An Overview of Pilot Decontamination Methods in TDD Massive MIMO Systems

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***Abstract*—The fundamental premises of *massive multiple-input multiple-output* (MIMO) communication systems are to deploy antenna arrays with a few hundred antennas at each base station and to serve a much smaller number of single-antenna terminals using multi-user MIMO transmission. Massive MIMO is an enabler for the development of future broadband wireless networks that scales up the advantages of MIMO by orders of magnitude. While massive MIMO renders many implementation issues, linked to channel estimation, detection and precoding schemes. This paper focuses on the impact of pilot contamination on massive MIMO systems caused by the use of non-orthogonal pilot sequences by the users in adjacent cells and presents an overview of the pilot contamination concept and contemporary research on the issue.**

***Index Terms*—Massive MIMO, multi-user MIMO, pilot contamination, precoding.**

I. Introduction

The ever-increasing demands of high-data rate and quality of service (QoS) have attracted many researchers to the enhancement of wireless capacity in the cellular networks. Multiple-input multiple-output (MIMO) technology has been extensively studied in the last two decades and seems to meet the demands of high-data rate and QoS through the spatial multiplexing gain and antenna diversity gain respectively. As a key attribute of all modern cellular systems; MIMO entails expensive multiple-antenna mobile stations (MSs). Furthermore, the multiplexing gains in MIMO may vanish near the cell edges where signal to interference ratios (SNRs) are low or system is more sensitive to the propagation environment [1], [2].

A more practical choice to a point-to-point MIMO system is a multi-user MIMO (MU-MIMO) system in which a base station (BS) with an antenna array simultaneously serves a multiplicity of autonomous single-antenna mobile terminals and the multiplexing throughput gain can be shared among all mobile terminals. Thus, the mobile terminals can be economical single antenna devices compared to expensive multiple antenna array equipment at the BS. A MU-MIMO system is less sensitive to the propagation environment than a point-to-point MIMO system due to multi-user diversity. In line-of-sight (LOS) propagation conditions the multiplexing gains will vanish for a point-to-point MIMO system, but are maintained in the MU-MIMO provided the angular separation of the terminals exceeds the Rayleigh resolution of the array. Therefore, MU-MIMO has become an standard integral part of the communication recommends, such as 802.11 (WiFi), 802.16 (WiMAX), LTE, and is gradually being installed throughout the world. However, MU-MIMO, where BS typically employs only a few (i.e., fewer than 10) antennas and the consequent enhancement in the spectral efficiency is still quite modest, is not a scalable technology [2]-[5].

Massive MIMO (M-MIMO) or Large Scale Antenna Systems (LSAS) brings revolution in wireless communication that scales up MU-MIMO by an order of magnitude contrasted to the current state-of-the-art. M-MIMO uses orders of magnitude more antennas, e.g., 100 or more, at each BS and Time Division Duplex (TDD) operation. M-MIMO owns all the advantages of MU-MIMO, but at a much larger scale [6]. Furthermore, asymptotic arguments based on the random matrix theory reveal that the effects of uncorrelated noise and small-scale fading are eradicated, the number of users per cell is independent of the cell size, and the required transmitted energy per bit disappears as the number of antennas in M-MIMO cell raises to infinity [3]. Moreover, these advantages of M-MIMO can be achieved even by using simple linear signal processing approaches, such as matched-filter (MF) precoding/detection.

It is revealed in [3] that under practical propagation conditions, MF-based non-cooperative massive MIMO systems could in principle achieve a data rate of 17 Mbps for each of 40 users in a 20 MHz channel in both the uplink and downlink directions, with an average throughput of 730 Mbps per cell and an overall spectral efficiency of 26.5 bpspHz. Since the number of antennas at the BS is typically assumed to be significantly larger than the number of users, a large number of degrees of freedom are available and can be used to shape the transmitted signals in a hardware-friendly way or to eliminate interference [7]. To make such a system practical, algorithms for M-MIMO systems are required to have low complexity.

