Interference Cancellation Based Channel Estimation for Massive MIMO Systems with Time Shifted Pilots

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Abstract—In massive multiple-input multiple-output (MIMO) systems with time shifted pilot (TSP) schemes, the inter-group interference caused by the pilot contamination can be eliminated when the number of base station (BS) antennas $M$ approaches infinity. However, $M$ is finite in practice and the effectiveness of the TSP is limited by channel estimation errors. In this paper, it is analytically shown that the mean square channel estimation error (MSCEE) of the TSP is dominated by the inter-group data interference. To reduce the MSCEE in the finite antenna massive MIMO systems, an interference cancellation based channel estimation for the TSP (IC-TSP) is proposed, where the dominant inter-group data interference is canceled based on BS cooperation. To show the advantage of the IC-TSP, the additional overhead of IC-TSP is evaluated by considering different $M$ and the coherence time of BS-BS channels. Furthermore, the impact of sectorization and compressed sensing based BS-BS channel estimation are also discussed. We show that when $128 \leq M \leq 2048$, with the inter-group data interference from the nearest two cell layers being canceled, the IC-TSP achieves a spectral efficiency gain of more than 1.2 bps/Hz over the TSP.

Index Terms—Finite antenna massive MIMO systems, pilot contamination, time shifted pilot.

I. INTRODUCTION

M ASSIVE multiple-input multiple-output (MIMO) is a promising candidate for the fifth generation (5G) or beyond 5G mobile communication system [1]-[7]. The main idea of massive MIMO is to deploy a large number of antennas at base stations (BSs), i.e., $M$, to serve a small number of mobile stations (MSs), i.e., $K (M \gg K)$. Under favorable propagation conditions, simple linear precoding and detecting methods are able to achieve significant gains in throughput compared with conventional MIMO systems, where channel estimation is needed. Due to the large number of antennas at the BS, the amount of pilots needed in downlink (DL) channel estimation is huge. In contrast, resources needed for uplink (UL) channel estimation are much less since the number of MSs is relatively small. Exploiting the channel reciprocity of time division duplex (TDD) transmission mode, the information of DL channel can be obtained from UL channel estimation, which is not easy in frequency division duplex (FDD) systems. However, even with TDD, massive MIMO faces serious pilot contamination [1]. This occurs because the time-frequency resource to carry pilots for channel estimation is limited, and different cells have to reuse the same resource which results in serious inter-cell interference (ICI) [1].

A number of studies have been carried out to tackle the pilot contamination problem. One straightforward solution is to avoid using pilot for channel estimation, i.e., the blind channel estimation [8]. However, it is difficult to be deployed in practice since the complexity increases proportionally to $M^2$. For pilot-based channel estimation, there are two pilot contamination reduction approaches, i.e., aligned pilot (AP) based and time shifted pilot (TSP) based methods [9]. For AP based methods, MSs in different cells transmit UL pilots using the same time-frequency resource. Various schemes have been proposed to mitigate the pilot contamination for the AP based methods [10]-[13]. However, due to the synchronized receptions/transmissions among different cells at both pilot and data transmission stage, the AP scheme actually stands for the worst case of TSP in terms of spectral efficiency [1]. This is because the ICI during data transmission is highly correlated with the channel estimation error caused by pilot contamination. The ICI will be significantly aggravated when using precoding or detection based on this polluted channel estimation. The TSP is proposed in [9], separating the transmission of pilot signals in different cells on different time resources of one coherence time. Due to the limited length of coherence time, the same time resources must be reused for pilot in different cells, similar to the frequency reuse. Define a cell cluster composed of adjacent cells with orthogonal resources for pilot, and a cell group including all the cells using the same resources for pilot transmission. With TSP, MSs in one cell group transmit UL pilots while other cell groups are transmitting DL data. Therefore, the UL pilot in one cell is contaminated by the UL pilot from the same cell group (i.e., intra-group interference) and DL data from all other cell groups (i.e., inter-group interference). Based on the channel estimated at UL, precoding can be carried out at the
BS to achieve good performance in DL transmission. It has been demonstrated in [9] that in a massive MIMO system with infinite number of BS antennas, the inter-group interference can be smartly canceled out by exploiting the asymptotic channel orthogonality.

Note that, current massive MIMO testbeds and commercial products can only support no more than 256 antennas due to the limitation of hardware [14]-[19]. It is expected that in practice, massive MIMO systems can only employ limited number of antennas, e.g., less than 10,000 for quite a long time. For a practical massive MIMO system, the previously discussed inter-group interference is not negligible [20] and it increases significantly with the channel estimation error. To reduce the channel estimation error, a receive beamforming (RBF) method based on the orthogonal basis decomposition is proposed in [21], where the RBF projects the pilot signal to the orthogonal space of the UL data, eliminating the interference from UL data transmission. However, using TSP, the pilot is mainly interfered by DL data transmission in nearby cells, but not UL data transmission. So the performance improvement of [21] is limited. Therefore, considering TSP with finite antennas, it is important to develop effective methods to improve the performance of channel estimation.

Considering a TDD massive MIMO system with TSP, this paper targets to improve the channel estimation accuracy for massive MIMO systems with a finite number of BS antennas $M$. The main contributions of our work are summarized as follows.

- The mean square channel estimation error (MSCEE) is analyzed with finite $M$. We show that the MSCEE of the TSP is determined by the inter-group data interference, i.e., the ICI from DL data transmission in other groups.
- We derive the DL and UL signal to interference plus noise ratio (SINR) for the TSP massive MIMO with finite $M$. We prove that the impact of the MSCEE on the SINR is significant when $M$ is finite. To achieve a practical target SINR $SINR_T$, the number of BS antenna needed for the TSP and, is analytically described. In particular, we show that $M_T$ increases rapidly with the MSCEE with a steep slope, which is inversely proportional to the large scale fading of target MS.
- We propose an interference cancellation (IC) based channel estimation for TSP (IC-TSP) to reduce the MSCEE. The basic idea is to cancel the dominant inter-group DL data interference by using BS cooperation. We demonstrate that the proposed IC-TSP can reduce the MSCEE by $15$ dB (with proper system settings) and achieves a spectral efficiency gain of more than $1.2$ bps/Hz over TSP when $128 \leq M \leq 2048$.

For IC-TSP, we evaluate the impact of the additional pilot overhead on the spectral efficiency by considering different coherence time of BS-BS channels and BS antenna number $M$. To achieve higher effective SINRs than the TSP, the IC-TSP needs a BS-BS channel coherence time longer than a specific value, to compensate the overhead introduced by BS-BS channel estimation. Since both the SINR and the pilot overhead increases as $M$ increases, there exist an optimal value for $M$ maximizing the spectral efficiency for the IC-TSP. Furthermore, when $M$ is sufficiently large, it is possible that spectral efficiency of IC-TSP become lower than that of TSP. We also evaluate the impact of sectorization and the compressed sensing (CS) based BS-BS channel estimation on the spectral efficiency of IC-TSP. Both these two approaches are more beneficial when $M$ is large due to the significantly reduced pilot overhead.

Note that the initial idea of our proposed methodology is presented in [22]. Different to [22], this paper analyzes the dominant component of MSCEE and studies the impact of the MSCEE on the SINR of TSP, which demonstrates the importance to improve the channel estimation quality. Furthermore, the advantage of the IC-TSP is strengthened by combining the IC-TSP with the sectorization and the CS based BS-BS channel estimation. Overall, this paper presents a further comprehensive study based on our initial research in [22].

The rest of the paper is organized as follows. In Sec. II, the system model is described. In Sec. III, with finite BS antennas, the MSCEE in TSP is derived and its impacts on DL and UL SINR are evaluated. Then the IC-TSP is proposed in Sec. IV, where the impact of system parameters and pilot overhead reducing approaches are also analyzed. Simulation results are presented in Sec. V. Finally, conclusions are drawn in the last section.

Throughout the paper, $\mathbf{A} \in \mathbb{C}^{M \times N}$ denotes an $M \times N$ complex matrix. $(\mathbf{A})^*$, $(\mathbf{A})^T$ and $(\mathbf{A})^H$ represent the conjugate, transpose and conjugate transpose of matrix $\mathbf{A}$, respectively. $\|\mathbf{a}\|$ denotes the Euclidean norm of vector $\mathbf{a}$, $\mathbf{I}_N$ is the $N \times N$ identity matrix, and $\mathbf{0}_N$ denotes all-zero $N \times 1$ vector. $\mathbf{n} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$ is a complex Gaussian vector with mean $\mathbf{0}$ and covariance matrix $\mathbf{A}$. $\mathbb{E}\{\cdot\}$ and $\mathbb{D}\{\cdot\}$ denote the operation to get expectations and variances, respectively. $\Re\{\cdot\}$ and $\Im\{\cdot\}$ denote the operation to get the real and imaginary parts, respectively. $[\mathbf{A}]_{p,q}$ denotes the $(p,q)$-th element of matrix $\mathbf{A}$. $|S|$ denotes the number of elements in set $S$.

