

Title

Cell-Free massive MIMO meets AirComp: Smart surfaces for networks that compute

Context

Future networks will not only transmit data but also process it. In many Internet-of-Things (IoT) applications (smart cities, distributed sensing, federated learning), the network only needs a function of the data of many devices, such as their average or sum, rather than each individual message. Over-the-air computation (AirComp) obtains this result directly “in the air”: all devices transmit simultaneously, and the superposition of their signals performs the computation, which saves time and spectrum. To further enhance resource utilization, AirComp can also share the same spectrum as ordinary data communication, leading to the integrated communication and computing (ICC) paradigm. Cell-free massive MIMO can constitute a natural host for this idea [1]. Many distributed access points (APs) cooperate through a central unit, so that every device is close to some APs, thereby providing a quasi-uniform coverage. A reconfigurable intelligent surface (RIS) [2, 3] adds further control over the propagation conditions, especially for devices with poor direct links (Figure 1).

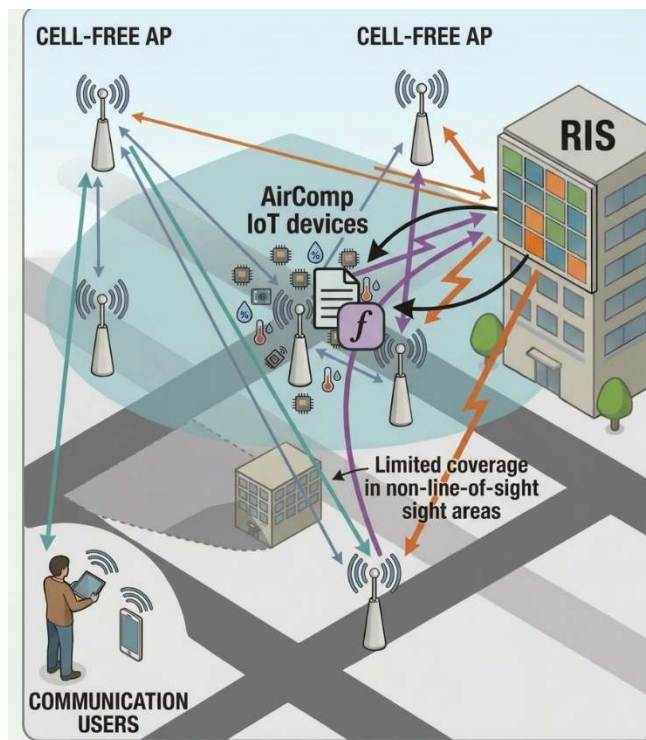


Figure 1. An integrated over-the-air computation and communication system in a cell-free massive MIMO network enhanced by a RIS.

Two recent works address complementary parts of this problem. The authors of [4] study RIS-aided AirComp and minimize the computation error by jointly optimizing the devices transmit powers, the receive beamforming at the fusion center, and the RIS phase shifts. They use a two-timescale approach: some variables are updated at every time slot using only low-dimensional channel information, while the RIS is updated less frequently, using channel statistics. This greatly reduces signaling overhead and complexity. The authors of [5] integrate AirComp with non-orthogonal multiple access (NOMA) communication through a multi-antenna relay. They maximize the sum rate of the communication users under a maximum tolerated computation error, and split the non-convex problem into subproblems

solved alternately with iterative convex approximations. However, both works consider a single receiver (one fusion center or one AP), and neither combines non-orthogonal access, AirComp devices, and a RIS in the same system.

This project bridges the two ideas: Can the low-overhead RIS design of [4] and the optimization framework of [5] be extended to a NOMA cell-free network, where many APs must cooperate and communication and computation signals interfere? This question has not been addressed yet.