Furthermore, another advantage of M-MIMO system over single-antenna system is its energy efficiency. In [8], H. Q. Ngo et al demonstrated that the uplink power of each single-antenna user in M-MIMO can be reduced in proportional to the number of antennas at the BS with perfect channel state information (CSI) or to the square root of the number of BS antennas with imperfect CSI, to obtain the same performance as a corresponding single-antenna system. This

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higher energy efficiency asset of M-MIMO system is of much importance as excessive energy consumption is a growing concern for future the wireless networks [9], [10]. However, if ample uplink power is available, then an M-MIMO system could significantly broaden the range of operation contrasted to single antenna system. Though the conclusions in [8] overlook the uplink power consumption of the radio front-end, M-MIMO is still a promising candidate for improving energy-efficiency of the future networks.

M-MIMO depends on spatial multiplexing; therefore BS should have a good CSI of the uplink and downlink channels. The channel estimation (CE) of the uplink channel is easy to achieve and can be done at the BS by letting the user terminals (UTs) send different pilot sequences. However, the CE of the downlink channel is estimated using a two-step process in conventional MIMO systems, such as the Long Term Evolution (LTE) standard. The BS first transmits pilot waveforms to all UTs, based on which the UTs estimate the channel responses and then feed them back to the BS. As the number of BS antennas grow large, this two-step process of downlink channel estimation becomes infeasible due to two reasons. First, the optimal downlink pilots should be mutually orthogonal among the antennas, which imply that the amount of time-frequency assets required for the downlink pilots sizes with the number of antennas. Therefore, an M-MIMO system would need hundreds of times more such assets than a conventional MIMO system. Second, the number of channel responses estimated for each UT is also proportional to the number of antennas of base station antennas. Therefore, the uplink assets desired to update the BS of the channel responses would be up to 100 times more than in conventional MIMO systems. Generally, the solution is to operate in TDD mode, and depend on the reciprocity between the uplink and downlink channels [1], [2].

In a TDD protocol, the BS estimates the uplink channel with uplink pilot sequences and acquires the downlink CSI by exploiting channel reciprocity. This approach is only practical when the pilot sequences employed in each cell are orthogonal to those in other cells. However, in practical cellular networks, the limited coherence time does not allow the perfect orthogonality among the pilots in different cells. As a result, the channel estimates obtained by a given BS in a multi-cell scenario with non-orthogonal pilots will be contaminated by the pilot sequences transmitted by the users of the neighboring cells. This effect of channel estimation contamination is so called "pilot contamination" [3], [11]-[13].

A number of pilot contamination elimination techniques have been proposed recently. One of the earliest schemes is Ref. [14], in which the authors proposed a minimum mean square error (MMSE) criterion based precoding method to diminish the pilot contamination. The proposed scheme of [15], analyzed the asymptotic behavior of the signal to interference plus noise ratio (SINR) for both time aligned and time staggered pilots, which disclosed that it may be achievable to terminate the interference of neighbor cells, only if the pilots do not overlap in time. However, the transmission of staggered pilots entails a central controller for managing the staggering of the pilot-intervals in all of the cells in order to safeguard their 'orthogonality' across different cells, which becomes difficult for an increasing number of users and cells. Recently, in [13] similar protocol as of [15] was used. However, [13] proposed the zero forcing (ZF) with the limited number of antennas to analyze the performance of M-MIMO systems with the time-shifted pilot protocol.

Coordinated CE based on linear MMSE (LMMSE) estimation was proposed in [16] to tackle the problem of pilot contamination. The LMMSE estimator produces better performance than least square (LS) estimator; however, it requires the knowledge of the second-order statistics of all the UL channels, including those of the interfering MSs roaming in the neighbor cells. Furthermore, the scheme of [16] employs the known second-order statistics of all the uplink channels for designing a covariance-aware pilot assignment strategy for improving the LMMSE CE.

In [17], J. Zhang *et al*. proposed a sophisticated amalgam of downlink training and scheduled uplink training to eradicate the pilot contamination in multi-cell TDD orthogonal frequency division multiplexing (OFDM) systems. The scheme of [17] did not need the knowledge about the channels' second-order statistics, unlike the schemes in [14] and [16], but it added the training overhead by a factor equal to the number of interfering cells. A smart pilot assignment (SPA) scheme was proposed in [12] to improve the performance of users with severe pilot contamination. The scheme of [17] also did not need the knowledge of the channels' second-order statistics.

