패킷기반 다중사용자 무선통신 시스템에서의 기회적 정합 빔포밍 기법

고재연 O, 이용환

서울대학교 전기컴퓨터공학부

Coherent opportunistic beamforming in packet-based multi-user wireless systems

Jae-Yun Ko O and Yong-Hwan Lee

School of Electrical Engineering and INMC, Seoul National University

paul@ttl.snu.ac.kr,

Abstract

In this paper, we propose a beamforming scheme that exploits the advantages of opportunistic beamforming and coherent beamforming in multi-user environments. It is analytically shown that the proposed scheme can provide multi-user diversity and beamforming gain simultaneously, achieving significant performance improvement over the conventional ones particularly when the channel is poor. The performance of the proposed scheme is analyzed using an upper bound method. Finally, the analytic results are verified by computer simulation.

1. Introduction

In recent years, the capacity of wireless systems has significantly been increased with the development of two key technologies; the use of multiple antennas known as multi-input multi-output (MIMO) [1,3] and opportunistic scheduling [4,5]. The use of multiple antennas at the transmitter and/or the receiver enables the increase of data rate or the decrease of transmission error rate for a given signal-to-noise power ratio (SNR). On the other hand, the system efficiency can remarkably be improved in a multi-user environment, by employing a scheduler that can achieve multi-user diversity (MUD) gain.

It is possible to achieve beamforming gain (i.e., the SNR and spatial diversity gain) by employing a coherent beamforming (also called maximum ratio transmission or dominant eigenmode transmission) scheme with the use of channel information at the transmitter [6,7,13]. In frequency division duplex (FDD) systems, the transmitter can acquire the channel information through a feedback signaling channel in the uplink. Since the amount of feedback signaling increases linearly in proportion to the number of users, it may not be practical to employ a coherent beamforming scheme in multi-user environments. Although quantization techniques can be applied to reduce the feedback signaling burden [8,9], they may suffer from the quantization noise as the number of users increases.

Opportunistic beamforming is a multi-antenna technique that can increase the MUD gain with the use of random beamforming [10]. Since it requires only partial channel information (e.g., the SNR) of users, it can remarkably reduce the feedback signaling burden. Besides, it can provide a coherent beamforming configuration with a probability of one as the number of users increases to infinity [10]. However, it may not provide desired performance unless the number of users is sufficiently large, because it exploits only the MUD gain. This problem can be alleviated by employing a receiver antenna selection technique [11]. However, the need of multiple receiver antennas may limit the flexibility of the receiver structure.

In this paper, we propose a new beamforming technique that exploits both the MUD gain and beamforming gain simultaneously in multi-user environments, which can be achieved by combining the opportunistic beamforming and the coherent beamforming technique. The proposed scheme can significantly improve the performance over the coherent beamforming and the opportunistic beamforming schemes at an expense of marginal increase of the feedback signaling burden.

This paper is organized as follows. Section II describes the system model in consideration. Conventional beamforming techniques are briefly discussed in Section III. The proposed scheme is described and its performance is analyzed in Section IV. The performance is verified by computer simulation in Section V. Finally, Section VI concludes this paper.

2. System model

Consider a downlink environment with K users, where the

This work was in part supported by the Ministry of Information & Communications, Korea, under the Information Technology Research Center (ITRC) Support Program.

base station (BS) has M transmit antennas and each user has a single receive antenna. The use of multiple receive antennas will be considered later. We assume that the gain of the wireless channel is described by independent zero mean complex Gaussian random variables, and that all users have the same average SNR γ_o and experience independent fading. We also assume that the channel information is available at the user terminal with the use of common pilot signal, but it is available at the BS with the use of a feedback signaling channel in the uplink.

When the signal is transmitted with beamforming weight $\mathbf{w} \in \mathbb{C}^{M \times 1}$, the received signal of user k can be represented as

$$y_k = \mathbf{h}_k \mathbf{w} s + n_k \tag{1}$$

where $\mathbf{h}_k \in \mathbb{C}^{1 \times M}$ is the channel gain vector of user k whose elements are zero mean complex Gaussian random variables with unit variance, s is the transmit symbol with average power P and n_k is additive white Gaussian noise (AWGN). We assume that the Frobenious norm of $\mathbf{w}$ is equal to one to preserve the total transmission power (i.e., $\| \mathbf{w} \| = 1$).

