Multi-user diversity and multiplexing with multiple coherent beams in wireless systems

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Abstract – **In this paper, we propose a multi-beam multiplexing scheme that can simultaneously achieve spatial multiplexing gain and multi-user diversity (MUD) gain by generating coherent multiple beams in the multi-user domain. Multiple beams are generated to provide multiple channels in parallel, making it possible to achieve the MUD gain through each channel. Since the transmission power is spilt into multiple channels, the signal-to-noise power ratio (SNR) of each channel is reduced inversely proportional to the number of beams. However, multiple beams are utilized to make the multiplexing gain much larger than the decrease of SNR, increasing the overall system capacity. The proposed scheme is applicable to both multi-input multi-output (MIMO) and multi-input single-output (MISO) schemes, enabling the use of flexible antenna structures in the receiver.**

I. INTRODUCTION

Next generation transmission systems should be able to provide high rate multimedia services to users in mobile, nomadic and fixed wireless environments. 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) [4,5].

The MIMO technology can increase the diversity or spatial multiplexing gain, increasing the system capacity in proportion to the number of antennas in rich scattering channel environment. Space-time coding (STC) is a typical MIMO diversity scheme [3], and diagonal Bell Laboratories layered space-time (D-BLAST), vertical BLAST (V-BLAST) and MIMO with singular value decomposition (SVD) are typical MIMO multiplexing schemes [1,2]. However, it is not easy to achieve both full diversity and multiplexing gain simultaneously due to trade-off issues between these two gains. Moreover, the diversity and multiplexing gain can substantially be reduced depending on the channel condition [3].

The results in [4] motivate us to use the MUD to take advantages of independent fading statistics. Allowing a user in the best channel condition to use the resource, we can achieve a system capacity much larger than that in additive white Gaussian noise (AWGN) channel with the same average signal-to-noise power ratio (SNR) [4]. However, when the channel gain has small fluctuation and/or varies slowly, the MUD gain may not significantly contribute to the improvement of capacity. To overcome this problem, the base station (BS) generates random beams using multiple antennas, known as opportunistic beamforming [4]. It was reported that the opportunistic beamforming in a multi-input single-output (MISO) scheme can achieve a throughput similar to coherent beamforming when the number of users is sufficiently large.

When the number of users is large, the system throughput can be improved significantly by scheduling multiple users simultaneously [5,6]. However, this scheduling may cause the selected user to be interfered from other scheduled users' signals. Thus, it is required to generate the beams so that the scheduled user interferes with other users at a minimum level. A number of schemes have been proposed for this problem [7-9]. However, most of these schemes require full channel information from all users for the generation of multiple beams, making it impractical due to heavy uplink signaling burden.

All aforementioned multi-user MIMO schemes [4-9] require a sufficiently large number of users or all users` channel state information (CSI) to provide desired performance. To alleviate this problem, a scheme, called multi-user diversity and multiplexing (MUDAM), was proposed [10], where multiple beams are generated in a sequential manner. It can achieve the diversity gain in the multi-user domain and the multiplexing gain simultaneously using multiple beams in parallel. However, the MUDAM scheme does not maximize the beamforming gain since the BS generates the beamforming weight in a random manner. In this paper, we consider the improvement of the MUDAM by employing a coherent beamforming technique [11], providing the overall system capacity larger than that of opportunistic beamforming [4], orthogonal multiple beams (OMB) [6] and even the MUDAM.

This paper is organized as follows. In Section II, we introduce basic concept of the MUDAM with MISO modeling. The proposed coherent MUDAM scheme is

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described in Section III. The performance of the proposed coherent MUDAM scheme is verified by computer simulation in Section IV. Finally, Section V concludes this paper.

