On the Degrees of Freedom of Wide-Band Multi-Cell Multiple Access Channels With No CSIT

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Abstract—This paper considers a $K$-cell multiple access channel with inter-symbol interference (ISI). The primary finding of this paper is that, without instantaneous channel state information at a transmitter, the interference-free sum degrees of freedom of $K$ is asymptotically achievable when the number of users per cell is sufficiently large, and also when the number of channel-impulse-response taps of desired links is greater than that of interfering links. This achievability is shown by a blind interference management method that exploits the relativity in delay spreads between desired and interfering links.

I. INTRODUCTION

A multi-cell multiple access channel (MAC) with inter-symbol interference captures the communication scenario in which multiple uplink users per cell communicate with their associated base stations (BSs) by utilizing the same time and frequency resources across both the users and the BSs. The spectral efficiency of this channel is fundamentally limited by three different types of interference:

- Inter-cell interference (ICI), which arises from simultaneous transmissions of users in neighboring cells;
- Inter-user-interference (IUI), which is caused by simultaneous transmissions of multiple users in the same cell; and
- Inter-symbol-interference (ISI), which occurs by the relativity between the transmit signal’s bandwidth and the coherence bandwidth of a wireless channel.

Orthogonal frequency division multiple access (OFDMA) is the most well-known approach to mitigate both IUI and ISI in the multi-cell systems [1], [2]. The key idea of OFDMA is to decompose a wideband (frequency-selective) channel into multiple orthogonal narrowband (frequency-flat) subchannels, each with no ISI. By allocating non-overlapping sets of subchannels to the users in a cell, each user is able to send information data without suffering from ISI and IUI in the cell. For instance, in a two-user MAC with ISI, which captures a single-cell uplink communication scenario, the capacity has been characterized by finding an optimal power allocation strategy across the subchannels [3], [4]. These approaches, however, still suffer from ICI, which is a major hindrance in attempting to increase spectral efficiency in multi-cell scenarios.

Multi-cell cooperation has been considered as an effective solution to manage ICI problems for future cellular networks where BSs are densely deployed and small cells overlap heavily with macrocells [5]–[7]. The common idea of multi-cell cooperation is to form a BS cluster, which allows the information exchange among the BSs within the cluster, in order to jointly eliminate ICI.

Among multi-cell cooperation strategies, coordinated beamforming, which only requires channel state information (CSI) exchange among the BSs in the same cluster, provides a good tradeoff between the overheads for the information exchange and the gains on the spectral efficiency [6], [7]. Interference alignment (IA) is a representative coordinated beamforming method, which aligns ICI in a subspace to confine the signal dimension occupied by interference [8]. For example, in a single-input-single-output (SISO) interference channel, IA has shown to be an optimal strategy in the sense of sum degrees-of-freedom (DoF) that is the approximate sum spectral efficiency in a high signal-to-noise-ratio (SNR) regime [8]. The concept of IA has also been extended to multi-cell MACs (or interfering MACs) in single antenna settings [9], [10] and multiple antenna settings [12]–[14]. One remarkable result is that, by an uplink IA method, the sum-DoF of $K$ is asymptotically achievable in the $K$-cell SISO MAC as the number of uplink users per cell approaches infinity [9]–[11]. The common requirement of the prior work in [8]–[14] is global and perfect CSI at a transmitter (CSIT), which is a major obstacle in implementing these IA methods in practice.

All the aforementioned multi-cell cooperation strategies have focused on the mitigation of ICI under the premise of perfect IUI and ISI cancellation by OFDMA. Recently, a blind interference management method has been proposed for the $K$-user SISO interference channel with ISI [15]. The key idea of this method is to exploit the relativity of multipath-channel lengths between desired and interfering links. This channel relativity allows the ICI alignment with discrete Fourier transform (DFT)-based precoding that needs no CSIT. One remarkable result in [15] is that, with completely no CSIT, the sum-DoF of the $K$-user interference channel can be made to scale linearly with the number of communication pairs $K$, 

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under some conditions on ISI channels.

