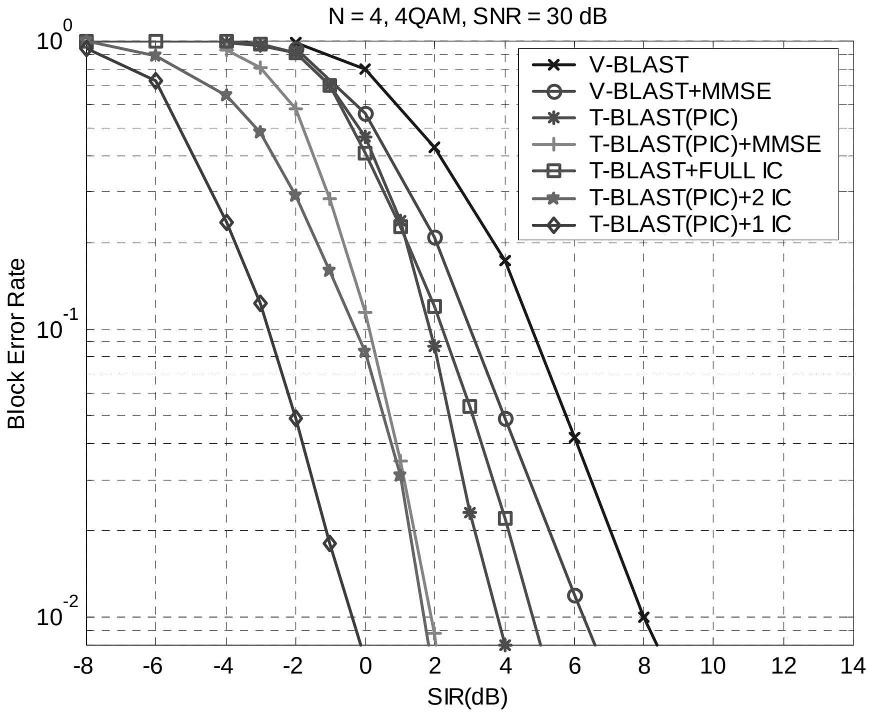

Fig. 10 Performance comparison of various MIMO receivers when one interferer dominates

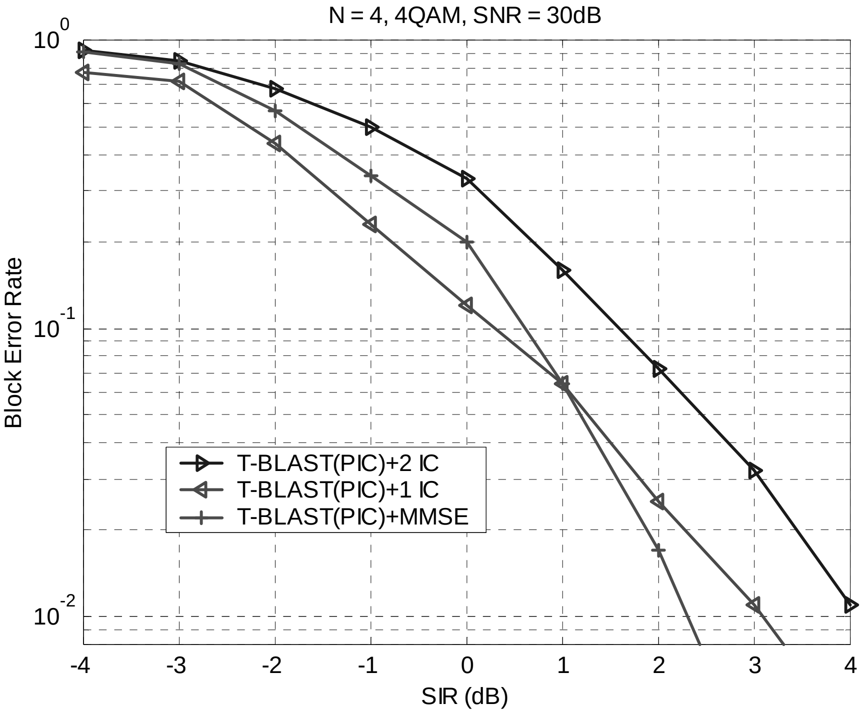

Fig. 11 Performance comparison of linear MMSE and group IC MUD when two interferers dominate with power ratio of 1dB

