Correlation-Based Cooperative Opportunistic Beamforming in Cellular Systems

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Abstract—**In this paper, we consider a cooperative opportunistic beamforming scheme that can mitigate other cell interference (OCI) in downlink cellular environments. By exploiting the spatial channel correlation of adjacent cells, a random beam is cooperatively generated to statistically avoid the OCI from adjacent cells. Selecting its user for the proposed random beam in an opportunistic manner, the proposed scheme can simultaneously achieve both the multi-user diversity (MUD) gain and OCI avoidance gain. Finally, the performance of the proposed scheme is verified by computer simulation. The simulation results show that the proposed scheme can noticeably improve the spectral efficiency and the outage probability of users near the cell boundary compared to conventional opportunistic beamforming scheme.**

Keywords-Cooperative transmission; opportunistic beamforming; other-cell interference (OCI); spatial channel correlation

I. INTRODUCTION

In recent years, the capacity of wireless systems has significantly been increased with the use of multiple antenna techniques [1]–[3]. Opportunistic beamforming is a multi-antenna technique that can work with partial channel information (e.g., the signal-to-noise ratio (SNR)) [4]. It can noticeably increase the system capacity by achieving so called multi-user diversity (MUD) gain by selecting users in best condition with the use of randomly generated beams. In fact, it can noticeably outperform coherent beamforming schemes as the number of users increases [5]. However, it may suffer from other-cell interference (OCI) in downlink cellular environments, diminishing the MUD gain [6]. In fact, users near the cell boundary may not properly communicate with the target base station (BS) due to the OCI effect. It is of great concern to reduce the OCI effect to increase the system performance.

A BSs cooperation-based beamforming scheme has been proposed [7]. By making multiple BSs operate in a cooperative manner, it can transform obstructive OCI into a constructive signal, providing remarkable performance improvement. However, it may not be practical because it requires large signaling overhead for the feedback and exchange of full channel state information (CSI) among multiple BSs. It may be desirable to design the BSs cooperative beamforming scheme that can reduce the OCI with low signaling overhead.

To this end, the use of the spatial channel correlation has recently been considered [8]. Since the spatial channel correlation varies relatively slowly in time, it can be shared with low feedback signaling burden compared to the use of instantaneous CSI [9], [10].

In this paper, we propose a spatial channel correlation-based cooperative opportunistic beamforming scheme to increase the signal-to-interference plus noise ratio (SINR) of users near the cell boundary. We assume that the BSs share the spatial channel correlation for the generation of beam weight. The proposed scheme generates cooperative random beams based on the spatial channel correlation so as to achieve the MUD gain as well as to avoid the OCI from adjacent cells in downlink multi-user cellular environments. Thus, it can improve the system capacity by increasing the SINR of users near the cell boundary compared to the conventional opportunistic beamforming schemes.

The remainder of this paper organized as follows. Section II describes the system model in consideration. Conventional beamforming schemes are briefly discussed in Section III. Section IV proposes spatial channel correlation-based cooperative opportunistic beamforming scheme. The performance is verified by computer simulation in Section V. Finally, conclusions are given in Section VI.

II. SYSTEM MODEL

Consider the downlink of multi-user cellular system comprising B BSs and K users, where each BS has M transmit antennas and each user has a single receive antenna as illustrated in Fig. 1.

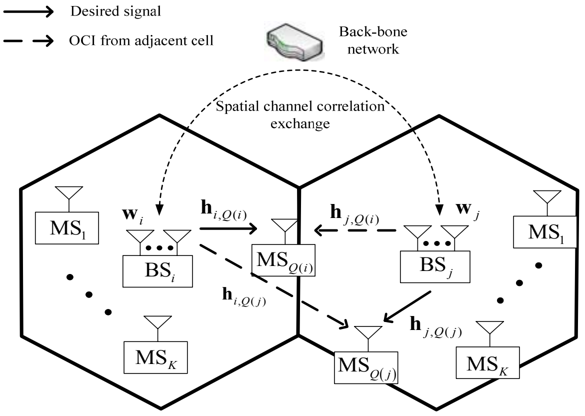

Fig 1. Downlink multi-user cellular systems

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Let $s_{Q(i)}$ be the transmitted signal from the target BS i, $Q(i)$ be a selected user for beam weight $\mathbf{w}_i$ generated by BS i, and P be the average power of $s_{Q(i)}$. Then, the received signal of user $Q(i)$ can be represented as

