

Evaluation of different quantization resolution levels on the BER performance of massive MIMO systems under different operating scenarios

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ABSTRACT

The massive MIMO system is one of the main technologies in the fifth generation (5G) of telecommunication systems, also recognized as a highly large-scale system. Constantly in massive MIMO systems, the base station (BS) is provided with a large number of antennas, and this large number of antennas need high-quantization resolution levels analog-to-digital converters (ADCs). In this situation, there will be more power consumption and hardware costs. This paper presents the simulation performance of a suggested method to investigate and analyze the effects of different quantization resolution levels of ADCs on the bit error rate (BER) performance of massive MIMO system under different operating scenarios using MATLAB software. The results show that the SNR exceeds 12 dB accounts for only 0.001% of BER signals when the number of antennas 60 with low quantization a 2 bits' levels ADCs, approximately. But when the antenna number rises to 300, the SNR exceeds 12 dB accounts for almost 0.01% of BER transmitted signals. Comparably with the BER performance of high quantization, 4 bits-quantization resolution levels ADCs with the same different antennas have a slight degradation. Therefore, the number of antennas is a very important influence factor.

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1. INTRODUCTION

Massive multi-input multi-output (MIMO) is a highly large-scale physical layer system. The Massive MIMO is considered one of the reliable technologies in fifth-generation (5G) telecommunication systems and beyond to improve spectral efficiency, energy efficiency, throughput, security and robustness, hardware complexity, cost, and signal processing [1]-[9]. The main idea in the massive MIMO system is to use a large number of transmitting antennas (T_x) in the base station (BS) than the number of receiving antennas (T_R), which represent the users, to provide simultaneous service within the coverage area with relatively simple signals processing [6], [7], [10]. However, the use of a large number of antennas in the BS of massive MIMO system increases the hardware cost and complexity, and power consumption of the circuit components in the radio frequency (RF) chain that consists of signal mixers, power amplifiers, dedicated filters, and high-quantization resolution level analog-to-digital converters (ADCs) [11], [12]. Consequently, the increased hardware costs and power consumptions represent a substantial obstacle in the practical implementation of the massive MIMO systems [13].

The power consumed by high-quantization resolution level ADCs represents the essential part of the total power consumed by the other circuit components of the RF chain [14], [15]. In parallel, the utilization of high-quantization resolution level ADCs contributes significantly to increasing the hardware costs and complexities and reducing quantization errors in the massive MIMO systems [16]-[18]. The power consumption in the ADCs decreases exponentially with quantization resolution levels (quantization bits) and linearly with sampling frequencies (sampling rates) [19]. Particularly, ADCs represent the main parts of receivers in the massive MIMO systems to convert the analog signals into digital signals through sampling and quantization processes and preparing them for subsequent digital signal processing operations [20].

In the literature, many investigations work conducted to study the effect of different quantization resolution levels of ADCs on the performance of massive MIMO systems under different operating scenarios, such as: using a different number of antennas, various modulation schemes, and signal symbols detectors. In [14], the authors investigated the effect of 3-to-12 bits-quantization resolution levels ADCs on the uplink energy efficiency (EE) in the massive MIMO system, with time division duplexing (TDD) mode and a different number of antennas at the BS using linear zero-forcing (ZF) and zero-forcing successive interference cancellation (ZFSIC) signal symbols detectors, with both perfect and imperfect channel state information (CSI). Their results showed that the consumed power is significant in the massive MIMO system when using low (3bits)-quantization resolution levels ADCs due to the increase in quantization errors, which needs to compensate with a large number of antennas at the BS. In addition, the use of the perfect CSI-based linear ZFSIC signal symbols detector is able to improve the EE of the system more than the perfect CSI-based linear ZF signal symbols detector. The authors in [16] investigated the role of using low-quantization resolution levels ADCs with the linear minimum mean squared error (LMMSE) and nonlinear lattice reduction-based successive interference cancellation (LR-SIC) signal symbols detectors in improving the EE in the massive MIMO systems under different operating scenarios. Their results showed that the bit error rate (BER) performance using the LR-SIC signal symbols detectors-based receivers is better than that of LMMSE signal symbols detectors-based receivers and that the EE of the system depends on the number of antennas, cell size, and signal processing efficiency employed at the BS. In addition, the authors suggested that for high EE, signal symbols detectors should be carefully selected and according to an appropriate operating scenario. In order to improve EE, they also suggested using medium (6-to-7 bits)-quantization resolution levels ADCs to achieve a trade-off between power consumed and nonlinear distortion.

