JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

"A Comprehensive Review of Deep Learning Aided Channel Estimation Techniques for Massive MIMO with 1-Bit ADCs"

Raksha Thakur[1], Dr. Vineeta (Nigam) Saxena[2]
[1]Ph.D Research Scholar, DoECE
[2]Professor, DoECE
University Institute of Technology, RGPV Bhopal, India

Abstract— Massive MIMO is the key technology introduced for the 5G wireless communication system. Massive MIMO system has a high number of antennas which allows the transmitting and receiving of more than one data signal simultaneously over the same radio channel. This technology enables applications such as channel estimation, signal detection, beamforming etc. For channel estimation, number of base station antennas that are able to train channel of the massive MIMO system. The number of pilots symbols received by these antennas is a part of the number of users and the base stations are trained in parallel as they measure signals from various users. Deep learning is efficiently used for these channel training and prediction purposes, fulfilling the evolving requirements of higher data rates and so on.

Keywords—Massive MIMO, Deep Learning, Channel estimation, One bit ADCs

I. INTRODUCTION

Channel estimation is a prevalent challenge in wireless systems, focusing on characterizing the channel attributes of a communication channel. In simpler terms, it describes how signals will travel from the sender to the recipient. Utilizing CSI, transmission can be adjusted based on real-time channel conditions to enhance overall communication quality. CSI plays a vital role in decisions regarding radio resource allocation, modulation, coding schemes, and related parameters. Conventional CSI estimation methods often demand significant computational resources. [1]

Furthermore, these conventional techniques may prove inadequate for the 5G framework, given the intricacies of the new settings and the coexistence of diverse technologies such as orthogonal frequency division multiplexing (OFDM), massive MIMO, and millimeter-wave, which can significantly influence the physical medium conditions [2]. Consequently, a number of researchers have turned to deep-learning models for Channel estimation.

MIMO, which stands for Multiple-Input, Multiple-Output, involves equipping the transmitter and receiver with arrays of antennas. This technology holds significant importance in the realm of 5G, providing substantial improvements in spectral and energy efficiency, far exceeding what LTE technologies can achieve[3].

In much of the research on massive MIMO, the assumption is that optimum hardware implementations with analog-to-digital converters (ADCs) having infinite resolution are in use. Limited prior investigations have explored the effects of inadequate hardware on massive MIMO systems, as seen in references [4]–[6]. These studies have delved into imperfections like additive distortion and phase drift, demonstrating that a substantial number of antennas can help eliminate these issues.

Concerning the hardware aspects of massive MIMO, one of the most critical challenges at the base station (BS) is the power utilization associated with ADCs which grows rapidly with an increase in quantization bits[7], and it also raises with higher sampling rates because of broader bandwidths. For instance, commercial ADCs with an accuracy of about 12 -16 bits took several watts of power [8]. In configurations of massive MIMO with large antenna arrays and numerous ADCs, the power utilization and cost become prohibitive, necessitating exploring more approaches.

Addressing this issue, a potential solution lies in employing low-resolution ADCs based on various reviews. This paper, in particular, concentrates on the use of straightforward one-bit ADCs. These one-bit ADCs are constructed with a basic comparator and consume minimal power, typically just a few milliwatts. Notably, one-bit ADCs do not necessitate "automatic gain control or linear amplifiers", enabling the associated radio frequency (RF) chains to be associated with minimum costs and power utilization, as discussed in references [9] and [10].

Placing multiple antennas within a limited space in a base station necessitates the installation of advanced, compact hardware components. In the case of a Massive Multiple-Input and Multiple-Output (MIMO) system, these advanced components are designed to maintain their intended performance levels despite their smaller form factor compared to larger counterparts.

Massive MIMO extends beyond the mere deployment of a multitude of antennas. This technology leverages artificial intelligence and machine learning to enhance frequency management, signal processing methods, and data transmission. The incorporation of these advanced processing algorithms introduces additional intricacy and cost to the design, implementation, and deployment of the entire system.

Also, various deep neural network (DNN) schemes for 5G Massive MIMO channel estimation are reviewed in [11]

This survey addresses the above requirements efficiently. The main contribution of this work is to survey with a comparative analysis of the existing work on deep learning-based models.

