Efficient Channel States Information Acquisition in Massive MIMO Systems using Non-Orthogonal Pilots

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***Abstract*—We consider the use of statistical channel state information (CSI) in the context of a multi-user Massive MIMO cellular communication system. If prior information about per-user channel spatial covariance is available, properly chosen non-orthogonal pilot sequences can significantly reduce the amount of spectral resources dedicated to acquiring instantaneous CSI. In this article, we introduce a CSI acquisition architecture which leverages the use of non-orthogonal pilots. We evaluate the performance of this architecture under practical considerations, including non-ideal covariance estimation and tracking, CSI and feedforward quantization, and realistic LTE-like system and channel models.**

I. Introduction

CSI acquisition is an important ingredient in multi-user Massive MIMO (Multiple-Input Multiple-Output) technology [1]. In cellular applications, accurate CSI is required in order to obtain the large multiplexing gain expected from massive MIMO systems and achieve the rates shown e.g. in [2]. In this context however, the training overhead—the time and frequency resources spent on channel state estimation—has been shown to increase linearly with the number of antennas on both sides of the transmission. The training overhead thus incurs a net loss in spectral efficiency. In the context of cellular massive MIMO systems, the channel exhibits a large degree of spatial correlation [3]; dense antenna arrays make the signals received at the base station (BTS) more spatially correlated, to the point of resulting in a rank deficient spatial correlation matrix [4]. This correlation can potentially help reduce the required training overhead, as noticed already by a number of authors.

In this work, we try to analyze the realistic gains enabled by tracking statistical CSI at the BTS in order to reduce the efficiency lost in estimating the channel states. To this end, we introduce and benchmark a particular architecture for the CSI acquisition strategy of future cellular networks operating in time-division duplex (TDD) mode[1]. Our proposed approach:

- Keeps track of statistical CSI (in the form of per-user spatial covariance matrices of the channel) at the BTS, based on the uplink training signals.

[1]We propose a different approach more adapted to systems where channel reciprocity does not hold, as in frequency division duplexing (FDD), in [5].

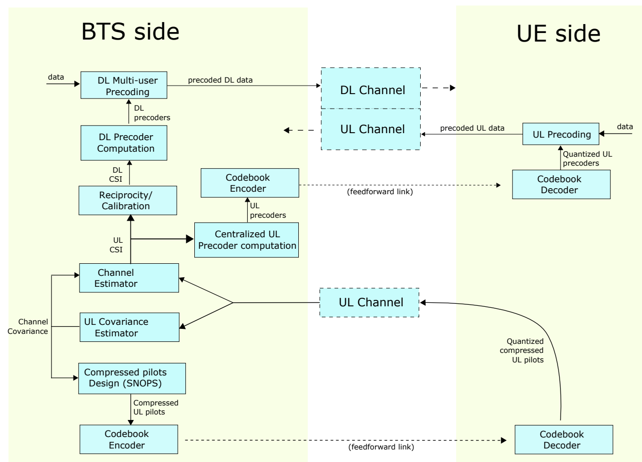

Fig. 1. Functional block diagram of the considered single-cell system.

- Periodically optimizes the allocation of pilots to users for the purpose of uplink CSI acquisition, based on the available statistical CSI. This allows for shorter (non-orthogonal) uplink training sequences.
- Informs the user equipments (UEs) of the pilots through quantization and transmission on a feedforward link.
- Estimates the uplink channels via the pilot sequences and downlink channels via reciprocity.
- Computes the downlink and uplink linear precoders based on the CSI available at the BTS.
- Informs the UEs about the uplink precoders through quantization and transmission on a feedforward link.

Our objective here is to evaluate the achievable *global* performance, taking into account: (i) a practical strategy for statistical CSI estimation, (ii) computationally feasible vector quantization approaches for the feedforward links, and (iii) low-complexity (linear) multi-user precoding and equalization approaches. Most of the above techniques have been studied separately before, sometimes under simplifying assumptions—for instance, pilot allocation based on statistical CSI is discussed e.g. in [4], [6], [7] without accounting for covariance estimation error.

II. System Description

We consider the single-cell, multi-user system architecture pictured in Figure 1. The proposed architecture has a number of desirable properties. The covariance estimation method that we consider does not require dedicated training signals and uses the short non-orthogonal pilots used for instantaneous CSI acquisition. The BTS can also compute the uplink (UL) and downlink (DL) precoders centrally, thereby avoiding the suboptimality associated with distributed decisions.

A realistic multi-user massive MIMO channel model capturing the aforementioned spatial channel correlation, together with a multi-carrier modulation model allowing to adjust the pilot density in time and frequency domains, ensures that we obtain a realistic benchmark of the spectral resources dedicated to CSI acquisition and a fair assessment of the associated performance and complexity.

A. Non-orthogonal pilot allocation

Various approaches have been proposed to allocate non-orthogonal pilots on the basis of statistical CSI. In [4] and [6] for instance, the authors propose to cluster the users based on their covariance. Pilots are reused among the users having sufficiently orthogonal channel subspaces and are therefore non-orthogonal between user groups. A more general approach was proposed in [7], where completely arbitrary pilot sequences (with varying degrees of orthogonality) can be adopted. In the complete version of this paper, we aim to compare various non-orthogonal pilot allocation approaches, in terms of the achieved sum-rate, and the amount of spectral resources dedicated to pilots, and their robustness to imperfect statistical CSI.

