Energy Efficiency Analysis of Full-Duplex Massive MIMO-Enabled Mobile UAVs

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Abstract

In this work we perform an energy efficiency analysis of a full-duplex (FD) massive multiple-input multiple-output (mMIMO) base station (BS) communicating with several FD mMIMO mobile unmanned aerial vehicles (UAVs). Due to the UAV mobility, there are fast varying channels between the BS and UAVs resulting in channel aging. The impact of channel aging on energy efficiency (EE) is also studied in this paper. It is shown that it has a negative impact on the EE. Also, low-resolution ADCs are employed at the BS and the UAVs hence the effect of quantization noise (QN) is considered.

Ⅰ. Introduction

The current advancement in communication systems has led to the deployment of many assistive technologies. This is to boost the quality of service (QoS) for users. One significant technology is unmanned aerial vehicles (UAVs) which can be used as either aerial base stations, relays, or user equipment. Coupling full-duplex massive multiple-input multiple-output (FD mMIMO) systems with UAVs provides a boost in spectral efficiency in addition to a higher probability of line of sight (LoS). However, FD mMIMO systems are plagued with self-interference issues due to the simultaneous transmission and reception [1]. Also, UAV mobility results in fast varying channels which leads to a phenomenon called channel aging. The effect of channel aging in cell free mMIMO systems is studied in [2]. Lastly, due to the power constraints of UAVs, it is necessary to deduce how energy efficient it is to employ them.

This paper focuses on the downlink (DL) energy efficiency (EE) analysis of a FD mMIMO system comprising of a FD mMIMO BS communicating with FD mMIMO UAVs. It is to be noted that low-resolution analog-to-digital converters (ADCs) are used hence the impact of quantization noise (QN) is considered.

Ⅱ. Method

The system consists of a FD BS deploying W_{rx} massive receive antennas and W_{tx} transmit antennas equal in number to the U UAVs. The k-th UAV deploys Z_{rx} massive receive antennas and a single transmit antenna. Due to the UAV mobility, there is a variation in channel estimate obtained in the pilot training and data transmission phases. This occurrence is termed channel aging. We assume block fading in the data transmission phase. Since UAVs have a higher probability of line of sight (LoS), we employ Rician fading. To consider the impact of channel aging, the aged DL channel is modeled with respect to its previous state at a time instant δ as follows:

$$\boldsymbol{c}_k[n] = \mu_k[\delta - n]\boldsymbol{c}_k[\delta] + \bar{\mu}_k[\delta - n]\left(\tilde{\boldsymbol{c}}_{L,k} + \boldsymbol{a}_{u,k}[n]\right), \quad (1)$$

where $\bar{\mu}_k = \sqrt{1 - \mu^2{}_k[n]}$, $\boldsymbol{a}_{u,k}[n] \sim \mathbb{CN}(0, V_{u,k})$. $\tilde{\boldsymbol{c}}_{L,k} = \boldsymbol{c}_{L,k}\sqrt{K_{u,k}\widetilde{K}_{u,k}}$ where $\boldsymbol{a}_{u,k}[\mathrm{n}]$ is called the innovation component and the temporal correlation coefficient, $\mu_k[\mathrm{n}] = J_0(2\pi f_{d,k} T_s(n))$ [2]. $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind, T_s is the sample time, and $f_{d,k} = v_k f_c/\mathrm{c}$ is the Doppler shift with v_k being the k-th UAV velocity. $V_{u,k} = \beta_k \widetilde{K}_{u,k}$, where β_k is the pathloss component and $K_{u,k} = (K_{u,k} + 1)^{-1}$, with $K_{u,k}$ being the Rician K-factor.

