IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received December 4, 2018, accepted December 19, 2018, date of publication December 27, 2018, date of current version January 23, 2019.

Digital Object Identifier 10.1109/ACCESS.2018.2889878

Performance Analysis of Mixed-ADC Massive MIMO Systems Over Spatially Correlated Channels

QINGFENG DING AND YICHONG LIAN
School of Electrical and Automation Engineering, East China Jiaotong University, Nanchang 330013, China
Corresponding author: Yichong Lian (lianyc1228@foxmail.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 61501186 and in part by the Jiangxi Province Science Foundation of China under Grant 20171BAB202001.

ABSTRACT This paper analyzes the uplink performance of multiuser massive multi-input-multi-output systems with spatially correlated channels by using a mixed analog-to-digital converter (ADC) architecture, where the base station (BS) is equipped with two resolution levels' ADC. More specifically, the exponential correlation matrix model is used for modeling spatially correlated channels. Meanwhile, the additive quantized noise model and the maximum ratio combining technique are used at the BS receiver. Thereby, closed-form approximations for the achievable rate are derived under perfect and imperfect channel state information (CSI), respectively. In addition, we have studied the tradeoff between achievable rate and energy efficiency. Then, the influence of physical parameters on the corresponding results is analyzed, including user transmit power, the number of BS antennas, spatial correlation coefficient, CSI errors, and ADC quantization resolution. The numerical results show that as the spatial correlation coefficient increases, the achievable rate is almost constant at the low signal-to-noise-ratio (SNR) stage, but the achievable rate is gradually reduced to near zero at the high SNR stage. Furthermore, in terms of the tradeoff between achievable rate and energy efficiency, the performance of the two-level ADC architecture is significantly better than the uniform ADC architecture.

INDEX TERMS Massive MIMO, mixed-ADCs, spatial correlation, achievable rate, energy efficiency.

I. INTRODUCTION

Massive multiple-input multiple-output (MIMO) antenna technology, one of the most attractive key technologies in the fifth-generation (5G) mobile cellular network, has recently captured a lot of researches and attentions from researchers and engineers around the world, because it has the potential to significantly improve throughput, spectral efficiency and energy efficiency in wireless communication systems [1]–[4]. The main idea of massive MIMO is to deploy hundreds of huge-scale antenna arrays at the base station (BS) and dozens of users simultaneously use the same time-frequency resources, which greatly develops space resources and improves the utilization of time-frequency resources, while the gain between spectral efficiency and energy efficiency have been significantly improved [5]–[8].

In a massive MIMO system, a large number of antennas (e.g., hundreds) are provided at each BS, and thus the limited physical space causes the spatial correlation among the antennas cannot be ignored [9]. Meanwhile, with the substantial increase in base station antennas containing high resolution analog to digital converters (ADCs), which causes the exponential growth in hardware cost and power consumption. However, the above mentioned problem has recently been addressed in massive MIMO systems, especially by using low resolution ADCs in the systems (e.g., using 1-3 bit) (e.g., [7]–[16]). The work in [12]–[16] are on massive MIMO systems with low-resolution ADCs, which widely use the nonlinear quantization noise model and the maximum ratio combined (MRC) receiver to derive the closed-form approximation expression of the uplink spectral efficiency, in which all ADCs are assumed to have the same resolution.

Moreover, ADCs with hybrid architectures have been extensively studied in Massive MIMO systems (e.g., [17]–[22]). In [18]–[20], a two level mixed-precision ADC architecture for massive MIMO uplink are proposed in Rayleigh and Rician channels, respectively, where a small portion of the ADCs with full resolution is used to improve system performance, while most of the remaining ADCs with low resolution are responsible for hardware cost and low power consumption. In addition, hybrid ADCs with multiple level of resolution have been emerged and studied in massive MIMO systems. In [17] and [23], a tight approximation expression of uplink spectral efficiency has been obtained for a mixed ADC architecture with any resolution profile, and the ADC resolution profile optimization are proposed by considering both the outage probability and energy efficiency or spectral efficiency and energy efficiency, respectively.

Recently, the spatial correlation of the channel has been noticed and some researches have emerged (e.g., [24]–[30]). Tong and Zekavat [24] proposed a spatially correlated Rayleigh fading channel technique for MIMO systems by using virtual channel representation. In [25], the closed form expression of the outage probability and the upper limit of the ergodic capacity are derived by considering the spatial channel correlation at the BS antennas. In [26] and [27], the exact closed expression of the probability density function is obtained by studying the channel capacity of the Rician spatial correlated channel. Moreover, the performance of massive MIMO systems with low resolution ADCs under spatially correlated channels has recently been analyzed, and the approximate expression for achievable rate of low resolution ADCs has been derived with imperfect channel state information (CSI) [9]. However, the performance of massive MIMO systems with mixed-resolution ADC under spatially correlated channels has not been investigated in the exiting literature.

In this paper, we aim to analyze the uplink achievable rate and energy efficiency of massive MIMO systems under spatially correlated channels with a mixed-ADC receiver architecture.[1] The main results and distinct contributions of our work can be summarized as follows.

- This new finding is different from the result in the previously published work [16], [18], [19], [23], our works are extended to massive MIMO systems with spatially correlated channels. In contrast to [9], we focus on the mixed-ADC architecture and consider perfect and imperfect CSI, respectively.
- Via assuming spatially correlated channels, our work derives a tractable closed-form approximate expression for the achievable rate of massive MIMO system with mixed-ADC architecture. These simulations reveal the influence of the number of BS antennas, user transmit power, ADC quantization bits, CSI error and spatial correlation coefficients on the achievable rate.
- By further simplified analyses of the achievable rate expressions that have been obtained, it is worth noting that our derivation results are more general, which contain many previously published works [9], [16], [18] as special cases via adjusting some parameters.
- A realistic power consumption model is considered. We have analyzed the trade-off between achievable rate and energy efficiency for different spatial correlation coefficients and CSI in massive MIMO with mixed-ADC architecture when ADC quantized bits and the number of BS antennas increase.

Notation : lowercase boldface, uppercase boldface and normal typeface represent vectors, matrices and scalars, respectively. The symbols $\|\cdot\|$, $(\cdot)^{\mathrm{T}}$, $(\cdot)^{*}$ and $(\cdot)^{\mathrm{H}}$ represent the Euclidean norm, transpose, conjugate and conjugate transpose, respectively. Moreover, $\mathbf{I}_M$ denote an $M \times M$ identity matrix, $\mathbf{R}$ is spatial correlated matrix, $[\mathbf{R}]_{mn}$ is the element at the mth row and nth column of $\mathbf{R}$, and η denotes spatial correlation coefficient. Finally, $\mathbb{E}\{\cdot\}$ is the expectation operator, $\mathbb{Q}(\cdot)$ denotes the quantization function of the ADCs and $\mathrm{diag}(\cdot)$ denotes the diagonal of matrix.

II. SYSTEM MODEL

In this section, we consider the uplink of a single-cell multi-user massive MIMO system with K single-antenna users and M ($M \gg K \geq 2$) receiver antennas at BS, where the users transmit their signals to the BS in the same time-frequency resource. Moreover, it is assumed that the system is a signal unit with no interference from neighboring cells, and the RF chain of each BS antenna is equipped with a pair of ADCs. However, the mixed-ADC structure consists of two parts, including the M_0 antennas are connected with high-resolution ADCs to improve performance, while the remaining M_1 (where $M_1 = M - M_0$) antennas are connected with low-resolution ADCs to reduce power consumption and hardware cost [18].

Let $\mathbf{F}$ be the $M \times K$ channel matrix from the users to the BS. According to the Kronecker correlation model [31], the channel matrix is modeled as

$$\mathbf{F} = \mathbf{R}^{\mathbf{1/2}}\mathbf{H}\mathbf{D}^{\mathbf{1/2}}, \tag{1}$$

where $\mathbf{R} \in \mathbb{C}^{M\times M}$ denotes the channel spatial correlation matrix at BS whose spectrum norm $\|\mathbf{R}\|$ is uniformly bounded, $\mathbf{H} \in \mathbb{C}^{M\times K}$ denotes the small scale fading coefficients, i.e., a complex Gaussian random variables with zero-mean and unit-variance, while $\mathbf{D} = \mathrm{diag}(\beta_1, \beta_2, \cdots, \beta_K)$ denotes the corresponding large scale fading coefficients, i.e., $[\mathbf{D}]_{kk} = \beta_k$, where $k = 1, \ldots, K$.

For the spatial correlation matrix $\mathbf{R}$,[2] the simple exponential Toeplitz correlation model [32], [33] is adopted, which the (m, n)th element of $\mathbf{R}$ is

$$[\mathbf{R}]_{mn} = \begin{cases} \eta^{n-m}, & m \leq n, \\ (\eta^{m-n})^{*}, & m > n, \end{cases} \tag{2}$$

where the magnitude η is the correlation coefficient between adjacent receive antennas (for $0 \leq |\eta| \leq 1$). Obviously, $\eta = 0$ means no spatial correlation between adjacent antennas, whereas $\eta = 1$ means full correlation.