B. Vector quantization on the feedforward link

Vector quantization is in heavy use in the considered design, on the feedforward link from the BTS to the UEs, where information about the uplink precoders as well as the uplink pilot sequences is periodically transmitted. We recently introduced the cube-split vector quantization method for Grassmannian variables [8], which enables high-resolution quantization at low computational complexity for large vector dimensions, while remaining efficient from a packing point of view. As we will show in the full paper, it performs favorably versus scalar quantization—the classical choice in complexity-constrained situations.

C. Multi-User Precoding

Stream allocation and precoding is designed to take into account the effects of linear equalization and per-stream decoding. We adopt for our setup a greedy approach following [9] for both UL and DL precoding. We evaluate the performance losses due to imperfect CSI at the decoding side through both estimation errors and CSI ageing. We furthermore take into account the *granularity* in the time and frequency dimensions of CSI acquisition and precoder computation, depending on how often we estimate the channel and on how many subcarriers the precoders are reused.

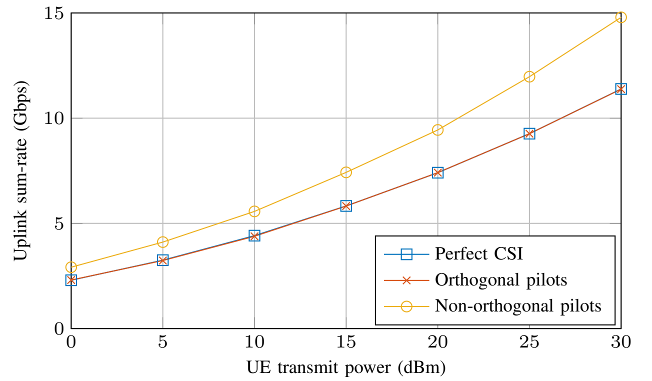

Fig. 2. Comparison of the uplink sum-rate performance between full pilots and shorter, non-orthogonal pilots from [7]. We consider here the greedy precoding method and the simulation parameters from Sec. II. Each precoder is applied on a 180 KHz block, spanning 12 frequency subcarriers.

D. Channel model

To obtain realistic channels, we adopt an implementation of the Third Generation Partnership Project (3GPP) channel model, from specifications in [10]. This channel model is linked to a system-level simulator matching the Long Term Evolution (LTE) specifications and parameters [11]. The main simulation parameters are described in Table I.

III. Preliminary Simulation Results

Our simulation platform is built in order to compare various *configurations* of the system depicted in Fig. 1. We can therefore evaluate and assess the benefits of different algorithms by swapping the functional blocks and running the simulation on a common set of channel realizations. As an example, we plot on Fig. 2 the basic performance of the short non-orthogonal pilots from [7] and compare it to orthogonal pilots and perfect CSI cases. The estimation performance using orthogonal pilots is extremely close to the perfect CSI case. However, for 12 users and 8 antennas per user, these pilots consume a large amount of the time and frequency resources. The non-orthogonal pilots on the other hand have an average length 5 times shorter than the orthogonal pilots, which translates into a 30% net efficiency gain when considering the setup described in Sec. II.

TABLE I
Channel parameters considered for the simulation.

Parameters	Value
# of UEs	12
Parameters set (from [10])	Urban Macro
BTS height	100 m
Maximum distance	700 m
Pathloss model	from [10]
Line-of-sight probability	0.5
# of BTS antennas	96 (Rectangular)
# of UE antennas	8 (Linear)
Frame structure	LTE compliant [11]
Bandwidth	200 MHz (10×20 MHz)
Uplink:Downlink frames	2:2 (LTE config. 1 [11])

REFERENCES

[1] E. G. Larsson, F. Tufvesson, O. Edfors, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, 2014.

[2] J. Hoydis, S. ten Brink, and M. Debbah, "Massive MIMO in the UL/DL of cellular networks: How many antennas do we need?" *IEEE J. Sel. Areas Commun.*, vol. 31, no. 2, pp. 160–171, 2013.

[3] J. Hoydis, C. Hoek, T. Wild, and S. ten Brink, "Channel measurements for large antenna arrays," in *Proc. IEEE International Symposium on Wireless Communication Systems (ISWCS)*, 2012.

[4] H. Yin, D. Gesbert, M. Filippou, and Y. Liu, "A coordinated approach to channel estimation in large-scale multiple-antenna systems," *IEEE Journ. Sel. Areas in Comm.*, vol. 31, no. 2, pp. 264–273, 2013.

[5] B. Tomasi, A. Decurninge, and M. Guillaud, "SNOPS: Short non-orthogonal pilot sequences for downlink channel state estimation in FDD massive MIMO," in *Proc. IEEE Global Telecommunications Conference (GLOBECOM)*, Washington DC, USA, 2016.

[6] A. Adhikary, J. Nam, J. Ahn, and G. Caire, "Joint spatial division and multiplexing: The large-scale array regime," *IEEE Trans. Inf. Theory*, vol. 59, no. 10, pp. 6441–6463, 2013.

[7] B. Tomasi and M. Guillaud, "Pilot length optimization for spatially correlated multi-user MIMO channel estimation," in *Proc. Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, USA, 2015.

[8] A. Decurninge and M. Guillaud, "Cube-split: Structured quantizers on the Grassmannian of lines."

[9] T. Yoo and A. Goldsmith, "On the optimality of multiantenna broadcast scheduling using zero-forcing beamforming," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 528–541, Mar. 2006.

[10] 3GPP Technical Specification Group Radio Access Network, "Study on 3D channel model for LTE (release 12)," Tech. Rep. TR 36.873, 2015.

[11] C. Cox, *An introduction to LTE.* John Wiley & Sons, 2014.