

Uplink Performance Analysis of Cell-Free MIMO with Low-Resolution ADCs and ZF Receiver

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Abstract—The cell-free massive multiple-input multiple-output (mMIMO) system is considered in this paper. In contrast to previous works, this paper quantizes the pilot and all the users' signals utilizing low-resolution analog-to-digital converters (ADCs) before they are transmitted to the central processing unit (CPU). The additive quantization noise model (AQNM) is used to characterize the quantization distortion. Moreover, a zero-forcing (ZF) receiver is advocated since it is free from inter-user interference. Based on the AQNM and the ZF receiver, a strict closed-form rate expression is derived, which motivates us to analyse the effect of quantization bits on the system performance. Simulation results show that 6-bit is the minimum quantized bit, which can achieve the same rate as a cell-free mMIMO system with perfect ADCs. In addition, 1-bit ADCs and 2-bit ADCs can result in severe rate degradation.

Keywords—Cell-free mMIMO, ZF receiver, low-resolution ADCs, AQNM.

I. INTRODUCTION

Massive multiple-input multiple-output (mMIMO) has been a promising fifth-generation (5G) wireless access technology. In the mMIMO system, a base station (BS) is equipped with a large number of antennas which can improve system throughput, spectral efficiency (SE), and energy efficiency (EE) and serves lots of users in the same time-frequency resource [1], [2]. Unlike traditional mMIMO system, the cell-free mMIMO system is no cell boundaries [3]. Since cell-free mMIMO has the advantages of the centralized mMIMO and the distributed mMIMO, it is regarded as sixth-generation (6G) technology. In the cell-free mMIMO system, massive antennas are distributed deployment called access points (APs) that serve small number users distributed over a large area. All APs are connected to a central processing unit (CPU) via a backhaul network.

A cell-free mMIMO system with conjugate beamforming (CB) precoder is considered and when the number of APs tends to infinity, the effects of small-scale fading, noise and non-coherent interference are proved to disappear in [3]. The authors in [4] consider zero-forcing (ZF) and CB precoder and propose two different power allocation algorithms for ZF and CB precoder respectively. A novel analytical expression of signal-to-interference-plus-noise ratio (SINR) with matched filtering (MF) precoder is derived and system performance of digital and analog MF precoder is analyzed in [5]. [6] proposes two power control algorithms for ZF and CB receivers. [7]

decouples the original problem into a geometry programming and a generalized eigenvalue problem, which are solved by iterative algorithms.

However, the above related studies are involved in the uplink and the downlink system models without quantization. [8] considers two strategies for pilot-based channel state information (CSI) acquisition: estimate-and-quantize and quantize-and-estimate. The authors in [9] consider the quantized versions of the channel estimates and the quantized versions of processed signals at the APs are available at the CPU. A mixed analog-to-digital converters (ADCs) architecture to cell-free mMIMO system under Rician fading channel is introduced in [10] and a tight approximate uplink SE expression is derived. [11] considers the enhanced power allocation algorithms for uplink mixed ADCs mMIMO systems and the closed-form expression for the uplink SE is derived based on the maximal-ratio combining (MRC) receiver and the additive quantization noise model (AQNM). The authors in [12] derive a tight approximate SE expression with MF receiver based on the AQNM. They also find that when the number of antennas of the user is small, deploying more antennas at the users can increase the sum SE. Quantized power allocation algorithms are proposed in [13], which do not need convex programming and are more simplified. Motivated by the above work, this paper quantizes the pilot in the pilot training phase and derives a tight approximate SINR expression based on the ZF receiver and AQNM. Simulation results show that 6-bit quantization can achieve the same rate as a cell-free mMIMO system with perfect ADCs and 1-bit and 2-bit quantization will produce server distortion.

This paper is structured as follows: After the introduction, the system model is presented in Section II. Section III gives the uplink quantization performance analysis. Simulation results is proposed in Section IV. Finally, Section V concludes this paper.

