Soft Pilot Reuse and Multicell Block Diagonalization Precoding for Massive MIMO Systems

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Abstract—The users at cell edge of a massive multiple-input–multiple-output (MIMO) system suffer from severe pilot contamination (PC), which leads to poor quality of service (QoS). To enhance the QoS for these edge users, soft pilot reuse (SPR) combined with multicell block diagonalization (MBD) precoding is proposed. Specifically, the users are divided into two groups according to their large-scale fading coefficients, which are referred to as the center users, who only suffer from modest PC, and the edge users, who suffer from severe PC. Based on this distinction, the SPR scheme is proposed for improving the QoS for the edge users, whereby a cell-center pilot group is reused for all cell-center users in all cells, whereas a cell-edge pilot group is applied for the edge users in the adjacent cells. By extending the classical block diagonalization precoding to a multicell scenario, the MBD precoding scheme projects the downlink transmit signal onto the null space of the subspace spanned by the intercell channels of the edge users in adjacent cells. Thus, the intercell interference contaminating the edge users’ signals in the adjacent cells can be efficiently mitigated, and hence, the QoS of these edge users can be further enhanced. Our theoretical analysis and simulation results demonstrate that both the uplink and downlink rates of the edge users are significantly improved, albeit at the cost of the slightly decreased rate of center users.

Index Terms—Intercell interference (ICI), massive multiple-input–multiple-output (MIMO) system, multicell block diagonalization (MBD) precoding, pilot contamination (PC), quality of service (QoS), soft pilot reuse (SPR).

I. INTRODUCTION

In an effort to meet the escalating demand for increasingly higher capacity and improved-reliability wireless systems, the “massive” or large-scale multiple-input–multiple-output (LS-MIMO) concept has been proposed [1]–[3], where, typically, each base station (BS) is equipped with a large number of antenna elements (AEs) to serve far fewer single-AE users. This way, each user may have access to several AEs. This 39 LS-MIMO technology offers several significant advantages in 40 comparison with the conventional MIMO concept having a 41 moderate number of AEs. First, asymptotic analysis based on 42 random matrix theory [2] demonstrates that both the intracell 43 interference and the uncorrelated noise effects can be efficiently 44 mitigated, as the number of AEs tends to infinity. Furthermore, 45 the energy consumption of cellular BSs can be substantially 46 reduced [4], and the LS-MIMO systems are robust, since the 47 failure of one or a few of the AEs and radio-frequency chains 48 would not appreciably affect the resultant system performance 49 [1]. Additionally, low-complexity signal processing relying on 50 matched filter (MF)-based transmit precoding (TPC) and de- 51 tection can be used for approaching the optimal performance, 52 when the number of AEs at the BS tends to infinity [2]. 53

Similar to conventional MIMO systems, knowledge of the 54 channel state information (CSI) is also required at the BS of 55 LS-MIMO systems, namely, for data detection in the uplink 56 (UL) and for multiuser TPC in the downlink (DL) [2], [5]. 57 In the time-division duplexing (TDD) protocol, the BS esti- 58 mates the UL channels and obtains the DL CSI by exploiting 59 the channel’s reciprocity [1], [3], [6]. However, this approach 60 suffers from the so-called pilot contamination (PC) problem 61 [1]–[3] in multicell multiuser scenarios due to the reuse of 62 the pilot sequences in adjacent cells, which imposes grave 63 interference on the channel estimate at the BS. Furthermore, 64 the commonly used MF and zero-forcing (ZF) TPC schemes 65 will impose intercell interference (ICI) on the DL transmission, 66 which cannot be reduced by increasing the number of AEs at 67 the BS.

Hence, the problems of ICI and PC have been extensively studied [7]–[21]. The fractional frequency reuse (FFR) scheme [7]–[8] adopted in LTE Release 9 aims for mitigating the 71 ICI by assigning orthogonal frequency bands to edge users in 72 the adjacent cells at the cost of additional spectral resources. 73 The original frequency-division duplexing (FDD)-based coor- 74 dinated multipoint (CoMP) transmission of LTE-A Release 11 [9] is able to avoid the ICI between adjacent cells, whereby 76 each user estimates and feeds back the quantized DL channel 77 from all adjacent cells to the corresponding BS, and then, the 78 BS distributes the CSI to adjacent cells. However, this kind of 79 FDD-based CoMP technique would not be feasible for massive 80 MIMO since the CSI feedback overhead would be huge as the 81
number of BS antennas increases [10]. Using time-shifted pilot sequences for asynchronous transmission among the adjacent cells [11], [12] partially mitigates this problem, but it leads to mutual interference between data transmission and pilot transmission. A TPC scheme can be used for mitigating the ICI with the aid of joint multicell processing [13], [14] but, again, imposes a high information exchange overhead. In [15], specific conditions on the channel’s covariance matrix were imposed, which is only valid for the asymptotic case of infinitely many AEs at the BS. The angle of arrival (AOA)-based methods of [16] and [17] exploit the fact that the users having mutually nonoverlapping AOs hardly contaminate each other even if they use the same pilot sequence, but naturally, the efficiency of these methods relies on the assumption that the AOA spread of each user is small, which is not always the case under realistic channel conditions. A data-aided channel estimation scheme was proposed in [18], whereby partially decoded data are used for estimating the channel, and the PC effects can be beneficially reduced by iterative processing at the cost of an increased computational complexity. Additionally, the blind method of [19] and [20] based on subspace partitioning is capable of reducing the ICI under the assumption that the channel vectors of different users are orthogonal, which is not often the case in practice. The scheme proposed in [21] is capable of eliminating PC altogether, but this is achieved with the aid of a complex DL and UL training procedure. Note that all these existing contributions treat all users in the same way, as though they suffer from the same PC, but in reality, the severity of PC varies among the users.

Against the preceding background, inspired by the FFR scheme [7] adopted in LTE Release 9, we propose a soft pilot reuse (SPR) scheme for mitigating the PC of LS-MIMO systems, whereby a cell-edge pilot group is applied for the cell-edge users in adjacent cells, whereas the cell-center users reuse the same center pilot group in all cells. Furthermore, by extending the classical block diagonalization (BD) precoding to a multicell scenario, a multicell block diagonalization (MBD) TPC technique is conceived for mitigating the ICI and for enhancing the quality of service (QoS) for the edge users. Specifically, the contributions of this paper are summarized as follows.

- We break away from the traditional practice of treating the PC for all users identically—instead, we divide the users into two different groups to be considered separately, namely, center users subjected to a slight PC and the edge users suffering from more severe PC. This way, the center users can benefit directly from the LS-MIMO technology, and the efforts can be directed toward improving the QoS for the edge users.

- In contrast to the FFR scheme, which assigns orthogonal frequency bands to the edge users in adjacent cells, the proposed SPR scheme divides the pilot types into two groups within the same frequency band, i.e., in a center pilot group, which is reused for the center users in all cells, and in an edge pilot group, which is applied for the edge users in adjacent cells. Thus, for the edge users, the accuracy of the channel estimation is improved, and the UL achievable rate is increased. Moreover, by using slightly more pilot resources for edge users, the BS becomes capable of estimating not only the intracell 141 channels of the users within the reference cell but the 142 knowledge of the “intercell channels” of the edge users in the adjacent cells as well.

- Different from the original CoMP technique that has to obtain the intercell channels by consuming large overhead [9], [10], the proposed MBD precoding can directly exploit the partial knowledge of the intercell channels and is capable of suppressing the ICI imposed on the 149 edge users of the adjacent cells. Specifically, by extending the classical BD TPC to a multicell scenario, the MBD 151 TPC projects the DL transmit signal onto the null space 152 of the subspace spanned by the partially known intercell 153 channels. Thus, the ICI imposed on the edge users of the 154 adjacent cells can be substantially mitigated; hence, the 155 QoS of the edge users is significantly enhanced.

- To analyze the performance of our proposal, we compare the associated pilot requirements, derive the attainable average UL and DL rates, and characterize the computational complexity imposed. Our theoretical derivation confirms that both the achievable UL and DL rates of the 161 edge users are significantly improved at the cost of requiring slightly more pilots. Moreover, our simulation results show that the average UL and DL cell throughputs in the 164 SPR- and MBD-aided system are able to approach and even exceed that of the conventional system, provided that a modestly increased number of BS AEs are affordable.

The rest of this paper is organized as follows. In Section II, we review the multicell LS-MIMO system model, whereas Section III is devoted to detailing the PC, which is the main performance-limiting factor of LS-MIMO systems. Section IV further details the motivation of this paper, whereas Section V describes the proposed SPR scheme and the MBD precoding are discussed in Section VI. Section VII provides our performance analysis of the proposed SPR scheme and MBD precoding. Our simulation results quantifying the benefits of our proposals are presented in Section VII, whereas our conclusions follow in Section VIII.

Throughout our discussions, boldface lower and uppercase symbols represent vectors and matrices, respectively. The transpose, conjugate, and Hermitian transpose operators are given by $(\cdot)^T$, $(\cdot)^\dagger$, and $(\cdot)^H$, respectively. The Moore–Penrose pseudoinverse operator is denoted by $(\cdot)^+\!$, and the trace operator $\text{Tr}(\cdot)$, whereas $\text{diag}\{a_1, a_2, \ldots, a_m\}$ denotes the diagonal matrix associated with $a_1, a_2, \ldots, a_m$ at its diagonal entries, and the $M \times M$ identity matrix is given by $I_M$. The number of elements in a set is denoted by $\text{card}\{\cdot\}$, and the 187 $l_p$-norm is denoted by $\|\cdot\|_p$, whereas the expectation operator $\mathbb{E}\{\cdot\}$ is given by $\mathbb{E}\{\cdot\}$.

II. System Model

A multicell multiuser LS-MIMO system is illustrated in Fig. 1, which is composed of $L$ hexagonal cells, each having $M$ antennas to serve $K$ ($K < M$) 193
shown in Fig. 2, each coherence interval is composed of four stages for each user [12]: 1) UL data transmission; 2) UL pilot transmission; 3) BS processing; and 4) DL data transmission. 229

At the first stage, all users in all cells synchronously send UL data to their corresponding BSs, and the user data received at the BS in the $i$th cell can be represented as $y_i = \sqrt{p_u} \sum_{j=1}^{L} \sum_{k=1}^{K} h_{i,j,k} x_{i,j,k}^u + n_i^u$, where $x_{i,j,k}^u$ with $E\{\|x_{i,j,k}^u\|^2\} = 1$ denotes the symbol transmitted from the $k$th user roaming in the $j$th cell, $p_u$ represents the UL data transmission power, and $n_i^u \in \mathbb{C}^{M \times 1}$ denotes the corresponding UL channel’s additive Gaussian white noise (AWGN) vector.

For a typical LS-MIMO system, the pilot sequences used within a specific cell are orthogonal, but the same pilot group is typically reused in the adjacent cells due to the limited number of orthogonal pilot sequences. Thus, during the second stage, the matrix of pilot sequences received at the BS of the $i$th cell, which is denoted by $Y_i^p \in \mathbb{C}^{M \times \tau}$, can be represented as $Y_i^p = \sqrt{p_p} \sum_{j=1}^{L} \sum_{k=1}^{K} h_{i,j,k} \Phi + N_i^p$, where the matrix $\Phi = [\phi_1, \phi_2, \ldots, \phi_K]^T \in \mathbb{C}^{K \times \tau}$ contains the transmitted pilot sequence satisfies $\Phi \Phi^H = I_K$, $p_p$ is the transmission power of the pilots, and $N_i^p \in \mathbb{C}^{M \times \tau}$ denotes the UL channel’s AWGN matrix.

During the third stage, the BS of the $i$th cell obtains an estimate of the channel matrix $H_{i,i}$ using any conventional channel estimation method by directly correlating the received pilot matrix with the local pilot matrix, yielding

$$\hat{H}_{i,i} = \frac{1}{\sqrt{p_p}} Y_i^p \Phi^H = H_{i,i} + \sum_{j \neq i} H_{i,j} + \frac{1}{\sqrt{p_p}} N_i^p \Phi^H. \quad (4)$$

It can readily be seen that the channel estimate of the $k$th user in the $i$th cell, namely, $\hat{H}_{i,i,k}$, is a linear combination of 255 the channels $h_{i,j,k}$ for $1 \leq j \leq L$, which include the channels of the users in the other cells associated with the same pilot sequence. This phenomenon is referred to as PC [1]–[3]. Given 258 the estimated channel matrix $\hat{H}_{i,i}$ and by adopting the low-complexity MF detector, the detected symbol arriving from the $k$th user in the $i$th cell can be represented as

$$\hat{x}_{i,k}^u = \sqrt{p_u} \left( \hat{H}_{i,i,k}^H h_{i,i,k} x_{i,k}^u + \sum_{j \neq i} \hat{H}_{i,j,k}^H h_{i,j,k} x_{i,j,k}^u \right) + \varepsilon_{i,k}^u \quad (a)$$

$$\approx M \sqrt{p_u} \left( \beta_{i,i,k} x_{i,k}^u + \sum_{j \neq i} \beta_{i,j,k} x_{i,j,k}^u \right) \quad (b)$$

III. PILOT CONTAMINATION

By considering the TDD protocol, we adopt the widely used block-fading channel model, whereby the channel vectors $h_{i,j,k}$ remain constant during the channel’s coherence interval. As shown in Fig. 2, each coherence interval is composed of four
where $v_{i,k}$ denotes the $k$th column of $(1/\sqrt{p})\mathbf{N}_p \mathbf{\Phi}^H$, $\varepsilon_{i,k}^u$ represents the interference, which can be reduced to an arbitrary low level by increasing the number of transmit antennas $M$ at the BS, and $(a)$ indicates that the approximation holds as $C_{i,k} \approx E\{\log_2(1 + \text{SINR}_{i,k}^u)\}$, where $0 < \mu < 1$ evaluates the statistical fading coefficients associated with $M \rightarrow \infty$. Thus, the UL signal-to-interference-plus-noise ratio (SINR) of the $k$th user in the $i$th cell can be calculated as

$$\text{SINR}_{i,k}^u = \frac{\left| h_{i,k}^H h_{i,k} \right|^2}{\sum_{j \neq i} \left| h_{j,k}^H h_{i,k} \right|^2 + \varepsilon_{i,k}^u / \rho_u} \approx \frac{\beta_{i,k}^2}{\sum_{j \neq i} \beta_{j,k}^2} \quad \text{(6)}$$

and the achievable UL rate can be expressed as $C_{i,k}^u = (1 - 0.270 \mu) E\{\log_2(1 + \text{SINR}_{i,k}^u)\}$, where $0 < \mu < 1$ evaluates the statistical fading coefficients associated with the pilot transmission [24].