II. BASIC CONCEPT OF MUDAM

For ease of description, consider a multi-user MISO system that employs a beamforming technique in the transmitter, where the BS has M transmit antennas and each of K users has a single receive antenna. Assume that the BS transmits M signals $\mathbf{s}=[s_1,s_2,...,s_M]^T$ to M out of K users through M parallel beams. Then, the received signal y_k of user k can be represented as

$$y_k=\mathbf{h}_k\mathbf{W}\mathbf{s}+n_k, \qquad k=1,\ 2,\ \ldots,\ K \tag{1}$$

where $\mathbf{s}$ is the M-dimensional (dim) data symbol vector, n_k is zero mean complex circular-symmetric Gaussian noise with variance σ_n^2, $\mathbf{h}_k$ is the ($1\times M$)-dim channel matrix of user k, and $\mathbf{W}=[\mathbf{w}_1,\mathbf{w}_2,\cdots,\mathbf{w}_M]$ is a beamforming weight matrix whose l-th column represents the l-th beam. We assume that the channel is unchanged while multiple beams are generated and varies independently after that. We also assume that each user has independent channel characteristics with fixed transmission power P at all times and that the BS assigns the channel resource to a user in the best channel condition at each time, exploiting the MUD.

The effective channel of user k can be represented as

$$\tilde{\mathbf{h}}_k=\mathbf{h}_k\mathbf{W} \tag{2}$$

Then the received signal y_k of user k can be represented as

$$\begin{aligned} y_k &= \tilde{\mathbf{h}}_k\mathbf{s}+n_k \\ &= \mathbf{h}_k\mathbf{w}_l s_l+\sum_{i=1,i\neq l}^{M}\mathbf{h}_k\mathbf{w}_i s_i+n_k \end{aligned} \tag{3}$$

where the first term is the desired signal through the l-th beam and the second term is the interference from other users and the third term is additive noise.

The short term signal-to-interference plus noise power ratio (SINR) of user k through the l-th beam can be represented as

$$\gamma_{l,k}=\frac{\frac{P}{M}\left|\mathbf{h}_k\mathbf{w}_l\right|^2}{\frac{P}{M}\sum_{i=1,\neq l}^{M}\left|\mathbf{h}_k\mathbf{w}_i\right|^2+\sigma_n^2} \tag{4}$$

where P/M represents the symbol power for each beam and σ_n^2 is the noise power.

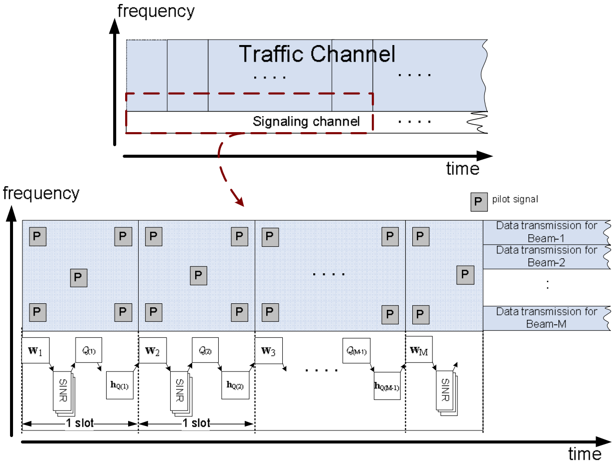


Fig 1. Transmission procedure of the MUDAM

In the MUDAM scheme, multiple beams are sequentially generated to reduce the interference term in (4). Fig 1 illustrates the procedure of the MUDAM scheme in a packet-based OFDM system.

The BS generates the first beam using a random weight $\mathbf{w}_1$. Then all users estimate the SINR for the first beam and report it to the BS. The BS selects the best user for the first beam and notifies it through a signaling channel. Only the selected user needs to report the BS on its channel information corresponding to this first beam. Letting $Q(l)$ be the index of the selected user for the l-th beam, the selected user reports its CSI $\mathbf{h}_{Q(1)}$ to the BS. Note that the scheduler only needs the CSI of the selected user. Next, the BS generates the next random beam $\mathbf{w}_2$ satisfying