The above mentioned studies have clearly shown the severity of the pilot contamination dilemma in a M-MIMO systems. This paper provides a comprehensive and detailed overview of this problem in the multi-cell TDD M-MIMO systems. The residue sections of the paper are as follows. The pilot contamination problem is presented in Section II. The Section III describes some well-known pilot contamination elimination schemes. The Section IV presents discussions and future recommendations about elimination of pilot contamination in a M-MIMO system. Finally, some conclusions are given in Section V.

Notation: Boldface lower and upper case symbols represent vectors and matrices, respectively. The transpose, Hermitian transpose operators are denoted by $(.)^T$ and $(.)^H$, respectively.

II. Pilot Contamination

Consider a cellular system consist on E hexagonal cells, tagged by $e = 1, 2, ..., E$. Each cell contains one BS with A transceiver antennas and U single transceiver antenna MSs, where $U \ll A$. All the BSs and MSs are synchronized and the cellular system is based on TDD protocol with unity frequency reuse (UFR).

A. Uplink Training

All the MSs in all BSs transmit their uplink training pilot sequences at the instigation of each coherence time. The uplink training pilot sequences are the column vectors with the ℓ length. Let $\mathbf{q}_{eu} = [q_{eu}^{[1]} \quad q_{eu}^{[2]} \quad q_{eu}^{[3]} \quad ... \quad q_{eu}^{[\ell]}]^T$ be the

pilot sequence of the u-th MS in the e-th cell, where $q_{eu}^{[ii]}$ is the ii-th element of the pilot sequence, and $\mathbf{q}_{eu}\mathbf{q}_{eu}^{H}=1$.

Now consider the BS of the x-th cell, shown in Fig. 1. The signal z_{xa} can be given as [1], [13], [14] which is received by the a-the antenna of the BS of the x-th cell during the uplink training phase,

$$z_{xa}=\sum_{e=1}^{E}\sum_{u=1}^{U}\sqrt{\rho_{up}\beta_{exu}}\,h_{exua}\mathbf{q}_{eu}+v_{xa}\,, \tag{1}$$

where ρ_{up} is the average uplink power of each user, β_{exu} is the path-loss and shadowing that change slowly and can be learned over long period of time which is the positive constant, h_{exua} is the independent and identically distributed (i.i.d.) zero-mean, circularly-symmetric complex Gaussian $\mathcal{CN}(0,1)$ random variables and model fading that change relatively fast and must be learned and used very quickly and v_{xa} is the i.i.d additive white Gaussian noise (AWGN) with $\mathcal{CN}(0,1)$.

Define $\mathbf{Z}_x=[z_{x1}\ \ z_{x2}\ \ \dots\ \ z_{xA}]_{\ell\times A}$, $\mathbf{V}_x=[v_{x1}\ \ v_{x2}\ \ \dots\ \ v_{xA}]_{\ell\times A}$, all cells must employ same set of pilot sequences to implement UFR, therefore $\mathbf{Q}=[\mathbf{q}_1\ \ \mathbf{q}_2\ \ \dots\ \ \mathbf{q}_U]_{\ell\times U}$ satisfying $\mathbf{Q}^{HT}\mathbf{Q}=\ell\mathbf{I}$.

