Sparse Subcarrier Activation in OFDM-IM for Low-Error Over-the-Air Computation

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Abstract

To address the challenges of low-latency and energy-efficient data aggregation in dense IoT networks, this paper proposes a novel Over-the-Air Computation (AirComp) framework based on Orthogonal Frequency Division Multiplexing with Index Modulation (OFDM-IM). By activating only a sparse subset of subcarriers per transmission, OFDM-IM reduces interference, lowers energy consumption, and improves spectral efficiency compared to conventional OFDM-based AirComp systems. The selective subcarrier activation enables compact and robust aggregation of distributed data directly over the wireless channel. A detailed system model is presented, incorporating index selection, channel effects, and receiver-side equalization under frequency-selective fading. Simulation results show that the proposed OFDM-IM AirComp scheme achieves consistently lower mean squared error (MSE) than conventional OFDM, particularly in low-SNR regimes and with increasing numbers of transmitting devices, confirming its effectiveness for reliable and scalable edge intelligence.

Index Terms: OTA, AirComp, IM, OFDM, MSE, 6G

Ⅰ. Introduction

The proliferation of Internet of Things (IoT) networks has led to an urgent need for low-latency, energy-efficient data aggregation. Over-the-Air Computation (AirComp) addresses this by exploiting the superposition property of wireless channels to compute functions (e.g., sums or averages) directly during transmission, thereby minimizing communication overhead and delay.

Conventional AirComp systems commonly use Orthogonal Frequency Division Multiplexing (OFDM) due to its robustness to multipath fading. However, full-band transmission by all devices leads to unnecessary energy consumption and increased interference. To overcome this, we explore OFDM with Index Modulation (OFDM-IM), which activates only a subset of subcarriers to embed information, thereby reducing the number of simultaneous transmissions and improving spectral efficiency.

Prior works have explored energy-efficient modulation [1], deep learning-based parameter selection [2], and non-orthogonal index modulation frameworks [3], but OFDM-IM has not been fully exploited for function aggregation in dense AirComp scenarios.

In this paper, we propose and evaluate an OFDM-IM-based AirComp system under frequency-selective fading. Simulation results show improved accuracy over traditional OFDM, particularly in low-SNR and high-user-density conditions.

II. System Model

We consider a wireless uplink scenario with K devices transmitting data simultaneously to a common fusion center (FC) over a shared frequency-selective channel. Each device employs **OFDM-IM** to encode its data sparsely across L subcarriers, where only P≪L subcarriers are activated per transmission.

$$b_{\gamma} = \left\lfloor \log_2 \binom{L}{P} \right\rfloor + P\log_2(Q)$$

Where Q is modulation order.

A. Transmitted Signal

Let $x_k \in \mathbb{C}^L$ denote the frequency-domain vector transmitted by the k-th device. The vector is sparse, containing nonzero values only on a set $\mathcal{P}_k \subset \{1,2,\dots,L\}$ of P active subcarriers. The time-domain signal is obtained via IFFT and each OFDM-IM symbol is prepended with a cyclic prefix (CP) of length N_{cp} to eliminate inter-symbol interference caused by channel delay spread.

B. Channel Model

We assume a frequency-selective multipath channel for each user with impulse response $h_k = [h_k[0], h_k[1], \dots, h_k[L-1]]$. The received time-domain signal at the FC is the superposition of circular convolutions of each user's transmitted signal with its respective channel:

$$y = \sum_{k=1}^{K} s_k \circledast h_k + w$$

where $\circledast$ denotes circular convolution and $w \sim \mathcal{CN}(0, \sigma^2 I)$ is additive white Gaussian noise.

After CP removal and FFT, the received frequency-domain signal becomes:

$$Y = \sum_{k=1}^{K} H_k \odot x_k + W$$

where $H_k = \mathrm{FFT}(h_k)$, $\odot$ is element-wise multiplication, and W is the frequency-domain noise vector.