[1] Extensions systems with ADC of multiple resolution levels are not straightforward and are left for future work.

[2] As mentioned after (1), r_{mn} denotes the (m, n)th element of $\mathbf{R}$ and r_{mm} denotes the (m, m)th element of $\mathbf{R}$, etc. For an uncorrelated massive MIMO system, the spatial correlation coefficient $\eta = 0$ i.e., $\mathbf{R} = \mathbf{I}$.

For the channel matrix of the mixed-ADC structure, we define $\mathbf{F} = [\mathbf{F_0}\ \mathbf{F_1}]^{\mathrm{T}}$, where $\mathbf{F_0}$ is the $M_0 \times K$ channel matrix from the users to the M_0 BS antennas with high-resolution ADCs, and $\mathbf{F_1}$ is the $M_1 \times K$ channel matrix from the users to the M_1 BS antennas with low-resolution ADCs [18]. The received analog signal vector of the high-resolution ADCs can be expressed as

$$\mathbf{y}_0 = \sqrt{p_u}\mathbf{F}_0\mathbf{x} + \mathbf{n}_0, \tag{3}$$

where p_u denotes the average transmitter power of each user, $\mathbf{x} = [x_1\ x_2\ \cdots\ x_k]^{\mathrm{T}}$ denotes the signal from all users to the BS and the energy of $\mathbf{x}$ is normalized as $\mathbb{E}\{\mathbf{x}\mathbf{x}^{\mathrm{H}}\} = \mathbf{I}_K$, and $n_0 \sim \mathcal{CN}(0, \sigma^2\mathbf{I}_{M_0})$ is the additive white Gaussian noise(AWGN) vector at BS. For tractability of analysis, the additive quantization noise model (AQNM) is used to model the quantization error as additive Gaussian random variable [17]. The received signal vector of low resolution ADC is expressed as $\widetilde{\mathbf{y}}_1 = \sqrt{p_u}\mathbf{F}_1\mathbf{x} + \mathbf{n}_1$, thus the quantized signal vector by $\widetilde{\mathbf{y}}_1$ can be written as $\mathbf{y}_1 = \mathbb{Q}(\widetilde{\mathbf{y}}_1)$. Then, the quantized received signal vector of the low-resolution ADCs can be approximated as

$$\mathbf{y}_1 \approx \alpha\widetilde{\mathbf{y}}_1 + \mathbf{n}_q = \sqrt{p_u}\alpha\mathbf{F}_1\mathbf{x} + \alpha\mathbf{n}_1 + \mathbf{n}_q, \tag{4}$$

where $n_1 \sim \mathcal{CN}(0, \sigma^2\mathbf{I}_{M_1})$ is the additive white Gaussian noise vector at the BS, and $n_q \sim \mathcal{CN}(0, \mathbf{R}_{n_q})$ is the additive Gaussian quantization noise vector which is uncorrelated with $\mathbf{y}_1$. Here, $\alpha = 1-\rho$ is the linear quantization gain, where ρ is the ratio of the quantizer error variance over its input variance, and the exact value of ρ have been listed in Table 1 for ADC quantization bits $b \leq 5$ [34]. For $b > 5$, the formula $\rho \approx \pi\sqrt{3}\cdot 2^{-2b-1}$ can be used [35], which can be found that ρ decreases as b increases.

TABLE 1. Quantization coefficient ρ for ADC with b bits resolution.

b	1	2	3	4	5
ρ	0.3634	0.1175	0.03454	0.009497	0.002499

For a fixed channel realization $\mathbf{F}$, the covariance of n_q can be expressed as

$$\mathbf{R}_{n_q} = \alpha\rho\mathrm{diag}(p_u\mathbf{F}\mathbf{F}^{\mathrm{H}} + \sigma^2\mathbf{I}_M), \tag{5}$$

whose mth diagonal entry represents the power of quantization error of the mth pair of ADCs.

Utilizing (3) and (4), the overall received signal at the BS can be expressed as

$$\mathbf{y} = \begin{bmatrix} \mathbf{y}_0 \\ \mathbf{y}_1 \end{bmatrix} \approx \begin{bmatrix} \sqrt{p_u}\mathbf{F}_0\mathbf{x} + \mathbf{n}_0 \\ \sqrt{p_u}\alpha\mathbf{F}_1\mathbf{x} + \alpha\mathbf{n}_1 + \mathbf{n}_q \end{bmatrix}. \tag{6}$$

III. ANALYSIS OF ACHIEVABLE RATE

In this section, closed-form approximate expressions for uplink achievable rate of mixed-ADCs massive MIMO systems are derived with perfect and imperfect CSI, respectively. Moreover, the effects of the user average transmitter power, the spatially correlated coefficient, the CSI error and the proportion of low resolution ADCs in the mixed-ADC structure are revealed.

A. PERFECT CSI

In this subsection, the case of perfect CSI is firstly considered at the BS, where the received signal vector is processed by $\mathbf{F}^{\mathrm{H}}$ before detection. By using (6), the received signal vector after the MRC combination $\mathbf{r} = \mathbf{F}^H\mathbf{y}$ can be further given by

$$\mathbf{r} = \sqrt{p_u}(\mathbf{F}_0^{\mathrm{H}}\mathbf{F}_0 + \alpha\mathbf{F}_1^{\mathrm{H}}\mathbf{F}_1)\mathbf{x} + (\mathbf{F}_0^{\mathrm{H}}\mathbf{n}_0 + \alpha\mathbf{F}_1\mathbf{n}_1) + \mathbf{F}_1^{\mathrm{H}}\mathbf{n}_q. \tag{7}$$

From (7), the output signal for the kth user can be expressed as

$$r_k = \sqrt{p_u}(\mathbf{f}_{0,k}^{\mathrm{H}}\mathbf{f}_{0,k} + \alpha\mathbf{f}_{1,k}^{H}\mathbf{f}_{1,k})x_k + (\mathbf{f}_{0,k}^{\mathrm{H}}\mathbf{n}_0 + \alpha\mathbf{f}_{1,k}^{\mathrm{H}}\mathbf{n}_1) + \sqrt{p_u}\sum_{i=1,i\neq k}^{K}(\mathbf{f}_{0,k}^{\mathrm{H}}\mathbf{f}_{0,i} + \alpha\mathbf{f}_{1,k}^{\mathrm{H}}\mathbf{f}_{1,i})x_i + \mathbf{f}_{1,k}^{\mathrm{H}}\mathbf{n}_q, \tag{8}$$

where $\mathbf{f}_{0,k}$ and $\mathbf{f}_{1,k}$ are the kth column of $\mathbf{F}_0$ and $\mathbf{F}_1$, respectively. Specifically, the last three terms in (8) as noise plus interference terms, which are random variable with zero-mean and variance.

According to (8), the ergodic achievable rate of the kth user under perfect CSI can be expressed as

$$R_{\mathrm{P},k}^{\mathrm{MRC}} = \mathbb{E}\left\{\log_2\left(1 + \frac{p_u|\mathbf{f}_{0,k}^{\mathrm{H}}\mathbf{f}_{0,k} + \alpha\mathbf{f}_{1,k}^{\mathrm{H}}\mathbf{f}_{1,k}|^2}{\Phi_1}\right)\right\}, \tag{9}$$

where

$$\Phi_1 = p_u\sum_{i=1,i\neq k}^{K}|\mathbf{f}_{0,k}^{\mathrm{H}}\mathbf{f}_{0,i} + \alpha\mathbf{f}_{1,k}^{\mathrm{H}}\mathbf{f}_{1,i}|^2 + |\mathbf{f}_{0,k}^{\mathrm{H}}\mathbf{n}_0 + \alpha\mathbf{f}_{1,k}^{\mathrm{H}}\mathbf{n}_1|^2 + \alpha\rho\mathbf{f}_{1,k}^{\mathrm{H}}\mathrm{diag}(p_u\mathbf{F}_1\mathbf{F}_1^{\mathrm{H}} + \sigma^2\mathbf{I}_{M_1})\mathbf{f}_{1,k}. \tag{10}$$

For the perfect CSI case, due to the expression of achievable rate in (9) is too complicated to be computed, it is necessary to make some approximate derivation, and the approximate expression of (9) is obtained in *Theorem 1*.

Theorem 1: For a multi-user massive MIMO uplink system with mxied-ADC architecture under spatially correlated channels and perfect CSI. The achievable rate of the kth user can be approximated by (11), as shown at the top of next page.