II. SYSTEM MODEL

Consider a TDD-based massive MIMO system composed of $L$ hexagonal macro-cells, denoted by $\mathcal{L} = \{1, 2, \ldots, L\}$. Each macro-cell has a radius of $r_\text{c}$, where a BS is deployed in the center of each cell. Assume that $K$ MSs are randomly and uniformly distributed over each cell except for a central disk of radius $r_d$ [23]. Each BS is equipped with $M$ antennas and each MS is equipped with a single antenna. The wireless channel is time-frequency flat over $T_c$ symbols (one coherence time) and $F_c$ sub-carriers (one coherence bandwidth), which is defined as one coherence block. In each cell, orthogonal pilot sequences are assigned to different MSs to avoid intra-cell interference, which occupies $F_c\tau_p$ time frequency resources ($0 < \tau_p \leq T_c$). In this paper, the number of simultaneously served MSs in one cell is assumed to be $K = F_c\tau_p$ for the ease of analysis. The same set of pilot sequences are

$^1$The assumption that MSs are not located within the central disk of each cell is to ensure that MSs will not be too close to their serving BSs so that the far-field propagation model is valid.
reused in different cells with shifted time resources [9]. Due to the limited time-frequency resources, it is difficult to ensure the non-overlapped pilot transmission of all cells. Therefore, the time shifted pilot transmission is conducted by cell groups like frequency reuse schemes [9]. First of all, the whole cell set \( \mathcal{L} \) is partitioned into \( \Gamma \) exclusive groups \( A_1, A_2, \ldots, A_{\Gamma} \), where \( \Gamma = b^2 + c^2 + bc, \) \( b, c \in \{0, 1, 2, \ldots\} \), and \( b + c \neq 0 \). The number of cells in cell group \( A_i \) is denoted by \( |A_i| \). Cells in the same group use the same time-frequency resources for UL pilot transmission. An example is shown in Fig. 1, illustrating the transmission of TSP with \( \Gamma = 7 \). The transmission of each frame is with the length of \( T_c \), which is composed of UL pilot transmission stage, cross-link (CL) data transmission stage, pure DL (PD) data transmission stage and UL data transmission stage. The frame of each group starts with its own first pilot symbol, which means that frames of different groups are not synchronous [20], [23]. The MS-BS channels corresponding to different frames are uncorrelated. As shown in the right side of Fig. 1, for each group of cells, channel estimation is conducted firstly in each frame and then be used to generate precoding/combining vector for DL/UL transmission. When the \( i \)-th group \( A_i \) starts to transmit pilot in the \( n \)-th frame, \( A_1, A_2, \ldots, A_{i-1} \) groups transmit DL data using the precoding vector based on the channel estimation of the \( n \)-th frame and \( A_{i+1}, \ldots, A_{\Gamma} \) groups transmit DL data using the precoding vector based on the channel estimation of the \( (n-1) \)-th frame. Hence, the UL pilot received at one BS is interfered by the UL pilots from the cells in the same group and the DL data from other groups. To ensure the non-overlapped pilot transmissions from different groups, \( \Gamma - 1 \leq T_d / \tau_p \), where \( T_d \) is the length of DL data on one subcarrier and within each \( T_c \). The length of UL data on one subcarrier and within each \( T_c \) is denoted by \( T_u \).

Let the \( l \)-th cell belong to the group \( A_p \). During the UL pilot transmission of the group \( A_p \), the pilot signal received at the BS of the \( l \)-th cell, i.e., the \( l \)-th BS, is given by (1), where \( y_l \) is an \( M \times F_c T_p \) matrix, \( p_{UL,l,k}^l \geq p_{UL} \) is the UL pilot transmission power of \( k \)-th MS in the \( l \)-th cell, \( p_{UL}^D \) is the largest pilot transmission power of MS, \( p_{DL,dk}^D \) is DL data transmission power for \( k \)-th MS in the \( l \)-th cell, which satisfies \( \sum_{k=1}^{K} p_{DL,dk}^D = \rho_{DL}^D \). \( \rho_{DL}^D \) is the total DL data transmission power of BS. \( \mathbf{g}_{ijk} \in \mathbb{C}^{M \times 1} \) is the UL channel vector from the \( k \)-th MS in the \( j \)-th cell to the \( l \)-th BS, \( \psi_k \in \mathbb{C}^{1 \times F_c T_p} \) denotes the mutually orthogonal pilot sequence allocated to the \( k \)-th MS with \( \psi_k \cdot \psi_k^T = F_c T_p \delta_{kk'} \) [9], [20], [23], where \( \delta_{kk'} \) is the Kronecker delta function. \( \mathbf{G}_{ld} \in \mathbb{C}^{M \times M} \) is the channel matrix from the \( d \)-th BS to the \( l \)-th BS, \( \mathbf{w}_{dk} \in \mathbb{C}^{M \times 1} \) is the normalized precoding vector for the \( k \)-th MS in the \( d \)-th cell, i.e., \( \| \mathbf{w}_{dk} \| = 1 \), \( \mathbf{x}_{dk}^D \in \mathbb{C}^{1 \times F_c T_p} \) is the vectorized DL data for the \( k \)-th MS in the \( d \)-th cell and \( \mathbf{n}_{p,l} \sim \mathcal{CN}(0, \sigma_{p,l}^2 \mathbf{I}_{M F_c T_p}) \) denotes the \( M \times F_c T_p \) noise matrix in the \( l \)-th cell, where \( \sigma_{p,l}^2 \) is the noise variance during the pilot transmission stage. Given the channel vector \( \mathbf{g}_{ijk} = \sqrt{\beta_{ijk}} \mathbf{h}_{ijk} \), where \( \beta_{ijk} = d_{ijk}^{-\eta} \) denotes the large scale fading, \( d_{ijk} \) and \( \vartheta_{ijk} \) are the distance and the shadow fading between the \( k \)-th MS in the \( j \)-th cell and the \( l \)-th BS, respectively, \( \eta > 2 \) is the decay exponent, and \( \mathbf{h}_{ijk} \sim \mathcal{CN}(0, \mathbf{I}_M) \) represents the \( M \times 1 \) small scale fading vector. The shadow fading \( \vartheta_{ijk} \) is modeled via a log-normal distributed variable, i.e., \( 10 \log_{10}(\vartheta_{ijk}) \sim \mathcal{N}(0, \sigma_{sh}^2) \), where \( \sigma_{sh} \) is the logarithmetic standard deviation [24]. Similarly, the channel between the \( l \)-th BS and the \( d \)-th BS is modeled as \( \mathbf{G}_{ld} = \sqrt{\alpha_{ld}} \mathbf{D}_{ld} \), where \( \alpha_{ld} = d_{BS,ld}^{-\eta} \) is the large scale fading, \( d_{BS,ld} \) and \( \vartheta_{BS,ld} \) are the distance and the shadow fading between the \( l \)-th BS and the \( d \)-th BS, respectively, and \( \mathbf{D}_{ld} \) is the \( M \times M \) small scale fading matrix. Note that BSs of macro cells are usually installed at high places and line of sight (LOS) paths may exist between BSs. In addition, there is not enough local scattering around BS antennas, which leads to the strong spatial correlation [25]-[29]. Thus the small scale fading matrix \( \mathbf{D}_{ld} \) is modeled as a correlated Ricean one, i.e., \( \mathbf{D}_{ld} = \mathbf{R}_{ld} \mathbf{F}_{rl} \mathbf{R}_{rl}^{\dagger} \mathbf{H}_{ld} \mathbf{F}_{rl}^{\dagger}, \mathbf{R}_{rl} \mathbf{F}_{rl}^{\dagger} \mathbf{H}_{ld} \mathbf{F}_{rl}^{\dagger} \) is the \( M \times M \) correlated scattering component. \( \mathbf{R}_{rl} \mathbf{F}_{rl}^{\dagger} \mathbf{H}_{ld} \mathbf{F}_{rl}^{\dagger} \) is the \( M \times M \) correlated scattering component. \( \mathbf{R}_{rl} \mathbf{F}_{rl}^{\dagger} \mathbf{H}_{ld} \mathbf{F}_{rl}^{\dagger} \) is the correlation matrices at the
receiver and transmitter, respectively, $H_{W,ld}$ is the independent Rayleigh channel matrix whose entries follow i.i.d complex Gaussian distribution, i.e., $[H_{W,ld}]_{p,q} \sim CN(0,1)$. Since all the BSs are assumed to be equipped with the same antenna configuration, $R_{R,lid} = R_{T,lid} = R$ for all $l$ and $d$. $R$ is modeled via the widely-used exponential model of Loyka, i.e., $[R]_{p,q} = \kappa^{p-q}$, where $\kappa \in [0,1]$ is the adjacent antenna correlation coefficient (or spatial correlation coefficient) [25]-[26]. Thus, $R$ is a real symmetric matrix, and the channel becomes more correlated when $\kappa$ gets larger.

