Multi-beam multiplexing using multiuser diversity and random beams in wireless systems

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Abstract— **In this paper, we propose a new multiple-access transmission scheme that can simultaneously achieve both diversity and multiplexing gain in the multi-user domain, by using multiple random beams. Multiple beams are generated so that the users encounter multiple channels at the same time, enabling the use of multi-user diversity through each channel. Since the transmit power is spilt into multiple channels, the signal-to-noise power ratio (SNR) of each channel is reduced in proportion to the number of beams. However, multiple beams are generated so that the multiplexing gain is much larger than the decrease of SNR, increasing the overall system capacity. The proposed scheme works well in both Rician and Rayleigh fading channels regardless of the channel correlation, providing the maximum capacity in multiuser and multi-antenna systems in practice. The proposed scheme is applicable to both MIMO and MISO systems, enabling the use of receivers with flexible antenna structure.**

Keywords-multiuser, multiple random beams, multiplexing, MIMO

I. INTRODUCTION

The next generation transmission system should be able to provide high data rate multimedia services to users in mobile, nomadic and fixed environment. The nature of multimedia services may need the downlink capacity much larger than the uplink. In recent years, the capacity of wireless systems has been increased significantly with the development of two key technologies; the use of multiple antennas known as multi-input multi-output (MIMO) [1-3] and packet scheduling known as opportunistic scheduling or multi-user diversity (MUD) [4-7].

In this paper, we consider a multi-antenna transmission scheme that can simultaneously provide multi-user diversity and multiplexing (MUDAM) gain, using multiple random beams. If we can provide multiple channels simultaneously by generating multiple beams, we can get both the diversity and multiplexing gain in the multi-user domain. Although the transmitted power is spilt into multiple channels, total system capacity can be increased by increasing the multiplexing gain much more than the decrease of the SNR.

The multiplexing scheme using multiple transmit antennas can be considered as a combination of transmission beamforming and 'dirty paper' pre-coding method [8-9]. However, these previous schemes require perfect channel state information (CSI) of all users. The use of multiple 'orthogonal' beams was briefly discussed in [6], but it may not provide a desired capacity gain when the number of users is small. In addition, the capacity increases very slowly as the number of users increases.

We consider the generation of multiple beams in a random manner so that multiple beams interfere with each other at a controlled level, without regarding orthogonality. Note that, unlike the opportunistic beamforming, the proposed MUDAM scheme can provide a capacity improvement even in fast Rayleigh fading channel since it exploits the multiplexing in the multi-user domain. The proposed scheme can also improve the capacity even in completely correlated channels since it utilizes independent channels between different users. The proposed scheme is applicable to both the multi-input single-output (MISO) and MIMO systems.

This paper is organized as follows. In Section II, we introduce the system. A MUDAM scheme using multiple random beams is proposed in Section III. The performance of the proposed MUDAM scheme is verified by computer simulation in Section IV. Finally, Section V concludes this paper.

II. SYSTEM MODEL

Consider an ($M \times N$) MIMO system, where the base station has M transmit antennas and each of K users has N receive antennas. The received signal $\mathbf{y}_k(t)$ of the k-th user at time t is can be represented as

$$\mathbf{y}_k(t) = \mathbf{H}_k^H(t)\mathbf{x}(t) + \mathbf{z}_k(t), \qquad k = 1,\ 2,\ \ldots,\ K \quad (1)$$

where $\mathbf{x}(t)$ is an M-dimensional (dim) transmitted symbol vector, $\mathbf{z}_k(t)$ is an N-dim noise vector whose elements are zero mean complex circular-symmetric Gaussian process with the same variance σ_z^2, and $\mathbf{H}_k^H(t)$ is an ($N \times M$)-dim channel matrix with element $h_{nm,k}^*(t)$ representing the channel from the m-th transmit antenna to the n-th receive antenna of the k-th user. Here the superscript * and H denote complex conjugate and conjugation of the transpose, respectively.