Proof: For the number of BS antennas M is very large but finite, we can use the following common approximation [36, Lemma 1]: $\mathbb{E}\{\log_2(1 + \frac{X}{Y})\} \approx \log_2(1 + \frac{\mathbb{E}\{X\}}{\mathbb{E}\{Y\}})$ for massive MIMO, where X and Y are random variables which don't require to be independent of each other, and converge to their means due to the law of large numbers. Thus, (9) can be written approximately as

$$R_{\mathrm{P},k}^{\mathrm{MRC}} \approx \log_2\left(1 + \frac{p_u\mathbb{E}\{|\mathbf{f}_{0,k}^{\mathrm{H}}\mathbf{f}_{0,k} + \alpha\mathbf{f}_{1,k}^{\mathrm{H}}\mathbf{f}_{1,k}|^2\}}{\mathbb{E}\{\Phi_1\}}\right), \tag{12}$$

where

$$\mathbb{E}\{\Phi_1\} = p_u\sum_{i=1,i\neq k}^{K}\mathbb{E}\{|\mathbf{f}_{0,k}^{\mathrm{H}}\mathbf{f}_{0,i} + \alpha\mathbf{f}_{1,k}^{\mathrm{H}}\mathbf{f}_{1,i}|^2\} + \mathbb{E}\{|\mathbf{f}_{0,k}^{\mathrm{H}}\mathbf{n}_0 + \alpha\mathbf{f}_{1,k}^{\mathrm{H}}\mathbf{n}_1|^2\} + \mathbb{E}\{\mathbf{f}_{1,k}^{\mathrm{H}}\mathbf{R}_{\mathbf{n}_q}\mathbf{f}_{1,k}\}. \tag{13}$$

$$R_{\mathrm{P},k}^{\mathrm{MRC}} \approx \log_2\left(1+\frac{p_u\beta_k(\xi_0+2\alpha\psi_0\psi_1+\alpha^2\xi_1)}{p_u\upsilon\sum\limits_{i=1,i\neq k}^{K}\beta_i+\sigma^2(\psi_0+\alpha\psi_1)+\alpha(1-\alpha)p_u\psi_1\sum\limits_{i=1}^{K}\beta_i}\right),$$

where

$$\psi_j=\sum_{m=1}^{M_j}|r_{mm}|,\quad \xi_j=\sum_{m=1}^{M_j}\sum_{n=1}^{M_j}(|r_{mn}|^2+r_{mm}r_{nn})+\sum_{m\neq n}^{M_j}\sum_{n=1}^{M_j}r_{mn}r_{nm},\quad j=0,1,$$
$$\upsilon=\sum_{m=1}^{M_0}\sum_{n=1}^{M_0}|r_{mn}|^2+\alpha^2\sum_{m=1}^{M_1}\sum_{n=1}^{M_1}|r_{mn}|^2. \tag{11}$$

By following the method in [16], the expected value of each term in (12) can be directly calculated, the calculation results are as follows:

$$\mathbb{E}\{|\mathbf{f}_{j,k}^{H}\mathbf{f}_{j,k}|^2\}=\beta_k^2\left(\sum_{m=1}^{M_j}\sum_{n=1}^{M_j}(|r_{mn}|^2+r_{mm}r_{nn})+\sum_{m\neq n}^{M_j}\sum_{n=1}^{M_j}r_{mn}r_{nm}\right), \tag{14}$$

$$\mathbb{E}\{|\mathbf{f}_{j,k}^{H}\mathbf{f}_{j,k}|\}=\beta_k\sum_{m=1}^{M_j}|r_{mm}|, \tag{15}$$

$$\mathbb{E}\{|\mathbf{f}_{j,k}^{H}\mathbf{f}_{j,i}|^2\}=\beta_k\beta_i\sum_{m=1}^{M_j}\sum_{n=1}^{M_j}|r_{mn}|^2. \tag{16}$$

Moreover, the last term in (13) is the most challenging to derive due to the introduction of channel correlation. Assume that $K\gg 1$ and thus $\mathbf{F}\mathbf{F}^{\mathrm{H}}\approx\mathbb{E}\{\mathbf{F}\mathbf{F}^{\mathrm{H}}\}=\sum_{i=1}^{K}\beta_i\mathbf{R}$ [9]. Then

$$\begin{aligned}\mathbb{E}\{\mathbf{f}_{1,k}^{\mathrm{H}}\mathbf{R}_{\mathbf{n}_q}\mathbf{f}_{1,k}\} &\approx \alpha\rho\mathbb{E}\left\{\mathbf{f}_{1,k}^{\mathrm{H}}\mathrm{diag}\left(p_u\sum_{i=1}^{K}\beta_i\mathbf{R}+\sigma^2\mathbf{I}_M\right)\mathbf{f}_{1,k}\right\}\\ &\overset{(\varsigma)}{=}\alpha\rho\mathbb{E}\left\{\mathbf{f}_{1,k}^{\mathrm{H}}\left(p_u\sum_{i=1}^{K}\beta_i+\sigma^2\right)\mathbf{f}_{1,k}\right\}\\ &=\alpha\rho\left(p_u\sum_{i=1}^{K}\beta_i+\sigma^2\right)\mathbb{E}\{\mathbf{f}_{1,k}^{\mathrm{H}}\mathbf{f}_{1,k}\}\\ &=\alpha\rho\beta_k\left(p_u\sum_{i=1}^{K}\beta_i+\sigma^2\right)\sum_{m=1}^{M_1}|r_{mm}|, \end{aligned}\tag{17}$$

where (ς) is obtained by assuming $[\mathbf{R}]_{mm}=1$ for $\forall_m=1,\ldots,M$ [31]. By substituting the above equalities into (9), the result in (11) can be directly obtained. ■

In order to facilitate a comprehensive understanding of *Theorem* 1, some system parameters with special values are provided to analyze uplink achievable rate performance, such as user transmit power, spatial correlation coefficient, the number of BS antennas and quantized bits of low-resolution ADC. Then, the uplink achievable rate can be further analyzed as follows.

Remark 1: Fixed M, η and b, when $p_u\to\infty$, (11) can be further reduced to

$$R_{\mathrm{P},k}^{\mathrm{MRC}}\to\log_2\left(1+\frac{\beta_k(\xi_0+2\alpha\psi_0\psi_1+\alpha^2\xi_1)}{\upsilon\sum\limits_{i=1,i\neq k}^{K}\beta_i+\alpha(1-\alpha)\psi_1\sum\limits_{i=1}^{K}\beta_i}\right), \tag{18}$$

which approaches a constant. Further, it depends on the quantization bit and spatial correlation coefficient when the user transmit power $p_u\to\infty$. Meanwhile, it can be concluded from (18) that the achievable rate of uplink massive MIMO cannot be improved indefinitely as the average transmit power of the user gradually increases.

Remark 2: Since the achievable rate in (11) includes the Rayleigh fading channel part as a special case. Under the uncorrelated massive MIMO chanel (for the spatial correlation coefficient $\eta=0$) for fixed M, p_u and b, the asymptotic achievable rate result in (11) can be further reduced to (19), as shown at the bottom of this page.

Comparing (19) and (11), it can be found that the original spatial correlated channels model degenerates to the general Rayleigh fading channel model when $\eta=0$. Moreover, the results of achievable rate in (19) are consistent with the previous results in [18, eq. (15)].

B. IMPERFECT CSI

For a massive MIMO systems, it is generally difficult to obtain accurate CSI at BS. Thus, for the most general cases

$$R_{\mathrm{P},k}^{\mathrm{MRC}}\to\log_2\left(1+\frac{p_u\beta_k((M_0^2+M_0)+2\alpha M_0M_1+\alpha^2(M_1^2+M_1))}{p_u(M_0+\alpha^2M_1)\sum\limits_{i=1,i\neq k}^{K}\beta_i+\sigma^2(M_0+\alpha^2M_1)+\alpha(1-\alpha)M_1(p_u\sum\limits_{i=1}^{K}\beta_i+\sigma^2)}\right). \tag{19}$$

of imperfect CSI, we consider a widely used channel model: $\mathbf{F} = \widehat{\mathbf{F}} + \Delta\mathbf{F}$, where $\widehat{\mathbf{F}} \sim \mathcal{CN}(0, (1-\delta_e^2)\mathbf{I}_M)$ is the channel estimation obtained from uplink training, $\Delta\mathbf{F} \sim \mathcal{CN}(0, \delta_e^2\mathbf{I}_M)$ is the CSI error, and δ_e^2 represents the power of CSI error [17]. Furthermore, $\widehat{\mathbf{F}}$ and $\Delta\mathbf{F}$ are assumed to be independent.[3] Therefore, the obtained estimated CSI after MRC is given by $\mathbf{r} = \widehat{\mathbf{F}}^{\mathrm{H}}\mathbf{y}$. Then, the output signal for the kth user under imperfect CSI can be expressed as