Moreover, Shao *et al.*, [21] proposed to increase the uplink EE of the massive MIMO systems under different operating scenarios, based on the use of low (1 bit)-quantization resolution levels ADCs, iterative detection and decoding (IDD) technique, and linear-low resolution aware MMSE (LRA-MMSE) signal symbols detector. Their results yielded a high EE gain and improved BER performance for the massive MIMO system. In [22], the authors investigated the EE in the massive MIMO system using arbitrary (1, 2, and infinity bits)-quantization resolution levels ADCs, superimposed pilots (SP) technology, and LMMSE and maximum ratio combining (MRC) signal symbols detectors under different operating scenarios. Their results showed that the pilots needed to specify a greater power in the massive MIMO system with higher quantization resolution levels ADCs or with a larger number of antennas at the BS. In addition, SP technology is superior to time-multiplexed pilots (TP) technology for low (1 bit)-quantization resolution levels ADCs, and SP technology is more suitable when using higher-quantization resolution levels ADCs and the used number of antennas in the BS is small.

Furthermore, the authors in [23] investigated the effects of using low (1-to-3 bits)-quantization resolution levels ADCs and the number of antennas available at the base station using LMMSE signal symbols detector in improving the uplink spectrum efficiency (SE) of the massive MIMO system under different operating scenarios. Their results proved to improve SE by more than 90% using low (3 bits)-quantization resolution levels ADCs. In addition, the SE improved when using 1 bit-quantization resolution levels ADCs with an increase in the number of antennas at the base station. In [24], the authors proposed a novel hybrid independent component analysis (HICA) signal symbols detector in order to improve the SE and reliability of the MIMO system under different operating scenarios. Their results showed that the HICA signal symbols detector showed improvement in the BER and MSE performances, but it was inefficient and failed to reduce the peak to average power rate (PAPR) rate compared to other state-of-the-art signal symbols detectors such as ICA and wavelet denoising ICA (WDICA).

In [25], the authors investigated the joint effects of the low (1 bit)-quantization resolution levels ADCs and the hardware impairments in the massive MIMO system, using a novel proposed alternating direction method of multipliers (ADMM)-based signal symbols detector, quadrature phase-shift keying (QPSK) modulation, and different numbers of antennas at the BS. The results of their investigations showed that the ADMM-based signal symbols detector achieved better performance than the other state-of-the-art linear signal symbols detectors in terms of improving BER performance and the gain with an increase in the number of antennas and users in the massive MIMO system.

In this paper, the main objective is to evaluate and measure the influences of different quantization resolution levels of analog-to-digital converters on the BER effectiveness in the massive MIMO system under different operating scenarios using the LMMSE signal symbols detector. The remainder of this paper is arranged: The descriptions of the quantized massive MIMO system equations with the LMMSE signal symbols detector are presented in Section 2. Matlab simulation results that explain the influence of quantization resolution levels analog-to-digital converters on the BER efficiency in the massive multiple-input, multiple-output system are presented in Section 3. Finally, Section 4 concludes this paper.

2. QUANTIZED MASSIVE MIMO WITH LMMSE SIGNAL SYMBOLS DETECTOR

First, in this section, we present the quantized massive MIMO system model, where different-quantization resolution levels ADCs are used in the receiver at the BS. Then we present the LMMSE detector to detect the transmitted signal symbols vector by the users at the BS receiver.

