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CENTRE FOR WIRELESS INNOVATION

Cell-free Massive MIMO for Next Generation Multiple Access

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QUEEN'S UNIVERSITY BELFAST

ECIT THE INSTITUTE OF ELECTRONICS COMMUNICATIONS AND INFORMATION TECHNOLOGY

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Queen's University Belfast

Established in 1845, 9th oldest university in the UK

CWI CENTRE FOR WIRELESS INNOVATION

Queen's University Belfast

Quick Stats

5
CONSECUTIVE TIMES HIGHER EDUCATION (THE AWARDS)
QS World Rankings

6
QUEEN'S ANNIVERSARY PRIZES FOR FURTHER EDUCATION

£700 MILLION
BEING INVESTED IN WORLD CLASS FACILITIES

TOP 1%
OF UNIVERSITIES IN THE WORLD
QS World Rankings

23,000+
STUDENTS FROM OVER 80 COUNTRIES

3,700
STAFF

150,000
ALUMNI IN 120 COUNTRIES

UK
LEADER FOR KNOWLEDGE TRANSFER

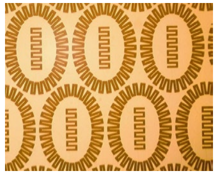
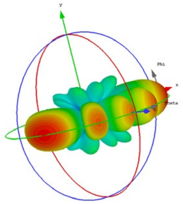
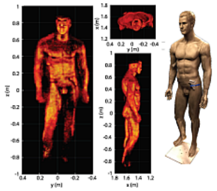
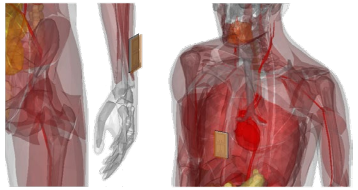
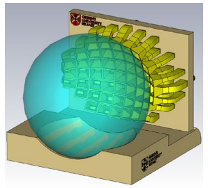
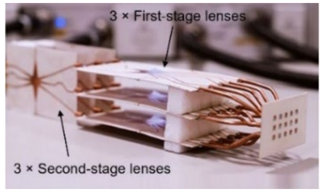
QUEEN'S UNIVERSITY BELFAST | SCHOOL OF ELECTRONICS, ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

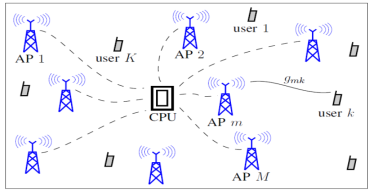
Centre for Wireless Innovation

- The **Centre for Wireless Innovation (CWI)** was formed in 2016 through the consolidation of research expertise in High Frequency Electronics and Wireless Communications at QUB.
- CWI is the UK's largest research, development and exploitation base in physical layer wireless, and one of the strongest in Europe (3 IEEE Fellows).
- Ranked 7th in the UK in the 2022 Shanghai Ranking's Global Ranking of Academic Subjects for telecoms engineering / wireless communications
- At present, the centre is home to around 65 academics, engineers, postdocs and PhD students.

Centre for Wireless Innovation

- Since its inception, CWI's mission has been to *develop truly disruptive, end-to-end physical layer wireless technologies and techniques that will assist in the creation of a data-driven, hyper-connected society.*
- Working primarily in the RF through to sub-millimeter wave bands, we are creating transformative technologies that will meet the future requirements of users whether it be *coverage, data rate, latency, security, connectivity on a massive scale or wireless imaging and sensing*.



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Centre for Wireless Innovation – Some of Our Collaborators

intel

esa

MVG Microwave Vision Group

Selex ES A Finmeccanica Company

COBHAM

QinetiQ

ANALOG DEVICES

Homeland Security

O2

KEYSIGHT TECHNOLOGIES

[dstl]

UK SPACE AGENCY

SAMSUNG

Ofcom

AIRBUS

NOKIA Bell Labs

Centre for EO Instrumentation

ERICSSON

RAL Space

infineon

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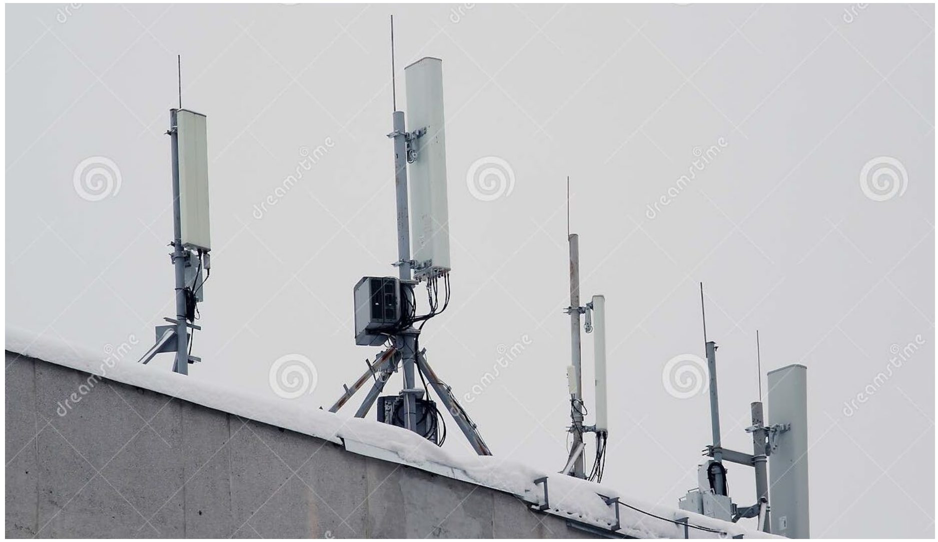
Cell-free massive MIMO: The basics