$$\mathbf{h}_{Q(1)}\mathbf{w}_2=\varepsilon \tag{5}$$

where ε denotes the amount of interference to the previously selected user by this beam. Similarly, the BS selects the best user for the second beam and gets the corresponding channel information $\mathbf{h}_{Q(2)}$ from the selected user. In this manner, the weight of the l-th beam can be generated randomly, while satisfying

$$\mathbf{h}_{Q(j)}\mathbf{w}_l=\varepsilon, \qquad j=1,2,...,l-1 \tag{6}$$

Making $\varepsilon=0$, the amount of the interference power in (6) can be represented as

$$\mathbf{h}_{Q(j)}\mathbf{w}_l=\begin{cases} 0, & j<l \\ \mu_l, & j=l \\ x_{j,l}, & j>l \end{cases} \tag{7}$$

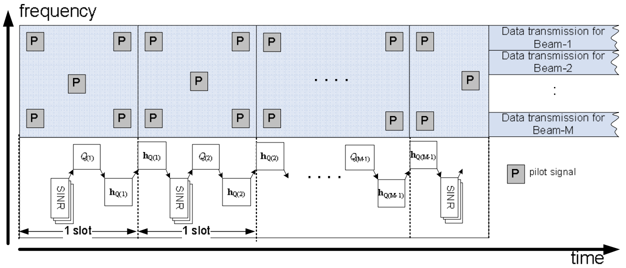


Fig 2. Procedure of the proposed coherent MUDAM scheme

where μ_l denotes the desired signal term for the l-th beam and $x_{j,l}$ denotes the amount of interference from previously generated beams, which is not controllable by this sequential beam generation. Note that as the number of users increases, the amount of interference can be lowered by selecting a user experiencing smaller interference. Thus, the instantaneous SINR of the selected user for the l-th beam can be represented as

$$\gamma_{l,Q(l)} = \frac{\frac{P}{M}\left|\mathbf{h}_{Q(l)}\mathbf{w}_l\right|^2}{\frac{P}{M}\sum_{i=1}^{l-1}\left|\mathbf{h}_{Q(l)}\mathbf{w}_i\right|^2+\sigma_n^2} = \frac{P\left|\mu_l\right|^2}{P\sum_{i=1}^{l-1}\left|x_{l,i}\right|^2+M\sigma_n^2} \tag{8}$$

The MUDAM scheme outperforms the previous schemes [4-9] by controlling the interference from other beams. However, it does not maximize the beamforming gain represented as a numerator in (8) because the BS generates multiple beams in a random manner.

III. THE PROPOSED COHERENT MUDAM

A. Multiple beam generation

We consider the improvement of MUDAM in [10] by using coherent multiple beams instead of random ones. Fig 2 illustrates the transmission procedure of the proposed coherent MUDAM (CMUDAM).

Unlike in the MUDAM, all active users in the CMUDAM estimate the SINR assuming the use of beams with optimum weight instead of random beams. Letting $\mathbf{w}_{1,k}$ be the optimum beam weight that maximizes the beamforming gain of user k for the first beam for given channel $\mathbf{h}_k$, $\mathbf{w}_{1,k}$ can be determined as

$$\mathbf{w}_{1,k} = \frac{\mathbf{h}_k^H}{\left\|\mathbf{h}_k^H\right\|} \tag{9}$$

where $\|\cdot\|$ is Frobenious norm. Then, each user reports the estimated SINR to the BS through an uplink signaling channel. The BS selects a user based on the reported SINR. Then, the user $Q(1)$ selected for the first beam reports its channel information $\mathbf{h}_{Q(1)}$ to the BS. Note that only the selected user needs to report its CSI to the BS, requiring a marginal increase of feedback signaling burden.