We assume that the channel $h_{nm,k}^*(t)$ has flat fading with a block-fading model (*i.e.*, the channel is unchanged during each slot time T and varies independently in the next time slot), the channels of each user are independent and the transmit power is fixed to P at all times, *i.e.*, $E\{\|\mathbf{x}(t)\|^2\}=P$, where $E\{x\}$ denotes the expectation of x. We also assume that instantaneous channel quality information such as the SNR is available at the base station. The base station assigns the channel resource to a user with the best channel quality at each time, exploiting the user diversity.

For ease of description, we first consider an (Mx1) MISO system. The received signal of user k can be represented as

$$y_k(t)=\mathbf{h}_k^H(t)\mathbf{w}(t)s(t)+z_k(t), \qquad k=1,\ 2,\ \ldots,\ K \quad (2)$$

where $\mathbf{h}_k^H(t)=[h_{1,k}^*(t),h_{2,k}^*(t),...,h_{M,k}^*(t)]$ denotes the impulse response of the MISO channel, $s(t)$ is the user signal and $\mathbf{w}(t)=[w_1(t),w_2(t),...,w_M(t)]^T$ is the weight vector of the beamformer.

III. MULTI-USER DIVERSITY AND MULTIPLEXING (MUDAM)

A. Basic concept of MUDAM

We consider a multiuser diversity system with a novel multiplexing scheme in the multi-user domain, using multiple random beams. For easy description, consider a (2x1) MISO system with two beams as illustrated in Fig. . 1, where two signals $d_1(t)$ and $d_2(t)$ are multiplexed by weight $\mathbf{w}_1=[w_{1,1},w_{2,1}]^T$ and $\mathbf{w}_2=[w_{1,2},w_{2,2}]^T$, yielding a transmitted signal

$$\mathbf{x}(t)=\mathbf{w}_1(t)d_1(t)+\mathbf{w}_2(t)d_2(t)\,. \quad (3)$$

The received signal of user k can be represented as

$$y_k(t)=\mathbf{h}_k^H(t)\mathbf{w}_1(t)d_1(t)+\mathbf{h}_k^H(t)\mathbf{w}_2(t)d_2(t)+z_k(t)\,. \quad (4)$$

where the weight $\mathbf{w}_1$ and $\mathbf{w}_2$ can be generated in a successive manner. First, the base station generates a random beam weight $\mathbf{w}_1$ (as in the opportunistic beamforming) and each user reports the SNR to the base station. The SNR of user k is given by $\left|\mathbf{h}_k^H\mathbf{w}_1\right|^2/\sigma_k^2$ where σ_k^2 is the noise power of user k. The base station selects a user having the maximum SNR

$$\gamma_1=\max_{k\in\{1,2,...K\}}\left\{\left|\mathbf{h}_k^H\mathbf{w}_1\right|^2/\sigma_k^2\right\} \quad (5)$$

where γ_1 is the maximum SNR achieved through the first beam. Assume that the base station selects user p in this process. The selected user p reports its channel response $\mathbf{h}_p(t)$ to the base station. Let $\mathbf{g}_1(t)=\mathbf{h}_p(t)$, where $\mathbf{g}_1(t)$ denotes the channel response corresponding to the first beam $\mathbf{w}_1$.

The base station can generates the second beam $\mathbf{w}_2$ so that it generates the interference to the user of $\mathbf{w}_1$ in a controlled manner, *i.e.*,

$$\mathbf{g}_1^H\mathbf{w}_2=\varepsilon \quad (6)$$

where ε should be chosen to be small enough for the SINR of the first beam is nearly unaffected as

$$\gamma_1=\frac{1}{2}\left|\mathbf{g}_1^H\mathbf{w}_1\right|^2\Big/\left(\sigma_p^2+\frac{1}{2}|\varepsilon|^2\right). \quad (7)$$

Then, the base station selects the best user through the second beam resulting an SINR represented as

$$\gamma_2=\max_{p\notin,k\in\{1,2,...K\}}\left\{\frac{1}{2}\left|\mathbf{h}_k^H\mathbf{w}_2\right|^2\Big/\left(\sigma_k^2+\frac{1}{2}\left|\mathbf{h}_k^H\mathbf{w}_1\right|^2\right)\right\}. \quad (8)$$

Note that the transmit power of each beam is reduced inversely proportional to the number of multiple beams since the total transmit power should be constant. Note that the interference from the second beam to the first beam user is controlled by $(1/2)|\varepsilon|^2$, but the interference $(1/2)|\mathbf{h}_k^H\mathbf{w}_1|^2$ from the first beam to the second beam user is not controllable. Thus, it is required for the base station to choose a user having the maximum SINR in an opportunistic manner.