Objectives

The goal of this project is to design and evaluate a low-overhead optimization framework for RIS-aided cell-free networks that serve NOMA data users and perform over-the-air computation on the same resources. Over 4-6 months, you will:

1. **Build the system model.** Aided by the previous works [1, 2, 4, 5], describe a cell-free network with several APs, one RIS, NOMA communication users, and computing devices, with the corresponding signal and channel models.
2. **Formulate the communication-computation trade-off.** Write the problem in a way to strike a balance between maximizing the sum rate of the NOMA users, including the successive interference cancellation (SIC) conditions, and minimizing (or guaranteeing) the computation error level for AirComp.
3. **Solve the problem with alternating optimization.** Split the difficult problem into smaller subproblems solved in turn.
4. **Analyze what the RIS and the cell-free architecture bring.** Compare your design with simple baselines (no RIS, random RIS phases, a centralized MIMO system, orthogonal access instead of NOMA), and study the effect of system parameters on performance.
5. **Analyze the trade-off, the overhead, and the complexity.** Quantify how the communication sum rate and the computation accuracy trade off against each other.
6. **(Optional) Explore extensions.** Depending on your interests, you can:
 - replace or complement the optimization framework with deep reinforcement learning (DRL): train an agent that directly learns some of the system variables from the network state, and compare its performance, computation time and training cost with those of alternating optimization;
 - consider a realistic RIS (elements with only a few phase states).
 - **Test it on real equipment.** If you are interested in hands-on work, validate the main idea on a real 5G testbed.

Keywords: Over-the-air computation (AirComp), Cell-free massive MIMO, Integrated communications and computing (ICC), Reconfigurable intelligent surface (RIS), Optimization, Reinforcement learning.

References

- [1] O. T. Demir, E. Bjornson, and L. Sanguinetti, "Foundations of User-Centric Cell-Free Massive MIMO," *Foundations and Trends® in Signal Processing*, vol. 14, no. 3-4, pp. 162–472, 2021.
- [2] M. Ousseily, J. Farah, M. Crussière, J. Doumit, C. Abdel Nour and E. Pierre Simon, "Uncoordinated RIS-Aided Uplink IoT Cell-Free Massive MIMO-NOMA Systems," in *IEEE Open Journal of the Communications Society*, vol. 6, pp. 9008-9026, 2025.
- [3] N. T. Nguyen, V. -D. Nguyen, H. V. Nguyen, H. Q. Ngo, S. Chatzinotas and M. Juntti, "Spectral Efficiency Analysis of Hybrid Relay-Reflecting Intelligent Surface-Assisted Cell-Free Massive MIMO Systems," in *IEEE Transactions on Wireless Communications*, vol. 22, no. 5, pp. 3397-3416, May 2023.

- [4] X. Zhai, G. Han, Y. Cai and L. Hanzo, "Beamforming Design Based on Two-Stage Stochastic Optimization for RIS-Assisted Over-the-Air Computation Systems," in *IEEE Internet of Things Journal*, vol. 9, no. 7, pp. 5474-5488, 1 April, 2022.
- [5] J. Sun, C. Hu, Q. Li, Q. Zhang and Y. Lv, "Joint Optimization for an Integrated Over-the-Air Computation and NOMA Communication System with MIMO Two-Way Relay Assistance," in *IEEE Wireless Communications Letters*, vol. 14, no. 12, pp. 4157-4161, Dec. 2025.

Duration: 4 to 6 month, preferably starting during February or March 2027.

Internship allowance: 670 Euros / month

Internship Location: Institut National des Sciences Appliquées (INSA)
20 Av. des Buttes de Coësmes, 35700 Rennes, France

Candidate profile

The candidate must be in the final stages of obtaining an engineering and/or Master's degree in Telecommunications, Electricity-Electronics, or other related fields.

Knowledge requirements include Mobile Communications, Signal Processing, and Matlab and/or Python programming.

To apply

Please send a CV, a motivation letter, copies of all academic records and grades (preferably with rankings), and (optionally) one or two recommendation letters to:

Joumana Farah: joumana.farah@insa-rennes.fr

Matthieu Crussière: Matthieu.Crussiere@insa-rennes.fr

Remarks

Only *complete applications* will be considered.

A remote **interview** will be scheduled for shortlisted candidates after the examination of the applications.

A **fully funded PhD position** is available upon successful completion of this Master's thesis.