SCIENCE CHINA
Information Sciences

• LETTER •

November 2021, Vol. 64 219302:1–219302:2
https://doi.org/10.1007/s11432-020-3050-9

An iterative BiGAMP-based receiver for coded massive MIMO systems with low-resolution ADCs

Yi SUN[1], Ming JIANG[1,2*] & Chunming ZHAO[1,2]

[1]*National Mobile Communications Research Laboratory, Southeast University, Nanjing* 210096*, China;*
[2]*Purple Mountain Laboratories, Nanjing* 210096*, China*

Received 25 March 2020/Revised 7 June 2020/Accepted 1 September 2020/Published online 13 October 2021

Citation Sun Y, Jiang M, Zhao C M. An iterative BiGAMP-based receiver for coded massive MIMO systems with low-resolution ADCs. Sci China Inf Sci, 2021, 64(11): 219302, https://doi.org/10.1007/s11432-020-3050-9

Dear editor,

The hundreds of antennas deployed in massive multiple-input-multiple-output (MIMO) systems lead to an insupportable burden in terms of hardware costs and power consumption. This has motivated the research on low-resolution analog-to-digital converters (ADCs), e.g., those using 1–3 bits [1–5]. However, channel estimation remains challenging under such coarse quantization. Results presented in [2] suggest that precise estimates for 1-bit quantized MIMO systems can be obtained with least-squares (LS) channel estimation, but an extremely long pilot sequence is required. Considering the restriction of pilot overhead in practice, a framework for joint channel-and-data (JCD) estimation was developed in [3] based on the bilinear generalized approximate message-passing algorithm (BiGAMP) [6]. However, further studies on coded systems were absent, which may have additional potential owing to the powerful correction capability of forward error correction codes. Sun et al. [5] studied the joint channel estimation, equalization, and decoding over frequency-selective channels, but the work was limited to single-input-single-output systems and the cyclic redundancy check (CRC) detection was not incorporated.

Motivated by the aforementioned considerations, we propose an iterative BiGAMP-based receiver for coded massive MIMO systems with low-resolution ADCs. In addition, for a large transmission block length, we adopt a partially active processing method to achieve a reasonable trade-off between the performance and computational complexity.

System model and linear quantizer model. Consider an uplink massive MIMO system wherein one base station equipped with M antennas serves K single-antenna users ($M > K$) simultaneously. In this study, we assume a block-independent Rayleigh fading channel model. The received signals $\boldsymbol{Y} = [y_{mt}] \in \mathbb{C}^{M\times T}$ during a block are expressed as

$$\boldsymbol{Y} = \boldsymbol{H}\boldsymbol{X} + \boldsymbol{N}, \tag{1}$$

where $\boldsymbol{H} = [h_{mk}] \in \mathbb{C}^{M\times K}$ refers to the uplink channel matrix with $h_{mk} \sim \mathcal{CN}(0, \frac{1}{K})$. Furthermore, $\boldsymbol{X} = [x_{kt}] \in \mathbb{C}^{K\times T}$ and $\boldsymbol{N} = [n_{mt}] \in \mathbb{C}^{M\times T}$ represent the normalized transmitted symbols and the additive white Gaussian noise (AWGN) with $n_{mt} \sim \mathcal{CN}(0, \sigma_n^2)$, respectively. Then, with the ADCs equipped at each receiving antenna, uniform mid-rise quantization is separately applied to the real and imaginary parts of the received signals [3]. Therefore, the quantized observations can be denoted as $\boldsymbol{R} = [r_{mt}] \in \mathbb{C}^{M\times T}$.