Consider a generalized MUDAM structure. The base station transmits B signals $\{d_1(t),d_2(t),...,d_B(t)\}$ to K users through B beams with weight vector $\{\mathbf{w}_1(t),\mathbf{w}_2(t),...,\mathbf{w}_B(t)\}$ at the same time. In this case, (2) can be rewritten as

$$y_k(t)=\mathbf{h}_k^H(t)\sum_{b=1}^{B}\mathbf{w}_b(t)d_b(t)+z_k(t),\ k=1,\ 2,\ \ldots,\ K \quad (9)$$

where $d_b(t)$ is the user signal such that

$$d_b(t)\in\{s_1(t),s_2(t),....,s_K(t)\},b=1,2,...,B\,. \quad (10)$$

We assume that each signal has the same power σ_s^2. Let $\mathbf{g}_i(t)$ denote the channel response of the best user through the i-th beam $\mathbf{w}_i(t)$, *i.e.*,

$$\mathbf{g}_i(t)\in\{\mathbf{h}_1(t),\mathbf{h}_2(t),....,\mathbf{h}_K(t)\},\ \ i=1,2,...,B\,. \quad (11)$$

Assume that the scheduler selects user p (*i.e.*, $k=p$) for the i-th beam (*i.e.*, $b=i$). That is, the base station transmits the user signal $s_p(t)$ using the i-th beam $\mathbf{w}_i(t)$ (or $d_i(t)=s_p(t)$ and $\mathbf{g}_i(t)=\mathbf{h}_p(t)$). The received signal $r_i(t)$ through the i-th beam (*i.e.*, the received signal of user p) can be represented as

$$\begin{aligned}r_i(t)&=y_p(t)\\&=\mathbf{h}_p^H(t)\left[\mathbf{w}_i(t)s_p(t)+\sum_{b=1,\neq i}^{B}\mathbf{w}_b(t)d_b(t)\right]+z_p(t)\\&=\mathbf{g}_i^H(t)\mathbf{w}_i(t)d_i(t)+\sum_{b=1,\neq i}^{B}\mathbf{g}_i^H(t)\mathbf{w}_b(t)d_b(t)+z_p(t)\end{aligned} \quad (12)$$

where the first term is the desired signal, the second term is the interference due to multi-beam multiplexing and the third term is additive noise.

As in the previous example, the base station performs the successive controlling the power of interference as

$$\mathbf{g}_i^H \mathbf{w}_b = \begin{cases} \varepsilon, & i < b \\ 1, & i = b \\ \text{x}, & i > b \end{cases} \quad (13)$$

where x denotes the amount of uncontrollable interference that varies depending on the situation. The proposed MUDAM scheme generates the weight matrix $\mathbf{W}(=[\mathbf{w}_1, \mathbf{w}_2, ..., \mathbf{w}_B])$ satisfying

$$\mathbf{G}^H \mathbf{W} = \mathbf{F} \quad (14)$$

where $\mathbf{G}$ is the channel matrix of the selected users defined by

$$\mathbf{G} = [\mathbf{g}_1,\ \mathbf{g}_2,\ ...,\ \mathbf{g}_B] \quad (15)$$

and $\mathbf{F}$ is a constraint matrix defined by

$$\mathbf{F} \triangleq \begin{bmatrix} 1 & \varepsilon & \varepsilon & \cdots & \varepsilon \\ \text{x} & 1 & \varepsilon & & \varepsilon \\ \text{x} & \text{x} & \ddots & & \vdots \\ \vdots & & & 1 & \varepsilon \\ \text{x} & \text{x} & \cdots & \text{x} & 1 \end{bmatrix}. \quad (16)$$

Note that the time index t is omitted for ease of description because the weight vector $\mathbf{w}_i(t)$ and the channel $\mathbf{g}_i(t)$ are assumed to unchanged during each slot time.