3. Conventional beamforming techniques

A. Opportunistic beamforming

We briefly review the opportunistic beamforming [10] for easy description of the proposed scheme. In the opportunistic beamforming, the beamforming weight $\mathbf{w}$ is generated in a random manner, while preserving the transmission power, i.e.,

$$\mathbf{w} = \frac{1}{\sqrt{\sum_{i=1}^{M} |w_i|^2}} [w_1 \, w_2 \cdots w_M]^T . \tag{2}$$

Here, w_i represents the random weight described as an independent and identically distributed (i.i.d.) zero mean complex Gaussian random variable and the superscript T denotes the transpose of a vector. Each user estimates the SNR for each given beam and reports it to the BS. Then, the BS selects a user based on a scheduling policy.

In an independent Rayleigh fading channel, the effective channel of user k

$$\tilde{h}_k = \mathbf{h}_k \mathbf{w} \tag{3}$$

can be described by a zero mean complex Gaussian random variable with unit variance. Note that $\tilde{h}_k$ has the same distribution as that in a single-input single-output (SISO) Rayleigh fading channel. This implies that the opportunistic beamforming with multiple transmit antennas does not provide any performance gain over the SISO scheme in Rayleigh fading channel [10].

Assuming that the scheduler in the BS chooses a user in the best channel condition, the effective channel gain of the selected user can be represented as

$$\Gamma_O = \max_{k=1,2,\cdots,K} \left\{ \left| \tilde{h}_k \right|^2 \right\} . \tag{4}$$

Thus, the channel capacity C_O of the opportunistic beamforming in Rayleigh fading channel can be represented as

$$C_O = E\left\{ \log_2 (1 + \gamma_o \Gamma_O) \right\} . \tag{5}$$

Since we cannot easily represent (5) in a closed form, we consider the use of an upper bound $\bar{C}_O$ using the Jensen's inequality as

$$\bar{C}_O = \log_2 \left(1 + \gamma_o E\left\{ \Gamma_O \right\} \right) \geq C_O . \tag{6}$$

Since the maximum of K i.i.d. exponential random variables has a mean value equal to the sum of harmonic numbers [14], (6) can be rewritten as

$$\begin{aligned} \bar{C}_O &= \log_2 \left[1 + \gamma_o \left(1 + \sum_{i=2}^{K} \frac{1}{i} \right) \right] \\ &\simeq \log_2 \left[1 + \gamma_o \left(\log(1+K) + \varsigma - \frac{1}{2(K+1)} \right) \right] \end{aligned} \tag{7}$$

where $\varsigma (\simeq 0.577216)$ is the Euler's constant. Although the opportunistic beamforming provides the same capacity as the SISO system in Rayleigh fading channel, the use of different beam weights at each scheduling time makes the user experience different SNR. Thus the opportunistic beamforming can virtually provide a fast fading channel even in a slowly time-varying channel environment, making it easy to satisfy the quality-of-service (QoS) requirement for traffic sensitive to the delay.

B. Coherent beamforming

The coherent beamforming technique generates the beam weight to maximize the received SNR. The optimum weight $\mathbf{w}_k^o$ for user k can be determined by [16]

$$\mathbf{w}_k^o = \frac{\mathbf{h}_k^H}{\|\mathbf{h}_k\|} \tag{8}$$

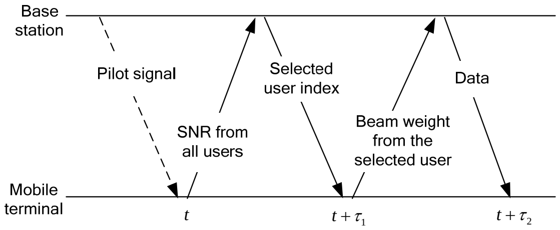
where the superscript H denotes the conjugate transpose of a vector. Since the effective channel of user k is described by

$$\tilde{h}_k = \mathbf{h}_k \mathbf{w}_k^o = \|\mathbf{h}_k\| , \tag{9}$$

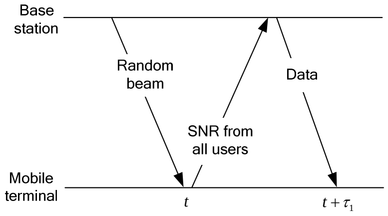
the effective channel gain $\Gamma_C = |\tilde{h}_k|^2$ can be described by a Chi-square random variable with $2M$ degrees of freedom in Rayleigh fading channel [15]. Thus, the channel capacity C_C of the coherent beamforming is bounded by