It is clear that the UL achievable rate remains limited by the 273 PC and it cannot be increased by simply assigning an increased transmission power and/or pilot power, i.e., by increasing $\rho_u$ and/or $\rho_p$.

The PC affects the DL transmission during the fourth stage as well. The normalized MF precoding matrix $[3]$ is commonly used for the DL transmission, which can be represented by $\mathbf{W}_i = \left( \frac{1}{\sqrt{\gamma_i}} \right) \mathbf{H}_{i,i}^H$, where $\gamma_i = \text{Tr}(\mathbf{H}_{i,i}^H \mathbf{H}_{i,i}^T) / K$ is a normalization factor. The BS in the $i$th cell transmits an $M$-dimensional signal vector as $s_i^T = \mathbf{W}_i x_i$, where $x_i = [x_{i,k}^1, x_{i,k}^2, \ldots, x_{i,k}^M]^T$ with $E\{|x_{i,k}^2|^2\}$ denotes the source symbol vector for the $K$ users in the $i$th cell. The received signals of the $K$ users in the $i$th cell can be collected together as $y_i^T = \sqrt{\rho_u} \sum_{j=1}^K h_{j,i}^T (1/\sqrt{\gamma_j}) \mathbf{H}_{j,i} x_j^T + n_i$, where $n_i$ denotes the DL channel AWGN vector associated with the $i$th cell, which is defined by $\mathbf{H}_{i,i} = \mathbf{I}_M$. Similar to the derivation shown in (6), the DL SINR of the $k$th user in the $i$th cell can be derived as

$$\text{SINR}_{i,k}^d = \frac{\left| h_{i,k}^T h_{i,k} \right|^2}{\sum_{j \neq i} \left| h_{j,k}^T h_{i,k} \right|^2 + \varepsilon_{i,k}^d / \rho_d} \approx \frac{\beta_{i,k}^2}{\sum_{j \neq i} \beta_{j,k}^2} \quad \text{(7)}$$

where $\varepsilon_{i,k}^d$ denotes the corresponding interference similar to $\varepsilon_{i,k}^u$, given in (5). The corresponding DL rate can be represented as

$$C_{i,k}^d = (1 - \mu) E\{\log_2(1 + \text{SINR}_{i,k}^d)\} \quad \text{(8)}$$

In summary, the PC caused by the reuse of the same orthogonal pilot group in adjacent cells cannot be reduced by increasing the number of antennas at the BS; hence, it limits the achievable performance of multicell multiuser LS-MIMO systems.

**IV. MOTIVATION OF OUR PROPOSAL**

In the existing state-of-the-art solutions [7], [8], [11]–[21], which aim for reducing the PC, all users are treated identically. However, according to (6) and (7), it becomes clear that the 300 attained SINR is proportional to the large-scale fading coefficients $\beta_{i,k}^2$, which are different for the $K$ users of each cell. Thus, we have to break away from this traditional concept of treating the PC for all users identically, which motivates our 303 idea of dividing the users of each cell into two groups, namely, the group of center users subjected to modest PC and the group of edge users suffering from severe PC. We will treat them 306 differently.

In fact, the limit of the UL SINR of the $k$th user in the $i$th cell, which is defined by

$$\eta_{i,k} = \frac{\beta_{i,k}^2}{\sum_{j \neq i} \beta_{j,k}^2}$$

specifies the severity of the PC for this user. Therefore, it is 310 easy to sort the users in a cell according to their SINR values 311 $\eta_{i,k}$, if all the large-scale fading coefficients $\{\beta_{i,k}^2\}$ are known at the BS, which is a key assumption stipulated in the state-of-the-art contributions [6], [11], [18]. However, in practice, it is 314 difficult for the BS to obtain an accurate estimate of the large-scale fading coefficients of the users in other cells, i.e., of $\beta_{j,k}^2$ for $j \neq i$, unless BS cooperation is invoked, which is typically 317 associated with a substantial side-information overhead. 318

Since we have $\eta_{i,k} \propto \beta_{i,k}^2$, we may also use $\beta_{i,k}^2$ for 319 estimating the severity of the PC for the $k$th user roaming in the $i$th cell. In contrast to $\beta_{i,k}^2$ for $j \neq i$, all the large-scale 321 fading coefficients $\{\beta_{j,k}^2\}$ of the $K$ users in the $i$th cell can be 322 readily obtained. Thus, the $K$ users in the $i$th cell can be readily 323 divided into two groups according to

$$\beta_{i,k}^2 > \rho_i \rightarrow \begin{cases} \text{Yes} & \rightarrow \text{center users} \\ \text{No} & \rightarrow \text{edge users.} \end{cases}$$

The user-grouping threshold $\rho_i$ can be set to

$$\rho_i = \frac{\lambda}{K} \sum_{k=1}^K \beta_{i,k}^2$$

where $\lambda$ can be adjusted according to the specific system configuration. A simple case is illustrated in Fig. 3, where, according to the large-scale fading coefficients $\{\beta_{i,k}^2\}$ and $\rho_i$, the users are divided into two groups, namely, the center users associated with only a slight PC and the group of edge users subjected to severe PC. Note that the threshold $\rho_i$ is not based on the geographic locations of the users—it is 332 rather based on the signal space of $\{\beta_{i,k}^2\}$. Since the center users only suffer from minor PC, the conventional LS-MIMO scheme outlined earlier is capable of attaining 335 a high performance. By contrast, the edge users suffer from 336
serious PC; hence, their performance based on the conventional LS-MIMO scheme is expected to be poor. To enhance the QoS of the edge users, who suffer from heavy PC, we propose the more sophisticated SPR scheme and MBD precoding in the following.

V. PROPOSED SOFT PILOT REUSE SCHEME AND MULTICELL BLOCK DIAGONALIZATION PRECODING

Based on the division of users into two groups as outlined in Section IV, it is plausible that the center users indeed benefit from the conventional LS-MIMO technique. By improved measures have to be considered for enhancing the QoS of the edge users, such as our SPR and MBD schemes, which will be discussed in detail in the following.

A. Proposed Soft Pilot Reuse Scheme

Inspired by the FFR scheme, which assigns orthogonal frequency bands to edge users in adjacent cells to prevent serious ICI in 3GPP LTE Release 9, we propose the SPR scheme to mitigate the PC, whereby orthogonal pilot subgroups are assigned to the edge users in the adjacent cells, whereas a center pilot group is reused for the center users of all cells.

More specifically, consider a typical LS-MIMO system, which is composed of $L$ hexagonal cells, where the $i$th cell supports $K_i$ users. In the conventional LS-MIMO scheme, each cell has $K$ orthogonal pilot sequences needed in the proposed SPR scheme can be calculated as

$$K_{CS} = \max\{K_i, i = 1, 2, \ldots, L\}. \quad (11)$$

In contrast to the conventional LS-MIMO scheme, where all users are treated identically, the $K_i$ users of the $i$th cell are first divided into two groups according to their large-scale fading coefficients $\{\beta_{i,t,k}^2\}$, which have cardinalities of

$$K_i = K_{i,c} + K_{i,e} \quad (12)$$

where $K_{i,c} = \text{card}\{k : \beta_{i,t,k}^2 > \rho_t\}$ denotes the number of center users, whereas $K_{i,e} = \text{card}\{k : \beta_{i,t,k}^2 \leq \rho_t\}$ represents the number of edge users. Thus, the number of orthogonal pilot sequences needed in the proposed SPR scheme can be calculated as

$$K_{SPR} = K_c + K_e \quad (13)$$

where $K_c = \max\{K_{i,c}, i = 1, 2, \ldots, L\}$ denotes the number of pilot sequences assigned to the center users, whereas $K_e = \sum_{i=1}^L K_{i,e}$ denotes the number of pilot sequences dedicated to the edge users. It should be pointed out that we assume having $L$ cooperating cells; thus, $L$ is a moderate value. For example, we have $L = 7$ for the classic seven-cell system. Then, the entire set of pilot resources $\Phi_{SPR} \in \mathbb{C}^{K_{SPR} \times \tau}$ associated with $\Phi_{SPR}^H \Phi_{SPR} = \mathbf{I}_{K_{SPR}}$ can be divided into

$$\Phi_{SPR} = [\Phi_c^T, \Phi_e^T]^T \quad (14)$$

where $\Phi_c \in \mathbb{C}^{K_c \times \tau}$ is reused for the center users in all cells, and $\Phi_e \in \mathbb{C}^{K_e \times \tau}$ is applied to the edge users of the adjacent cells. Furthermore, $\Phi_e$ can be divided into $L$ partitions, as

$$\Phi_e = [\Phi_{e,1}^T, \Phi_{e,2}^T, \ldots, \Phi_{e,L}^T]^T \quad (15)$$

where $\Phi_{e,i} \in \mathbb{C}^{K_{e,i} \times \tau}$ is applied to the $K_{e,i}$ edge users in the $i$th cell. Thus, the pilot sequences applied to edge users are orthogonal to those of the other users roaming in the adjacent cells.

In the example in Fig. 4, there are three hexagonal cells associated with $K_1 = 4$, $K_2 = 5$, and $K_3 = 6$ users. To completely eliminate the PC, whereby orthogonal pilot subgroups are assigned to the edge users in the adjacent cells, which is the dominant source of the ICI inflicted upon these edge users of the adjacent cells during the BS’s DL transmissions.

Specifically, we consider the same LS-MIMO system as in Section V-A, which is composed of $L$ hexagonal cells, where the $i$th cell has $K_i$ users. Based on the proposed SPR scheme, we divide the channel matrix $H_{i,j}$ as defined in (2) into two $M$ parts, i.e.,

$$H_{i,j} \rightarrow [H_{e,i,j}^c, H_{e,i,j}^e] \quad (16)$$

where $H_{i,j}^c \in \mathbb{C}^{M \times K_{i,e}}$ denotes the channel matrix of the link spanning from the center users in the $j$th cell to the BS in the $i$th cell, whereas $H_{i,j}^e \in \mathbb{C}^{M \times K_{i,e}}$ denotes the channel matrix of the link spanning from the edge users in the $j$th cell to the BS.
412 BS in the $i$th cell. Then, the pilot sequence received at the BS in the $i$th cell can be represented by

\[
\bar{Y}_i = \sqrt{p_p} \left( \sum_{j=1}^{L} H_{i,j}^e \Phi_c (r : K_{j,c}) + \sum_{j=1}^{L} H_{i,j}^e \Phi_{e,j} \right) + \bar{N}_i^c
\]  

(17)

414 where $\Phi_c (r : K_{j,c})$ denotes the submatrix composed of the first $K_{j,c}$ rows of $\Phi_c$, whereas $\bar{N}_i^c$ denotes the corresponding AWGN matrix at the UL receiver.

417 Then, the BS becomes capable of estimating the channel of its center users as

\[
\hat{H}_{i,i}^c = \frac{1}{\sqrt{p_p}} \bar{Y}_i^p \Phi_c^H (r : K_{i,c})
\]

418

419 where $\bar{N}_i^c = (1/\sqrt{p_p}) \bar{N}^p_i \Phi_c^H (r : K_{i,c})$, which can be reduced to an arbitrarily small value by increasing $M$, and $\hat{H}_{i,i}^c (c : K_{i,c})$ denotes the matrix composed of the first $K_{i,c}$ columns of $\hat{H}_{i,i}^c$. Note that, if we have $K_{i,c} < K_{j,c}$, then $K_{i,c} - K_{j,c}$ zero vectors are used to fill $\hat{H}_{i,i}^c (c : K_{i,c})$. In contrast to the conventional scheme of (4), the proposed scheme only allows the BS to use the partially acquired signal of its edge users without excessive PC, yielding the severity of the PC inflicted upon the channel estimation of the BS of the $i$th cell given in (18) is minor.

420 On the other hand, by adopting the proposed SPR scheme, the BS of the $i$th cell becomes capable of acquiring the channel estimate of its edge users without excessive PC, yielding

\[
\hat{H}_{i,e}^c = \frac{1}{\sqrt{p_p}} \bar{Y}_i^p \Phi_c^H (r : K_{i,e}) = \hat{H}_{e,i}^c + \bar{N}_i^c
\]  

(19)

422 where we have $\bar{N}_i^c = (1/\sqrt{p_p}) \bar{N}_i^p \Phi_c^H (r : K_{i,e})$, which can be made arbitrarily small by increasing the number of antennas at the BS. It is clear that the PC is completely eliminated for these edge users, and therefore, the channel estimation accuracy of these edge users is significantly enhanced. By contrast, with the conventional scheme, these edge users suffer from grave PC, and hence, their channel estimates have extremely poor quality, which severely limits the achievable UL detection performance.