B. Generation of multiple random beams

We consider the generation of such multiple beams in a random manner. We assume that the channel condition is unchanged during the feedback process as in the opportunistic beamforming.

The base station generates the first beam $\mathbf{w}_1 = [w_{1,1}, w_{2,1}, ..., w_{M,1}]^T$ in a random manner as

$$w_{m,1} = \sqrt{\alpha_{m,1}} e^{j\theta_{m,1}}, \qquad m = 1, 2, ..., M \quad (17)$$

where $\alpha_{m,b}$ and $\theta_{m,b}$, b=1,…,B, are time-variant over a time slot, having a random value between 0 and 1, and 0 and 2π, respectively. Let $\mathbf{g}_1$ be the impulse response of the channel of the first user selected by the scheduler.

Next, the base station generates the next random beam $\mathbf{w}_2$ such that $\mathbf{g}_1^H \mathbf{w}_2 = \varepsilon$. Here, for ease of implementation, we assume $\varepsilon_i = \varepsilon$ and $\mu_i = \mu$ for all i. Note that the scheduler does not need the channel information of all the users, but only that of the selected user. Since the weight of the second beam is an M-dim vector with a single constraint (*i.e.*, an under-determined system), we can arbitrarily determine (M-1) elements by (17). Thus, we need to solve a single equation satisfying

$$\sum_{m=1}^{M-1} g_{m,1}^* \sqrt{\alpha_{m,2}} e^{j\theta_{m,2}} + g_{M,1}^* w_{M,2} = \varepsilon \quad (18)$$

Then, we have

$$w_{m,2} = \begin{cases} \frac{1}{\sqrt{p_2}} \cdot \sqrt{\alpha_{m,2}} e^{j\theta_{m,2}}, & m = 1, 2, ..., M-1 \\ \frac{1}{\sqrt{p_2}} \cdot \frac{1}{g_{M,1}^*} \cdot \left[\varepsilon - \left(\sum_{m=1}^{M-1} g_{m,1}^* \sqrt{\alpha_{m,2}} e^{j\theta_{m,2}} \right) \right], & m = M \end{cases} \quad (19)$$

where the constant $1/\sqrt{p_b}$ is the normalization constant making $\|\mathbf{w}_b\|^2 = 1$.

Similarly, the weight of the b-th beam can be generated by determining ($M-b+1$) elements randomly and the rest (b-1) elements are determined by solving equations,

$$\mathbf{g}_i^H \mathbf{w}_b = \varepsilon,\ i = 1, 2, ..., b-1 \quad (20)$$

where

$$\mathbf{w}_b = \begin{bmatrix} \mathbf{w}_{rand} \\ \mathbf{w}_{sol} \end{bmatrix} \quad (21)$$

whose elements are given by

$$(\mathbf{w}_{rand})_m = \left(\sqrt{p_b}\right)^{-1} \sqrt{\alpha_{m,b}} e^{j\theta_{m,b}}, \qquad m = 1, 2, ..., M-b+1 \quad (22)$$

and

$$\mathbf{w}_{sol} = \left(\sqrt{p_b}\right)^{-1} \begin{bmatrix} g_{M-b+2,1}^* & g_{M-b+3,1}^* & \cdots & g_{M-1,1}^* & g_{M,1}^* \\ g_{M-b+2,2}^* & g_{M-b+3,2}^* & \cdots & g_{M-1,2}^* & g_{M,2}^* \\ \vdots & & & & \vdots \\ g_{M-b+2,b-2}^* & & & \ddots & g_{M,b-2}^* \\ g_{M-b+2,b-1}^* & g_{M-b+3,b-1}^* & \cdots & g_{M-1,b-1}^* & g_{M,b-1}^* \end{bmatrix}^{-1} \cdot \begin{bmatrix} \varepsilon - \sum_{m=1}^{M-b+1} g_{m,1}^* \sqrt{\alpha_{m,b}} e^{j\theta_{m,b}} \\ \varepsilon - \sum_{m=1}^{M-b+1} g_{m,2}^* \sqrt{\alpha_{m,b}} e^{j\theta_{m,b}} \\ \vdots \\ \varepsilon - \sum_{m=1}^{M-b+1} g_{m,b-1}^* \sqrt{\alpha_{m,b}} e^{j\theta_{m,b}} \end{bmatrix} \quad (23)$$