Then, (1) can be rewritten as

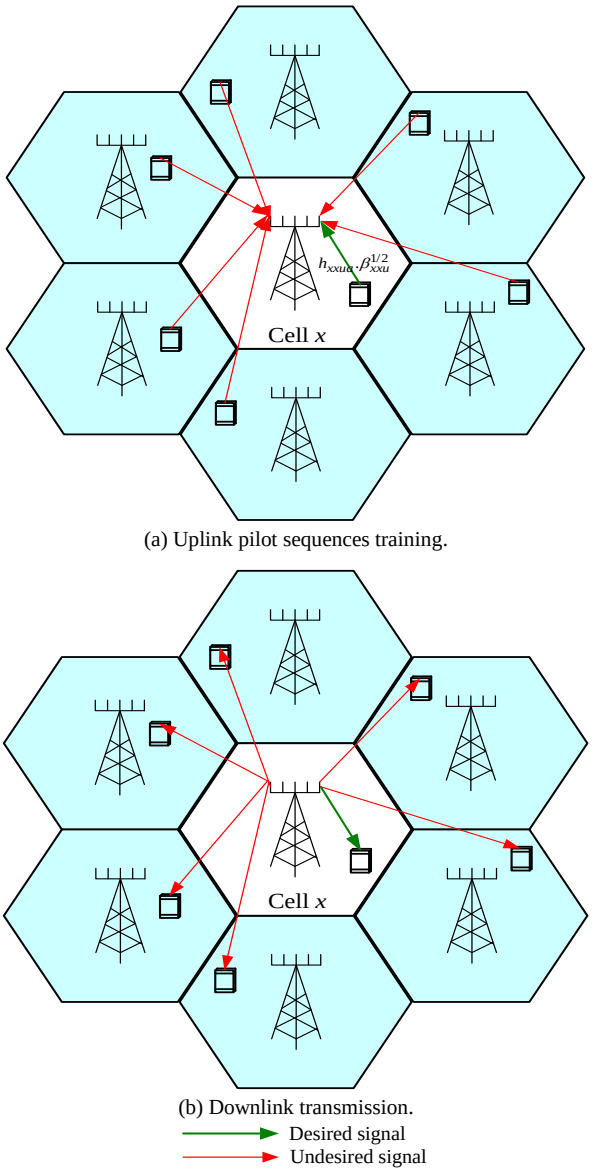
$$\mathbf{Z}_x=\sqrt{\rho_{up}}\sum_{e=1}^{E}\sqrt{\mathbf{D}_{ex}}\mathbf{H}_{ex}\mathbf{Q}+\mathbf{V}_x\,. \tag{2}$$

The LS CE and MMSE CE of (2) can be given as, respectively [1], [3], [16], [17]

$$\begin{aligned}\hat{\mathbf{H}}_{xx}^{\mathbf{LS}}&=\mathbf{Z}_x\mathbf{Q}^{HT}(\mathbf{Q}\mathbf{Q}^{HT})^{-1}=\mathbf{Z}_x\mathbf{Q}_x^{HT}(\ell\mathbf{I})^{-1}\\&=\mathbf{D}_{xx}^{1/2}\mathbf{H}_{xx}+\underbrace{\sum_{e\neq x,e=1}^{E}\mathbf{D}_{ex}^{1/2}\mathbf{H}_{ex}}_{\text{pilot contamination}}+\frac{1}{\sqrt{\rho_{up}\ell}}\mathbf{V}_x\mathbf{Q}^{HT}\end{aligned} \tag{3}$$

$$\begin{aligned}\hat{\mathbf{H}}_{xx}^{\mathbf{MMSE}}&=\sqrt{\rho_{up}}\mathbf{D}_{xx}^{1/2}\left(\mathbf{I}+\rho_{up}\mathbf{Q}\left(\sum_{e=1}^{E}\mathbf{D}_{ex}\right)\mathbf{Q}^{HT}\right)^{-1}\mathbf{Z}_x\mathbf{Q}^{HT}\\&=\sqrt{\rho_{up}}\mathbf{D}_{xx}^{1/2}\left(\mathbf{I}+\rho_{up}\ell\sum_{e=1}^{E}\mathbf{D}_{ex}\right)^{-1}\mathbf{Z}_x\mathbf{Q}^{HT}\\&=\left(\frac{\mathbf{I}}{\rho_{up}\ell}\mathbf{D}_{xx}^{-1}+\sum_{e=1}^{E}\mathbf{D}_{ex}\mathbf{D}_{xx}^{-1}\right)^{-1}\\&\quad\left(\mathbf{D}_{xx}^{1/2}\mathbf{H}_{xx}+\underbrace{\sum_{e\neq x,e=1}^{E}\mathbf{D}_{ex}\mathbf{H}_{ex}}_{\text{pilot contamination}}+\frac{1}{\sqrt{\rho_{up}\ell}}\mathbf{V}_x\mathbf{Q}^{HT}\right)\end{aligned} \tag{4}$$