$$\begin{aligned}\hat{\mathbf{r}}_k = &\sqrt{p_u}(\hat{\mathbf{f}}_{0,k}^{\mathrm{H}}\hat{\mathbf{f}}_{0,k} + \alpha\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\hat{\mathbf{f}}_{1,k})\hat{x}_k + (\hat{\mathbf{f}}_{0,k}^{\mathrm{H}}\mathbf{n}_0 + \alpha\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\mathbf{n}_1)\\ &+\sqrt{p_u}\sum_{i=1,i\neq k}^{K}(\hat{\mathbf{f}}_{0,k}^{\mathrm{H}}\hat{\mathbf{f}}_{0,i} + \alpha\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\hat{\mathbf{f}}_{1,i})\hat{x}_i\\ &+\sqrt{p_u}\sum_{i=1}^{K}(\hat{\mathbf{f}}_{0,k}^{\mathrm{H}}\Delta\mathbf{f}_{0,i} + \alpha\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\Delta\mathbf{f}_{1,i})\hat{x}_i + \hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\mathbf{n}_q, \end{aligned}\quad (20)$$

where $\hat{\mathbf{f}}_{0,k}$ and $\hat{\mathbf{f}}_{1,k}$ are the kth column of $\hat{\mathbf{F}}_0$ and $\hat{\mathbf{F}}_1$, respectively. More specifically, the channel estimate is considered as a real channel at BS, which the last four terms of (20) as interference, noise and CSI error terms when decoding the signal.

According to (20), the ergodic achievable rate of the kth user under imperfect CSI can be expressed as

$$R_{\mathrm{IP},k}^{\mathrm{MRC}} = \mathbb{E}\left\{\log_2\left(1+\frac{p_u|\hat{\mathbf{f}}_{0,k}^{\mathrm{H}}\hat{\mathbf{f}}_{0,k} + \alpha\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\hat{\mathbf{f}}_{1,k}|^2}{\Phi_2}\right)\right\}, \quad (21)$$

where

$$\begin{aligned}\Phi_2 = &p_u\sum_{i=1,i\neq k}^{K}|\hat{\mathbf{f}}_{0,k}^{\mathrm{H}}\hat{\mathbf{f}}_{0,i} + \alpha\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\hat{\mathbf{f}}_{1,i}|^2 + |\hat{\mathbf{f}}_{0,k}^{\mathrm{H}}\mathbf{n}_0 + \alpha\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\mathbf{n}_1|^2\\ &+p_u\sum_{i=1}^{K}|\hat{\mathbf{f}}_{0,k}^{\mathrm{H}}\Delta\mathbf{f}_{0,i} + \alpha\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\Delta\mathbf{f}_{1,i}|^2\\ &+\alpha\rho\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\mathrm{diag}((\widehat{\mathbf{F}}_1+\Delta\mathbf{F}_1)(\widehat{\mathbf{F}}_1+\Delta\mathbf{F}_1)^{\mathrm{H}} + \sigma^2\mathbf{I}_{M_1})\hat{\mathbf{f}}_{1,k}.\end{aligned}\quad (22)$$

Following the same derivations as in Section **II − A** for the case of imperfect CSI, a tight form approximate expression of achievable rate can be obtained in the following *Theorem 2*.

Theorem 2: For a multi-user massive MIMO system with mxied-ADC using spatially correlated channels with imperfect CSI. The achievable rate of the kth user can be approximated by (23), as shown at the top of next page.

Proof: For the number of BS antennas M is very large but finite, by following the same method in Section **II − A** to approximate (21) as

$$R_{\mathrm{IP},k}^{\mathrm{MRC}} \approx \log_2\left(1+\frac{p_u\mathbb{E}\{|\hat{\mathbf{f}}_{0,k}^{\mathrm{H}}\hat{\mathbf{f}}_{0,k} + \alpha\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\hat{\mathbf{f}}_{1,k}|^2\}}{\mathbb{E}\{\Phi_2\}}\right), \quad (24)$$

[3]The channel estimation scheme for ADCs in massive MIMO can be found in [6], [17], and [21].

where

$$\begin{aligned}\mathbb{E}\{\Phi_2\} = &p_u\sum_{i=1,i\neq k}^{K}\mathbb{E}\{|\hat{\mathbf{f}}_{0,k}^{\mathrm{H}}\hat{\mathbf{f}}_{0,i} + \alpha\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\hat{\mathbf{f}}_{1,i}|^2\}\\ &+p_u\sum_{i=1}^{K}\mathbb{E}\{|\hat{\mathbf{f}}_{0,k}^{\mathrm{H}}\Delta\mathbf{f}_{0,i} + \alpha\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\Delta\mathbf{f}_{1,i}|^2\}\\ &+\mathbb{E}\{|\hat{\mathbf{f}}_{0,k}^{\mathrm{H}}\mathbf{n}_0 + \alpha\hat{\mathbf{f}}_{1,k}^{H}\mathbf{n}_1|^2\} + \mathbb{E}\{\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\mathbf{R}_{\mathbf{n}_q}\hat{\mathbf{f}}_{1,k}\}.\end{aligned}\quad (25)$$

The expected value of each term in (24) can be directly calculated, and the calculation results are as follows:

$$\begin{aligned}\mathbb{E}\{|\hat{\mathbf{f}}_{j,k}^{\mathrm{H}}\hat{\mathbf{f}}_{j,k}|^2\} = &(1-\delta_e^2)^2\beta_k^2\left(\sum_{m=1}^{M_j}\sum_{n=1}^{M_j}(|r_{mn}|^2 + r_{mm}r_{nn})\right.\\ &\left.+\sum_{m\neq n}^{M_j}\sum_{n=1}^{M_j}r_{mn}r_{nm}\right),\end{aligned}\quad (26)$$

$$\mathbb{E}\{|\hat{\mathbf{f}}_{j,k}^{\mathrm{H}}\hat{\mathbf{f}}_{j,k}|\} = (1-\delta_e^2)\beta_k\sum_{m=1}^{M_j}|r_{mm}|, \quad (27)$$

$$\mathbb{E}\{|\hat{\mathbf{f}}_{j,k}^{\mathrm{H}}\hat{\mathbf{f}}_{j,i}|^2\} = (1-\delta_e^2)^2\beta_k\beta_i\sum_{m=1}^{M_j}\sum_{n=1}^{M_j}|r_{mn}|^2, \quad (28)$$

$$\mathbb{E}\{|\hat{\mathbf{f}}_{j,k}^{\mathrm{H}}\Delta\mathbf{f}_{j,i}|^2\} = \delta_e^2(1-\delta_e^2)\beta_k\beta_i\sum_{m=1}^{M_j}\sum_{n=1}^{M_j}|r_{mn}|^2. \quad (29)$$

Following a similar method in [9], assume that $K \gg 1$ and then $\mathbf{F}\mathbf{F}^{\mathrm{H}} \approx \mathbb{E}\{\mathbf{F}\mathbf{F}^{\mathrm{H}}\} = \sum_{i=1}^{K}\beta_i\mathbf{R}$, the expectation of the last term in the (25) can be directly derived as

$$\begin{aligned}\mathbb{E}\{\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\mathbf{R}_{\mathbf{n}_q}\hat{\mathbf{f}}_{1,k}\} &\approx \alpha\rho\mathbb{E}\left\{\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\mathrm{diag}\left(p_u\sum_{i=1}^{K}\beta_i\mathbf{R} + \sigma^2\mathbf{I}_M\right)\hat{\mathbf{f}}_{1,k}\right\}\\ &\overset{(\varrho)}{=} \alpha\rho\mathbb{E}\left\{\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\left(p_u\sum_{i=1}^{K}\beta_i + \sigma^2\right)\hat{\mathbf{f}}_{1,k}\right\}\\ &= \alpha\rho\left(p_u\sum_{i=1}^{K}\beta_i + \sigma^2\right)\mathbb{E}\{\hat{\mathbf{f}}_{1,k}^{\mathrm{H}}\hat{\mathbf{f}}_{1,k}\}\\ &= \alpha\rho\beta_k(1-\delta_e^2)\left(p_u\sum_{i=1}^{K}\beta_i + \sigma^2\right)\sum_{m=1}^{M_1}|r_{mm}|,\end{aligned}\quad (30)$$

where (ϱ) is obtained by assuming $[\mathbf{R}]_{mm} = 1$ for $\forall_m = 1, \ldots, M$ [31]. By substituting the above equalities into (21), the result in (23) can be directly obtained. ■

In order to facilitate a comprehensive understanding of *Theorem 2*, the impact of CSI error, the number of BS antenna and spatial correlation coefficient on the uplink achievable rate are analyzed. By simple numerical setting of the above system parameters, the uplink achievable rate can be further analyzed as follows.

