An orthogonal multi-beam based MIMO scheme for multi-user wireless systems

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Abstract

In this paper, we propose a multiple-access transmission scheme that can simultaneously achieve both diversity and multiplexing gain in the multi-user multi-input multi-output (MIMO) domain, by using orthogonal multiple random beams. Orthogonal 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. Although the signal-to-noise power ratio (SNR) of each channel is reduced in proportion to the number of beams, multiple beams are utilized so that the multiplexing gain is larger than the decrease of SNR, increasing the overall system capacity. The proposed scheme can generate spatial channels as many as the number of transmit antennas regardless of the number of receiver antennas, while requiring partial channel information at the transmitter. Thus, the proposed scheme is applicable to multi-input single-output (MISO) schemes as well as MIMO schemes, enabling the use of flexible antenna structures in the receiver.

I. Introduction

[1]The next generation transmission system should be able to provide high data rate multimedia services to users in mobile, nomadic and fixed wireless environment in a seamless manner. The demand for high data rate signaling has led to the development of various advanced transceiver techniques for provision of near channel capacity. In recent years, the capacity of wireless systems has been increased significantly with the development of two advanced technologies; multi-antenna technique known as multi-input and multi-output (MIMO) [1-4] and packet scheduling known as opportunistic scheduling or multi-user diversity (MUD) [6,7].

The MIMO system can improve the capacity by increasing the diversity or spatial multiplexing gain using multi-antenna channels. Thus, the system capacity can be increased 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 [1,2,4]. However, it is not easy to get both full diversity and multiplexing gain simultaneously due to the trade-off issue between the diversity and multiplexing gain. In addition, the diversity and multiplexing gain can substantially be reduced depending on the channel condition [5]. For example, the STC cannot provide the diversity gain if all the elements of the channel matrix experience a fading null [3]. The spatial multiplexing like the BLAST cannot provide the multiplexing gain if the rank of the channel matrix is equal to one [2].

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Motivated by the information theoretic results in [1], we can use the MUD to take advantage of independent fading statistics of each user [8]. Allowing a user in the best channel condition to send the signal, we can achieve a system capacity even larger than in additive white Gaussian noise (AWGN) channel with the same signal-to-noise power ratio (SNR) [7]. However, when the channel gain has a small fluctuation and/or varies slowly as in fixed wireless or nomadic channels, the MUD may not significantly contribute the improvement of capacity. To overcome this problem, the base station generates beams using multiple antennas with random weights, known as opportunistic beamforming [7]. It was reported that the opportunistic beamforming can provide a diversity gain larger than the STC. Moreover, the opportunistic beamforming in a MISO scheme can achieve a throughput similar to the coherent beamforming when the number of users is large [7].

It was briefly mentioned that the opportunistic beamforming can be extended to the use of multiple beams in a multi-antenna scheme [7]. However, no further result has been reported on the design of multi-beam-based MIMO structure, particularly with the use of multi-antennas in the receiver. In this paper, we propose a MIMO scheme that can simultaneously achieve the diversity and multiplexing gain in the multi-user MIMO domain, with the use of MMSE detection at the receiver. The MMSE criterion is applied to maximize the SINR, which is equivalent to maximizing the system performance [1]. The SNR of each channel is reduced in proportion to the number of beams. However, the proposed scheme generates multiple beams orthogonal to each other and utilizes them so that the multiplexing gain is larger than the decrease of SNR. Moreover the use of an efficient antenna technique at the receiver can substantially suppress the interference from other beams. As a result, the overall system capacity of the proposed scheme is larger than that of the opportunistic beamforming scheme [7]. Spatial multiplexing gain can be obtained by combining the transmission beamforming and 'dirty paper' pre-coding in [9]. However, the previous schemes require perfect channel state information (CSI) of all users. In practical applications, it may not be feasible for the transmitter to use accurate CSI with limited bandwidth for feedback signaling. Thus, it may be desirable to use a scheme that can perform with partial CSI without significant performance degradation. The proposed scheme needs only the signal-to-interference-and-noise power ratio (SINR) from each user, significantly reducing the feedback signaling burden for the CSI.