It is clear from (3) and (4) that the estimation of the desired channel $\hat{\mathbf{H}}_{xx}$ relies on correlating the received signal with the known pilot sequence, which suffers from significant pilot contamination due to the lack of orthogonality between the pilots of desired BS and interfering BS, respectively. In particular, when the same pilot sequences are reused in all the E cells, which is the worst case scenario. Therefore, both channel estimates endure pilot contamination, which increases the estimation error of the desired CE significantly, particularly when the path loss coefficients between the interfering cells and the serving cell are similar to those within the serving cell. This also shows the severity of the pilot contamination problem and necessitates overcoming this problem to obtain the maximum benefits from M-MIMO system.



(a) Uplink pilot sequences training.

(b) Downlink transmission.

Fig. 1. Pilot contamination problem.

B. Downlink Transmission

After estimating the desired channels, the BS of the x-th cell will transmit data symbols to its MSs. Let the transmitted data symbols to be transmitted are $\mathbf{m}_x=[m_{x1}\ m_{x1}\ \dots\ m_{xU}]^T$ and the $A\times U$ linear precoding matrix is $\mathbf{L}_x=\mathfrak{f}(\hat{\mathbf{H}}_{xx})$, where $\mathfrak{f}(.)$ denotes a particular linear precoding method executed at the BS. Then the transmission vector transmitted by the BS of the x-th cell is $\mathbf{L}_x\mathbf{m}_x$.

Now, the transmission vector received by the MSs of the x-th cell is

$$\mathbf{t}_x = \sqrt{\rho_{dl}\mathbf{D}_{xx}}\mathbf{H}_{xx}\mathbf{L}_x\mathbf{m}_x + \mathbf{w}_x, \quad (5)$$

where ρ_{dl} is the average downlink power and $\mathbf{w}_x$ is the additive noise.

The transmission vector of (5) is intended to transmit data symbols to the MSs in the x-th cell, however, due to channel estimation error caused by pilot contamination, the BS of the x-th cell will also transmit these data symbols to the MSs of the adjacent cells, as shown in Fig. 1.

III. Pilot Contamination Elimination Schemes

Several methods have been proposed in the literature to eliminate pilot contamination in the TDD M-MIMO system. These methods can be categorized as protocol-based methods, precoding-based methods; angle of arrival (AOA) based methods and blind methods. There are also some recent methods, which are not fitting in these categories such as [12], [17] and [18]. Therefore, we present some of the well-known and recent methods of pilot contamination elimination in the TDD MIMO system.

A. Elimination of Pilot Contamination Using Time-Shifted Pilots

The simplest and hassle free way to eliminate pilot contamination is to employ frequency reuse; however, it has the drawback of degrading system capacity [1].

To achieve maximum number of advantages from TDD M-MIMO system, all MSs should transmit pilot sequences synchronously, as proposed in [3]. However, a scheme based on time-shifted (asynchronous) pilots was proposed in [13] and [15] to eradicate the pilot contamination. The proposed scheme segregates the entire network of E cells into the clusters of cells $G_1, G_2, ..., G_\Phi$ and employs the time-shifted protocol in each cluster as shown in Fig. 2. It is clear from the Fig. 2 that only MSs belong to a certain cluster can transmit uplink pilot sequences at a given time, whereas BSs belong to other clusters can transmit downlink data symbols. This asynchronous transmission helps to eliminate pilot contamination *and it* is repeated until MSs of all other clusters transmit their uplink pilot sequences. After that, all MSs of the entire network start transmitting their uplink data to their BSs.