423 With the aid of the proposed SPR scheme, the full channel estimate at the BS of the $i$th cell is then given by

\[
\hat{H}_{i,i} = \begin{bmatrix} \hat{H}_{i,i}^c & \hat{H}_{i,i}^e \end{bmatrix}
\]  

(20)

424 which is significantly more accurate than that of the conventional channel estimation scheme of (4). Thus, given this more accurate channel estimate, the UL achievable rate of the edge users can be significantly increased, which will be analyzed in detail in Section VI.

427 Moreover, since the edge users of the adjacent cells rely on orthogonal pilot sequences, a BS can also acquire the partial intercell channels for the edge users of the adjacent cells. Specifically, by correlating the received pilot matrix $\bar{Y}_i^p$ with $\Phi_{e,j}$, the BS of the $i$th cell becomes capable of acquiring the partial intercell channels from the edge users in the $j$th cell without PC, as follows:

\[
\hat{H}_{i,j}^e = \frac{1}{\sqrt{p_p}} \bar{Y}_i^p \Phi_{e,j}^H = \hat{H}_{i,j}^e + \bar{N}_{i,j}^e, \quad j \neq i
\]  

(21)

429 where $\bar{N}_{i,j}^e = (1/\sqrt{p_p}) \bar{N}_i^p \Phi_{e,j}^H$ can be rendered arbitrarily small upon increasing $M$. Thus, the BS of the $i$th cell becomes capable of accurately estimating all the partial intercell channels of the links spanning from the edge users of the adjacent cells, which comprises an estimate of the intercell channel matrix $\hat{A}_i = \hat{H}_{i,1}, \ldots, \hat{H}_{i,i-1}, \hat{H}_{i,i+1}, \ldots, \hat{H}_{i,L}^c$.

430 For instance, in the simple example depicted in Fig. 4, the BS is capable of estimating the channel of all of its edge users as well.

431 C. Multicell Block Diagonalization Precoding

432 By selecting the TPC vector for a specific user from the null space spanned by the channels of other users, the classical 472 BD TPC scheme [23] adopted in single-cell multiuser MIMO systems is capable of eliminating the multiuser interference. 474 Armed with the accurate estimate $\hat{A}_i$, the BS of the $i$th cell will be able to benefitfully preprocess its transmissions for the sake of reducing the ICI inflicted upon its neighboring edge users roaming in the adjacent cells, which is the topic in the 486 following.

477 To obtain the null space of the intercell channels, we first apply the classic singular value decomposition (SVD) [22] to the intercell channel matrix $\hat{A}_i$, yielding

\[
\hat{U}_i = \hat{U}_i \hat{\Sigma}_i \hat{V}_i^H
\]  

(23)

479 where $\hat{U}_i \in \mathbb{C}^{(K_e - K_{i,e}) \times (K_e - K_{i,e})}$ denotes the left singular 480 vector matrix, $\hat{V}_i \in \mathbb{C}^{M \times M}$ denotes the right singular vector matrix, and $\hat{\Sigma}_i \in \mathbb{C}^{(K_e - K_{i,e}) \times M}$ is composed of the singular values as

\[
\hat{\Sigma}_i = \begin{bmatrix} \hat{\Sigma}_i & 0_{(K_e - K_{i,e} - r_i) \times (M - r_i)} \\ 0_{(K_e - K_{i,e} - r_i) \times (M - r_i)} & 0_{(K_e - K_{i,e} - r_i) \times (M - r_i)} \end{bmatrix}
\]  

(24)

in which $r_i = \text{rank}(\hat{A}_i)$ is the rank of $\hat{A}_i$, $\hat{\Sigma}_i = \text{diag}(\sigma_{i,1}, \ldots, \sigma_{i,2}, \ldots, \sigma_{i,r_i})$, and the singular values satisfy

\[
\sigma_{i,1} \geq \sigma_{i,2} \geq \ldots \geq \sigma_{i,r_i} > 0.
\]  

(25)

480 According to the properties of full SVD, the null space of the 490 intercell channels, namely, $\text{Null}(\hat{A}_i) \subseteq \mathbb{C}^M$, can be spanned 491
by the columns of the matrix $B_i \in \mathbb{C}^{M\times(M-r_i)}$, which is a 
493 submatrix of $V_i$ defined by
\begin{equation}
B_i = [v_{i,r_1+1} v_{i,r_1+2}, \ldots, v_{i,M}] \tag{26}
\end{equation}
494 where $v_{i,j}$ denotes the $j$th column of $V_i$. Note that the exist-
495 tence of this null space is guaranteed owing to the fact that the 
496 number of antennas at the BS of LS-MIMO systems is much 
497 larger than that of the edge users, i.e., we have
\begin{equation}
M \gg K_e \geq K_i - K_i,e \geq r_i. \tag{27}
\end{equation}
498 The large null space of the intercell channels indicates that, 
499 for any TPC matrix chosen from this null space, i.e., $W_i \in \text{Null}(\hat{A}_i)$, we have
\begin{equation}
\hat{A}_i W_i = 0 \Rightarrow \left(\hat{H}_{i,j}^*\right)^T W_i = 0 \quad \forall j \neq i \tag{28}
\end{equation}
500 which means that this TPC matrix calculated for the $i$th cell 
501 is capable of eliminating the ICI inflicted upon the edge users 
502 roaming in the adjacent cells. It is plausible, however, that 
503 a precoding matrix, which is randomly chosen from the null 
504 space $\text{Null}(\hat{A}_i)$ may cause severe intracell interference. To 
505 avoid the deleterious effects of intracell interference, we may 
506 adopt a conventional TPC matrix onto this null space.

507 For example, by projecting this conventional MF precoding 
508 matrix $W_i^{MF} = (1/\sqrt{\gamma_i^{MF}})\hat{H}_{i,i}^*$ onto the null space Null$(\hat{A}_i)$, 
509 we can generate the MF-based MBD matrix as
\begin{equation}
W_i^{MF,MBD} = \frac{1}{\sqrt{\gamma_i^{MF}}} P_B, \hat{H}_{i,i}^* \tag{29}
\end{equation}
510 where $P_B = B_i B_i^H$ denotes the projection operator based on 
511 the matrix $B_i$, and $\gamma_i^{MF,MBD}$ is a normalization factor given by
\begin{equation}
\gamma_i^{MF,MBD} = \frac{1}{K_i} \text{Tr}\left(\hat{H}_{i,i}^T P_B H_{i,i}^*\right) \tag{30}
\end{equation}
512 in which $P_B^H = P_B$ and $P_B P_B^H = P_B$ are applied.
513 Similarly, by projecting the conventional ZF TPC matrix 
514 onto the null space Null$(\hat{A}_i)$, we can generate the ZF-based 
515 MBD matrix as
\begin{equation}
W_i^{ZF,MBD} = \frac{1}{\sqrt{\gamma_i^{ZF}}} \left(P_B^H, \hat{H}_{i,i}^*\right)^T \tag{31}
\end{equation}
516 where the normalization factor $\gamma_i^{ZF,MBD}$ is calculated as
\begin{equation}
\gamma_i^{ZF,MBD} = \frac{1}{K_i} \text{Tr}\left(\hat{H}_{i,i}^T P_B H_{i,i}^*\right)^{-1} \tag{32}
\end{equation}

Both the precoding matrices $W_i^{MF,MBD}$ and $W_i^{ZF,MBD}$ are 518 capable of eliminating the ICI imposed on the edge users 519 of the adjacent cells. An illustrative example is depicted in 520 Fig. 5, where, based on the proposed SPR scheme, the BS 521 becomes capable of estimating the partial intercell channels 522 of the edge users roaming in the adjacent cells. The MBD 523 TPC then projects the DL transmission signal onto the null 524 space of the partial intercell channels to eliminate the ICI 525 contaminating the reception of these edge users in the adjacent 526 cells. Therefore, the MBD TPC significantly increases the DL 527 achievable rate of edge users, and consequently, the QoS of 528 edge users is considerably enhanced.

A. Pilot Resource Consumption

As seen in (11), the conventional scheme requires $K_{CS} = 537 \max\{K_i, 1 \leq i \leq L\}$ number of orthogonal pilot sequences, 538 and it suffers from grave PC. Again, to eliminate the PC caused 539 by the reuse of the same pilot group in adjacent cells, the most 540 plausible solution is to apply orthogonal pilot sequences to 541 all users in all cells. However, the number of orthogonal pilot 542 sequences would be increased to
\begin{equation}
K_{OS} = \sum_{i=1}^{L} K_i \tag{33}
\end{equation}
which leads to a substantial spectral efficiency reduction.

Recall that the proposed SPR and MBD schemes are capable 545 of enhancing the QoS for edge users at the expense of a slightly 546 increased number of pilot resources. More specifically, by 547 comparing (11) and (13), the additional pilot resources required 548 by the proposed SPR scheme can be derived as
\begin{equation}
K_{SPR} = K_{CS} - \sum_{i=1}^{L} K_{i,e} \tag{34}
\end{equation}
where $i_0$ denotes the index of the cell that has the most users, 550 i.e., $K_{i_0} = K_{CS}$. It is clear that the additional number of pilot 551 sequences is close to the total number of the edge users. Since 552 the edge users are classified according to the threshold $\rho_i$, 553 which can be adjusted by the parameter $\lambda$, the number of edge 554 users can be flexibly adjusted.
More explicitly, the careful choice of the parameter $\lambda$ provides a flexible tradeoff between the pilot resources required for the achievable system performance of the proposed SPR scheme. At one extreme, when the parameter $\lambda$ is set to 0, all the users will be regarded as edge users, and the proposed SPR scheme becomes equivalent to the orthogonal scheme, where all users in all cells use orthogonal pilot sequences. Naturally, this achieves the best performance but relies on the most pilot resources, requiring $K_{OS}$ orthogonal pilot sequences. At the other extreme, when the parameter $\lambda$ is set to a sufficiently large value, e.g., $\lambda = K_{CS}$, then all users are regarded as center users, and the proposed SPR scheme degrades to the conventional scheme that reuses the same pilot group in all cells. Hence, the resultant arrangement attains the worst performance but consumes the minimum pilot resources, hence requiring only $K_{CS}$ orthogonal pilot sequences.

### 572 B. Uplink Transmission

For the center users, the average SINR performance of SPR-aided UL transmission becomes almost the same as that of applying the conventional scheme. This is because, for the center users in a cell, the estimated channel matrix of (4) is obtained by applying the conventional scheme is very similar to that of (18) obtained by applying the SPR scheme. However, the achievable rate of the center users of the SPR-aided UL transmission is slightly reduced, since the pilot overhead increases, i.e., $\mu \rightarrow (K_{SPR}/K_{CS})\mu$. On the other hand, the performance of UL transmission for the edge users is much more complex, as shown in the following.

Similar to the received signal given in Section III based on the conventional scheme, the received signal at the BS of the $i$th cell based on the SPR scheme can be represented as

$$ y_i = \sqrt{p_u} \sum_{j=1}^{L} \left( H_{i,j}^e x_j^{u,e} + H_{i,j}^e x_j^{u,e} \right) + n_i $$

where $x_j^{u,e} = [x_j^{u,e}, x_j^{u,e}, \ldots, x_j^{u,e}]^T$ denotes the symbol vector transmitted from the $K_{j,e}$ center users in the $j$th cell, $x_j^{u,e} = [x_j^{u,e}, x_j^{u,e}, \ldots, x_j^{u,e}]^T$ is the symbol vector transmitted from the $K_{j,e}$ edge users in the $j$th cell, and $n_i$ denotes the corresponding UL AWGN vector.

