Energy Efficiency Analysis of Cell-free Massive MIMO Systems with Multi-Antenna Users and Channel Aging

Kwadwo Mensah Obeng Afrane*, Theodore Woode*, Suho Shin*, Prince Anokye†, Kyoung-Jae Lee*
*Department of Electronic Engineering, Hanbat National University, Daejeon, South Korea .
†IMT-Atlantique, Department of Mathematics and Electrical Engineering, Brest, France
kobeng@edu.hanbat.ac.kr, woodtheodore@edu.hanbat.ac.kr, suhoshin0628@edu.hanbat.ac.kr
princemanokye@yahoo.com, kyoungjae@hanbat.ac.kr

Abstract

This paper investigates the energy efficiency (EE) of a cell-free (CF) massive multiple-input multiple-output (mMIMO) system with multi-antenna user equipment (UEs) and access points (AP) over a time varying Rayleigh fading channel. We characterize the joint impact of channel aging and pilot contamination on the total EE. Furthermore, we optimize the pilot length to manage the corresponding channel estimation overhead associated with deploying multiple antennas at the UEs. The results show that in a CF mMIMO system with multi-antenna UEs, the optimal operating point of the total EE can be achieved by optimizing the pilot length

Ⅰ. Introduction

In CF mMIMO, many APs are distributed over a large coverage area and connected to a central processing unit (CPU) to serve a smaller number of users [1]. The existing literature on CF mMIMO systems with multi-antenna UEs consider a block-fading model where the channel realization in a coherence block is approximately constant. However, practical channels continuously evolve due to UE mobility. This paper analyzes EE performance of CF mMIMO systems with multi-antenna APs and UEs in a channel aging environment.

Ⅱ. System Model

In this work we consider a CF mMIMO system with M APs and K UEs. All APs and UEs are equipped with L and N antennas respectively. The UEs are assumed to be mobile. For a given resource block length of τ_c, τ_p time instants are used for uplink training and the remaining time instants are used for UL/downlink (DL) data transmission. This work considers only the UL data transmission. The relative motion between the APs and UEs results in a continuously evolving channel usually referred to as the channel aging effect. Let the channel between the m-th AP and the k-th UE at the q-th time instant be, $\boldsymbol{G}_{mk}[q] = \beta_{mk}{}^{\frac{1}{2}}\boldsymbol{H}_{mk}[q]$, where β_{mk} denote the large scale fading coefficient and $\boldsymbol{H}_{mk}[q] \in \mathbb{C}^{LxN}$ is the small scale fading matrix whose elements are modeled as $\mathbb{CN}(0,1)$. To characterize the channel aging effect, $\boldsymbol{G}_{mk}[q]$ is modeled as a function of its initial state $\boldsymbol{G}_{mk}[0]$ such that $\boldsymbol{G}_{mk}[q] = \rho_k[q]\boldsymbol{G}_{mk}[0] + \bar{\rho}_k[q]\boldsymbol{F}_{mk}[q]$, where $\boldsymbol{F}_{mk}[q] \in \mathbb{C}^{LxN}$ is the independent innovation component with elements modeled as $\mathbb{CN}(0, \beta_{mk})$. Also, $\rho_k[q] = J_0(2\pi f_{D,k} T_s q)$ is the temporal correlation coefficient, where $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind, T_s is the sampling time, and $f_{D,k} = \frac{\nu_k f_c}{c}$ is the Doppler Shift of a UE moving with velocity ν_k , a carrier frequency of f_c and c denotes the speed of light. Moreover $\bar{\rho}_k[q] = \sqrt{1 - \rho_k^2[q]}$ In this work, the channel aging effect is neglected during the channel estimation phase. Therefore the MMSE estimate of the uplink channel is derived as $\widehat{\boldsymbol{G}}_{mk}[0] = \omega_{mk}(\sqrt{\tau_p p_p}\sum_{k' \epsilon \rho_k} \boldsymbol{G}_{mk'}[0] + \boldsymbol{W}_{mk}[0])$ where $\omega_{mk} = \sqrt{\tau_p p_p}\beta_{mk}/(\tau_p p_p \sum_{k' \epsilon \rho_k} \beta_{mk'} + 1)$ and $\boldsymbol{W}_{mk}[0] = \boldsymbol{W}_m[0]\boldsymbol{\Phi}_k$. Additionally $\boldsymbol{W}_m[0] \in \mathbb{C}^{Lx\tau}$, $\boldsymbol{\Phi}_k \epsilon \mathbb{C}^{\tau xN}$, p_p, ρ_k denote the additive white Gaussian noise, pilot matrix assigned to k-th UE, pilot power, and the index subset of UEs using the same pilot matrix as k-th UE (including UE k itself), respectively. In the uplink data transmission phase, i.e. $1 + \tau_p \leq q \leq \tau_c$, all users transmit their signals to the APs simultaneously. The APs apply the maximum ration combining (MRC) receive filter and forward the signal to the CPU. By applying the use-and-then-forget methodology, the aggregated signal of the n-th antenna of the k-th UE at the CPU is expressed as $y_{k,n}[q] = A_{k,n} + B_{k,n} + C_{k',n} + C_{k',n'} + D_{k,n} + E_{k,n}$ (1) , where $A_{k,n} \triangleq \sqrt{p_u \mu_k}\, \rho_k[q]\mathbb{E}\{\sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{g}_{mk,n}[0]\} s_{k,n}[q]$, $B_{k,n} \triangleq \sqrt{p_u \mu_k}\, \rho_k[q](\sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{g}_{mk,n}[0] - \mathbb{E}\{\sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{g}_{mk,n}[0]\}) s_{k,n}[q]$, $C_{k',n} \triangleq \sqrt{p_u}\sum_{k' \neq k}^{K} \sqrt{\mu_{k'}} \sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{g}_{mk',n}[q] s_{k',n}[q]$, $C_{k',n'} \triangleq \sqrt{p_u}\sum_{k'=1}^{K}\sum_{n' \neq n}^{N} \sqrt{\mu_{k'}} \sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{g}_{mk',n'}[q] s_{k',n'}[q]$, $D_{k,n} \triangleq \sqrt{p_u \mu_k}\bar{\rho}_k[q] \sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{f}_{mk,n}[q] s_{k,n}[q]$ and $E_{k,n} \triangleq \sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{w}_m[q]$ denote the desired signal, beamforming gain uncertainty, n-th antenna multi-user interference, interference from other antennas of all users, channel aging effect and noise respectively. Also $\boldsymbol{g}_{mk,n}[0]$, $\widehat{\boldsymbol{g}}_{mk,n}[0]$, $\boldsymbol{f}_{mk,n}[q]$ and $\boldsymbol{g}_{mk,n}[0]$ represent the n-th column of $\widehat{\boldsymbol{G}}_{mk}[0]$, $\boldsymbol{F}_{mk}[q]$ and $\boldsymbol{G}_{mk}[0]$, respectively. p_u, $s_{k,n}[q]$ and μ_k $(0 \leq \mu_k \leq 1/N)$ denote the transmit power, n-th data stream of the k-th user and the power control coefficient, respectively. The achievable uplink SE of the k-th user is given as $S_k = \frac{1}{\tau_c}\sum_{q=1}^{\tau_c - \tau_p}\sum_{n=1}^{N} \log_2(1 + SINR_{k,n}[q])$, (2) where the $SINR_{k,n}[q]$ is the signal-to-interference-plus-noise ratio (SINR) of the n-th antenna of k-th UE at the q-th time instant. The SINR is expressed as