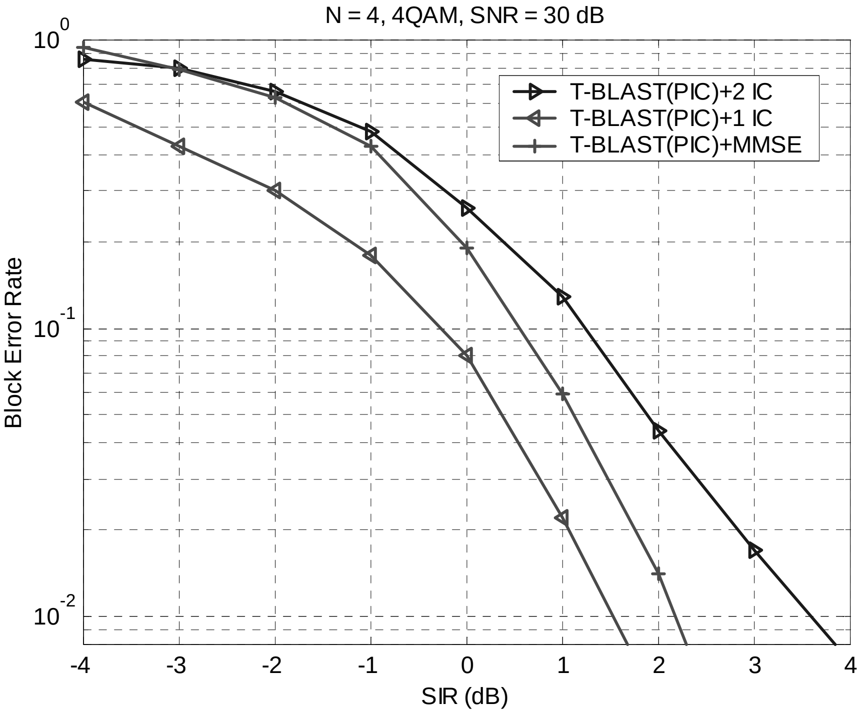

Fig. 12 Performance comparison of linear MMSE and group IC MUD when two interferers dominate with power ratio of 3dB