By adopting the MF detector based on the channel estimation obtained by the SPR scheme for the edge users in the $i$th cell, i.e., $\hat{H}_{i,j}^e$ of (19), the detected symbol vector for the $K_{i,e}$ users in the $i$th cell is given by

$$ \hat{x}_{i}^{u,e} = \left( \hat{H}^e_{i,i} \right)^H y_i $$

$$ = \left( H_{i,i}^e + N_i^e \right)^H \sqrt{p_u} \sum_{j=1}^{L} \left( H_{i,j}^e x_j^{u,e} + H_{i,j}^e x_j^{u,e} \right) + n_i $$

$$ \approx \sqrt{p_u} \left( H_{i,i}^e \right)^H H_{i,j}^e x_j^{u,e} + \eta_i^{u,e} = M \sqrt{p_u} D_{i,i}^{e} x_i^{u,e} $$

where $D_{i,i}^{e} = \text{diag} \{ \beta_{1,i,i} \cdot \beta_{2,i,i}, \ldots \} \cdot \beta_{K_{j,e},i,i} \}$ denotes the sub-diagonal matrix of $D_{i,i}$ consisting of the $K_{i,e}$ edge users' large-scale fading coefficients, and $\eta_i^{u,e} = \left[ \eta_{i,1}^{u,e}, \eta_{i,2}^{u,e}, \ldots, \eta_{i,K_{i,e}}^{u,e} \right]^T$ denotes the interference, which can be made arbitrarily small by increasing the number of antennas at the BS. In particular, for the $k$th edge user in the $i$th cell, the detected symbol is given by

$$ \hat{x}_{i,k}^{u,e} = \sqrt{p_u} \left( H_{i,i}^e \right)^H H_{i,j}^e x_j^{u,e} + \mu_{i,k}^{u,e} + \eta_i^{u,e} $$

$$ \approx M \sqrt{p_u} D_{i,i}^{e} x_i^{u,e} + \mu_{i,k}^{u,e} $$

where $\mu_{i,k}^{u,e} = \sqrt{p_u} \sum_{j \neq k} \left( H_{i,j}^e \right)^H H_{i,j}^e x_j^{u,e} \approx M \sqrt{p_u} D_{i,i}^{e} x_i^{u,e}$ is the intracell interference arising from the other edge users in the same cell, which can be rendered arbitrarily small by increasing $M$. Similar to the derivation in (6), the UL SINR of the $k$th edge user in the $i$th cell can be calculated as

$$ \text{SINR}_{i,k}^{u,e} = \rho_u \left( \frac{H_{i,i}^e}{\mu_{i,k}^{u,e} + \eta_i^{u,e}} \right)^2 \left( \frac{H_{i,i}^e}{\mu_{i,k}^{u,e} + \eta_i^{u,e}} \right)^2 $$

and the achievable UL rate can be calculated as $C_{i,k}^{u,e} = (1 - 608 (K_{SPR}/K_{CS}))E\{\log_2(1 + \text{SINR}_{i,k}^{u,e})\}$. Note that, unlike the UL result of the conventional scheme given in (6), $\text{SINR}_{i,k}^{u,e}$ increases as $M$ increases, and in the asymptotic case of $M \rightarrow \infty$, we have $\text{SINR}_{i,k}^{u,e} \rightarrow \infty$.

In summary, in contrast to the conventional scheme, which is unable to remove the PC by simply increasing the number of antennas at the BS $M$, for the edge users, we eliminated the PC 615 imposed on the UL data transmission, and consequently, the UL achievable rate is significantly improved. Similar results can be obtained if we adopt the ZF detector for UL transmission in 618 our proposal, and the ZF detector outperforms the MF detector, 619 which will be verified by our numerical results.

### 573 C. Downlink Transmission

Similar to the analysis of the UL transmission, here, we focus on our attention on the DL transmission of the edge users in our 623 proposal.

By adopting the MFMBD precoding matrix as derived in 625 (29), the received signal vector of the $K_{i,e}$ edge users in the 626 $i$th cell can be represented as

$$ y_i^{d,e} = \sqrt{\rho_d} \sum_{j=1}^{L} \left( H_{i,j}^c \right)^T W_{ij}^{MFMBD} x_j^{d,e} + n_i^{d,e} $$

$$ = \sqrt{\rho_d} \sum_{j=1}^{L} \frac{1}{\sqrt{\gamma_{MFMBD}}} \left( H_{i,j}^c \right)^T B_j B_i^H y_j^{d,e} + n_i^{d,e} $$

$$ \approx \sqrt{\rho_d} \gamma_{MFMBD} \left( H_{i,i}^c \right)^T B_j B_i^H x_j^{d,e} + n_i^{d,e} $$

where $x_j^{d,e} = [x_j^{d,e}, x_j^{d,e}, \ldots, x_j^{d,e}]^T$ are the symbols transmitted to the $K_{j,e}$ center users in the $j$th cell, $x_j^{d,e} = 629 [x_j^{d,e}, x_j^{d,e}, \ldots, x_j^{d,e}]^T$ are the symbols destined for the $K_{j,e}$ 630
631 edge users in the $j$th cell, $\mathbf{n}_{j,k}^{d,e} = [\mathbf{n}_{j,k,1}^{d,e}, \mathbf{n}_{j,k,2}^{d,e}, \ldots, \mathbf{n}_{j,k,K_{i}}^{d,e}]^{T}$ denotes the corresponding DL AWGN vector, and the approximation $\approx$ holds as we apply $\mathbf{H}_{j, i}^{e} = \mathbf{H}_{j, i}$ and $(\mathbf{H}_{j, i}^{e})^{T} \mathbf{B}_{j} = 0$ for $j \neq i$ [see (28)].

633 Thus, for the $k$th edge user in the $i$th cell, the received symbol $\mathbf{y}_{i,k}^{d,e}$ can be represented as

$$\mathbf{y}_{i,k}^{d,e} \approx \sqrt{\frac{\rho_{a}}{\gamma_{\text{MBD}}}} \left( \mathbf{h}_{i,k,i}^{e} \right)^{T} \mathbf{B}_{i} \mathbf{B}_{i}^{\dagger} \left( \mathbf{h}_{i,k,i}^{e} \right)^{*} x_{i,k}^{d,e} + \mu_{i,k}^{d,e}$$

(40)

637 where the intracell interference $\mu_{i,k}^{d,e}$ is given by

$$\mu_{i,k}^{d,e} = \sqrt{\frac{\rho_{a}}{\gamma_{\text{MBD}}}} \left( \sum_{k' = 1}^{K_{i}} \mathbf{h}_{i,k,i}^{e} \right)^{T} \mathbf{B}_{i} \mathbf{B}_{i}^{\dagger} \left( \mathbf{h}_{i,k,i}^{e} \right)^{*} x_{i,k}^{d,e} + \sum_{k' \neq k} \left( \mathbf{h}_{i,k,i}^{e} \right)^{T} \mathbf{B}_{i} \mathbf{B}_{i}^{\dagger} \left( \mathbf{h}_{i,k,i}^{e} \right)^{*} x_{i,k}^{d,e}.$$

(41)

638 Both $\mathbf{n}_{i,k}^{d,e}$ and $\mu_{i,k}^{d,e}$ can be made arbitrarily small by increasing the number of antennas at the BS. The DL SINR of the $k$th edge user in the $i$th cell can be then calculated as

$$\frac{\text{SINR}_{i,k}^{d,e}}{\gamma_{\text{MBD}}} \approx \frac{\rho_{a}}{\gamma_{\text{MBD}}} \frac{\left( \mathbf{h}_{i,k,i}^{e} \right)^{T} \mathbf{B}_{i} \mathbf{B}_{i}^{\dagger} \left( \mathbf{h}_{i,k,i}^{e} \right)^{*}}{\mu_{i,k}^{d,e} + \mathbf{n}_{i,k}^{d,e}}.$$

(42)

641 and the achievable DL rate can be calculated as $\bar{C}_{i,k}^{d,e} = (1 - (K_{i}/K_{CS}) \mu) E\{\log_{2}(1 + \text{SINR}_{i,k}^{d,e})\}$. In contrast to the rest of the conventional scheme given in (7), the SINR increases as $M$ increases and in the asymptotic case of $M \rightarrow \infty$; hence, we have $\text{SINR}_{i,k}^{d,e} \rightarrow \infty$.

644 It is clear that, for the edge users, the PC is eliminated by our proposed scheme during the DL data transmission, and additionally, both the ICI and the intracell interference imposed on these edge users have been reduced by the MBD scheme. Similar results can be obtained if we adopt the ZF-based MBD TPC matrix, i.e., $\mathbf{W}_{i}^{\text{ZMBD}}$, for DL transmission in our proposal.

653 Taking into account the extra pilot resource, the achievable DL rate of the edge users has been significantly improved, whereas that of the center users is slightly reduced. Moreover, the average UL and DL cell throughputs of the SPR- and MBD-assisted system will be confirmed later by our simulation study.

658 D. Computational Complexity

659 The computational complexity of implementing the MBD scheme at the BS for the edge users will be quantified in terms of the number of complex-valued multiplications required, which includes the following two main contributions.

661 1) For the SVD operator, the complexity is on the order of $MK_{CS}^{2}$, which is denoted by $O(MK_{CS}^{2})$, which allows us to calculate $\hat{\mathbf{A}}_{i} = \mathbf{U}_{i} \Sigma_{i} \mathbf{V}_{i}^{H}$ by using the QR decomposition.

663 2) For the matrix pseudoinverse operation, the complexity is on the order of $O(MK_{CS}^{2})$, which allows us to generate the ZF-based MBD precoding matrix by using the Gram–Schmidt algorithm.

670 The total computational complexity of implementing the 671 MBD scheme at the BS is therefore on the order of $O(M(K_{CS}^{2} + 2K_{CS}^{2}))$, which is comparable with that of the conventional 673 scheme, and it is within the computational capability of a 674 typical state-of-the-art BS.

VII. SIMULATION STUDY

676 We evaluated the performance of the proposed SPR and 677 MBD schemes using a set of Monte Carlo simulations. A typical hexagonal cellular network of $L_{\text{total}}$ cells was considered, where the BS of each cell employed $M$ AEs, and the $i$th cell had $K_{i}$ single-AE users [2], [25], [26]. The default values of the various parameters of this simulated hexagonal cellular network are summarized in Table I. The large-scale fading coefficient $\beta_{i,j,k}$ was generated according to [2]

$$\beta_{i,j,k} = \frac{z_{i,j,k}}{(r_{i,j,k}/R)^{\alpha}}$$

(43)

684 where $R$ denotes the cell radius, and $\alpha$ is the path loss exponent, $685$ whereas $r_{i,j,k}$ is the distance between the $k$th user in the $686$ $j$th cell and the BS in the $i$th cell, whereas $z_{i,j,k}$ denotes the shadow fading factor, which obeys the log-normal distribution, i.e., $10 \log_{10}(z_{i,j,k})$ follows the zero-mean Gaussian 688 distribution having a standard deviation of $\sigma_{\text{shadow}}$. The reuse 689 factor of center pilot group $\Phi_{c}$ is 1, i.e., it is reused in all 690 $L_{\text{total}}$ cells, whereas the reuse factor of edge sub pilot groups 691 $\Phi_{e} = [\Phi_{e,1}^{T}, \Phi_{e,2}^{T}, \ldots, \Phi_{e,L_{\text{total}}}^{T}]$ is 7, i.e., the $i$th cell utilizes 692 $\Phi_{e,\text{mod}(i,7)+1}$ and nonadjacent cells reuse the same edge sub pilot group. The locations of the users in each cell were all 693 randomly generated in each trial. A particular simulation trial 694 is shown in Fig. 6, where the red crosses and green dots in each 695 cell denote the center users and edge users, respectively, which 696 are classified by the BS based on the threshold $\rho_{i}$ associated 697 with the parameter $\lambda = 0.1$. As stated previously and shown 698 in Fig. 6, the classification of center users and edge users is not 699 based on their distance from the serving BS.
Fig. 6. Instantiation of the randomly generated user distribution in the simulated hexagonal cellular network, where red crosses, green dots, and black numbers denote center users, edge users, and cell numbers, respectively.

Fig. 7. Channel estimation accuracy comparison for the conventional and proposed SPR schemes with $M = 128$.

Fig. 8. CDF of UL SINR for the conventional and proposed SPR schemes with $M = 128$ and $\lambda = 0.1$.

where $\hat{h}_{i,i,k}^c$ denotes the estimate of the true channel vector $h_{i,i,k}^c$. The average results over 100 random simulation runs are presented in Fig. 7. By increasing the grouping parameter $\lambda$, more users will be regarded as edge users. As expected, for the center users, who only suffer from a slight PC, both the conventional and proposed SPR schemes attain the same excellent channel estimation accuracy. However, the conventional scheme attains a poor channel estimation accuracy for the edge users, who suffer from severe PC. By contrast, since the PC is eliminated by applying orthogonal pilot sequences for the edge users in the adjacent cells, the channel estimation accuracy achieved by the proposed SPR scheme is significantly improved.

Fig. 8 shows the cumulative density function (CDF) of UL SINR for both the conventional and proposed SPR schemes with $M = 128$ and $\lambda = 0.1$, where the results are presented by 1000 random simulation trials. In each simulation run, the conventional scheme calculates the UL SINR of a center or an edge user according to the first line of (5). For our SPR scheme, the UL SINR of center users is similar to that for the conventional scheme, whereas the UL SINR of edge users is calculated by the first line of (36) in each simulation trial. Since the UL transmission of the proposed SPR scheme is almost the same as that of the conventional scheme for the center users, their curves in Fig. 8 are almost coincided. Observed in Fig. 8, our SPR scheme attains a significantly higher UL SINR for the edge users than the conventional scheme. Furthermore, the ZF detector is always better than the MF detector by about 2 dB for both center users and edge users.

Fig. 9 shows the CDF of UL achievable rate for the conventional and proposed SPR schemes with $M = 128$ and $\lambda = 0.1$, where the results are obtained from 500 random simulation runs. In each simulation trial, we generate the user positions first and then generate the channels of users for 50 times to obtain the UL achievable rate. Although the UL SINR results of the center users of the conventional and SPR schemes are the same as that of the conventional scheme, the UL achievable rate of the center users of the proposed SPR scheme is significantly improved.
are different due to the different pilot overheads, i.e., $\mu \rightarrow (K_{\text{SPR}}/K_{\text{CS}})\mu$. It is clear that the UL achievable rate of edge users is significantly improved by the SPR scheme, whereas the UL achievable rate of center users decreases due to the increased pilot overhead. Moreover, the ZF detector always outperforms the MF detector by about 0.3 b/s/Hz per user.

Fig. 10 shows the average UL cell throughput for the conventional and proposed SPR schemes with $M = 128$. It is clear that, by increasing the group parameter $\lambda$, there will be more users regarded as edge users, which leads to the increase of pilot overhead and the decrease of UL achievable rate of center users. Thus, the proper selection of grouping parameter is important, e.g., $\lambda \leq 0.2$, which improves the performance of edge users and ensures the cell throughput. Otherwise, e.g., $\lambda > 0.5$, it is clear that the loss caused by overlarge pilot overhead outweighs the gain of the SPR scheme. In addition, the ZF detector always provides a gain about 5 b/s/Hz of average cell throughput compared with the MF detector.

