LETTER

Network Coordinated Opportunistic Beamforming in Downlink Cellular Networks*

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SUMMARY We propose a network coordinated opportunistic beamforming (NC-OBF) protocol for downlink K-cell networks with M-antenna base stations (BSs). In the NC-OBF scheme, based on pseudo-randomly generated BF vectors, a user scheduling strategy is introduced, where each BS opportunistically selects a set of mobile stations (MSs) whose desired signals generate the minimum interference to the other MSs. Its performance is then analyzed in terms of degrees-of-freedom (DoFs). As our achievability result, it is shown that KM DoFs are achievable if the number N of MSs in a cell scales at least as SNR^{KM-1}, where SNR denotes the received signal-to-noise ratio. Furthermore, by deriving the corresponding upper bound on the DoFs, it is shown that the NC-OBF scheme is DoF-optimal. Note that the proposed scheme does not require the global channel state information and dimension expansion, thereby resulting in easier implementation.

key words: *cellular network, degrees-of-freedom (DoFs), downlink, interference, network coordinated opportunistic beamforming (NC-OBF), user scheduling*

1. Introduction

Interference between wireless links have been taken into account as a critical problem in communication systems. There are three categories of the conventional interference management in wireless networks: decoding and cancellation, avoidance (i.e., orthogonalization), and averaging (or spreading). To consider both intra-cell and inter-cell interference of wireless cellular networks, a simple infinite cellular multiple-access channel model, referred to as Wyner's model, was characterized and then its achievable throughput performance was analyzed in [1], [2]. Even if the work in [1], [2] leads to a remarkable insight into complex and analytically intractable practical cellular environments, the model under consideration is hardly realistic. Recently, as an alternative approach to show Shannon-theoretic limits, interference alignment (IA) was introduced for fundamentally solving the interference problem when there are multiple communication pairs [3]. It was shown that the IA scheme can achieve the optimal degrees-of-freedom (DoFs), which are equal to $K/2$, in the K-user interference channel with time varying channel coefficients. Since then, interference management strategies based on IA have been further developed and analyzed in various wireless network environments: multiple-input multiple-output (MIMO) interference network [4], X network [5], and cellular network [6]–[8].

Now we would like to consider practical downlink cellular networks with K-cells each of which has N mobile stations (MSs). An efficient IA scheme that requires feedback only within a cell was developed in the downlink K-cell network [8], but it remains open how to design a constructive scheme that can achieve the optimal DoFs under the network.

In this paper, we introduce a *network coordinated opportunistic beamforming (NC-OBF)* protocol to show the DoF optimality for downlink K-cell networks. In the literature, there are some results on the usefulness of fading in single-cell broadcast channels, where one can obtain a multi-user diversity (MUD) gain as the number of MSs is sufficiently large: opportunistic scheduling [9], opportunistic BF [10], and random BF [11]. Similarly as in [9]–[11], the proposed NC-OBF scheme adopts the notion of MUD gain for performing interference management. An opportunistic user scheduling strategy is used in downlink environments with time-invariant channel coefficients and base stations (BSs) having M antennas. In the NC-OBF scheme, each BS opportunistically selects a set of MSs affecting the minimum interference to the other MSs, while in the conventional opportunistic algorithms [9]–[11], MSs with the maximum received signal are selected for data transmission. More specifically, each BS broadcasts a set of M orthonormal BF vectors, generated in a pseudo-random manner, to all the MSs. Each MS then computes M interferences, based on the vector set, and feeds back the values along with the corresponding BF indices to its home cell BS. We analyze their performance in terms of DoFs. As our main result, we derive the scaling condition between the number N of MSs per cell and the received signal-to-noise ratio (SNR) under which our achievability holds. We then show that KM DoFs are achieved asymptotically with the NC-OBF protocol, provided that N scales faster than SNR^{KM-1}. In addition, by showing an upper bound on the DoFs, it is shown that the proposed scheme achieves the optimal DoFs with help of the opportunism. As in [4], the NC-OBF protocol

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operates with local channel state information (CSI) and no dimension expansion, which thus leads to easier implementation.

We remark that the terminology coordinated BF has also been used in [12] in the sense that the transmit and receive BF vectors are jointly designed in MIMO systems, which basically differs from our NC-OBF protocol.