Base station tower

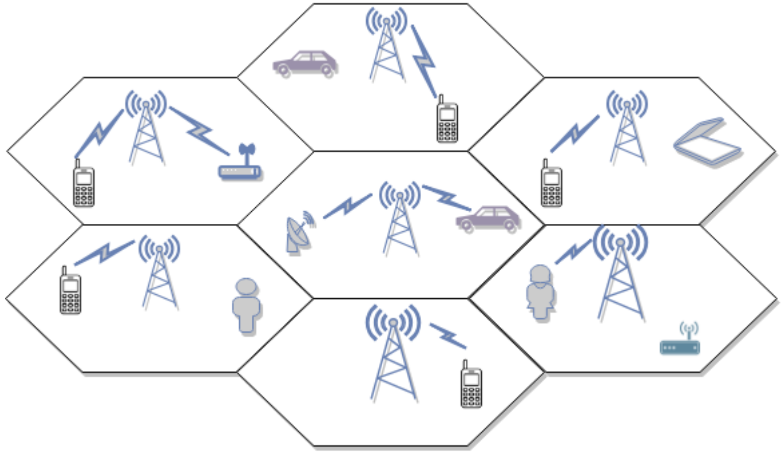
Rooftops



Large variations in distance to users → Large signal strength variations

Cell-free massive MIMO: The basics

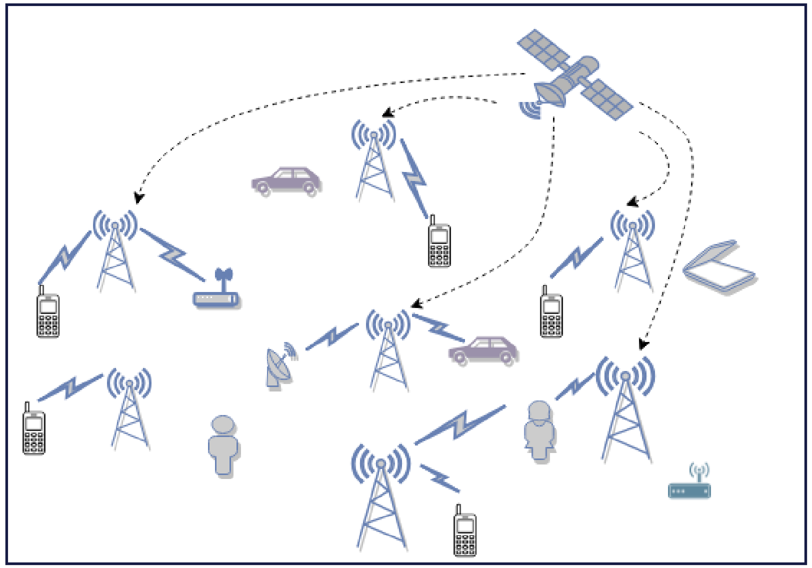
1970s-Present: cellular networks



Cellular topology

Future requirement

The innovation: Cell-free Massive MIMO



- **Not suitable** for future wireless networks
- Subject to **cell boundary effect**
- **Largely homogeneous**, human-user based systems

- **No longer** require cells
- **Human** and **machine type communications**
- The way to deliver **connectivity in the future!**

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Cell-free massive MIMO research at QUB: A long journey

IEEE TRANSACTIONS ON GREEN COMMUNICATIONS AND NETWORKING, VOL. 2, NO. 1, MARCH 2018 25

On the Total Energy Efficiency of Cell-Free Massive MIMO

Hien Quoc Ngo, *Member, IEEE*, Le-Nam Tran, *Senior Member, IEEE*, Trung Q. Duong, *Senior Member, IEEE*, Michail Matthaiou, *Senior Member, IEEE*, and Erik G. Larsson, *Fellow, IEEE*

***Abstract*—We consider the cell-free massive multiple-input multiple-output (MIMO) downlink, where a very large number of distributed multiple-antenna access points (APs) serve many single-antenna users in the same time-frequency resource. A simple (distributed) conjugate beamforming scheme is applied at each AP via the use of local channel state information (CSI). This CSI is acquired through time-division duplex operation and the reception of uplink training signals transmitted by the users. We derive a closed-form expression for the spectral efficiency taking into account the effects of channel estimation errors and power control. This closed-form result enables us to analyze the effects of backhaul power consumption, the number of APs, and the number of antennas per AP on the total energy efficiency, as well as, to design an optimal power allocation algorithm. The optimal power allocation algorithm aims at maximizing the total**

I. Introduction

THE PERFORMANCE of cellular networks is typically limited by inter-cell interference. In particular, users close to the cell boundaries suffer from strong interference (relative to their desired signal power). Network multiple-input multiple-output (MIMO) (also referred to as distributed MIMO, coordinated multi-point transmission, and distributed antenna systems) can reduce such inter-cell interference through coherent cooperation between base stations [2]. In network MIMO, the base stations cooperate via advanced backhaul links to jointly transmit signals in the downlink and jointly detect signals in the uplink. However, it was shown in [3] that base station cooperation has fundamental limita-

Mostly cited paper in the history of IEEE Transactions on Green Communications and Networking

60 scientific papers on cell-free massive MIMO since 2017!

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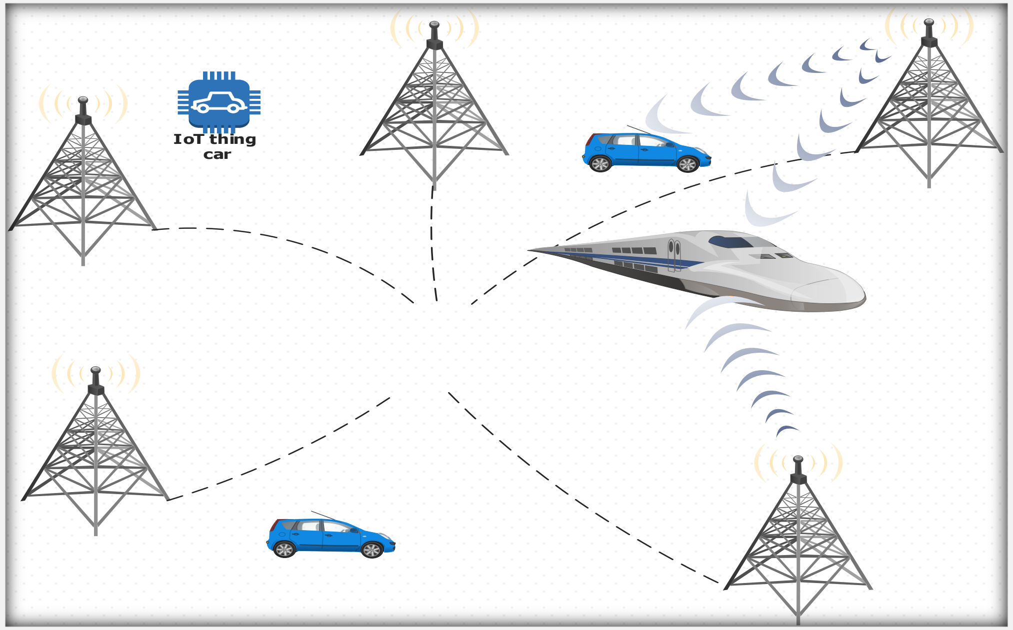
Cell-free massive MIMO

- **Cell-free Massive MIMO with OTFS Modulation**

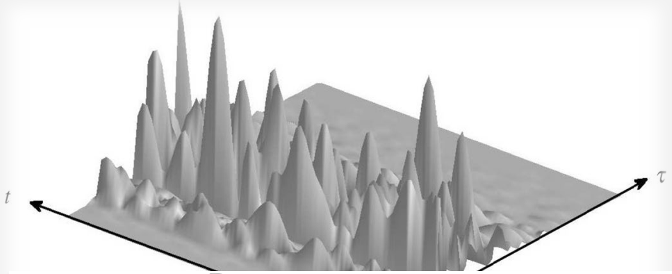
Cell-free massive MIMO and OTFS: The basic