$$y_{Q(i)} = \sqrt{P}\mathbf{h}^*_{i,Q(i)}\mathbf{w}_i s_{Q(i)} + \sum_{j=1,\, j\neq i}^{B} \sqrt{P}\mathbf{h}^*_{j,Q(i)}\mathbf{w}_j s_{Q(j)} + n_{Q(i)} \quad (1)$$

where $\mathbf{h}_{i,Q(i)}$ denotes the $(M\times 1)$-dimensional channel vector between the target BS i and user $Q(i)$, $\mathbf{h}_{j,Q(i)}$ denotes the $(M\times 1)$-dimensional channel vector between the adjacent BS j and user $Q(i)$, $n_{Q(i)}$ is additive white Gaussian noise (AWGN), and the superscript $*$ denotes conjugate transpose.

In a spatially correlated channel environment, $\mathbf{h}_{j,Q(i)}$ can be represented as [11]

$$\mathbf{h}_{j,Q(i)} = \mathbf{R}^{1/2}_{j,Q(i)}\tilde{\mathbf{h}}_{j,Q(i)} \quad (2)$$

where $\tilde{\mathbf{h}}_{j,Q(i)}$ denotes the $(M\times 1)$-dimensional uncorrelated channel vector between BS j and user $Q(i)$, whose elements are independent and identically distributed (i.i.d.) zero-mean complex Gaussian random variables with unit variance, and $\mathbf{R}_{j,Q(i)}$ denotes the $(M\times M)$-dimensional spatial channel correlation matrix defined by

$$\mathbf{R}_{j,Q(i)} = E\left\{\mathbf{h}_{j,Q(i)}\mathbf{h}^*_{j,Q(i)}\right\} \quad (3)$$

where $E\{\cdot\}$ denotes the expectation.

We define an active set $\Omega_{Q(i)}$ by a set of cells that strongly affect the signal reception of the target user $Q(i)$. The active set $\Omega_{Q(i)}$ comprises a target cell and dominant OCI cells which affect user $Q(i)$ as strong OCI sources. Thus, (1) can be rewritten as

$$\begin{aligned} y_{Q(i)} &= \sqrt{P}\mathbf{h}^*_{i,Q(i)}\mathbf{w}_i s_{Q(i)} + \sum_{j\in\Omega_{Q(i)},\, j\neq i} \sqrt{P}\mathbf{h}^*_{j,Q(i)}\mathbf{w}_j s_{Q(j)} \\ &\quad + \sqrt{I_{Q(i)}} + n_{Q(i)} \end{aligned} \quad (4)$$

where $I_{Q(i)}$ denotes the average interference power from neighbor cells not belonging to $\Omega_{Q(i)}$.

The SINR $\gamma_{i,Q(i)}$ of user $\Omega_{Q(i)}$ can be represented as

$$\gamma_{i,Q(i)} = \frac{\left|\mathbf{h}^*_{i,Q(i)}\mathbf{w}_i\right|^2}{\sum_{j\in\Omega_{Q(i)},\, j\neq i}\left|\mathbf{h}^*_{j,Q(i)}\mathbf{w}_j\right|^2 + I_{Q(i)} + N_0/(\gamma_0 P)} \quad (5)$$

where γ_0 denotes the average SNR. It can be seen that the SINR of users near the cell boundary can be improved by mitigating the OCI term in the denominator of (5). Since the OCI highly depends on the beam weight $\mathbf{w}_j$ of dominant OCI BSs, the performance of users near the cell boundary can be improved by adjusting the beam weigh $\mathbf{w}_j$ of dominant OCI BSs as well as that of the target BS.