2.1. Quantized massive MIMO model with ADCs

We consider that the uplink of the massive multiuser (MU) MIMO system, as shown in Figure 1, has a total M antennas at the BS and simultaneously serves K single-antenna users, where $M \gg K \gg 1$. Thus, the channel matrix (H) connecting the channel coefficients between K single-antenna users and M antennas at the BS is given by (1) [7], [26], [27],

$$H = \begin{bmatrix} h_{11} & \dots & h_{1j} \\ \vdots & \ddots & \vdots \\ h_{i1} & \dots & h_{ij} \end{bmatrix} \tag{1}$$

where $H \in \mathbb{C}^{M \times K}$ and the element h_{ij} represent the channel attenuation coefficient from the i th receiving antenna to the j th transmitter antenna. The channel matrix (H) in the massive MIMO system provides us with the necessary knowledge about the channel state information (CSI) and thus helps solve many problems that we face in wireless communication systems such as path losses, fading, shadowing, scattering, diffractions, and properties of the channel [27], [28].

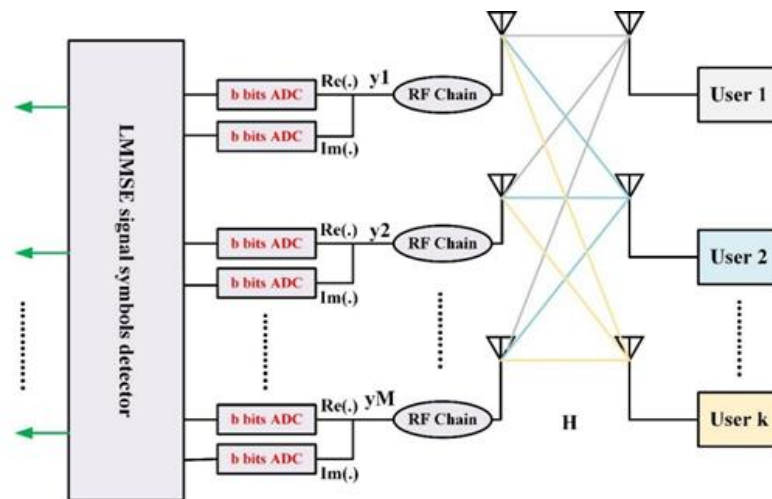


Figure 1. Uplink system model of quantized massive MU-MIMO

The information signals symbols (a_k) transmitted by all the K single-antenna users are encoded first by the channel encoders and then modulated according to the given modulation schemes to the signal symbols (x_k). These modulated signal symbols (x_k) are transmitted through the channels. The M antennas at the BS receive these modulated signal symbols (x_k) corrupted by the channel effects and noise. The corrupted and unquantized signal symbols vector received in the base station is given by (2),

$$y = Hx + n \tag{2}$$

where $x = [x_1, x_2, x_3, \dots, x_K]^T$ is the vector of the transmitted signal symbols from all users, $y = [y_1, y_2, y_3, \dots, y_M]^T$ is the vector of the received signal symbols, and n is the additive white Gaussian noise vector. The model given in (2) represents the massive MIMO system model through which it is possible to find the channel matrix (H) based on the provided information about the x and y signal symbols vectors.

Generally, the structure of ADCs consists of filters, sampling and hold circuits, and quantizers. Particularly, the quantizers represent the cores of ADCs that perform the quantization processes for the received signal symbols vector (y) given in (2) into the quantized signal symbols version vector (r) [14], [18]. As shown in Figure 1, by utilization of two b bit-quantization resolution levels ADCs for the real and imaginary parts of the complex received signal symbols vector (y), the outcome quantized signal symbols vector (r) is given by (3),

$$r = Q(y) = Q[\mathcal{R}_e(y) + j I_m(y)] \tag{3}$$

where $Q(\cdot)$ describes the quantization process for the real ($\mathcal{R}_e(y)$) and imaginary ($I_m(y)$) parts of the complex received signal symbols vector (y), and it is a non-linear process.