After receiving the channel information, the BS recalculates the optimum beam weight $\mathbf{w}_{1,Q(1)}$ for the first beam from $\mathbf{h}_{Q(1)}$ and broadcasts $\mathbf{h}_{Q(1)}$ to all users through a downlink signaling channel. Note that the beam weight in the MUDAM is generated in a random manner [10], yielding no beamforming gain. After receiving the channel vector $\mathbf{h}_{Q(1)}$, each user calculates the SINR assuming the use of optimum beam weight $\mathbf{w}_{2,k}$ for the second beam satisfying zero interference to previously selected user $Q(1)$, i.e.,

$$\mathbf{h}_{Q(1)}\mathbf{w}_{2,k} = 0 \tag{10}$$

The optimum beam weight $\mathbf{w}_{2,k}$ of user k for the second beam can be determined as

$$\mathbf{w}_{2,k} = \frac{\left(\mathbf{h}_k^H\right)_{\perp\mathbf{h}_{Q(1)}}}{\left\|\left(\mathbf{h}_k^H\right)_{\perp\mathbf{h}_{Q(1)}}\right\|} \tag{11}$$

where $(\cdot)_{\perp\mathbf{h}_{Q(1)}}$ denotes the projection onto the subspace orthogonal to $\mathbf{h}_{Q(1)}$. Similarly, the optimum weight of user k for the l-th beam can be determined as

$$\mathbf{w}_{l,k} = \frac{\left(\mathbf{h}_k^H\right)_{\perp\mathbf{h}_{Q(1)},\ldots,\mathbf{h}_{Q(l-1)}}}{\left\|\left(\mathbf{h}_k^H\right)_{\perp\mathbf{h}_{Q(1)},\ldots,\mathbf{h}_{Q(l-1)}}\right\|}, \qquad l = 1,\ldots,l-1 \tag{12}$$

Under the constraint on zero interference to previously selected users, the SINR through the l-th beam can be represented as

$$\gamma_{l,Q(l)} = \frac{\frac{P}{M}\left|\mathbf{h}_{Q(l)}\mathbf{w}_{l,Q(l)}\right|^2}{\frac{P}{M}\sum_{i=1}^{l-1}\left|\mathbf{h}_{Q(l)}\mathbf{w}_{i,Q(i)}\right|^2+\sigma_n^2} \tag{13}$$

Note that the proposed CMUDAM maximizes the desired signal term $\left|\mathbf{h}_{Q(l)}\mathbf{w}_{l,Q(l)}\right|^2$ in (13), while yielding zero interference to previously selected users. After generating M beams, the BS transmits M data to the selected M users in parallel. Note that since all the signaling is performed through a signaling channel different from the traffic channel. Thus, the CMUDAM can contiguously transmit the data without loss of timing resource for the traffic.

B. Performance analysis

Consider an ($M \times 1$) MISO environment with M transmit beams, where the transmit power is equally split into each antenna. For ease of description, we assume that the total transmitted power P is one. Then, the received SINR of the k-th user through the l-th beam can be expressed as

$$\gamma_{l,k} = \frac{\frac{1}{M}\left|\mathbf{h}_k \mathbf{w}_{l,k}\right|^2}{\frac{1}{M}\sum_{i=1}^{l-1}\left|\mathbf{h}_k \mathbf{w}_{i,k}\right|^2 + \sigma_n^2} = \frac{\left|\mathbf{h}_k \mathbf{w}_{l,k}\right|^2}{\sum_{i=1}^{l-1}\left|\mathbf{h}_k \mathbf{w}_{i,k}\right|^2 + M\sigma_n^2} \tag{14}$$

Assuming that $\{\gamma_{l,k}\}$ have the same distribution, we can omit the subscript k in (14) without loss of generality. Let S_D and S_N be the denominator and numerator of γ_l, respectively. Then, S_N can be modeled as a $2(M-l+1)$-th order Chi-square random variable and S_D as a $2(l-1)$-th order Chi-square random variable plus a constant $M\sigma_n^2$. Letting f_{S_D} and f_{S_N} be the probability density function (*pdf*) of S_D and S_N, respectively, the *pdf* of γ_l can be calculated as [12]

$$f_{\gamma_l}(\gamma) = \int_0^\infty \frac{1}{w^3} f_{s_D}\left(\frac{1}{w}\right) f_{s_N}\left(\frac{\gamma}{w}\right) dw \tag{15}$$

where $w = \frac{1}{s_D}$ and $\gamma = \frac{s_N}{s_D}$.