Notation: Lowercase bold letters indicate vectors, and uppercase bold letters indicate matrices. $\mathbf{A}^T$, $\mathbf{A}^*$ and $\mathbf{A}^H$ represent transpose, conjugate, and conjugate transpose of matrix $\mathbf{A}$, respectively. $\mathbb{E}\{\cdot\}$ and $|\cdot|$ represent the expectation operator and the absolute operator. $\mathbb{C}$ represents a set of complex numbers. $\mathbf{I}$ represents the unit matrix. Finally, $z \sim \mathcal{CN}(0, \xi^2)$ denotes a complex Gaussian random variable (RV) with a mean of zero and a variance of ξ^2 .

II. SYSTEM MODEL

It is assumed that M APs and K single-antenna users are randomly distributed in a large area and each AP has N antennas in the cell-free mMIMO system. It is considered that two low-resolution ADCs are implemented in each antenna of the AP. Fig. 1 describes a typical uplink cell-free mMIMO system model with low-resolution ADCs. This paper also considers that all users transmit symbols to all APs simultaneously and synchronously and all signals are quantized by low-resolution ADCs in the APs. Then, the quantized signals are transmitted to a CPU which performs complicated signal processing. In addition, this paper assumes that APs equip perfect digital-to-analog converters (DACs) and use the same number of bits to simplify the research. Time division duplex (TDD) model is used in this paper. Therefore, the pilot signals are quantized before the users' signals are quantized.

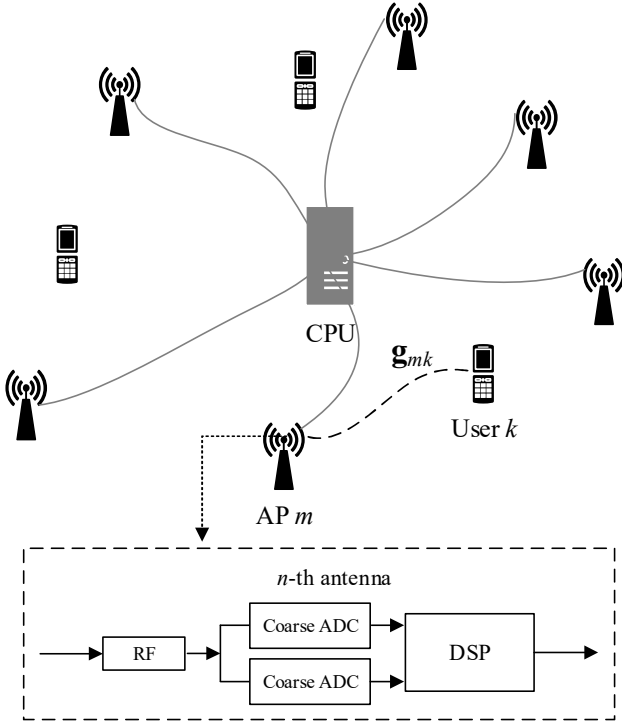


Figure 1. A typical cell-free system model with low-resolution ADCs.

A. Uplink Pilot Training

In order to obtain the quantized estimation of the CSI, APs need to know the information of users' pilot. Channel coefficient between APs and users is shown as follow

$$\mathbf{g}_{mk} = \beta_{mk}^{1/2} \mathbf{h}_{mk}, \quad (1)$$

where $\mathbf{g}_{mk} = [g_{mk,1}, \dots, g_{mk,N}]^T$, β_{mk} denotes the large-scale fading, and $\mathbf{h}_{mk} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_N)$ is the small-scale fading. This paper considers the case of pilot reuse, which can reduce pilot power consumption and focus resources on the data transmission. However, it can lead to pilot contamination. It is assumed that pilot assigned to the k -th user is $\boldsymbol{\phi}_k \in \mathbb{C}^{\tau \times 1}$, where

TABLE 1. The distortion for different ADC quantization bits.

q	1	2	3	4
σ	0.6366	0.8825	0.96546	0.950503
q	5	6	7	8
σ	0.997501	0.999336	0.999834	0.999958