For ease of derivation, we introduce the linear quantizer model [7], which can be expressed as

$$r_{mt} \approx \rho y_{mt} + w_{mt} = \rho \sum_k h_{mk} x_{kt} + \rho n_{mt} + w_{mt}, \tag{2}$$

where ρ is the distortion factor and w_{mt} is the additive quantization noise. In addition, considering $\rho n_{mt} + w_{mt}$ as a whole, the variance of the effective noise can be written as

$$\gamma^2 = \rho^2\sigma_n^2 + \rho(1-\rho)(1+\sigma_n^2). \tag{3}$$

Iterative BiGAMP-based JCD and decoding. Compared with conventional receivers, the BiGAMP-based receiver enables realizing joint channel estimation and data detection iteratively. Furthermore, we propose utilizing the feedback of the decoder to refine the BiGAMP-based JCD and improve the overall performance. Details of the algorithm are presented in Appendix A.

Note that the variables related to pilots, as well as correctly decoded data symbols, will keep constant during iterations because they are already known to the receiver (or can be reconstructed). For other data symbols, based on the assumption that $\hat{r}_{kt}$ can be regarded as an equivalent AWGN channel output of x_{kt} with a noise variance of v_{kt}^r [3], the updated expectation and variance of x_{kt} in line 13 of Appendix A can be calculated with respect to

$$\mathcal{P}(x_{kt}) = \frac{P_X(x_{kt})\mathcal{CN}(x_{kt}\,|\hat{r}_{kt}(\xi), v_{kt}^r(\xi))}{\sum_{x\in\Omega} P_X(x)\mathcal{CN}(x\,|\hat{r}_{kt}(\xi), v_{kt}^r(\xi))}. \tag{4}$$

In particular, the prior probability $P_X(x_{kt})$ is initialized to be equal for each point on the constellation Ω, and then updated by the decoder for the following outer iterations. Once the JCD process is completed, the extrinsic log likelihood ratios (LLRs) $\boldsymbol{\Lambda}$ are computed for channel decoding.

* Corresponding author (email: jiang_ming@seu.edu.cn)

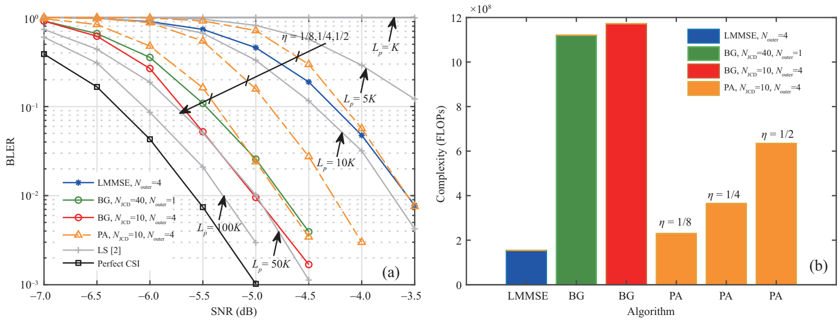

Figure 1 (Color online) (a) Block error rate (BLER) performances and (b) computational complexity (floating point operations per second) comparisons of different receiving algorithms under 2-bit quantization with $M = 64$, $K = 8$, $L_p = K$, code length $N = 2048$, code rate $R = 1/2$, and quadrature phase-shift keying constellations.

After decoding, the correctly decoded bits (as indicated by the CRC result) are re-encoded and modulated to recover the original symbols, which will be treated as pilots in subsequent iterations. For the decoded bits that have not passed the CRC detection, the soft outputs $\mathbf{\Pi}$ of the decoder are utilized to generate the prior symbol probability for the JCD as follows:

$$P_X(x_{kt} = a) = \prod_{q=1}^{Q} \frac{1}{2}\left[1 + (2b_q - 1)\tanh\left(\frac{\Pi(x_{kt}^q)}{2}\right)\right], \quad (5)$$

where Q is the modulation order and b_q is the corresponding bit value of x_{kt}^q. Then, $\hat{x}_{kt}(\xi)$ and $v_{kt}^x(\xi)$ can be renewed through soft modulation, which will be set as the initial values for the next outer iteration. Thus, the BiGAMP-based JCD and decoding can be executed iteratively until the termination conditions are satisfied.