The received signal at the k-th UAV at the n-th time instant is given as:

$$y_{qu,k}[n] = \underbrace{\varepsilon\sqrt{p_w}\hat{\boldsymbol{c}}_k^H[\delta]\boldsymbol{c}_k[n]s_k[n]}_{\text{Desired Signal}} + \underbrace{\varepsilon\sqrt{p_w}\textstyle\sum_{j\neq k}^{U}\hat{\boldsymbol{c}}_k^H[\delta]\boldsymbol{c}_j[n]s_j[n]}_{\text{Multi-user interference}} + \underbrace{\varepsilon\sqrt{p_u}\textstyle\sum_{j\neq k}^{U}\hat{\boldsymbol{c}}_k^H[\delta]\boldsymbol{t}_{c,kj}x_j[n]}_{\text{UAV-to-UAV interference}} + \underbrace{\varepsilon\sqrt{p_u}\hat{\boldsymbol{c}}_k^H[\delta]\boldsymbol{t}_{u,k}x_k[n]}_{\text{Self interference}} + \underbrace{\hat{\boldsymbol{c}}_k^H[\delta]\boldsymbol{v}_{q,k}}_{\text{Quantization noise}} + \underbrace{\varepsilon\hat{\boldsymbol{c}}_k^H[\delta]v_k[n]}_{\text{Noise}}, \quad (2)$$

where $s_k[n] \sim \mathbb{CN}(0,1)$, $x_k[n] \sim \mathbb{CN}(0,1)$, are the signals from the BS and k-th UAV, respectively. p_w and p_u are the BS and k-th UAV transmit powers, respectively. ε is the ADC resolution at the k-th UAV. $t_{u,k} \sim \mathbb{CN}(0, \zeta_{u,k}^2)$ and $t_{c,kj} \sim \mathbb{CN}\left(0, \zeta_{c,kj}^2\right)$, where $\zeta_{u,k}^2$, and $\zeta_{c,kj}^2$ are the covariances of the SI at the k-th UAV and UAV-to-UAV interference, respectively. Maximum ratio combining (MRC) scheme is used because it is decentralized and simple to implement. The DL sum SE expression is given as:

$$R_{u,k} = \frac{1}{\tau_c}\sum_{n=\delta}^{\tau_c}\log_2\left(1 + \frac{\mathbb{E}[\mathcal{D}_{u,k}]}{\mathbb{E}[\mathcal{J}_{u,k}] + \mathbb{E}[\mathcal{Q}_{u,k}]}\right), \quad (3)$$

where τ_c is the total coherence period. The squared norm of the desired signal term, sum of the interference terms plus noise, and quantization noise

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Due to space constraints, the channel estimation is omitted. This can however be obtained from [2].

term are given as $\mathcal{D}_{u,k}$, $\mathcal{I}_{u,k}$, and $\mathcal{Q}_{u,k}$, respectively. The downlink energy efficiency is expressed as:

$$EE = \frac{B\sum_{k=1}^{U} R_{u,k}}{\sum_{k=1}^{U} P_{C,uk}} \text{ bit/Joule}, \quad (4)$$

$$P_{C,uk} = Z_{rx}(P_{\text{LNA}} + P_{\text{RFC}} + 2P_{\text{ADC}}) + P_{\text{BB}}, \quad (5)$$

$$P_{\text{ADC}} = \text{FOM}_W \times f_s \times 2^q, \quad (6)$$

where $P_{C,uk}$ is the consumed power at the k-th UAV. The power consumed by the RF chain, ADC, baseband processor and low-noise amplifier are denoted as P_{RFC}, P_{ADC}, P_{BB}, and P_{LNA}, respectively. FOM_W, f_s, and q are the figure of merit, sampling frequency, and number of quantization bits, respectively.

III. Simulation Results

In this section, we provide insights into the simulation results obtained from (3) and (4), respectively. Unless otherwise specified, $p_w = 60$ dB, $p_u = 15$ dB, $U = 10$, $\tau_c = 200$, $\tau_p = 2U$, $P_{\text{LNA}} = 5.4$ mW, $P_{\text{RFC}} = 27.8$ mW, $P_{\text{BB}} = 200$ mW).