Example scenario with high-speed users

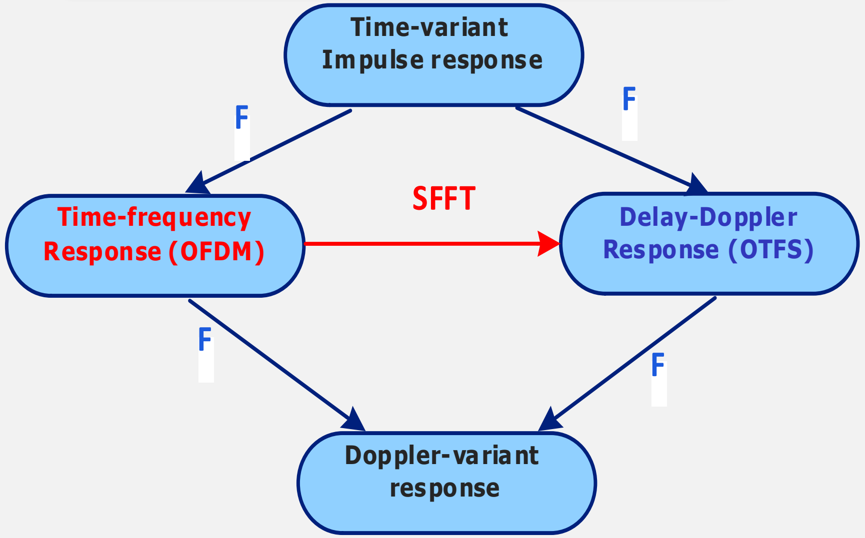


- **High mobility scenarios,** Heterogeneous user speed profiles with speeds beyond 300 Km/h
- **OFDM modulation fails** due to ICI caused by high Doppler shifts
- **OTFS modulation,** Doppler Resilient

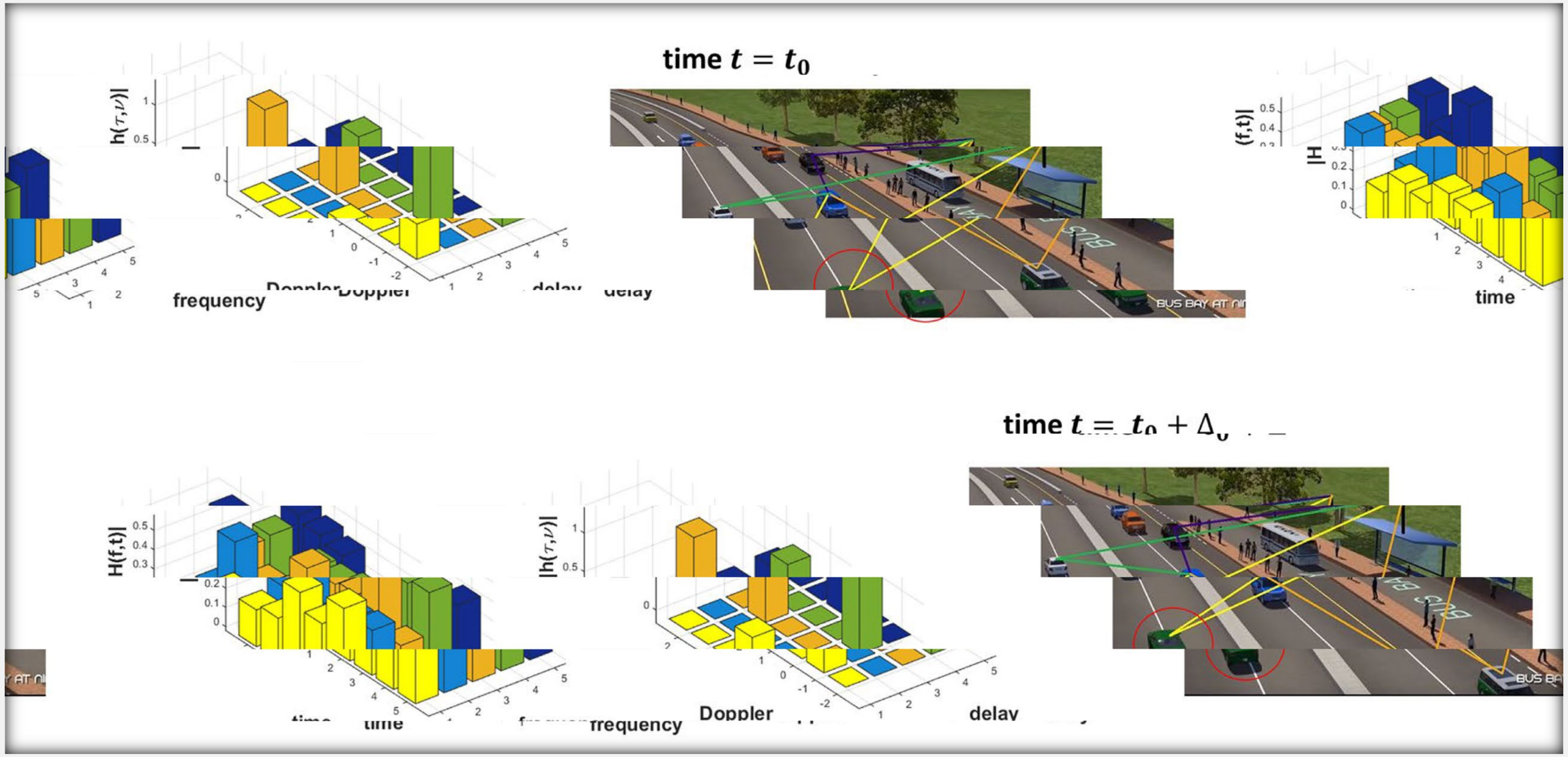
Time-variant channel response in high-mobility environment



$$h(t,\tau) = \sum_{p=1}^{P} h_p e^{j2\pi\nu_p t} \delta(\tau - \tau_p(t))$$



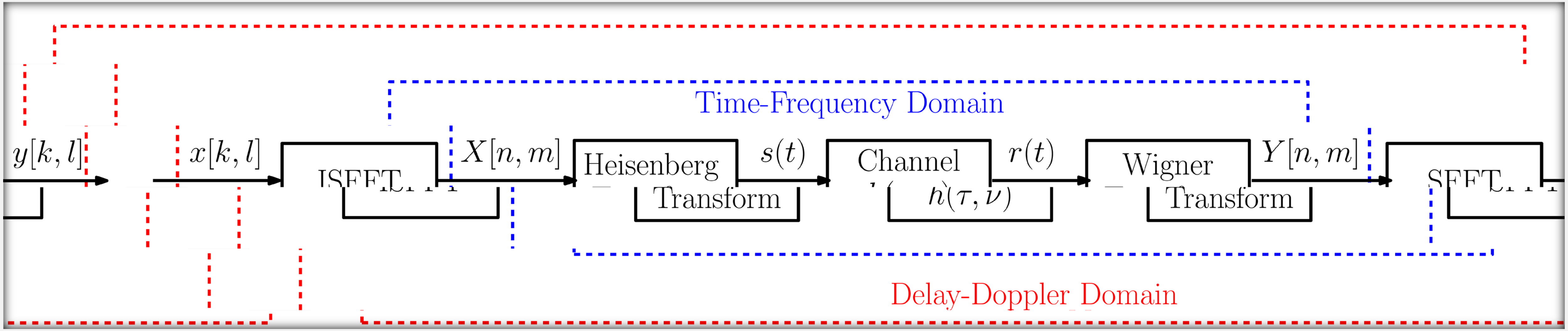
Delay-Doppler domain channel representation: Basics



