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MACHINE LEARNING FOR DATA DETECTION IN LOW-RESOLUTION QUANTIZATION-BASED SYSTEMS

In the ever-evolving world of wireless communication, the demand for faster, more efficient systems has never been greater. As 5G becomes widespread and the world prepares for 6G, new wireless technologies, such as using many antennas together (massive MIMO) and operating at very high frequencies like millimeter-wave and Terahertz, are becoming increasingly important. These innovations promise unprecedented data rates and connectivity, but they come with a significant challenge: power consumption. At the heart of this issue lies the analog-to-digital converter (ADC), a critical component in wireless base stations that converts the received analog signals into digital signals. High-resolution ADCs, while precise, are power-hungry, consuming energy at levels that threaten the sustainability of next-generation networks.

The Power Problem in Modern Wireless Systems

To understand the scale of the challenge, consider the numbers. Research shows that ADCs account for the lion's share of power dissipation at a base station. Their energy use scales exponentially with resolution (the number of bits used to represent a signal) and linearly with sampling rate (how frequently the signal is measured). In a massive MIMO setup, where hundreds of antennas each rely on dedicated radio frequency (RF) chains equipped with high-resolution ADCs, this translates to a staggering power demand. Add mmWave technology, which requires massive bandwidths and thus higher sampling rates, and the problem intensifies. A single high-speed (≥ 20 GSamples/s), high-resolution (8-12 bits) ADC can consume around 500 milliwatts. Since each RF chain needs two ADCs, with one for the in-phase component and one for the quadrature component, it needs 1 Watt per chain. Scale this up to a system with 256 RF chains, and you're looking at 256 watts just for the ADCs. For context, that's enough to power a small household appliance, and it's simply unsustainable for widespread deployment.

The traditional approach of cranking up resolution and sampling rates to boost performance is hitting a wall. High-resolution quantization, while effective for signal detection, drags down energy efficiency, which is a critical metric as the world pushes toward greener technologies. Therefore, researchers have explored alternatives, such as low-speed sub-ADCs with high resolution, but these often introduce errors due to mismatches between components. Therefore, the more promising path is to use high-speed but low-resolution ADCs (1-3 bits).

Nonlinear MIMO Channel Model

Employing low-resolution ADCs at a receiver disrupts the conventional linear input-output relationship inherent in the traditional MIMO channel model, resulting in a nonlinear MIMO channel model. That means what comes out of the receiver is no longer just a scaled or mixed version of what was transmitted. This shift introduces nonlinearity that fundamentally alters the foundational principles of signal processing methods used for beamforming, channel estimation, and data detection. This is because the conventional signal-processing techniques rely on the assumption that the MIMO channel is linear. Specifically, the traditional physical-layer (PHY) design approach depends on estimating the channel and then using that estimate for data detection. However, in low-resolution quantization-based systems, the nonlinear quantization error drastically undermines the precision of the channel estimate. Consequently, this inaccuracy degrades the effectiveness of the subsequent channel-based data detection process.

Machine Learning for Data Detection

Machine Learning (ML) emerges as a robust solution for estimating the nonlinear input-output relationship of a MIMO system equipped with low-resolution ADCs. To achieve this, machine learning (ML) can be applied within two distinct frameworks: model-based and model-free.

Model-based AI Framework:

A model-based AI framework first assumes a mathematical model for how the quantized received signal behaves, and then uses training data to learn the parameters of that model.

Unlike the traditional approach, where pilot signals are used to estimate the wireless channel, this framework repurposes them to create training data for learning the AI model's parameters. Traditional pilot-assisted channel estimation is replaced with parameter learning, where the model's parameters are trained using training data. Traditional data detection relying on channel information is replaced with a model-driven approach, where data detection is designed and optimized based on the learned model.

