A Study on Performance Enhancement of Variable Bit-Length Massive MIMO CSI Feedback using Softmax-based Curriculum Learning

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Softmax 기반 커리큘럼 러닝을 이용한 가변 비트 길이 Massive MIMO CSI 피드백 성능 향상 연구

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Abstract

In Massive MIMO systems, acquiring accurate Channel State Information (CSI) is essential; however, it entails significant feedback overhead due to the increasing number of antennas and subcarriers. Recently, variable bit-length CSI feedback techniques combining Concrete Feedback Layers and Feedback Bit Masking Unit (FBMU) have been studied. Nevertheless, these methods exhibit performance degradation for long bit lengths—a phenomenon known as the ablation problem—when trained within limited epochs. To address this issue, this paper proposes a Softmax-based Curriculum Learning technique that dynamically adjusts the sampling probability of bit lengths according to training progress. Experimental results demonstrate that the proposed method optimizes training efficiency, significantly improving the Normalized Mean Squared Error (NMSE) performance in long bit-length intervals even under resource-constrained environments.

Ⅰ. Introduction

In wireless communication systems, Channel State Information (CSI) feedback plays a critical role in the effective deployment of Massive MIMO technology. Accurate CSI at the base station is essential to fully exploit the spatial multiplexing gains offered by Massive MIMO. However, as wireless systems continue to evolve and become more complex, the CSI feedback overhead increases significantly due to the growing number of transmit antennas and subcarriers [1].

To address this challenge, numerous CSI feedback schemes have been proposed to reduce feedback overhead. Among them, the variable bit-length CSI feedback method based on Concrete Feedback Layers has demonstrated excellent performance when sufficient training epochs are available. Nevertheless, when the number of training epochs is limited, notable performance degradation occurs for longer bit lengths, which is commonly observed as an ablation performance issue [2].

In this paper, we verify the ablation performance degradation of the Concrete Feedback Layers-based variable bit-length CSI feedback scheme. To address this performance degradation, we propose a Softmax-based curriculum learning approach. By adjusting the Softmax probability distribution during training, the probability of selecting longer bit lengths is increased. Through experimental results, we demonstrate that the ablation performance of variable bit-length CSI feedback models can be improved under limited training epoch conditions.

Ⅱ. Problem Statement

Due to the structural characteristics of the Feedback Bit Masking Unit (FBMU), leading bits always participate in training regardless of the sampling scenario, whereas trailing bits only participate when a long bit length is selected. In conventional uniform random sampling methods, these trailing bits are exposed to training for only a fraction of the total time, leading to the "Trailing-Bit Under-Trained" problem, where the model lacks sufficient opportunities to learn detailed channel phase information.

To verify this ablation performance degradation, tests were conducted at a 256-bit level. The results showed that while the Normalized Mean Squared Error (NMSE) was approximately 0.03 after 2000 epochs of training, it deteriorated to 0.06—a nearly twofold decrease in performance—when limited to 500 epochs. This suggests that conventional methods fail to secure precise reconstruction accuracy for long bit lengths in resource-constrained environments.

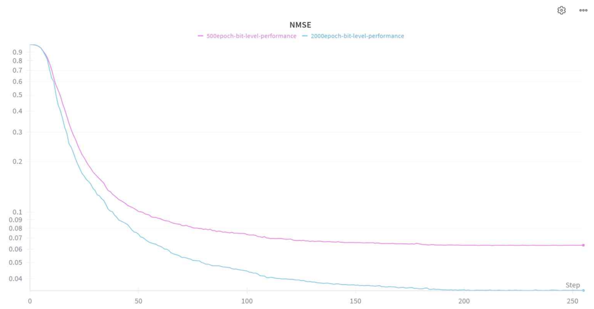

Fig 1. Test NMSE results at the 256-bit level for 2000 training epochs and 500 training epochs.

