

A Study on the Optimal Degree-of-Freedoms of Cellular Networks: Opportunistic Interference Mitigation

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Abstract—We introduce an opportunistic interference mitigation (OIM) protocol for cellular networks, where a user scheduling strategy is utilized in uplink K -cell environments with time-invariant channel coefficients and base stations (BSs) having M receive antennas. In the OIM scheme, each BS opportunistically selects a set of users who generate the minimum interference to the other BSs. We consider two OIM protocols according to the number S of simultaneously transmitting users per cell. Then, their performance is analyzed in terms of degrees-of-freedom (DoFs). As our main result, it is shown that KS DoFs are achievable if and only if the total number N of users in a cell scales at least as $\text{SNR}^{(K-1)S}$. These results indicate that there exists a trade-off between the achievable number of DoFs and the scaling parameter N by tuning the number S of selected users. By showing an upper bound on the DoFs, it is also shown that the OIM scheme with M selected users is DoF-optimal. Finally, numerical evaluation is performed.

I. INTRODUCTION

Interference between wireless links has been taken into account as a critical problem in communication systems. Especially, there exist three categories of the conventional interference management in wireless networks: decoding and cancellation, avoidance (i.e., orthogonalization), and averaging (or spreading). Recently, interference alignment (IA) was proposed for fundamentally solving the interference problem when there are multiple communication pairs [2]. 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 schemes based on IA have been further developed and analyzed in various wireless network environments: multiple-input multiple-output (MIMO) interference network [3], [4], X network [5], [6], and cellular network [7], [8]. However, the conventional IA schemes [2], [4], [9] require global channel state information (CSI) which includes the CSI of other communication links. Furthermore, a huge number of dimensions based on time/frequency expansion are needed to achieve the optimal DoFs [2], [4]–[7], [9].

We now consider practical cellular networks with K -cells, each of which has N users. IA was first applied to cellular

networks in [7], where the interference from other cells is aligned into multi-dimensional subspace instead of one dimension. This scheme also has practical challenges including the dimension extension to achieve the optimal DoFs.

In the literature, there are some results on the usefulness of fading in broadcast channels, where one can obtain a multi-user diversity (MUD) gain: opportunistic scheduling [10], opportunistic BF [11], and random BF [12]. Scenarios exploiting the MUD gain have also been extended in cooperative networks by applying an opportunistic two-hop relaying protocol [13] and an opportunistic routing [14], and in cognitive radio networks with opportunistic scheduling [15].

In this paper, we introduce an *opportunistic interference mitigation (OIM)* protocol for cellular networks. The scheme adopts the notion of MUD gain for performing interference management. The opportunistic user scheduling strategy is utilized in uplink K -cell environments with time-invariant channel coefficients and base stations (BSs) having M receive antennas. In the proposed OIM scheme, each BS opportunistically selects a set of users who generate the minimum interference to the other BSs. Specifically, two OIM protocols are proposed according to the number S of simultaneously transmitting users per cell: opportunistic interference nulling (OIN) and opportunistic interference alignment (OIA) protocols. For the OIA scheme, each BS broadcasts its pre-defined interference direction, e.g., a set of orthonormal random vectors, to all the users in other cells, whereas for the OIN scheme, no broadcast is needed at each BS. Then, each user computes the amount of its generating interference, affecting the other BSs, and feedbacks it to its home cell BS.

Their performance is then analyzed in terms of achievable DoFs. It is shown that KM DoFs are achievable under the OIN protocol with M selected users per cell, while the OIA scheme with S selected users (less than M) achieves KS DoFs. It is analyzed that the aforementioned DoFs are achieved, provided N scales faster than $\text{SNR}^{(K-1)M}$ and $\text{SNR}^{(K-1)S}$ for the OIN and OIA protocols, respectively. From the result, it is seen that there exists a fundamental trade-off between the achievable number of DoFs and the

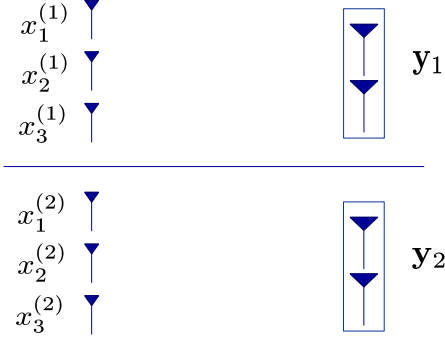


Fig. 1. The IMAC model with $K=2$, $N=3$, and $M=2$.

scaling parameter N , based on the two proposed schemes. In addition, by showing an upper bound on the DoFs, it is shown that the OIN scheme achieves the optimal DoFs. To validate the OIA scheme, computer simulations are finally performed. Note that the OIM protocol basically operates with local CSI and no time/frequency expansion, thereby resulting in easier implementation. No iteration is also needed prior to data transmission.

