International Journal of New Technology and Research (IJNTR)
ISSN:2454-4116, Volume-3, Issue-2, February 2017 Pages 19-23

Pilot Contamination Effect in Massive MIMO and Analysis of Mitigation Techniques

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***Abstract*— Pilot contamination is the major factor to limit the performance of massive MIMO systemsdue to degraded channel estimation. In this paper, we have tried to provide an extensive survey on pilot contamination, and identify all possible sources causing it. We mostly cover the theoretical aspect and review the established theories that have analyzed the effect of pilot contamination on the performance of massive MIMO systems. We studied about a pilot pattern design where zero pilot symbols are inserted into the pilot sequence to reduce the pilot contamination impact on uplink channel estimate and bit error rate performance. We evaluate the achievable rate in forward link with maximum-ratio and zero-forcing precoding at the BS. We analyze spectral efficiency when employing maximum ratio transmission or zero forcing precoding at the base station. We investigate the performance of simple least-squares channel estimator with the higher-complexity minimum mean square error estimator. A brief analysis of mitigation techniques based on existing long term evolution (LTE) measurements - open loop power control (OLPC) and pilot sequence reuse schemes, that avoid PC within a group of cells has been done. Finally, some open problems are highlighted and concluded with broader perspective and a look at future trends in pilot contamination inmassive MIMO systems.**

***Index Terms*—About four key words or phrases in alphabetical order, separated by commas.**

I. Introduction

Over the past decade multi input, multiple-output (MIMO) has emerged as one of the prime technologies for achieving high data rates and spectral efficiency in wireless communication systems. Recently, it was experimented that the use of very large antenna arrays, typically of the order of few thousands, at the base station (BS) can potentially provide huge gains in system throughput, energy efficiency, security and robustness of wireless communication systems. Use of massive MIMO is a promising technology that is expected to deliver high data rates as well as enhanced link reliability, coverage, and energy efficiency; and has therefore attracted lots of research interests. Hand in hand with the advantages, there are entirely new research challenges that need to be tackled for massive MIMO. Due to the dense network deployment and limited orthogonal pilot sequences, multiple neighbor cells may use the same pilot sequence, and the pilot positions in pilot patternsof the multiple neighbor cells may overlap, which will directly affect the performance of the channel estimation. This is called pilot contamination.

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It means that the subscribers in different cells transmit the same pilot simultaneously and thus the receiver at the desired BS cannot effectively distinguish the signals, therebyforming contamination in the data.

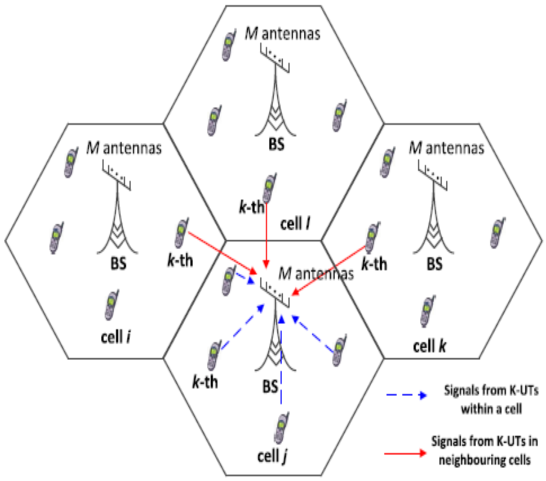

Fig 1:

Pilot contamination compelled us to carefully design pilot schemes for a large-scale MIMO system. With this thesis, our aim is to evaluate the scenarios under which pilot contamination becomes a significant problem in realistic systems, and study techniquesthat mitigate its impact.It is proposed a time-shifted pilot transmissionscheme to reduce the number of simultaneous transmissionsof users applying correlated pilot sequences. Weanalyzed the evaluation of a least-squares (LS) channel estimator for simple implementation and concluded that it does not require any prior knowledge of channel statistics. We observe that this approach leads to significant contamination of channel estimates. Next, we investigated a minimum mean square error (MMSE) channel estimator assuming perfect knowledge of channel covariance matrices. We find that the MMSE estimator improves the channel estimates, albeit with significantly higher complexity.

The rest of this paper is organized as follows. In Section II, we overviewed the system model. In Section III, we present the MMSE and LS based channel estimation in the presence of AWGN only and discuss their limitations for massive MIMO. In section IV, to enhance estimation performance, the data-aided approach is considered. Following this, we present the sources of pilot contamination, analyze the problem of pilot contamination and explain the capacity and achievable rate in multi-cell system in Section V. In Section VI, we review the different methods for mitigation of pilot contamination. Open issues on pilot contamination in massive MIMO are listed and some broader perspectives are also discussed in Section VII, and Section VIII concludes the paper.