$$\begin{aligned} C_C &= E\left\{ \log_2 (1 + \gamma_o \Gamma_C) \right\} \\ &\leq \log_2 \left[1 + \gamma_o \left(1 + (M-1) \right) \right] \equiv \bar{C}_C \end{aligned} \tag{10}$$

where (M-1) represents the SNR gain achieved by the coherent beamforming. It can be seen from (7) and (10) that the conventional opportunistic beamforming and coherent beamforming can achieve only the MUD gain and the beamforming gain, respectively. Thus, we consider the



(a) Procedure of the proposed beamforming



(b) Procedure of the opportunistic beamforming

Fig. 1. Procedures of different beamforming schemes

performance improvement by exploiting the MUD and beamforming gain simultaneously.

4. Proposed beamforming scheme

Fig. 1 illustrates the procedure of the proposed beamforming and conventional opportunistic beamforming scheme. In the proposed scheme, each user estimates the SNR from the received common pilot signal and then reports it to the BS. Here, each user estimates the SNR assuming the use of a beamforming weight optimized to its channel condition. The BS selects a user based on the reported SNR. Then the selected user reports its optimum beam weight to the BS. Finally, the BS transmits the data to the selected user using this optimum beam weight. Note that the opportunistic beamforming transmits the data using a random beam weight, but the proposed beamforming transmit the data using an optimized beam weight. As a result, the proposed scheme requires additional information on the beam weight from the selected user. However, this additional feedback signaling burden may not be serious except additional delay.

The optimum beam weight $\mathbf{w}_k^o$ of user *k* for a given channel vector $\mathbf{h}_k$ can be determined by

$$\mathbf{w}_k^o = \frac{\mathbf{h}_k{}^H}{\|\mathbf{h}_k\|}. \tag{11}$$

Assuming that the scheduler selects a user with the largest channel gain, the effective channel gain of the selected user can be represented by

$$\Gamma_{P-O} = \max_{k=1,2,\cdots,K}\left\{\|\mathbf{h}_k\|^2\right\} \tag{12}$$

where the subscript *P-O* denotes the proposed beamforming scheme with the use of optimum beam weight. The corresponding capacity C_{P-O} of the proposed scheme can be represented as

$$C_{P-O} = E\left\{\log_2\left(1+\gamma_o\Gamma_{P-O}\right)\right\}. \tag{13}$$

Note that Γ_{P-O} and Γ_O are the maximum of *K* i.i.d. Chi-square random variables with 2*M* and 2 degrees of freedom, respectively. This indicates that the proposed scheme provides a capacity larger than that of the opportunistic beamforming.

In a slow fading channel, however, a user in good channel condition can be served for a long time by the scheduler. This situation may not be desirable in the presence of traffic with strict delay requirements. This problem can be alleviated by using a randomly generated beam instead of optimum one. This modification can provide the same delay QoS as the opportunistic beamforming. Note that although the user estimates its SNR from a randomly generated beam, the user data is transmitted using the optimum beam weight. With the use of random beam weight $\mathbf{w}_k$**,** the effective channel of user *k* can be written as

$$\tilde{h}_k = \mathbf{h}_k\mathbf{w}_k. \tag{14}$$

A MISO channel vector $\mathbf{h}_k$ can be represented as

$$\mathbf{h}_k = \alpha_{k,1}\mathbf{O}_{k,1} + \alpha_{k,2}\mathbf{O}_{k,2} + \cdots + \alpha_{k,M}\mathbf{O}_{k,M} \tag{15}$$

where $\{\mathbf{O}_{k,1},\mathbf{O}_{k,2},\cdots,\mathbf{O}_{k,M} \in \mathbb{C}^{1\times M}\}$ denotes ortho-normal bases. Since each element of $\mathbf{h}_k$ can be represented as an i.i.d. zero mean complex Gaussian random variable with unit variance in spatially uncorrelated Rayleigh fading channel, the coefficients $\{\alpha_{k,1},\alpha_{k,2},\cdots,\alpha_{k,M}\}$ can also be modeled as i.i.d. zero mean complex Gaussian random variables with unit variance.