Example of wireless channel in an urban multi-lane scenario, illustrating the sparsity and slow variability of the channel in delay-Doppler domain compared to the time-frequency domain

Ramachandran, M. K., G. D. Surabhi, and A. Chockalingam. "OTFS: A new modulation scheme for high-mobility use cases." *Journal of the Indian institute of science* 100 (2020): 315-336.

OTFS Modulation: Fundamentals: Basics



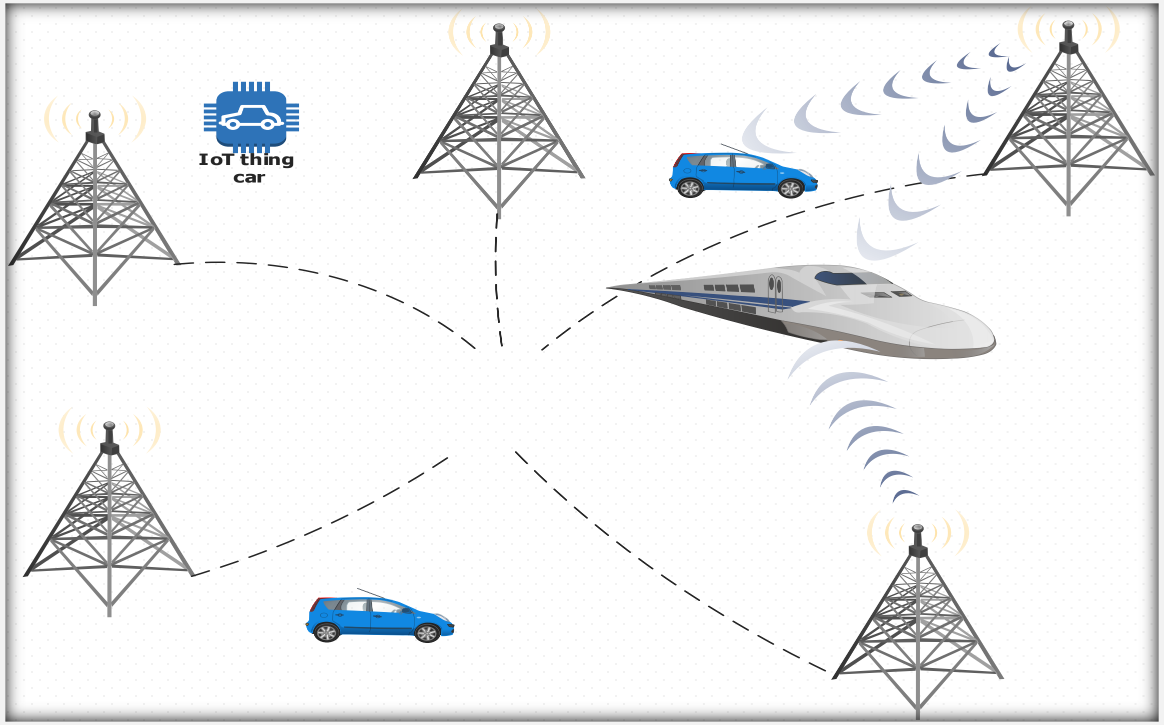
- **Time-frequency domain** is similar to OFDM system with N symbol in a frame
- By applying **ISFFT at the modulator and SFFT at the demodulator**, delay-Doppler domain system is realized
- The input-output relation in the delay-Doppler domain is a **2D convolutional**
- Detection of the information symbols is performed by using **message passing algorithm**

OTFS-based cell-free massive MIMO: Literature and research gap

OTFS modulation has been studied in the collocated massive MIMO systems, but

- **Existing research has overlooked the importance of a SE analysis** and has merely focused on the pilot design and channel estimation.
- **The insights for colocated massive MIMO design** cannot be directly extrapolated to the cell-free massive MIMO setting due to distributed nature of both APs and users and large number of APs
- The effects of non-coherent interference, small-scale fading, and noise **in asymptotic scenarios (i.e., when the number of APs is high)** is unknown!

OTFS-based Cell-free massive MIMO : Our proposal



M. Mohammadi, H. Q. Ngo, and M. Matthaiou, "Cell-free massive MIMO meets OTFS modulation," IEEE Transactions on Communications, vol. 70, no. 11, pp. 7728–7747, Nov. 2022.

❑ Objectives:

- ✓ Performance analysis for OTFS-based cell-free massive MIMO in presence of channel estimation errors
- ✓ Design and apply embedded pilot-based channel estimation (EP-CHE) and superimposed pilot-based (SP-CHE) to estimate all channels at the APs
- ✓ Apply DL power control to improve the SE, relying on the closed-form SE analysis and subject to per-AP power constraint
- ✓ Compare the performance with OFDM modulation

M. Mohammadi, H. Q. Ngo, and M. Matthaiou, " Cell-free massive MIMO with OTFS modulation: Statistical CSI-based detection," IEEE Wireless Communication Letters, vol. 12, Accepted, 2023.

OTFS based cell-free massive MIMO: Main findings

First

Closed-form DL and UL SE expression for individual DL and UL user, with codebook based multiuser detector, for finite numbers of APs and users, considering the effects of channel estimation errors

Second

Achievable UL SE expressions for minimum mean-squared error-based successive interference cancellation (MMSE-SIC) detector and arbitrary combining schemes with centralized and distributed processing designs

Third

power-scaling laws: when the number of APs, i.e., M, gets asymptotically large, we can reduce the transmit power of each user proportionally to 1/M and 1/M^2 during the uplink and downlink transmissions.