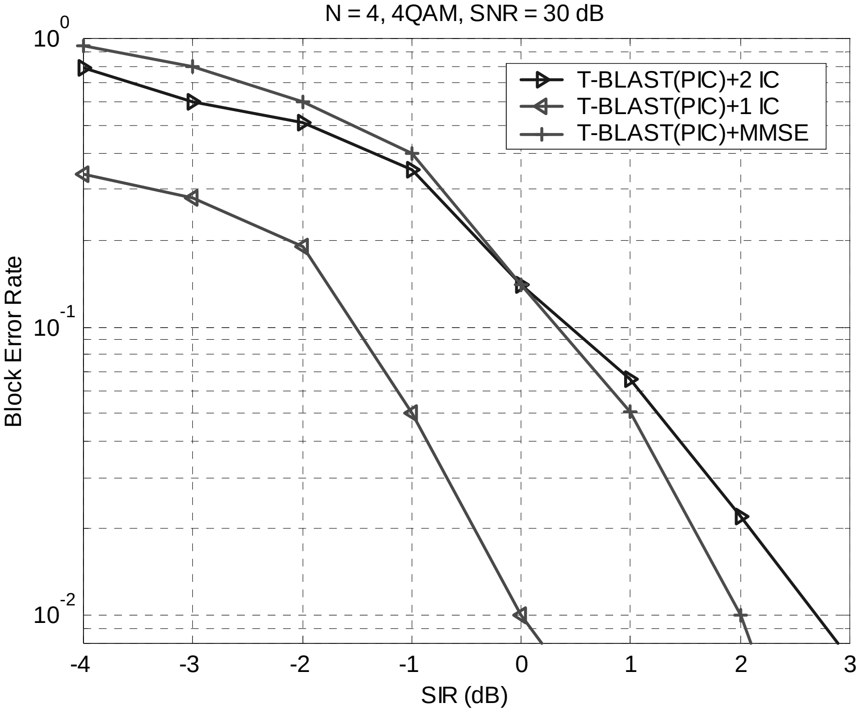

Fig. 13 Performance comparison of linear MMSE and group IC MUD when two interferers dominate with power ratio of 5dB

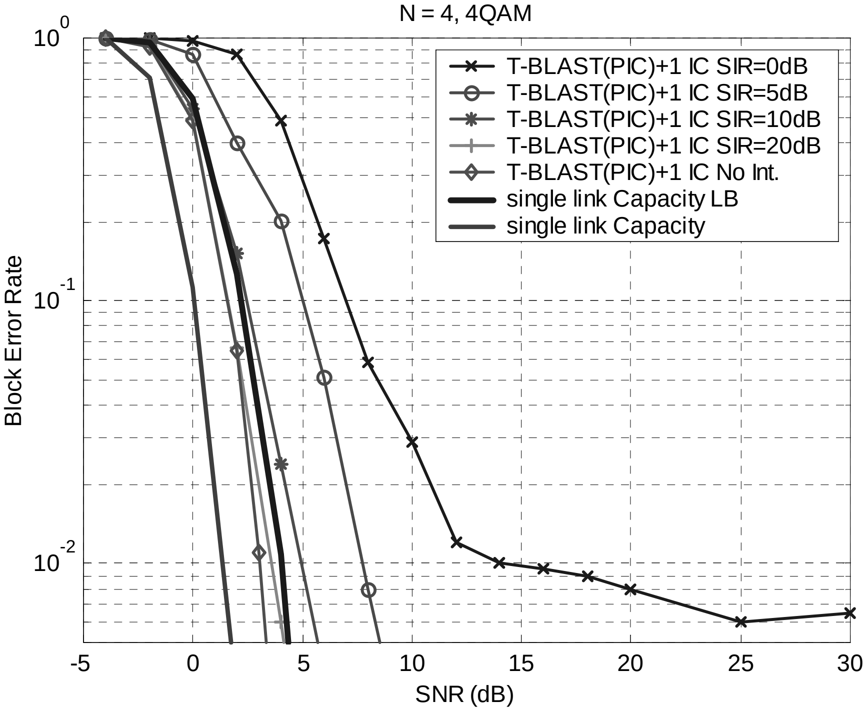

Fig. 14 Downlink capacity of interference-limited MIMO when one interferer dominates