$\|\boldsymbol{\phi}_k\|^2 = 1, k=1, \dots, K$ and τ is the length of the pilot sequence. Then, the received total pilot at m -th AP is given by

$$\mathbf{y}_m^p = \sqrt{\tau \rho_p} \sum_{k=1}^K \mathbf{g}_{mk} \boldsymbol{\phi}_k^H + \mathbf{w}_m^p, \quad (2)$$

where ρ_p represents the normalized uplink power of each pilot and $\mathbf{w}_m^p$ is an additive noise matrix whose elements are independent and identically distributed (i.i.d.) $\mathcal{CN}(0,1)$ RVs. According to the AQNM, the quantized pilot signals via low-resolution ADCs are shown as

$$\tilde{\mathbf{y}}_m^p = \sigma \sqrt{\tau \rho_p} \sum_{k=1}^K \mathbf{g}_{mk} \boldsymbol{\phi}_k^H + \sigma \mathbf{w}_m^p + \mathbf{e}^p, \quad (3)$$

where $\sigma = 1 - \sqrt{3}\pi 2^{-2q-1}$ when $q \geq 5$, q is the number of quantization bits, and $\mathbf{e}^p$ is the Gaussian quantization noise. The values of σ are listed in Table 1. Multiply $\tilde{\mathbf{y}}_m^p$ by $\boldsymbol{\phi}_k$ to estimate the channel coefficient $\mathbf{g}_{mk}$. The expression is written as

$$\tilde{\mathbf{y}}_{mk} = \tilde{\mathbf{y}}_m^p \boldsymbol{\phi}_k = \sigma \sqrt{\tau \rho_p} \sum_{k=1}^K \mathbf{g}_{mk} \boldsymbol{\phi}_k^H \boldsymbol{\phi}_k + \sigma \mathbf{w}_m^p \boldsymbol{\phi}_k + \mathbf{e}^p \boldsymbol{\phi}_k. \quad (4)$$

Then, based on the MMSE principle [1], the $\hat{\mathbf{g}}_{mk}^H$ is shown as

$$\hat{\mathbf{g}}_{mk}^H = \frac{\mathbb{E}\{(\mathbf{g}_{mk})^H \tilde{\mathbf{y}}_{mk}\}}{\mathbb{E}\{(\tilde{\mathbf{y}}_{mk})^H \tilde{\mathbf{y}}_{mk}\}} \tilde{\mathbf{y}}_{mk}^H = c_{mk} \tilde{\mathbf{y}}_{mk}^H, \quad (5)$$

where

$$c_{mk} = \frac{\sqrt{\tau \rho_p} \beta_{mk}}{\tau \rho_p \sum_{i=1}^K \beta_{mi} |\boldsymbol{\phi}_i^H \boldsymbol{\phi}_k|^2 + 1}. \quad (6)$$

The mean-square of $[\hat{\mathbf{g}}_{mk}]_n$ is represented by

$$\alpha_{mk} = \mathbb{E}\left\{ \left| [\hat{\mathbf{g}}_{mk}]_n \right|^2 \right\} = \frac{\sigma \tau \rho_p \beta_{mk}^2}{\tau \rho_p \sum_{i=1}^K \beta_{mi} |\boldsymbol{\phi}_i^H \boldsymbol{\phi}_k|^2 + 1}. \quad (7)$$

Proof: Please refer to Appendix A.

B. Uplink Data Transmission

The data signals received at the m -th AP are given by

$$\mathbf{y}_m^d = \sqrt{\rho_u} \sum_{k=1}^K \mathbf{g}_{mk} \sqrt{\eta_k} s_k + \mathbf{w}_m^d, \quad (8)$$

where s_k denotes the data signals sent by the k -th user and $\mathbb{E}\{|s_k|^2\} = 1$, ρ_u is the normalized signal-to-noise ratio (SNR), η_k represents the power control coefficient and $\mathbf{w}_m^d$ is

an additive noise vector. It is assumed that $0 \leq \eta_k \leq 1$ and $[\mathbf{w}_m^d]_n \sim \mathcal{CN}(0,1)$.

Therefore, the total data signals received at M APs can be shown as

$$\mathbf{y} = \sqrt{\rho_u} \sum_{k=1}^K \mathbf{g}_k \sqrt{\eta_k} s_k + \mathbf{w}, \quad (9)$$

where $\mathbf{g}_k = [\mathbf{g}_{1k}^T, \dots, \mathbf{g}_{Mk}^T]^T$ and $\mathbf{w} = [\mathbf{w}_1^d, \dots, \mathbf{w}_M^d]^T \in \mathbb{C}^{MN \times 1}$.