Remark 3: For a quantized mixed-ADC massive MIMO system with imperfect CSI over spatially correlated channel.

$$R_{\mathrm{IP},k}^{\mathrm{MRC}} \approx \log_2\left(1+\frac{p_u\beta_k(\vartheta_0+2\alpha\varphi_0\varphi_1+\alpha^2\vartheta_1)}{p_u\lambda\sum_{i=1,i\neq k}^{K}\beta_i+p_u\phi\sum_{i=1}^{K}\beta_i+\sigma^2(\varphi_0+\alpha\varphi_1)+\alpha(1-\alpha)p_u\varphi_1\sum_{i=1}^{K}\beta_i}\right),$$

where

$$\varphi_j=(1-\delta_e^2)(\sum_{m=1}^{M_j}|r_{mm}|),\quad \vartheta_j=(1-\delta_e^2)^2(\sum_{m=1}^{M_j}\sum_{n=1}^{M_j}(|r_{mn}|^2+r_{mm}r_{nn})+\sum_{m\neq n}^{M_j}\sum_{n=1}^{M_j}r_{mn}r_{nm}),\quad j=0,1,$$

$$\lambda=(1-\delta_e^2)^2(\sum_{m=1}^{M_0}\sum_{n=1}^{M_0}|r_{mn}|^2+\alpha^2\sum_{m=1}^{M_1}\sum_{n=1}^{M_1}|r_{mn}|^2),\quad \phi=\delta_e^2(1-\delta_e^2)(\sum_{m=1}^{M_0}\sum_{n=1}^{M_0}|r_{mn}|^2+\alpha^2\sum_{m=1}^{M_1}\sum_{n=1}^{M_1}|r_{mn}|^2). \tag{23}$$

$$R_{\mathrm{IP},k}^{\mathrm{MRC}} \to \log_2\left(1+\frac{(1-\delta_e^2)p_u\alpha\beta_k(M+1)}{(1-\delta_e^2)p_u\alpha\sum_{i=1,i\neq k}^{K}\beta_i+\delta_e^2p_u\alpha\sum_{i=1}^{K}\beta_i+\sigma^2+(1-\alpha)p_u\sum_{i=1}^{K}\beta_i}\right). \tag{31}$$

When the system with CSI error $\delta_e^2=0$, it can be found that formula (23) and formula (11) are completely consistent by simple derivation and calculation. Therefore, it is obvious that the formula (11) is a special case for imperfect CSI.

Remark 4: If only low resolution ADC and no spatial correlation are considered at BS, i.e., $M_0=0$, $M_1=M$ and $\mathbf{R}=\mathbf{I}_M$. Then, the asymptotic achievable rate result in (23) can be further reduced to (31), as shown at the top of this page.

The formula (31) coincides with [16, eq. (12)] under the assumption of $M\gg 1$, $K\gg 1$, $\sigma^2=1$ and $\delta_e^2=0$. Therefore, such an approximation process is completely reasonable. And the analysis process for a full resolution ADC is completely similar to this case.

C. EXTENSIONS TO ACHIEVABLE RATE OF WHOLE SYSTEM

In Section **II** − **A** and Section **II** − **B**, we have studied the achievable rate of a single user. It is possible to calculate the achievable rate of any user in the system by considering the perfect and imperfect CSI, respectively. Since the expected value of each user's achievable rate is equal, the expectation of the kth user achievable rate is selected, and then the optimizing sum-rate is obtained by adjusting the structure of ADCs (e.g., adjust the quantization precision of low-resolution ADCs or adjust the ratio between high-resolution ADCs and low-resolution ADCs). Thus, the optimizing sum-rate of whole system are as shown follow:

$$\arg\max_{\mathrm{ADCs}}\min_{k}\mathbb{E}\{R_{\Omega,k}\}, \tag{32}$$

where $\Omega\in\{\mathrm{P},\mathrm{IP}\}$ and $R_{\Omega,k}$ denotes the achievable rate of user k. Moreover, obtaining the optimal achievable rate is a trade-off process, and the energy efficiency is gradually reduced as the achievable rate increases.

IV. NUMERICAL RESULTS

In this section, we provide Monte Carlo simulation and approximated analytical results on the uplink sum achievable rate of mixed-ADC massive MIMO systems. The impact of spatial correlation on the rate loss caused by mixed-resolution ADC is considered. By following a similar analysis in [6], the large-scale fading is modeled via $\beta_k=z_k/(d_k/r_d)^{-v}$, where $v=3.8$ is the path loss exponent, d_k is the user randomly and uniformly distributed in a cell with radius of 1000 meters, r_d is the minimum distance between the user and the BS of 100 meters and z_k is a log-normal random variable with standard deviation $\sigma_{shad}=4.9$ dB. Since the large-scale fading coefficient of the user is randomly generated, in order to facilitate the simulation work, a set of data is selected from it as follows: {13.13, 6.49, 11.01, 4.87, 29.00, 8.69, 50.02, 96.00, 1.24, 41.04} × 10^{-4} [18]. To help the analysis, we set $K=10$ and $\sigma^2=1.5$ dB for all simulations.

In Fig. 1, the first to consider are systems where set $M_0=28$, $M_1=100$, $\delta_e^2=0.1$ and $b=2$. The Monte Carlo simulation and the analytical uplink achievable rate versus

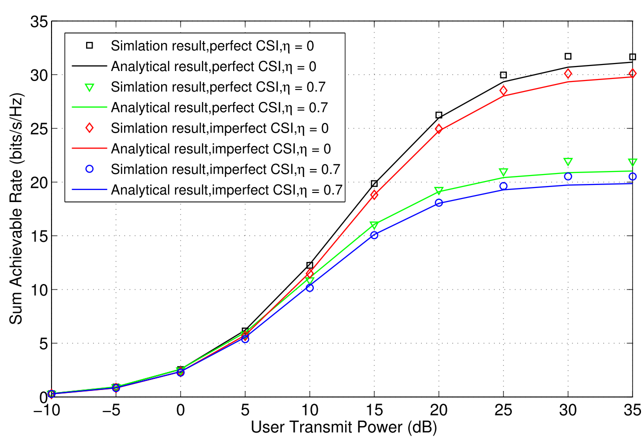

FIGURE 1. The sum achievable rate with perfect and imperfect CSI versus user transmit power for different correlation coefficients η where $K=10$, $M_0=28$, $M_1=100$, $\delta_e^2=0.1$, $b=2$.

user transmit power p_u are compared for different spatial correlations coefficient η with perfect and imperfect CSI. Both the Monte Carlo simulation and the analytical values are provided ((9) and (11) for achievable rate with perfect CSI, (21) and (23) for achievable rate with imperfect CSI). Fig. 1 shows that the analytical and simulated curves are very tight in all considered cases, which confirms the correctness of our derived results. Moreover, it can be seen that the achievable rate of different spatial correlation coefficients under perfect and imperfect CSI are almost the same when the user transmit power is less than 5 dB. With the user transmit power increasing, the achievable rates with perfect CSI cases are generally larger than with imperfect CSI cases. While in the same CSI condition, the case of achievable rate with smaller spatial correlation coefficient is relatively higher.

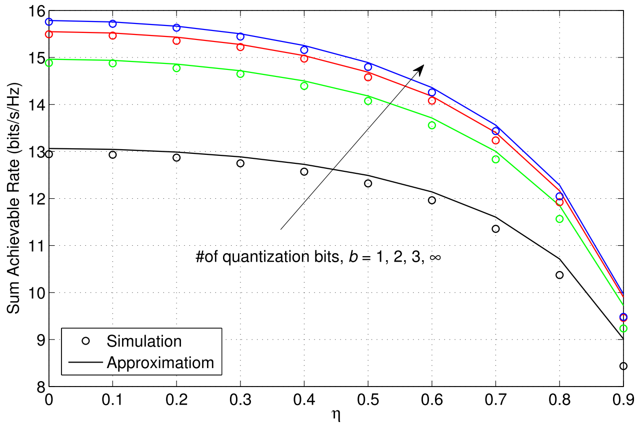

FIGURE 2. **The sum achievable rate with perfect CSI versus correlation coefficients η for different ADC quantization bit where $K = 10$, $M_0 = 28$, $M_1 = 100$, $p_u = 15$ dB, $b = 2$.**

Next, the effect of spatial correlation coefficients for achievable rate performance are discussed in massive MIMO systems. Fig. 2 shows the Monte Carlo simulation and approximate achievable rate versus correlation coefficient for different ADC quantization bits with perfect CSI on spatially correlated channels. Obviously, it can be observed that the overall achievable rate of all cases decreases significantly as the spatial correlation coefficient increases. However, with the spatial correlation coefficient increasing, the achievable rate of ADCs with high quantized bits are still larger than ADCs with low quantized bits (e.g., 1-bit). From this, it obvious that the magnitude of the spatial correlation coefficient value has a large impact on the achievable rate of ADCs with different quantization bits.