The rest of this paper is organized as follows. In Section II, we introduce the system and channel models. In Section III, the OIM technique is proposed for cellular networks and its achievability in terms of DoFs is also analyzed. Section IV shows an upper bound on the DoFs. Numerical results are shown in Section V. Finally, we summarize the paper with some concluding remark in Section VI. We refer to the full paper [16] for the detailed description and all the proofs.

II. SYSTEM AND CHANNEL MODELS

Consider the interfering multiple-access channel (IMAC) model in [7], which is one of uplink scenarios, to describe practical cellular networks. As illustrated in Fig. 1, there are multiple cells, each of which has multiple mobile users. The example for $K=2$, $N=3$, and $M=2$ is shown in Fig. 1. Under the model, each BS is interested only in traffic demands of users in the corresponding cell. Suppose that there are K cells and there are N users in a cell. We assume that each user is equipped with a single transmit antenna and each cell is covered by one BS with M receive antennas. The channel in a single-cell can then be regarded as the single-input multiple-output (SIMO) MAC.

The term $\mathbf{h}_{i,j}^{(k)} \in \mathbb{C}^{M \times 1}$ denotes the channel vector between user j in the k -th cell and BS i , where $j \in \{1, \dots, N\}$ and $i, k \in \{1, \dots, K\}$. The channel 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 to a new independent value for every block. The receive signal vector $\mathbf{y}_i \in \mathbb{C}^{M \times 1}$ at BS

i is given by

$$\mathbf{y}_i = \sum_{j=1}^S \mathbf{h}_{i,j}^{(i)} x_j^{(i)} + \sum_{k=1, k \neq i}^K \sum_{n=1}^S \mathbf{h}_{i,n}^{(k)} x_n^{(k)} + \mathbf{z}_i, \quad (1)$$

where $x_j^{(i)}$ is the transmit symbol of user j in the i -th cell and S represents the number of users transmitting data simultaneously in each cell for $S \in \{1, \dots, M\}$. The received signal \mathbf{y}_i at BS i is corrupted by the independently identically distributed (i.i.d.) and circularly symmetric complex additive white Gaussian noise vector $\mathbf{z}_i \in \mathbb{C}^{M \times 1}$ whose elements have zero-mean and variance N_0 . We assume that each user has an average transmit power constraint $\mathbb{E} \left[|x_j^{(i)}|^2 \right] \leq P$. Then, the received SNR at each BS is expressed as a function of P and N_0 , which depends on the decoding process at the receiver side. In this work, we take into account a simple zero-forcing (ZF) receiver based on pre-defined random vectors and the channel vectors between the BS and its selected home cell users, which will be discussed in detail in Section III-A.

III. ACHIEVABILITY RESULT

We propose the following two OIM protocols: an opportunistic interference nulling (OIN) and an opportunistic interference alignment (OIA). Then, their performance is analyzed in terms of achievable DoFs.

A. OIM in Cellular Networks

We mainly focus on the case for $SK > M$, since otherwise we can simply achieve the maximum DoFs by applying the conventional ZF receiver (at BS $i \in \{1, \dots, K\}$) based on the following channel transfer matrix

$$\begin{bmatrix} \mathbf{h}_{1,1}^{(i)} & \cdots & \mathbf{h}_{1,S}^{(i)} & \cdots & \mathbf{h}_{K,1}^{(i)} & \cdots & \mathbf{h}_{K,S}^{(i)} \end{bmatrix}.$$

1) *OIN Protocol*: We first introduce an OIN protocol with which M selected users in a cell transmit their data simultaneously, i.e., the case where $S = M$. It is possible for user j in the i -th cell to obtain all the cross-channel vectors $\mathbf{h}_{k,j}^{(i)}$ by utilizing a pilot signaling sent from other cell BSs, where $j \in \{1, \dots, N\}$, $i \in \{1, \dots, K\}$, and $k \in \{1, \dots, i-1, i+1, \dots, K\}$.