III. CONVENTIONAL BEAMFORMING SCHMEMS

In this section, we briefly review conventional beamforming schemes for easy description of the proposed scheme.

A. *Conventional Opportunistic Beamforming* [6]

The BS i transmits the signal using a beam weight $\mathbf{w}_i$ randomly generated as [6]

$$\mathbf{w}_i = \mathbf{v}_i / \|\mathbf{v}_i\| \quad (6)$$

where $\mathbf{v}_i$ and $\|\mathbf{v}_i\|$ denote a $(M\times 1)$-dimensional random vector and its Probenius norm, respectively.

Each user estimates the SNR received from the random beam $\mathbf{w}_i$ and reports it to BS i. Then, BS i selects a user based on the reported SNR. Assuming the use of a scheduler that assigns the resource to a user having the highest SNR, the SNR $\gamma_{i,Q(i)}$ of user $Q(i)$ selected from BS i can be represented as

$$\gamma_{i,Q(i)} \triangleq \max_{k=1,\ldots,K} \gamma_0 \left|\mathbf{h}^*_{i,k}\mathbf{w}_i\right|^2 \quad (7)$$

where $\mathbf{h}^*_{i,k}\mathbf{w}_i$ has the same distribution as the channel gain in a single-input single-output (SISO) Rayleigh fading channel.

Using the Jensen's inequality [12], it can be shown that the capacity of the conventional opportunistic beamforming is bounded as

$$C_{\text{Opp}} = E\left\{\log_2\left(1+\gamma_{i,Q(i)}\right)\right\} \le \log_2\left(1+E\left\{\gamma_{i,Q(i)}\right\}\right) \triangleq \bar{C}_{\text{Opp}}. \quad (8)$$

Since $\gamma_{i,Q(i)}$ is the maximum of K i.i.d. exponential random variables, it has a mean value equal to the K-th harmonic number [4]. Thus, (8) can be rewritten as

$$\bar{C}_{\text{Opp}} = \log_2\left(1+\gamma_0\left(1+\sum_{k=2}^{K}\frac{1}{k}\right)\right) \quad (9)$$

where the term $\sum_{k=2}^{K} 1/k$ represents the MUD gain by opportunistic scheduling. Although the conventional opportunistic beamforming scheme can improve the capacity in single cell environments, it can suffer from the OCI when applied to multi-cell environments [13]. This problem can be alleviated by means of BSs cooperative beamforming among multiple BSs in cellular environments.

B. *Conventional Cooperative Beamforming* [7]

For the BSs cooperative transmission, we assume that BSs are synchronized to each other with universal frequency reuse. When full CSI is available at the multiple BSs transmitter, the minimum mean square error (MMSE) beam weight can be generated in a cooperative manner as [7]

$$\mathbf{w}_{i,\text{MMSE}} = \left(\mathbf{h}_{i,Q(j)} \mathbf{h}^*_{i,Q(j)} + \frac{N_0}{\gamma_0 P} \mathbf{I}_M \right)^{-1} \mathbf{h}_{i,Q(i)} \tag{10}$$

where $\mathbf{I}_M$ denotes an $(M \times M)$-dimensional identity matrix. The corresponding capacity of user $Q(i)$ can be approximated as [7]

$$C_{\text{Coop}} \approx \log_2 \left(1 + \left(\sum_{j \neq i} \left| \mathbf{h}^*_{j,Q(i)} \mathbf{w}_{j,\text{MMSE}} \right|^2 + \frac{N_0}{P} \right)^{-1} \left| \mathbf{h}^*_{i,Q(i)} \mathbf{w}_{i,\text{MMSE}} \right|^2 \right) \tag{11}$$

Although the use of this BSs cooperative MMSE beam weight is effective, it may not be applicable due to huge signaling overhead for the feedback and exchange of full CSI among the BSs in cooperation.