Before being transmitted to the CPU, the total data signals need to be quantized by the low-resolution ADCs. Based on the AQNM, the quantized signals can be shown as

$$\tilde{\mathbf{y}} = \sigma \sqrt{\rho_u} \sum_{k=1}^K \mathbf{g}_k \sqrt{\eta_k} s_k + \sigma \mathbf{w} + \mathbf{e}, \quad (10)$$

where $\mathbf{e}$ denotes the Gaussian quantization noise. For simplicity, this paper considers the same number of bits are used to quantize the total data signal. Then, according to the principle of the ZF receiver, the decode matrix is given by

$$\mathbf{A} = \hat{\mathbf{G}} (\hat{\mathbf{G}}^H \hat{\mathbf{G}})^{-1}, \quad (11)$$

where $\hat{\mathbf{G}} = [\hat{\mathbf{g}}_1, \dots, \hat{\mathbf{g}}_K]$ and $\hat{\mathbf{g}}_k = [\hat{\mathbf{g}}_{1k}^T, \dots, \hat{\mathbf{g}}_{Mk}^T]^T \in \mathbb{C}^{MN \times 1}$. After de-spread by the ZF receiver, the k -user quantized signals are shown as

$$\begin{aligned} v_k &= \mathbf{a}_k^H \tilde{\mathbf{y}} = \sigma \sqrt{\rho_u} \sum_{i=1}^K \mathbf{a}_k^H \mathbf{g}_i \sqrt{\eta_i} s_i + \sigma \mathbf{a}_k^H \mathbf{w} + \mathbf{a}_k^H \mathbf{e} \\ &= \underbrace{\sigma \sqrt{\rho_u} \sqrt{\eta_k} s_k}_{B_1} + \underbrace{\sigma \sqrt{\rho_u} \sum_{i=1}^K \mathbf{a}_k^H \tilde{\mathbf{g}}_i \sqrt{\eta_i} s_i}_{B_2} + \underbrace{\sigma \mathbf{a}_k^H \mathbf{w}}_{B_3} + \underbrace{\mathbf{a}_k^H \mathbf{e}}_{B_4}, \end{aligned} \quad (12)$$

where $\mathbf{a}_k^H$ is the k -th column of $\mathbf{A}$, $\tilde{\mathbf{g}}_k = [\tilde{\mathbf{g}}_{1k}^T, \dots, \tilde{\mathbf{g}}_{Mk}^T]^T$, B_1 is the desired signal part, B_2 is the channel estimation error, B_3 is the additive noise, and B_4 is the quantization noise.

III. QUANTIZATION PERFORMANCE ANALYSIS

In this section, a closed-form uplink SINR expression with low-resolution ADCs and ZF receiver is derived. This tight approximate expression is novel and an achievable rate expression is given based on the SINR expression.

Theorem 1: An achievable rate of k -th user for any M, N, K , is formulated as

$$R_k = \log_2(1 + \text{SINR}_k), \quad (13)$$

where

$$\text{SINR}_k = \frac{\sigma \rho_u \eta_k \mu_k}{\rho_u \sum_{i=1}^K \eta_i d_i + 1}, \quad (14)$$

where $\mu_k = \mathbb{E}^{-1} \left\{ \|\mathbf{a}_k\|^2 \right\}$ and $d_i = \arg \max_m (\beta_{mi} - \sigma \alpha_{mi})$.

Proof: Please refer to Appendix B.