$$SINR_{k,n}[q] = \frac{Ds_{k,n}}{BU_{k,n} + I_{k',n} + I_{k',n'} + CA_{k,n}\, NS_{k,n}} \quad (3)$$

where, $Ds_{k,n} = p_u \mu_k \rho_k^2[q]\left|\mathbb{E}\{\sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{g}_{mk,n}[0]\}\right|^2$, $BU_{k,n} = p_u \mu_k \rho_k^2[q]\mathbb{E}\left\{\left|(\sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{g}_{mk,n}[0] - \mathbb{E}\{\sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{g}_{mk,n}[0]\})\right|^2\right\}$, $I_{k',n} \triangleq p_u \sum_{k' \neq k}^{K} \mu_{k'}\, \mathbb{E}\left\{\left|\sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{g}_{mk',n}[q]\right|^2\right\}$, $I_{k',n'} \triangleq p_u \sum_{k'=1}^{K}\sum_{n' \neq n}^{N} \mu_{k'}\mathbb{E}\left\{\left|\sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{g}_{mk',n'}[q]\right|^2\right\}$, $CA_{k,n} \triangleq p_u \mu_k \bar{\rho}_k^2[q]\mathbb{E}\left\{\left|\sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}[0]\boldsymbol{f}_{mk,n}[q]\right|^2\right\}$, and $NS_{k,n} \triangleq \mathbb{E}\left\{\left|\sum_{m=1}^{M} \widehat{\boldsymbol{g}}_{mk,n}^{H}\boldsymbol{w}_m\right|^2\right\}$, respectively. It is observed that the SE grows with the number of UE antennas. However, there is an increase in multi-user interference $I_{k',n'}$ and a decrease in the effective data transmission period (i.e. $\tau_c - \tau_p$) limiting the SE gain that can be achieved by deploying multiple antennas at the UEs. Thus, with the objective of maximizing the sum SE, we optimize the pilot length by employing exhaustive search over the feasible set, $N \leq \tau_p \leq \tau_c$.