Fig. 11 shows the average UL cell throughput comparison of the conventional and proposed SPR schemes with $\lambda = 0.1$ against the number of BS antennas $M$. When the number of BS antennas is small, i.e., $M = 32$, the average UL cell throughput of the proposed SPR scheme is smaller than that of the conventional scheme about 5 b/s/Hz with MF detector adopted. It is obvious that, to obtain the performance gain for edge users as shown in Fig. 9, the proposed SPR scheme sacrifices the spectral efficiency due to the increased pilot overhead and leads to the average UL cell throughput reduction. However, by increasing the number of BS antennas, e.g., $M = 256$, it becomes clear that the average UL cell throughput of the proposed SPR scheme approaches that of the conventional scheme since the performance of edge users can be significantly improved by increasing $M$. Moreover, the ZF detector outperforms the MF detector a lot when $M$ is small, and the gap shrinks as $M$ increases.

Fig. 12 shows the CDF of DL achievable rate for the conventional system, the SPR-aided system, and the SPR- and MBD-assisted system with $M = 128$ and $\lambda = 0.1$. Despite the MBD precoding scheme, it is clear that the results of DL achievable rate are similar with that of UL achievable rate, as shown in Fig. 9, due to their duality property. When the MBD precoding is considered, we find that the DL achievable rate of edge users can be significantly improved due to the elimination of the ICI, whereas the DL achievable rate of center users slightly decreases since the projecting operator of the MBD precoding sacrifices degrees of freedom of the DL signals for center users. Again, we can find that the ZFMBD precoding achieves a gain about 0.4 b/s/Hz compared with the MFMBD precoding for edge users.

Fig. 13 shows the average DL cell throughput for the conventional system, the SPR-aided system, and the SPR- and MBD-assisted system with $\lambda = 0.1$ against $M$. The conventional system outperforms the SPR-aided system, whereas the MBD-assisted system performs worst when small number of BS antennas is considered, e.g., $M = 32$. However, considering the typical massive MIMO configuration as
Fig. 12. CDF of DL achievable rate for the conventional system, the SPR-aided system, and the SPR- and MBD-assisted system with $M = 128$ and $\lambda = 0.1$.

Fig. 13. Average DL cell throughput for the conventional system, the SPR-aided system, and the SPR- and MBD-assisted system with $\lambda = 0.1$ against $M$.

This grouping allows us to apply the proposed SPR scheme, whereby a center pilot group is reused for the center users in all $M$ cells, whereas the edge pilot group is applied to the edge users in the adjacent cells. By requiring a slightly increased number of pilot sequences, the proposed SPR scheme eliminates the PC inflicted upon the edge users who would otherwise suffer from severe PC in the conventional scheme. This significantly enhances the QoS for the edge users and, at the same time, ensures both the average UL and DL cell throughputs with slight and negligible reduction compared with that of the conventional system. Second, we further exploit the fact that the BS becomes capable of estimating the intercell channels of the edge users in the adjacent cells with the aid of the SPR regime without the deliterious effects of PC. Finally, we extend the classical BD precoding to a multicell scenario and propose the MBD precoding to eliminate the ICI imposed on the edge users of the adjacent cells in the DL. This MBD precoding further enhances the performance of edge users in DL transmission and improved the average DL cell throughput, in addition to the gain obtained by the SPR scheme.

VIII. CONCLUSION

We have developed an SPR and MBD precoding regime for LS-MIMO systems, which are capable of significantly enhancing both the achievable UL and DL rates for edge users. Our contribution is twofold. First, we break away from the traditional practice of treating all users as though they suffer from the same level of PC and propose a simple yet effective means of dividing the users into cell-center and cell-edge users.

REFERENCES


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AUTHOR QUERIES

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AQ1 = The phrase “meanwhile ensures both the average UL and DL cell throughput” was changed to “and, at the same time, ensures both the average UL and DL cell throughput....” Please check if appropriate. Otherwise, please make the necessary changes.

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Abstract—The users at cell edge of a massive multiple-input–
multiple-output (MIMO) system suffer from severe pilot contamina-
tion (PC), which leads to poor quality of service (QoS). To
enhance the QoS for these edge users, soft pilot reuse (SPR)
combined with multicell block diagonalization (MBD) precoding
is proposed. Specifically, the users are divided into two groups ac-
cording to their large-scale fading coefficients, which are referred
to as the center users, who only suffer from modest PC, and the
dge users, who suffer from severe PC. Based on this distinction,
the SPR scheme is proposed for improving the QoS for the edge
users, whereby a cell-center pilot group is reused for all cell-center
users in all cells, whereas a cell-edge pilot group is applied for
the edge users in the adjacent cells. By extending the classical
block diagonalization precoding to a multicell scenario, the MBD
precoding scheme projects the downlink transmit signal onto the
null space of the subspace spanned by the intercell channels of
the edge users in adjacent cells. Thus, the intercell interference
contaminating the edge users’ signals in the adjacent cells can be
efficiently mitigated, and hence, the QoS of these edge users can be
further enhanced. Our theoretical analysis and simulation results
demonstrate that both the uplink and downlink rates of the edge
users are significantly improved, albeit at the cost of the slightly
decreased rate of center users.

Index Terms—Intercell interference (ICI), massive multiple-
input–multiple-output (MIMO) system, multicell block diagonal-
ization (MBD) precoding, pilot contamination (PC), quality of
service (QoS), soft pilot reuse (SPR).

I. INTRODUCTION

An effort to meet the escalating demand for increasingly
higher capacity and improved-reliability wireless systems,

the “massive” or large-scale multiple-input–multiple-output
(LS-MIMO) concept has been proposed [1]–[3], where, typi-
cally, each base station (BS) is equipped with a large number of
antenna elements (AEs) to serve far fewer single-AE users. 38
This way, each user may have access to several AEs. This 39
LS-MIMO technology offers several significant advantages in
comparison with the conventional MIMO concept having a 41
moderate number of AEs. First, asymptotic analysis based on 42
random matrix theory [2] demonstrates that both the intracell 43
interference and the uncorrelated noise effects can be efficiently 44
mitigated, as the number of AEs tends to infinity. Furthermore, 45
the energy consumption of cellular BSs can be substantially 46
reduced [4], and the LS-MIMO systems are robust, since the 47
failure of one or a few of the AEs and radio-frequency chains 48
would not appreciably affect the resultant system performance 49
[1]. Additionally, low-complexity signal processing relying on 50
matched filter (MF)-based transmit precoding (TPC) and de- 51
tection can be used for approaching the optimal performance, 52
when the number of AEs at the BS tends to infinity [2]. 53

Similar to conventional MIMO systems, knowledge of the 54
channel state information (CSI) is also required at the BS of 55
LS-MIMO systems, namely, for data detection in the uplink 56
(UL) and for multiuser TPC in the downlink (DL) [2], [5]. 57
In the time-division duplexing (TDD) protocol, the BS esti-
mates the UL channels and obtains the DL CSI by exploiting 58
the channel’s reciprocity [1], [3], [6]. However, this approach 59
suffers from the so-called pilot contamination (PC) problem 60
[1]–[3] in multicell multiuser scenarios due to the reuse of 61
the pilot sequences in adjacent cells, which imposes grave 62
interference on the channel estimate at the BS. Furthermore, 63
the commonly used MF and zero-forcing (ZF) TPC schemes 64
will impose intercell interference (ICI) on the DL transmission, 65
which cannot be reduced by increasing the number of AEs at 66
the BS.

Hence, the problems of ICI and PC have been extensively 67
studied [7]–[21]. The fractional frequency reuse (FFR) scheme 68
[7], [8] adopted in LTE Release 9 aims for mitigating the 71
ICI by assigning orthogonal frequency bands to edge users in 72
the adjacent cells at the cost of additional spectral resources. 73
The original frequency-division duplexing (FDD)-based coor-
dinated multipoint (CoMP) transmission of LTE-A Release 11 74
[9] is able to avoid the ICI between adjacent cells, whereby 75
each user estimates and feeds back the quantized DL channel 76
when the number of AEs at the BS tends to infinity [2]. 53

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number of BS antennas increases [10]. Using time-shifted pilot sequences for asynchronous transmission among the adjacent cells [11], [12] partially mitigates this problem, but it leads to mutual interference between data transmission and pilot transmission. A TPC scheme can be used for mitigating the ICI with the aid of joint multicell processing [13], [14] but, again, imposes a high information exchange overhead. In [15], specific conditions on the channel’s covariance matrix were imposed, which is only valid for the asymptotic case of infinitely many AEs at the BS. The angle of arrival (AOA)-based methods of [16] and [17] exploit the fact that the users having mutually nonoverlapping AOAs hardly contaminate each other even if they use the same pilot sequence, but naturally, the efficiency of these methods relies on the assumption that the AOA spread of each user is small, which is not always the case under realistic channel conditions. A data-aided channel estimation scheme was proposed in [18], whereby partially decoded data are used for estimating the channel, and the PC effects can be beneficially reduced by iterative processing at the cost of an increased computational complexity. Additionally, the blind method of [19] and [20] based on subspace partitioning is capable of reducing the ICI under the assumption that the channel vectors of different users are orthogonal, which is not often the case in practice. The scheme proposed in [21] is capable of eliminating PC altogether, but this is achieved with the aid of a complex DL and UL training procedure. Note that all these existing contributions treat all users in the same way, as though they suffer from the same PC, but in reality, the severity of PC varies among the users.

Against the preceding background, inspired by the FFR scheme [7] adopted in LTE Release 9, we propose a soft pilot reuse (SPR) scheme for mitigating the PC of LS-MIMO systems, whereby a cell-edge pilot group is applied for the cell-edge users in adjacent cells, whereas the cell-center users reuse the same center pilot group in all cells. Furthermore, by extending the classical block diagonalization (BD) precoding to a multicell scenario, a multicell block diagonalization (MBD) TPC technique is conceived for mitigating the ICI and for enhancing the quality of service (QoS) for the edge users. Specifically, the contributions of this paper are summarized as follows.

- We break away from the traditional practice of treating the PC for all users identically—instead, we divide the users into two different groups to be considered separately, namely, center users subjected to a slight PC and the edge users suffering from more severe PC. This way, the center users can benefit directly from the LS-MIMO technology, and the efforts can be directed toward improving the QoS for the edge users.
- In contrast to the FFR scheme, which assigns orthogonal frequency bands to the edge users in adjacent cells, the proposed SPR scheme divides the pilot types into two groups within the same frequency band, i.e., in a center pilot group, which is reused for the center users in all cells, and in an edge pilot group, which is applied for the edge users in adjacent cells. Thus, for the edge users, the accuracy of the channel estimation is improved, and the UL achievable rate is increased. Moreover, by using slightly more pilot resources for edge users, the BS becomes capable of estimating not only the intracell channels of the users within the reference cell but the intercell channels of the “intercell channels” of the edge users in the adjacent cells as well.
- Different from the original CoMP technique that has to obtain the intercell channels by consuming large overhead head [9], [10], the proposed MBD precoding can directly exploit the partial knowledge of the intercell channels and is capable of suppressing the ICI imposed on the edge users of the adjacent cells. Specifically, by extending the classical BD TPC to a multicell scenario, the MBD TPC projects the DL transmit signal onto the null space of the subband spanned by the partially known intercell channels. Thus, the ICI imposed on the edge users of the adjacent cells can be substantially mitigated; hence, the QoS of the edge users is significantly enhanced.
- To analyze the performance of our proposal, we compare the associated pilot requirements, derive the attainable PC for all users identically—instead, we divide the users into two different groups to be considered separately, namely, center users subjected to a slight PC and the edge users suffering from more severe PC. This way, the center users can benefit directly from the LS-MIMO technology, and the efforts can be directed toward improving the QoS for the edge users.

The rest of this paper is organized as follows. In Section II, we briefly review the multicell LS-MIMO system model, whereas Section III is devoted to detailing the PC, which is the main performance-limiting factor of LS-MIMO systems. Section IV further details the motivation of this paper, whereas Section V discuses the proposed SPR scheme and the MBD precoding are discussed in Section V. Section VI provides our performance analysis of the proposed SPR scheme and MBD precoding. Our simulation results quantifying the benefits of our proposals are presented in Section VII, whereas our conclusions follow in Section VIII.

Throughout our discussions, boldface lower and uppercase symbols represent vectors and matrices, respectively. The transpose, conjugate, and Hermitian transpose operators are given by $(\cdot)^\top$, $(\cdot)^\dagger$, and $(\cdot)^H$, respectively. The Moore–Penrose pseudoinverse operator is denoted by $(\cdot)^+$, and the trace operator is represented by $\text{Tr}(\cdot)$, whereas $\text{diag}\{a_1, a_2, \ldots, a_m\}$ denotes the diagonal matrix associated with $a_1, a_2, \ldots, a_m$ at its diagonal entries, and the $M \times M$ identity matrix is given by $I_M$. The number of elements in a set is denoted by $\text{card}\{\cdot\}$, and the $l_p$ norm is denoted by $\|\cdot\|_p$, whereas the expectation operator is given by $E\{\cdot\}$.
shown in Fig. 2, each coherence interval is composed of four stages for each user [12]: 1) UL data transmission; 2) UL pilot transmission; 3) BS processing; and 4) DL data transmission. 