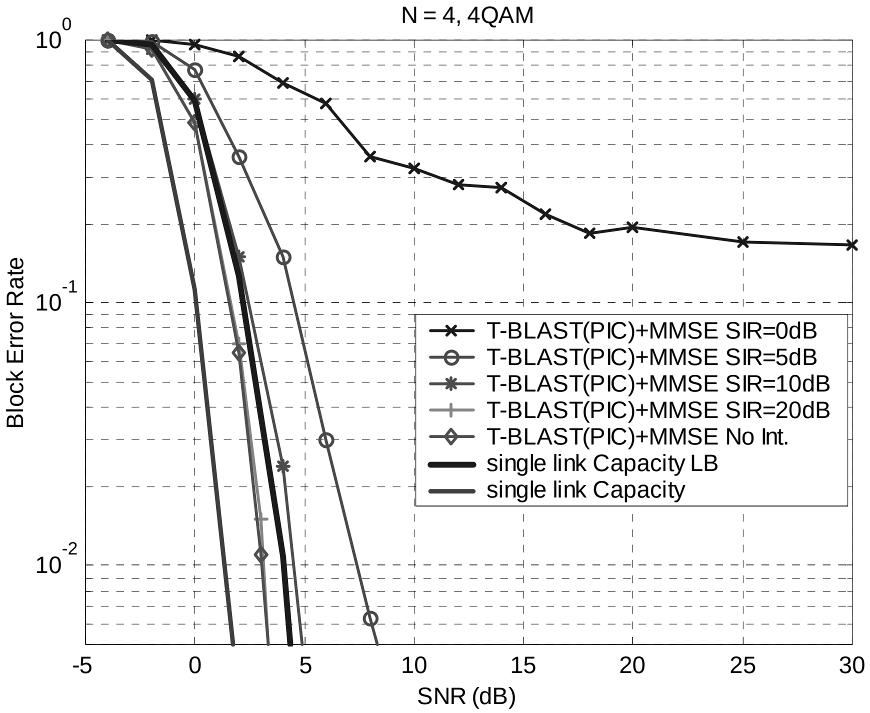

Fig. 15 Downlink capacity of interference-limited MIMO when two interferers dominate

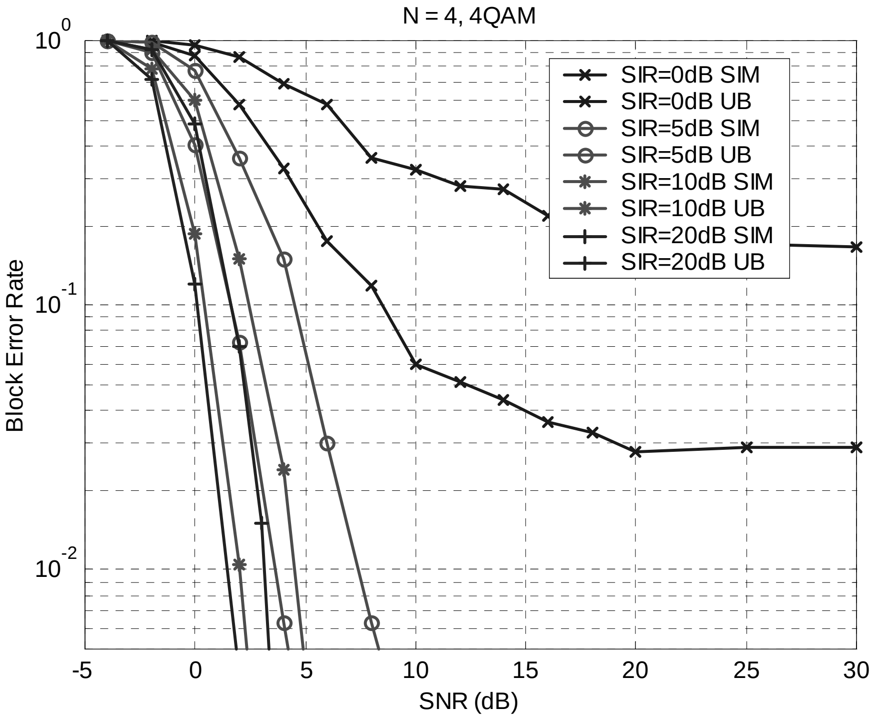

Fig. 16 Comparison of theoretical and simulated results of the capacity of interference-limited MIMO Systems with linear MMSE front end