Ⅲ. Proposed Method

This paper proposes a training strategy that first stabilizes core information and subsequently refines detailed information. In the early stages of training, the model selects shorter bit lengths with high probability to allow the encoder to learn how to compress dominant channel features within a limited bit budget. As training progresses, the proportion of longer bit lengths is gradually increased to refine the model, layering detailed information onto the already learned core features.

To implement this, a probability distribution based on the Softmax function was introduced. The score (Logit) for each bit-length index was designed to be proportional to the product of the training progress and the index number. By utilizing a scheduling intensity parameter, alpha set to 3.0, we ensured that longer bit lengths are selected exponentially more often toward the end of training, thereby maximizing overall training efficiency.

The training progress, or progress, was calculated as 'current_epoch/total_epochs', and the Logit calculation formula is as follows:

$$Logit_i = \alpha \times progress \times i$$

The N_{fb} (number of feedback bits) is sampled for each batch based on the probability distribution obtained by applying the Softmax function to these Logits. This realizes "Curriculum Length Scheduling," which starts with a nearly uniform distribution and shifts toward an exponential preference for longer bit lengths as the training concludes.

Ⅳ. Experimental Results

To verify the performance of the proposed method, we analyzed the NMSE convergence curves in a 256-bit environment. The conventional uniform sampling method recorded an NMSE of approximately 0.063 at 500 epochs, showing a stagnation in performance improvement. In contrast, while the proposed curriculum learning model showed a slightly slower initial convergence, the NMSE began to drop sharply again after the 50% progress mark, driven by the intensive input of long bit-length samples.

Ultimately, the proposed model achieved an NMSE of 0.044 under the same 500-epoch training condition, representing a 30.1% performance improvement over the conventional method. These results demonstrate that curriculum scheduling allows the model to stabilize core information early on and concentrate on improving precision reconstruction in the later stages, significantly boosting training efficiency.

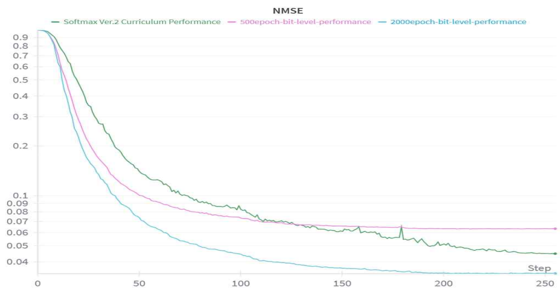

Fig 2. Test NMSE comparison of Softmax-based curriculum learning and conventional training (2000 vs. 500 epochs).

Ⅴ. Conclusion

In this study, we proposed a Softmax-based curriculum learning technique to address the "ablation performance degradation" and the under-training of trailing bits observed in variable-length CSI feedback models combining Concrete Feedback Layers and FBMU.

Experimental results demonstrate that the proposed method effectively overcomes the stagnation of NMSE performance in the later stages of training by dynamically adjusting bit-selection probabilities according to the training progress, achieving an NMSE of 0.044—a 30.1% improvement over the conventional approach within a limited budget of 500 epochs.

Notably, achieving significant performance gains solely through training strategy optimization without structural modifications proves highly practical for enhancing the reliability of a single model in resource-constrained mobile network environments. Future research is expected to further maximize this utility by extending the curriculum learning mechanism to maintain optimal ablation performance across diverse and complex channel conditions.

ACKNOWLEDGMENT

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Reference

[1] C. -K. Wen, W. -T. Shih and S. Jin, "Deep Learning for Massive MIMO CSI Feedback," in IEEE Wireless Communications Letters, vol. 7, no. 5, pp. 748-751, Oct. 2018, doi: 10.1109/LWC.2018.2818160.

[2] D. Jin Ji and B. C. Chung, "Concrete Feedback Layers: Variable-Length, Bit-Level CSI Feedback Optimization for FDD Wireless Communication Systems," in IEEE Transactions on Wireless Communications, vol. 23, no. 10, pp. 15353-15366, Oct. 2024, doi: 10.1109/TWC.2024.3428863.