Partially active processing. The computational complexity is mainly contributed by the steps of BiGAMP-based JCD, in which the transmission block length is a dominant factor. Therefore, to avoid high complexity when the block length is large, a partially active processing method is adopted for our proposed receiver as a feasible instance of the strategy noted in [4]. In the first stage, only part of the data symbols will be activated to participate in the BiGAMP-based JCD with pilots, whereas others will remain inactive. In the second stage, with the channel estimates $\hat{\boldsymbol{H}}$ obtained previously, the left symbols $\boldsymbol{X}^{\rm left}$ are detected using a simple detector by applying minimum mean square error (MMSE) detection with CRC-aided hard interference cancellation. The detailed steps, with the linear quantizer model considered, are described in Appendix B.

Simulation results. We assume an uplink massive MIMO system encoded by the fifth-generation (5G) low-density parity check codes with 16-bit CRC codes embedded in the information bits. The number of pilot symbols and data symbols are denoted by L_p and L_d, while η is used to represent the proportion of active data symbols. In addition, the linear (L) MMSE-based data-aided channel estimation proposed in [8] is adapted to our scenario for comparison. To simplify the legend, these different receiving algorithms are distinguished by BG (iterative BiGAMP-based JCD and decoding), PA (partially active processing), and LMMSE.

We compared the BLER performance and computational complexity of different receiving algorithms under 2-bit quantization with a large transmission block length. As illustrated in Figure 1, the performance advantage of the iterative BiGAMP-based receiver compared with the LMMSE-based counterpart was higher than 1 dB. In particular, by dividing 40 JCD iterations into four parts and using the feedback of the decoder to form outer loops, an additional 0.3 dB gain was obtained with a minimal increase in the complexity. On the other hand, it can be observed that the complexity significantly dropped when only half of the data symbols were activated to participate in the JCD, whereas the performance suffered only a slight loss. However, when the proportion η decreased to 1/8, the receiver performed poorly, despite its complexity remaining higher than the LMMSE-based counterpart, which indicated the importance of selecting η appropriately. We also plotted the BLER performance of the LS method [2] with different L_p. Results showed that when L_p increased to $50K$ or $100K$, the LS method outperformed the iterative BiGAMP-based approach with only K pilots; however, the corresponding pilot overheads were typically unavailable in practical systems.

Acknowledgements This work was supported by National Key Research and Development Program of China (Grant No. 2018YFB1801103) and National Natural Science Foundation of China (Grant No. 61771133).

Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Wang D M, Zhang Y, Wei H, et al. An overview of transmission theory and techniques of large-scale antenna systems for 5G wireless communications. Sci China Inf Sci, 2016, 59: 081301
2 Risi C, Persson D, Larsson E G. Massive MIMO with 1-bit ADC. 2014. ArXiv:1404.7736
3 Wen C K, Wang C J, Jin S, et al. Bayes-optimal joint channel-and-data estimation for massive MIMO with low-precision ADCs. IEEE Trans Signal Process, 2016, 64: 2541–2556
4 Xiong Y Z, Zhang Z P, Wei N, et al. A bilinear GAMP-based receiver for quantized mmWave massive MIMO using expectation maximization. IEEE Commun Lett, 2019, 23: 84–87
5 Sun P, Wang Z Y, Heath R W, et al. Joint channel-estimation/decoding with frequency-selective channels and few-bit ADCs. IEEE Trans Signal Process, 2018, 67: 899–914
6 Parker J T, Schniter P, Cevher V. Bilinear generalized approximate message passingpart I: derivation. IEEE Trans Signal Process, 2013, 62: 5839–5853
7 Fletcher A K, Rangan S, Goyal V K, et al. Robust predictive quantization: analysis and design via convex optimization. IEEE J Sel Top Signal Process, 2007, 1: 618–632
8 Ma J J, Li P. Data-aided channel estimation in large antenna systems. IEEE Trans Signal Process, 2014, 62: 3111–3124