Throughout this paper, the matched filtering (MF) method is used for precoding and detection due to its simplicity for analysis. Furthermore, the performances of other linear precoding and detection such as zero-forcing (ZF) method are evaluated by simulations, where the ZF method shows similar trend with the MF method.

III. PERFORMANCE OF CHANNEL ESTIMATION

A. Analysis of Channel Estimation Error

In the $l$-th cell ($l \in A_p$), the channels between the $k'$-th MS and the $l$-th BS can be estimated by $\hat{g}_{lk'} = \left(\mathbf{y}_{l} \psi_{k'}^{H}\right) / \left(\mathbf{F}_{c}\mathbf{r}_{l} \mathbf{P}_{UL,lk'} \right)$, which is expanded by (2), where $\mathbf{e}_{lk'} = \mathbf{e}_{lk',pilot} + \mathbf{e}_{lk',data} + \mathbf{e}_{lk',noise}$ is the $M \times 1$ channel estimation error, composed of intra-group interference $\mathbf{e}_{lk',pilot}$ caused by UL pilot interference from cells in the same group $A_p$, inter-group interference $\mathbf{e}_{lk',data}$ caused by DL data transmission from other groups, and background noise $\mathbf{e}_{lk',noise}$. The MSCEE of the $k'$-th MS in the $l$-th cell is defined as $\varepsilon_{lk'} = \frac{1}{nr} \mathbb{E}\left\{ \left\| \mathbf{e}_{lk'} \right\|_2^2 \right\}$. Omitting the weak correlation between the precoding vector $\mathbf{w}_{lk}$ and the BS-BS channel $G_{ld}$, $\varepsilon_{lk'}$ is approximated by (3) (see Appendix A), where $\varepsilon_{lk',pilot}$, $\varepsilon_{lk',data}$, and $\varepsilon_{lk',noise}$ stand for the impact of intra-group pilot interference, inter-group data interference, and noise, respectively. It can be seen that the MSCEE is independent of the spatial correlation coefficient $\kappa$ and the Rician factor $\kappa r$. This is because the spatial correlation does not impact the total power of interference. For $\Gamma = 1$, the TSP is equivalent to the AP and there is only intra-group pilot interference, so $\varepsilon_{lk'} = E_{\beta} \sum_{j \notin l}^L \frac{\rho_{UL,lk'}}{\rho_{UL,lj}} \cdot \varepsilon_{lj} + \frac{\sigma^2}{\mathbf{F}_{c}\mathbf{r}_{l} \mathbf{P}_{UL,lk'}}$ (exact result). When $\Gamma$ increases from 1 to 3, $\varepsilon_{lk'}$ increases significantly, because $\frac{1}{2}L$ cells (including the nearest 6 cells) generate high powered DL data interference instead of relatively low powered UL pilot interference.

B. The impact of the MSCEE on the SINR

At the UL data transmission stage, the detected signal of the $k'$-th MS in the $l$-th cell ($l \in A_p$) at its serving BS is
\[
\begin{align*}
\mathbf{y}^{UL}_{lk'} &= a_{lk'} \left( \sum_{k=1}^{K} \sqrt{\rho_{UL,lk}^D} \mathbf{g}_{lk} \mathbf{x}^{UL}_{lk'} + \sum_{j=1, j \neq k}^{L} \sum_{k'=1}^{K} \sqrt{\rho_{UL,jk'}^D} \mathbf{g}_{jk'} \mathbf{x}^{UL}_{jk'} + n_{UL,lk'} \right) \\
&= \sqrt{\rho_{UL,lk}^D} a_{lk'} \mathbf{g}_{lk} \mathbf{x}^{UL}_{lk'} + \sum_{j=1, j \neq k}^{L} \sqrt{\rho_{UL,jk'}^D} a_{lk'} \mathbf{g}_{jk'} \mathbf{x}^{UL}_{jk'} + \sum_{j \in A_p, j \neq k}^{K} \sqrt{\rho_{UL,jk'}^D} a_{lk'} \mathbf{g}_{jk'} \mathbf{x}^{UL}_{jk'} + n_{UL,lk'},
\end{align*}
\]

where \( \rho_{UL,lk}^D \) is the UL data transmission power of the \( k \)-th MS in the \( l \)-th cell, \( \rho_{UL,lk}^D \) is the UL data transmission power of the \( k \)-th MS in the \( l \)-th cell, \( \rho_{UL,jk'}^D \) is the largest UL data transmission power of MS, \( \mathbf{x}^{UL}_{lk'} \in C^{1 \times F_c T_u} \) is the UL data of the \( k \)-th MS in the \( l \)-th cell, \( n_{UL,lk'} \sim \mathcal{C}\mathcal{N}(0, \sigma_{UL}^2 I_{M \times F_c \cdot T_u}) \) is the additive Gaussian noise matrix, and \( \sigma_{UL}^2 \) is noise variance for UL data transmission stage. The inter-group interference, intra-group UL data interference and inter-group UL data interference is approximated as (7) (see Appendix B), where \( \gamma_{lk'} \sim \mathcal{C}\mathcal{N}(0, \sigma_{UL}^2 I_{M \times F_c \cdot T_u}) \) is the small scale fading, and \( n_{CL,UL} \sim \mathcal{C}\mathcal{N}(0, \sigma_{CL}^2 I_{1 \times F_c \cdot T_u}) \) is the background noise, \( \sigma_{CL}^2 \) is the noise variance for the CL stage.

A closed form DL SINR at the CL stage is approximated as (9), where

\[
SINR_{lk'}^{DL} = \frac{(M + 1) \beta_{lk'}^2 + \varepsilon_{lk'} \beta_{lk'}}{M \sum_{j \neq l}^{K} \frac{\beta_{lk'}^2 + \varepsilon_{lk'} \beta_{lk'}}{\rho_{UL,ik}^D} + \beta_{lk'}^2 - \varepsilon_{lk'} \beta_{lk'}},
\]

where \( \beta_{lk'}^2 \) is the impact of correlated intra-group data interference, \( (\beta_{lk'} + \varepsilon_{lk'}) \mathbf{c}_{UL,lk'} \) shows the impact of all uncorrelated interference plus noise with \( \mathbf{c}_{UL,lk'} \) showing the impact of all uncorrelated interference plus noise with \( \mathbf{c}_{UL,lk'} \).
When $M$ grows to infinity, TSP achieves an ideal SINR performance that the impacts of MSCE, the uncorrelated intra-group interference and the inter-group interference on the UL SINR become negligible. However, when $M$ is finite, the impact of MSCE on the UL SINR is significant, which will be illustrated in the following.

To achieve a practical target $SINR_T$, the number of BS antennas needed for the TSP can be derived by solving $SINR_{\text{T}} \approx SINR_T$, which is given by

$$M_T = \frac{\left(\frac{\rho_{\text{T}}}{\text{T}} - \sum_{j \neq i \in A_p} r_{\text{T}}\right)}{\left(SINR_T \frac{\rho_{\text{T}}}{\text{T}} - 1\right)}.$$  

It can be seen that $M_T$ increases rapidly with $\epsilon_{\text{T}}$, with a slope larger than $\frac{1}{\sum_{j \neq i \in A_p}}$. Hence, with a small number of BS antennas, it is important to reduce the MSCE in order to achieve a target performance.

IV. IC BASED TIME-SHIFTED PILOT SCHEME

As illustrated before, the channel estimation is severely contaminated by the inter-group interference from DL data transmission in other groups. Therefore, it is highly desirable to cancel out the inter-group interference. Note that the inter-group interference can be estimated using the DL data and precoding vectors shared among BSs. Although in distributed radio access networks (D-RAN), this data sharing requires a large backhaul among BSs, in centralized radio access networks (C-RAN) [35]-[38] and open radio access networks (O-RAN) [39], it can be naturally supported with much additional cost. With the idea to cancel out inter-group interference, an IC based channel estimation is proposed.

To cancel the dominant inter-group data interference $e_{\text{I}}$ in (2), the channel between the target BS and its main interfering BSs should be estimated. As shown in the right side of Fig. 3, this can be realized via a super TSP frame structure with the length of one coherence time of BS-Bs channel $T_{BSS}$. The super TSP frame structure consists of two parts, i.e., the BS-Bs channel estimation stage with a duration of $T_{BSP}$ at the beginning of each frame and $N_{TSP}$ consecutive TSP frames. Compared to MSs, BSs lack
of mobility so it is expected longer than that of BS-MS channels, i.e., $T_{BS,C} \gg T_c$ and $N_{TSP} \gg 1$. Assuming that $N_L \geq 1$ layers of BS-BS interference is to be canceled, channels between the target BS and up to $L_{D_{main}}=3N_L(N_L+1) \geq 6$ nearest BSs should be estimated during the BS-BS channel estimation stage, which is conducted in a round-robin manner. Define a cell cluster $A_{D1,l}$ consisting of the target BS and its $L_{D_{main}}$ nearest cells. As shown in the left side of Fig. 3, considering $L_{D_{main}} = 6$, BSs in the cluster $A_{D1,l} = \{1, 2, \cdots, 7\}$ transmit pilot signals sequentially. The BS-BS channel estimation is also conducted like frequency reuse schemes with the reuse factor of $L_{D_{main}}+1$. Thus, the BS-BS channel can be estimated without severe interference from nearby cells in the cluster.