The rest of this paper is organized as follows. Section 2 describes the system and channel models. In Sect. 3, the NC-OBF protocol is proposed for downlink cellular networks and its achievability in terms of DoFs is also analyzed. The DoF optimality and the sum-rate performance are then discussed in Sect. 4. Finally, we summarize the paper with some concluding remark in Sect. 5.

Throughout this paper, the superscript H denotes the conjugate transpose of a vector. $\|\cdot\|$ and $E[\cdot]$ indicate the L_2-norm of a vector and the statistical expectation. Unless otherwise stated, all logarithms are assumed to be to the base 2.

2. System and Channel Models

Consider the interfering broadcast channel (IBC) model [8], referred to as a downlink scenario, to describe practical cellular networks with K cells, each of which has one BS and N MSs. Under the model, MSs are assumed to be interested in traffic demands generated only from the BS in the corresponding cell (i.e., home cell BS). We assume that each cell is covered by one BS having M antennas and each MS is equipped with a single-antenna. The channel in a single-cell can then be regarded as the multiple-input single-output (MISO) BC. The example for $K = 2$, $M = 2$, and $N = 3$ is illustrated in Fig. 1. If N is much greater than M, then it is possible to exploit the channel randomness and thus to obtain the MUD gain in the IBC environment.

The term $\beta_{ki}\mathbf{h}_{j,i}^{(k)} \in \mathbb{C}^{1\times M}$ denotes the channel vector between BS i and MS j in the k-th cell, consisting of the large-scale path-loss component $0 < \beta_{ki} \leq 1$ and the small-scale complex fading component $\mathbf{h}_{j,i}^{(k)}$, where $i, k \in \{1, \cdots, K\}$ and $j \in \{1, \cdots, N\}$. For simplicity, we assume that receivers (MSs) in the same cell experience the same degrees of path-loss attenuation. Especially, when $k = i$, the large-scale term β_{ki} is assumed to be 1 since it corresponds to intra-cell received signal strengths, which are much stronger than inter-cell interferences. The fading term $\mathbf{h}_{j,i}^{(k)}$ is assumed to be Rayleigh, whose elements have zero-mean and unit variance, and to be independent across different i, j, and k. We assume a block-fading model, i.e., the channel vectors are constant during one block (e.g., frame) and changes independently between blocks. The received signal $y_j^{(i)}$ at MS j in the i-th cell is given by $y_j^{(i)} = \sum_{k=1}^{K} \beta_{ik}\mathbf{h}_{j,k}^{(i)}\mathbf{x}_k + z_j^{(i)}$, where $\mathbf{x}_k \in \mathbb{C}^{M\times 1}$ is the signal vector sent from BS k. The received signal $y_j^{(i)}$ at MS j in the i-th cell is corrupted by the independent and identically distributed and circularly symmetric complex additive white Gaussian noise $z_j^{(i)}$ that has zero-mean. We assume that the total transmit power at each BS is MP, i.e., $E\left[\mathbf{x}_k^H\mathbf{x}_k\right] \leq MP$, where P (constant) denotes the transmit power per antenna.

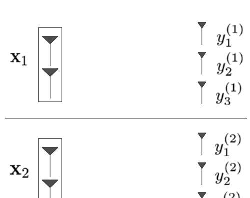

Fig. 1 The IBC model with K=2, $M = 2$, and $N = 3$.

3. Achievability Result

In this section, we propose an NC-OBF protocol and then analyze its performance in terms of achievable DoFs.

3.1 NC-OBF Protocol

The fact that the existing BF schemes [10], [11] do not guarantee the DoF optimality in the IBC model motivates the introduction of an NC-OBF protocol, in which multiple random beams are generated and certain MSs are then selected in the sense of minimizing intra-cell and inter-cell interferences.