We now examine how much the cross-channels of selected users are in deep fade by computing the following value $L_{k,j}^i$:

$$L_{k,j}^i = \left\| \mathbf{h}_{k,j}^{(i)} \right\|^2,$$

which is called *leakage of interference (LIF)*, for $k \in \{1, \dots, i-1, i+1, \dots, K\}$. For user j in the i -th cell, the user scheduling metric L_j^i is given by

$$L_j^i = \sum_k L_{k,j}^i \quad (2)$$

for $k \in \{1, \dots, i-1, i+1, \dots, K\}$. After computing the metric representing the total sum of $K-1$ LIF values in

(2), each user feedbacks the value to its home cell BS i .¹ Thereafter, BS i selects a set $\{\pi_i(1), \dots, \pi_i(M)\}$ of M users who feedback the values up to the M -th smallest one in (2), where $\pi_i(j)$ denotes the index of users in cell i whose value is the j -th smallest one. The selected M users in each cell start to transmit their data packets.

At the receiver side, each BS performs a simple ZF filtering based on intra-cell channel vectors to detect the signal from its home cell users, which is sufficient to capture the full DoFs in our model. The resulting signal (symbol), postprocessed by ZF matrix $\mathbf{G}_i \in \mathbb{C}^{M \times M}$ at BS i , is then given by

$$\begin{bmatrix} \hat{x}_1^{(i)} & \dots & \hat{x}_M^{(i)} \end{bmatrix}^T = \mathbf{G}_i \mathbf{y}_i,$$

where

$$\mathbf{G}_i = \begin{bmatrix} \bar{\mathbf{g}}_1^{(i)} & \dots & \bar{\mathbf{g}}_M^{(i)} \end{bmatrix}^T$$

and $\bar{\mathbf{g}}_m^{(i)} \in \mathbb{C}^{M \times 1}$ is the unit-norm ZF column vector.

2) *OIA Protocol*: The fact that the OIN scheme needs a great number of per-cell users motivates the introduction of an OIA protocol in which S transmitting users are selected in each cell for $S \in \{1, \dots, M-1\}$. The OIA scheme is now described as follows. First, BS i in the i -th cell generates a set of orthonormal random vectors $\mathbf{v}_m^{(i)} \in \mathbb{C}^{M \times 1}$ for all $m = 1, \dots, M-S$ and $i = 1, \dots, K$, where $\mathbf{v}_m^{(i)}$ corresponds to its pre-defined interference direction, and then broadcasts the random vectors to all the users in other cells.² That is, the interference subspace is broadcasted. If $m_1 = m_2$, then $\mathbf{v}_{m_1}^{(i)H} \mathbf{v}_{m_2}^{(i)} = 1$ for $m_1, m_2 \in \{1, \dots, M-1\}$. Otherwise, it is obtained that $\mathbf{v}_{m_1}^{(i)H} \mathbf{v}_{m_2}^{(i)} = 0$. For example, if $M-S$ is set to 1, i.e., single interference dimension is used, then $M-1$ users in a cell are selected to transmit their data packets simultaneously. This can be easily extended to the case where a multi-dimensional subspace is allowed for IA (e.g., $M-S \geq 2$).

With this scheme, it is important to see how closely the channels of selected users are aligned with the *span* of broadcasted interference vectors. To be specific, let $\{\mathbf{u}_1^{(i)}, \dots, \mathbf{u}_S^{(i)}\}$ denote an orthonormal basis for the null space $U^{(i)}$ (i.e., kernel) of the interference subspace. User $j \in \{1, \dots, N\}$ in the i -th cell then computes the orthogonal projection onto $U^{(k)}$ of its channel vector $\mathbf{h}_{k,j}^{(i)}$, which is given by

$$\text{Proj}_{U^{(k)}} \left(\mathbf{h}_{k,j}^{(i)} \right) = \sum_{m=1}^S \left(\mathbf{u}_m^{(k)H} \mathbf{h}_{k,j}^{(i)} \right) \mathbf{u}_m^{(k)},$$

and the value

$$L_{k,j}^i = \left\| \text{Proj}_{U^{(k)}} \left(\mathbf{h}_{k,j}^{(i)} \right) \right\|^2,$$

¹An opportunistic feedback strategy can be adopted in order to reduce the amount of feedback overhead without any performance loss, as done in MIMO broadcast channels [17], even if the details are not shown in this paper.