Here, we use the same system parameter settings as in Figure 2, and further analyze the effect of ADC quantized bits on the uplink achievable rate under different spatial correlation coefficients. Fig. 3 presents the Monte Carlo simulated and approximated result of the achievable rate with perfect CSI. Obviously, it can be seen from the figure that all curves have similar trends. Meanwhile, it can be observed that the trends of achievable rate growth are relatively larger in all

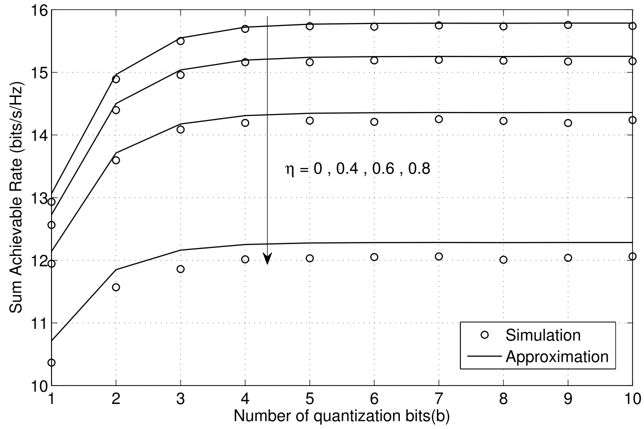

FIGURE 3. **The sum achievable rate with perfect CSI versus different ADC quantization bits for different spatially correlation coefficients η where $K = 10$, $p_u = 15$ dB, $M_0 = 28$, $M_1 = 100$.**

cases when ADCs have very few quantized bits (e.g., $b < 3$). However, the achievable rate grows slowly and gradually reaches the limit with increasing b. Therefore, it can be known that the achievable rate of all spatial correlation coefficient cases are more sensitive when the number of ADCs quantization bits are small. Moreover, the achievable rate with a smaller spatial correlation coefficient case always relatively larger.

In Fig. 4, systems with CSI error are considered while comparing the case of perfect CSI and imperfect CSI. Here, it shows the achievable rate for three CSI case: perfect CSI, $\delta_e^2 = 0.01$ and $\delta_e^2 = 0.1$, where the BS receiving antenna are selected to two groups: (1) $M_0 = 28, M_1 = 100$; (2) $M_0 = 50, M_1 = 150$. As expected, the approximate analysis results obtained by analyzing expression (23) tightly match the three constant curves of the Monte Carlo simulation results. Each point on the curve is obtained by increasing the user transmit power to maximize the achievable rate. Obviously, the achievable rate gradually improve as the user transmit power increases, and this improvement becomes

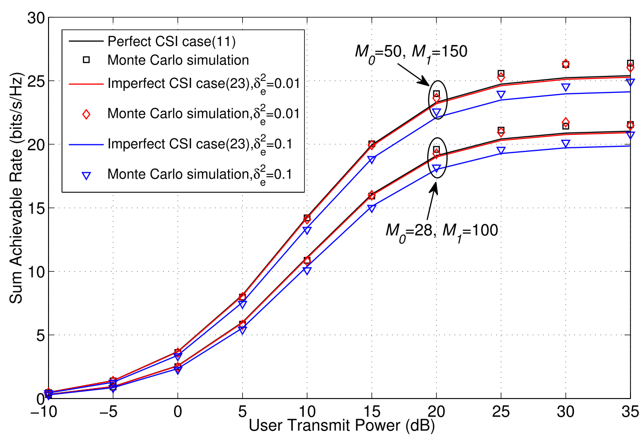

FIGURE 4. **The sum achievable rate of mixed-ADC massive MIMO systems over spatially correlated channels versus user transmit power for different CSI error where $K = 10$, $\eta = 0.7$, $b = 2$.**

more significant by increasing M, which is consistent with our analysis. Moreover, with the CSI error decreasing, the performance of the imperfect CSI case gradually approaches to the perfect CSI case.

Next, assume that only pure low-precision ADC and BS antenna spatial uncorrelation are considered. In Fig. 5, it presents the achievable rate various BS antennas of low-resolution ADC massive MIMO systems with imperfect CSI. Here, the three ADC quantization cases of the asymptotic results in (31) are considered in Fig. 5, i.e., $b = 1, 2, \infty$. It can be found that the curves of the three cases of approximation analysis and Monte Carlo simulation are very tight and have similar growth trends. The achievable rate of all cases of low-resolution ADCs improves with the number of BS antennas increasing. Moreover, the achievable rate becomes larger with the ADC quantization bits.

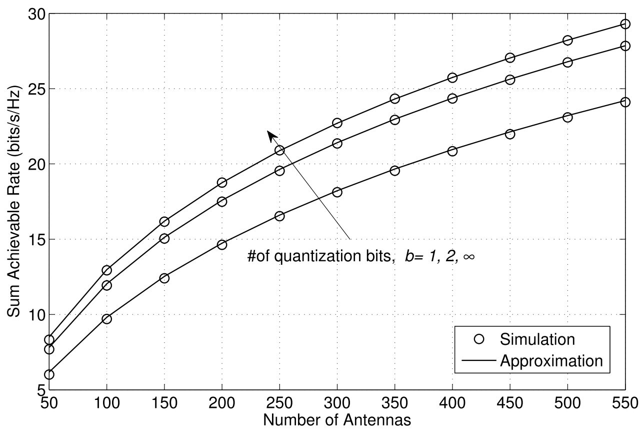

FIGURE 5. **The sum achievable rate with imperfect CSI versus BS antennas for different ADC quantization bit where $M_0 = 0$, $M_1 = M$, $p_u = 15$ dB, $K = 10$, $\delta_e^2 = 0.1$.**

Next, we evaluate the performance of the proposed spatially correlated channel in a multiuser uplink systems. Fig. 6 illustrates the Monte Carlo simulation and approximate sum achievable rate versus user transmit power with perfect CSI. In particular, we include three channel case for comparison: 1) Reyleigh channel case in [18], 2) Rician channel case in [19], and 3) spatially correlated channel case in this paper. From fig. 6, it can be seen that as the user transmit power increases, the overall achievable rate for all cases has a similar growth trend. It is clear that the achievable rate performance of the Rician channel case is the best, while the Rayleigh channel case performance is between the Rician channel case and the spatially correlated channel case. However, it is worth noting that the curve of the Rayleigh channel case completely coincides with the spatial correlation channel case of $\eta = 0$, which indicates that the spatial correlation channel has degraded to the original Rayleigh channel in the case of $\eta = 0$.

Based on the mixed-ADC massive MIMO system architecture, it is assumed that the energy consumption in massive MIMO systems originates entirely from base stations rather than the users. Then, the received energy efficiency is defined as [23]

$$\Theta_{\mathbf{EE}} \triangleq \frac{B \cdot R_{\text{sum}}}{P_{\text{Tot}}}, \tag{33}$$

where R_{sum} denotes the sum achievable rate, and B denotes the communication bandwidth which is set to 1 MHz. P_{Tot} is the total power consumption of the BS. The energy consumption models include $P_{\text{high}} = 0.43 M_0$ Watt for high-resolution ADCs and $P_{\text{low}} = c_0 2^b M_1 + c_1$ for low-resolution ADCs, where $c_0 = 10^{-4}$ Watt and $c_1 = 0.02$ Watt [18], [37], while b is ADCs quantization bits. Thus, the energy consumption models can be expressed as

$$P_{\text{Tot}} = P_{\text{high}} + P_{\text{low}}. \tag{34}$$

Fig. 7 presents the energy efficiency of mixed-ADC massive MIMO systems with perfect and imperfect CSI for different ADCs quantization bits. As the number of quantization bits increases, it can be seen that the energy efficiency curves of different spatial correlation coefficients have a tendency to rise first but then decrease. This shows that the energy efficiency curves of the three different correlation coefficients

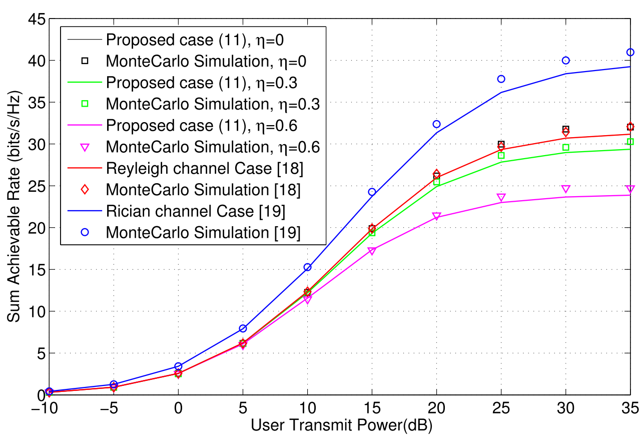

FIGURE 6. **The sum achievable rate with perfect CSI versus user transmit power for different channel condition where $K = 10$, $M_0 = 28$, $M_1 = 100$, $b = 2$.**