Assuming that the first orthonormal basis is $\mathbf{w}_k{}^H$ (i.e., $\mathbf{O}_{k,1} = \mathbf{w}_k{}^H$), the effective channel can be represented as

$$\begin{aligned}\tilde{h}_k &= \left(\alpha_{k,1}\mathbf{w}_k{}^H + \alpha_{k,2}\mathbf{O}_{k,2} + \cdots + \alpha_{k,M}\mathbf{O}_{k,M}\right)\mathbf{w}_k \\ &= \alpha_{k,1}\end{aligned} \tag{16}$$

Let *Q* be the index number of the selected user. Then the effective channel gain of the selected user can be represented as

$$\left|\alpha_{Q,1}\right|^2 = \max_{k=1,2,\cdots,K}\left\{\left|\alpha_{k,1}\right|^2\right\}. \tag{17}$$

Since $|\alpha_{Q,1}|^2$ is the maximum of *K* i.i.d. exponential random variables, it has the same distribution as the effective gain of the opportunistic beamforming. However, the proposed scheme uses the optimum weight $\mathbf{w}_Q^o = \mathbf{h}_Q{}^H / \|\mathbf{h}_Q\|$ for the data transmission, yielding an effective channel represented as

$$\begin{aligned}\tilde{h}_Q &= \mathbf{h}_Q\mathbf{w}_Q^o \\ &= \sqrt{\Gamma_O + \left|\alpha_{Q,2}\right|^2 + \cdots + \left|\alpha_{Q,M}\right|^2}\end{aligned}. \tag{18}$$

Thus, the channel capacity of the proposed scheme can be represented as

$$C_{P-R} = E\left\{\log_2\left(1+\gamma_o(\Gamma_O + \left|\alpha_{k,2}\right|^2 + \cdots + \left|\alpha_{k,M}\right|^2\right)\right\} \quad (19)$$

where the subscript *P-R* denotes the proposed scheme with the use of random beam weight for the estimation of SNR. It can be shown that

$$\begin{aligned} C_{P-R} &\le \log_2\left[1+\gamma_o E\left\{\Gamma_O + \left|\alpha_{k,2}\right|^2 + \cdots + \left|\alpha_{k,M}\right|^2\right\}\right] \\ &= \log_2\left[1+\gamma_o\left(1+\sum_{i=2}^{K}\frac{1}{i}+\left(M-1\right)\right)\right] \equiv \bar{C}_{P-R} \end{aligned} . \quad (20)$$

Thus, the proposed scheme can achieve both the MUD gain and the beamforming gain simultaneously.

We compare the performance of the proposed scheme under the same delay QoS constraint as the opportunistic beamforming. We evaluate the performance improvement over the conventional schemes by using upper bounds $\bar{C}_{P-R}$, $\bar{C}_O$ and $\bar{C}_C$. Define G_O and G_C respectively by

$$G_O \triangleq \frac{C_{P-R}}{C_O} \cong \frac{\log_2\left[1+\gamma_o\left(1+\sum_{i=2}^{K}\frac{1}{i}+\left(M-1\right)\right)\right]}{\log_2\left[1+\gamma_o\left(1+\sum_{i=2}^{K}\frac{1}{i}\right)\right]} \quad (21)$$

and

$$G_C \triangleq \frac{C_{P-R}}{C_C} \cong \frac{\log_2\left[1+\gamma_o\left(1+\sum_{i=2}^{K}\frac{1}{i}+\left(M-1\right)\right)\right]}{\log_2\left(1+\gamma_o M\right)} . \quad (22)$$

Since $\partial G_O / \partial \gamma_o \le 0$ and $\partial G_C / \partial \gamma_o \le 0$, the performance improvement of the proposed scheme over the conventional ones decreases as the SNR increases. Using the Lopital's theorem, it can be shown that the maximum performance gain is obtained as $\gamma_o \to 0$, i.e.,

$$\lim_{\gamma_o \to 0} G_O = 1 + \frac{M-1}{1+\sum_{i=2}^{K}\frac{1}{i}} \quad (23)$$

and

$$\lim_{\gamma_o \to 0} G_C = 1 + \frac{\sum_{i=2}^{K} 1/i}{M} . \quad (24)$$

On the other hand, it can be shown that no performance gain is achieved as $\gamma_o \to \infty$, i.e.,

$$\lim_{\gamma_o \to \infty} G_O = \lim_{\gamma_o \to \infty} G_C = 1 . \quad (25)$$

Thus, the proposed scheme has a marginal gain over the conventional schemes in good channel condition, but it is quite effective in poor channel condition.