Fig. 2 depicts the procedure of the proposed MUDAM scheme when two beams are employed. Note that we can choose single beam mode (C) if the multi-beam mode (C_M) cannot achieve capacity gain (*i.e.*,C_M<C).

C. Extension to MIMO systems

The proposed scheme can be applied to the MIMO system in a straightforward manner, where the transmitted signals are multiplexed as

$$\mathbf{x}(t) = \sum_{b=1}^{B} \mathbf{w}_b(t) d_b(t) \ . \quad (24)$$

The received signal of user k with an N-element receive antenna array can be represented as

$$\mathbf{y}_k(t) = \mathbf{H}_k^H(t) \sum_{b=1}^{B} \mathbf{w}_b(t) d_b(t) + \mathbf{z}_k(t), \quad k = 1,\ 2,\ \ldots,\ K \quad (25)$$

where $\mathbf{z}_k$ denotes the noise vector. Assume that the receiver is exploiting the receive antenna diversity such as the maximum ratio combining (MRC) or MMSE combining with combining weight $\mathbf{v}_k(t) = [v_{1,k}(t), v_{2,k}(t), ..., v_{N,k}(t)]^T$.

The output of the combiner can be represented as

$$r_k(t) = \mathbf{v}_k^H(t)\mathbf{H}_k^H(t)\sum_{b=1}^{B}\mathbf{w}_b(t)d_b(t) + \mathbf{v}_k^H(t)\mathbf{z}_k(t) \qquad (26)$$

Thus, the proposed MUDAM scheme can be applied to the MIMO system with an equivalent channel

$$\mathbf{h}_k^H(t) = \mathbf{v}^H(t)\mathbf{H}_k^H(t). \qquad (27)$$

and an equivalent noise $z_k'(t) = \mathbf{v}_k^H(t)\mathbf{z}_k(t)$.

IV. Performance Evaluation

The performance of the proposed MUDAM scheme is verified by computer simulation. The simulation results are obtained by averaging over 1000 independent channel realizations per user. We assume that channels of all the users are mutually independent flat fading channel and have the same average SNR. Since the multiplexing is usually employed when the SNR is high, we consider the performance when the SNR is 20dB.

Fig. 3 compares the performance of the opportunistic beamforming (denoted as 'single beam'), the multiple orthogonal beam [6] (denoted as 'orthogonal') and the proposed MUDAM scheme when a (2x1) MISO system is employed in Rayleigh fading channel with average SNR of 20 dB. The proposed MUDAM scheme is designed using $\varepsilon = 0.01$. Multiple 'orthogonal' beams can simultaneously be generated such that $\mathbf{W}^H\mathbf{W} = \mathbf{I}$, where **I** is an identity matrix. Note that the 'orthogonal' beam scheme in [6] does not consider the separation of effective channels $\mathbf{g}_b^H\mathbf{w}_b$, but only the separation of beams $\mathbf{w}_b$, $b = 1, ..., B$. As a result, unlike the proposed MUDAM scheme, the orthogonal multiple beam scheme can provide a MUM gain only when the users are separated by orthogonal beams. It can be seen that the proposed MUDAM scheme always provides a larger capacity than the single beam and orthogonal beam schemes. It can be also seen that the orthogonal beam scheme is poorer than the single beam scheme for a small number of users. This is mainly due to the fact that the orthogonal scheme cannot guarantee orthogonal separation of multiple users. Although it can achieve the MUM gain for a large number of users, it is still poorer than that the proposed MUDAM scheme.

