

# Digital Over-the-Air Computation with Space-Time Processing for 6G Massive IoT Networks

Saebom Kim, Young-Seok Lee<sup>†</sup>, and Bang Chul Jung<sup>†</sup>

Department of Electronics Engineering, Chungnam National University, Daejeon, South Korea

<sup>†</sup>Department of Electrical and Computer Engineering, Ajou University, Suwon, South Korea

Email: newspring1015@o.cnu.ac.kr, {youngseoklee; bcjung}@ajou.ac.kr

**Abstract**—In this paper, we propose a novel digital over-the-air computation (AirComp) framework employing space-time line codes (STLC) to achieve optimal spatial diversity gain with only local channel state information (CSI) at transmitters in uplink scenarios. The proposed technique alleviates the overhead of conventional AirComp, where the access point (AP) must acquire global CSI from all sensors, and is tailored to compute target functions under peak power constraints. Each sensor uniformly quantizes its measurement, applies bit slicing with low-order modulation, and transmits STLC-encoded symbols over two time slots. The AP subsequently performs linear combining of the received signals to detect the superimposed symbols and reconstruct the target sum. Simulation results demonstrate that the proposed technique achieves lower normalized mean-squared error than conventional analog and digital AirComp approaches.

**Index Terms**—6G, Internet-of-Things (IoT), over-the-air computation (AirComp), space-time line codes (STLC).

## I. INTRODUCTION

In next-generation(6G) Internet-of-Things (IoT) sensor networks, low latency and high efficiency are essential for handling massive sensing data traffic [1]. Over-the-air computation (AirComp) exploits the superposition property of wireless channels, allowing multiple sensors to transmit analog-modulated signals simultaneously so that the receiver directly computes the desired function [2]. In [3], a uniform-forcing transceiver was proposed to compensate for channel fading, and [4] introduced an analog AirComp scheme with space-time line codes (STLC) to overcome power inefficiency and performance limitations. More recently, [5] proposed a digital AirComp framework to mitigate noise vulnerability by exploiting the superposition of digitally modulated, bit-mapped symbols. However, existing digital AirComp schemes assume ideal channel inversion and overlook practical constraints such as peak power limitations at sensors.

Therefore, in this paper, we propose a novel STLC-based digital AirComp framework tailored for practical IoT networks. By incorporating the peak power constraints of IoT sensors, the proposed framework applies bit slicing for low-order digital modulation and leverages STLC to enhance power efficiency with optimal spatial diversity gain. Since STLC encoding can be applied when only transmitters possess channel state information (CSI), it significantly reduces the overhead compared to conventional AirComp, where the access point (AP) must estimate the global CSI of all sensors. Simulation results demonstrate that the proposed scheme consistently outperforms conventional analog and digital AirComp in terms of normalized mean-squared error (NMSE).

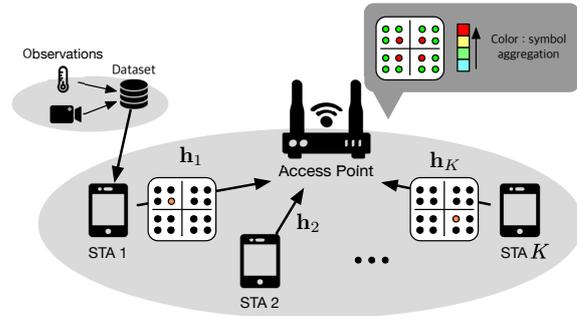


Fig. 1. System model of the proposed STLC-based digital AirComp.

## II. SYSTEM MODEL

In this paper, we consider a wireless environment consisting of  $K$  IoT sensors (STAs: stations), each equipped with a single antenna, and a single AP with two receive antennas, as illustrated in Fig. 1. In addition,  $\mathbf{h}_k (\in \mathbb{C}^2)$  denotes the wireless channel vector between the AP and  $k (\in \{1, \dots, K\})$ -th STA, which is assumed to follow a Rayleigh fading model, i.e.,  $\mathbf{h}_k \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_2)$ . Each STA is assumed to estimate its local CSI from pilot signals broadcast by the AP, while the AP is assumed to know only the minimum channel gain [4].