II. SYSTEM MODEL

We consider a multi-cell massive MIMO-OFDM wireless system as shown in Fig. 2, where the BS in each cell is equipped with uniform planar array (UPA) consisting of a large number of antennas. Moreover, we assume that each BS serves a number of single antenna user terminals. The antennas on UPAs are distributed across M rows and G columns with horizontal and vertical spacing of dx and dy respectively. We define the (m, g)th antenna as the antenna element in m^{th} row and g^{th} column which corresponds to $r=m+M(g-1)^{th}$ antenna index where $1 \leq m \leq M$, $1 \leq g \leq G$ and $1 \leq r \leq R$, where R=MG is the total number of antennas in a UPA. Fig. 3 shows an example of a M×G UPA structure with antenna indexing.

Note that, depending on values of G and M, the antennas could have linear or a rectangular configuration.

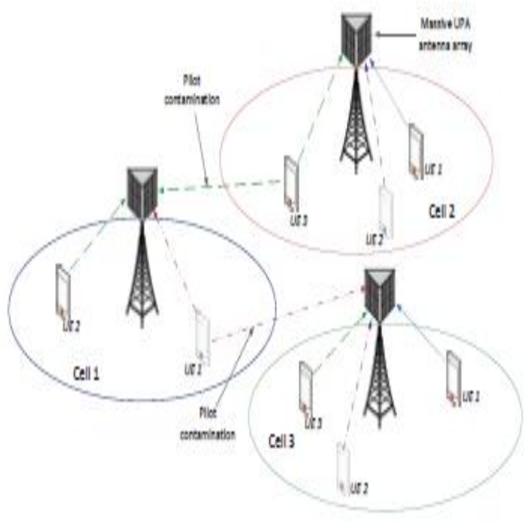

Fig 2:

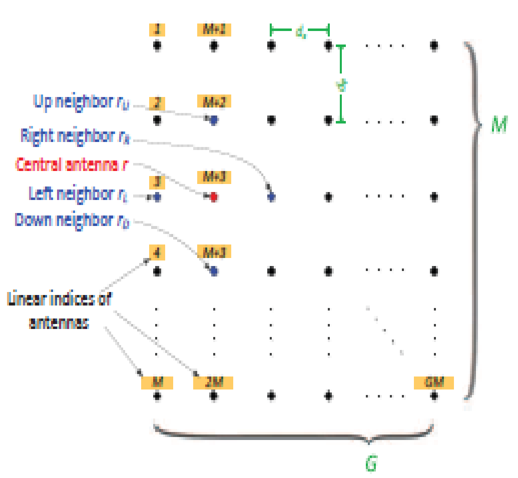

Fig 3:

Each user communicates with the BS using OFDM and transmits uplink pilots for channel estimation. We assume that all users in a particular cell are assigned orthogonal frequency tones so that there is no intra-cell interference. However, due to necessary reuse of pilots, there are users in the neighboring cells that transmit pilots at the same frequency tones, resulting in an inter-cell interference or pilot contamination. Since only the user in a particular cell of interest will experience interference from the users of neighboring cells that share pilots at the same frequency tones, hence without loss of generality, it suffices to consider one user per cell with all users transmitting pilots at same OFDM frequency tones.

A. Signal Model

We assume that the k^{th} terminal in every j^{th} cell, j ∈ J synchronously transmits a pilot sequences k comprising _ pilot symbols,

$$s_k= [s_{k1}\ s_{k2} \ldots s_{kT}]^T \quad (3.1)$$

$$\sum_i \| s_{ki} \| = \tau\, P\, T.$$

The M × 1 signal received at the j^{th} BS due to transmission of the k^{th} pilot Sequence is given by

$$X_{jk}=\sum g_{jkl}\, s_k^{\,T} + Nj \quad (3.2)$$

where g_{jkl} is the M × 1 channel vector between j^{th} BS and the k^{th} terminal in l^{th} cell, and Nj is thermal noise at the BS, modeled as white Gaussian. Since we assume the pilot signals within a cell to be mutually orthogonal, we can safely ignore the reception of all other pilot sequences s_i, i ≠k at the BS during this analysis.

III. ESTIMATION TECHNIQUES

A. LS Estimation

The LS approach to channel estimation seeks to minimize the squared error between the received pilot sequence and its noise-and-interference free version.

$g_{jk}^{LS}= g_{jk}$ + X, l6=jgjkl +Njs∗k τPT

The LS estimator has low complexity and treats the channel coefficients as a Deterministic variable to obtain a "best-fit" estimate from the observed pilot signal.