IV. SIMULATION RESULTS

In this section, the numerical simulations are provided to verify the performance of the cell-free mMIMO with low-resolution ADCs and ZF receiver. This paper considers an

area of $1 \times 1 \text{ km}^2$. The large-scale fading coefficient $\beta_{mk} = \text{PL}_{mk} \cdot 10^{\sigma_{sh} z_{mk}/10}$, where $10^{\sigma_{sh} z_{mk}/10}$ represents the shadow fading, $z_{mk} \sim \mathcal{CN}(0,1)$, and $\sigma_{sh} = 8 \text{ dB}$. PL_{mk} is given by

$$\text{PL}_{mk} = \begin{cases} -L - 35 \log_{10}(d_{mk}), & d_{mk} > d_1 \\ -L - 15 \log_{10}(d_1) - 20 \log_{10}(d_{mk}), & d_0 < d_{mk} \leq d_1 \\ -L - 15 \log_{10}(d_1) - 20 \log_{10}(d_0), & d_{mk} \leq d_0 \end{cases} \quad (15)$$

where d_{mk} is the distance between the m -th AP and the k -th user and L is shown as follow

$$L = 46.3 + 33.9 \log_{10}(f) - 13.82 \log_{10}(h_{AP}) - (1.1 \log_{10}(f) - 0.7) h_u + (1.56 \log_{10}(f) - 0.8), \quad (16)$$

and where carrier frequency $f = 1.9 \text{ GHz}$, AP height $h_{AP} = 15 \text{ m}$, and user antenna height $h_u = 1.65 \text{ m}$. This paper adopts the system parameters given in [6, Table I].

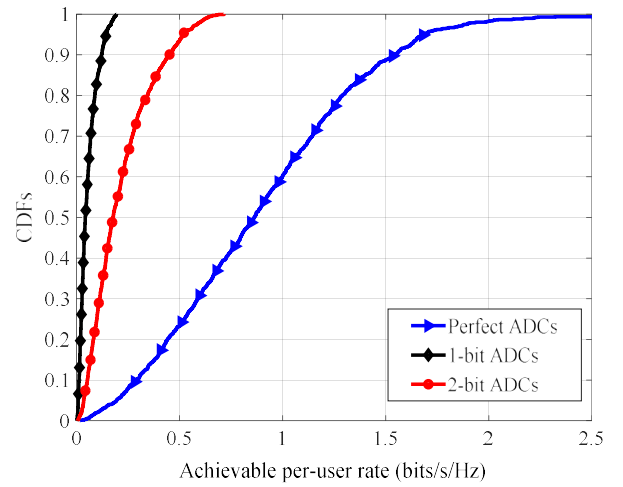


Figure 2. CDFs of the achievable per-user rate, with $M=40$, $K=20$, and $N=5$.

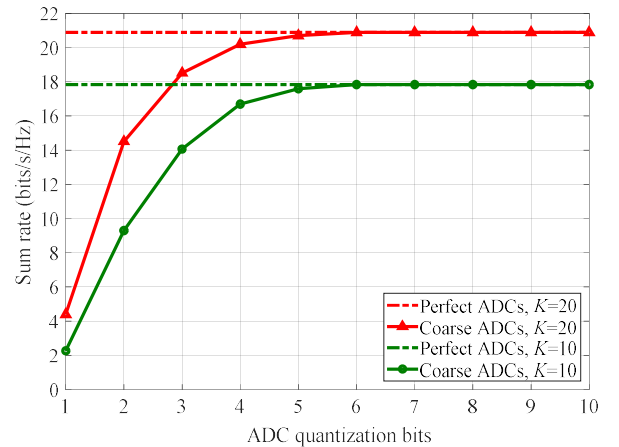


Figure 3. The sum rate versus ADC quantization bits, with $M=40$, $N=5$.

In Fig. 2, the cumulative distribution functions (CDFs) of the uplink achievable per-user rate are shown, with $M=40$, $K=20$, and $N=5$. It is observed that the perfect ADCs

$$\text{SINR}_k = \frac{\sigma \rho_u \eta_k}{\sigma \rho_u \sum_{m=1}^M \sum_{n=1}^N [\mathbf{a}_{mk}]_n^2 \sum_{i=1}^K \eta_i (\beta_{mi} - \alpha_{mi}) + \mathbb{E}\{\|\mathbf{a}_k\|^2\} + (1-\sigma) \rho_u \sum_{m=1}^M \sum_{n=1}^N [\mathbf{a}_{mk}]_n^2 \sum_{i=1}^K \eta_i \beta_{mi}}. \quad (29)$$

outperform the 1-bit ADCs and the 2-bit ADCs in 5%-outage performance. Specifically, the 5%-outage rate of the perfect ADCs is about 0.19 bits/s/Hz, which is the 19 times that of the 1-bit ADCs (about 0.01 bits/s/Hz) and 6 times that of the 2-bit ADCs (about 0.03 bits/s/Hz). That means 1-bit ADCs and 2-bit ADCs can lead to severe rate degradation.