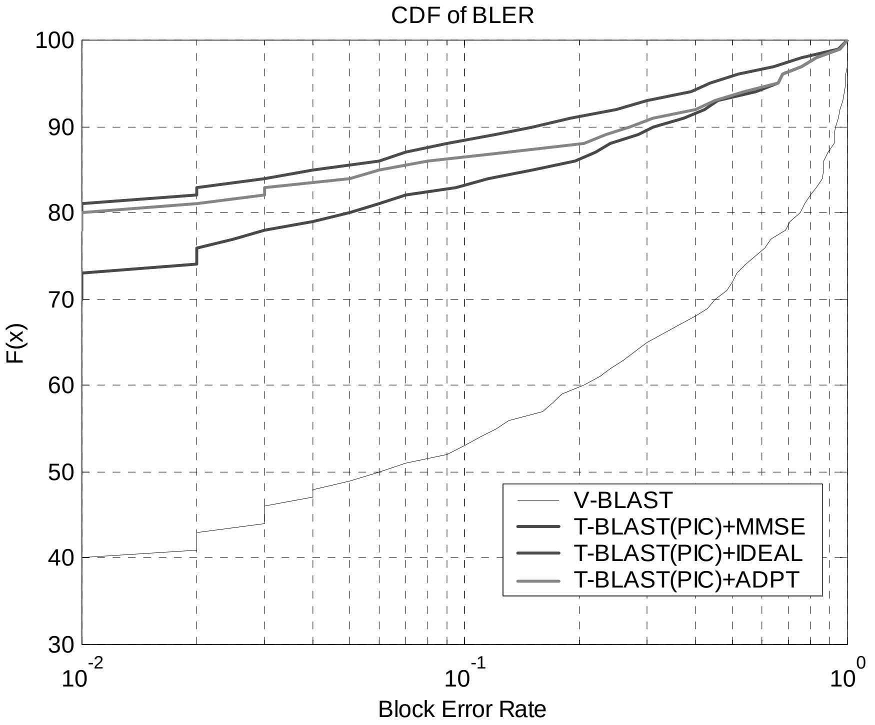

Fig. 17 CDF of block error rate for different receivers experienced by a mobile in Rayleigh fading

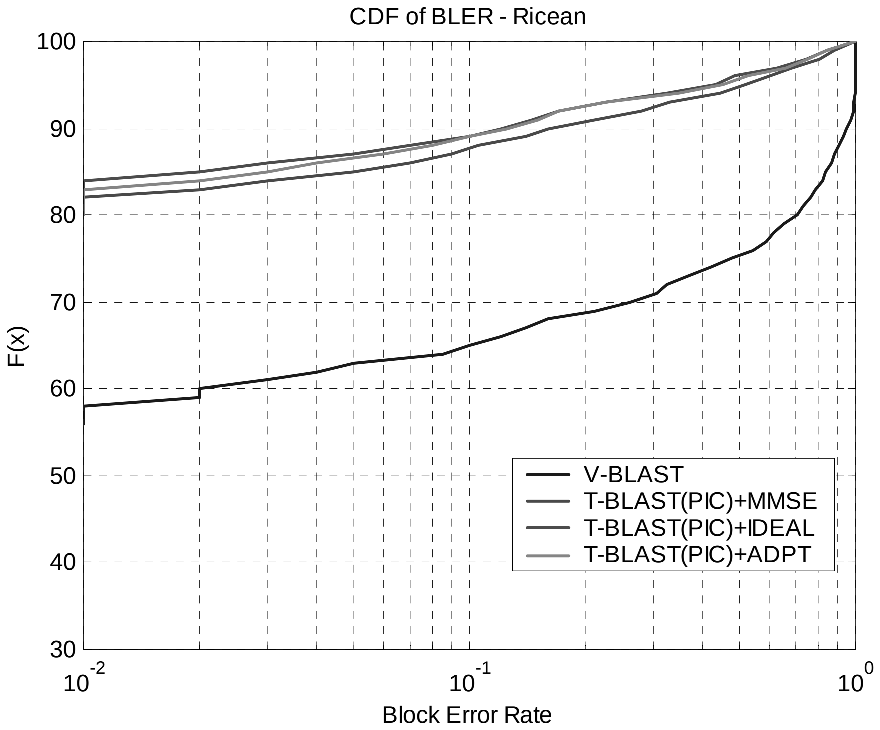

Fig. 18 CDF of block error rate for different receivers experienced by a mobile in Ricean fading