It was demonstrated in [15] that the proposed time-shifted protocol could achieve remarkable SINR gain with infinite number of BS antennas and conjugate beamforming in TDD M-MIMO system. The uplink and downlink SINR of the u-th user in the x-th cell according to [15] are given as under, respectively

$$\mathrm{SINR}_{ux}^{up} = \frac{\beta_{xux}^2}{\sum_{e\in G_\gamma, e\neq x}\beta_{xue}^2}, \quad (6)$$

$$\mathrm{SINR}_{ux}^{dl} = \frac{\beta_{xux}^2 / \alpha_{ux}^2}{\sum_{e\in G_\gamma, e\neq x}\beta_{eux}^2 / \alpha_{ux}^2}, \quad (7)$$

where α is the power normalization factor and can be given as

$$\alpha_{ux}^2 = \sum_{e\neq x, e=1}^{E}\beta_{xue} + \frac{1}{K},$$

K is the total number pilot sequences available to each cell.

The time-shifted protocol is also used in [13]; however, it used both finite and infinite number of BS antennas with the ZF transceiver in TDD M-MIMO system. Unlike [13], which is based on a unrealistic assumption, the CSI is available at BS. Whereas [15] estimates the CSI by the uplink pilot sequences. Ref. [15] derives the closed-form expressions for achievable sum rates and associated effective SINRs and based on which it concludes that the system performance is influenced by the cell size, the transmission powers, the cell group number, the numbers of BS antennas and the scheduled MSs. Furthermore, the differences of ZF and conjugate precoders have been evaluated, from which a simple but effective user scheduling algorithm named large-scale channel fading based user scheduling (LCFS) was proposed which is able to promote both the rate and fairness performance for the conjugate precoder when the number of BS antennas is either finite or infinite, and also to greatly boost the rate of ZF precoder while only slightly compromising its fairness.

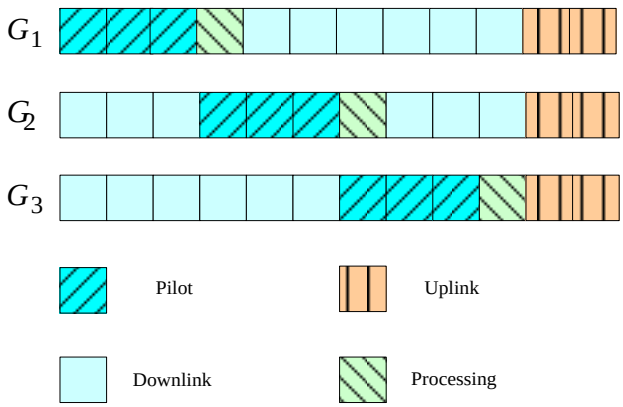


Fig. 2. Time shifted pilot scheme with $\Phi = 3$.

B. Elimination of Pilot Contamination Using Pilot Assignment

A partial sounding resource reuse (PSRR) method was proposed in [19], which aimed to alleviate pilot contamination and support MSs as many as possible. The PSPR method divides each cell into two locations; one is the center area and other is the edge area, as shown in Fig. 3. Furthermore, PSPR applies different pilot sequence assignment methods for each MS according to its location. Precisely, PSPR applies reuse factor-1and reuse factor-3 scheme in center and edge area, respectively [19].

The set of orthogonal pilot sequences is denoted as Q. The PSPR form two subsets Q_C and Q_E from Q. After that, PSPR allocates Q_C to the center area MSs with the reuse factor-1, and Q_E to the edge area MSs with the reuse factor-3. Moreover, PSPR form three equal sized subsets Q_{En} for $n = 1, 2, 3$, from Q_E and allocates a different Q_{En} for each neighboring cell [19].

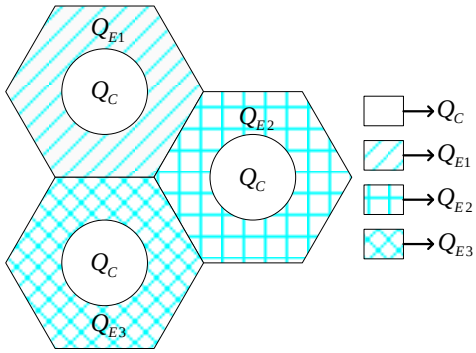


Fig. 3. PSPR overview.