In this paper, we consider the $K$-cell SISO MAC with ISI, as illustrated in Fig. 1. Continuing in the same spirit with [15], we attempt to characterize the sum-DoF of the multi-cell MAC with ISI in the absence of CSIT. Our major contribution is to demonstrate that, without instantaneous CSIT, the sum-DoF of the considered channel is

$$
(1 - \frac{L_1}{L_D}) K,
$$

provided that the number of users per cell is larger than $L_D - L_1$ with $L_D > 2L_1$, where $L_D$ and $L_1$ are the maximum channel-impulse-response (CIR) lengths of desired and ICI links in each cell, respectively. Our result implies that interference-free DoF per cell (i.e., sum-DoF of $K$) is achievable as $\frac{L_0}{L_1}$ approaches infinity with a sufficiently large number of users per cell. This result extends the sum-DoF result in [15], where the sum-DoF of $K$ is shown to be achievable without CSIT when each BS communicates with a single user. Therefore, our result also shows that communicating with multiple users in a cell provides a significant DoF gain compared to the single-user case, even in the absence of CSIT.

To show our result, we modify the blind interference management method introduced in [15]. The underlying idea of this method is to exploit the relativity in delay spreads between desired and ICI links. Specifically, by adding the cyclic prefix at transmitters with an appropriate length and by removing it at receivers, we create non-circulant matrices for the desired link, while generating circulant channel matrices for the ICI links in the absence of CSIT knowledge. This relativity in the matrix structure allows us to align all the ICI signals to the same direction, while making the desired signals spread over the entire signal dimensions. As a result, all ICI can be simply canceled by using linear receive beamforming that does not depend on channel realizations. After the ICI cancellation, each BS reliably decodes data symbols sent from the associated users by eliminating the remaining IUI and ISI perfectly, based on local CSI at a receiver (CSIR).

II. SYSTEM MODEL

We consider a $K$-cell SISO MAC with ISI, where $U_k$ uplink users attempt to access the BS in the $k$-th cell, $k \in \mathcal{K} = \{1, 2, \ldots, K\}$, by using the common time-frequency resources. Let $(k, u)$ be the user index denoting the $u$-th user in cell $k$. We assume that all users and BSs are equipped with a single antenna. The CIR between a user (a transmitter) and a BS (a receiver) is represented by a finite number of channel taps. Thus, we denote the CIR between user $(i, u)$ and the $k$-th BS by $[h_{i,u}^k[\ell]]_{\ell=0}^{L_{k,i}-1}$, where $L_{k,i}$ is the length of the CIR. This length is typically defined as $L_{k,i} = \lfloor T_{D,k}^{\text{BW}} \rfloor$, where $T_{D,k}^{\text{BW}}$ and $T_{D,k}^{\text{BW}}$ are the transmission bandwidth of the system and the delay spread of the wireless channel from user $(i, u)$ to the $k$-th BS, respectively.

We assume a block-fading channel model in which channel coefficients $[h_{i,u}^k[\ell]]$ are time-invariant during each block transmission. We also assume that channel coefficients $[h_{i,u}^k[\ell]]$ are drawn from an independent and continuous distribution. For example, in a rich-scattering propagation environment, channel coefficients can be modeled as circularly symmetric complex Gaussian random variables.

Let $x_{k,n}[n]$ be the transmitted signal of user $(k, u)$ at time slot $n$ with the power constraint of $\mathbb{E}[|x_{k,n}[n]|^2] = P$. Then the received signal of the $k$-th BS at time slot $n$ is

$$
y_k[n] = \sum_{i=1}^{K} \sum_{u=1}^{U_i} \sum_{\ell=0}^{L_{k,i}-1} h_{i,u}^k[\ell] x_{i,u}[n-\ell] + z_k[n],
$$

where $z_k[n]$ is noise at the $k$-th BS in time slot $n$. We assume that $z_k[n]$ is independent and identically distributed (IID) circularly symmetric complex Gaussian random variable with zero mean and variance $\sigma^2$, i.e., $\mathcal{CN}(0, \sigma^2)$.

Throughout the paper, we assume no CSIT, implying that all users (transmitters) do not have any knowledge of channel realizations $[h_{i,u}^k[\ell]]_{\ell=0}^{L_{k,i}-1}$ for $i \neq k$ and $i, k \in \mathcal{K}$. Furthermore, it is assumed that each BS is available to access knowledge of CSI between itself and the associated users in the cell, i.e., $[h_{k,u}^i[\ell]]_{\ell=0}^{L_{k,i}-1}$ for $k \in \mathcal{K}$. This is referred to as local CSIR. Note that local CSIR is necessary to perform coherent detection at the BSs.

