Computing ML and Other Functions Over-the-Air Using Digital Modulations

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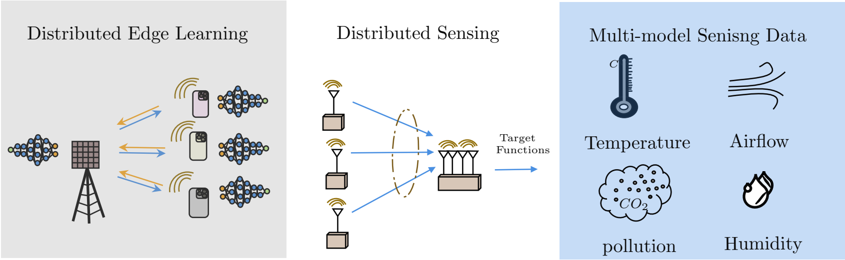
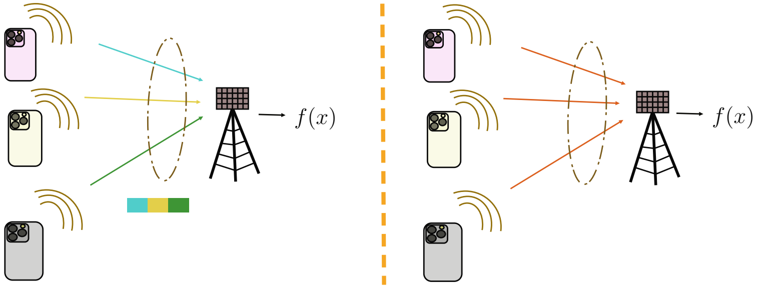
Machine Learning in Wireless IoT



- Distributed ML can be used to support several wireless IoT applications which need to perform data aggregation from multiple data sources [1].
- Current communication protocols are highly inefficient for such aggregation.

[1] G. Zhu *et al.*, "Over-the-air computing for wireless data aggregation in massive IoT," *IEEE Wireless Commun.*, 2021

Over-the-Air Computation - AirComp



- The idea: computation over-the-air in the wireless medium.
- Integrate communication and computation.
- Bandwidth is shared among all users in the time, frequency, and code domain.
- Transmission relies on analog communication.

Literature Review and Challenges

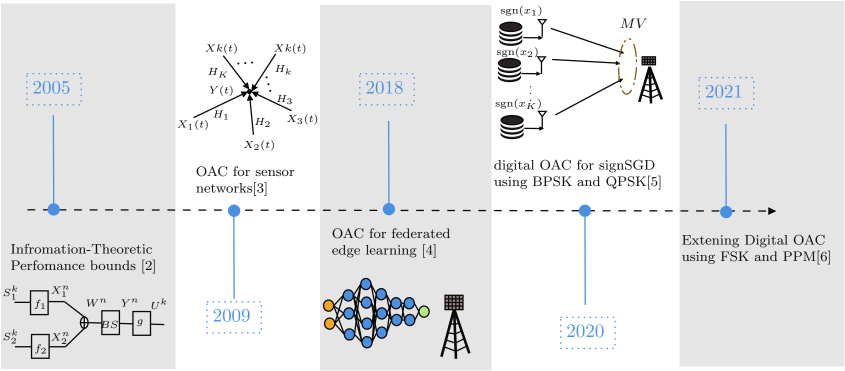
System Model and Problem Formulation

The ChannelComp Solution Method

Simulation Results

Conclusion

History of AirComp



[2] B. Nazer *et al.*, "Reliable computation over multiple-access channels," in *Allerton Conf. on Commun., Control, and Computing*, 2005

[3] M. Goldenbaum *et al.*, "On function computation via wireless sensor multiple-access channels," in *IEEE Wire. Commun. and Net. Conf.*, 2009

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[6] A. Şahin *et al.*, "Distributed learning over a wireless network with FSK-based majority vote," in *IEEE CommNet*, 2021