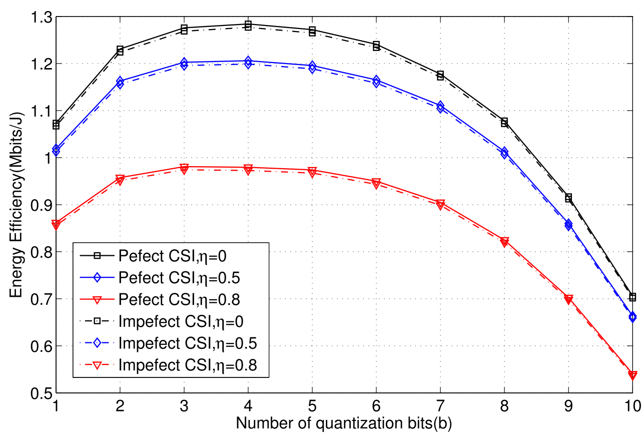

FIGURE 7. **The energy efficiency of mixed-ADC massive MIMO systems with perfect and imperfect CSI for different ADC quantization bits where $M_0 = 28$, $M_1 = 100$, $K = 10$, $p_u = 15$ dB, $\delta_e^2 = 0.01$.**

have peaks, but the ADC quantization bits are not as large as possible. Moreover, the curve with a larger correlation coefficient is less energy efficient when the number of quantized bits increases. It implies that the performance of the system with spatial correlation is significantly worse than ideal system. Through the above analysis, it can be concluded that a massive MIMO system with a large number of antenna arrays cannot ignore the spatial correlation between adjacent antennas.

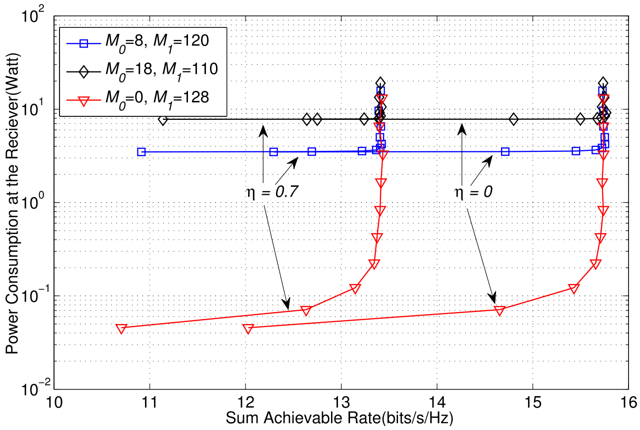

FIGURE 8. The trade-off between achievable rate and power consumption of mixed-ADC massive MIMO systems with perfect CSI for different number of BS antennas where $K = 10$, $p_u = 15$ dB.

To comprehensively analyze massive MIMO systems, Figure 8-10 show the trade-off curves for achievable rate and energy efficiency. In Fig. 8, the trade-off between power consumption and achievable rate for mixed-ADC system with different antenna configurations is shown. Here, only considering the case of two spatial correlation coefficients, it is clear that the power consumption required for a pure low-resolution ADC structure is significantly lower than a mixed-resolution ADC structure. Moreover, as the number of quantization bits varies from 1 to 10, the achievable rate has significant improvement but power consumption is also gradually increasing. In addition, it can be seen that the growth trend of curves with different spatial correlation coefficients are almost similar. However, by comparing the curves of the two spatial correlation coefficients, it can be seen that the curve with the spatial correlation coefficient $\eta = 0$ contains a region area significantly larger than $\eta = 0.7$. Therefore, it can be concluded that a case with smaller spatial correlation coefficient at the same power consumption has better performance.

In Fig. 9, the trade-off between achievable rate and energy efficiency of mixed-ADC architecture is shown with different spatial correlated coefficient. Here, the curves of three different ADCs architecture for analysis are presented. It can be seen that slightly increasing in achievable rate can result in lager decreasing in energy efficiency, especially when the achievable rate is near its end. Moreover, it is obvious that a pure low-resolution ADC architecture has higher energy efficiency than a mixed-resolution ADC architecture when the number of quantization bits is small. As expected, in the case of the same energy efficiency, the case of the spatial correlation coefficient $\eta = 0$ has higher achievable rate. It is obvious that the system can obtain a better achievable rate and a relatively high energy efficiency by properly deploying the structure of the mixed-ADC and selecting a certain spatial correlation coefficient.

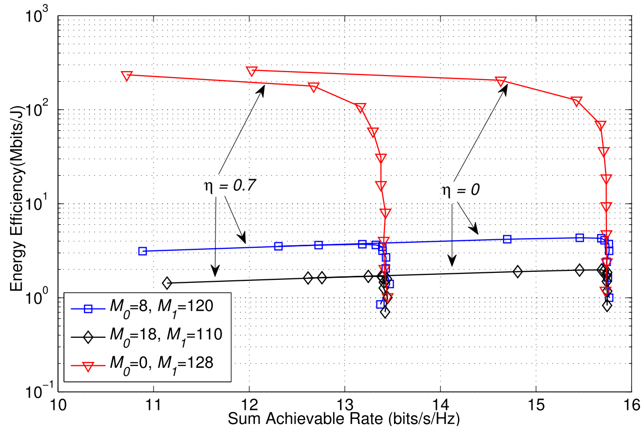

FIGURE 9. The trade-off between achievable rate and energy efficiency of mixed-ADC massive MIMO systems with perfect CSI for different number of BS antennas where $K = 10$, $p_u = 15$ dB.

Finally, the performance of the achievable rate and energy efficiency are analyzed by considering the case with CSI errors. In Fig. 10, it shows that the trade-off between achievable rate and energy efficiency of mixed-ADC systems with perfect and imperfect CSI over spatially correlated channel. In order to facilitate the analysis, two CSI cases are considered, i.e. perfect CSI and $\delta_e^2 = 0.1$ where $p_u = 15$dB, $\eta = 0.7$, (1) $M_0 = 8, M_1 = 120$, (2) $M_0 = 18, M_1 = 110$ and (3) $M_0 = 0, M_1 = 128$. From the figure, it can be seen that the performance of perfect CSI case is significantly better than the imperfect CSI case. This means that the channel estimation error has a certain impact on system performance in mixed-ADC massive MIMO systems.

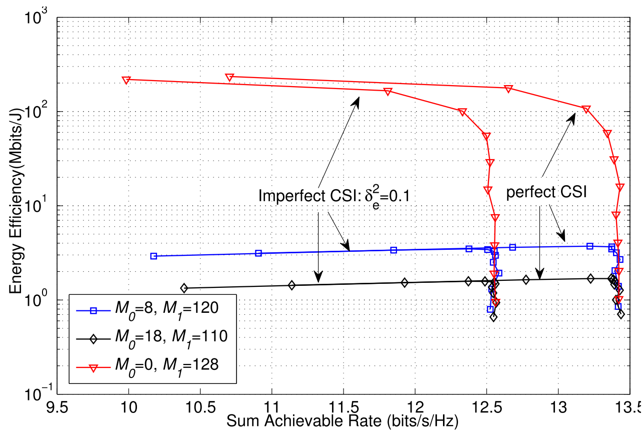

FIGURE 10. The trade-off between achievable rate and energy efficiency of mixed-ADC massive MIMO systems with perfect and imperfect CSI for different number of BS antennas where $K = 10$, $p_u = 15$ dB and $\eta = 0.7$.

V. CONCLUSION

In this paper, the performance of mixed-ADC massive MIMO systems over spatially correlated channels is investigated. Closed-form approximate expressions for the achievable rate are derived under perfect and imperfect CSI, respectively. From the simulation results, it can be found that the achievable rate of mixed-ADC structure will be much better than the uniform ADC case over spatially correlated channels. Moreover, it can be seen that the achievable rate of different spatial correlation coefficients is almost the same when the user power is less than 5dB. In addition, the achievable rate increases with the number of BS antennas, quantization ADC bits and user transmit power increasing, respectively. On the similar hardware condition, the achievable rate decrease as the spatially correlation coefficient increase. Further, numerical results show that the mixed-ADC architecture can bring most of the required performance enjoyed by massive MIMO receivers, but the spatial correlation among large-scale antennas in massive MIMO systems cannot be neglected. Therefore, in the implementation of massive MIMO, we can obtain a better achievable rate and a relatively high energy efficiency by properly deploying the mixed-ADC structure and selecting a certain spatial correlation coefficient.

REFERENCES

[1] J. G. Andrews *et al.*, "What will 5G be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[2] C.-X. Wang *et al.*, "Cellular architecture and key technologies for 5G wireless communication networks," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 122–130, Feb. 2014.