Another pilot assignment method named as the smart pilot assignment (SPA) proposed in [12], which aims to maximize the minimum uplink signal-to-interference-plus-noise-ratio (SINR) of all MSs with severe pilot contamination in the target cell. Unlike those conventional schemes which assign the available pilot sequences to the MSs in a random way, in SPA the BS of the target cell firstly measures the inter-cell interference of each pilot sequence caused by the MSs with the same pilot sequence in other adjacent cells.

After that, the channel qualities from different users in the target cell to the BS can be detected, which usually differ with each other. The proposed SPA method assigns the pilot sequence with the smallest inter-cell interference to the user having the worst channel quality in a sequential way until all users have been assigned by their corresponding pilot sequences.

The SPA method, for the target cell, considers a series of parameters $\{\alpha_k\}_{k=1}^{K}$ to quantify the channel quality of K MSs as

$$\alpha_k = \beta_{xxk}^2, \qquad k = 1, 2, ..., K. \tag{8}$$

Similarly, for the K pilot sequences $[\mathbf{q}_1 \quad \mathbf{q}_2 \quad ... \quad \mathbf{q}_K]$, the SPA method define another series of parameters $\{\gamma_k\}_{k=1}^{K}$ to quantify the inter-cell interference of each pilot sequence caused by the users with same pilot sequence in other adjacent cells as

$$\gamma_k = \sum_{y \neq x} \beta_{xyk}^2, \qquad k=1,2,...,K. \tag{9}$$

which varies among K pilot sequences.

In SPA method, for a precise pilot assignment $\mathcal{J}_s = \left[j_s^1, j_s^2, ..., j_s^K \right]$, the pilot sequence $\mathbf{q}_k$ is allocated to the MS $U_{j_s^k}$, whereby the limit of uplink SINR of the MS $U_{j_s^u}$, i.e., $\mathrm{SINR}_{xk}^{\mathrm{ul}} \rightarrow \alpha_{j_s^k} / \gamma_k$, is decided by two factors: 1) the channel quality $\alpha_{j_s^k}$ of the MS $U_{j_s^k}$; 2) the inter-cell interference γ_k caused by the MSs with the same pilot sequence $\mathbf{q}_k$ in the neighboring cells. In order to maximize the minimum uplink SINR of all MSs in the target cell, the SPA method avoids the pilot sequence with great inter-cell interference assigned to the MS having bad channel quality, which leads to relatively low uplink SINR. Based on this incentive, the SPA scheme assigns the pilot sequence with the smallest inter-cell interference to the MS having the worst channel quality in a sequential way. It first sorts the K pilot sequences according to the severity of inter-cell interference in descending order and then sorts the K users according to their channel qualities in descending order.

Another pilot assignment method named pilot assisted channel estimation (PACE) is proposed in [17], which aims to eliminate pilot contamination in large scale multiple-antenna aided OFDM systems. Unlike the schemes of [12] and [19], the scheme in [17] assigns orthogonal pilot sequences to the BSs for their downlink broadcasting. These BS-specific pilot sequences can be exploited by the MSs for estimating their unique downlink channels. Because, the downlink training will not be contaminated by the neighboring cells, since orthogonal pilot sequences have been assigned to different BSs. Thus, the estimated downlink channel information can be encapsulated into the MSs's pilot sequences for assisting the uplink channel estimate. Considering this idea, J. Zhang *et al*. proposed a two-stage channel estimate scheme consisting of the downlink training and properly scheduled uplink training to eliminate the uplink pilot contamination.

The PACE scheme consists of a complicated combination of a downlink and an uplink training stage. Additionally, the downlink training consists of two phases, while uplink training contains $(E+1)$ phases, where each phase occupies K OFDM symbol durations.