The characteristics of 3 bits regular mid ascending quantization processes are shown in Figure 2. Assuming that $Q(\cdot)$ representing b bits regular mid ascending quantization processes achieved by the quantizer with $N = 2^b$ resolution levels of the ADCs. Consequently, the quantizer performs the conversion process to the real part of the input signal symbols vector (y) into a real evaluated output signal symbols vector (r), where $r = [r_1, r_2, r_3, \dots, r_s]$ and $s = 1, 2, 3, \dots, N$. The endpoints of the input interval (y_s) are given by (4),

$$y_s = \begin{cases} -\infty & \text{for } s = 1 \\ (-N/2 - 1 + s)\Delta & \text{for } s = 2, 3, 4, \dots, N \\ +\infty & \text{for } s = N + 1 \end{cases} \tag{4}$$

where Δ represents the period size of quantization process. The produced signal symbols values (r_s) of the quantizer are given by (5),

$$r_s = \left(-\frac{N}{2} - \frac{1}{2} + s\right)\Delta \quad \text{for } s = 2, 3, 4, \dots, N \tag{5}$$

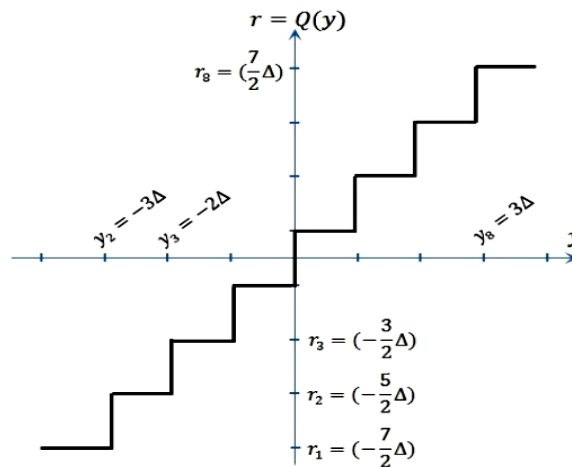


Figure 2. Staircase representation of a three bits regular mid ascending quantization processes

2.2. LMMSE signal symbols detector

As a result of the interuser interference among the users, the signal symbols detector is used to evaluate the vector of the transmitted signal symbols (x) from the vector of the received signal symbols (y). In this work, we have adopted the LMMSE signal symbols detector from the other state-of-the-art detectors because of its advantages, including [7], [16],

- It has lower computational complexity.
- It has noise improvement.
- It outperforms the ZF signal symbol detector.

Implementation the linear signal detector by using $M \times K$ matrix (A) to the received signal symbols vector (y), the transmitted signal symbols vector is given by (6),

$$\hat{x} = A^H y = A^H (Hx + n) \tag{6}$$

where $\hat{x} = [\hat{x}_1, \hat{x}_2, \hat{x}_3, \dots, \hat{x}_K]^T$ is $K \times 1$ signal characters vector consists of data information stream of K single-antenna user. Employing the LMMSE signal symbols detector by defining the detection matrix data stream (A) as given by (7),

$$A = H \left[H^H H + \frac{\sigma_n^2}{\sigma_x^2} I_K \right]^{-1} \tag{7}$$

where σ_x^2 and σ_n^2 are the transmitted original signal and the received noise signal variances correspondingly. For a quantized massive MU-MIMO system, we have the Kth element of \hat{x} as given by (8),

$$\hat{x} = A^H r = A^H Q(y) = A^H Q(Hx + n) = a_K^H h_K x_K + \sum_{i \neq k}^K a_K^H h_i x_i + a_K^H n \tag{8}$$

where the first term in (8) represents the desired signal, the second term represents the interuser interference, and the third term represents the noise.

3. SIMULATION RESULTS

In this section of the paper, MATLAB simulations are applied to explain the effects of different quantization resolution levels of analog-to-digital converter (ADCs) on the BER performance in massive multiple input multiple output (MIMO) systems under different operating scenarios.