During the BS-BS channel estimation stage, the pilot signal received at the $l$-th BS from the $d$-th BS ($d \in A_{D1,l}$) is given by

$$y_{ld}^{BS} = \sqrt{p_{BS-p}} G_{ld} P + \sqrt{p_{BS-p}} \sum_{b \neq d, b \in B_d} G_{lb} P + N_{ld}^{BS},$$  

(11)

where $p_{BS-p}$ is the pilot power for BS channel estimation, $P \in \mathbb{C}^{M \times \tau_{BS}}$ is the pilot matrix, $\tau_{BS}$ is the length of pilot sequence on each BS antenna, $B_d$ denotes a group of BSs which transmit pilot signals simultaneously with the $d$-th BS (including the $d$-th BS). As shown in Fig. 3, $B_2 = \{2, 12, 15, 23, 34\}$. Here, $N_{ld}^{BS} \sim \mathcal{CN}(0, \sigma_{BS}^2 I_M)$ is the $M \times \tau_{BS}$ additive noise matrix. $J_{ld} = \sqrt{p_{BS-p}} \sum_{b \neq d, b \in B_d} G_{lb} P + N_{ld}^{BS}$ is the sum of the interference and the noise.

Firstly, we consider the traditional LS BS-BS channel estimation, i.e., $\tau_{BS} = M$ and the pilot matrix satisfies $\frac{1}{M}P \cdot P^H = I_M$. In this way, the estimation of channel matrix from the $d$-th BS to the $l$-th BS is given by

$$\hat{G}_{ld} = \frac{y_{ld}^{BS} P^H}{M \sqrt{p_{BS-p}}} = G_{ld} + \frac{1}{M \sqrt{p_{BS-p}}} \sum_{b \neq d, b \in B_d} G_{lb} P + N_{ld}^{BS} J_{ld}^{-1},$$  

(12)

where $E_{ld}$ denotes the BS-BS channel estimation error.

Given the estimated BS-BS channel $\hat{G}_{ld}$, the target BS can estimate the main inter-group interference generated by DL data transmission of BSs in $A_{D1,l}$. Assuming that the DL data and precoding vectors are shared among the BSs in $A_{D1,l}$, the estimated inter-group interference is given by

$$ICI_l = \sum_{d \in A_{D1,l}, d \neq A_p} \rho_{DL,dk}^{\ast} w_d x_{dk}^D,$$  

(13)

which can then be canceled from the received signal as

$$\tilde{y}_l = y_l - ICI_l.$$  

(14)

In (1), the inter-group data interference in $y_l$ can be divided into two parts, i.e., the interference from cells in $A_{D1,l}$ and other cells, given by $\sum_{d \in A_{D1,l}, d \neq A_p} \rho_{DL,dk}^{\ast} w_d x_{dk}^D$ plus noise caused by the error of BS-BS channel estimation. After the IC, the channel estimation of the $k$-th MS in the $l$-th cell is given by

$$\hat{g}_{llk'}^{IC} = \left(\mathbf{y}_l \psi_l^H\right)^{-1} \left(F_c \tau_P \rho_{DL,lk'}^D\right).$$  

(15)

Then, the MSCEE of the IC-TSP can be derived as (16), where the approximation is caused by omitting the correlation between the precoding vector $w_{dk}$ and the BS-BS channel $G_{ld}$ (similar to the derivation in Appendix A), $\varepsilon_{llk',\text{pilot}}$ and $\varepsilon_{llk',\text{data,other}}$ are the same as those in (3), $\varepsilon_{llk',\text{data,residual}}$ is the impact of inter-group data interference from cells other than $A_{D1,l}$, $\varepsilon_{llk',\text{data, residual}}$ is the impact of residual interference after IC (which is caused by the interference during the BS-BS estimation stage), $\varepsilon_{llk',\text{noise, residual}}$ is the impact of residual interference from nearby cells in the cluster.
noise after IC (which is caused by the additional noise during the BS-BS channel estimation stage). The deriving process of above-mentioned expectations are similar to that in Appendix A.

Compared to the TSP, the IC-TSP reduces the dominating component in MSCEEE, i.e., the DL data interference from \(A_{DL,l} \), from \(\varepsilon_{ilk'},data, A_{DL,l} = \frac{p_{Dl}}{F_{C}TP_{UL,ilk'}} \sum_{d \in A_p, d \neq A_{DL,l}} \alpha_{BS,lb} \) to \(\varepsilon_{ilk',data, residual} + \varepsilon_{ilk',noise, residual} + \varepsilon_{ilk',pilot} = \frac{\sum_{d \neq A_p, d \neq A_{DL,l}} \alpha_{BS,lb}}{F_{C}TP_{UL,ilk'}}\), where the distance between the \(l\)-th BS to BS in BS group \(B_d\) is larger than the distance between the \(l\)-th BS to the \(d\)-th BS due to the reuse of pilot matrix. Therefore, the IC-TSP can reduce the MSCEE effectively.

Note that the BS-BS channel estimation error \(E_{ld}\) could be reduced by using the linear minimum mean square error (LMMSE) channel estimation (for the detailed channel estimation process, please see Theorem 1 in [20]). Compared to the LS channel estimation, the LMMSE channel estimation is generally much smaller than \(\alpha_{ld}\) in \(\varepsilon_{ilk',data, residual}\). This is because the distance between the \(L\)-th BS to BS in BS group \(B_d\) is larger than the distance between the \(l\)-th BS to BS in BS group \(B_d\) due to the reuse of pilot matrix. Therefore, the IC-TSP can reduce the MSCEE efficiently.

Based on the analysis in Sec. III-B, we conclude that the SINR of IC-TSP scheme can be improved significantly due to the reduced MSCEEE. Using the IC-TSP, the UL SINR is given by \(\text{SINR}^{UL}_{ilk'} = \text{SINR}^{IC,UL}_{ilk'} = f(x) \rightarrow f(x')\), where \(f(x) \rightarrow f(x')\) denotes the operation of replacing \(x\) of \(f(x)\) by \(x'\). Other SINRs for DL can be obtained similarly. Similar to the TSP, the SINRs are almost the same for UL, PD and CL transmission.

Although IC-TSP can improve the SINR, additional radio resources are needed for the BS channel estimation. As a comparison, for TSP, the UL spectral efficiency is given by \(v_{ilk'}^{UL} = \varpi_p \log_2 \left(1 + \text{SINR}^{IC,UL}_{ilk'} \right)\), where \(\varpi_p = \left(1 - \frac{\tau_T}{\tau_p} \right)\) is the effective resource ratio of TSP [1]. For IC-TSP, the effective resource ratio is given by \(\varpi_p \varpi_T\), where \(\varpi_T = 1 - \tau_{BS} (L_{D_{main} + 1}) / F_{C}T_{BS, C}'\) and \(\tau_{BS} (L_{D_{main} + 1})\) is the additional pilot overhead needed by the BS-BS channel estimation. Therefore, the UL spectral efficiency of IC-TSP is given by \(v_{ilk'}^{IC,UL} = \varpi_p \varpi_T \log_2 \left(1 + \text{SINR}^{IC,UL}_{ilk'} \right)\). The spectral efficiency for PD and CL can be obtained similarly.

On one hand, the spectral efficiency can be improved by IC-TSP since it can reduce MSCEEE significantly. On the other hand, the resource overhead needed for the BS-BS channel estimation would degrade the spectral efficiency. Therefore, the performance of IC-TSP depends on various system parameters. Since the spectral efficiencies at UL, PD and CL transmissions are almost the same, the following analysis will only be conducted for UL.