It can be shown that the proposed scheme using optimum beam weight for the selection of user achieves the sum capacity C_{DPC} of the dirty paper coding (DPC) as the average SNR approaches to zero, i.e.,

$$\lim_{\gamma_o \to 0} G_{P-O} = C_{DPC} . \quad (26)$$

Notice that the sum capacity of the DPC converges to the capacity of the beamforming scheme that transmits a single data stream to the user in the best channel condition as the average SNR approaches to zero [12]. Since the DPC provides the optimum channel capacity, it can be said that the proposed scheme is optimum in low SNR environments.

5. Performance evaluation

To verify the design and analysis of the proposed scheme, we evaluate the performance by computer simulation assuming that all the users experience mutually independent channel with the same average SNR. We consider a MISO system in flat Rayleigh fading channel with $\gamma_o = 1$ (i.e., 0 dB), unless explicitly stated otherwise. We assume that perfect channel information is available to the BS without delay. Here, we do not consider any quantization effect.

Fig. 2 depicts the performance of the proposed scheme in terms of the capacity gain when M = 4 and K = 8. It can be seen that the proposed scheme provides significant gain improvement over the conventional schemes at low SNR. It can also be seen that the analytic upper bound is quite valid.

Fig. 3 and 4 depict the performance gain of the proposed scheme for different numbers of users and transmit antennas, respectively. It can be seen from Fig. 3 that as the number of users increases, the proposed scheme provides significant performance gain over the coherent beamforming by exploiting the MUD gain. On the other hand, the proposed scheme provides significant performance gain over the opportunistic beamforming when the number of users is small. This is mainly due to fact that the opportunistic beamforming cannot achieve large MUD gain when the number of users is small. It can be seen from Fig. 4 that as the number of transmit antennas increases, the proposed scheme can achieve significant performance gain over the opportunistic beamforming by exploiting the beamforming gain. On the other hand, the proposed scheme has significant performance gain over the coherent beamforming when a small number of antennas are used. This is mainly due to that the MUD gain becomes dominant over the beamforming gain as the number of antennas decreases.

6. Conclusions

We have proposed an improved beamforming scheme by exploiting the advantages of opportunistic beamforming and coherent beamforming. By using a beam weight optimized to the selected user, the proposed scheme can achieve the beamforming gain as well as the MUD gain, without noticeable increase of feedback signaling burden. The performance of the proposed scheme is analytically evaluated using an upper bound method and verified by computer simulation. The simulation results verify that the proposed beamforming scheme provides noticeable performance gain over the conventional schemes particularly in low SNR environments.