This paper is organized as follows. In Section II, we describe the proposed orthogonal multi-beam (OMB) based OFDM system, including the generation of OMBs. The proposed MIMO system is verified by computer simulation in Section III. Finally, we summarize the conclusion in Section IV.

II. Proposed OMB based OFDM system

We consider the downlink transmission of multi-user data signal in a packet-based cellular system. We assume that each user has perfect information on the channel between the base station and mobile user. On the other hand, the base station has partial information on the channel (e.g., only instantaneous SINR) due to limited bandwidth for the feedback signaling. We consider the use of a packet scheduling scheme that allocates the resource to the user based on the channel condition. The base station assigns the channel to a user in the best quality (e.g., highest short-term SINR), exploiting the MUD. As the dynamic range of the channel fluctuations increases, the MUD gain increases. However, this MUD gain can be limited in the presence of a line-of-sight (LOS) path or little scattering environment [7]. To increase the MUD gain, we consider the use of orthogonal random beams.

Fig.1 depicts the proposed OMB based MIMO system, where the base station transmits M multiple user signals simultaneously over M parallel channels generated by M antennas and each user receives the signal using N

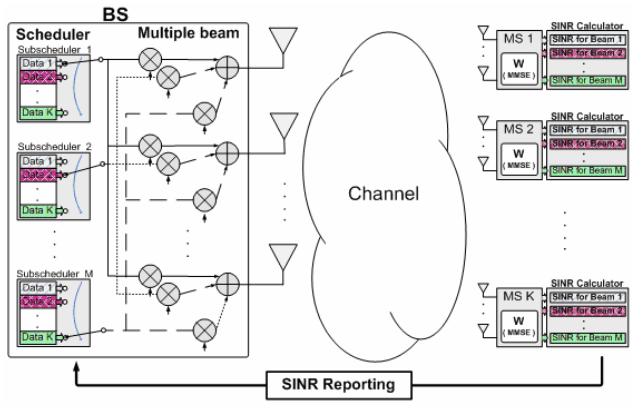


Fig. 1. The proposed OMB based MIMO system

antennas. The received signal of the *k*-th user can be represented as

$$\mathbf{r}_k = \mathbf{H}_k \mathbf{P}\mathbf{d} + \mathbf{n}_k, \qquad k = 1,\ 2,\ \ldots,\ K \tag{1}$$

where $\mathbf{d}$ is the *M*-dimensional (dim.) signal vector, $\mathbf{n}_k$ is the *N*-dim. noise vector whose elements are zero mean complex circular-symmetric Gaussian random variables with the same unit variance, $\mathbf{H}_k$ is the ($N \times M$)-dim channel matrix of the *k*-th user, and $\mathbf{P} = \left[\mathbf{p}_1, \mathbf{p}_2, \ \ldots\ , \mathbf{p}_M\right]$ denotes a unitary matrix whose *j*-th column represents the beamforming weight for the *j*-th beam. We assume that each user experiences independent fading.

Satisfying the orthogonality condition, the weight vector $\mathbf{p}_i$ can randomly be generated as [7]

$$p_m(t) = \sqrt{\alpha_m(t)}\, e^{j\theta_m(t)} \qquad m = 1, 2, \ldots, M \tag{2}$$

where $\alpha_m(t)$ and $\theta_m(t)$ are random processes in the range of $0 \le \alpha_m(t) \le 1$ and $0 \le \theta_m(t) < 2\pi$. We assume as normalized transmit power, i.e., $\sum_{m=1}^{M} \left|\sqrt{\alpha_m(t)}\right|^2 = 1$.

Then, the effective channel of the *k*-th user is given by

$$\mathbf{H}_{e_k} = \mathbf{H}_k \mathbf{P} \tag{3}$$

Each user adjusts the receiver weight matrix to maximize the SINR using a minimum mean squared error (MMSE) method. The MMSE criterion is applied to maximize the SINR, which is equivalent to maximizing the mutual information (i.e., maximizing the entropy) [1].