To analyze the total EE of the proposed system, the total power consumption is modeled as [2]

$$P_{tot} = \sum_{k=1}^{K} P_k + B\left(\sum_{m=1}^{M} P_{bt,m}\right) + \sum_{k=1}^{K} S_k + \sum_{m=1}^{M} LP_{tc,m} + P_{o,m}, (4)$$

, where P_k, $P_{bt,m}$, $P_{tc,m}$, $P_{o,m}$ is the power consumption at the k-th UE due to amplifier and the circuit power consumption, traffic-dependent backhaul link power related to the m-th AP, power required to run the circuit components of the m-th AP, and traffic-independent power of each fronthaul, respectively. P_k is defined as $P_k = \frac{1}{\alpha_k} p_u N_o N \mu_k + NP_{tc,k}$, where $0 < \alpha_k \leq 1$, $P_{tc,k}$, and N_o denote the power amplifier efficiency, power required to operate circuit components of the k-th UE, and noise power, respectively. Finally, the total EE (bits/Joule) is defined as

$$EE_{tot} = \frac{B\sum_{k=1}^{K} S_k}{P_{tot}}, (5)$$

where B denotes the bandwidth.

Ⅲ. Simulation Results

In the simulation setup, all M APs and K UEs are uniformly distributed in a $1\,\text{km}^2$ square area wrapped at the edges to avoid boundary effects. The results are obtained by (5) and unless otherwise specified, we use the following parameters: $\tau_c = 200$, $M = 100$, $T_s = 0.01$, $\tau_p = KN/2$, $p_p = p_u = 20\,\text{dBm}$, $L = 4$, $K = 20$, $f = 2\text{GHz}$, $B = 20$ MHz, and $N_o = -92$ dBm. The total power consumption parameters include $P_{tc,k} = 0.1\,\text{W}$, $P_{tc,m} = 0.2$ W, $P_{o,m} = 0.825\,\text{W}$, $\alpha_k = 0.4$, $P_{bt,m} = 0.25\,\text{W/Gbit/s}$. The large scale fading coefficient is obtained according to the three-slope pathloss model [1]. Also, the pilot sequences are randomly assigned. Fig. 1 shows the total EE versus the number of APs for different values of $f_D T_s$. It is clearly observed that a relatively lower total EE is achieved when the normalized Doppler shift is increased. This is due to corresponding decline in SE due to channel aging as seen from (3). the SE reducing effects of channel aging. Moreover, having a larger number of antennas per UE incurs channel estimation overhead resulting in lower SE. However, the channel estimation overhead incurred makes the system robust to channel aging since the SE degradation towards the end of the resource block becomes relatively lower. For e.g. when $M = 100$ increasing the normalized Doppler shift from 0 to 0.002 results in a total EE loss of 11% and 3% for $N = 4$ and $N = 8$, respectively. In Fig. 2 we analyze the total EE performance against the UL transmit power for different values of N. Generally, there is an increase in total EE with increasing UL transmit power until a maximum at 16 dBm and a decline towards 0 afterwards. This observation is consistent for all the considered τ_p and N configurations. The SE saturates beyond 16 dBm thus any further increase in transmit power only increases the total power consumption hence the decline in the total EE. For $N = 6$ and $\tau_p = KN$, we observe the lowest total EE because the SE obtained at high N is lower when τ_p is not optimized. Also, the corresponding increase in the power consumption at each user P_k further reduces the EE of the system. However, the EE can be significantly (67% and 6% for $N = 6$ and $N = 2$ at 16 dBm, respectively) improved by optimizing the pilot length. Therefore, when a high number of antennas are deployed at the UEs, optimizing the pilot length is required to achieve the optimal operating point of the total EE.

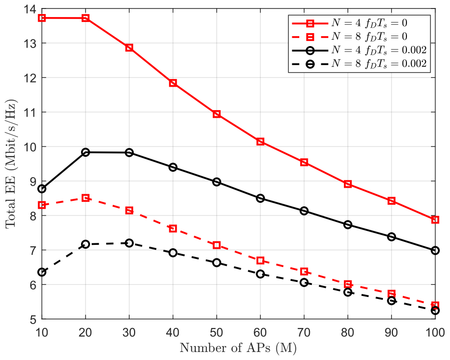

Figure 1: Total EE versus number of APs M $(\tau_p = KN/2)$

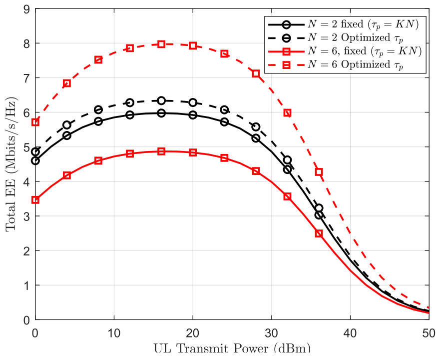

Figure 2: Total EE versus UL transmit power $(f_D T_s = 0.001)$

Ⅲ. Conclusion

It is shown that the channel estimation overhead incurred by deploying multiple antennas at the UEs makes the system robust to channel aging. Furthermore, the optimal operating point of the total EE can be achieved by optimizing the pilot length.

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