The CMUDAM chooses a user having the maximum SINR for the l-th beam as

$$\gamma_{l,Q(l)} = \max\{\mathbf{c}_l\} \tag{16}$$

where $\mathbf{c}_l = [\gamma_{l1}, \gamma_{l2}, \cdots, \gamma_{lK}]$. Let $\Gamma^K_{r,l}$ be the r-th smallest element of $\mathbf{c}_l$. Since the BS chooses a user with the highest SINR, $\gamma_{l,Q(l)}$ is equal to $\Gamma^K_{K,l}$. Thus, the *pdf* of $\Gamma^K_{K,l}$ can be calculated as [13]

$$f_{\Gamma^K_{K,l}}(z) = K\left[F_{\gamma_l}(z)\right]^{K-1} f_{\gamma_l}(z) \tag{17}$$

where $F_{\gamma_l}(z)$ denotes the cumulative distribution function (*cdf*) of γ_l. The CMUDAM can achieve a capacity through the l-th beam, given by

$$\begin{aligned} E_{\Gamma^K_{K,l}}\left\{C\left(\Gamma^K_{K,l}\right)\right\} &= \int_0^\infty \log_2(1+z) f_{\Gamma^K_{K,l}}(z)dz \\ &= \int_0^\infty \log_2(1+z) K\left[F_{\gamma_l}(z)\right]^{K-1} f_{\gamma_l}(z)dz \end{aligned} \tag{18}$$

Thus, the CMUDAM with M multiple beams can provide a total capacity represented as

$$\begin{aligned} C_M &= E\left\{C\left(\Gamma^K_{K,1}\right) + C\left(\Gamma^{K-1}_{K-1,2}\right) + \cdots + C\left(\Gamma^{K-M+1}_{K-M+1,M}\right)\right\} \\ &= \sum_{l=1}^{M} E\left\{C\left(\Gamma^{K-l+1}_{K-l+1,l}\right)\right\} \end{aligned} \tag{19}$$

C. MIMO extension

The proposed CMUDAM can easily be applied to an MIMO scheme by using an eigenmode transmission technique [14]. For a transmitted signal $\mathbf{d}$ with beam weight $\mathbf{W}$, the received signal vector of user k can be represented as

$$\mathbf{r}_k = \mathbf{H}_k \mathbf{W}\mathbf{d} + \mathbf{n}_k \tag{20}$$

where $\mathbf{H}_k$ is the ($N \times M$)-dim channel matrix of user k and $\mathbf{n}_k$ is the ($N \times 1$)-dim noise vector whose components are zero mean complex circular-symmetric Gaussian random variables with unit variance.

The received signal aggregated from multiple antennas with a combining weight $\mathbf{g}_k$ can be represented as

$$\begin{aligned} y_k^{'} &= \mathbf{g}_k \mathbf{r}_k \\ &= \mathbf{g}_k \mathbf{H}_k \mathbf{W}\mathbf{d} + \mathbf{g}_k \mathbf{n}_k \end{aligned} \tag{21}$$

where, $\mathbf{g}_k$ is the ($1 \times N$)-dim combining weight vector. Thus, the proposed CMUDAM can easily be applied to a MIMO scheme having an equivalent channel $\mathbf{h}_k^{'} = \mathbf{g}_k \mathbf{H}_k$ and equivalent noise $\mathbf{n}_k^{'} = \mathbf{g}_k \mathbf{n}_k$. Thus, the CMUDAM can provide user k with a received SINR through the l-th beam, given by

$$\gamma_{l,k} = \frac{\frac{P}{M}\left|\mathbf{g}_l \mathbf{H}_k \mathbf{w}_l\right|^2}{\frac{P}{M}\sum_{j=1}^{l-1}\left|\mathbf{g}_i \mathbf{H}_k \mathbf{w}_j\right|^2 + \sigma_n^2} \tag{22}$$