Each user sends independent $m_{k,u}$ data symbols to the associated BS during $M$ time slots. In this case, the rate of the $k$-th BS is given by $R_k(P) = \frac{\sum_{u=1}^{U_i} \log_2 |m_{k,u}|}{M}$. The rate $R_k(P)$ is achievable if the $k$-th BS is able to decode the transmitted data symbols with an arbitrarily-small error probability by choosing a sufficiently large $M$. Then the sum-DoF that characterizes an approximate sum of achievable rates of the system at high SNR is defined as

$$
d_2 = \lim_{P \to \infty} \frac{\sum_{k=1}^{K} R_k(P)}{\log(P)}.
$$

III. MAIN RESULT

The following theorem is the main result of this paper, which characterizes the sum-DoF of a $K$-cell SISO MAC with ISI in the absence of CSIT.
Theorem 1. Consider a $K$-cell MAC with ISI, each cell with $U_k$ uplink users. Let $L_1 = \max_k \max_{i \neq k} L_{k,i}$ and $L_D = \max_k L_{k,k}$. The achievable sum-DoF of this channel with completely no CSIT is

$$d^\text{MAC}_S = \max \left\{ \sum_{k=1}^K \min \left\{ \frac{U_k(L_{k,k} - L_1)^+}{\max \{L_D,2L_1-1\}} \right\}, 1 \right\},$$

where $(x)^+ = \max(x,0)$.

Proof: See Section IV.

Theorem 1 shows the achievable sum-DoF for a general ISI condition, yet it is unwieldy to provide a clear intuition in the result. Considering a symmetric ISI scenario, we simplify Theorem 1 to the following Corollary:

Corollary 1. (Symmetric ISI condition) Consider a $K$-cell MAC with symmetric ISI, i.e., $L_{k,k} = L_D$ and $L_{k,i} = L_1$ for $i \neq k$ and $i,k \in \mathcal{K}$. When the number of users per cell is larger than $L_D - L_1$ with $L_D > 2L_1$ for $k \in \mathcal{K}$, one can achieve the sum-DoF of

$$d^\text{MAC}_S = \left( 1 - \frac{L_1}{L_D} \right) K \rightarrow K, \quad \text{as} \quad \frac{L_D}{L_1} \rightarrow \infty.$$

Proof: This result is directly obtained from (3) for the considered scenario.

Corollary 1 implies that interference-free DoF per cell is asymptotically achievable even without CSIT, as the number of users per cell approaches infinity under the derived ISI condition. In other words, a total of $K$ DoF is asymptotically achievable if there exists a sufficient number of users whose channel condition satisfies that $L_D \gg L_1$.

IV. PROOF OF THEOREM 1

We start by providing a lemma that is essential for our proof.

Lemma 1. A circulant matrix $C \in \mathbb{C}^{n \times n}$ is decomposed as

$$C = FAF^H,$$

where $F = [f_1, f_2, \ldots, f_n] \in \mathbb{C}^{n \times n}$ is the $n$-point IDFT matrix, $f_k = \frac{1}{\sqrt{n}} \left[ 1, \omega^{k-1}, \omega^{2(k-1)}, \ldots, \omega^{(n-1)(k-1)} \right]^H$ and $\omega = \exp \left( -j \frac{2\pi}{n} \right)$ for $k = \{1, 2, \ldots, n\}$.

Proof: See [17].

In this proof, we focus on the case that

$$\sum_{k=1}^K \min \left\{ \frac{U_k(L_{k,k} - L_1)^+}{\max \{L_D,2L_1-1\}} \right\} > 1,$$

because otherwise, the trivial sum-DoF of one is achievable by using time-division multiple access with OFDMA in each cell. Furthermore, we assume that the number of active users in cell $k$ is given by $U'_k = \min \{U_k(L_{k,k} - L_1)^+\}$ among $U_k$ users. This assumption implies that when $L_{k,k} \leq L_1$, none of the users in cell $k$ transmit the desired signal.