It can be assumed that the channels { $\mathbf{h}_1, \mathbf{h}_2, ..., \mathbf{h}_K$ } are independent. However the channel $h_{1,k}, h_{2,k}, ..., h_{M,k}$ of user k can be correlated unless the channel has rich scattering. We assume a fully correlated channel with a linear uniform array. Then, the channel of user k is given by

$$h_{m,k} = h_{1,k}\exp\{j2(m-1)\pi(d/\lambda)\sin\beta\} \qquad (28)$$

where m=1, 2, …, M,   is uniformly distributed over $[0, 2\pi]$, d is the antenna spacing and λ is the wave length of the carrier frequency.

Fig. 4 compares the capacity of (2x1) MISO MUDAM system with two beams and (2x2) MIMO system in [7] in independent and fully correlated Rayleigh channel when the SNR is 20dB. The MIMO scheme in [7] (denoted as 'MIMO SVD') can be interpreted as a combination of the MUD and MIMO SVD. Although the proposed MUDAM scheme is a (2x1) MISO system, the total system can be considered as (2x2) MIMO system, where the receiver antennas are allocated to each user. It can be seen that the orthogonal beam scheme and MIMO SVD have similar performance in independent channel. Note that the use of water-filling method has little effect in an independent channel whose eigen-spread is not large. On the other hand, it can be seen that the proposed MUDAM scheme works well regardless of the channel correlation condition and thus outperforms the other schemes. It can also be seen that the orthogonal beam scheme is effective when the channel has correlation, outperforming the MIMO SVD scheme.

The MIMO SVD can alleviate the performance degradation due to the channel correlation by allocating more power to the antenna whose eigen-value is large by using water-filling. When the channel is fully correlated, the channel elements $h_{1,k}, h_{2,k}, ..., h_{M,k}$ experience the same fading null or peak. Thus, the correlated channel may have peaks higher than the independent channel. As a result, the beamforming method can provide a larger capacity gain in a correlated channel.

V. Conclusions

In this paper, we have proposed a new multiple antenna transmission scheme that can simultaneously achieve the diversity and multiplexing gain by generating multiple random beams. The multiple random beams are generated so that each beam interferes with other beams in a controlled manner. Unlike the opportunistic beamforming scheme, the proposed MUDAM scheme can provide the multiplexing gain in Rician and Rayleigh fading channel regardless of the channel correlation. Simulation results show that the proposed MUDAM scheme can provide a large system capacity than the orthogonal multi-beam and MIMO schemes. In practice, the proposed scheme can provide the maximum capacity in multi-user and multi-antenna systems. The proposed MUDAM scheme can be applicable to MIMO as well as MISO systems, enabling the use of receivers with flexible antenna structure.

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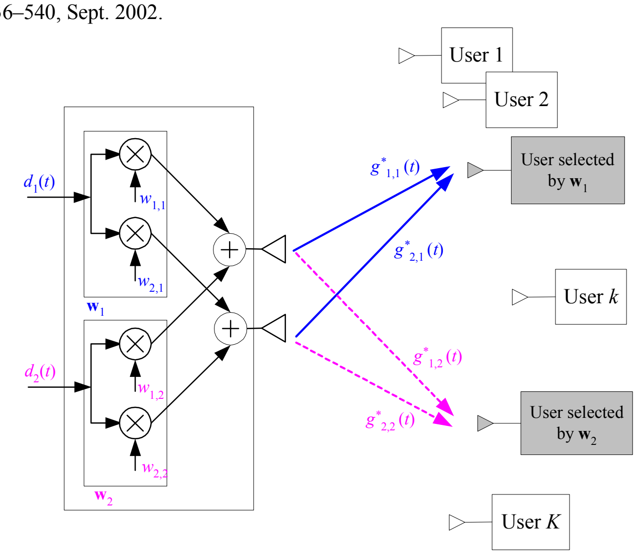