For a given channel matrix $\mathbf{H}$, the optimum weight $\mathbf{w}_{opt}$ and $\mathbf{g}_{opt}$ can be determined in terms of the input and output singular vectors corresponding to the maximum singular value of $\mathbf{H}$ [14]. The desired signal power term in (22) can be maximized using a singular value decomposition

(SVD) method. The channel matrix $\mathbf{H}_k$ can be represented as

$$\mathbf{H}_k = \mathbf{U}\Sigma\mathbf{V}^H \tag{23}$$

where $\mathbf{U} = [\mathbf{u}_1^T\,\mathbf{u}_2^T \cdots \mathbf{u}_N^T]$ and $\mathbf{V} = [\mathbf{v}_1\,\mathbf{v}_2 \cdots \mathbf{v}_M]$ are unitary matrices, and Σ is a diagonal matrix whose elements are $\sqrt{\lambda_1} > \sqrt{\lambda_2} > \cdots > \sqrt{\lambda_{\min(M,N)}}$. Here, $\{\lambda_j\}$ are the eigenvaules of $\mathbf{H}_k$. The optimum weight can be determined as [14]

$$\begin{aligned} \mathbf{w}_{opt} &= conj(\mathbf{u}_1) \\ \mathbf{g}_{opt} &= \mathbf{v}_1 \end{aligned} \tag{24}$$

IV. PERFORMANCE EVALUATION

The performance of the proposed CMUDAM is verified by computer simulation. We assume that all users experience mutually independent flat fading channel with the same average SNR. Since spatial multiplexing schemes are usually employed when the SNR is high, we consider the performance at an SNR of 10dB.

Fig 3 depicts the performance of the proposed CMUDAM and MUDAM in term of the spectral efficiency. It can be observed that the CMUDAM outperforms the MUDAM. This is mainly due to that the proposed CMUDAM generates multiple beams to maximize the beamforming gain for the selected user, while yielding zero interference to previously selected users.

Fig 4 compares the performance of the proposed CMUDAM with other conventional schemes, the MUDAM, OMB [6] and opportunistic beamforming [4], with the use of a (4x1) MISO scheme at an average SNR of 10dB. It can be seen that the proposed CMUDAM always provides a capacity larger than the other schemes. It can also be seen that the performance of the OMB can be poorer than that of the opportunistic beamfoming when the number of users is small. This is mainly due to that the OMB cannot guarantee orthogonal separation of multiple users unless the number of users is large.

Fig 5 depicts the effect of user mobility on the performance when the number of users is 32 at an average SNR of 10 dB in a (4X1) MISO scheme. The correlation of a uniformly scattered channel can be represented by $\rho = J_0(2\pi f_d \Delta t)$, where $J_0(\cdot)$ is the zero-th order Bessel function of the first kind, Δt denotes the amount of feedback delay, and f_d is the maximum Doppler frequency [15]. Assume that each slot has a time duration equal to the amount of feedback delay for the generation of each beam in the proposed CMUDAM and MUDAM. The OMB needs only one half slot because it simultaneously generates multiple beams and chooses all the scheduled users at one time. We assume that the length of a slot is 1.63ms in this simulation. It can be seen that the user mobility significantly affects the interference control of users. As a result, as the mobility increases, it degrades the performance of the MUDAM and CMUDAM, being even worse than that of the OMB. Since the amount of delay for the beam generation in a (4x1) MISO is almost double that in a (2x1) MISO, it can be seen that the performance of the CMUDAM and MUDAM is susceptible to the user mobility. Although the proposed CMUDAM is quite effective for users in low mobility environments, it may be desirable to further reduce the time for the generation of multiple beams to make the performance robust to the user mobility with the use of multiple transmit antennas.