Fig. 3 depicts the sum rate versus the ADC quantization bits against different K , with $M=40$, $N=5$. It can be observed intuitively that the 6-bit ADCs can meet the performance requirement of the perfect ADCs, which indicates that the 6-bit low-resolution ADCs can be used to substitute the perfect ADCs to reduce the hardware costs and power consumptions.

V. CONCLUSIONS

A tight approximate rate expression is derived for the uplink cell-free mMIMO system with low-resolution ADCs and ZF receiver. Simulation results show that 1-bit ADCs and 2-bit ADCs can lead to severe rate degradation. Besides, it suggests that 6-bit ADCs are the minimum low-resolution ADCs, which can achieve the same rate as a cell-free mMIMO system with perfect ADCs.

ACKNOWLEDGMENT

This work was supported in part by the National Key Research and Development Program of China under Grant 2018YFC1314903, in part by the Natural Science Foundation of China under Grants 61861039, 61561043, 61372124, 61427801 and 6126105, in part by the Postgraduate Research & Practice Innovation Program of Jiangsu Province under Grant SJKY19_0740.

APPENDIX A

The numerator of c_{mk} is

$$\mathbb{E}\{(\mathbf{g}_{mk})^H \tilde{\mathbf{y}}_{mk}\} = \sigma N \sqrt{\tau \rho_p} \beta_{mk}, \quad (17)$$

the denominator of c_{mk} is

$$\begin{aligned} & \mathbb{E}\{(\tilde{\mathbf{y}}_{mk})^H \tilde{\mathbf{y}}_{mk}\} \\ &= \sigma^2 N \tau \rho_p \sum_{i=1}^K \beta_{mi} |\boldsymbol{\Phi}_k^H \boldsymbol{\Phi}_i|^2 + \sigma^2 N + \mathbb{E}\{\boldsymbol{\Phi}_k^H (\mathbf{e}^p)^H \mathbf{e}^p \boldsymbol{\Phi}_k\}, \end{aligned} \quad (18)$$

according to [12], the $\mathbb{E}\{(\mathbf{e}^p)^H \mathbf{e}^p\}$ can be written as

$$\begin{aligned} \mathbb{E}\{(\mathbf{e}^p)^H \mathbf{e}^p\} &= \sigma(1-\sigma) \mathbb{E}\{(\mathbf{y}_m^p)^H \mathbf{y}_m^p\} \\ &= \sigma(1-\sigma) N \left(\tau \rho_p \sum_{i=1}^K \beta_{mi} \boldsymbol{\Phi}_i^H \boldsymbol{\Phi}_i + 1 \right) \mathbf{I}_\tau, \end{aligned} \quad (19)$$

substituting (19) into (18), it can be obtained that

$$\mathbb{E}\{(\tilde{\mathbf{y}}_{mk})^H \tilde{\mathbf{y}}_{mk}\} = \sigma N \left(\tau \rho_p \sum_{i=1}^K \beta_{mi} |\boldsymbol{\Phi}_i^H \boldsymbol{\Phi}_k|^2 + 1 \right). \quad (20)$$

Then, since $[\hat{\mathbf{g}}_{mk}]_n$ is an independent circular Gaussian random variable, α_{mk} is calculated as follow

$$\alpha_{mk} = \mathbb{E}\{[\hat{\mathbf{g}}_{mk}]_n\} = c_{mk}^2 \mathbb{E}\{[\tilde{\mathbf{y}}_{mk}]_n\} = \sqrt{\tau \rho_p} \sigma \beta_{mk} c_{mk}. \quad (21)$$

APPENDIX B

Proof of Theorem 1: It is easy to show that B_1 , B_2 , B_3 , and B_4 are mutually independent. The achievable lower bound rate is given by $\log_2(1 + \text{SINR}_k)$, where

$$\text{SINR}_k = \frac{\mathbb{E}\{|B_1|^2\}}{\mathbb{E}\{|B_2|^2\} + \mathbb{E}\{|B_3|^2\} + \mathbb{E}\{|B_4|^2\}}. \quad (22)$$