C. AirComp Objective

The fusion center aims to compute the sum:

$$\hat{X} = \sum_{k=1}^{K} x_k$$

from the received signal Y, using per-subcarrier equalization:

$$\hat{X} = \frac{Y}{\sum_{k=1}^{K} H_k}$$

This assumes perfect channel state information (CSI) at the receiver and that all active subcarriers are known.

D. MSE Calculation

The aggregation error is measured using the average MSE between the estimated sum $\hat{X}$ and the ideal sum $\sum_{k=1}^{K} x_k$, computed over the active subcarriers $\mathcal{P} \subseteq \{1,2,\ldots,L\}$. The MSE is defined as:

$$\mathrm{MSE} = \frac{1}{|\mathcal{P}|} \sum_{l \in \mathcal{P}} E\left[\left|\hat{X}[l] - \sum_{k=1}^{K} x_k[l]\right|^2\right]$$

III. Results

We evaluate the performance of the proposed OFDM-IM-based AirComp scheme compared to conventional OFDM under frequency-selective Rayleigh fading with AWGN. Unless stated otherwise, we use L=64 subcarriers, P=8 active subcarriers for OFDM-IM, and a cyclic prefix of length $N_{\mathrm{cp}} = 8$. Each user's channel is modeled as a length-h=16 complex Gaussian impulse response. The receiver is assumed to have perfect channel state information.

Figure 1 shows that OFDM-IM achieves lower MSE than OFDM across all SNR values. The gain is more prominent at low SNRs due to reduced interference from sparse subcarrier activation. In figure, we can see that as the number of devices increases, OFDM-IM exhibits a steeper MSE reduction compared to OFDM, highlighting its scalability and aggregation efficiency. The results demonstrate that OCDM consistently achieves a lower MSE compared to OFDM, owing to its chirp-based modulation's resilience to interference and channel imperfections. The MSE for OFDM grows more steeply with the number of devices, highlighting its sensitivity to increasing system load.

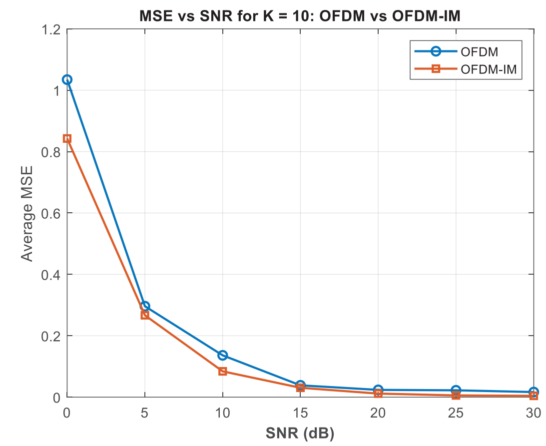

Figure 1: Average MSE for OFDM and OFDM-IM versus SNR

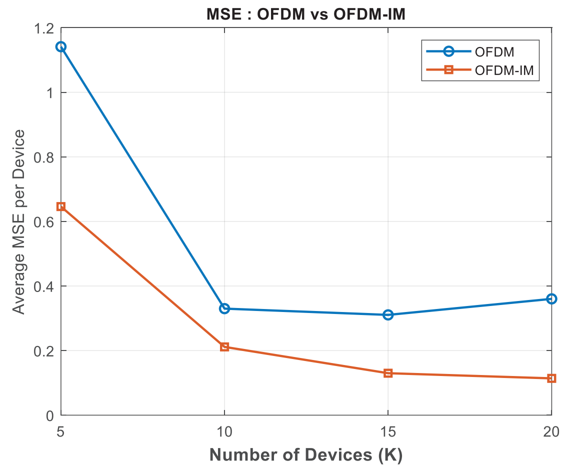

Figure 2: Average MSE for OFDM and OFDM-IM versus number of devices

Acknowledgment

This research was supported by the MSIT (Ministry of Science and ICT), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2025-RS-2024-00437190) supervised by the IITP (Institute for Information & Communications Technology Planning & Evaluation, 50%). This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2025-00553810, 50%).

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