II. Related Literature

In [12], the authors explore the performance of the MIMO uplink scenario employing 1-bit “Analog to Digital converters” (ADCs) for each antenna at the receiver side. By utilizing 1-bit ADCs the need for energy-intensive components like automatic gain control (AGC) gets eliminated, resulting in cost savings both in terms of ADC implementation and operation. The system design accounts for the impact of 1-bit ADCs on channel estimation. The authors provide an in-depth exploration of maximum a posteriori probability (MAP) channel estimation in the context of 1-bit ADCs.

Also, utilize the closed-form expressions which results in a reduction of computational complexity since it eliminates the need for a Monte Carlo simulation while calculating mutual information.

Furthermore, the paper's findings lead to the conclusion that massive MIMO systems offer outstanding SER and mutual information performance across a wide spectrum of system parameters.

In [13], the authors developed channel estimation techniques tailored for millimeter-wave (mm-Wave) MIMO systems equipped with 1-bit “Analog to Digital converters” (ADCs) at the receiver. In the mm-Wave channel, due to its characteristics, such as the presence of fewer propagation paths and the utilization of large antenna arrays at both the transmitter and receiver, the channel exhibits sparsity in the angular domain. Capitalizing on the assumption of perfect sparsity, put it in forth low-complexity channel estimation algorithms.

The main focus here is on the channel estimation problem involving one-bit ADCs and the exclusive use of digital combining at the receiver. The authors introduce a modified expectation-maximization (EM) algorithm that leverages the inherent sparsity of the mmWave channel and outperforms the conventional EM algorithm.

Additionally, by applying an efficient algorithm called generalized approximate message passing (GAMP) to address the channel estimation challenge notably excels in achieving superior performance in the low and medium signal-to-noise ratio (SNR) regions.

The review work in [14] focuses on channel estimation and system performance in the uplink of a single-cell massive multiple-input multiple-output (MIMO) system. In this system, each receive antenna at the base station (BS) is equipped with a pair of one-bit analog-to-digital converters (ADCs) to quantize both the real and imaginary components of the received signal.

Initially, an innovative approach to channel estimation is introduced based on the Bussgang decomposition, which converts non linear to linear functions. The resulting channel estimator surpasses previously proposed methods across all signal-to-noise ratios (SNRs).

Furthermore, derive closed-form expressions for the achievable rate for low SNR and a substantial number of users. These expressions account for channel estimation errors due to both noise and one-bit quantization. Further offers valuable insights into design considerations, such as “optimal resource allocation, maximal sum spectral efficiency, overall energy efficiency, and the optimal number of antennas”.Below is the pictorial representation of the MIMO system receiver enabled with 1-bit ADCs.

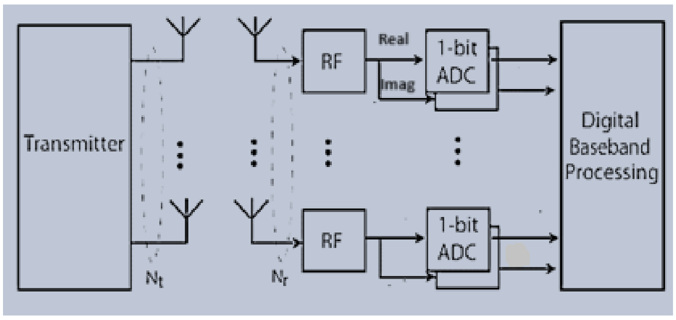

Fig 1. One-bit quantization at the MIMO system receiver

III. DEEP LEARNING-BASED 1-BIT ADC FOR CHANNEL ESTIMATION

The main intention of performing this survey is to choose and categorize the best available deep-learning approaches to signal processing at the receiver end for channel estimation.

Traditional signal processing methodologies have been harnessed to devise low-complexity near-maximum likelihood (ML) data detectors and efficient channel estimation techniques for massive MIMO and millimeter-wave (mmWave) systems. A common challenge these solutions encounter is the requirement for lengthy pilot sequences to achieve robust data detection or channel estimation performance.