IV. PROPOSED COOPERATIVE OPPORTUNISTIC BEAMFORMING

Although the use of cooperative MMSE beamforming can be effective for reduction of OCI in multi-cell environments, it may need to reduce the signaling overhead to make it applicable. To this end, we consider the use of the spatial channel correlation information for the cooperative opportunistic beamforming to simultaneously achieve the MUD gain and OCI reduction gain.

Unlike the conventional BSs cooperative beamforming scheme, the proposed scheme only utilizes the spatial correlation $\mathbf{R}_{j,Q(i)}$ of the channel between the target user $Q(i)$ and adjacent BS j. By exchanging the spatial channel correlation $\mathbf{R}_{j,Q(i)}$, BS j generates an opportunistic random beam $\mathbf{w}_{j,\text{pro}}$ as

$$\mathbf{w}_{j,\text{pro}} = \left(\mathbf{R}_{j,Q(i)} + \frac{N_0}{\gamma_0 P} \mathbf{I}_M \right)^{-1} \frac{\mathbf{v}_j}{\left\| \mathbf{v}_j \right\|} \tag{12}$$

where $\mathbf{v}_j$ is the $(M \times 1)$-dimensional random beam weight and $\left\| \mathbf{v}_j \right\|$ is its Probenius norm. Here, the pseudo inverse term in (12) means the rotation of random beam weight $\mathbf{v}_j$ according to $\mathbf{R}_{j,Q(i)}$ to reduce the OCI, strongly affecting the signal reception of user $Q(i)$, induced by BS j in average sense. Thus, BS j selects its user for the proposed random beam in an opportunistic manner (i.e., selects a user with the best channel quality). Thus, the proposed cooperative opportunistic beamforming scheme can simultaneously achieve OCI reduction gain and MUD gain by only exploiting the spatial channel correlation information.

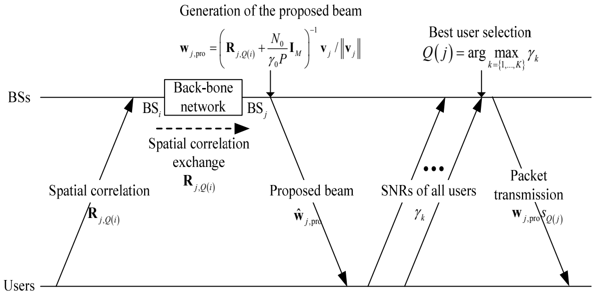

Fig 2. Procedure of the proposed beamforming scheme

As illustrated in Fig. 2, the proposed cooperative beamforming scheme can be processed as follows

1. Target user $Q(i)$ estimates the spatial channel correlation $\mathbf{R}_{j,Q(i)}$ from the pilot signal from BS j in active set $\Omega_{Q(i)}$ and reports it to BS i.
2. BS i notices $\mathbf{R}_{j,Q(i)}$ to adjacent BS j through a back-bone network.
3. BS j generates a random beam weight $\mathbf{w}_{j,\text{pro}}$ by (12).
4. Each user estimates the SNR γ_k received from random beam $\mathbf{w}_{j,\text{pro}}$ and reports it to BS j.
5. BS j selects the best user $Q(j)$ based on the reported SNR in an opportunistic manner (7).
6. Finally, BS j transmits the packet to user $Q(j)$ using random beam $\mathbf{w}_{j,\text{pro}}$.