Model-free AI Framework:

The model-free AI framework treats a communication system with low-resolution ADCs as a black box, where the input is a data symbol, and the output is a quantized received signal. From this perspective, data detection can be viewed as a classi-

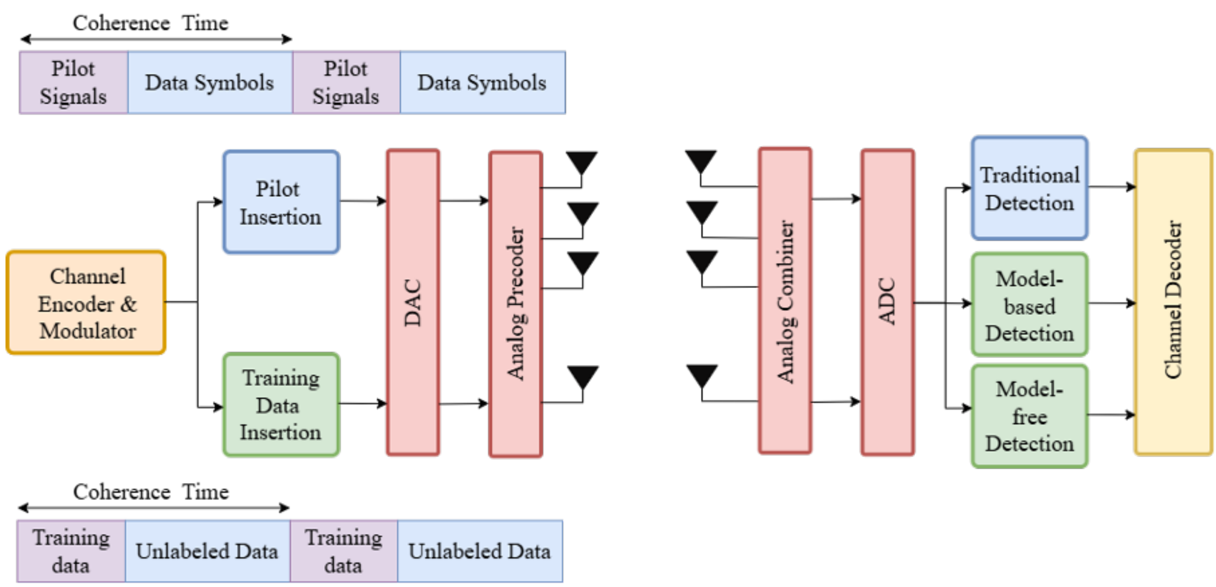

Figure 1: A block diagram of different PHY design frameworks for a MIMO system with low-resolution ADCs. Adopted from [1].

fication task, where the goal is to map the quantized received signal to the most likely data symbol.

In this approach, pilot signals are used to create training data for a classifier instead of estimating the channel. The receiver learns a data-detection classifier from this training data, and then detects symbols by classifying the quantized received signal into the most likely transmitted symbol.

Conclusion

This article provides a high-level review of the benefits and potential of using ML in data detection of MIMO communications with low-resolution ADCs. By highlighting the connections between ML and PHY design, we emphasize two key advantages: reducing model mismatch and enabling model-free communication. Further, ML could also be valuable in addressing other nonlinearities in communication systems beyond low-resolution ADCs.

It is important to recognize the practical trade-offs involved: while low-resolution ADCs offer significant power savings, often scaling exponentially with fewer bits, they do so at the cost of reduced data detection accuracy and lower achievable data rates compared to high-resolution systems. Striking the right balance between power efficiency and performance remains a key design challenge, and ML-based approaches show promise in narrowing this gap by enhancing the performance of low-resolution systems without sacrificing their energy benefits.

References.
[1] Y. S. Jeon, D. Kim, S. N. Hong, N. Lee and R. W. Heath, "Artificial Intelligence for Physical-Layer Design of MIMO Communications with One-Bit ADCs," in IEEE Communications Magazine, vol. 60, no. 7, pp. 76-81, July 2022.
[2] S. Gayan, R. Senanayake, H. Inaltekin and J. Evans, "Low-Resolution Quantization in Phase Modulated Systems: Optimum Detectors and Error Rate Analysis," in IEEE Open Journal of the Communications Society, vol. 1, pp. 1000-1021, 2020.

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