To be specific, BS $i \in \{1, \cdots, K\}$ uses M orthonormal BF vectors $\phi_{i,m} \in \mathbb{C}^{M\times 1}$ for $m = 1, \cdots, M$, where $\phi_{i,m}$'s are generated according to an isotropic distribution. The m-th vector is multiplied by the m-th transmit symbol $s_{i,m}$ so that the resulting transmit signal vector $\mathbf{x}_i \in \mathbb{C}^{M\times 1}$ is $\mathbf{x}_i = \sum_{m=1}^{M} \phi_{i,m}s_{i,m}$, where $i \in \{1, \cdots, K\}$. In this case, suppose that a central coordinator generates a set of KM total BF vectors, i.e., $\{\phi_{1,1}, \cdots, \phi_{1,M}, \cdots, \phi_{K,1}, \cdots, \phi_{K,M}\}$, in a pseudo-random manner, which can be shared by all the BSs before data transmission without any signaling[†]. This assumption has been similarly made in previous work on coordinated multi-cell systems [13]. Note that the other global coordination over multiple cells (e.g., the exchange of CSI between BSs) is not needed, thus resulting in easier implementation.

The overall procedure of the proposed NC-OBF protocol is now described. We assume that MS j in the i-th cell is served with BF vector $\phi_{i,l}$, where $j \in \{1, \cdots, N\}$, $i \in \{1, \cdots, K\}$, and $l \in \{1, \cdots, M\}$. Then, it is possible for the MS to obtain all the *effective* channel gains, each of which consists of both plain downlink channel and random BF vectors, by utilizing a pilot signaling sent from BSs. We examine how much the interfering signal of selected users is affected to the other MSs by computing the following metric at MS j:

$$I_{i,j}^{l} = \sum_{m=1, m\neq l}^{M} \left|\mathbf{h}_{j,i}^{(i)}\phi_{i,m}\right|^2 + \sum_{k=1,k\neq i}^{K} \sum_{m=1}^{M} \beta_{ik}^2 \left|\mathbf{h}_{j,k}^{(i)}\phi_{i,m}\right|^2, \quad (1)$$

[†]Alternatively, one of the BSs can be designated as a central coordinator.

where the first and second terms in (1) indicate the intra- and inter-cell interferences, respectively. After computing the set $\left\{I^1_{i,j}, \cdots, I^M_{i,j}\right\}$ of the metric, each MS feeds back the M values together with the corresponding BF indices to its home cell BS. Thereafter, each BS selects a set $\{\pi_i(1), \cdots, \pi_i(M)\}$ of the MSs in its cell, where $\pi_i(l)$ denotes the index of the MS in the i-th cell that reports the minimum among the N values $\{I^l_{i,1}, \cdots, I^l_{i,N}\}$ for $l \in \{1, \cdots, M\}$. That is, a suitable MS is chosen for one BF vector. BSs start to transmit data packets to their selected MSs.

3.2 Analysis of Achievable DoFs

In this subsection, we show that the NC-OBF scheme achieves KM DoFs, i.e., full DoFs, asymptotically. The achievability is conditioned by the scaling behavior between the number N of MSs per cell and the received SNR.

The total number of DoFs is defined as

$$\text{dof}_{\text{total}} = \sum_{i=1}^{K}\sum_{j=1}^{N}\left(\lim_{\text{SNR}\to\infty}\frac{R^{(i)}_j(\text{SNR})}{\log \text{SNR}}\right), \tag{2}$$

where $R^{(i)}_j(\text{SNR})$ denotes the rate for the transmission of MS $j \in \{1, \cdots, N\}$ in the i-th cell ($i = 1, \cdots, K$). Under the NC-OBF protocol, (2) is then lower-bounded by

$$\text{dof}_{\text{total}} \geq \sum_{i=1}^{K}\sum_{l=1}^{M}\left(\lim_{\text{SNR}\to\infty}\frac{\log\left(1+\text{SINR}_{i,l}\right)}{\log \text{SNR}}\right), \tag{3}$$

where $\text{SINR}_{i,l}$ denotes the received signal-to-interference-and-noise ratio (SINR) for MS $\pi_i(l)$ in the i-th cell and is represented by

$$\frac{\left|\mathbf{h}^{(i)}_{\pi_i(l),i}\phi_{i,l}\right|^2 \text{SNR}}{1 + I^l_{i,\pi_i(l)}\text{SNR}} \geq \frac{\left|\mathbf{h}^{(i)}_{\pi_i(l),i}\phi_{i,l}\right|^2 \text{SNR}}{1 + \tilde{I}^l_{i,\pi_i(l)}\text{SNR}}. \tag{4}$$