At the first stage, all users in all cells synchronously send UL data to their corresponding BSs, and the user data received at the BS in the $i$th cell can be represented as $y_i^n = \sqrt{\rho_0} \sum_{j=1}^L \sum_{k=1}^K h_{i,j,k} x_{i,j,k}^u + n_i^n$, where $x_{i,j,k}^u$ with 233 $E\{|x_{i,j,k}^u|^2\} = 1$ denotes the symbol transmitted from the $k$th user roaming in the $j$th cell, $\rho_0$ represents the UL data transmission power, and $n_i^n \in \mathbb{C}^{M \times 1}$ denotes the corresponding 236 UL channel’s additive Gaussian white noise (AWGN) vector 237 associated with $E\{n_i^n(n_i^n)^H\} = (\sigma_n^2)I_M$. 

For a typical LS-MIMO system, the pilot sequences used within a specific cell are orthogonal, but the same pilot group 240 is typically reused in the adjacent cells due to the limited number of orthogonal pilot sequences. Thus, during the second 242 stage, the matrix of pilot sequences received at the BS of the 243 $i$th cell, which is denoted by $Y_i^n \in \mathbb{C}^{M \times \tau}$, can be represented as $Y_i^n = \sqrt{\rho_p} \sum_{j=1}^L H_{i,j} \Phi + N_i^n$, where the matrix 245 $\Phi = [\phi_1, \phi_2, \ldots, \phi_K]^T \in \mathbb{C}^{K \times \tau}$ containing the transmitted 246 pilot sequence satisfies $\Phi^H = \Phi$, $\rho_p$ is the transmission power of the pilots, and $N_i^n \in \mathbb{C}^{M \times \tau}$ denotes the UL channel’s 248 AWGN matrix.

During the third stage, the BS of the $i$th cell obtains an estimate of the channel matrix $H_{i,j}$ using any conventional 251 channel estimation method by directly correlating the received 252 pilot matrix with the local pilot matrix, yielding

\[ \hat{H}_{i,j} = \frac{1}{\sqrt{\rho_p}} Y_i^n \Phi^H = H_{i,j} + \sum_{j \neq i} H_{i,j} + \frac{1}{\sqrt{\rho_p}} N_i^n \Phi^H. \] (4)

It can readily be seen that the channel estimate of the $k$th user in the $i$th cell, namely, $\hat{h}_{i,i,k}$, is a linear combination of 255 the channels $h_{i,j,k}$ for $1 \leq j \leq L$, which include the channels 256 of the users in the other cells associated with the same pilot 257 sequence. This phenomenon is referred to as PC [1]–[3]. Given 258 the estimated channel matrix $\hat{H}_{i,j}$ and by adopting the low-259 complexity MF detector, the detected symbol arriving from the 260 $k$th user in the $i$th cell can be represented as

\[ \hat{x}_{i,k}^u = \sqrt{\rho_n} \left(h_{i,i,k}^H \hat{h}_{i,i,k} + \sum_{j \neq i} h_{i,j,k}^H \hat{h}_{i,j,k} \right) + \eta_{i,k} \approx M \sqrt{\rho_n} \left( \beta_{i,i,k}^u x_{i,k}^u + \sum_{j \neq i} \beta_{i,j,k} x_{i,j,k}^u \right). \] (5)
where $\mathbf{v}_{i,k}$ denotes the $k$th column of $(1/\sqrt{p})\mathbf{N}_p\Phi^H$, $\varepsilon_{i,k}^u$ represents the interference, which can be reduced to an arbitrary low level by increasing the number of transmit antennas $M$ at the BS, and $\approx$ indicates that the approximation holds by invoking the asymptotic orthogonality associated with $M \to \infty$. Thus, the UL signal-to-interference-plus-noise ratio (SINR) 269 of the $k$th user in the $i$th cell can be calculated as

$$\text{SINR}_{i,k}^u = \frac{|h_{i,k}^H h_{i,k}|^2}{\sum_{j \neq i} |h_{j,k}^H h_{j,k}|^2 + |\varepsilon_{i,k}^u|^2 / \rho_u}$$

and the achievable UL rate can be expressed as $C_{i,k}^u = (1 - \mu) E\{\log_2(1 + \text{SINR}_{i,k}^u)\}$, where $0 < \mu < 1$ evaluates the spectral efficiency reduction caused by the pilot transmission [24]. It is clear that the UL achievable rate remains limited by the transmission power and/or pilot power, i.e., by increasing $\rho_u$ and/or $\rho_p$.

The PC affects the DL transmission during the fourth stage as well. The normalized MF precoding matrix [3] is commonly used for the DL transmission, which can be represented by $\mathbf{W}_i = (1/\sqrt{\gamma_i})\mathbf{H}_i^H$, where $\gamma_i = \text{Tr}(\mathbf{H}_i^H \mathbf{H}_i)/K$ is a normalization factor. The BS in the $i$th cell transmits an $M$-dimensional signal vector as $\mathbf{s}_i = \mathbf{W}_i \mathbf{x}_i$, where $\mathbf{x}_i = [x_{i,1}^d, x_{i,2}^d, \ldots, x_{i,K}^d]^T$ with $E\{|x_{i,k}^d|^2\} = 1$ denotes the source symbol vector for the $K$ users in the $i$th cell. The received signals of the $K$ users in the $i$th cell can be collected together as $\mathbf{y}_i^d = \sqrt{\rho_d} \sum_{j=1}^K \mathbf{H}_j^H (1/\sqrt{\gamma_j}) \mathbf{H}_j \mathbf{x}_j^d + n_i$, where $\mathbf{n}_i$ denotes the DL channel AWGN vector associated with $E\{|\mathbf{n}_i^d|^2\} = (\sigma_n^d)^2 I_M$. Similar to the derivation shown in [6], the DL SINR of the $k$th user in the $i$th cell can be derived as

$$\text{SINR}_{i,k}^d = \frac{|h_{i,k}^H h_{i,k}|^2}{\sum_{j \neq i} |h_{j,k}^H h_{j,k}|^2 + |\varepsilon_{i,k}^d|^2 / \rho_d}$$

where $\varepsilon_{i,k}^d$ denotes the corresponding interference similar to $\varepsilon_{i,k}^u$ given in (5). The corresponding DL rate can be represented as $C_{i,k}^d = (1 - \mu) E\{\log_2(1 + \text{SINR}_{i,k}^d)\}$. In summary, the PC caused by the reuse of the same orthogonal pilot group in adjacent cells cannot be reduced by increasing the number of antennas at the BS; hence, it limits the achievable performance of multicell multiuser LS-MIMO systems.

**IV. MOTIVATION OF OUR PROPOSAL**

In the existing state-of-the-art solutions [7], [8], [11]–[21], which aim for reducing the PC, all users are treated identically. However, according to (6) and (7), it becomes clear that the 300 attainable SINR is proportional to the large-scale fading coefficients $\beta_{i,k}^j$, which are different for the $K$ users of each cell. Thus, we have to break away from this traditional concept of 302 treating the PC for all users identically, which motivates our 303 idea of dividing the users of each cell into two groups, namely, 304 the group of center users subjected to modest PC and the group 305 of edge users suffering from severe PC. We will treat them 306 differently.

In fact, the limit of the UL SINR of the $k$th user in the $i$th cell, which is defined by

$$\eta_{i,k} = \frac{\beta_{i,k}^2}{\sum_{j \neq k} \beta_{i,j,k}^2}$$

specifies the severity of the PC for this user. Therefore, it is 310 easy to sort the users in a cell according to their SINR values. 311 If all the large-scale fading coefficients $\{\beta_{i,j,k}^j\}$ are known 312 at the BS, which is a key assumption stipulated in the state-of-313 the-art contributions [6], [11], [18]. However, in practice, it is 314 difficult for the BS to obtain an accurate estimate of the large-315 scale fading coefficients of the users in other cells, i.e., of $\beta_{j,k}^j$ for $j \neq i$, unless BS cooperation is invoked, which is typically 317 associated with a substantial side-information overhead.

Since we have $\eta_{i,k} \propto \beta_{i,k}^2$, we may also use $\beta_{i,k}^2$ for 319 estimating the severity of the PC for the $k$th user roaming in the 320 $i$th cell. In contrast to $\beta_{i,k}^2$ for $j \neq i$, all the large-scale 321 fading coefficients $\{\beta_{i,k}^j\}$ of the $K$ users in the $i$th cell can be 322 readily obtained. Thus, the $K$ users in the $i$th cell can be 323 divided into two groups according to

$$\beta_{i,k}^2 > \rho_i \rightarrow \begin{cases} \text{Yes} & \rightarrow \text{center users} \\ \text{No} & \rightarrow \text{edge users}. \end{cases}$$

The user-grouping threshold $\rho_i$ can be set to

$$\rho_i = \frac{\lambda}{K} \sum_{k=1}^K \beta_{i,k}^2$$

where $\lambda$ can be adjusted according to the specific system 326 configuration. A simple case is illustrated in Fig. 3, where, 327 according to the large-scale fading coefficients $\{\beta_{i,k}^j\}$ and 328 the given threshold $\rho_i$, the users are divided into two groups, 329 namely, the center users associated with only a slight PC and 330 the edge users subjected to severe PC. Note that the threshold $\rho_i$ 331 is not based on the geographic locations of the users—it is 332 rather based on the signal space of $\{\beta_{i,k}^j\}$. Since the center users only suffer from minor PC, the conven- 334 tional LS-MIMO scheme outlined earlier is capable of attaining 335 a high performance. By contrast, the edge users suffer from 336
serious PC; hence, their performance based on the conventional LS-MIMO scheme is expected to be poor. To enhance the QoS of the edge users, who suffer from heavy PC, we propose the more sophisticated SPR scheme and MBD precoding in the following.

V. PROPOSED SOFT PILOT REUSE SCHEME AND MULTICELL BLOCK DIAGNOSTIC PRECODING

Based on the division of users into two groups as outlined in Section IV, it is plausible that the center users indeed benefit from the conventional LS-MIMO technique. By contrast, improved measures have to be considered for enhancing the QoS of the edge users, such as our SPR and MBD schemes, which will be discussed in detail in the following.

A. Proposed Soft Pilot Reuse Scheme

Inspired by the FFR scheme, which assigns orthogonal frequency bands to edge users in adjacent cells to prevent serious ICI in 3GPP LTE Release 9, we propose the SPR scheme to mitigate the PC, whereby orthogonal pilot subgroups are assigned to the edge users in the adjacent cells, whereas a center pilot group is reused for the center users of all cells. In contrast to the conventional LS-MIMO scheme, where all users are treated identically, the \( K_i \) users of the \( i \)th cell are first divided into two groups according to their large-scale fading coefficients \( \{ \beta^2_{i,i,k} \} \), which have cardinalities of

\[
K_i = K_{i,c} + K_{i,e}
\]

where \( K_{i,e} = \text{card}\{ k : \beta^2_{i,i,k} > \rho_i \} \) denotes the number of center users, whereas \( K_{i,e} = \text{card}\{ k : \beta^2_{i,i,k} \leq \rho_i \} \) represents the number of edge users. Thus, the number of orthogonal pilot sequences needed in the proposed SPR scheme can be calculated as

\[
K_{\text{SPR}} = K_c + K_e
\]

where \( K_c = \max\{ K_{i,c}, i = 1, 2, \ldots, L \} \) denotes the number of pilot sequences assigned to the center users, whereas \( K_e = \sum_{i=1}^{L} K_{i,e} \) denotes the number of pilot sequences dedicated to the edge users. It should be pointed out that we assume having \( L \) cooperating cells; thus, \( L \) is a moderate value. For example, we have \( L = 7 \) for the classic seven-cell system. Then, the entire set of pilot resources \( \Phi_{\text{SPR}} \in \mathbb{C}^{K_{\text{SPR}} \times \tau} \) associated with \( \Phi_{\text{SPR}} \Phi^H_{\text{SPR}} = I_{K_{\text{SPR}}} \) can be divided into

\[
\Phi_{\text{SPR}} = \left[ \Phi^T_{e} \Phi^T_{e} \right]^T
\]

where \( \Phi_{e} \in \mathbb{C}^{K_e \times \tau} \) is reused for the center users in all cells, and \( \Phi_{e} \in \mathbb{C}^{K_e \times \tau} \) is applied to the edge users of the adjacent cells. Furthermore, \( \Phi_{e} \) can be divided into \( L \) partitions, as

\[
\Phi_{e} = \left[ \Phi^T_{e,1} \Phi^T_{e,2} \cdots \Phi^T_{e,L} \right]^T
\]

where \( \Phi_{e,i} \in \mathbb{C}^{K_{i,e} \times \tau} \) is applied to the \( K_{i,e} \) edge users in the \( i \)th cell. Thus, the pilot sequences applied to edge users are orthogonal to those of the other users roaming in the adjacent cells.

In the example in Fig. 4, there are three hexagonal cells associated with \( K_1 = 4, K_2 = 5, \) and \( K_3 = 6 \) users. To completely eliminate the PC, \( \Phi_{e} \) would require 15 orthogonal pilot sequences. It can be readily calculated that we have \( K_{\text{CS}} = 6 \) for this simple case. Although the proposed SPR scheme requires slightly more pilot resources than the conventional scheme, the QoS of the edge users can be significantly improved, which will be verified in the following.