The key proof idea is similar to [15] using a block transmission method. We consider a block transmission that consists of $B$ subblock transmissions each with $\bar{N} = N + L_1 - 1$ time slots, where $N = \max \{L_D - L_1 + 1, L_1\}$. At the end of each transmission block, we use $L_D - 1$ additional time slots to avoid inter-block interference between two subsequent block transmissions. Therefore, the total number of time slots needed for a block transmission is $M = BN + L_1 - 1$.

Let $\tilde{x}^b_{k,u} \in \mathbb{C}^N$ be the input data vector of user $(k,u)$ during the $b$-th subblock transmission, defined as

$$\tilde{x}^b_{k,u} = [x_{k,u}(b-1)\bar{N} + 1, \cdots, x_{k,u}(b-1)\bar{N} + N]^T,$$

where $b \in \{1, 2, \ldots, B\}$. In each block $b$, user $(k,u)$ sends the data symbol $s^b_{k,u}$ by using precoding vector $f_1$, i.e., $\tilde{x}^b_{k,u} = f_1s^b_{k,u}$. We generate the transmitted signal vector of the $b$-th subblock with length $\bar{N}$ by adding a cyclic prefix with length $L_1 - 1$ to $\tilde{x}^b_{k,u}$ as follows: $\tilde{x}^b_{k,u} = \left[ \tilde{x}^b_{k,u}, \tilde{x}^b_{k,u} \right]^T$, where $\tilde{x}^b_{k,u} = [x_{k,u}(b-1)\bar{N} + N - L_1 + 2, \cdots, x_{k,u}(b-1)\bar{N} + N + 1]^T$.

After the transmission of $B$ subblocks, we append $L_D - 1$ zeros at the end of each block transmission, to avoid inter-block interference. The transmitted signal vector from user $(k,u)$ during a block transmission is given by

$$x_{k,u} = \left[ (\tilde{x}^1_{k,u})^T, (\tilde{x}^2_{k,u})^T, \cdots, (\tilde{x}^B_{k,u})^T, 0, \ldots, 0 \right]^T \bigg|_{\bar{N} - L_1 - 1}.$$

From (1), the received signal of the $k$-th BS at time slot $n$ of the $b$-th subblock transmission is

$$y_k[(b-1)\bar{N} + n] = \sum_{u=1}^U U'_k \sum_{\ell=0}^{L_k-1} h^b_{k,u}(\ell)x_{k,u}[(b-1)\bar{N} + n - \ell]$$

$$+ \sum_{i=1,i\neq k}^K \sum_{u=1}^U U'_i \sum_{\ell=0}^{L_i-1} h^b_{i,u}(\ell)x_{i,u}[(b-1)\bar{N} + n - \ell]$$

$$+ z_k[(b-1)\bar{N} + n],$$

where $n \in \{1, 2, \ldots, N\}$ and $b \in \{1, 2, \ldots, B\}$. Let $\tilde{y}^b_k = [y_k[(b-1)\bar{N} + L_1], \cdots, y_k[(b-1)\bar{N} + N]]^T \in \mathbb{C}^N$ and $\tilde{z}^b_k = [z_k[(b-1)\bar{N} + L_1], \cdots, z_k[(b-1)\bar{N} + N]]^T \in \mathbb{C}^N$ be the received signal and noise vectors of the $k$-th BS during the $b$-th subblock transmission after discarding the cyclic prefix, respectively. Then the received signal vector $\tilde{y}^b_k$ is expressed in a vector form:

$$\tilde{y}^b_k = \sum_{u=1}^{U'_k} \sum_{i=1,i\neq k}^K \tilde{H}^b_{i,u} f_{i,s^b_{i,u}} + \sum_{u=1}^{U'_k} \sum_{i=1,i\neq k}^K \tilde{H}^b_{i,u} f_{i,s^b_{i,u}} + z^b_k,$$

where $\tilde{H}^b_{i,u} \in \mathbb{C}^{N \times N}$ is a matrix representation of the convolution involved with $\tilde{x}^b_{k,u}$.