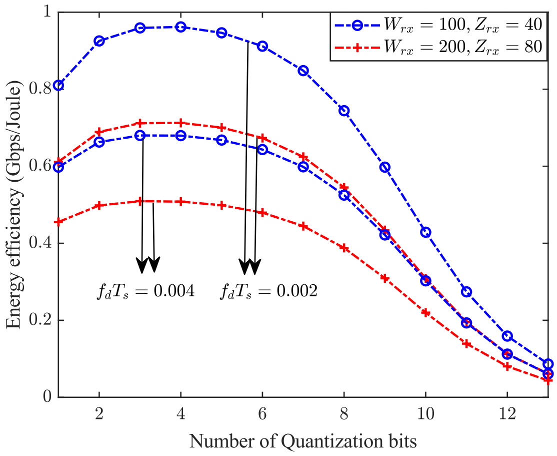

Fig. 1. DL EE vs Number of Quantization bits ($p_w = 60$ dB, $p_u = 15$ dB, $U = 10$, $K = -10$ dB)

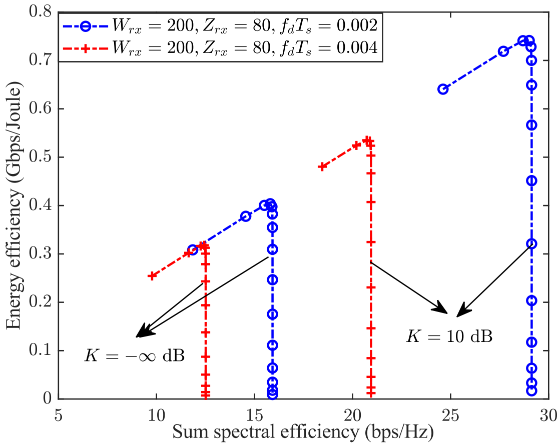

Fig. 2. EE vs SE ($p_w = 60$ dB, $p_u = 15$ dB, $U = 10$)

Fig. 1 shows a plot of DL EE against quantization bits, q. It is observed that the EE increases from $q = 1$ to $q = 4$. For $q > 4$, it is realized that there is a decline in EE. This is a result of the increase in the ADC power which is a function of q. Also, the EE envelope for a Doppler shift, $f_d T_s = 0.002$ is higher than that observed for $f_d T_s = 0.004$. This is because an increase in Doppler shift results in a declining SE which corresponds to a degrading EE.

In Fig. 2, the EE and SE trade-off is shown. Comparison is done for two scenarios namely a Rayleigh fading setup ($K = -\infty$ dB) and our Rician fading system ($K = 10$ dB). The quantization bits, q is varied from 1 to 15. Both EE and SE are observed to rise from $q = 1$ to $q = 4$. For $q > 4$, there is a fast decline in EE due to the rise in ADC power while the SE saturates. The EE/SE envelope is higher in the Rician scenario due to the significant LoS component. Also, the EE/SE envelope is lower for a greater Doppler shift.

Ⅲ. Conclusion

This work has analyzed the energy efficiency of mobile FD mMIMO UAVs communicating with a FD mMIMO BS. It has been deduced that increasing quantization bits provides a good EE to a certain point after which there is a decline. This is attributed to the ADC power overwhelming the system after a certain limit. The effect of channel aging is also studied. It is realized that a higher Doppler shift results in a lower EE envelope. Also, the EE and SE trade-off is studied.

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References

[1] P. Anokye, R. K. Ahiadormey, H.-S. Jo, C. Song, and K.-J. Lee, "Low-resolution ADC quantized full-duplex massive MIMO-enabled wireless backhaul in heterogeneous networks over Rician channels," *IEEE Trans. Wirel. Commun*, vol. 19, no. 8, pp. 5503–5517, Aug. 2020.

[2] J. Zheng, J. Zhang, E. Björnson, and B. Ai, "Impact of Channel Aging on Cell-Free Massive MIMO Over Spatially Correlated Channels," *IEEE Trans. Wirel. Commun.*, vol. 20, no. 10, pp. 6451–6466, Oct. 2021, doi: 10.1109/TWC.2021.3074421.