Numerical results: Benchmarks and UL/DL detectors

Benchmarks

OFDM modulation with block type (BT) pilot pattern

OTFS with uniform power allocation at the APs

UL processing And combiners

UL Processing schemes

- **L2:** Local Processing and Simple Centralized Decoding
- **L4:** Fully Centralized Processing

UL combiners

- **L-MMSE :** Local minimum mean square error combiner
- **MR:** Maximum ratio combiner

DL processing schemes

- **Low-complexity delay-Doppler detector** [R]: separate detection for each information symbol, relying on different information codebooks for each sub-channel of each user
- **MMSE-SIC:** minimum mean-squared error-based successive interference cancellation , each user has access to statistic CSI

[R] B. C. Pandey, et.al., "Low complexity precoding and detection in multi-user massive MIMO OTFS downlink," IEEE Trans. Veh. Technol., vol. 70, no. 5, pp. 4389–4405, May 2021.

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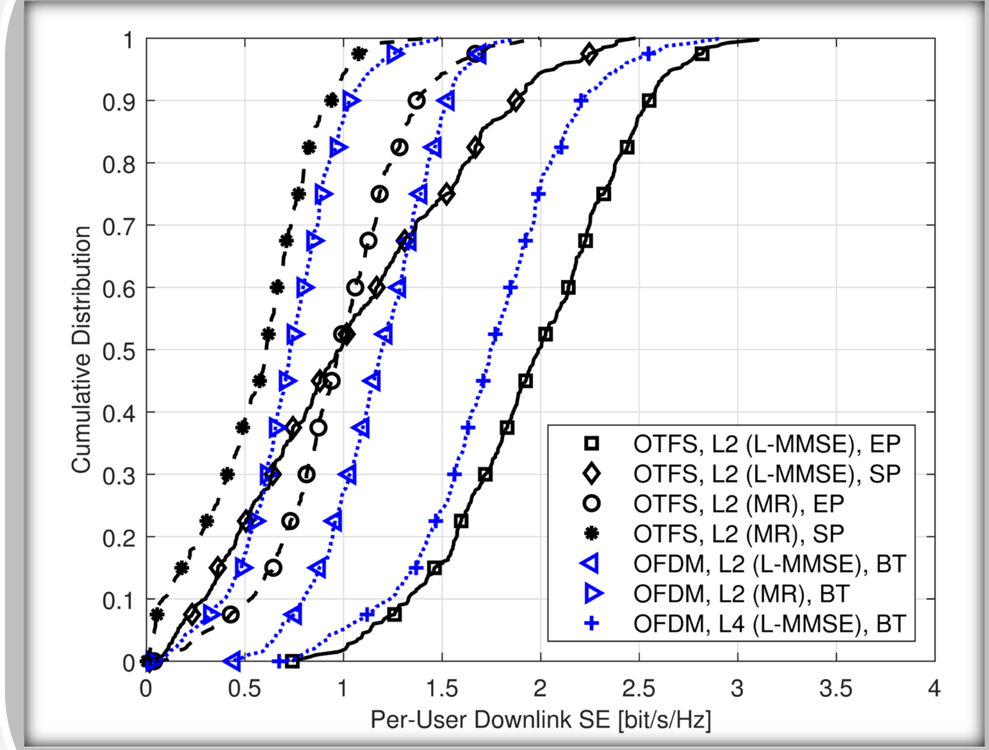
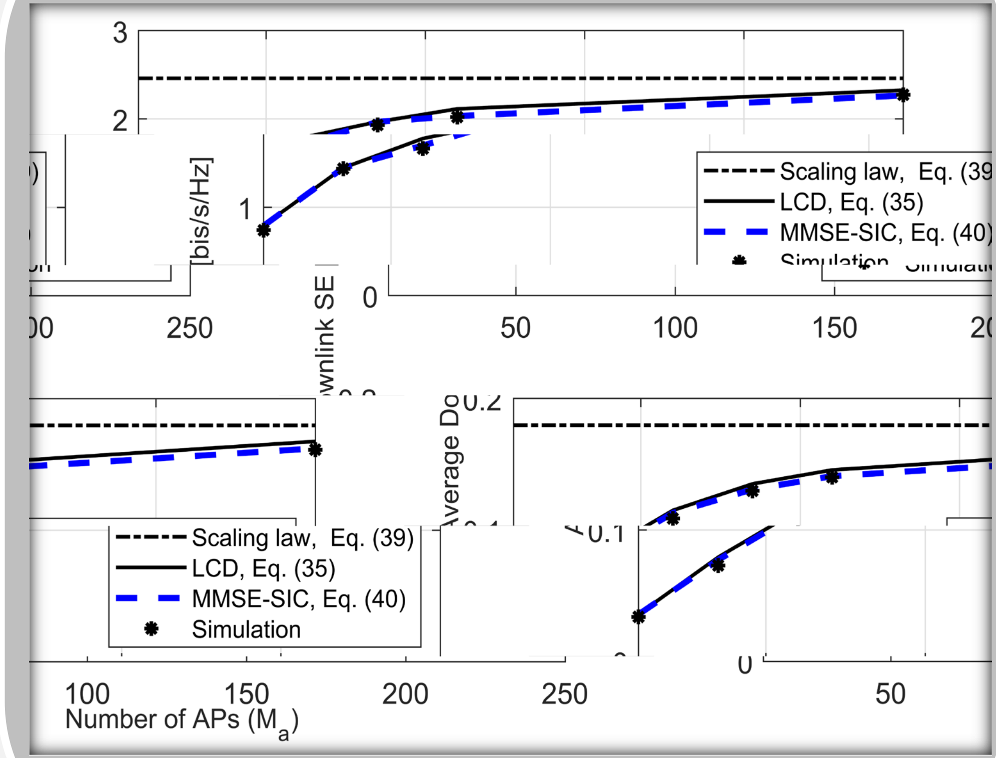
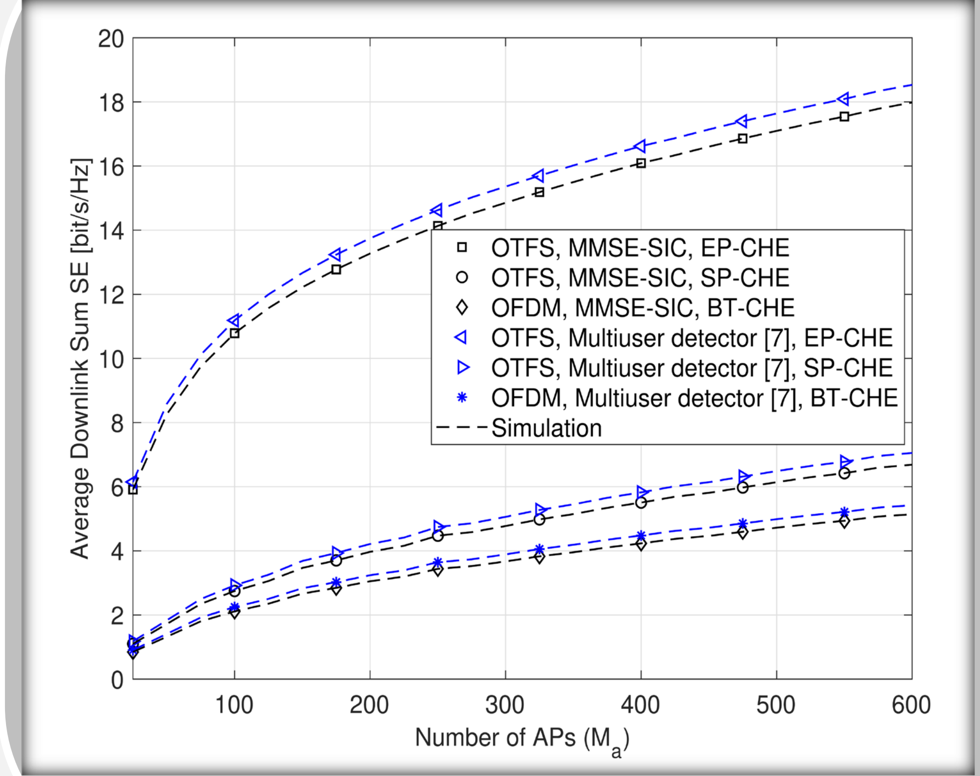
UL SE for MMSE-SIC detector