On the other hand, machine-learning approaches have been explored to tackle various issues associated with 1-bit "Analog to Digital converters" (ADCs). Few addressed the channel estimation problem in orthogonal frequency-division multiplexing (OFDM) systems, but solely for systems equipped with single antennas. While some deep learning solutions were proposed for channel equalization in MIMO systems, but their effectiveness was limited to low-dimensional MIMO scenarios, as the proposed network failed to converge when applied to a large number of antennas. Here is the list of review work done based on deep learning-enabled massive MIMO with 1-bit ADCs.Below is the block diagram representation for deep learning based MIMO receiver with 1-bit ADCs:

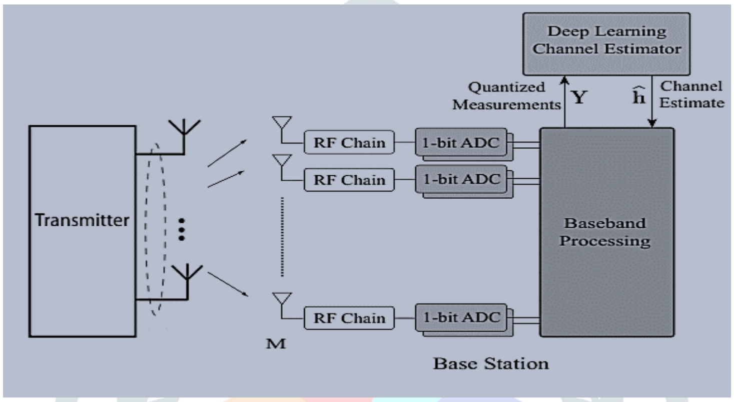

Fig 2. One-bit ADC with deep learning channel estimation

"Deep Learning for Massive MIMO with 1-Bit ADCs: When More Antennas Need Fewer Pilots"[15]

This paper delves into uplink massive MIMO systems equipped with 1-bit "Analog to Digital converters" (ADCs) and introduces a channel estimation framework based on deep learning. This framework requires prior channel estimation measurements and with the help of deep neural networks channel information can be fetched by mapping to the received quantized measurements. To facilitate the above process, the necessary length and structure of the pilot sequence should be determined, ensuring the existence of this mapping function.

Remarkably, the paper's findings challenge intuition by revealing that employing a huge amount of base-station antennas leads to the improved potential of channel estimation with a similar pilot sequence range. Conversely, for equivalent channel estimation behavior, this implies that with many antennas, fewer pilots are needed. This intriguing observation is also substantiated through analytical proofs for specific channel models.

Simulation results validate their observations and establish that the use of more antennas enhances channel estimation in favor of "normalized mean squared error" and the "receive signal-to-noise ratio per antenna".

"One-bit mmWave MIMO Channel Estimation using Deep Generative Networks"[16]

With the evolution of wireless systems for various ranges of frequencies and the integration of large antenna arrays, the exploration of receivers equipped with one-bit "Analog to Digital converters" (ADCs) has gained prominence due to their reduced power consumption. However, the synergy of extensive antenna arrays and one-bit ADCs presents challenges in channel estimation.

This paper tackles the problem of channel estimation from a limited set of one-bit quantized pilot measurements, treating it as an inverse problem. The authors devise a methodology using input vector of a pre-trained "deep generative model", aiming to maximize a channel prediction.

Results demonstrate that above deep generative priors, designed to align with the underlying channel model, yield significant performance improvements compared to the Bernoulli-Gaussian Approximate Message Passing (BG-GAMP) approach. Additionally, they observe Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) channel scenarios, outperform BG-GAMP in LOS channels, and attain relevant performance in NLOS channels, as quantified by the normalized channel reconstruction error.

"Deep Learning for Estimation and Pilot Signal Design in Few-Bit Massive MIMO Systems"[17]

Estimating parameters in MIMO systems with low-bit resolution ADCs presents a notable challenge, as these receivers introduce non-linear distortion in the received signals. This work put forward a deep learning model design to tackle channel estimation, signal detection, and pilot sequencing, aiming to address the non-linearity inherent in such systems.