B. Channel Estimation Based on Soft Pilot Reuse

By applying the proposed SPR scheme, the BS becomes capable of estimating the channels for its edge users in the absence of PC, since the pilot sequences assigned to the edge users are all orthogonal. Moreover, the BS can also obtain the partial knowledge of the intercell channels of the edge users in adjacent cells, which is the dominant source of the ICI inflicted upon these edge users of the adjacent cells during the BS’s DL transmissions.

Specifically, we consider the same LS-MIMO system as in Section V-A, which is composed of \( L \) hexagonal cells, where the \( i \)th cell has \( K_i \) users. Based on the proposed SPR scheme, we divide the channel matrix \( \mathbf{H}_{i,j} \) as defined in (2) into two parts, i.e.,

\[
\mathbf{H}_{i,j} \rightarrow \left[ \mathbf{H}^c_{i,j} \mathbf{H}^e_{i,j} \right]
\]

where \( \mathbf{H}^c_{i,j} \in \mathbb{C}^{M \times K_{i,e}} \) denotes the channel matrix of the link spanning from the center users in the \( j \)th cell to the BS in the \( i \)th cell, whereas \( \mathbf{H}^e_{i,j} \in \mathbb{C}^{M \times K_{i,e}} \) denotes the channel matrix of the link spanning from the edge users in the \( j \)th cell to the BS in the adjacent \( i \)th cell.
BS in the $i$th cell. Then, the pilot sequence received at the BS of the $i$th cell can be represented by

$$\mathbf{y}_i^p = \sqrt{p_p} \left( \sum_{j=1}^{L} \mathbf{H}_{ij}^c \Phi_c (r : K_{j,c}) + \sum_{j=1}^{L} \mathbf{H}_{ij}^c \Phi_{e,j} + \mathbf{N}_i^c \right)$$

(17)

where $\Phi_c (r : K_{j,c})$ denotes the submatrix composed of the first $K_{j,c}$ rows of $\Phi_c$, whereas $\mathbf{N}_i^c$ denotes the corresponding AWGN matrix at the UL receiver.

Then, the BS becomes capable of estimating the channel of its center users without excessive PC, yielding partial intercell channels from the edge users in the $j$th cell without PC, as follows:

$$\hat{\mathbf{H}}_{i,j}^c = \frac{1}{\sqrt{p_p}} \mathbf{Y}_i^p \Phi_{e,j}^H = \mathbf{H}_{i,j}^c + \mathbf{N}_i^c, \quad j \neq i$$

(21)

where $\mathbf{N}_i^c = (1/\sqrt{p_p}) \mathbf{N}_i^c$ can be rendered arbitrarily small upon increasing $M$. Thus, the BS of the $i$th cell becomes capable of accurately estimating all the partial intercell channel matrices of the links spanning from the edge users of the adjacent cells, which comprises an estimate of the intercell channel matrix $\mathbf{A}_i \in \mathbb{C}^{(K_e - K_{i,c}) \times M}$ as

$$\hat{\mathbf{A}}_i = \left[ \hat{\mathbf{H}}_{i,1}^c, \ldots, \hat{\mathbf{H}}_{i,i-1}^c, \hat{\mathbf{H}}_{i,i+1}^c, \ldots, \hat{\mathbf{H}}_{i,L}^c \right]^T.$$  \hspace{1cm} (22)

For instance, in the simple example depicted in Fig. 4, the BS in the first cell is able to acquire the accurate channel estimates of both its edge user and of the partial intercell channels of the other edge users in two adjacent cells. The intercell channel matrix $\mathbf{A}_i$ provides important information for the DL TPC design. Armed with its accurate estimate $\hat{\mathbf{A}}_i$, the BS of the $i$th cell will be able to beneficially preprocess its transmissions for the sake of reducing the ICI inflicted upon its neighboring edge users roaming in the adjacent cells, which is the topic in the following subsection.

C. Multicell Block Diagonalization Precoding

By selecting the TPC vector for a specific user from the null space spanned by the channels of other users, the classical BD scheme of (4) adopted in single-cell multiuser MIMO systems is capable of eliminating the multuser interference. However, with the estimate of the partial intercell channels, we propose the MBD TPC by extending the classical BD scheme to a multicell multiuser scenario. Specifically, by projecting the DL transmit signal onto the null space of the intercell channels, the proposed MBD TPC becomes capable of eliminating the ICI imposed on these edge users. To obtain the null space of the intercell channels, we first apply the classic singular value decomposition (SVD) to the intercell channel matrix $\mathbf{A}_i$, yielding

$$\hat{\mathbf{A}}_i = \mathbf{U}_i \hat{\mathbf{\Sigma}}_i \mathbf{V}_i^H$$

(23)

where $\mathbf{U}_i \in \mathbb{C}^{(K_e - K_{i,c}) \times M}$ denotes the left singular vector matrix, $\mathbf{V}_i \in \mathbb{C}^{M \times M}$ denotes the right singular vector matrix, and $\hat{\mathbf{\Sigma}}_i \in \mathbb{C}^{M \times M}$ is composed of the singular values as

$$\hat{\mathbf{\Sigma}}_i = \begin{bmatrix} \hat{\Sigma}_i & 0 \end{bmatrix} \begin{smallbmatrix} 0_{(K_e - K_{i,c}) \times r_i (M-r_i)} & 0_{(K_e - K_{i,c} - r_i) \times (M-r_i)} \end{smallbmatrix}$$

(24)

in which $r_i = \text{rank}(\hat{\mathbf{A}}_i)$ is the rank of $\hat{\mathbf{A}}_i$, $\hat{\Sigma}_i = \text{diag} \{ \sigma_{i,1}, \ldots, \sigma_{i,2}, \ldots, \sigma_{i,r_i} \}$, and the singular values satisfy

$$\sigma_{i,1} \geq \sigma_{i,2} \geq \ldots \geq \sigma_{i,r_i} > 0.$$  \hspace{1cm} (25)

According to the properties of full SVD, the null space of the $i$th intercell channel, namely, $\text{Null}(\hat{\mathbf{A}}_i) \subseteq \mathbb{C}^{M}$, can be spanned 491
onto the null space Null \( \mathbf{W} \) a conventional TPC matrix onto this null space. For example, by projecting this conventional MF precoding matrix \( \mathbf{W} \) onto the null space Null(\( \mathbf{A}_i \)), we have

\[
\mathbf{A}_i \mathbf{W}_i = 0 \Rightarrow \left( \mathbf{H}^{H}_{i,j} \right)^T \mathbf{W}_i = 0 \quad \forall j \neq i
\]

which means that this TPC matrix calculated for the \( i \)th cell is capable of eliminating the ICI inflicted upon the edge users roaming in the adjacent cells. It is plausible, however, that a precoding matrix, which is randomly chosen from the null space Null(\( \mathbf{A}_i \)) may cause severe intracell interference. To avoid the deleterious effects of intracell interference, we project a conventional TPC matrix onto this null space.

For example, by projecting this conventional MF precoding matrix \( \mathbf{W} \) onto the null space Null(\( \mathbf{A}_i \)), we can generate the MF-based TPC matrix as

\[
\mathbf{W}_i^{MFMBD} = \frac{1}{\sqrt{\gamma_i^{MFMBD}}} \mathbf{P}_i \mathbf{H}^{*}_{i,i}
\]

where \( \mathbf{P}_i = \mathbf{B}_i \mathbf{B}_i^H \) denotes the projection operator based on the matrix \( \mathbf{B}_i \), and \( \gamma_i^{MFMBD} \) is a normalization factor given by

\[
\gamma_i^{MFMBD} = \frac{1}{K_i} \text{Tr} \left( \mathbf{H}^{H}_{i,i} \mathbf{P}_i \mathbf{H}^H \mathbf{B}_i \mathbf{H}^{*}_{i,i} \right)
= \frac{1}{K_i} \text{Tr} \left( \mathbf{H}^{H}_{i,i} \mathbf{P}_i \mathbf{H}^H \mathbf{P}_i \mathbf{H}^{*}_{i,i} \right)
\]

Similarly, by projecting the conventional ZF TPC matrix onto the null space Null(\( \mathbf{A}_i \)), we can generate the ZF-based MBD matrix as

\[
\mathbf{W}_i^{ZFMBD} = \frac{1}{\sqrt{\gamma_i^{ZFMBD}}} \left( \mathbf{P}_i \mathbf{H}^{*}_{i,i} \right)^H
= \frac{1}{\sqrt{\gamma_i^{ZFMBD}}} \mathbf{P}_i \mathbf{H}^{*}_{i,i} \left( \mathbf{H}^{H}_{i,i} \mathbf{P}_i \mathbf{P}_i \mathbf{H}^{*}_{i,i} \right)^{-1}
= \frac{1}{\sqrt{\gamma_i^{ZFMBD}}} \mathbf{P}_i \mathbf{H}^{*}_{i,i} \left( \mathbf{H}^{H}_{i,i} \mathbf{P}_i \mathbf{H}^{*}_{i,i} \right)^{-1}
\]

where the normalization factor \( \gamma_i^{ZFMBD} \) is calculated as

\[
\gamma_i^{ZFMBD} = \frac{1}{K_i} \text{Tr} \left( \mathbf{H}^{H}_{i,i} \mathbf{P}_i \mathbf{P}_i \mathbf{H}^{*}_{i,i} \right)^{-1}
= \frac{1}{K_i} \text{Tr} \left( \mathbf{H}^{H}_{i,i} \mathbf{P}_i \mathbf{H}^{*}_{i,i} \right)^{-1}
\]
More explicitly, the careful choice of the parameter $\lambda$ provides a flexible tradeoff between the pilot resources required and the achievable system performance of the proposed SPR scheme. At one extreme, when the parameter $\lambda$ is set to 0, all the users will be regarded as edge users, and the proposed SPR scheme becomes equivalent to the orthogonal scheme, where all users in all cells use orthogonal pilot sequences. Naturally, this achieves the best performance but relies on the most pilot resources, requiring $K_{OS}$ orthogonal pilot sequences. At the other extreme, when the parameter $\lambda$ is set to a sufficiently large value, e.g., $\lambda = K_{CS}$, then all users are regarded as center users, and the proposed SPR scheme degrades to the conventional scheme that uses the same pilot group in all cells. Hence, the resultant arrangement attains the worst performance but consumes the minimum pilot resources, hence requiring only $K_{CS}$ orthogonal pilot sequences.

572 B. Uplink Transmission

For the center users, the average SINR performance of SPR-aided UL transmission becomes almost the same as that of applying the conventional scheme. This is because, for the center users in a cell, the estimated channel matrix of (4) obtained by applying the conventional scheme is very similar to that of (18) obtained by applying the SPR scheme. However, the achievable rate of the center users of the SPR-aided UL transmission is slightly reduced, since the pilot overhead increases, i.e., $\mu \rightarrow (K_{SPR}/K_{CS})\mu$. On the other hand, the performance of UL transmission for the edge users is much more complex, as shown in the following.

Similar to the received signal given in Section III based on the conventional scheme, the received signal at the BS of the $i$th cell based on the SPR scheme can be represented as

$$y_i^u = \sqrt{p_u} \sum_{j=1}^{L} \left( H_{j,i}^u x_j^{u,c} + H_{j,i}^e x_j^{e,c} \right) + n_i^u$$

where $x_j^{u,c} = [x_{j,1}^{u,c}, x_{j,2}^{u,c}, \ldots, x_{j,K_{j,e}}^{u,c}]^T$ denotes the symbol vector transmitted from the $K_{j,e}$ center users in the $j$th cell, $x_j^{e,c} = [x_{j,1}^{e,c}, x_{j,2}^{e,c}, \ldots, x_{j,K_{j,e}}^{e,c}]^T$ is the symbol vector transmitted from the $K_{j,e}$ edge users in the $j$th cell, and $n_i^u$ denotes the corresponding uplink AWGN vector.

By adopting the MF detector based on the channel estimation obtained by the SPR scheme for the edge users in the $i$th cell, i.e., $\hat{H}_{i,j}^e$, the detected symbol vector for the $K_{i,e}$ users in the $i$th cell is given by

$$\hat{x}_{i,j}^{u,e} = \left( \hat{H}_{i,j}^e \right)^H y_i^u$$

$$= \left( \hat{H}_{i,j}^e + N_i^u \right)^H \left( \sqrt{p_u} \sum_{j=1}^{L} \left( H_{j,i}^u x_j^{u,c} + H_{j,i}^e x_j^{e,c} \right) + n_i^u \right)$$

$$= \sqrt{p_u} \left( \hat{H}_{i,j}^e \right)^H H_{i,j}^e x_j^{e,c} + \left( \eta_i^{u,e} \right) \approx M \sqrt{p_u} \hat{D}_{i,j}^e x_j^{e,c}$$

where $\hat{D}_{i,j}^e = \text{diag} \left\{ \hat{\beta}_{i,j,1}^e, \hat{\beta}_{i,j,2}^e, \ldots, \hat{\beta}_{i,j,K_{j,e}}^e \right\}$ denotes the sub-diagonal matrix of $D_{i,j}$ consisting of the $K_{i,e}$ edge users’ large-scale fading coefficients, and $\eta_i^{u,e} = [\eta_i^{u,e,1}, \eta_i^{u,e,2}, \ldots, \eta_i^{u,e,K_{i,e}}]^T$ denotes the interference, which can be made arbitrarily small by increasing the number of antennas at the BS. In particular, for the $k$th edge user in the $i$th cell, the detected symbol is given by

$$\hat{x}_{i,k}^{u,e} = \sqrt{p_u} \left( h_{i,k}^e \right)^H h_{i,k}^e x_k^{e,c} + \mu_{i,k}^u + \eta_i^{u,k}$$

where $\mu_{i,k}^u = \sqrt{p_u} \sum_{j \neq k} (h_{i,j}^e)^H h_{i,j}^e x_j^{e,c}$ is the intracell interference arriving from the other edge users in the same cell, which can be rendered arbitrarily small by increasing $M$. Similar to the derivation in (6), the UL SINR of the $k$th edge user in the $i$th cell can be calculated as

$$\text{SINR}_{i,k}^{u,e} = \rho_u \left( \left| \frac{h_{i,k}^e \left( \hat{H}_{i,k}^e \right)^H}{\mu_{i,k}^u + \eta_i^{u,k}} \right|^2 \right)$$

where $\rho_u = (K_{SPR}/K_{OS})\mu$. On the other hand, the performance of the conventional scheme given in (6), the UL SINR of the $k$th edge user is

$$\text{SINR}_{i,k}^{u,e} = \rho_u \left( \left| \frac{h_{i,k}^e \left( \hat{H}_{i,k}^e \right)^H}{\mu_{i,k}^u + \eta_i^{u,k}} \right|^2 \right)$$

In summary, in contrast to the conventional scheme, which is unable to remove the PC by simply increasing the number of antennas at the BS $M$, for the edge users, we eliminated the PC imposed on the UL data transmission, and consequently, the UL $M$ achievable rate is significantly improved. Similar results can be obtained if we adopt the ZF detector for UL transmission in our proposal, and the ZF detector outperforms the MF detector, which will be verified by our numerical results.