For the ease of exposition, we define $\text{Circ}(e)$ as an $n$ by $n$ circulant matrix with its first column is a vector $e \in \mathbb{C}^n$. Then the effective channel matrices of all the interfering links, $\tilde{H}^b_{i,u}$ for $i \neq k$, are represented as

$$\tilde{H}^b_{i,u} = \text{Circ}\left( \left[ h^b_{k,u}[0], \cdots, h^b_{k,u}[L_{k,k}-1],0,\ldots,0 \right] \right).$$
Whereas, the effective channel matrix of the desired link, \( \tilde{H}_{k,u}^k \), for \( k \in \mathcal{K} \), is decomposed into two matrices:

\[
\tilde{H}_{k,u}^k = \tilde{H}_{k,u}^C + \tilde{H}_{k,u}^{NC},
\]

where

\[
\tilde{H}_{k,u}^C = \text{Circ}\left( \begin{bmatrix} h_{k,u}^k[0], \ldots, h_{k,u}^k[N_k'-1] \end{bmatrix} \right),
\]

with \( N_k' = \min(L_k,k,N) \), and \( \tilde{H}_{k,u}^{NC} \) has the form of

\[
\tilde{H}_{k,u}^{NC} = \begin{bmatrix} -\tilde{H}_{k,u}^{up} & 0_{(N-L_k-1) \times (N-L_k+1)} \\ 0_{(L_k-1) \times (N-L_k+1)} & \tilde{H}_{k,u}^{low} \end{bmatrix}.
\]

In (15), \( \tilde{H}_{k,u}^{up} \in \mathbb{C}^{(N-L_k+1) \times (N-L_k+1)} \) and \( \tilde{H}_{k,u}^{low} \in \mathbb{C}^{(L_k-1) \times (N-L_k+1)} \) are upper and lower toeplitz matrices defined in (16) (see the top of the next page). Note that when \( N \geq L_k,k \), \( \tilde{H}_{k,u}^k \) is a circulant matrix, while \( \tilde{H}_{k,u}^{NC} \) is non-circulant matrices. This difference is due to the fact that the length of cyclic prefix is selected as \( L_k-1 \) such that \( L_k - 1 \leq L_k - 1 < L_k,k-1 \) for \( i \neq k \) and \( i,k \in \mathcal{K} \). This creates the relativity between desired links and ICI links by a matrix structure.

**Inter-cell-interference cancellation:** We explain a ICI cancellation method that exploits the relativity in the matrix structure between desired and ICI links. Plugging (13) into (11), we have

\[
\tilde{s}^b_k = \sum_{u=1}^{U'_k} \left( \tilde{H}_{k,u}^{NC} + \tilde{H}_{k,u}^C \right) f_i s^b_{k,u} + \sum_{i=1,i \neq k}^{K} \tilde{H}_{i,u}^{NC} f_i s^b_{i,u} + \tilde{z}^b_k.
\]

In (17), \( \tilde{H}_{k,u}^C \) and \( \tilde{H}_{i,u}^{NC} \) for \( i \neq k \) and \( i,k \in \mathcal{K} \) are circulant matrices, so from Lemma 1, the column vectors of a \( N \)-point IDFT matrix \( \mathbf{F} \) are the eigenvectors of these circulant matrices. Since \( f_1 \) is the first eigenvector of these matrices, we can rewrite the received signal expression in (11) as:

\[
\tilde{s}^b_k = \sum_{u=1}^{U'_k} \tilde{H}_{k,u}^{NC} f_i s^b_{k,u} + \tilde{z}^b_k
\]

\[
\quad + \sum_{i=1,i \neq k}^{K} \tilde{H}_{i,u}^{NC} f_i s^b_{l,u} + \sum_{i=1,i \neq k}^{K} \tilde{H}_{i,u}^{NC} f_i s^b_{l,u} + \tilde{z}^b_k.
\]

where \( \lambda_{k,u,1}^C \) and \( \lambda_{k,u,1}^{NC} \) are the eigenvalues of \( \tilde{H}_{k,u}^C \) and \( \tilde{H}_{i,u}^{NC} \) that correspond to the eigenvector \( f_1 \), respectively. As can be seen in (18), all the ICI signals are aligned in the same direction of \( f_1 \). As a result, it is possible to eliminate all the ICI signals by multiplying a projection matrix \( \mathbf{W} = [\mathbf{F}_1, \mathbf{F}_2, \ldots, \mathbf{F}_N]^H \in \mathbb{C}^{(N-1) \times N} \) to \( \tilde{s}^b_k \) in (18), which yields

\[
\tilde{s}^b_k = \mathbf{W} \tilde{s}^b_k = \sum_{u=1}^{U'_k} \mathbf{W} \tilde{H}_{k,u}^{NC} f_i s^b_{k,u} + \mathbf{W} \tilde{z}^b_k,
\]