The MMSE weight vector $\mathbf{w}_k$ of the *k*-th user for the i-th beam is given by [10]

$$\mathbf{w}_{k,i} = \left(\mathbf{H}\mathbf{p}_i\right)^H \left(\mathbf{H}_{ek}\mathbf{H}_{ek}^H + \frac{\sigma_N^2 M}{P}\mathbf{I}_N\right)^{-1} \tag{4}$$

where P is the received signal power, σ_N^2 is the noise power of each receiver antenna and $\mathbf{I}_N$ is an $(N \times N)$ identity matrix. The data signal can be estimated by combining $\mathbf{r}_k$ with weight vector $\mathbf{w}_{k,i}$

$$\hat{d}_i = \mathbf{w}_{k,i}\mathbf{r}_k = \mathbf{w}_{k,i}\left(\mathbf{H}_{e_k}\mathbf{d} + \mathbf{n}_k\right) \tag{5}$$

The short term SINR of the i-th beam of the *k*-th user after controlling the interference can be estimated as

$$\gamma_{k,i} = \frac{P_R \left|\left[\mathbf{W}_k \mathbf{H}_{ek}\right]_{i,i}\right|^2}{\sigma_N^2 N \sum_{m=1}^{M} \left|\left[\mathbf{W}_k\right]_{i,m}\right|^2 + P_R \sum_{m=1, m\neq i}^{M} \left|\left[\mathbf{W}_k \mathbf{H}_{ek}\right]_{i,m}\right|^2} \tag{6}$$

Based on this SINR information, the base station allocates each spatial channel to a user with the highest SINR.

It is known that the use of *N* receiver antennas can control the interference from (*N*-1) beams. In case of $N < M$, the receiver may not sufficiently suppress the interference from other beams. However, this problem can be alleviated by combining an opportunistic scheduler that chooses a user with high power, while being less interfered. The total system capacity can be represented as

$$C_{OMB} = \sum_{n=1}^{M} \log_2\left(1 + \eta \cdot \gamma_n\right) \tag{7}$$

where γ_n is the SINR of the scheduled user through the *n*-th beam and η is a system loss factor representing the SINR loss due to system realization.

Fig. 2 summarizes the operation of the proposed OMB based MIMO system. First, the transmitter generates orthogonal multiple beams equal to the number of transmit antennas. Then, each user reports the SINR of each beam to the base station. Note that the SINR is calculated assuming the use of multiple antennas with the optimum combining coefficient in a MMSE sense. Based on the reported SINR of each user, the base station selects M

Table 1. System parameters in simulation

Iteration	1000
Number of users	1, 2, 4 … 128
Avg. user SNR	10dB, 0dB
Antenna configuration	(Tx-by-Rx) 4-by-4, 4-by-2, 4-by-1
Channel	Rayleigh ~ $CN(0,1)$ Rician (K factor : 5)
System loss factor	η : -4dB

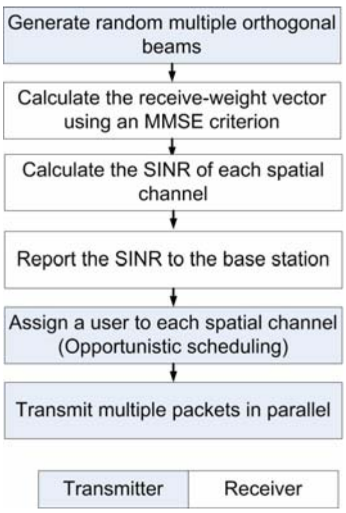


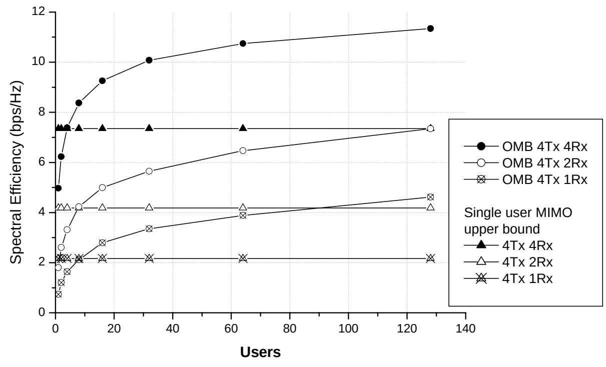
Fig.2. Flow chart of the proposed OMB system

users who have the highest SINR through one of M multi-beams. Finally, the base station sends out multiple user packets (data) in parallel.