Here, the inequality holds due to the Cauchy-Schwarz inequality and $\tilde{I}^l_{i,\pi_i(l)} = (M-1)\left\|\mathbf{h}^{(i)}_{\pi_i(l),i}\right\|^2 + M\sum_{k=1,k\neq i}^{K}\beta^2_{ik}\left\|\mathbf{h}^{(i)}_{\pi_i(l),k}\right\|^2$. Then, $\tilde{I}^l_{i,\pi_i(l)}$ can be upper-bounded by $\tilde{I}^{l,\text{up}}_{i,\pi_i(l)}$, which is given by

$$\tilde{I}^{l,\text{up}}_{i,\pi_i(l)} = (M-1)\left\|\mathbf{h}^{(i)}_{\pi_i(l),i}\right\|^2 + M\sum_{k=1,k\neq i}^{K}\left\|\mathbf{h}^{(i)}_{\pi_i(l),k}\right\|^2 \tag{5}$$

due to the fact that $\beta_{ik} \leq 1$ for all $k \in \{1, \cdots, K\}$. Since the M-dimensional MISO channel vector $\mathbf{h}^{(i)}_{\pi_i(l),i}$ is isotropically distributed, the random variable $\tilde{I}^{l,\text{up}}_{i,j}$ follows the chi-square distribution with $2(KM-1)$ degrees of freedom for any $i = 1, \cdots, K$ and $j = 1, \cdots, N$. The cumulative distribution function (cdf) $F_I(x)$ of $\tilde{I}^{l,\text{up}}_{i,j}$ is given by

$$F_I(x) = \frac{\gamma(KM-1, x/2)}{\Gamma(KM-1)}, \tag{6}$$

where $\Gamma(z) = \int_0^\infty t^{z-1}e^{-t}dt$ is the Gamma function and $\gamma(z, y) = \int_0^y t^{z-1}e^{-t}dt$ is the lower incomplete Gamma function. We start from the following lemma.

Lemma 1. *For any $0 \leq x < 2$, the cdf $F_I(x)$ of $\tilde{I}^{l,up}_{i,j}$ in (5) is lower-bounded by*

$$F_I(x) \geq c_0 x^{KM-1}, \tag{7}$$

where $c_0 = \frac{e^{-1}\cdot 2^{-(KM-1)}}{(KM-1)\Gamma(KM-1)}$ and $\Gamma(z)$ is the Gamma function.

The proof of this lemma is presented in Appendix Appendix. Now we are ready to derive the achievable DoFs based on the NC-OBF protocol.

Theorem 1. *Suppose that the NC-OBF scheme is used in the IBC model. Then,* $\text{dof}_{\text{total}} \geq KM$ *is achievable with high probability (whp) if $N = \omega\left(\text{SNR}^{KM-1}\right)$*†.

Proof. From (3) and (4), the NC-OBF scheme achieves KM DoFs if the value $\tilde{I}^{l,\text{up}}_{i,\pi_i(l)}\text{SNR}$ for all $i \in \{1, \cdots, K\}$ and $l \in \{1, \cdots, M\}$ is smaller than or equal to some constant $\epsilon > 0$ independent of SNR. The number $\text{dof}_{\text{total}}$ of DoFs is lower-bounded by $P_{\text{NC-OBF}}KM$, which holds since KM DoFs are achieved for a fraction $P_{\text{NC-OBF}}$ of the time, where

$$P_{\text{NC-OBF}} = \lim_{\text{SNR}\to\infty}\Pr\left\{\tilde{I}^{l,\text{up}}_{i,\pi_i(l)}\text{SNR} \leq \epsilon \text{ for all } i \text{ and } l\right\}.$$

