Pilot Contamination Analysis of Cell-Free Massive MIMO with Multi-Antenna Users

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Abstract

This paper investigates the impact of pilot contamination and multi-antenna arrays at both user equipments (UEs) and access points (APs) on the uplink rate and spectral efficiency (SE) of a cell-free (CF) massive multiple-input multiple-output (mMIMO) system. The result shows a trade-off between rate and SE for increasing user antenna.

Ⅰ. Introduction

In CF mMIMO, many APs are distributed over a wide coverage area and connected to a central processing unit (CPU) [1]. Many existing publications focus their analysis on single antenna UEs. Practically, moderately sized UEs like smart vehicles can already support multiple antennas thus making this analysis relevant in future mobility scenarios. This paper seeks to determine how many UE antennas is enough to achieve a comparable improvement in the uplink SE and rate with and without pilot contamination.

Ⅱ. System Model

We consider a CF mMIMO system with M APs and K UEs. All APs and UEs are equipped with L and N antennas respectively. Let the channel between the m-th AP and the k-th UE be, $\boldsymbol{G}_{mk} = {\beta_{mk}}^{1/2}\boldsymbol{H}_{mk}$ where β_{mk} denote the large scale fading coefficient and $\boldsymbol{H}_{mk} \in \mathbb{C}^{LxN}$ is the small scale fading matrix whose elements are modeled as independent and identically distributed $\mathbb{C}\mathrm{N}(0,1)$. Using the standard block fading model, for a given coherence interval T, τ and $T-\tau$ timeslots are reserved for uplink pilot training and data transmission respectively. The MMSE estimate of the uplink channel is given as $\widehat{\boldsymbol{G}}_{mk} = \omega_{mk}(\sqrt{\tau\rho_p}\sum_{k'\epsilon\rho_k}\boldsymbol{G}_{mk'} + \boldsymbol{W}_{mk})$ where $\omega_{mk} = \sqrt{\tau\rho_p}\beta_{mk}/(\tau\rho_p\sum_{k'\epsilon\rho_k}\beta_{mk'}+1)$ and $\boldsymbol{W}_{mk} = \boldsymbol{W}_m\emptyset_k$. Additionally $\boldsymbol{W}_m \in \mathbb{C}^{Lx\tau}$, $\emptyset_k \epsilon\, \mathbb{C}^{\tau xN}, \rho_p, \rho_k$ denote the additive white Gaussian noise, pilot sequence assigned to UE k, normalized pilot power and the index subset of UEs using the same pilot matrix as UE k including UE k respectively. In the uplink data transmission phase, all UEs send their signals to APs simultaneously. The APs apply the MRC receive filter and forward the signal to the CPU. The received signal of the n-th antenna of UE k at the CPU is similarly defined in [1]. The achievable uplink SE of the k-th user is given as $SE_k = \frac{T-\tau}{T}\sum_{n=1}^{N}\log_2\left(1+SINR_{k,n}\right)$ (1) .Where the $SINR_{k,n}$ is the signal-to-interference-plus-noise ratio of the n-th antenna of UE k.

$$SINR_{k,n} = \frac{\rho_u\mu_k\left|Ds_{k,n}\right|^2}{\rho_u\mu_k BU_{k,n} + \rho_u\sum_{k'\neq k}^{K}\mu_{k'} I_{k',n} + \rho_u\sum_{k'=1}^{K}\sum_{n'\neq n}^{N}\mu_{k'}I_{k',n'} + NS_{k,n}} \quad (2)$$

where, $Ds_{k,n} = \mathbb{E}\{\sum_{m=1}^{M}{\widehat{\boldsymbol{g}}_{mk,n}}^{H}\boldsymbol{g}_{mk,n}\}$, $BU_{k,n} = \mathbb{E}\left\{\left|\left(\sum_{m=1}^{M}{\widehat{\boldsymbol{g}}_{mk,n}}^{H}\boldsymbol{g}_{mk,n} - \mathbb{E}\{\sum_{m=1}^{M}{\widehat{\boldsymbol{g}}_{mk,n}}^{H}\boldsymbol{g}_{mk,n}\}\right)\right|^2\right\}$, $I_{k',n} = \mathbb{E}\left\{\left|\sum_{m=1}^{M}{\widehat{\boldsymbol{g}}_{mk,n}}^{H}\boldsymbol{g}_{mk',n}\right|^2\right\}$, $I_{k',n'} = \mathbb{E}\left\{\left|\sum_{m=1}^{M}{\widehat{\boldsymbol{g}}_{mk,n}}^{H}\boldsymbol{g}_{mk',n'}\right|^2\right\}$, $Ns_{k,n} = \mathbb{E}\left\{\left|\sum_{m=1}^{M}{\widehat{\boldsymbol{g}}_{mk,n}}^{H}\boldsymbol{w}_m\right|^2\right\}; 0 \le \mu_k \le 1/N, \rho_u, \boldsymbol{g}_{mk,n}$ corresponds to the power control coefficient, uplink transmit power, and the n-th column of $\boldsymbol{G}_{mk}$ respectively.

Ⅲ. Simulation Results

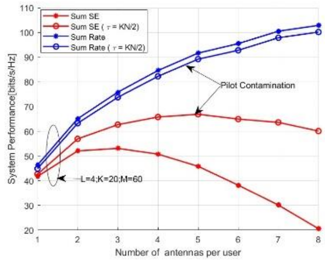

Figure 1; System performance vs. Number of antennas per user

The simulation result is obtained for; $T = 200, \tau = NK, \rho_p = \rho_u = 100mW, M = 60, K = 20, B = 20MHz, NF = 9dB\ \alpha = 1.380649x10^{-23}\ Noise\ power = 290\alpha BNF$. The three slope path loss model is applied. It is observed that increasing N yields a corresponding increase in sum rate. This however comes at the cost of sum SE which degrades with increasing N due to pilot estimation overhead. With pilot contamination,($\tau = KN/2$), an optimum sum SE of $66.91\ bits/s/Hz$ is achieved at $N = 5$ at a corresponding sum rate of $89.22\ bits/s/Hz$ as compared to the ideal case($\tau = KN$) which achieves an optimum sum SE of $53.10\ bits/s/Hz$ at $N = 3$ and a corresponding sum rate of $75.85\ bits/s/Hz$.

III. Conclusion

It is shown that yielding the full benefits of multi-antenna UEs in CF mMIMO comes at the cost of SE degradation and the use of non-orthogonal pilots shows a lower pilot estimation overhead thus a higher SE.

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