Fig. 1: The proposed MUDAM scheme applied to a (2x1) MISO system

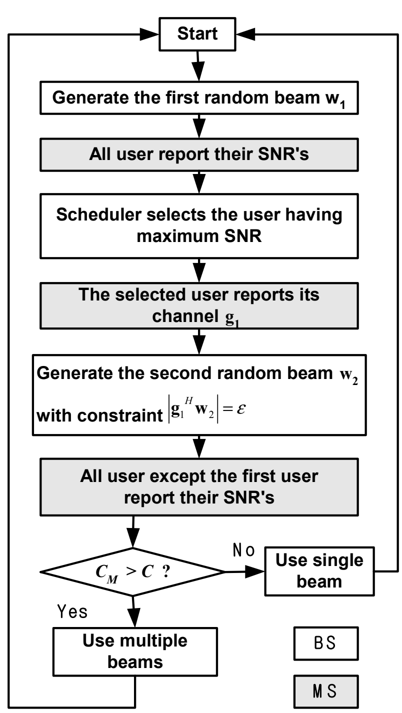


Fig.2: The procedure of (2x1) MUDAM scheme

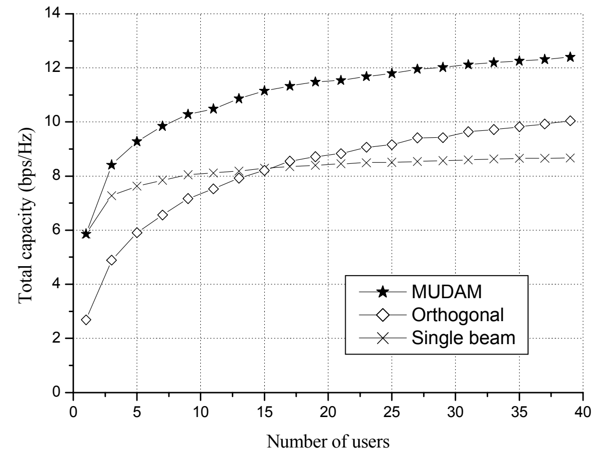
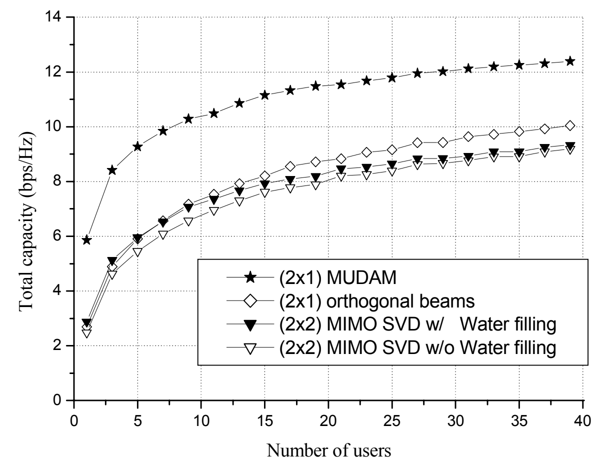
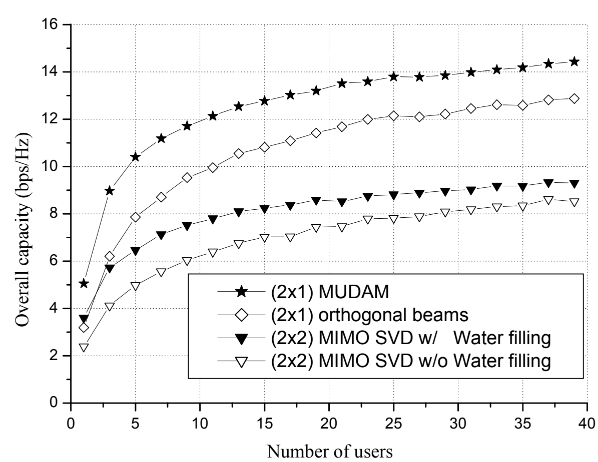


Fig. 3 The capacity in Rayleigh fading channel (SNR =20dB)



(a) Independent channel



(b) Correlated channel

Fig. 4 The capacity of (2x1) MISO and (2x2) MIMO SVD