We now examine the scaling condition such that $P_{\text{NC-OBF}}$ converges to one whp. For a constant $\epsilon > 0$, it follows that

$$P_{\text{NC-OBF}} \geq \lim_{\text{SNR}\to\infty}\left(\Pr\left\{\tilde{I}^{1,\text{up}}_{1,\pi_1(1)} \leq \epsilon\text{SNR}^{-1}\right\}\right)^{KM}, \tag{8}$$

where the inequality holds from the fact that the random variable $\tilde{I}^{l,\text{up}}_{i,j}$ is independent for different $i \in \{1, \cdots, K\}$ and $l \in \{1, \cdots, M\}$. Then, (8) can further be lower-bounded by using

$$\begin{aligned}
&\lim_{\text{SNR}\to\infty}\Pr\left\{\tilde{I}^{1,\text{up}}_{1,\pi_1(1)} \leq \epsilon\text{SNR}^{-1}\right\} \\
&= 1 - \lim_{\text{SNR}\to\infty}\left(1 - F_I\left(\epsilon\text{SNR}^{-1}\right)\right)^N \\
&\geq \lim_{\text{SNR}\to\infty}\left(1 - c_0\epsilon^{KM-1}\text{SNR}^{-(KM-1)}\right)^N, \qquad (9)
\end{aligned}$$

where the inequality holds due to Lemma 1. If $N = \omega\left(\text{SNR}^{KM-1}\right)$, then the term in (9) decays exponentially with increasing SNR. It thus follows that the lower bound in (8) converges to one. As a consequence, our result indicates that $\tilde{I}^{l,\text{up}}_{i,\pi_i(l)}$ scales as $O\left(\text{SNR}^{-1}\right)$ whp if $N = \omega\left(\text{SNR}^{KM-1}\right)$, thereby yielding $\text{dof}_{\text{total}} \geq KM$, which completes the proof. □

It is now examined how our scheme is fundamentally different from the existing DoF-optimal schemes [3], [5], [6]. The minimum number N of per-cell MSs needs to be

† We use the following notations: i) $f(x) = O(g(x))$ means that there exist constants C and c such that $f(x) \leq Cg(x)$ for all $x > c$. ii) $f(x) = \omega(g(x))$ if $\lim_{x\to\infty}\frac{g(x)}{f(x)} = 0$.

guaranteed in order that the NC-OBF scheme works properly even in the time-invariant channel condition without any dimension expansion. On the other hand, in [3], [5], [6], a huge number of dimensions are required to asymptotically achieve the optimal DoFs.

4. Discussion

To verify the optimality of the proposed scheme, we derive an upper bound on the DoFs in downlink cellular networks. For the IBC model shown in Fig. 1, a genie-aided removal of all the inter-cell interferences is taken into account, which gives an upper bound on the performance. Then, we obtain K parallel BC systems, each of which has an M-antenna transmitter (BS) and N single-antenna receivers (MSs). Since the maximum DoFs of the MISO BC are given by M, the total number $\text{dof}_{\text{total}}$ of DoFs for the IBC model is finally upper-bounded by KM due to the fact there exist K cells. It is hence shown that the upper bound on the DoFs matches the achievable DoFs as long as N scales faster than SNR^{KM-1}.

In addition, note that we aim to show the user scaling for achieving the optimal DoFs, i.e, $N = \omega(\text{SNR}^{KM-1})$, in downlink multi-cell networks. Regarding sum-rate performance, it can be shown that when N tends to infinity, the sum-rate scales as $KM \log\log N$, thereby achieving the best result we can hope for, by using an MS selection metric based on the received SINR, which is a simple extension of [11]. It however remains open what is the user scaling required to guarantee the optimal sum-rate scaling law.

5. Conclusion

The NC-OBF protocol was proposed in downlink K-cell networks, where it does not require the global CSI and infinite dimension expansion. The achievable DoFs were then analyzed — the proposed protocol asymptotically achieves KM DoFs as long as N scales faster than SNR^{KM-1}. By showing the upper bound on the DoFs, it was shown that the NC-OBF protocol achieves the optimal DoFs with the help of the MUD gain. As a result, a feasible example for applying opportunism in practical multi-cell environments was provided with the optimal solution.

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Appendix: Proof of Lemma 1

The cdf $F_I(x)$ of $\tilde{I}_{i,j}^{l,\text{up}}$ satisfies the inequality $\gamma(z,y) \geq \frac{1}{z}y^z e^{-1}$ for $z > 0$ and $0 \leq y < 1$ since

$$\gamma(z,y) = \frac{1}{z}y^z e^{-y} + \frac{1}{z}\gamma(z+1,y)$$
$$= \frac{1}{z}y^z e^{-y} + \frac{1}{z(z+1)}y^{z+1}e^{-y} + \cdots .$$

Applying the above inequality to (6), we finally obtain (7), which completes the proof.