Each STA then quantizes its observation, applies digital modulation, and transmits the signal simultaneously to the AP over the same wireless resource. Furthermore, considering the peak power constraint of the STAs, bit slicing is introduced to enable the use of low-order digital modulation. Specifically, the  $k$ -th STA uniformly quantizes its analog measurement into  $B$  bits and performs bit slicing to generate a bit sequence  $\mathbf{b} = [b_1, b_2, \dots, b_L]$  for transmission where  $\sum_{l=1}^L b_l = B$ . Two consecutive samples within the same slice are mapped onto the in-phase (I) and quadrature (Q) axes of a quadrature amplitude modulation (QAM) symbol. For example, when  $L = 2$  with  $b_1 = 2$  and  $b_2 = 1$ , a 2-bit symbol is mapped onto the I-axis and a 1-bit symbol onto the Q-axis. The combination of these axes yields a complex symbol corresponding to an 8-ary QAM constellation, where the resultant modulation order is assumed to be limited by the peak power constraint of the STA. The detailed procedures for quantization, bit slicing, and bit mapping can be found in [5], while the network is assumed to target the computation of the sum of the sensing data transmitted by all STAs.

## III. PROPOSED STLC-BASED DIGITAL AIRCOMP

In this paper, without loss of generality, we focus on the case of  $L = 4$ . In this case, the  $k$ -th STA transmits the QAM

symbol  $x_{k,1}$  corresponding to  $b_1$  and  $b_2$ , and the symbol  $x_{k,2}$  corresponding to  $b_3$  and  $b_4$  to the AP.

In the STLC-based digital AirComp framework, each STA transmits STLC-encoded signals over two time slots within the coherence time, considering the peak power constraint of the STAs and the requirement for channel inversion in AirComp, as follows.

$$s_{k,1} = \sqrt{\eta} \frac{h_{k,1}^* x_{k,1} + h_{k,2}^* x_{k,2}}{|h_{k,1}|^2 + |h_{k,2}|^2}, s_{k,2} = \sqrt{\eta} \frac{h_{k,2}^* x_{k,1} - h_{k,1}^* x_{k,2}}{|h_{k,1}|^2 + |h_{k,2}|^2}, \quad (1)$$

where  $s_{k,t}$  denotes the STLC symbol transmitted by the  $k$ -th STA in the  $t \in \{1, 2\}$ -th time slot, and  $h_{k,j}$  represents the wireless channel between the  $k$ -th STA and the  $j \in \{1, 2\}$ -th antenna of the AP. Meanwhile,  $\eta$  is defined as a power control factor to satisfy the peak power constraint of the STAs, ensuring that the transmit power of each STA does not exceed  $P_0$ , as follows

$$\eta = \frac{P_0}{2} \min_k (|h_{k,1}|^2 + |h_{k,2}|^2). \quad (2)$$

Then, all STAs simultaneously transmit STLC symbols to the AP over the same frequency during two time slots. The received signals at each antenna of the AP over the two slots are given by

$$\begin{bmatrix} r_{1,1} & r_{1,2} \\ r_{2,1} & r_{2,2} \end{bmatrix} = \sum_{k=1}^K \mathbf{h}_k [s_{k,1} \ s_{k,2}] + \begin{bmatrix} w_{1,1} & w_{1,2} \\ w_{2,1} & w_{2,2} \end{bmatrix}, \quad (3)$$

where  $r_{j,t}$  and  $w_{j,t}$  denote the received signal and the additive noise at the  $j$ -th antenna in the  $t$ -th time slot, respectively. And, it is assumed that all noise components follow the  $\mathcal{CN}(0, \sigma_n^2)$  distribution. The AP calculates signals  $y_1$  and  $y_2$  by performing the linear combination from the four received signals in (3) as follows

$$y_1 = \frac{1}{\sqrt{\eta}} (r_{1,1} + r_{2,2}^*) = \sum_{k=1}^K x_{k,1} + \frac{w_{1,1} + w_{2,2}^*}{\sqrt{\eta}}, \quad (4)$$

$$y_2 = \frac{1}{\sqrt{\eta}} (r_{2,1}^* - r_{1,2}) = \sum_{k=1}^K x_{k,2} + \frac{w_{2,1}^* - w_{1,2}}{\sqrt{\eta}}. \quad (5)$$

Due to the property of the bit-symbol mapping structure in [5], the superimposed symbols in the constellation inherently represent the same logical sum of bits, regardless of the individual bits transmitted by each STA. Exploiting this property, the AP applies the maximum a posteriori (MAP) detection rule to identify the actual superimposed symbols. The detected symbols are then used to reconstruct the sliced bits, which are subsequently dequantized to compute the desired sum function required by the network.