where \( \tilde{s}^b_k \in \mathbb{C}^{N-1} \) is the effective received signal vector of the \( k \)-th BS from the \( b \)-th subblock transmission.
output relationship during an entire block transmission is

\[
\begin{bmatrix}
\tilde{y}^k_s \\
\tilde{y}^B_k
\end{bmatrix} = \begin{bmatrix}
\tilde{H}_k & 0^{\text{sub}} & \ldots & 0^{\text{sub}} \\
0^{\text{sub}} & \tilde{H}_k & \ldots & 0^{\text{sub}} \\
\ldots & \ldots & \ldots & \ldots \\
0^{\text{sub}} & 0^{\text{sub}} & \ldots & \tilde{H}_k
\end{bmatrix} \begin{bmatrix}
\bar{s}_k \\
\bar{s}_k \\
\ldots \\
\bar{s}_k
\end{bmatrix},
\]  

(24)

where \(\tilde{H}_k^{\text{sub}} \in \mathbb{C}^{(N-1) \times U'_k}\) is the effective channel matrix for ISBI at the \(k\)-th BS, and \(0^{\text{sub}} = \mathbf{0}_{(N-1) \times U'_k}\). By definition, one can easily verify that \(\tilde{H}_k^{\text{sub}}\) is given by

\[
\tilde{H}_k^{\text{sub}} = W \begin{bmatrix}
\tilde{H}_k^{\text{sub}1} f_1, \tilde{H}_k^{\text{sub}2} f_1, \ldots, \tilde{H}_k^{\text{sub}U'_k} f_1
\end{bmatrix},
\]  

(25)

where \(\tilde{H}_k^{\text{sub}u} \in \mathbb{C}^{N \times N}\) is

\[
\tilde{H}_k^{\text{sub}} = \begin{bmatrix}
\mathbf{0}_{(N-L_k-1) \times (L_k-1)} & \tilde{H}_k^{\text{app}}_{k,u} \\
\mathbf{0}_{(L_k-1) \times (L_k-1)} & \mathbf{0}_{(L_k-1) \times (N'-L_k-1)}
\end{bmatrix},
\]  

(26)

by letting \(N'_k = L_{k,k}\). Since there is no ISBI during the first subblock transmission, i.e., \(\tilde{y}^k_s = \tilde{H}_k s_k + \tilde{z}^B_k\), it is possible to reliably decode \(s_k^b\) for sufficiently large SNR. Once the data symbol vector for the previous subblock transmission, say \(s_k^{b-1}\), is reliably decoded, it is possible to decode \(s_k^b\) by subtracting the effect of \(s_k^{b-1}\) from the received signal \(\tilde{y}^k_s\) as follows: \(\tilde{y}^k_s - \tilde{H}_k^{\text{sub}} s_k^{b-1} = \tilde{H}_k s_k^b + \tilde{z}^B_k\).

Achievable sum-DoF calculation: Applying the above ISBI cancellation strategy over \(B\) subblocks recursively, each BS \(k\) is capable of decoding \(BU'_k\) data symbol vectors \(s_k^1, s_k^2, \ldots, s_k^B\), with \(M = BN + L_D - 1\) channel uses. For sufficiently large coherence time, \(B\) can be taken to be infinity, so the achievable DoF of the \(k\)-th BS is

\[
d_k = \lim_{B \to \infty} \frac{BU'_k}{BN + L_D - 1} = \frac{U'_k}{N'}.
\]  

(27)

By plugging \(N = N + L_1 - 1\), \(N = \min\{L_D - L_1 + 1, L_1\}\), and \(U'_k = \min\{U_k, (L_{k,k} - L_1)^{\ast}\}\) to (27), we arrive at the expression in Theorem 1.

V. CONCLUSION

In this work, we showed that the interference-free sum-DoF of \(K\) is asymptotically achievable in a \(K\)-cell SISO MAC with ISI, even in the absence of CSIT. This achievability was demonstrated by blind interference alignment method that exploits the relativity in delay spreads between desired and interfering links. We observed that a significant DoF gain compared to the result in [15] is obtained when multiple users exist in a cell by improving the utilization of signal dimensions.

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