Research Gap in AirComp

Methods / Subjects	Analog Modulation		Digital Modulation			
Papers	[1], [3], [4]	[7]	[5]	[6], [8]	[9]	Ours
Spectral Efficiency	✓	✗	✓	✗	✓	✓
Low Latency	✓	✗	✓	✗	✓	✓
BPSK and QPSK	✗	✗	✓	✗	✓	✓
QAM $16, 32, \ldots$	✗	✗	✗	✗	✗	✓
Analog Modulation	✓	✓	✗	✗	✗	✓
Sign Function	✗	✗	✓	✓	✓	✓
Nomographic Functions	✓	✓	✗	✗	✗	✓
General Functions	✗	✗	✗	✗	✗	✓
Ubiquitous implementation	✗	✗	✓	✓	✓	✓

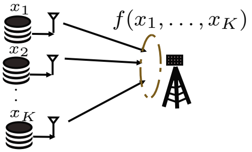
✓: Performance is very good!   ✗: It is not studied at all.

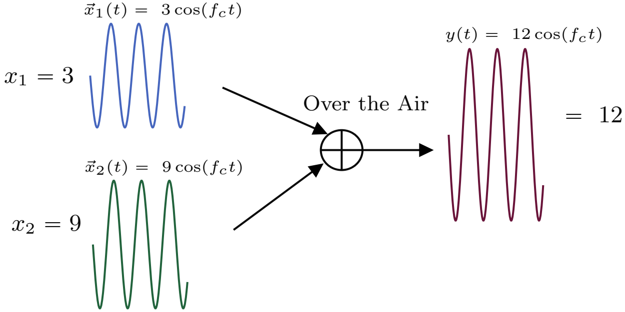
[7] M. Goldenbaum *et al.*, "Robust analog function computation via wireless multiple-access channels," *IEEE Trans. on Commun.*, 2013

[8] A. Şahin, "A demonstration of over-the-air computation for federated edge learning," in *IEEE Globecom Workshops*, 2022

[9] A. Şahin *et al.*, "Over-the-air computation over balanced numerals," in *IEEE Globecom Workshops*, 2022

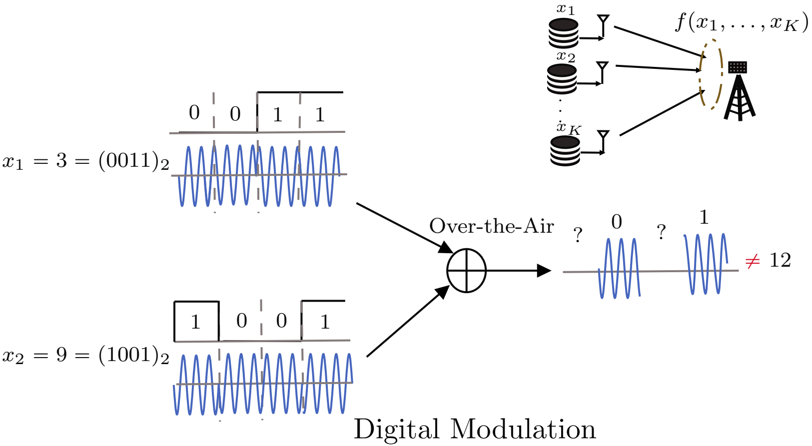
AirComp uses Analog Amplitude Modulations





The state-of-the-art is based on Amplitude Modulation

No AirComp with Digital Modulations



- Currently, Digital AirComp is thought to be impossible because the overlapping of digital waveforms returns incomprehensible signals.

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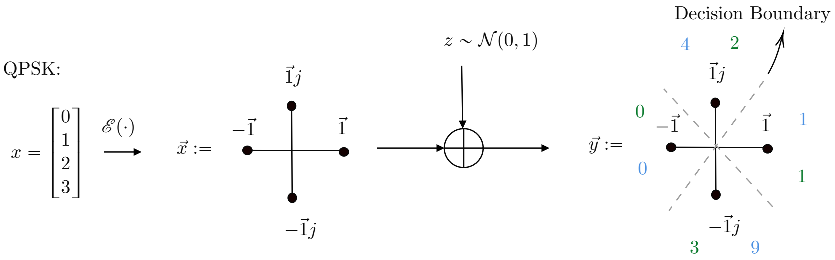
Standard Digital Communication



Identity function $\mathcal{T}_1\{\vec{y}\} = f_1(x) = x$

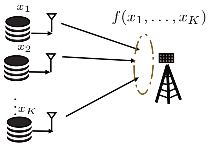
Quadratic function $\mathcal{T}_2\{\vec{y}\} = f_2(x) = x^2$