3.1. BER performance using different schemes of modulation

Figures 3 and 4 show the BER performances using two different schemes of quadrature amplitude modulation, 4 QAM and 16 QAM, and different quantization resolution levels of ADCs and LMMSE signal symbols detector have been used at the BS. Simulations results are implemented with 80 antennas at the transmitter and serving 5 antennas as a user's. The effects of different quantization resolution levels of ADCs on the BER performance are shown as a signal to noise ratio (SNR) get bigger, the result demonstrate that the BER degradation exponentially in a similar way for both schemes of modulations when using the same quantization resolution levels of ADCs. Nevertheless, the results illustrate that by increasing the quantization resolution levels of ADCs, the BER performance becomes more ideal.

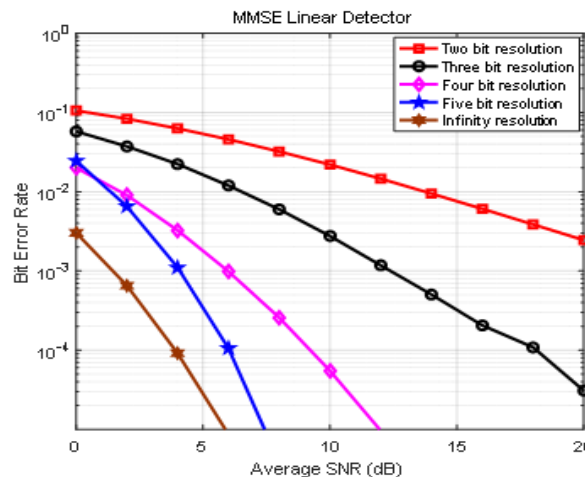


Figure 3. BER performance using different quantization resolution levels of ADCs, $T_X = 80$, $R_X = 5$, and 4 QAM

In order to study higher-order modulations, we observe that with using 2 and 3 bits-quantization resolution levels of ADCs, the BER showing degrades, while using the condition 4 bits-quantization resolution levels, the BER becomes acceptable. Furthermore, having 5 bits-quantization resolution levels and

overhead, the BER effectiveness is very close to the infinity bits-quantization resolution levels. The outcomes show when using higher order of modulation (4 QAM and 16 QAM), the BER increases correspondingly for specific quantization resolution levels of ADCs. Consequently, higher quantization resolution levels of ADCs are obligatory for advanced order modulations to attain the equivalent performance.

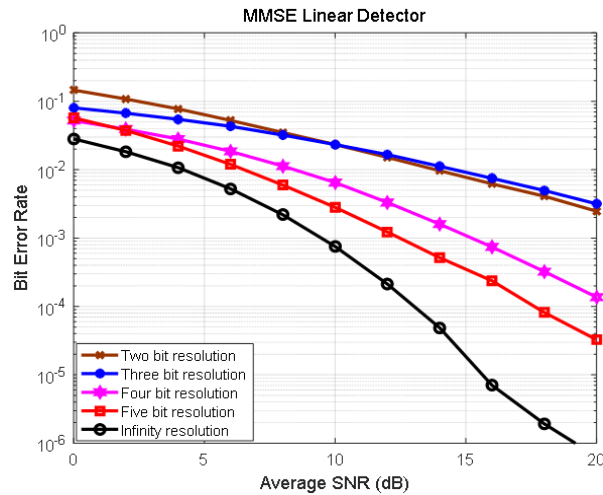


Figure 4. BER performance using different quantization resolution levels of ADCs, $T_X = 80$, $R_X = 5$, and 16 QAM

3.2. BER performance using different number of antennas

Further simulation is accomplished to determine BER performance as a function of quantization resolution levels of ADCs with a different number of BS antennas, and LMMSE signal symbols detector have been used. We examine a constant number of users as a receiver $T_X = 5$, and the number of antennas at the BS will be taken from 60 to 300 antennas. Figures 5 and 6 explain that increasing the number of antennas at the transmitter will decrease the BER regression caused by the low quantization resolution levels of ADCs. Figure 5 illustrate a 2 bits-quantization resolution levels ADCs with three different number of the antenna (60, 120, and 300) has an obvious change with the increase the number of antennas. Comparably, with Figure 6, the BER performance of 4 bits-quantization resolution levels ADCs with the same different antennas have a slight degradation. Wherefore, the higher number of antennas at the BS is proposed to recover the BER performance regression in the situation of having constant low quantization resolution levels ADCs.

