Channel Model Driven LMMSE Power Control for Over-the-Air Computation

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Abstract

Over-the-air computation (Aircomp) enables direct function aggregation by exploiting the superposition property of wireless multiple-access channels. Most existing approaches rely on full power transmission or channel inversion strategies that are designed from a communication-centric perspective. In this paper, a channel model driven linear minimum mean square error (LMMSE) power control scheme is considered for analog aggregation under per-device power constraints. The wireless channel is treated as an integral component of the computation model rather than a limiting factor. A dimension wise LMMSE formulation is adopted to minimize aggregation distortion while satisfying individual power budgets. Simulation results demonstrate that the proposed approach achieves reduced aggregation error compared to orthogonal transmission with full power and channel-aware aggregation methods, particularly in noise and interference limited regimes. The presented results highlight the effectiveness of classical LMMSE designs when interpreted from a computation oriented perspective.

Index Terms: AirComp, OFDM, Channel Model

I. Introduction

Over-the-air computation enables direct function aggregation by exploiting signal superposition in wireless multiple access channels. In OFDM systems, this approach supports analog aggregation while preserving physical layer compatibility [1], but remains sensitive to noise, inter-carrier interference, and heterogeneous power constraints. Full power and channel aware scaling methods improve robustness in limited cases, yet aggregation accuracy degrades as the number of devices increases, indicating that communication centric optimization is insufficient for reliable aggregation. Recent learning-driven wireless designs emphasize the importance of channel-aware optimization and structured signal representations. Deep learning assisted channel estimation has been shown to enhance robustness in non-orthogonal and massive MIMO systems [4], while emerging representation learning paradigms highlight the role of efficient aggregation in data driven wireless intelligence [2]. In addition, latency aware control mechanisms in B5G/6G systems further motivate computation-oriented signal design [3].

In this work, linear minimum mean-square error (LMMSE) power control under per-device power constraints is revisited for AirComp in OFDM systems. The aggregation task is formulated as an MSE minimization problem, where the wireless channel is treated as part of the computation model rather than a distortion to be eliminated. The objective of this paper is to present the core concept and evaluate its effectiveness through simulation, providing a baseline for future robust and learning aware extensions.

II. System Model

Consider a wireless multiple-access system consisting of K devices and a single fusion center. Each device holds an L-dimensional complex-valued data vector, and the objective is to compute the element-wise sum of all transmitted data vectors at the fusion center. This aggregation task is performed using over-the-air computation, where all devices transmit their signals simultaneously over a shared wireless channel.

Due to the broadcast nature of the wireless medium, signals transmitted by different devices naturally superimpose at the receiver. As a result, the fusion center observes a combined signal that includes contributions from all devices, distorted by wireless channel effects and additive noise. Each device applies a transmit scaling factor to its data prior to transmission in order to control its power usage and compensate for channel variations. The wireless channel between each device and the fusion center is modeled as a linear channel, and the receiver is affected by additive white Gaussian noise.

The received signal at the fusion center can be expressed as

$$\mathbf{y} = \sum_{k=1}^{K} \mathbf{H}_k \mathbf{B}_k \mathbf{x}_k + \mathbf{n},$$

where $\mathbf{H}_k$ represents the channel of the k-th device, $\mathbf{B}_k$ denotes the transmit scaling matrix, and $\mathbf{n}$ is additive noise.

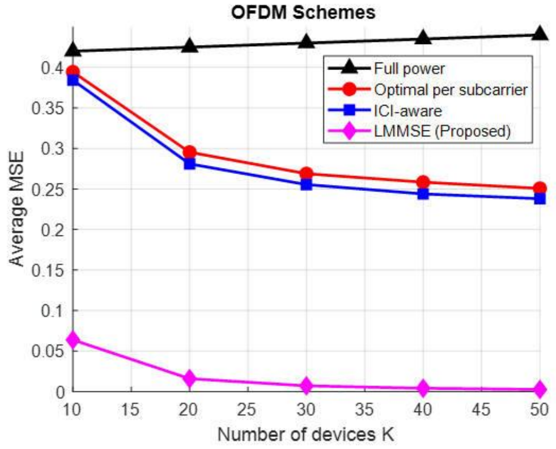

Fig. 1: *Average MSE versus number of devices K for different OFDM-based aggregation schemes.*

Aggregation performance is evaluated using the mean-square error between the estimated result and the desired sum of transmitted data vectors.

A. Channel-Model-Driven LMMSE Aggregation

To reduce aggregation distortion under per-device power constraints, a channel-model-driven LMMSE aggregation approach is adopted. The receiver is designed by explicitly accounting for channel distortion and noise, rather than attempting full channel inversion or relying on full-power transmission.

For fixed transmit scaling matrices, the fusion center applies an LMMSE receive filter that minimizes the aggregation mean-square error while balancing noise suppression and interference mitigation. The resulting receive filter follows the standard LMMSE structure

$$\mathbf{V} = \left(\sum_{k=1}^{K} \mathbf{H}_k \mathbf{B}_k \mathbf{B}_k^H \mathbf{H}_k^H + \sigma^2 \mathbf{I} \right)^{-1} \sum_{k=1}^{K} \mathbf{H}_k \mathbf{B}_k.$$

A dimension-wise formulation is used to reduce complexity, allowing devices with weaker channels or tighter power budgets to contribute less to the aggregated signal. This design avoids excessive noise amplification and introduces an implicit regularization effect on the aggregation process.

III. Results

Simulation results show that the proposed CMD-LMMSE scheme consistently achieves lower aggregation mean-square error compared to orthogonal full-power, channel-aware, and interference-aware aggregation methods. As illustrated in Fig.1, conventional schemes exhibit performance saturation as the number of devices increases due to noise accumulation and reduced superposition efficiency, whereas CMD-LMMSE maintains improved accuracy by jointly accounting for channel distortion and noise. Fig.2 further indicates that although all schemes degrade at low SNR because of noise dominance, CMD-LMMSE achieves more pronounced gains at moderate and high SNR levels by effectively balancing noise suppression and

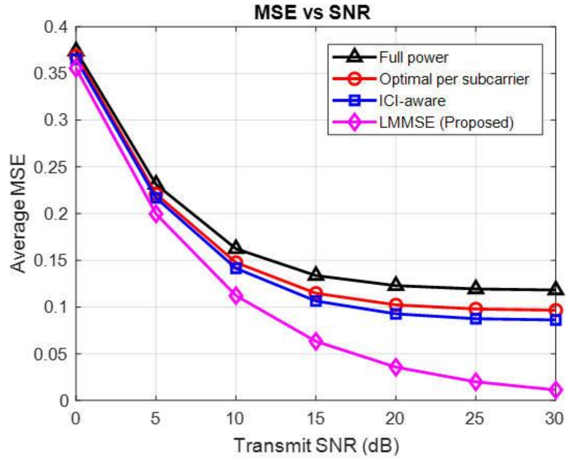

Fig. 2: *Average MSE versus transmit SNR for different OFDM-based aggregation schemes.*

interference mitigation. These results confirm the robustness of the proposed approach under both dense device deployment and varying channel conditions.

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