A. Impact of \(T_{BS,C}'\)

The spectral efficiency of IC-TSP depends on the length of coherence time of BS-BS channel \(T_{BS,C}'\) since \(\varpi_T\) is proportional to \(T_{BS,C}'\). For small \(T_{BS,C}'\), \(\varpi_T\) is small and the overhead needed for the BS-BS channel estimation may be so large that there will be not enough resources left for data transmission. Thus, the spectral efficiency of IC-TSP may be inferior to that of TSP. A lower bound of \(T_{BS,C}'\) can be found, below which the spectral efficiency of IC-TSP is less than that of TSP. \(T_{min, BS,C}'\) can be derived by solving \(v_{ilk'}^{IC,UL} = v_{ilk'}^{UL}\) (i.e., \(\varpi_p \varpi_T \log_2 \left(1 + \text{SINR}^{IC,UL}_{ilk'} \right) = \varpi_p \varpi_T \log_2 \left(1 + \text{SINR}^{UL}_{ilk'} \right)\)), given by

\[
T_{min, BS,C}' = \left(1 - \frac{\log_2 (1 + \text{SINR}^{UL}_{ilk'})}{\log_2 (1 + \text{SINR}^{IC,UL}_{ilk'})} \right) F_{C} T_{BS, C}'.
\]

In (17), both \(\tau_{BS}\) and \(\frac{\log_2 (1 + \text{SINR}^{UL}_{ilk'})}{\log_2 (1 + \text{SINR}^{IC,UL}_{ilk'})}\) monotonically increase with \(M\), thus \(T_{min, BS,C}'\) increases with \(M\). Moreover, both the numerator and the denominator are increasing functions of \(L_{D_{main}}\). However, the increment of the numerator with \(L_{D_{main}}\) is larger than that of the denominator in (17) since the increasing speed of \(\log_2 \left(1 + \text{SINR}^{UL}_{ilk'} \right)\) with \(L_{D_{main}}\) is lower than 1. Therefore, \(T_{min, BS,C}'\) also increases with \(L_{D_{main}}\). It should be noted that \(T_{BS,C,ilk}'\) derived from (17) is different from one MS to another. To this end, the average of \(T_{min, BS,C,ilk}'\) over large numbers of random MS realizations should be used to guide the system design. The impacts of \(M\) and \(L_{D_{main}}\) are the same for the average of \(T_{min, BS,C,ilk}'\).

B. Impact of \(M\)

\(\varpi_T\) is also closely related to the pilot length \(\tau_{BS}\). For the considered LS BS-BS channel estimation, \(\tau_{BS} = M\). Therefore, \(\varpi_T\) is inversely proportional to the BS antenna number \(M\), while the SINRs increase with \(M\). Hence, there exists an optimal value for BS antenna number, \(M_{opt}\), maximizing the spectral efficiency of IC-TSP. When \(M\) is larger than \(M_{opt}\), the spectral efficiency will decrease as \(M\) increases.
Moreover, when $M$ is sufficiently large, it is possible that spectral efficiencies of IC-TSP may be lower than those of TSP, due to the resource overhead introduced by the BS-BS channel estimation. Hence, there is a cross point $M$ of IC-TSP and TSP, $M_{cross}$, beyond which the spectral efficiency of IC-TSP will be inferior to that of TSP.

### C. Impact of sectorization

When directional antennas are deployed at the BSs and signals are received (and transmitted) at only part of the angular space of each BS antenna, cell sectorization can be used to reduce the inter-cell interference and improve the system capacity [40]-[42]. In this paper, we consider an ideal sectorization where each cell is divided into $\delta$ sectors and each sector is served by $\frac{M}{\delta}$ BS antennas. The signals in the direction of target sector over MS-BS channel obtain antenna directivity gain of $\delta$ (i.e., the signals will be multiplexed by $\sqrt{\delta}$), while signals in other directions will be restricted to zero [48].

Differently, the signals in the direction of target sector over BS-BS channel obtain antenna directivity gain of $\delta^2$ since both the transmitter and the receiver are equipped with directional antennas. Furthermore, compared to the unsectorized case, the number of interferers is reduced by $\delta$ times.

For the TSP with sectorization, to obtain the estimate of wireless channel $g_{llk}$, we should firstly divide the received pilot signal by $\delta$ and then conduct the channel estimation as that in (2), i.e., $\hat{g}_{llk} = \frac{\gamma_{l}^{rec}P_{l}^{{UL,lk}}}{\delta F_{c}T_{s}T_{p}P_{l}^{{UL,lk}}}$, where $\gamma_{l}^{rec}$ is the received pilot signal when sectorization is adopted. The MSCEE $\varepsilon_{llk}^{IC} = \frac{1}{M} \mathbb{E} \left\{ \| \hat{g}_{llk} - g_{llk} \|^2 \right\}$ can be approximated by using the similar analysis in Sec. III-A. Compared to the unsectorized case, the power of intra-group pilot interference (which is the signal over MS-BS channel) from each interferer in the direction of target sector will remain the same since the loss of the effective BS antenna and the antenna directivity gain cancel out. Therefore, the reduction of interferers will lead to the reduction of intra-group pilot interference $\varepsilon_{llk,pilot}$ by $\delta$ times. The power of inter-group data interference (which is the signal over BS-BS channel) from each interferer in the direction of target sector will increase $\delta$ times since the antenna directivity gain is $\delta$ times higher than the loss of the effective BS antenna (because both transmitter and receiver are equipped with directional antennas). The sectorization also reduces the number of inter-group data interferers by $\delta$ times. As a result, using the sectorization, the inter-group data interference $\varepsilon_{llk,data}$ keeps the same with that in the unsectorized case. Recall that the MSCEE is dominated by the inter-group data interference. Therefore, thus the MSCEE of TSP experiences a marginal reduction after sectorization.

Next, we turn to the impact of the sectorization on the SINR. As seen from Appendix B, the power of target signal and the correlated interference from each interferer are quadratic functions about the number of effective BS antennas while the power of uncorrelated interference is only linearly proportional to the number of effective BS antennas. Considering the loss of the number of effective BS antennas and the benefit derived from the antenna directivity gain and the interferer cancelling gain, we conclude that the sectorization will reduce the power of target signal and the power of uncorrelated interference by $\delta$ times while the power of correlated interference by $\delta^2$ times. As a result, compared to the unsectorized case, the SINR will increase marginally when $M$ is small (where the interference is dominated by the uncorrelated interference) and will increase significantly by $\delta$ times when $M$ is large (where the interference is dominated by the correlated interference).

For the IC-TSP, the intra-group pilot interference $\varepsilon_{llk,pilot}$ can be reduced by $\delta$ times while its proportion in the MSCEE of IC-TSP is larger than that in the TSP. Furthermore, the residual interference caused by the BS-BS channel estimation error, i.e., $\varepsilon_{llk,data,residual}$, can be reduced by $\delta$ times. This is because both the number of the interferers during the BS-BS channel estimation stage, i.e., $|B_{l}|$, and the number of interferers generating the dominant interference during the MS-BS channel estimation stage, i.e., $|A_{D,l}|$, can be reduced by $\delta$ times. Therefore, compared to the TSP, the MSCEE of IC-TSP can be reduced more significantly by the sectorization due to the reduction of $\varepsilon_{llk,data,residual}$ and $\varepsilon_{llk,pilot}$. The analysis of SINR is similar to that in the TSP. Due to the decrease in the MSCEE, the SINR will be always improved by the sectorization whether $M$ is small or large. Furthermore, when $M$ is small, $\omega_{T}$ approaches 1 and the impact of reducing the overhead for BS-BS channel estimation on $\omega_{T}$ is marginal. However, when $M$ is large, $\omega_{T}$ is significantly affected by the pilot overhead and the sectorization will lead to remarkable increase in $\omega_{T}$. As a result, the spectral efficiency of the IC-TSP will be improved more significantly when $M$ is large. Besides, the sectorization is also beneficial in reducing the backhaul overhead in the IC-TSP with D-RAN structure since fewer BSs have to exchange their DL data and precoding vectors. Therefore, the sectorization is more useful for the IC-TSP.

### D. CS based BS-BS channel estimation

As analyzed above, the overhead of BS-BS channel estimation has a significant impact on the spectral efficiency of IC-TSP, especially when $M$ is large. Therefore, it is important to reduce this overhead [43]. Since the BS-BS channel is Ricean and spatially correlated, it is expected that the BS-BS channel has a sparse representation in the spatial-frequency domain [44]. To realize a sparse representation of BS-BS channel in the spatial-frequency domain by fully exploiting channel correlations, the discrete Fourier transform (DFT) can be employed as the sparsifying-basis. Let $\mathbf{G}_{ld}$ denote the sparse representation of the BS-BS channel $G_{ld}$, given by

$$
\mathbf{G}_{ld} = \mathbf{A}^{H} \mathbf{G}_{ld}^{H} \mathbf{A},
$$

(18)

where $\mathbf{A} \in \mathbb{C}^{M \times M}$ is the unitary DFT matrix which follows $\mathbf{A} \mathbf{A}^{H} = \mathbf{A}^{H} \mathbf{A} = I_{M}$. Using the DFT matrix, the received pilot signal in the spatial-frequency domain is given by

$$
\mathbf{Y}_{ld}^{BS} = \mathbf{P} \mathbf{G}_{ld} + \mathbf{J}_{ld},
$$

(19)

where $\mathbf{Y}_{ld}^{BS} = \mathbf{(Y}_{ld}^{BS})^{H} \mathbf{A}$, $\mathbf{P} = \sqrt{\rho_{BS}T} \mathbf{P}^{H}$, and $\mathbf{J}_{ld} = \mathbf{J}_{ld}^{H} \mathbf{A}$. In the spatial-frequency domain, $\mathbf{G}_{ld}$ is approximately
is lower than that of the LS based IC-TSP with sectorization. This is because the MSCEE of the CS based BS-BS channel estimation is higher than that of the LS based BS-BS channel estimation while the impact of reduction in the pilot overhead is marginal when $M$ is small.