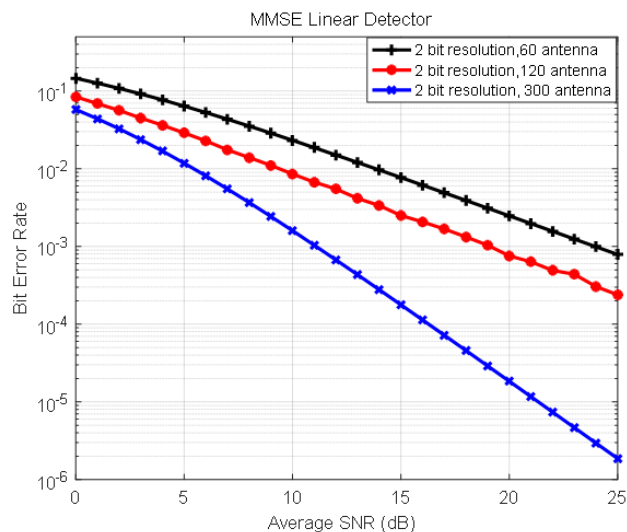


Figure 5. BER performance using 2 bit-quantization resolution levels ADCs and 4 QAM

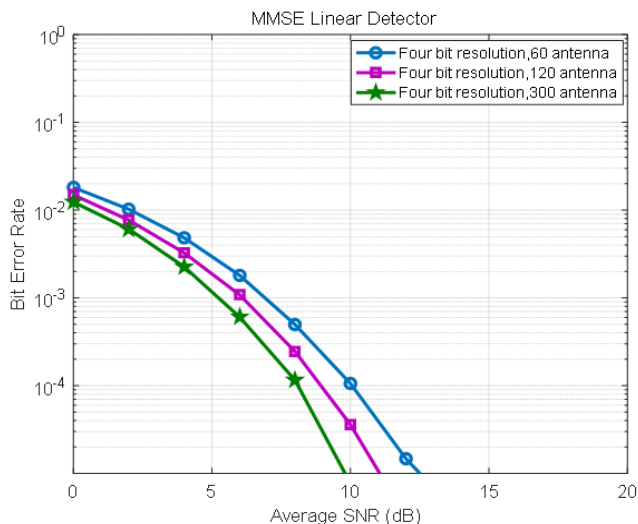


Figure 6. BER performance using 4 bit-quantization resolution levels ADCs and 4 QAM

4. CONCLUSION

In this work, we evaluated and measured the effects of different quantization resolution levels of ADCs on the BER performance of massive MIMO systems under different operating scenarios. The two typical modulations, 4 QAM and 16 QAM have been used with LMMSE signal symbols detector to evaluate the system. The results demonstrated that the performance of BER in massive MIMO technology is affected directly by the quantization resolution levels of ADCs, the number of antennas, and modulation schemes. Low (1 bit and 2 bits)-quantization resolution levels ADCs can realize appropriate BER performances compared to the high quantization resolution levels ADCs when the number of antennas at the BS high. Moreover, we observe that using 4 bits-quantization resolution levels ADCs in 16 QAM, the SNR of around 15.5 dB is obligatory to attained the BER of 10^{-3} , whereas using 4 bits-quantization resolution levels ADCs in 4 QAM require only 6 dB SNR. We conclude that increasing the modulation order will significantly affect the BER performance of high-quantization resolution levels ADCs while slightly affected the BER performance when low-quantization resolution levels have been used.

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