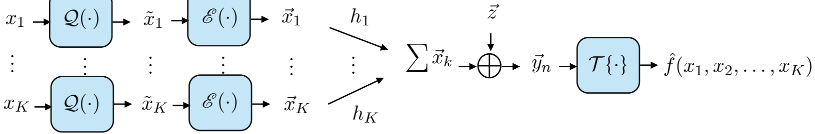
- $\mathscr{E}(\cdot)$ encodes the real input data $x \in \mathbb{R}$ to complex domain with $\vec{x} \in \mathbb{C}$.
- Tabular $\mathcal{T}(\cdot)$ simply maps the complex value $\vec{y}$ to the desired function, which can be the identity function for the standard communication.

Our Goal

- Create Over-the-Air computing methods that are inherently built for digital communications.
- To meet this goal, we need to look at the primary idea of standard digital communication.
- The proposed method should be able to perform general function computation.

System Model and Problem Formulation

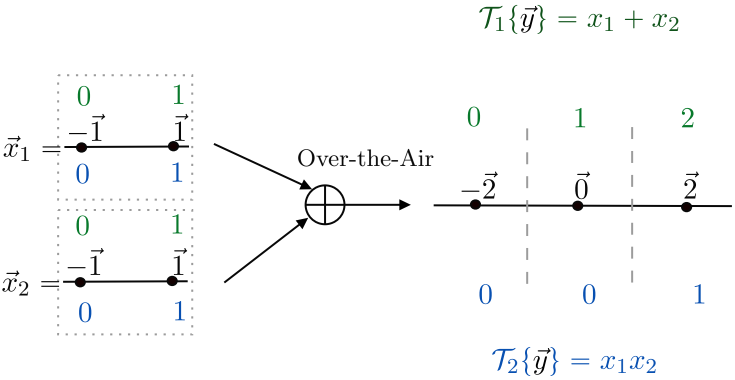




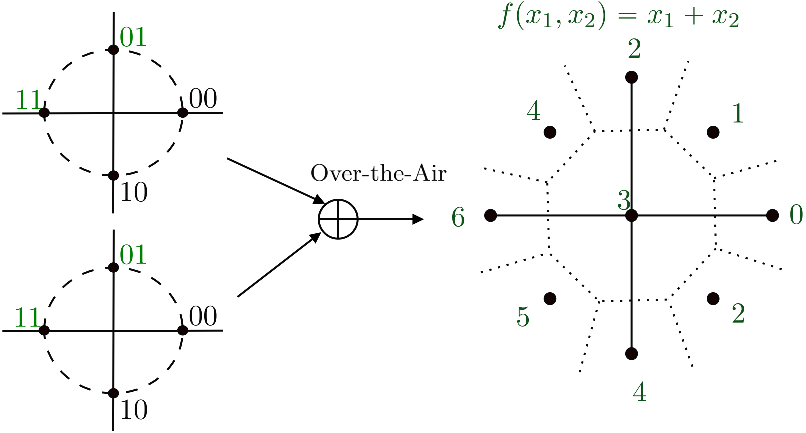
Goal: Finding the encoder $\mathscr{E}(\cdot)$ and the mapping $\mathcal{T}\{\cdot\}$ to do the computation for a given quantisation $\mathcal{Q}(\cdot)$.

$$\mathcal{T}^*, \mathscr{E}(\cdot)^* = \underset{\mathscr{E}}{\operatorname{argmin}} \sum_{x_1,\ldots,x_K \in \mathcal{D}_f} \left| f(x_1, \ldots, x_K) - \underbrace{\mathcal{T}\{\vec{y}_n\}}_{\hat{f}} \right|^2$$