V. PERFORMANCE EVALUATION

The performance of the proposed cooperative opportunistic beamforming scheme is verified by computer simulation. For comparison, the performance of the opportunistic beamforming scheme [6] and the BSs cooperative MMSE beamforming scheme [7] is also evaluated. We assume that the BS uses two transmit antennas and each user uses a single receive antenna, and the corresponding spatial channel correlation matrix $\mathbf{R}_{j,Q(i)}$ is given by [11]

$$\mathbf{R}_{j,Q(i)} = \begin{bmatrix} 1 & \rho_{j,Q(i)} \\ \rho^*_{j,Q(i)} & 1 \end{bmatrix} \tag{13}$$

where $\rho_{j,Q(i)} \left(= \alpha_{j,Q(i)} e^{j\theta_{j,Q(i)}} \right)$ represents the complex-valued spatial channel correlation coefficient, $\alpha_{j,Q(i)}$ and $\theta_{j,Q(i)}$ denote its amplitude and phase, respectively. Common simulation parameters are summarized in Table I.

Table 1. Simulation parameter

PARAMETERS	Values
Cell configuration	19 cells / 2-tier
Cell radius (r)	1 Km
Frequency reuse factor	1
Antenna configuration	2-Tx, 1-Rx
Transmit power (P)	1
Number of active cells ($\Omega_{Q(i)}$)	2
Path-loss exponent	4
Fading channel	Rayleigh fading
Link adaptation	Ideal (i.e., using the Shannon's capacity formula)
Occurrence of an outage stage	When the SINR according to QPSK 1/2 is less than 2.5 dB

Fig. 3 depicts the performance of the proposed scheme according to the number of users K when the average SNR is 0 dB. It can be seen that the performance of all beamforming schemes is improved as the number of users increase. This is mainly due to the MUD gain by dynamically allocating users according to the channel condition. It can also be seen that the proposed scheme outperforms the conventional opportunistic beamforming scheme mainly due to the reduction of OCI from adjacent cells. Although the proposed scheme is somewhat inferior to the conventional BSs cooperative MMSE beamforming scheme that fully utilizes CSI, it is quite applicable with significant reduction of the signaling overhead.

Fig. 4 depicts the performance of the proposed scheme according to the distance d between BS and MS. It can be seen that all beamforming schemes deteriorate as the distance d increases. It can also be seen that the proposed scheme is quite effective over the conventional opportunistic beamforming scheme for users near the cell boundary, which is mainly due to the reduction of OCI from adjacent cells. Again, the proposed scheme is inferior to the BSs cooperative MMSE beamforming scheme since it only exploits the spatial channel correlation.

Fig. 5 depicts the outage probability according to the distance d between BS and MS when QPSK with 1/2 code rate is employed. We assume that the outage occurs when the SINR is lower than 2.5 dB. It can be seen that the proposed scheme can provide noticeable performance gain over the conventional opportunistic beamforming scheme and performance comparable to the BSs cooperative MMSE beamforming scheme near the cell boundary.

Fig. 6 depicts the performance of the proposed scheme according to the spatial channel correlation coefficient α . It can be seen that the performance of two conventional beamforming schemes is indifferent from α . However, as $\alpha \to 0$, the performance of the proposed scheme becomes similar to that of the conventional opportunistic beamforming scheme since the spatially correlated channel becomes an i.i.d. channel. As $\alpha \to 1$, the performance of the proposed scheme becomes similar to that of the BSs cooperative MMSE beamforming scheme since the channel becomes a fully correlated channel.

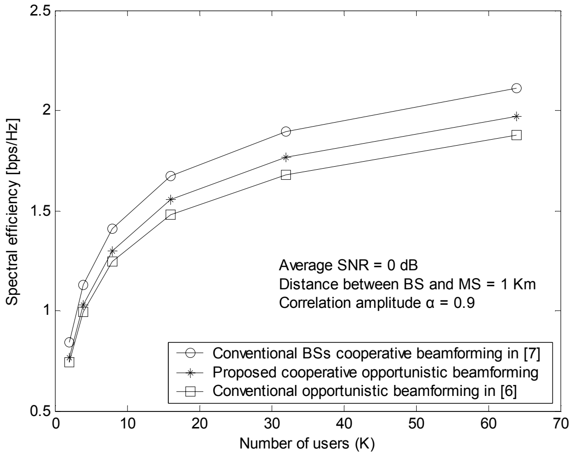

Fig. 3. Spectral efficiency associated with the number of users (K)