The proposed signal detection and channel estimation networks are model-driven and feature specialized structures that leverage knowledge related to the few bit process of quantization. First, the channel estimation network and the second data detection network, denoted as Few-Bit massive MIMO Channel Estimation Network (FBM-CENet) and Few-Bit massive MIMO Data Detection Network (FBM-DetNet), respectively, rely on the original quantized modeling. To develop FBM-CENet and FBM-DetNet, reframing of "maximum-likelihood channel estimation" and signal detection problems has been done to overcome the challenge of indeterminate gradients.

An essential characteristic of the proposed "FBM-CENet" structure is the integration of the pilot matrix into the weight matrices of its channel estimator. Consequently, training "FBM-CENet" facilitates a joint optimization of both the channel estimator at the base station and the pilot signal transmitted by users. Finally, simulation results indicate substantial gains to achieve accurate estimation by the proposed deep learning modeling.

"Deep Learning-Based Channel Estimation for Massive MIMO With Mixed-Resolution ADCs"[18]

This work leverages deep learning techniques to predict uplink channels in mixed "Analog to Digital converters" (ADCs) MIMO systems. These systems feature a combination of high-resolution ADCs and low-resolution ADCs at the base station, creating a unique challenge.

Initially, introduces a "direct-input deep neural network" (DI-DNN) that estimates channels by utilizing received signals from all antennas. To mitigate the side effects of roughly quantized signals, authors develop a "selective-input prediction deep neural network" (SIP-DNN). In this approach, only signals received by "high-resolution" ADC antennas are employed to predict the entire channel to estimate their own.

Final numerical results underscore the primacy of the proposed DNN-based approaches over existing methods, particularly in scenarios involving mixed one-bit ADCs. Furthermore, these approaches prove effective across a range of ADC resolution patterns.

"End-to-end approach for MU massive MIMO uplink transmission under 1-bit ADC"[19]

This article has addressed the enhancement of transmission quality in Multi-User Massive MIMO wireless communication systems, considering the non-linearity of 1-bit ADC as a prevalent factor. The primary challenge in this research lies in sustaining both high energy efficiency and robust reliability.

The author's approach begins with the introduction of an end-to-end system design using an autoencoder within a deep neural network (DNN). This design aimed to mitigate the performance degradation induced by 1-bit ADC in the uplink system. Subsequently, proposes a mixed low-resolution ADC architecture, wherein a subset of antennas employed 1-bit ADCs, while others operated without ADCs, leveraging the autoencoder concept. The main goal is to strike an optimal balance between transmission quality and energy efficiency. Simulation results indicate that the end-to-end (E2E) technique outperformed the others, while the mixed ADC architecture combined with the E2E approach demonstrated significant potential, exhibiting performance curves that closely approached those of an ideal system.

IV. CONCLUSIONS

This work presents the comparisons between conventional signal processing methods for channel estimation using one or few-bit ADCs for massive MIMO systems. All work based on Deep neural networks concludes their superiority over existing conventional methods in terms of various parameters i.e "normalized mean squared error" and the "received signal-to-noise ratio per antenna". Further algorithms based on deep learning scenarios can be applied to continuous improvement of channel conditions using various channel models.

REFERENCES

[1] Caire, G.; Jindal, N.; Kobayashi, M.; Ravindran, N. Multiuser MIMO achievable rates with downlink training and channel state feedback. *IEEE Trans. Inf. Theory* 2010, *56*, 2845–2866. [Google Scholar] [CrossRef][Green Version]

[2] Luo, C.; Ji, J.; Wang, Q.; Chen, X.; Li, P. Channel state information prediction for 5G wireless communications: A deep learning approach. *IEEE Trans. Netw. Sci. Eng.* 2018, *7*, 227–236. [Google Scholar] [CrossRef]

[3] Prasad, K.S.V.; Hossain, E.; Bhargava, V.K. Energy efficiency in massive MIMO-based 5G networks: Opportunities and challenges. *IEEE Wirel. Commun.* 2017, *24*, 86–94. [Google Scholar] [CrossRef][Green Version]

[4] E. Bjornson, J. Hoydis, M. Kountouris, and M. Debbah, "Massive ¨ MIMO systems with non-ideal hardware: Energy efficiency, estimation, and capacity limits," IEEE Transactions on Information Theory, vol. 60, no. 11, pp. 7112–7139, Nov 2014.