Example: BPSK Modulation

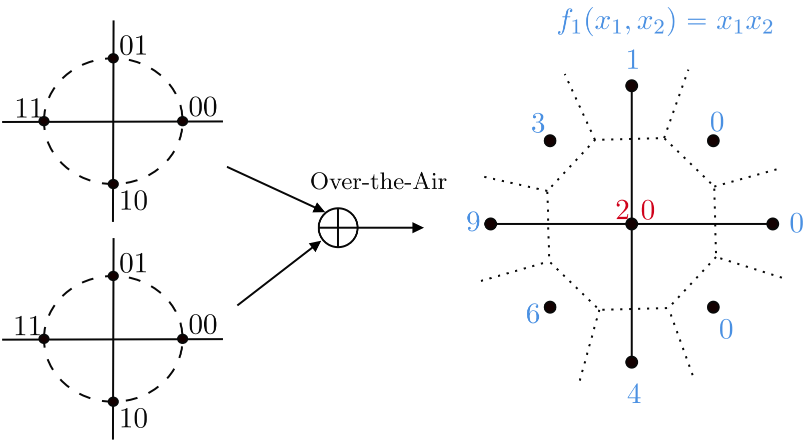


Example: QPSK Modulation (1/2)



By assigning specific values to the reshaped constellation points, QPSK modulation enables the computation of the summation function.

Computing using QPSK Modulation (2/2)



The overlaps of the reshaped constellation points of QPSK modulation do not allow us to compute the product function.

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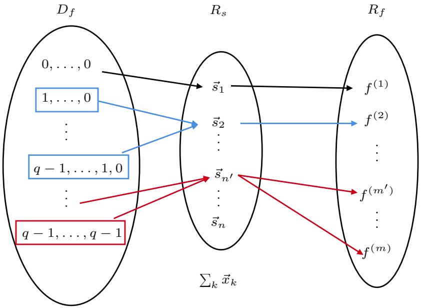
Solution Method



We pose the following feasibility optimization

$$
\begin{aligned}
\mathcal{P}_1 = \text{find} \quad & \boldsymbol{x} \\
\text{s.t.} \quad & f^{(i)} \neq f^{(j)} \Rightarrow \vec{s}_i \neq \vec{s}_j, \ \forall (i,j) \in [M]^2, && \text{(1a)} \\
& \|\boldsymbol{x}\|_2^2 = P. && \text{(1b)}
\end{aligned}
$$

To remove non-smoothness in (1a),

$$\mathcal{P}_2 = \text{find} \quad \boldsymbol{x},$$
$$\text{s.t.} \quad \left\| \boldsymbol{a}_i^\mathsf{T} \boldsymbol{x} - \boldsymbol{a}_j^\mathsf{T} \boldsymbol{x} \right\|^2 \geqslant \gamma |f^{(i)} - f^{(j)}|^2, \tag{2a}$$
$$\|\boldsymbol{x}\|_2^2 = P, \tag{2b}$$

where $\boldsymbol{a}_i$ is a vector whose elements are determined such that $\boldsymbol{a}_i^\mathsf{T} \boldsymbol{x} = \vec{s}_i$ gives the constellation point corresponding to $f^{(i)}$.

- Problem $\mathcal{P}_2$ is a quadratically constrained quadratic programming (QCQP)[10].
- Unfortunately, Problem $\mathcal{P}_2$ is an *NP-hard* problem[11].

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[10] J. Park *et al.*, "General heuristics for nonconvex quadratically constrained quadratic programming," *arXiv preprint arXiv:1703.07870*, 2017

[11] N. D. Sidiropoulos *et al.*, "Transmit beamforming for physical-layer multicasting," *IEEE Trans. Sig. Proc.*, 2006

Solving QCQP Optimization $\mathcal{P}_2$ (1/2)

We can use the *lifting trick* $\boldsymbol{X} := \boldsymbol{x}\boldsymbol{x}^\mathsf{T}$ and equivalently recast the optimization to the following formulation

$$\begin{aligned}
\mathcal{P}_2 = \text{find} \quad & \boldsymbol{X}, \\
\text{s.t.} \quad & \langle \boldsymbol{X}, \boldsymbol{B}_{i,j} \rangle \geqslant \gamma_{i,j}, \ \operatorname{trace}(\boldsymbol{X}) = P, && \text{(3a)} \\
& \boldsymbol{X} \succeq \mathbf{0}, \quad \operatorname{rank}(\boldsymbol{X}) = 1, && \text{(3b)}
\end{aligned}$$

where

$$\boldsymbol{B}_{i,j} = (\boldsymbol{a}_i - \boldsymbol{a}_j)(\boldsymbol{a}_i - \boldsymbol{a}_j)^\mathsf{T}, \quad \gamma_{i,j} = \gamma |f^{(i)} - f^{(j)}|^2.$$