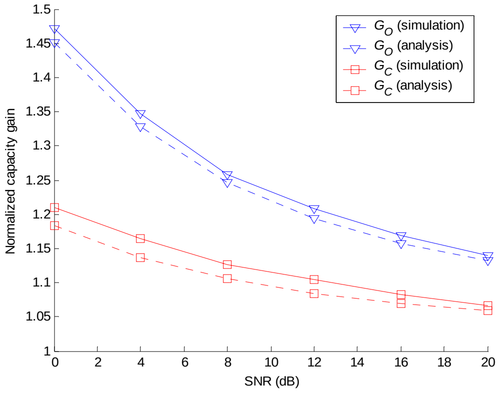


Fig. 2. Performance gain of the proposed beamforming scheme when *M*=4 and *K*=8

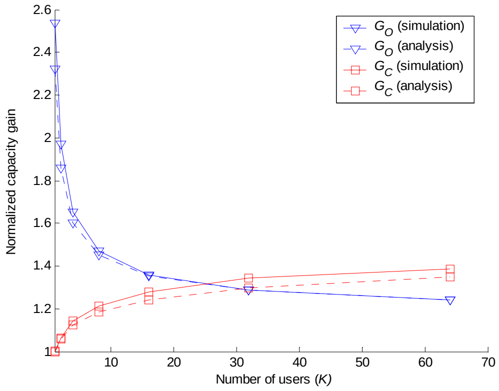


Fig. 3. Performance gain associated with *K* when *M*=4 and SNR=0dB

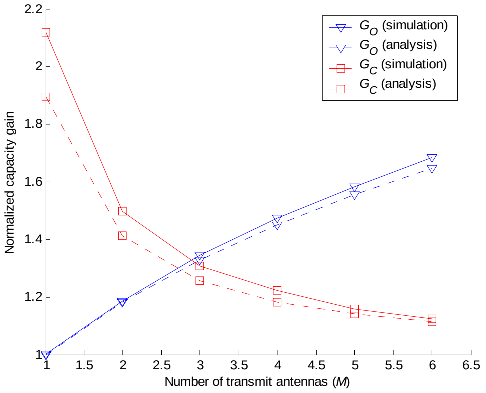


Fig. 4. Performance gain associated with *M* when *K*=8 and SNR=0dB

References

[1] G. J. Foschini and M. J. Gans, “On limits of wireless communications in a fading environment when using multiple antennas,” *Wireless Personal Commun.*, vol. 6, no. 3, pp. 311–335, June 1998.

[2] S. M. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE J. Select. Areas Commun*., vol. 16, no. 8, pp. 1451 –1458, Oct. 1998.

[3] V. Tarokh, N. Seshadri and A. R. Calderbank, “Space-time codes for high data rate wireless communication: Performance criterion and code construction,” *IEEE Trans. Inform. Theory*, vol. 44, pp. 744-765, Mar. 1998.

[4] Xin Liu, Edwin K. P. Chong and N. B. Shroff, “A Framework for Opportunistic Scheduling in Wireless Networks,” *Computer Networks*, vol. 41, pp. 451-474, Mar. 2003

[5] W. Rhee, W. Yu and J.M. Cioffi, “Utilizing multiuser diversity for multiple antenna systems,” in *Proc. of Wireless Commun. Network. Conf*., vol. 1, pp. 420 –425, Sept. 2000.

[6] T. K. Y. Lo, “Maximum ratio transmission,” *IEEE Trans. Comm*., vol. 47, pp. 1458–1461, Oct. 1999.

[7] S. Thoen, L. Van der Perre, B. Gyselinckx and M. Engels, “Performance analysis of combined transmit-SC/receive-MRC,” *IEEE Trans. Comm*., vol. 49, pp. 5–8, Jan. 2001.

[8] K. K. Mukkavilli, A. Sabharwal, E. Erkip and B. Aazhang, “On beamforming with finite rate feedback in multiple antenna systems,” *IEEE Trans. Inform. Theory*, vol. 49, pp. 2562-2579, Oct. 2003.

[9] D. J. Love, R.W. Heath, Jr. and T. Strohmer, “Grassmannian beamforming for multiple-input multiple-output wireless systems,” *IEEE Trans. Inform. Theory*, vol. 49, pp. 2735-2747, Oct. 2003.

[10] P. Viswanath, D. N. C. Tse and R. Laroia, “Opportunistic beamforming using dumb antennas,” *IEEE Trans. Inform. Theory*, vol. 48, no. 6, pp. 1277–1294, June 2002.

[11] L. Zan and S. A. Jafar, “Combined opportunistic beamforming and receive antenna selection,” in *Proc. of Wireless Commun. Network. Conf*., vol. 2, pp. 1007 –1011, Mar. 2005.

[12] N. Jindal, *Multi-user communication systems: capacity, duality, and cooperation*, Ph. D. dissertation, Department of electrical engineering, Stanford University, July 2004.

[13] A. Paulraj, R. Nabar, and D. Gore, *Introduction to Space-Time Wireless Communications*, Cambridge University Press, 2003.

[14] G. L. Stuber, *Principles of Mobile Communication*, Kluwer academic publishers, 1996.

[15] J. G. Proakis, *Digital Communications*, McGraw-Hill, 4-th ed., 2001.

[16] E. Visotsky and U. Madhow, “Optimum beamforming using transmit antenna arrays,” in *Proc. of IEEE Proc. Vehicular Tech. Conf.*, vol. 1, pp. 851-856, May 1999.