V. PERFORMANCE EVALUATION

Simulations are carried out to evaluate the performance of the proposed IC-TSP and verify our analysis. System configurations are shown in Table I. The power parameters are chosen according to the LTE-A standard [33]. If there is no special declaration, the uniform power allocation, the LS channel estimation, the MF precoding and detection are adopted in simulations. Since the MSCEE, SINR and spectral efficiency are still random due to the impact of shadow fading and MSs’ location, we generate 10000 random realizations of MS locations and shadow fading profiles to provide the average performance in the simulations.

Firstly, Table II shows the channel estimation performance of TSP with different channel estimation (LS and linear minimum mean square error (LMMSE)) and precoding methods (MF and ZF). The normalized MSCEE is defined as the ratio between the average MSCEE $\mathbb{E}\{\varepsilon_{ilk}\}$ (average over all MSs) and the average power of the target channel $P_{TC} = \mathbb{E}\{\|g_{ilk}\|^2\}$ [27-28], [44]. At first, it can be seen that the analytical results of normalized MSCEE (which are calculated using (3)) match well with the simulated ones, which verifies the validity of the approximated MSCEE. Considering the MSCEE performance with MF precoding and different channel estimation schemes, it can be seen that the average normalized MSCEE is larger than 6 dB for $\Gamma \geq 3$. This stands for an extremely high channel estimation error which deteriorates the system performance seriously. Meanwhile, the average normalized MSCEE increases rapidly when $\Gamma$ increases from 1 to 3, which verifies the analysis in Sec. III-A. Note that the gain in the average normalized MSCEE of LMMSE over LS is limited (smaller than 1dB). This is because the interference suffered by channel estimation of TSP is extremely severe. Next, the MSCEE performance with different precoding schemes is compared. It can be seen that with LS channel estimation, MF and ZF precoding present similar performance in MSCEE. This is because the precoding is designed to cancel the intra-cell interference (based on the MS-BS channel estimation) while the dominant component of MSCEE is the inter-group data interference (from the BS-BS channel), as also demonstrated in this table. Meanwhile, the composition of MSCEE is also evaluated. It can be seen that with LS/LMMSE channel estimation and MF/ZF precoding, the power of inter-group data interference $\mathbb{E}\{\varepsilon_{ilk',data}\}$ always dominates the MSCEE, which contributes more than 88% to the total value. This verifies the analysis in Sec. III-A. In summary, for various TSP with LS and LMMSE channel estimations and MF and ZF precoding schemes, the system presents similar MSCEE performance, and the dominating MSCEE components are the same. Therefore, the analytical results obtained for TSP with LS channel estimation and MF precoding can also be insightful for TSP with LMMSE channel estimation and ZF precoding.
TABLE I
PARAMETER SETTINGS

| Parameter               | Value                  | Parameter               | Value                  |
|-------------------------|------------------------|-------------------------|------------------------|
| Default cell number     | \( L = 3 \)            | MS transmitter power    | \( 23 \) dBm           |
| Default group number    | \( K \)                | Symbol number per coherence time | \( T_c = 385 \) [23] |
| MS number each cell     | \( 1 \)                | Default pilot sequence length | \( \tau_p = 4 \)       |
| Cell radius             | \( r_c = 500 \) m      | DL data length          | \( T_p = 96 \)         |
| Protection radius       | \( r_d = 20 \) m       | UL data length          | \( T_u = 85 \)         |
| Carrier frequency       | 2 GHz                  | Sub-carrier number per coherence frequency | \( F_c = 5 \) [20]     |
| Bandwidth               | 10 MHz                 | Noise power for all transmitting stages | \(-174 \) dBm/Hz        |
| Rician factor           | \( k_T = 10 \)         | Default coherence time of BS-BS channel | \( T_{BS-BS} = 500 \tau_c \) |
| Decaying exponent       | \( \eta_{P,S} = 3.8 \) | Default number of main DL data interfering cells | \( L_{BS-main} = 18 \) |
| Shadow fading factor    | \( \sigma_{sh} = 8 \) dB [34] | Spatial correlation coefficient | \( \kappa = 0.8 \) [25] |
| BS transmitter power    | 46 dBm                 | Certain accuracy \( P \) to describe approximate sparsity | \( P = 99\% \)         |

TABLE II
EVALUATION OF AVERAGE NORMALIZED MSCEE AND MSCEE COMPOSITION FOR TSP SCHEME

| Parameter | Value |
|-----------|-------|
| Channel estimation + precoding method | \( \Gamma = 1 \), \( \Gamma = 3 \), \( \Gamma = 4 \), \( \Gamma = 7 \), \( \Gamma = 9 \), \( \Gamma = 12 \) |
| LS+MF (analytical) | \( \varepsilon_{\text{LS+MF}} \) |
| LS+MF | \( \varepsilon_{\text{LS+MF} \, \text{data}} \) |
| LMMSE+MF | \( \varepsilon_{\text{LMMSE+MF} \, \text{data}} \) |
| LS+ZF | \( \varepsilon_{\text{LS+ZF} \, \text{data}} \) |
| LS+M (analytical) | \( \varepsilon_{\text{LS+M} \, \text{data}} \) |
| LS+M | \( \varepsilon_{\text{LS+M} \, \text{data}} \) |
| LMMSE+M | \( \varepsilon_{\text{LMMSE+M} \, \text{data}} \) |
| LS+ZF | \( \varepsilon_{\text{LS+ZF} \, \text{data}} \) |

Fig. 4. Average SINRs as a function of the average normalized MSCEE in TSP.

Fig. 5. Average UL SINRs as a function of the average normalized MSCEE in TSP with different detection and power control.

Fig. 4 investigates the impact of average normalized MSCEE on the average SINRs of TSP where different MSCEE is derived by changing the DL data transmission power of interfering cells during the channel estimation of target cell. It can be seen that the analytical results (derived from (5), (7), and (8)) are quite close to the simulated ones. For the considered finite BS antenna cases, the UL SINR, PD SINR and CL SINR decrease with the increase of the average normalized MSCEE. The typical average normalized MSCEE from Table II with \( \Gamma \geq 3 \) is about 7.5 dB for LS channel estimation. When the average normalized MSCEE increases from -20 dB to this typical average normalized MSCEE, the UL SINR, PD SINR and CL SINR degrade by about 8 dB for both \( M=1024 \) and \( M=128 \). Therefore, it is important to improve channel estimation accuracy. Furthermore, the UL SINR, PD SINR and CL SINR are close to each other for different \( M \) and MSCEE, which verifies the previous analysis in Sec. III. In the following simulations, the UL SINR is taken as an example to show the system performance.

The average UL SINR performance of TSP with ZF detection is shown in Fig. 5, and the impact of power control is also evaluated with MF method. It can be seen that the average UL SINR always decreases as the average normalized MSCEE increases, no matter which detection method and power control scheme are employed. When the average normalized MSCEE is small, using uniform power allocation, TSP with ZF method performs better than that with MF method, and the performance gain is larger with a smaller \( M \). This is because the orthogonalization of MF method is strengthened with the increase of \( M \) (which is called the asymptotic orthogonality in massive MIMO systems [1]) and the MF method approaches the performance of ZF method with larger \( M \). Using the MF precoding, TSP with path-loss
based power control performs better than that with uniform power allocation. The performance gap between path-loss based power control and uniform power allocation keeps stable as $M$ changes since the power allocation is independent with $M$. The previously mentioned performance gaps caused by different channel estimation and power control schemes reduce as the average normalized MSCEE increases. This is because TSP is trapped in severe channel estimation error with a large MSCEE and the advantages of ZF method and path-loss based power control become negligible. In summary, the insights derived from the analysis with MF method and uniform power control also hold for TSP with ZF method and path-loss based power control.

![Fig. 6. The required $M$ to achieve a target SINR as a function of average normalized MSCEE.](image)

Fig. 6 shows the required $M$ ($M_T$) to achieve a target SINR for UL transmission of TSP. $M_T$ increases rapidly with the average normalized MSCEE especially when the average normalized MSCEE is higher than 0 dB, which verifies the analyses in (10). To achieve a target SINR of 10 dB, TSP with the average normalized MSCEE of -10 dB requires about 170 antennas while the TSP with the average normalized MSCEE of 10 dB needs more than 2500 antennas, which becomes impractical for implementation. Hence, it is important to reduce MSCEE, so that less BS antennas are required to achieve the target performance.