Solving QCQP Optimization $\mathcal{P}_2$ (2/2)

By dropping the rank constraint in (3b),

$$\begin{aligned} \mathcal{P}_3 = \text{find} \quad & \boldsymbol{X}, \\ \text{s.t.} \quad & \langle \boldsymbol{X}, \boldsymbol{B}_{i,j} \rangle \geqslant \gamma_{i,j}, && \text{(4a)} \\ & \boldsymbol{X} \succeq \boldsymbol{0}, \quad \text{trace}(\boldsymbol{X}) = P. && \text{(4b)} \end{aligned}$$

- Problem $\mathcal{P}_3$ is an SDP problem, and it can be efficiently solved[12].
- Using Cholesky decomposition, we have $\hat{\boldsymbol{X}} = \hat{\boldsymbol{x}}\hat{\boldsymbol{x}}^{\mathsf{H}}$ where $\hat{\boldsymbol{X}}$ and $\hat{\boldsymbol{x}}$ are the solutions to Problem $\mathcal{P}_3$ and Problem $\mathcal{P}_2$, respectively.
- Another sub-optimal solution to Problem $\mathcal{P}_2$ is to use the Gaussian randomization method [13].

[12] M. Grant *et al.*, *CVX: MATLAB software for disciplined convex programming*, 2014

[13] Z.-Q. Luo *et al.*, "Semidefinite relaxation of quadratic optimization problems," *IEEE Sig. Proc. Mag.*, 2010

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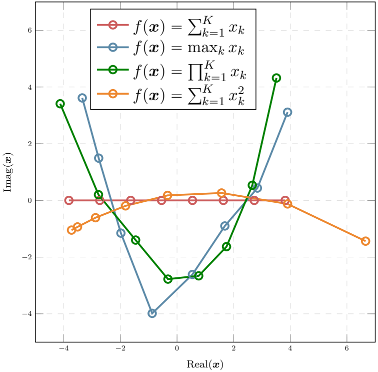
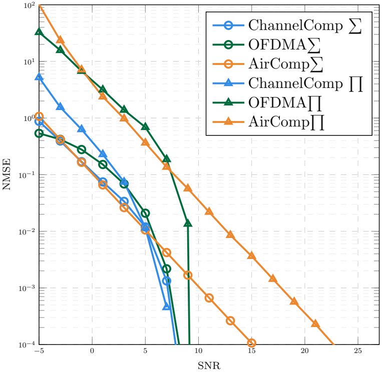
Simulations Setup

- ChannelComp (Problem $\mathcal{P}_3$) performance is compared to
  - OFDMA (modulation vector from (4)).
  - AirComp, which uses analog modulation.
- Functions tested with $K = 4$ nodes:
  - $f_1 = \sum_{k=1}^{4} x_k$
  - $f_2 = \prod_{k=1}^{4} x_k$
  - $f_3 = \sum_{k=1}^{4} x_k^2$
  - $f_4 = \max_k x_k$

  for $x_k \in \{0, 1, 2, \ldots, 7\}$
- Input signals transmitted over an AWGN channel.
- NMSE used to characterize computation error over $N_s = 100$ Monte Carlo trials for different SNRs.

Performance Comparison





- Thanks to constructive overlaps of the reshaped modulation, ChannelComp outperforms AirComp and OFDMA with more than **10** dB improvement for the product function.

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Conclusion

- Our work is *the first attempt* to propose general digital modulations for function computation over the MAC.
- The proposed ChannelComp properties:
  - Ultra-low-latency
  - General functions computation
  - Any digital modulations
  - Simple communication architecture
  - Integration of both the encoder and modulation
  - Extension of AirComp (it works for analog as well)
- Generalization to MIMO, fading channels, asynchronous, etc.
- Applications of ChannelComp for, e.g., federated edge learning, sensor networks, and distributed sensing problems.

Q&A

- S. Razavikia, J. M. Barros da Silva Jr., C. Fischione, "Computing Function Over-the-Air Using Digital Modulations", *IEEE ICC*, 2023.

- Thanks for your attention! Any question?

References I

[1] G. Zhu *et al.*, “Over-the-air computing for wireless data aggregation in massive IoT,” *IEEE Wireless Commun.*, 2021.

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References II

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References III

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