²Alternatively, a set of vectors can be generated with prior knowledge in a pseudo-random manner, and thus can be acquired by all users before data transmission without any signaling.

which can be interpreted as the LIF in the OIA scheme, for $k \in \{1, \dots, i-1, i+1, \dots, K\}$. For example, if the LIF of a user is given by 0 for a certain another BS $k \in \{1, \dots, i-1, i+1, \dots, K\}$, then it indicates that the user's channel vectors are perfectly aligned to the interference direction of BS k and the user's signal does not interfere with signal detection at the BS. For user j in the i -th cell, the user scheduling metric L_j^i is finally given by (2), as in the OIN protocol. The remaining scheduling steps are the same as those of OIN except that a set $\{\pi_i(1), \dots, \pi_i(S)\}$ of S users is selected at BS i instead of M users.

A ZF filtering at BS i is performed based on both random vectors $\{\mathbf{v}_1^{(i)}, \dots, \mathbf{v}_{M-S}^{(i)}\}$ and the intra-cell channel vectors $\{\mathbf{h}_{i,1}^{(i)}, \dots, \mathbf{h}_{i,S}^{(i)}\}$. Then, the resulting signal, postprocessed by ZF matrix $\mathbf{G}_i \in \mathbb{C}^{S \times M}$, is given by

$$\begin{bmatrix} \hat{x}_1^{(i)} & \dots & \hat{x}_S^{(i)} \end{bmatrix}^T = \mathbf{G}_i \mathbf{y}_i,$$

where

$$\begin{aligned} \mathbf{G}_i &= \begin{bmatrix} \bar{\mathbf{g}}_1^{(i)} & \dots & \bar{\mathbf{g}}_S^{(i)} \end{bmatrix}^T \\ &= \mathbf{A} \cdot \begin{bmatrix} \mathbf{h}_{i,1}^{(i)} & \dots & \mathbf{h}_{i,S}^{(i)} & \mathbf{v}_1^{(i)} & \dots & \mathbf{v}_{M-S}^{(i)} \end{bmatrix}^\dagger \end{aligned}$$

and \mathbf{A} is the $S \times M$ matrix made by the first S rows of M -dimensional identity matrix \mathbf{I}_M .

B. Analysis of Achievable DoFs

In this subsection, we analyze the scaling behavior between system parameters K, M, N, S , and the received SNR such that the OIM scheme with S simultaneously transmitting users per cell achieves the total number KS of DoFs. Here, the total number of DoFs is defined as [18]

$$\sum_{i=1}^K \sum_{j=1}^N d_j^{(i)} = \lim_{\text{SNR} \rightarrow \infty} \frac{R(\text{SNR})}{\log \text{SNR}},$$

where $d_j^{(i)}$ and $R(\text{SNR})$ denote the DoFs for the transmission of user j in the i -th cell and the sum-rate capacity, respectively, for $i = 1, \dots, K$ and $j = 1, \dots, N$. Note that under the assumed protocols, the achievable sum-rate $R(\text{SNR})$ is given by

$$R(\text{SNR}) = \sum_{i=1}^K \sum_{m=1}^S \log \left(1 + \frac{\left| \bar{\mathbf{g}}_m^{(i)H} \mathbf{h}_{i,\pi_i(m)}^{(i)} \right|^2 \text{SNR}}{1 + \sum_{k=1, k \neq i}^K \sum_{j=1}^S \left| \bar{\mathbf{g}}_m^{(i)H} \mathbf{h}_{i,\pi_k(j)}^{(k)} \right|^2 \text{SNR}} \right).$$

Since the m -dimensional SIMO channel vector $\mathbf{h}_{i,\pi_k(j)}^{(k)}$ is isotropically distributed and is independent of the ZF vectors $\bar{\mathbf{g}}_m^{(i)}$ for all $m \in \{1, \dots, S\}$, each projection on $\bar{\mathbf{g}}_m^{(i)}$ is a complex Gaussian random variable with zero-mean and unit variance. Thus, the user scheduling metric L_j^i in (2), representing the total sum of $K-1$ LIF values, follows the chi-square distribution with $2(K-1)S$ degrees of freedom

for any $j = 1, 2, \dots, N$. The cumulative distribution function (cdf) $F_L(l)$ of the metric L_j^i is given by

$$F_L(l) = \frac{\gamma((K-1)S, l/2)}{\Gamma((K-1)S)},$$

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

Lemma 1: For any $0 \leq l < 2$, the cdf $F_L(l)$ of the metric L_j^i is lower- and upper-bounded by

$$C_1 l^{(K-1)S} \leq F_L(l) \leq C_2 l^{(K-1)S},$$

where

$$C_1 = \frac{e^{-1} 2^{-(K-1)S}}{(K-1)S \cdot \Gamma((K-1)S)},$$

$$C_2 = \left(\frac{1}{(K-1)S} + \frac{l}{(K-1)S + 2 - l} \right) \frac{2^{-(K-1)S}}{\Gamma((K-1)S)},$$

and $\Gamma(z)$ is the Gamma function.