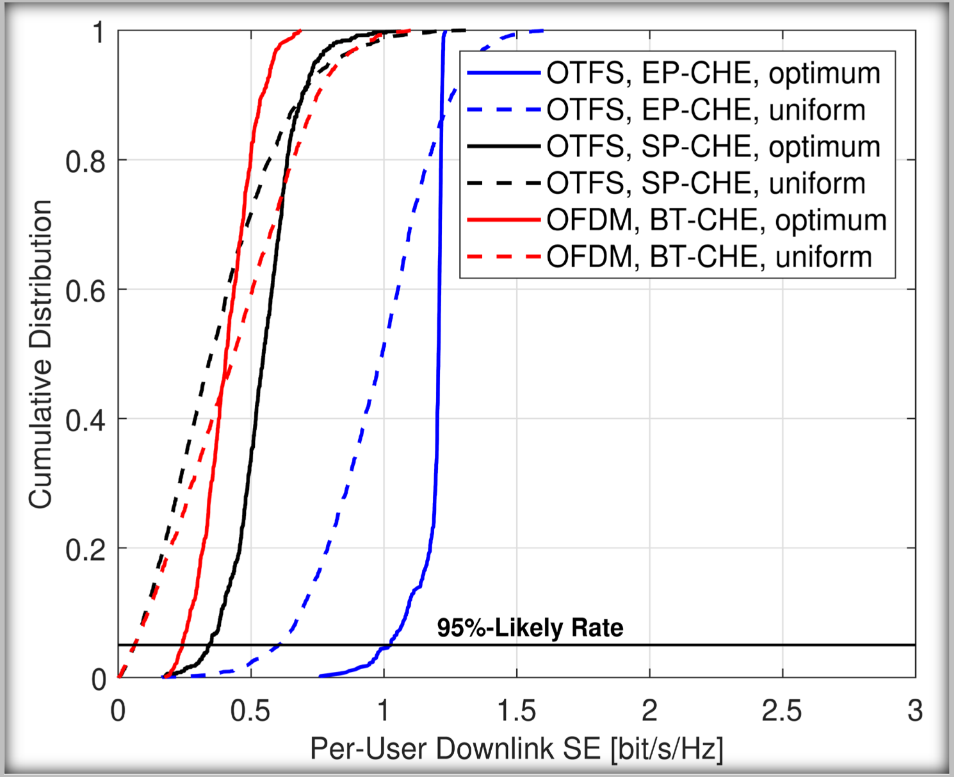
DL SE for EP (top) and SP (bottom) channel estimation



DL SE for different detectors



Impact of power control at APs

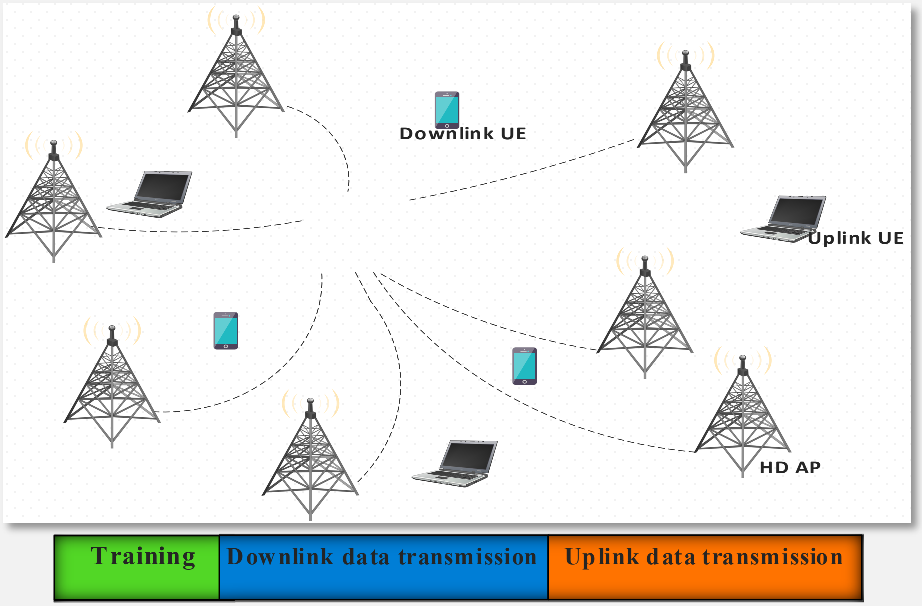


Cell-free massive MIMO

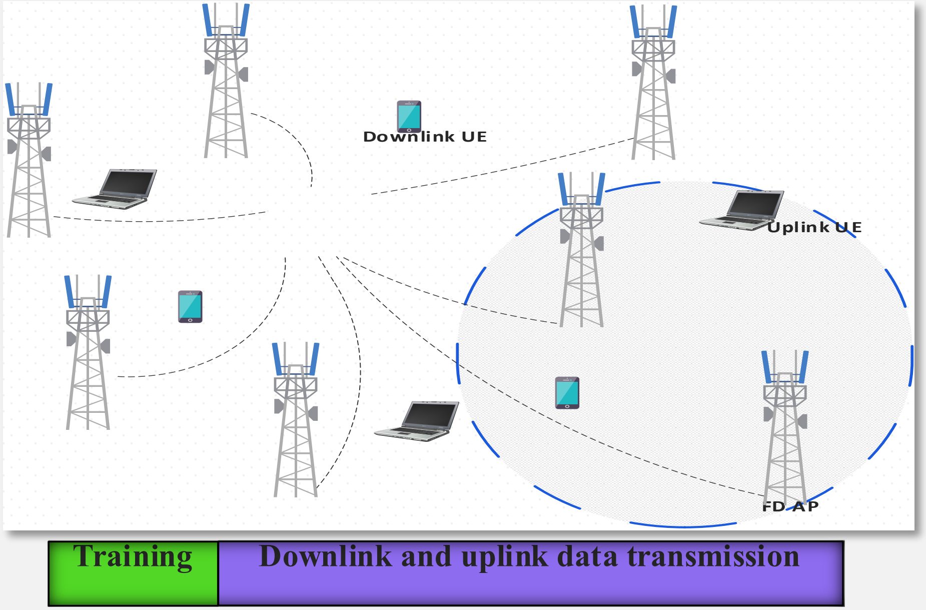
- ❑ **Network-Assisted Full-duplex Cell-free Massive MIMO**