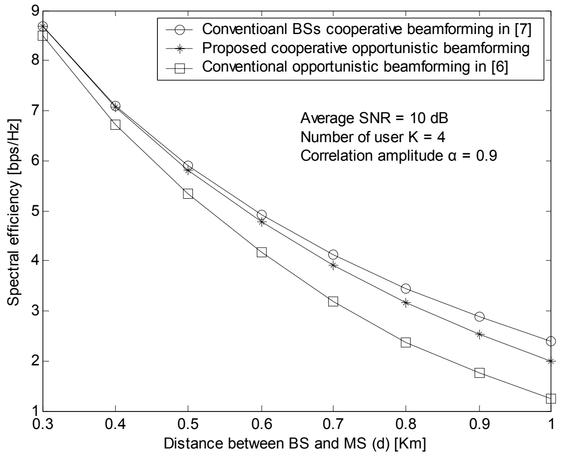

Fig. 4. Spectral efficiency according to the distance between BS and MS (d)

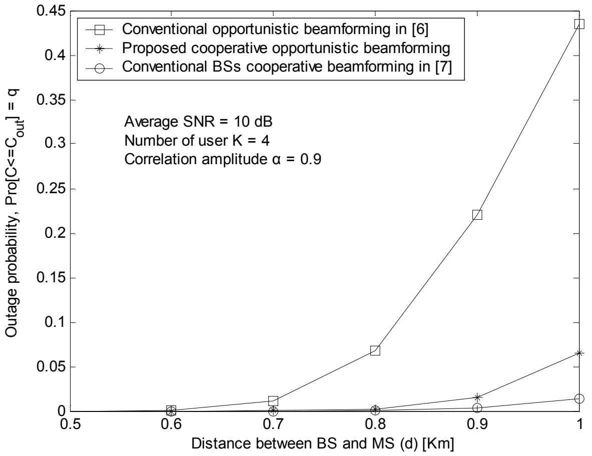

Fig. 5. Outage probability corresponding to QPSK 1/2 of the proposed scheme

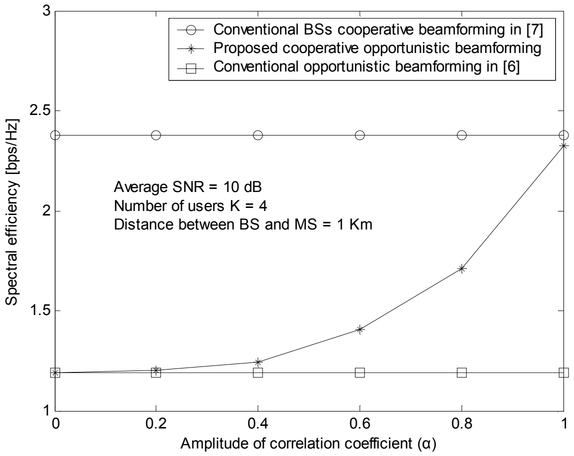

Fig. 6. Spectral efficiency of the proposed scheme according to the correlation coefficient (α)

VI. CONCLUSION

We have proposed a new cooperative opportunistic beamforming scheme that exploits the spatial channel correlation information in cellular environments. The proposed scheme can improve the SINR of users near the cell boundary by generating the random beam weight to reduce the OCI from adjacent cells in a cooperative manner and selecting the users in an opportunistic manner. The simulation results show that the proposed scheme provides noticeable performance improvement over the conventional opportunistic beamforming scheme, especially in highly correlated channel environments. Compared to the BSs cooperative MMSE beamforming that utilizes full CSI, the proposed scheme can provide affordable performance while significantly reducing the signaling overhead.

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