The proof of this lemma is presented in [16]. It is now possible to derive the achievable DoFs for cellular networks using the OIM protocol.

Theorem 1: Suppose that the OIM scheme with S simultaneously transmitting users in a cell is used in the IMAC model. Then,

$$\sum_{i=1}^K \sum_{j=1}^N d_j^{(i)} = KS$$

is achievable with high probability if and only if $N = \omega(\text{SNR}^{(K-1)S})$, where $S = \{1, \dots, M\}$.³

Proof: A brief sketch of the proof is provided in this paper. The OIM scheme achieves KS DoFs if the value

$$\sum_{k=1, k \neq i}^K \sum_{j=1}^S \left| \bar{\mathbf{g}}_m^{(i)H} \mathbf{h}_{i, \pi_k(j)}^{(k)} \right|^2 \text{SNR} \quad (3)$$

for all $i \in \{1, 2, \dots, K\}$ and $m \in \{1, 2, \dots, S\}$ is smaller than or equal to some constant $\epsilon > 0$ independent of SNR. The number of DoFs is lower-bounded by

$$\sum_{i=1}^K \sum_{j=1}^N d_j^{(i)} \geq P_{\text{OIM}} KS,$$

which holds since KS DoFs are achieved for a fraction P_{OIM} of the time, where

$$P_{\text{OIM}} = \lim_{\text{SNR} \rightarrow \infty} \Pr \left\{ \sum_{k=1, k \neq i}^K \sum_{j=1}^S \left| \bar{\mathbf{g}}_m^{(i)H} \mathbf{h}_{i, \pi_k(j)}^{(k)} \right|^2 \text{SNR} \leq \epsilon \right. \\ \left. \text{for all } i \in \{1, 2, \dots, K\} \text{ and } m \in \{1, 2, \dots, S\} \right\}.$$

³We 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) $f(x) = o(g(x))$ means that $\lim_{x \rightarrow \infty} \frac{f(x)}{g(x)} = 0$. iii) $f(x) = \Omega(g(x))$ if $g(x) = O(f(x))$. iv) $f(x) = \omega(g(x))$ if $g(x) = o(f(x))$. v) $f(x) = \Theta(g(x))$ if $f(x) = O(g(x))$ and $g(x) = O(f(x))$ [19].

It can be analyzed that P_{OIM} converges to one only if $N = \omega(\text{SNR}^{(K-1)S})$. This implies that for the decoded symbol $\hat{x}_m^{(i)}$, the value in (3) is smaller than or equal to ϵ with probability approaching one as the received SNR tends to infinity, where $i \in \{1, \dots, K\}$ and $m \in \{1, \dots, S\}$, thereby resulting in KS DoFs. ■

From the above theorem, it is seen that the achievable DoFs are given by KM and KS ($S \in \{1, \dots, M-1\}$) when the OIN and OIA protocols are used in cellular networks, respectively. In fact, the OIN scheme achieves the optimal DoFs, which will be proved in Section IV by showing an upper bound on the DoFs, while it works under the condition that the total number N of required users per cell scales faster than $\text{SNR}^{(K-1)M}$. On the other hand, the OIA scheme operates with at least $\text{SNR}^{(K-1)S}$ users per cell, which is surely smaller than those of the OIN scheme, at the expense of some DoF loss. This gives us a trade-off between the achievable number of DoFs and the number N of possible users in a cell. Note that for the case where N is not sufficiently large to utilize the OIN scheme, the OIA scheme can instead be applied in the networks.