Cell-free massive MIMO: Half-duplex versus full-duplex

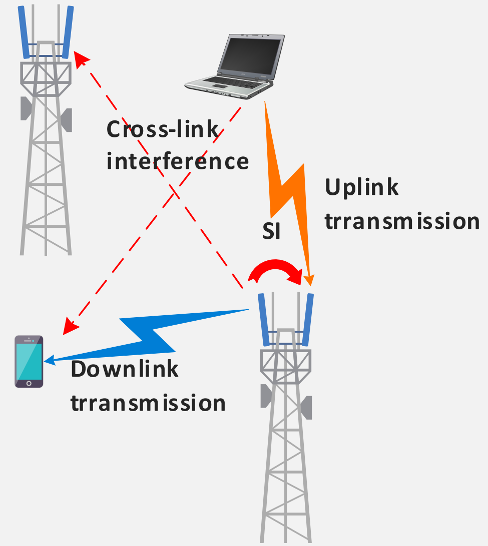
Half-duplex topology



Full-duplex topology



Interference sources

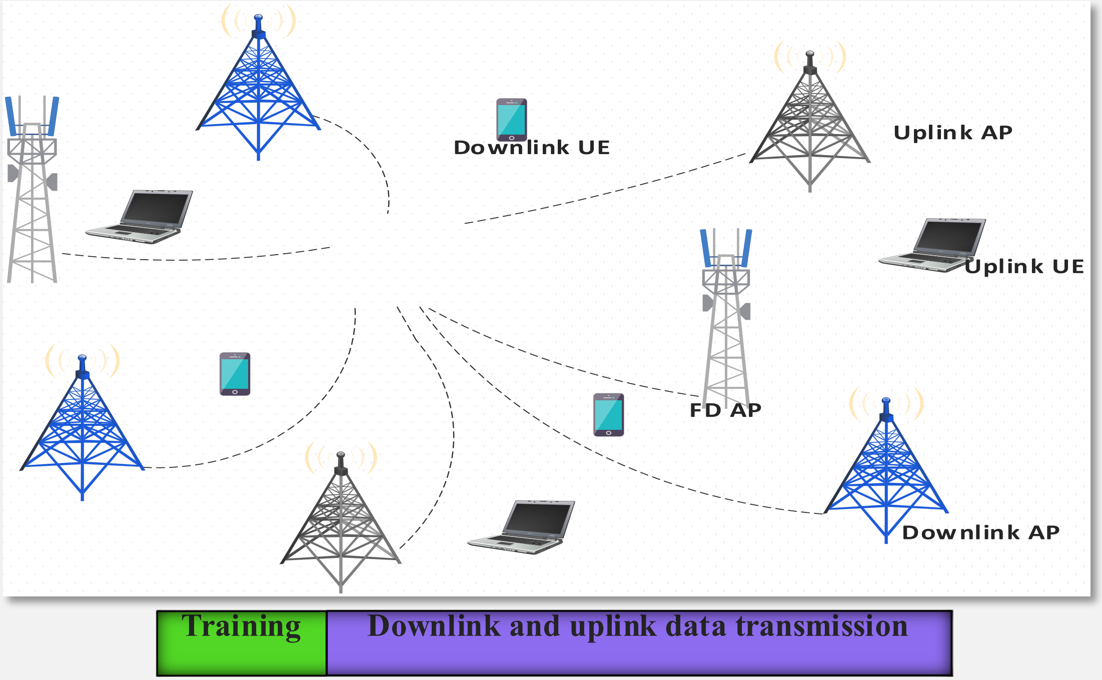


- **Not suitable** for emerging low latency applications with different UL/DL priorities
- **Inefficient** in terms of delivery delay and power consumption

- **Transceiver complexity,** to mitigate the self-interference (SI)
- **Power-hungry hardware,** for SI cancellation
- **Additional sources of interference,** cross-link interference (CLI)

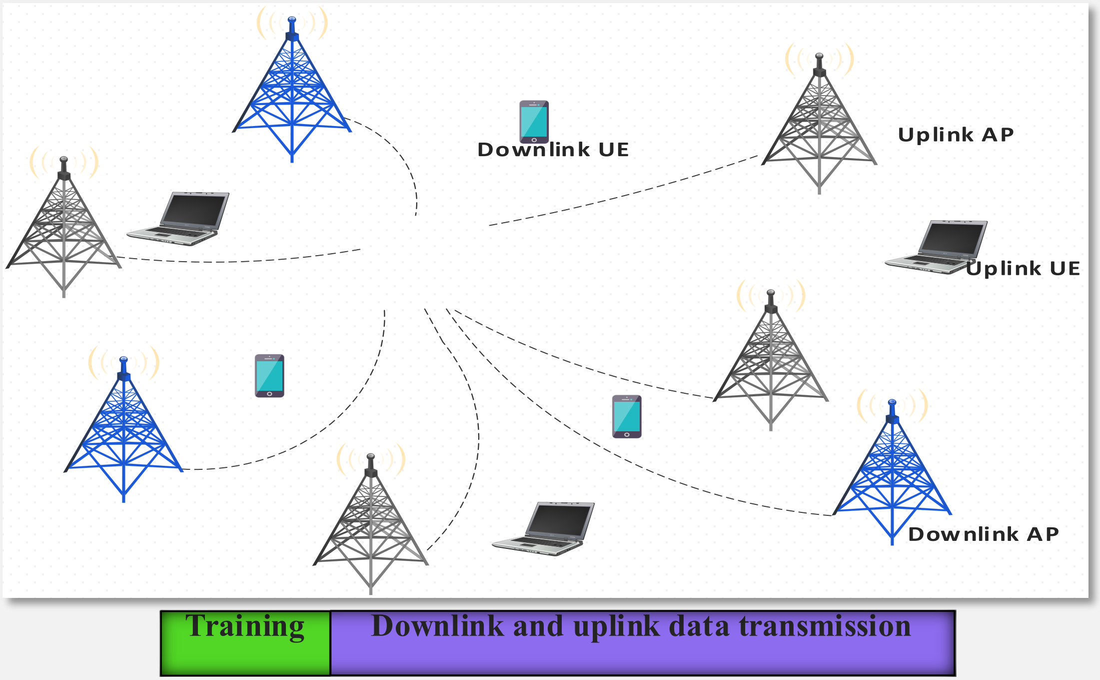
Network-assisted full-duplex cell-free massive MIMO: Basics