C. Elimination of Pilot Contamination Based on Angle of Arrival (AOA) Methods

MSs with the same pilot sequences may have no interference with each other under realistic channel models, as shown in [16] and [18]. The multipath channel model for the uniform linear array (ULA) in the regime of large number of antennas A can be given in the form

$$\mathbf{h}_{exu} = \frac{1}{\Theta} \sum_{\theta=1}^{\Theta} \mathbf{a}(\phi) \eta_{exu} \tag{10}$$

where Θ is the number of i.i.d paths, $\eta_{exu} \sim \mathcal{CN}\left(0, \sigma_{exu}^2\right)$ is independent of the path index θ, σ_{exu}^2 is the MS's average attenuation. $\mathbf{a}(\phi)$ is the steering vector and can be given as

$$\mathbf{a}(\phi) = \begin{bmatrix} 1 \\ e^{-i2\pi \frac{D}{\lambda} \cos(\phi)} \\ \vdots \\ e^{-i2\pi \frac{(A-1)D}{\lambda} \cos(\phi)} \end{bmatrix} \tag{11}$$

where D is the antenna spacing at the BS and λ is the wavelength of the carrier and ϕ is a random angle of arrival (AOA).It is demonstrated in [16] and [18] that MSs with mutually non-overlapping AOAs scarcely contaminate each

other even if they have been assigned with the same pilot sequence. Scheme [16], which is a coordinated scheme, assigns identical pilot sequences to MSs of this type, whereas scheme [18] reuses the pilots among MSs of this type.

Precisely, coordinated approach to CE (CATCE) of [16] reduces pilot contamination by exploiting the side information lying in the second order statistics of the channel vectors. The CATCE scheme exploits covariance matrices to capture the structure information related to the distribution of the multipath angles of arrival at the BS. As, almost all the BSs have elevated position, therefore signals received at the antennas with finite angle-of-arrival (AOA) and a mean angle depending on the location of MS. This scheme accomplishes a considerable reduction in inter-cell interference and a equivalent increase in the uplink and downlink SINRs.

Whereas, scheme [18] aims to reduce pilot contamination via reusing pilots over spatially correlated Rayleigh fading channels. Scheme [18] also shows that when the number of antennas of BS approaches to infinity, eigenvectors of the channel covariance matrix are resolved by the BS array response vectors, while eigenvalues depend on the channel power angle spectrum (PAS), which disclose a relationship between channel spatial correlations and channel power distribution in the angular domain. For this channel model, it shows that if the channel AOA intervals of MSs reusing the pilots are non-overlapping then sum mean square error of channel estimation (MSE-CE) can be diminished. This scheme accomplishes significant performance gains over the conventional orthogonal training scheme in terms of net spectral efficiency.

IV. A Possible Solution to Eliminate Pilot Contamination

All the schemes that have been discussed in section III either divides the set of pilot sequences into a number of groups, like [13],[15] and [19], or assign pilot sequences to MSs based on some parameters, like [12] considers the channel quality and inter-cell interference, whereas [16] and [18] consider the AOA intervals of MSs. The only exception is scheme [17], which consists of a sophisticated combination of downlink and uplink training stages. Neither of these schemes [12], [13] and [15]-[19] consider the pilot sequence itself nor try to make same pilot sequence orthogonal.

A novel solution to eliminate pilot contamination may consider a particular sequence as pilot sequence, like the Zadoff-Chu sequence, which has been used as the pilot sequence in long term evolution (LTE). Moreover, orthogonal codes, like the Hadamard code, orthogonal variable spreading factor (OVSF) code and Walsh code, can also be used to make same pilot sequences orthogonal to eliminate pilot contamination in M-MIMO systems [20]-[23].

V. Conclusion and Future Work

Massive MIMO is an enabler technology for the development of future wireless communication networks that scales up the advantages of MU-MIMO by orders of magnitude compared to the current state-of-the-art. One of the main drawbacks of M-MIMO systems is the pilot contamination. To make the advantages of M-MIMO a reality, pilot contamination must be eliminated. In this paper, several pilot contamination elimination schemes have been discussed and a novel possible solution to eliminate pilot contamination is also suggested. In future work, pilot elimination in limination in M-MIMO using suggested solution may be showed and compared with existing pilot elimination schemes.

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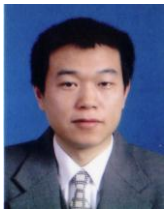

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