IV. UPPER BOUND FOR DOFS

In this section, to verify the optimality of the proposed OIN scheme, we derive an upper bound on the DoFs in cellular networks, especially for the IMAC model shown in Fig. 1. Suppose that \tilde{N} users (i.e., N streams) per cell transmit their packets simultaneously to the corresponding BS, where $\tilde{N} \in \{1, 2, \dots, N\}$.⁴ This is a generalized version of the transmission since it is not characterized how many users in a cell need to transmit their packets simultaneously to obtain the optimal DoFs. Now an upper bound on the total DoFs is simply obtained as follows.

Consider a genie-aided removal of all the inter-cell interferences. Then, we obtain K parallel MAC systems, each of which has an M antenna receiver and \tilde{N} single-antenna transmitters. If $\tilde{N} \geq M$, then the maximum DoFs of the SIMO MAC is given by M [20], [21], and hence the total number of DoFs for the IMAC model is finally upper-bounded by

$$\sum_{i=1}^K \sum_{j=1}^N d_j^{(i)} = KM,$$

where $d_j^{(i)}$ denotes the DoFs for the transmission of user j in the i -th cell for $i = 1, \dots, K$ and $j = 1, \dots, N$, since there are K cells in the network.

From Theorem 1, when the OIN scheme is used (i.e., the case of $S = M$), it is shown that the upper bound on the DoFs matches the achievable DoFs as long as the received SNR tends to infinity and N scales faster than $\text{SNR}^{(K-1)M}$. Therefore, the proposed OIN scheme is optimal in terms of DoFs.

⁴Note that \tilde{N} is different from S in Section II since \tilde{N} can be greater than M in general.

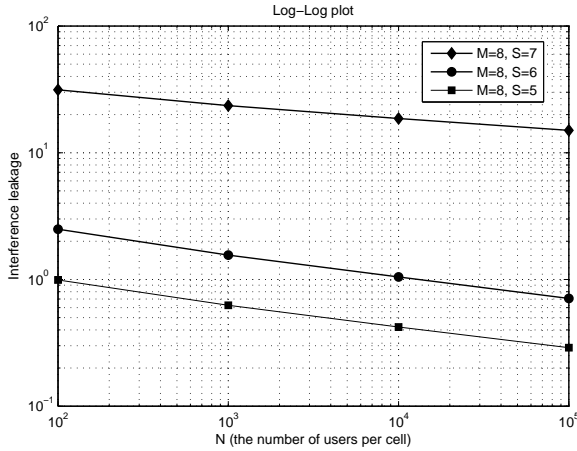


Fig. 2. The interference leakage with respect to N for some S . The system with $M = 8$, $K = 2$, and $SK > M$ is considered.

V. NUMERICAL EVALUATION

We perform computer simulations to validate the performance of the proposed OIA scheme in cellular networks. The average amount of interference leakage is evaluated as the number N of users in each cell increases. In our simulation, the channel vectors in (1) are generated 1×10^5 times for each system parameter.

In Fig. 2, the log-log plot of interference leakage versus N is shown as N increases.⁵ The interference leakage is interpreted as the total interference power remaining in each desired signal space (from the users in other cells) after the ZF filter is applied, assuming that the received signal power from a desired transmitter is normalized to 1 in the signal space. This performance measure enables us to measure the quality of the proposed IA scheme, as shown in [3]. We now evaluate the interference leakage for various system parameters. In Fig. 2, the case with $M = 8$, $K = 2$, and $SK > M$ is considered, where S denotes the number of simultaneously transmitting users per cell. It is shown that when the parameter S varies from 7 to 5, the interference leakage decreases due to less interferers, which is rather obvious. The result, illustrated in Fig. 2, indicates that the interference leakage tends to decrease linearly with N , while the slopes of the curves are almost identical to each other as N increases. It is further seen how many users per cell are required to guarantee that the interference leakage is less than an arbitrarily small $\epsilon > 0$ for given parameters M , S , and K .

VI. CONCLUSION

Two types of OIM protocols were proposed in cellular networks, where they do not require the global CSI, infinite dimension extension, and parameter adjustment through iteration. The achievable DoFs were then analyzed—the OIM protocol achieves KS DoFs as long as N scales faster than

$SNR^{(K-1)S}$, where $S \in \{1, \dots, M\}$. It has been seen that there exists a trade-off between the achievable number of DoFs and the parameter N based on the two OIM schemes. From the result of the upper bound on the DoFs, it was shown that the OIM protocol with $S = M$ achieves the optimal DoFs with the help of the MUD gain.

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⁵Even if it seems unrealistic to have a great number of users in a cell, the range for parameter N is taken into account to precisely see some trends of curves varying with N .