[5] E. Bjornson, M. Matthaiou, and M. Debbah, "Massive MIMO with non- ̈ ideal arbitrary arrays: Hardware scaling laws and circuit-aware design," IEEE Transactions on Wireless Communications, vol. 14, no. 8, pp. 4353–4368, Aug 2015.

[6] X. Zhang, M. Matthaiou, M. Coldrey, and E. Bjornson, "Impact of ̈ residual transmit RF impairments on training-based MIMO systems," IEEE Transactions on Communications, vol. 63, no. 8, pp. 2899–2911, Aug 2015.

[7] R. Walden, "Analog-to-digital converter survey and analysis," IEEE Journal on Selected Areas in Communications, vol. 17, no. 4, pp. 539– 550, Apr 1999.

[8] "Texas instruments ADC products." [Online]. Available: http://www.ti. com/lsds/ti/data-converters/analog-to-digital-converter-products.page

[9] J. Mo and R. W. Heath Jr., "Capacity analysis of one-bit quantized MIMO systems with transmitter channel state information," IEEE Transactions on Signal Processing, vol. 63, no. 20, pp. 5498–5512, Oct 2015.

[10] J. Singh, S. Ponnuru, and U. Madhow, "Multi-gigabit communication: The ADC bottleneck," in IEEE International Conference on UltraWideband (ICUWB), Sept 2009, pp. 22–27

[11] R. Thakur and V. N. Saxena, "A Survey on Learning-Based Channel Estimation Methods Used for 5G Massive Mimo System," 2023 14th International Conference on Computing Communication and Networking Technologies (ICCCNT), Delhi, India, 2023, pp. 1-5, doi: 10.1109/ICCCNT56998.2023.10308216.

[12] Risi, Chiara & Persson, Daniel & Larsson, Erik. (2014). Massive MIMO with 1-bit ADC.

[13] J. Mo, P. Schniter, N. G. Prelcic and R. W. Heath, "Channel estimation in millimeter wave MIMO systems with one-bit quantization," 2014 48th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, USA, 2014, pp. 957-961, doi: 10.1109/ACSSC.2014.7094595.

[14] Y. Li, C. Tao, G. Seco-Granados, A. Mezghani, A. L. Swindlehurst and L. Liu, "Channel Estimation and Performance Analysis of One-Bit Massive MIMO Systems," in IEEE Transactions on Signal Processing, vol. 65, no. 15, pp. 4075-4089, 1 Aug.1, 2017, doi: 10.1109/TSP.2017.2706179.

[15] Y. Zhang, M. Alrabeiah and A. Alkhateeb, "Deep Learning for Massive MIMO With 1-Bit ADCs: When More Antennas Need Fewer Pilots," in IEEE Wireless Communications Letters, vol. 9, no. 8, pp. 1273-1277, Aug. 2020, doi: 10.1109/LWC.2020.2987893.

[16] A. Doshi and J. G. Andrews, "One-Bit mmWave MIMO Channel Estimation Using Deep Generative Networks," in IEEE Wireless Communications Letters, vol. 12, no. 9, pp. 1593-1597, Sept. 2023, doi: 10.1109/LWC.2023.3283926.

[17] L. V. Nguyen, D. H. N. Nguyen and A. L. Swindlehurst, "Deep Learning for Estimation and Pilot Signal Design in Few-Bit Massive MIMO Systems," in IEEE Transactions on Wireless Communications, vol. 22, no. 1, pp. 379-392, Jan. 2023, doi: 10.1109/TWC.2022.3193885.

[18] S. Gao, P. Dong, Z. Pan and G. Y. Li, "Deep Learning Based Channel Estimation for Massive MIMO With Mixed-Resolution ADCs," in IEEE Communications Letters, vol. 23, no. 11, pp. 1989-1993, Nov. 2019, doi: 10.1109/LCOMM.2019.2936393.

[19] A. Arfaoui, M. Cherif and R. Bouallegue, "End-to-end approach for MU massive MIMO uplink transmission under 1-bit ADC," 2022 International Wireless Communications and Mobile Computing (IWCMC), Dubrovnik, Croatia, 2022, pp. 79-82, doi: 10.1109/IWCMC55113.2022.9824668.