It makes no prior assumption about the channel statistics. It is the most common approach to channel estimation in practice. Some prior knowledge of the channel statistics is required in other channel estimators. These so-called Bayesian estimators have a higher complexity, but potentially perform better than the LS estimator in terms of the MSE of channel estimation. We study one particularly common Bayesian estimator, the MMSE estimator, in the next section.

B. MMSE Estimation

The MMSE estimator requires the prior knowledge of covariance matrices to improve the channel estimates, by amplifying the signal from spatial direction of desired terminal and attenuating the interferers. The rank of the covariance matrices depends upon the angular spread of corresponding channel. A full-rank covariance matrix corresponds to a wide angular spread.

While observing, it depicts that the MMSE estimator has significantly higher implementation and processing complexity than the LS estimator. It requires the knowledge of all cross-channel covariance matrices at all BSs, which must be estimated prior to MMSE channel estimation. To

reduce the additional latency overhead, we can assume that the interference from terminals to be negligible and not estimate the corresponding cross-channel matrices, at the cost of slightly poorer estimator performance. In terms of processing requirements, the complexity of M × M matrix inversion required during evaluation of MMSE estimate is proportional to the cube of array size, and may be not effective for massive MIMO systems.

IV. PILOT CONTAMINATION

The designed pilot pattern for the uplink is shown in Figure 1. The multi-cell system under consideration includes a desired cell and three interfering cells. Every line in Figure 1 corresponds to an OFDM symbol, and the first line shows the desired cell pilot positions, the second, third and fourth line show the first, second and third interfering cell pilot positions respectively. After a zero pilot symbol was inserted, the neighbor subcarrier spacing between the training symbols is 2 τ. number of non-zero training symbols is N u m _ p i l o t = [N sc /2 τ] ,where [·] represents taking the smallest integer. After inserting a zero pilot symbol, the number of sub-carriers for the data transmission is reduced by N u m _ p i l o t. The desired cell and interfering cell I use he same training sequences (a pilot multiplexing), but pilot positions are different (or semi-time- shifted). Interfering cell 1 and interfering cell 2 use the same pilot positions, but use different orthogonal training sequences. Thus, interfering cell I and interfering cell 2 do not produce pilot interference to the desired cell. The pilot positions of interfering cell 3 coincident with the pilot positions of the desired cell, i.e. interfering cell 3 (e.g. X 31) produces a direct pilot contamination to the desired cells (e.g. XII). Next, Figure 2 shows the pilot pattern II, the spacing between the training symbol X il and the training symbol Xi2 (i = 1,2,3,4) is also 2T . The pilot positions of all cells in pattern II completely overlap. Pattern II corresponds to the strong pilot contamination scenarios.

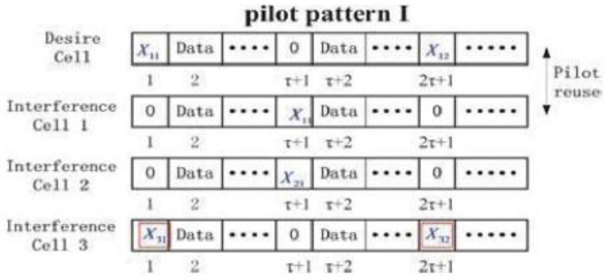

Fig 4:

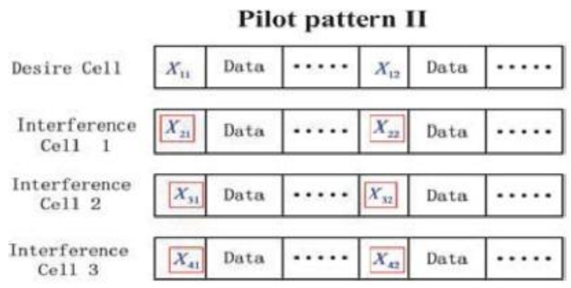

Fig 5:

V. SOURCES OF PILOT CONTAMINATION

The possible causes of pilot contamination and basic theory are highlighted in this section.

A. *Sources*

1) *Non-Orthogonal Pilot Schemes:*

In a multi-cell system where the same frequency is shared by all L cells, the intra cell interference is considered negligible since the pilots are assumed to be mutually orthogonal. When frequency reuse factor of 1 is used, the pilot signals are affected by inter cell interference leading to pilot contamination from adjacent cells brought into the system.

Each BS correlates its received pilot signals with its own orthogonal pilot signals while all terminals in the other cells contribute to the pilot contamination [11].