[3] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014.

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

[5] 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, Feb. 2013.

[6] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, "Energy and spectral efficiency of very large multiuser MIMO systems," *IEEE Trans. Commun.*, vol. 61, no. 4, pp. 1436–1449, Apr. 2013.

[7] K. Liu, C. Tao, L. Liu, T. Zhou, and Y. Liu, "Asymptotic analysis for low-resolution massive MIMO systems with MMSE receiver," *China Commun.*, vol. 15, no. 9, pp. 189–199, Sep. 2018.

[8] M. Zhang, W. Tan, J. Gao, and S. Jin, "Spectral efficiency and power allocation for mixed-ADC massive MIMO system," *China Commun.*, vol. 15, no. 3, pp. 112–127, Mar. 2018.

[9] P. Dong, H. Zhang, W. Xu, G. Y. Li, and X. You, "Performance analysis of multiuser massive MIMO with spatially correlated channels using low-precision ADC," *IEEE Commun. Lett.*, vol. 22, no. 1, pp. 205–208, Jan. 2018.

[10] M. Chiani, M. Z. Win, and A. Zanella, "On the capacity of spatially correlated MIMO Rayleigh-fading channels," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2363–2371, Oct. 2003.

[11] T. C. Zhang, C. K. Wen, S. Jin, and T. Jiang, "Mixed-ADC massive MIMO detectors: Performance analysis and design optimization," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7738–7752, Sep. 2016.

[12] J. Singh, O. Dabeer, and U. Madhow, "On the limits of communication with low-precision analog-to-digital conversion at the receiver," *IEEE Trans. Commun.*, vol. 57, no. 12, pp. 3629–3639, Dec. 2009.

[13] A. K. Fletcher, S. Rangan, V. K. Goyal, and K. Ramchandran, "Robust predictive quantization: Analysis and design via convex optimization," *IEEE J. Sel. Topics Signal Process.*, vol. 1, no. 4, pp. 618–632, Dec. 2007.

[14] O. Orhan, E. Erkip, and S. Rangan, "Low power analog-to-digital conversion in millimeter wave systems: Impact of resolution and bandwidth on performance," in *Proc. Inf. Theory Appl. Workshop (ITA)*, Feb. 2015, pp. 191–198.

[15] S. Jacobsson, G. Durisi, M. Coldrey, U. Gustavsson, and C. Studer, "Throughput analysis of massive MIMO uplink with low-resolution ADCs," *IEEE Trans. Wireless Commun.*, vol. 16, no. 6, pp. 4038–4051, Jun. 2017.

[16] L. Fan, S. Jin, C. K. Wen, and H. Zhang, "Uplink achievable rate for massive MIMO systems with low-resolution ADC," *IEEE Commun. Lett.*, vol. 19, no. 12, pp. 2186–2189, Oct. 2015.

[17] Q. Ding and Y. Jing, "Outage probability analysis and resolution profile design for massive MIMO uplink with mixed-ADC," *IEEE Trans. Wireless Commun.*, vol. 17, no. 9, pp. 6293–6306, Sep. 2018.

[18] W. Tan, S. Jin, C.-K. Wen, and Y. Jing, "Spectral efficiency of mixed-ADC receivers for massive MIMO systems," *IEEE Access.*, vol. 4, pp. 7841–7846, Sep. 2016.

[19] J. Zhang, L. Dai, Z. He, S. Jin, and X. Li, "Performance analysis of mixed-ADC massive MIMO systems over Rician fading channels," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 6, pp. 1327–1338, Jun. 2017.

[20] N. Liang and W. Zhang, "A mixed-ADC receiver architecture for massive MIMO systems," in *Proc. IEEE Inf. Theory Workshop–Fall (ITW)*, Oct. 2015, pp. 229–233.

[21] N. Liang and W. Zhang, "Mixed-ADC massive MIMO," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 983–997, Sep. 2016.

[22] H. Pirzadeh and A. L. Swindlehurst, "Spectral efficiency under energy constraint for mixed-ADC MRC massive MIMO," *IEEE Signal Process. Lett.*, vol. 24, no. 12, pp. 1847–1851, Dec. 2017.

[23] Q. Ding and Y. Jing, "Receiver energy efficiency and resolution profile design for massive MIMO uplink with mixed ADC," *IEEE Trans. Veh. Technol.*, vol. 67, no. 2, pp. 1840–1844, Feb. 2018.

[24] H. Tong and S. A. Zekavat, "Spatially correlated MIMO channel-generation via virtual channel representation," *IEEE Commun. Lett.*, vol. 10, no. 5, pp. 332–334, May 2006.

[25] Z. Xu, S. Sfar, and R. S. Blum, "Analysis of MIMO systems with receive antenna selection in spatially correlated Rayleigh fading channels," *IEEE Trans. Veh. Technol.*, vol. 58, no. 1, pp. 251–262, Jan. 2009.

[26] B. O. Hogstad, G. Rafiq, V. Kontorovitch, and M. Pätzold, "Capacity studies of spatially correlated MIMO Rice channels," in *Proc. 5th IEEE Int. Symp. Wireless Pervasive Comput. (ISWPC)*, May 2010, pp. 45–50.

[27] M. R. McKay and I. B. Collings, "General capacity bounds for spatially correlated Rician MIMO channels," *IEEE Trans. Inf. Theory*, vol. 51, no. 9, pp. 3121–3145, Sep. 2005.

[28] W. Xu, B. Wen, M. Lin, and X. Yu, "Energy-efficient power allocation scheme for distributed antenna system over spatially correlated Rayleigh channels," *IET Commun.*, vol. 12, no. 5, pp. 533–542, Mar. 2018.

[29] J. Cao, D. Wang, J. Li, Q. Sun, and Y. Hu, "Uplink spectral efficiency analysis of multi-cell multi-user massive MIMO over correlated Ricean channel," *Sci. China*, vol. 61, no. 8, Aug. 2018, Art. no. 082305.

[30] X. Yu, S. Qiu, Y. Li, and B. Wu, "Performance of heterogeneous multiuser MIMO system with cross-layer design over spatially correlated Rayleigh channel," *Optik-Int. J. Light Electron Opt.*, vol. 127, no. 5, pp. 2467–2475, 2016.

[31] D.-S. Shiu, G. J. Foschini, M. J. Gans, and J. M. Kahn, "Fading correlation and its effect on the capacity of multielement antenna systems," *IEEE Trans. Commun.*, vol. 48, no. 3, pp. 502–513, Mar. 2000.

[32] S. L. Loyka, "Channel capacity of MIMO architecture using the exponential correlation matrix," *IEEE Commun. Lett.*, vol. 5, no. 9, pp. 369–371, Sep. 2001.

[33] E. Björnson, J. Hoydis, M. Kountouris, and M. Debbah, "Massive MIMO systems with non-ideal hardware: Energy efficiency, estimation, and capacity limits," *IEEE Trans. Inf. Theory*, vol. 60, no. 11, pp. 7112–7139, Nov. 2014.

[34] J. Max, "Quantizing for minimum distortion," *IRE Trans. Inf. Theory*, vol. 6, no. 1, pp. 7–12, Mar. 1960.

[35] D. Qiao, W. Tan, Y. Zhao, C. K. Wen, and S. Jin, "Spectral efficiency for massive MIMO zero-forcing receiver with low-resolution ADC," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2016, pp. 1–6.

[36] Q. Zhang, S. Jin, K.-K. Wong, H. Zhu, and M. Matthaiou, "Power scaling of uplink massive MIMO systems with arbitrary-rank channel means," *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 966–981, Oct. 2014.

[37] Q. Bai, A. Mezghani, and J. A. Nossek, "On the optimization of ADC resolution in multi-antenna systems," in *Proc. IEEE Int. Symp. Wireless Commun. Syst.*, Aug. 2013, pp. 1–5.

QINGFENG DING received the B.Eng. and M.Eng. degrees from the East China Jiaotong University of China, Nanchang, China, in 2002 and 2007, respectively, and the Ph.D. degree in communication and information system from Shanghai University, Shanghai, China, in 2015. From 2017 to 2018, he was a Visiting Scholar with the University of Alberta, Edmonton, AB, Canada. He is currently an Associate Professor with the School of Electrical and Automation Engineering, East China Jiaotong University. His research interests include massive MIMO systems, cooperative relay networks, train communication networks, and intelligent optimization.

YICHONG LIAN received the B.S. degree in electronic and information engineering from Wuyi University, Nanping, Fujian, China, in 2017. He is currently pursuing the M.S. degree with the School of Electrical and Automation Engineering, East China Jiaotong University, Nanchang, Jiangxi, China. His main research interests include massive MIMO systems and mixed-ADC.