#### IV. SIMULATION RESULTS

Fig. 2 shows the NMSE performance of the proposed STLC-based digital AirComp as a function of the number of STAs. The proposed technique is compared against conventional antenna selection (AS)-based analog AirComp with a uniform-forcing structure, (AS-based) digital AirComp, and STLC-based analog AirComp. In the simulations, the signal-to-noise ratio (SNR),  $P_0/\sigma_n^2$ , is fixed at 10 dB. For sensing data

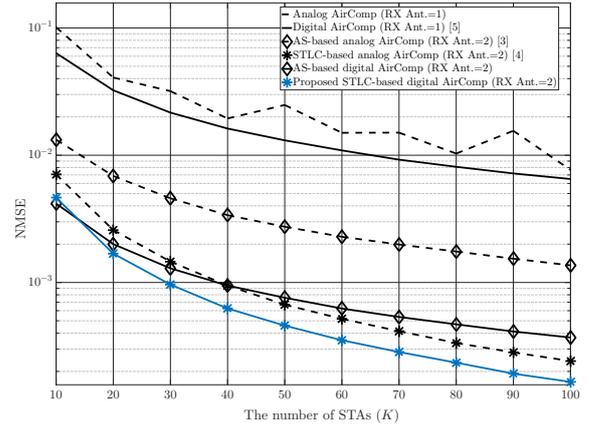


Fig. 2. NMSE performance versus the number of STAs for the proposed STLC-based digital AirComp. NMSE is defined as  $\mathbb{E}[\|\hat{f} - f\|^2] / \mathbb{E}[\|f\|^2]$ , measuring the normalized function reconstruction error.

following a Gaussian distribution with zero mean and unit variance, the digital AirComp scheme quantizes the data into 4-bit values and further slices them into 1-bit streams for transmission, while for fair comparison, the analog AirComp scheme employs  $L = 4$  repetitions. The results demonstrate that the proposed method achieves lower NMSE performance than conventional analog and digital AirComp schemes.

#### V. CONCLUSION

In this paper, we have proposed a space-time line code (STLC)-based digital over-the-air computation (AirComp) framework to enable efficient function computation in massive Internet-of-Things (IoT) sensor networks. The proposed technique employs a channel inversion structure that takes into account the peak power limitation of IoT sensors and the fading characteristics of practical wireless channels, thereby achieving superior performance compared to conventional AirComp methods through spatial diversity gain.

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#### REFERENCES

- [1] A. Perez-Neira *et al.*, "Waveforms for computing over the air: A groundbreaking approach that redefines data aggregation," *IEEE Signal Process. Mag.*, vol. 42, no. 2, pp. 57–70, Mar. 2025.
- [2] S.-W. Jeon and B. C. Jung, "Opportunistic function computation for wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 6, pp. 4045–4059, Jun. 2016.
- [3] L. Chen, X. Qin, and G. Wei, "A uniform-forcing transceiver design for over-the-air function computation," *IEEE Wireless Commun. Lett.*, vol. 7, no. 6, pp. 942–945, Dec. 2018.
- [4] Y.-S. Lee, K.-H. Lee, and B. C. Jung, "Space-time coded over-the-air computation with receive diversity for 6G massive IoT networks," *IEEE Wireless Commun. Lett.*, Oct. 2025 (Early access).
- [5] J. Liu, Y. Gong, and K. Huang, "Digital over-the-air computation: Achieving high reliability via bit-slicing," *IEEE Trans. Wireless Commun.*, vol. 24, no. 5, pp. 4101–4113, May 2025.