2). *Hardware Impairment:*

The impact of transceiver hardware impairments on massive MIMO system has been studied. The hardware components in radio frequency chain are prone to impairments such as phase noise, amplifier non-linearity, quadrature imbalance (I/Q) and quantization errors. The impairment has been shown to affect the accuracy of the CE which leads to pilot contamination as well as impact the performance of massive MIMO system. To overcome the challenge of this impairment, non-ideal behavior of each component has been modeled so as to design compensation algorithm. However, modeling of aggregate residual transceiver impairments is considered more effective to system performance rather than the modeling of individual components.

VI. MITIGATION TECHNIQUES

A. *Pilot Open-Loop Power Control*

We study a pilot open loop power control (pilot OLPC) scheme that allows the terminal to adjust the transmit power of its pilot signal based on its estimate of the path loss to its serving Pilot OLPC attempts to maximize SNR fairness of pilot signals for cell-edge terminals by compensating for their additional path loss. This path loss compensation has the intended effect of reducing overall pilot interference in the network at the cost of SNR degradation for terminals located close to the BS. OLPC provides a coarse operating point for the terminal power in terms of transmit power per RB. With closed-loop power control, the BS sends periodic power increment/decrement messages based on the SINR estimates, that defines a tighter short-term operating point. The

open-loop operating point for transmit power per RB depends on two
factors:
(i) a semi-static base level, P0, assumed to be same across the network, and
(ii) an open-loop path loss compensation component. In presence of OLPC, the terminals with strong channel conditions at the BS back-off their transmit power reduce their SNR to the desired level. The gains in rate in a multi-cell setup with OLPC depend on the operating point P0, the number of terminals in each cell and their distribution within the cells. We assume the criteria for goodness of channel estimates for spatial multiplexing as NMSE $\leq$ 0dB. At NMSE= 0dB, the mean square error of channel estimation is equal to the average channel gain, which implies that half of the transmitted signal power with maximum ratio transmission is expected to be directed away from the desired terminal.

B. Less Aggressive Pilot Reuse

Full pilot reuse leads to maximum inter-cell interference during channel estimation which can be mitigated using a less aggressive pilot reuse factor. However with pilot reuse, each terminal is free to use all the available resources for communication for the rest of the coherence interval.
The pilot reuse factor 1/U is the rate at which pilot resources may be reused in the network, where U is the number of cells that are assigned orthogonal pilots. A factor U > 1 always reduces the pilot contamination effect by assigning orthogonal pilots to neighboring cells, the next- neighbor cells and so on. The trivial case of pilot reuse is full pilot reuse with U = 1. Here we 8 consider a less aggressive reuse factor in detail, where orthogonal pilot sequences are assigned to interfering terminals in the adjacent cells.

C. Inter-cell Coordinated Pilot Allocation

A slow-rate, inter-cell coordinated pilot assignment (CPA) algorithm that investigates this approach has been proposed. CPA relies on all cross-channel covariance matrices being available at all BS. This information is used to evaluate a closed-form expression for the expected channel estimation error when a given set of terminals reuse a pilot sequence. A greedy algorithm iteratively assigns pilots in every cell to the terminal that minimizes this error.

VII. OPEN ISSUES

While massive MIMO renders many traditional problems in communication theory less relevant, it uncovers entirely new problems that need research. Few of them are discussed below:

1) Training Overhead: There is a need to determine if the subspace-based approach can achieve sufficient CSI quality required for same target SINRs in the pilot-based approach. Moreover, the subspace methods require additional techniques or information to identify which eigenvector corresponds to which UT and the assumption that all desired channels are stronger than all interfering channels does not always hold in practical systems.

2) Deployment Scenario: There is a need to investigate the effect of pilot contamination. Using a more realistic channel model for large MIMO systems by considering statistical channel properties, in particular the spatial-temporal-frequency correlation properties and the role of large-scale fading.

3) Computational Complexity and Cost: there is a need for less complex pre-coding techniques and CE methods. While some of the proposed methods to mitigate pilot contamination sound promising theoretically, there is a need to evaluate their performance by considering the trade-off between its accuracy and complexity.

VIII. CONCLUSION:

Channel estimation is a challenging problem in massive MIMO systems as the conventional techniques applicable to MIMO systems cannot be employed owing to an exceptionally large number of unknown channel coefficients. Different methods for mitigating pilot contamination due to limited coherence time proposed by various authors are reviewed. Sources of pilot contamination have also been studied. Some mitigation techniques have been reviewed like OLPC & Pilot Reuse factor. Some Open issues have also been discussed and highlighted.

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