C. Downlink Transmission

Similar to the analysis of the UL transmission, here, we focus on our attention on the DL transmission of the edge users in our 623 proposal.

By adopting the MFMBD precoding matrix as derived in (29), the received signal vector of the $K_{i,e}$ edge users in the $i$th cell can be represented as

$$y_i^{d,e} = \sqrt{\rho_d} \sum_{j=1}^{L} \left( H_{j,i}^e \right)^T W_{j} \left[ x_j^{d,e} \right] + n_i^{d,e}$$

$$= \sqrt{\rho_d} \sum_{j=1}^{L} \left[ \frac{1}{\sqrt{\text{MFMBD}}} \left( H_{j,i}^e \right)^T B_j B_j^H \left[ x_j^{d,e} \right] \right] + n_i^{d,e}$$

$$\approx \sqrt{\rho_d} \sum_{j=1}^{L} \left[ \frac{1}{\sqrt{\text{MFMBD}}} \left( H_{j,i}^e \right)^T B_j B_j^H \left[ x_j^{d,e} \right] \right] + n_i^{d,e}$$

where $x_j^{d,e} = [x_{j,1}^{d,e}, x_{j,2}^{d,e}, \ldots, x_{j,K_{j,e}}^{d,e}]^T$ are the symbols destined for the $K_{j,e}$ center users in the $j$th cell.
edge users in the $j$th cell, $\mathbf{n}_{i,j,k}^{d,e} = [\mathbf{n}_{i,1,j,k}^{d,e}, \mathbf{n}_{i,2,j,k}^{d,e}, \ldots, \mathbf{n}_{i,K_i,j,k}^{d,e}]^T$ denotes the corresponding DL AWGN vector, and the approximation $\approx$ holds as we apply $H_{i,j,k}^{-1} = H_{i,j,k}^T$ and $(H_{i,j,k}^e)^T B_j = 0$ for $j \neq i$ [see (28)].

Thus, for the $k$th edge user in the $i$th cell, the received symbol $y_{i,k}^{d,e}$ can be represented as

$$y_{i,k}^{d,e} = \sqrt{\rho_{d,e}^{\text{MFMBD}}} (h_{i,i,k}^{e})^T B_i B_i^T (h_{i,i,k}^e)^* x_{i,k}^{d,e} + \mu_{i,k}^{d,e} + n_{i,k}^{d,e}$$

where the intracell interference $\mu_{i,k}^{d,e}$ is given by

$$\mu_{i,k}^{d,e} = \sqrt{\rho_{d,e}^{\text{MFMBD}}} \left( \sum_{k' = 1}^{K_{i,c}} (h_{i,i,k}^{e})^T B_i B_i^T (h_{i,i,k'}^e)^* x_{i,k'}^{d,e} + \sum_{k' \neq k} (h_{i,i,k}^{e})^T B_i B_i^T (h_{i,i,k'}^e)^* x_{i,k'}^{d,e} \right).$$

Both $n_{i,k}^{d,e}$ and $\mu_{i,k}^{d,e}$ can be made arbitrarily small by increasing the number of antennas at the BS. The DL SINR of the $k$th edge user in the $i$th cell can be then calculated as

$$\text{SINR}_{i,k}^{d,e} \approx \frac{\rho_{d,e}^{\text{MFMBD}} \left| (h_{i,i,k}^e)^T B_i B_i^T (h_{i,i,k}^e)^* \right|^2}{\left| \mu_{i,k}^{d,e} \right|^2 + \left| n_{i,k}^{d,e} \right|^2}$$

and the achievable DL rate can be calculated as $C_{i,k}^{d,e} = (1 - \left( K_{\text{SPR} / K_{\text{CS}}} \right) \mu) E \{ \log_2 (1 + \text{SINR}_{i,k}^{d,e}) \}$. In contrast to the results of the conventional scheme given in (7), $\text{SINR}_{i,k}^{d,e}$ increases as $M$ increases and in the asymptotic case of $M \to \infty$, we have $\text{SINR}_{i,k}^{d,e} \to \infty$.

It is clear that, for the edge users, the PC is eliminated by our proposed scheme during the DL data transmission, and additionally, both the ICI and the intracell interference imposed on these edge users have been reduced by the MBD scheme. Similar results can be obtained if we adopt the ZF-based MBD TPC matrix, i.e., $\mathbf{W}_i^{\text{ZFMBD}}$, for DL transmission in our proposal.

Taking into account the extra pilot resource, the achievable DL rate of the edge users has been significantly improved, whereas that of the center users is slightly reduced. Moreover, the average UL and DL cell throughputs of the SPR- and MBD-based systems will be confirmed later by our simulation study.

**D. Computational Complexity**

The computational complexity of implementing the MBD scheme at the BS for the edge users will be quantified in terms of $\mathcal{O}(MK_{\text{CS}}^2)$, which allows us to calculate $\tilde{A}_i = \mathbf{U}_i \Sigma_i \mathbf{V}_i^H$ by using the QR decomposition.
Fig. 6. Instantiation of the randomly generated user distribution in the simulated hexagonal cellular network, where red crosses, green dots, and black numbers denote center users, edge users, and cell numbers, respectively.

Fig. 7. Channel estimation accuracy comparison for the conventional and proposed SPR schemes with $M = 128$. Fig. 8 compares the channel estimation accuracies as functions of the grouping parameter $\lambda$ for both the conventional and proposed SPR schemes with $M = 128$. In each simulation trial, the channel estimation mean square error (MSE) of the edge users is calculated as

$$\text{MSE}_e = \mathbb{E} \left\{ \frac{1}{K_e} \sum_{i=1}^{L} \sum_{k=1}^{K_e} \left\| \hat{h}_{e,i,k} - h_{e,i,k} \right\|_2^2 \right\}$$

(44) where $\hat{h}_{e,i,k}$ denotes the estimate of the true channel vector $h_{e,i,k}$. The average results over 100 random simulation runs are presented in Fig. 7. By increasing the grouping parameter $\lambda$, more users will be regarded as edge users. As expected, for the center users, who only suffer from a slight PC, both the conventional and proposed SPR schemes attain the same excellent channel estimation accuracy. However, the conventional scheme attains a poor channel estimation accuracy for the edge users, who suffer from severe PC. By contrast, since the PC is eliminated by applying orthogonal pilot sequences for the edge users in the adjacent cells, the channel estimation accuracy achieved by the proposed SPR scheme is significantly improved.

Fig. 8 shows the cumulative density function (CDF) of UL SINR for both the conventional and proposed SPR schemes with $M = 128$ and $\lambda = 0.1$, where the results are presented by 1000 random simulation trials. In each simulation run, the conventional scheme calculates the UL SINR of a center or edge user according to the first line of (5). For our SPR scheme, the UL SINR of center users is similar to that for the conventional scheme, whereas the UL SINR of edge users is calculated by the first line of (36) in each simulation trial. Since the UL transmission of the proposed SPR scheme is almost the same as that of the conventional scheme for the center users, their curves in Fig. 8 are almost coincided. Observed in Fig. 8, our SPR scheme attains a significantly higher UL SINR for the edge users than the conventional scheme. Furthermore, the ZF detector is always better than the MF detector by about 2 dB for both center users and edge users.

Fig. 9 shows the CDF of UL achievable rate for the conventional and proposed SPR schemes with $M = 128$ and $\lambda = 0.1$, where the results are obtained from 500 random simulation runs. In each simulation trial, we generate the user positions first and then generate the channels of users for 50 times to obtain the UL achievable rate. Although the UL SINR results of the center users of the conventional and SPR schemes are the same as shown in Fig. 8, the UL achievable rates...
Fig. 9. CDF of UL achievable rate for the conventional and proposed SPR schemes with $M = 128$ and $\lambda = 0.1$.

Fig. 10. Average UL cell throughput for the conventional and proposed SPR schemes with $M = 128$ against $\lambda$.

Fig. 11. Average UL cell throughput for the conventional and proposed SPR schemes with $\lambda = 0.1$ against $M$.

Fig. 12 shows the average UL cell throughput comparison of the conventional and proposed SPR schemes with $\lambda = 0.1$ against the number of BS antennas $M$. When the number of BS antennas is small, i.e., $M = 32$, the average UL cell throughput of the proposed SPR scheme is smaller than that of the conventional scheme about 5 b/s/Hz with MF detector adopted. It is obvious that, to obtain the performance gain for edge users as shown in Fig. 9, the proposed SPR scheme sacrifices the spectral efficiency due to the increased pilot overhead and leads to the average UL cell throughput reduction. However, by increasing the number of BS antennas, e.g., $M = 256$, it becomes clear that the average UL cell throughput of the proposed SPR scheme approaches that of the conventional scheme since the performance of edge users can be significantly improved by increasing $M$. Moreover, the ZF detector outperforms the MF detector a lot when $M$ is small, and the gap shrinks as $M$ increases.

Fig. 13 shows the CDF of DL achievable rate for the conventional system, the SPR-aided system, and the SPR- and MBD-assisted system with $M = 128$ and $\lambda = 0.1$. Despite the MBD precoding scheme, it is clear that the results of DL achievable rate are similar with that of UL achievable rate, as shown in Fig. 9, due to their duality property. When the MBD precoding is considered, we find that the DL achievable rate of edge users can be significantly improved due to the elimination of the ICI, whereas the DL achievable rate of center users slightly decreases since the projecting operator of the MBD precoding sacrifices degrees of freedom of the DL signals for center users. Again, we can find that the ZFMBD precoding achieves a gain about 0.4 b/s/Hz compared with the MFMBD precoding for edge users.

Fig. 14 shows the average DL cell throughput for the conventional system, the SPR-aided system, and the SPR- and MBD-assisted system with $\lambda = 0.1$ against $M$. The conventional system outperforms the SPR-aided system, whereas the SPR- and MBD-assisted system performs worst when small number of BS antennas is considered, e.g., $M = 32$. However, considering the typical massive MIMO configuration as...
12 IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY

Fig. 12. CDF of DL achievable rate for the conventional system, the SPR-aided system, and the SPR- and MBD-assisted system with $M = 128$ and $\lambda = 0.1$.

Fig. 13. Average DL cell throughput for the conventional system, the SPR-aided system, and the SPR- and MBD-assisted system with $\lambda = 0.1$ against $M$.

This grouping allows us to apply the proposed SPR scheme, whereby a center pilot group is reused for the center users in all 821 cells, whereas the edge pilot group is applied to the edge users 822 in the adjacent cells. By requiring a slightly increased number 823 of pilot sequences, the proposed SPR scheme eliminates the 824 PC inflicted upon the edge users who would otherwise suffer 825 from severe PC in the conventional scheme. This significantly 826 enhances the QoS for the edge users and, at the same time, en- 827 sures both the average UL and DL cell throughputs with slight 828 and negligible reduction compared with that of the conventional 829 system. Second, we further exploit the fact that the BS becomes 830 capable of estimating the intercell channels of the edge users 831 in the adjacent cells with the aid of the SPR regime without 832 the deliterious effects of PC. Finally, we extend the classical 833 BD precoding to a multicell scenario and propose the MBD 834 precoding to eliminate the ICI imposed on the edge users of the 835 adjacent cells in the DL. This MBD precoding further enhanced 836 the performance of edge users in DL transmission and improved 837 the average DL cell throughput, in addition to the gain obtained 838 by the SPR scheme.

VIII. CONCLUSION

We have developed an SPR and MBD precoding regime 841 for LS-MIMO systems, which are capable of significantly 842 enhancing both the achievable UL and DL rates for edge users. 843 Our contribution is twofold. First, we break away from the 844 traditional practice of treating all users as though they suffer 845 from the same level of PC and propose a simple yet effective 846 means of dividing the users into cell-center and cell-edge users.

REFERENCES


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AUTHOR QUERIES

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AQ1 = The phrase “meanwhile ensures both the average UL and DL cell throughput” was changed to “and, at the same time, ensures both the average UL and DL cell throughput...” Please check if appropriate. Otherwise, please make the necessary changes.

END OF ALL QUERIES