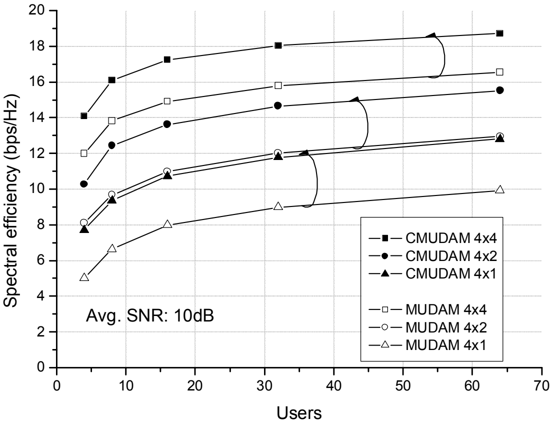


Fig 3. Spectral efficiency of the MUDAM and CMUDAM

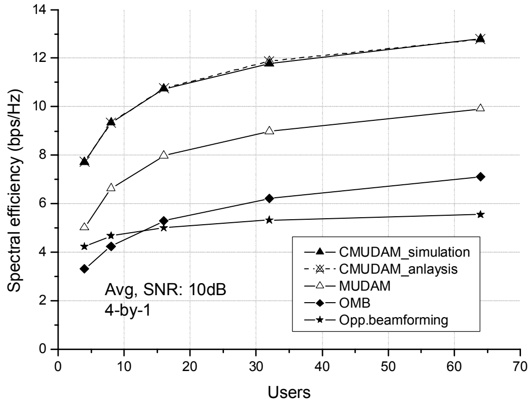
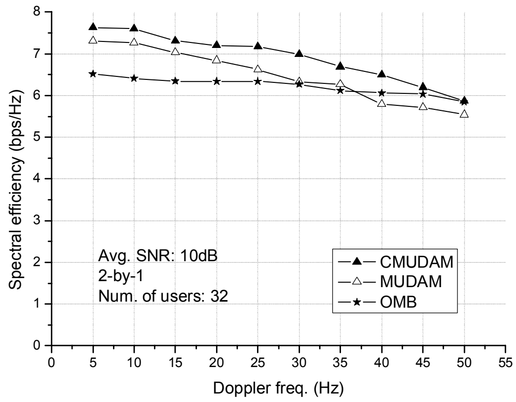
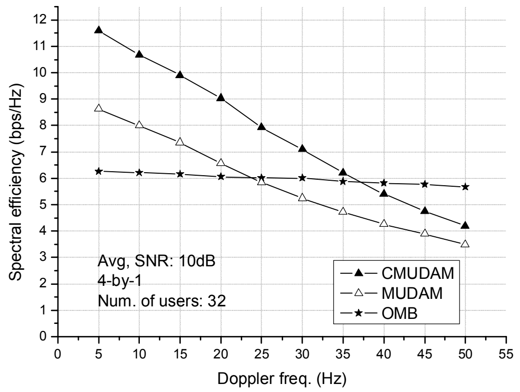


Fig 4. Performance of MISO schemes



(a) When the antenna configuration is (2x1)



(b) When the antenna configuration is (4x1)

Fig 5. The effect of user mobility on the performance

V. CONCLUSIONS

In this paper, we have proposed a coherent MUDAM scheme that provides performance improvement over the MUDAM. Multiple beams are generated to maximize the desired signal power, while preserving the interference controllability of the MUDAM. The simulation results show that the proposed CMUDAM can outperform the MUDAM, OMB, and opportunistic beamforming schemes regardless of the number of users. The proposed CMUDAM is easily applicable to MIMO systems by using an eigenmode transmission, enabling the use of receivers with flexible antenna structure. Although the proposed CMUDAM is quite effective for users in low mobility, it may need to further study to reduce the time for the generation of multiples beams, making it applicable to high mobility environments.

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