![Fig. 7. The average MSCEE as a function of $L_{D_{main}}$.](image)

Given $M=128$ and $L=61$, Fig. 7 shows the average normalized MSCEE performance of IC-TSP, TSP and RBF [21]. IC-TSP with different channel estimation schemes are evaluated, including LS (and LMMSE) based IC-TSP where all the BS-BS and MS-BS channels are estimated by LS (and LMMSE) method, and CS based IC-TSP where the BS-BS channels are estimated by CS based method and the MS-BS channels are estimated by LS method. IC-TSP always performs the best while the performance of traditional TSP is the worst. The RBF method in [21] outperforms TSP, thanks to the cancellation of UL data transmission. But its improvement is limited since the channel estimation error is dominated by DL data transmission but not UL data transmission. Furthermore, for IC-TSP, the average normalized MSCEE decreases as $L_{D_{main}}$ increases since more inter-group data interference can be canceled. Considering the scenario with $\Gamma = 7$, IC-TSP with LS channel estimation can reduce the average normalized MSCEE of the TSP by 15 dB and 19 dB for $L_{D_{main}} = 18$ and 36, respectively. The average normalized MSCEEs of TSP and the RBF method in [21] increase with $\Gamma$ since a higher $\Gamma$ leads to more DL data interference. However, the average normalized MSCEE of IC-TSP shows different trend with the change of $\Gamma$ for different $L_{D_{main}}$. When $L_{D_{main}} = 6$, during the channel estimation, IC-TSP can only cancel the severe ICI generated from the nearest layer of cells transmitting DL data. So the channel estimation mainly suffers from the interference generated by the 12 cells in the second nearest layer. When $\Gamma = 3$, 6 cells in this layer transmit DL data while another 6 cells transmit UL pilot. However, when $\Gamma = 7$, all 12 cells in this layer transmit DL data. Since DL data interference is much higher than UL pilot interference, the interference with $\Gamma = 3$ is less than that with $\Gamma = 7$, and its channel estimation performance is better. Differently, when $L_{D_{main}} = 18$, IC-TSP with $\Gamma = 7$ cancels interference from all 18 cells in the nearest two layers. However, IC-TSP with $\Gamma = 3$ cancels interference from only 12 cells among the 18 cells, and the interference from the rest 6 cells transmitting UL pilot cannot be canceled. Therefore, the average normalized MSCEE of IC-TSP with $\Gamma = 7$ becomes lower than that with $\Gamma = 3$. When $L_{D_{main}}$ increases from 18 to 36, the DL data interference generated from cells in the 3-rd layer is also cancelled. Due to the larger distance between the target cell and the cells in the 3-rd layer, the DL data interference is relatively small and the reduction in the MSCEE is limited. Furthermore, larger $L_{D_{main}}$ leads to higher overhead. Thus, it is no need to apply $L_{D_{main}}$ larger than 18. At last, for IC-TSP with different BS-BS channel estimation schemes, LMMSE based IC-TSP can achieve the lowest normalized MSCEE since the LMMSE BS-BS channel estimation utilizes the channel correlation information to reduce the interferences. Furthermore, the MSCEE of the LMMSE based IC-TSP shows the similar trend with that of the LS based IC-TSP. The CS based IC-TSP presents the highest average normalized MSCEE among these three IC-TSP schemes. As analyzed in Sec. IV-D, the BS-BS channel in the spatial-frequency domain is only approximately sparse (not strictly sparse), thus the BS-BS channel estimation error of CS based method is higher than LS and LMMSE method due to reconstruction error caused by the approximate sparsity.

Fig. 8 investigates the impact of the coherence time of the BS-BS channel $T_{BS_{coherence}}$ on average UL spectral efficiency. It
can be seen that the average UL spectral efficiency of the proposed IC-TSP increases with $T_{BS,C}$ while the curves of TSP do not change with $T_{BS,C}$. When $T_{BS,C}$ is small, the overhead dominates the communication resources in $T_{BS,C}$ and the overall performance is poor even if the channel estimation quality is improved. When $T_{BS,C}$ increases, the impact of overhead decreases and the gains brought by good channel estimation become obvious. The cross point where IC-TSP exceeds TSP increases with $M$. This is because the overhead of BS-BS channel estimation increases with $M$. When $T_{BS,C}$ increases further, the performance of IC-TSP keeps stable. This is because the overhead of BS-BS channel estimation becomes negligible for a large $T_{BS,C}$, and the gain provided by improved channel estimation becomes saturated. When $T_{BS,C}$ is large, it can be seen that IC-TSP achieves an average spectral efficiency gain of about 1.3 bps/Hz and 1.7 bps/Hz for $M=128$ and 1024, respectively.

![Fig. 8. Impact of $T_{BS,C}$ on average UL spectral efficiency.](image)

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Improves with $M$ for the considered range. However, for IC-TSP, when $M$ is sufficiently large, it achieves the highest average spectral efficiency, then the average spectral efficiency decreases with $M$. This is because the overhead of BS-BS channel estimation increases linearly with $M$ and this reduces the spectral efficiency. A cross point occurs at certain $M$, beyond which the spectral efficiency of IC-TSP is worse than that of TSP. With $L_{D_{main}}=18$, the optimal $M$ of IC-TSP is larger than 2048 and the cross point of $M$ is larger than 4096, which shows the effective range of $M$ for IC-TSP. The average spectral efficiency gain achieved by the IC-TSP with $L_{D_{main}}=36$ is close to that with $L_{D_{main}}=18$ while the optimal $M$ and cross-point $M$ is much smaller. Therefore, the spectral efficiency result also demonstrates that it is no need to apply $L_{D_{main}}$ larger than 18. Comparing the IC-TSP with MF and ZF method, it is shown that IC-TSP with ZF method can achieve better performance than that with MF method when $M$ is smaller than 1000. When $M$ is large, the asymptotic orthogonality of massive MIMO system improves the performance of MF method and the gain of ZF method will vanish. However, for TSP, the spectral efficiencies of ZF and MF method are almost the same for all considered $M$. This is because the MSCEE is so large for TSP that the ZF method based on severely polluted channel estimation is hard to orthogonalize the multi-MS signals.

Fig. 9 illustrates the UL spectral efficiency as a function of $M$, when TSP and IC-TSP are employed with various sectorization and channel estimation schemes. For IC-TSP, we set $L_{D_{main}} = 18$. Compared to the unsectorized case, the sectorization always improves the UL spectral efficiency while the improvement is more significant when $M$ is large. The difference is due to the fact that the correlated interference can be reduced more significantly than the uncorrelated one. Furthermore, compared to the TSP, the improvement of the UL spectral efficiency is more significant for the IC-TSP since the sectorization reduce the MSCEE more significantly in the IC-TSP. Next, we consider the performance of IC-TSP with CS based channel estimation (CS based IC-TSP). When $M$ is small, the average spectral efficiency of CS based IC-TSP is lower than that of LS based IC-TSP. This is because the $\varpi_T$ approaches 1 for both CS and LS based IC-TSP while the LS based IC-TSP achieves lower MSCEE. When $M$ increases, the performance of CS based IC-TSP increases with $M$ even when $M = 3 \times 10^4$. This is because using the CS based BS-BS channel estimation, the pilot overhead can be reduced significantly. As a result, the CS based IC-TSP achieves higher average spectral efficiency than LS based one for large $M$. In summary, it is recommended to use LS based IC-TSP for small $M$ (e.g., for $M \leq 2000$ under the configuration in this paper) and CS based IC-TSP for large $M$ (e.g., for $M > 2000$ under the configuration in this paper). Furthermore, the spectral efficiency of the CS based IC-TSP using the precoded DL data as the pilot is also evaluated. The utilization of precoded DL data will slightly improve the spectral efficiency when $M$ is large due to the reduction of pilot overhead. However, the spectral efficiency will be reduced when $M$ is small where the RIP of sensing matrix cannot be well ensured. At last, we show the performance with the combination of the CS based BS-BS
channel estimation and sectorization. When \( M \) is large, this combination achieves the highest spectral efficiency. However, when \( M \) is small, the spectral efficiency of the CS based IC-TSP with sectorization is lower than that of the LS based IC-TSP with sectorization, which is the same as that in the unsectored case.

VI. CONCLUSIONS

This paper focused on the finite antenna analysis for massive MIMO systems with TSP. After analytically demonstrating that the channel estimation error is critical for the system when the number of antenna is finite, an IC-based channel estimation method has been proposed in this paper. The main idea is to cancel out the inter-group data interference in the channel estimation, exploiting the shared information of preceding vectors, DL data and the estimated channels among BSs. The impacts of system parameters (including the length of the coherence time of BS-BS channel and \( M \)) and the pilot overhead reducing approaches (including the sectorization and the CS based BS-BS channel estimation) on IC-TSP have been extensively investigated. Both analytical results and simulations have shown that the proposed IC-TSP can effectively reduce the channel estimation error and improve the SINR and the spectral efficiency in the finite antenna massive MIMO system. For future work, the feasibility of machine learning based channel estimation should also be discussed for finite antenna massive MIMO systems to cancel the pilot contamination.