The mean-square of the desired signal is

$$\mathbb{E}\{|B_1|^2\} = \sigma^2 \rho_u \eta_k. \quad (23)$$

The mean-square of the estimation error is

$$\begin{aligned} \mathbb{E}\{|B_2|^2\} &= \mathbb{E}\left\{\left|\sigma \sqrt{\rho_u} \sum_{i=1}^K \mathbf{a}_k^H \tilde{\mathbf{g}}_i \sqrt{\eta_i} s_i\right|^2\right\} = \sigma^2 \rho_u \sum_{i=1}^K \eta_i \mathbb{E}\{|\mathbf{a}_k^H \tilde{\mathbf{g}}_i|^2\} \\ &= \sigma^2 \rho_u \sum_{m=1}^M \sum_{n=1}^N [\mathbf{a}_{mk}]_n^2 \sum_{i=1}^K \eta_i (\beta_{mi} - \alpha_{mi}), \end{aligned} \quad (24)$$

where $\mathbf{a}_{mk} = [\mathbf{a}_{mk}]_1, [\mathbf{a}_{mk}]_2, \dots, [\mathbf{a}_{mk}]_N]^T$.

The mean-square of the additive noise is

$$\mathbb{E}\{|B_3|^2\} = \sigma^2 \mathbb{E}\{\|\mathbf{a}_k\|^2\}. \quad (25)$$

The mean-square of the quantization noise is

$$\mathbb{E}\{|B_4|^2\} = \mathbb{E}\{\mathbf{a}_k^H \mathbf{e}^H \mathbf{e} \mathbf{a}_k\}, \quad (26)$$

the $\mathbb{E}\{\mathbf{e}^H \mathbf{e}\}$ can be written as

$$\mathbb{E}\{\mathbf{e}^H \mathbf{e}\} = \sigma(1-\sigma) \mathbb{E}\{\mathbf{Y} \mathbf{Y}^H\} = \sigma(1-\sigma) \left(\rho_u \sum_{i=1}^K \mathbf{g}_i \mathbf{g}_i^H \eta_i + \mathbf{I}_{MN} \right), \quad (27)$$

substituting (27) into (26), $\mathbb{E}\{|B_4|^2\}$ is shown as follow

$$\mathbb{E}\{|B_4|^2\} = \sigma(1-\sigma) \left(\mathbb{E}\{\|\mathbf{a}_k\|^2\} + \rho_u \sum_{m=1}^M \sum_{n=1}^N [\mathbf{a}_{mk}]_n^2 \sum_{i=1}^K \eta_i \beta_{mi} \right), \quad (28)$$

therefore, the SINR_k is expressed as (29) (defined at the top of this page).

According to [6, Theorem 1], an approximate achievable uplink SINR_k for any M , K , and N , is formulated as

$$\text{SINR}_k = \frac{\sigma \rho_u \eta_k \mu_k}{\rho_u \sum_{i=1}^K \eta_i d_i + 1}, \quad (30)$$

where d_i , μ_k , $\mathcal{M}_k$, and m_j are given as follow, respectively

$$d_i = \arg \max_m (\beta_{mi} - \sigma \alpha_{mi}), \quad (31)$$

$$\mu_k = \frac{1}{\mathbb{E}\{\|\mathbf{a}_k\|^2\}} = \frac{\sum_{m \in \mathcal{M}_k} \alpha_{mk}^2}{\sum_{m \in \mathcal{M}_k} \alpha_{mk}} \left[\frac{N \left(\sum_{m \in \mathcal{M}_k} \alpha_{mk} \right)^2}{\sum_{m \in \mathcal{M}_k} \alpha_{mk}^2} - 1 \right], \quad (32)$$

$$\mathcal{M}_k = \{\forall m \neq m_j, |j \neq k\}, \quad (33)$$

$$m_j = \arg \max_m \beta_{mj}. \quad (34)$$

Proof: See [6, Appendix A].

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