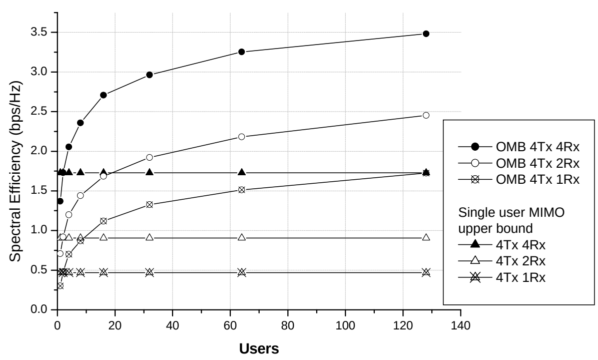
III. Performance evaluation

The performance of the proposed OMB based MIMO system is verified by computer simulation. We assume the transmission of packet signal over flat Rayleigh or Rician fading channel with a Rician factor of 5. The simulation parameters are summarized in Table 1. We assume that the users experience mutually independent channel with the same average SNR.

Fig. 3 depicts the system capacity of the proposed OMB-based MIMO system in Rayleigh fading channel in term of the spectral efficiency. The upper bound of the single user MIMO represents an upper bound achievable in a single user system (i.e., without the MUD). It can be seen that the performance of the proposed OMB-based MIMO system increases as the number of users increases, mainly due the MUD gain. Thus, unless the number of users is too small, the proposed scheme outperforms the single-user MIMO scheme. It can also be seen that, as the number of receiver antennas increases, the receiver antennas can effectively suppress the interference effect, significantly improving the spectral efficiency. In high SNR environment, the system performance is mainly limited by the interference form other beams. Thus, the use of multiple receiver antennas is quite effective for improvement of the SINR.



(a) When the average SNR is 10dB



(b) When the average SNR is 0dB

Fig. 3. The spectral efficiency of the proposed OMB system

Fig. 4 compares the spectral efficiency of the proposed OMB and opportunistic beamforming with a (4X2) MIMO scheme when the average SNR is 10dB. It can be seen that the proposed OMB scheme outperforms the opportunistic

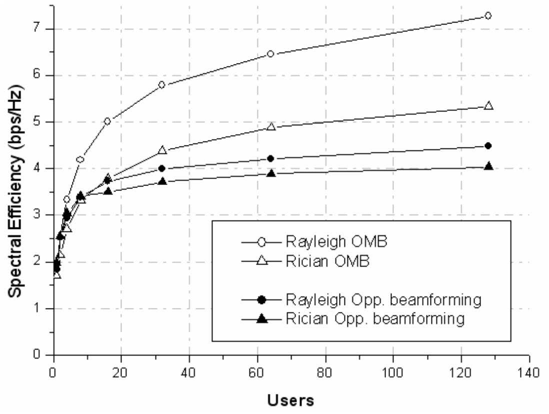


Fig. 4. Throughput of (4X2) OMB and Opportunistic beamforming MIMO schemes system

beamforming scheme in both Rayleigh and Rician channel. This can be explained as follows. Although the transmit power for each beam is changed inversely proportional to the number of beams in the OMB scheme, multiple beams are utilized so that the multiplexing gain is larger than the decrease of the SNR. In addition, the receiver antenna technique can effectively suppress the interference from other beams.

IV. Conclusion

We have considered the use of orthogonal multiple random beams in a MIMO scheme for multiple access wireless systems. Utilizing multiple random beams orthogonal to each other, the proposed OMB MIMO scheme can provide both the multi-user diversity and multiplexing gain simultaneously. Although the SNR of each channel is reduced in proportion to the number of beams, multiple beams are utilized so that the MUD and multiplexing effect is larger than the decrease of SNR, increasing the overall system capacity. In addition, we have proposed an MMSE-based detection scheme applicable to multiple receiver antenna structures with flexibility. The performance of the proposed OMB-based MIMO scheme has been verified by computer simulation. Simulation results show that the performance of the proposed scheme even can be better than that of the single user MIMO, when the number of users is moderately large. Simulation results also show that the proposed OMB scheme outperforms the opportunistic beamforming scheme in both Rayleigh and Rician channel.

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