APPENDIX A

The MSCEE of the \( k' \)-th MS in the \( l \)-th cell is given by (20), where

\[
\mathbb{E} \left\{ \left| \sum_{j \neq l, j \in A_p} \sqrt{\frac{p_{UL,ik'}}{p_{UL,ik'}}} g_{lj,k'} \right|^2 \right\} = \frac{M}{\sum_{j \neq l, j \in A_p} \sqrt{\frac{p_{UL,ik'}}{p_{UL,ik'}}} g_{lj,k'}}
\]

However, the accurate result of

\[
\mathbb{E} \left\{ \left| \sum_{d=1, d \notin A_p}^L \sum_{k=1}^K \sqrt{\frac{p_{UL,ik'}}{p_{UL,ik'}}} G_{ld} \mathbf{w}_{dk} \mathbf{x}_{dk}^H \mathbf{w}_{dk}^H \right|^2 \right\}
\]

is hard to derive since the BS-BS channel \( G_{ld} \) is slightly correlated with the preceding vector \( \mathbf{w}_{dk} \). Fortunately, this correlation is very weak. \( \mathbf{w}_{dk} \) is generated by using the channel estimation \( \hat{G}_{ddk} \), where \( \hat{G}_{ddk} = G_{ddk} + e_{ddk} \).

\[
e_{ddk} = e_{ddk, \text{pilot}} + e_{ddk, \text{data}} + e_{ddk, \text{noise}}
\]

and

\[
e_{ddk, \text{data}} = \frac{c}{L + k_y} \left( \sqrt{\frac{c}{L + k_y}} C_{ld} + \frac{1}{\sqrt{1 + k_y}} C_{ld} \right)
\]

The numerator of \( e_{ddk, \text{data}} \), only the term with \( b = l \) is correlated to \( C_{ld} \), which occupies \( \frac{1}{L + |A_p|} \) of all the cumulated terms in the numerator of \( e_{ddk, \text{data}} \) where \( L \) is the number of cells, \( A_p \) is the set of pilot transmitting cells. Considering a common scenario described in Fig. 1 in this revision, \( L = 37 \), \( |A_p| = 7 \) then the ratio \( \frac{1}{L + |A_p|} \) is only \( \frac{1}{37} \). Therefore, we omit this correlation and derive approximate analysis. Furthermore, the BS-BS channel \( G_{ld} \) is given by

\[
G_{ld} = \sqrt{\alpha_{ld}} \left( \frac{1}{\sqrt{1 + k_y}} C_{ld} + \frac{1}{\sqrt{1 + k_y}} C_{ld} \right)
\]

and

\[
\mathbb{E} \left\{ \left| \sum_{d=1, d \notin A_p}^L \sum_{k=1}^K \sqrt{\frac{p_{UL,ik'}}{p_{UL,ik'}}} G_{ld} \mathbf{x}_{dk}^H \mathbf{w}_{dk}^H \right|^2 \right\} = \frac{1}{1 + k_y} \left( \sum_{d=1, d \notin A_p}^L \sum_{k=1}^K \sqrt{\frac{p_{UL,ik'}}{p_{UL,ik'}}} \alpha_{ld} \mathbf{C}_{ld} \mathbf{x}_{dk}^H \mathbf{w}_{dk}^H \right)^2
\]

where the expectation in the first term equals to

\[
\sum_{d=1, d \notin A_p}^L \sum_{k=1}^K \sqrt{\frac{p_{UL,ik'}}{p_{UL,ik'}}} \alpha_{ld} \mathbf{C}_{ld} \mathbf{x}_{dk}^H \mathbf{w}_{dk}^H \right|^2 \approx M \frac{1}{1 + k_y} \left( \sum_{d=1, d \notin A_p}^L \sum_{k=1}^K \sqrt{\frac{p_{UL,ik'}}{p_{UL,ik'}}} \alpha_{ld} \mathbf{C}_{ld} \mathbf{x}_{dk}^H \mathbf{w}_{dk}^H \right)^2
\]

and the expectation in the second term is

\[
\sum_{d=1, d \notin A_p}^L \sum_{k=1}^K \sqrt{\frac{p_{UL,ik'}}{p_{UL,ik'}}} \alpha_{ld} \mathbf{R}_{\mathbf{H}^{H} \mathbf{H}} \mathbf{R}^H \mathbf{w}_{dk} \mathbf{x}_{dk}^H \mathbf{w}_{dk}^H \right|^2 \approx M \frac{1}{1 + k_y} \left( \sum_{d=1, d \notin A_p}^L \sum_{k=1}^K \sqrt{\frac{p_{UL,ik'}}{p_{UL,ik'}}} \alpha_{ld} \mathbf{R}_{\mathbf{H}^{H} \mathbf{H}} \mathbf{R}^H \mathbf{w}_{dk} \mathbf{x}_{dk}^H \mathbf{w}_{dk}^H \right)^2
\]

APPENDIX B

For the UL transmission stage, SINR of the detected signal of the \( k' \)-th MS in the \( l \)-th cell is given by (22). In (22), the
channel estimation $\hat{g}_{ilk'} = g_{ilk'} + e_{ilk'}$. As shown in Fig. 1, when a target group transmits pilot in the $n$-th frame, the channel estimation is interfered by the precoded DL data of other groups. The precoding vectors of these interferences are generated using channel estimations conducted earlier, which are correlated with the channel estimation of the target group of the $(n-1)$-th frame, but not those of the $n$-th frame. Since the wireless channels estimated at the $(n-1)$-th and $n$-th frame are uncorrelated, $w_{dlk}$ in $e_{ilk'} \cdot data$ is uncorrelated with $g_{ilk'}$ corresponding to the $n$-th frame. As a result, in (2), $g_{ilk'}$ and $e_{ilk'}$ are uncorrelated. $E \left\{ \| \hat{g}_{ilk'}^H g_{ilk'} \|^2 \right\}$ is given by

$$E \left\{ \| \hat{g}_{ilk'}^H g_{ilk'} \|^2 \right\} = \sum_{m=1}^{M} E \left\{ \| \hat{g}_{ilk'}^H g_{ilk'} \|^2 \right\} = E \left\{ \| \hat{g}_{ilk'}^H g_{ilk'} \|^2 \right\} + E \left\{ \| e_{ilk'}^H g_{ilk'} \|^2 \right\},$$

where

$$E \left\{ \| \hat{g}_{ilk'}^H g_{ilk'} \|^2 \right\} = \beta_{ilk'}^2 \left(M + M^2 \right)$$

and

$$\sum_{m=1}^{M} \left( \sqrt{2} \cdot \text{real} \left(h_{ilk'} \right) \right) + \left( \sqrt{2} \cdot \text{imag} \left(h_{ilk'} \right) \right)$$

is a random variable follows Chi-squared distribution with $2M$ degrees of freedom, whose expectation is $2M$ and variance is $4M$. Furthermore, the channel estimation error $e_{ilk'}$ is uncorrelated with the target channel $g_{ilk'}$ (see (2)). Then $E \left\{ \| e_{ilk'}^H g_{ilk'} \|^2 \right\}$ is given by (24). Therefore,

$$E \left\{ \| \hat{g}_{ilk'}^H g_{ilk'} \|^2 \right\} = M \left(M + 1 \right) \beta_{ilk'}^2 + M \varepsilon_{ilk'} \beta_{ilk'}.$$  

Similarly, other expectations in (22) can be derived as

$$E \left\{ \sum_{k=1}^{K} \frac{P_{UL,jk'}^D}{\sqrt{P_{UL,lk}}} \beta_{ilk'} \right\} = M \left(M + 1 \right) \beta_{ilk'}^2 + M \varepsilon_{ilk'} \beta_{ilk'}.$$
\[ S_{\text{CL}} = \sum_{j=1}^{L} \rho_{\text{DL},lk}^T \mathbb{E} \left\{ \left\| g_{lk}^T w_j \right\|^2 \right\} + \sum_{j=1}^{L} \rho_{\text{UL},j}^T \mathbb{E} \left\{ \left\| g_{l,j} \right\|^2 \right\} + \rho_{\text{DL},lk}^T \mathbb{E} \left\{ \left\| g_{lk}^T w_j \right\|^2 \right\} + \frac{\mathbb{E} \left\{ \left\| n_{\text{DL}-\text{CL},lk} \right\|^2 \right\}}{F_C T_P}, \] (26)

Therefore, the SINR of the CL stage is approximated by (29), where \[ \varepsilon_{\text{CL},lk} = \frac{\beta_{\text{UL},lk} + (\beta_{\text{UL},lk} + \varepsilon_{\text{UL},lk} k) \varepsilon_{\text{CL},lk}}{M}. \]

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