Hybrid-duplex architecture



- **Support UL and DL transmissions at the same time,** via both FD and HD APs
- **Bottleneck:** SI cancellation and cross-link interference (CLI) management are required

Flexible-duplex architecture



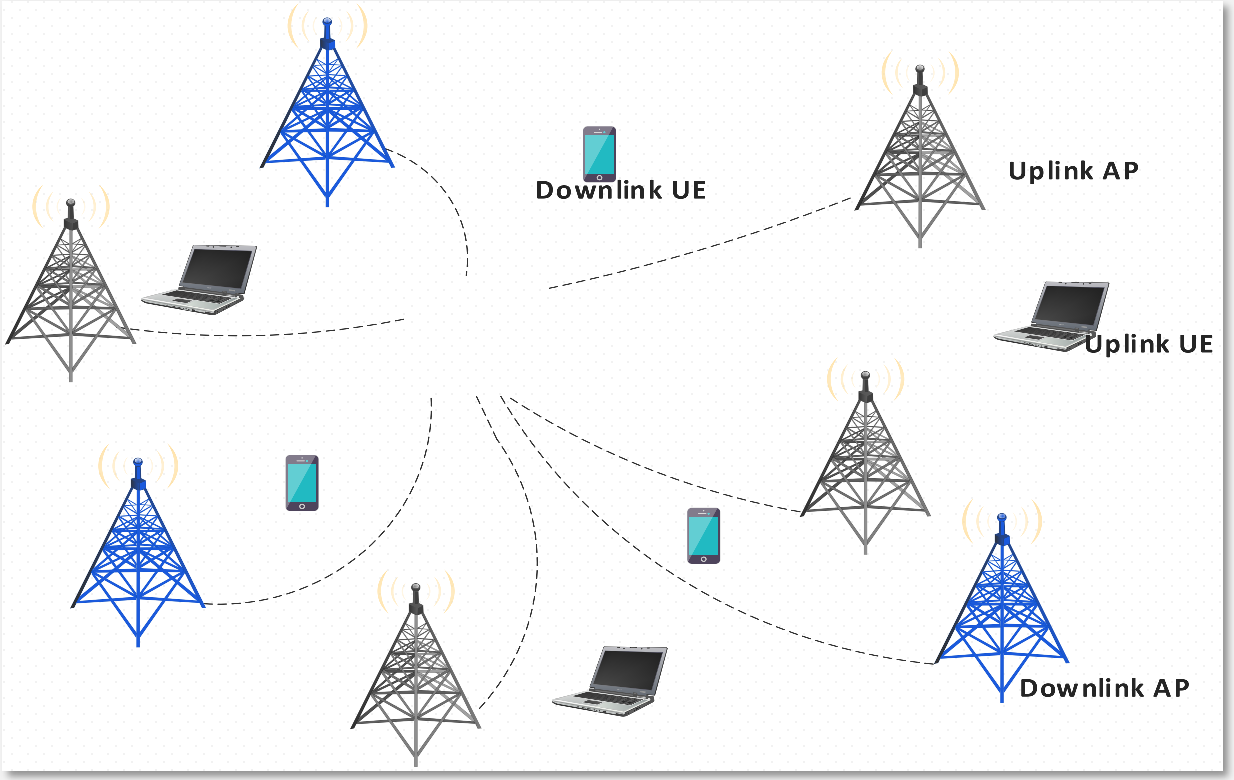
- **Support UL and DL transmissions at the same time,** via only HD APs
- **NO SI,** lower implementation complexity and power consumption at the AP

NAFD cell-free massive MIMO: Literature and research gap

Active research area with numerous recent research efforts, but

- **Fixed AP mode assignment considered** for both architecture, only power control coefficients and beamforming vectors/matrices optimized
- System level designs are based on **instantaneous channel state information (CSI)** rather than statistical CSI
- **Sub-optimal optimization frameworks proposed, since** the optimization problems have been decoupled and solved via alternative optimization
- **Energy efficiency (EE) optimization** has been remained untouched!

Flexible-duplex architecture: Our proposal



M. Mohammadi, T. T. Vu, H. Q. Ngo, and M. Matthaiou, "Network-assisted full-duplex cell-free massive MIMO: Spectral and energy efficiencies," *IEEE Journal on Selected Areas in Communications*, 2023.

- **Design parameters:**
  - ✓ AP mode assignment (UL reception or DL transmission)
  - ✓ Power control (at APs and UL UEs)
  - ✓ Large scale fading decoding (LSFD) weights
- **Design objectives**
  - ✓ SE enhancement
  - ✓ EE improvement
- **Design constraints**
  - ✓ Minimum individual SE requirements at UEs
  - ✓ Maximum transmit power at APs and UL UEs
  - ✓ Hardware and backhaul energy consumption
  - ✓ Backhaul constraints

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Flexible-duplex architecture: Main features

First

Cross-link interference still exist, but

- ✓ It is much lower compared to the FD and NAFD with hybrid-duplex structure
- ✓ and more meanable through the intelligent AP mode assignment

Second

Spectral efficiency is enhanced, due to

- ✓ Dynamic cross-link interference management via AP mode assignment and power control
- ✓ Efficient use of all available time and frequency resources to serve both UL and DL UEs

Third

Energy efficiency is significantly improved, as

- ✓ The same individual SE requirement are achieved through using smaller number of APs for UL and DL operation
- ✓ Power-hungry circuits for SI cancellation are no longer required

NAFD cell-free massive MIMO: Our contributions

First

SE and EE optimization by taking the effects of
1) imperfect CSI, 2) QoS requirement of all UEs, 3) per-AP and UE power control, 4) AP mode assignment, 5) and large-scale fading decoding (LSFD) weights

Second

Providing a comprehensive and realistic power consumption model,
encompassing the power consumption for hardware and backhaul links

Third

Developing two efficient algorithms,
to solve the challenging formulated mixed-integer non-convex problems
Providing a comprehensive comparison with 4 benchmark systems

Numerical results: Benchmarks

R-NAFD

NAFD with random AP mode assignment,
AP modes are randomly assigned. The AP and UL UE power control coefficients and LSFD weights are optimized, under the same SE QoS constraints for UL and DL UEs.

G-NAFD

NAFD with greedy AP mode assignment,
Fixed power control coefficients and LSFD weights are considered, and the AP mode assignment is performed by a greedy algorithm proposed in [R]

HD

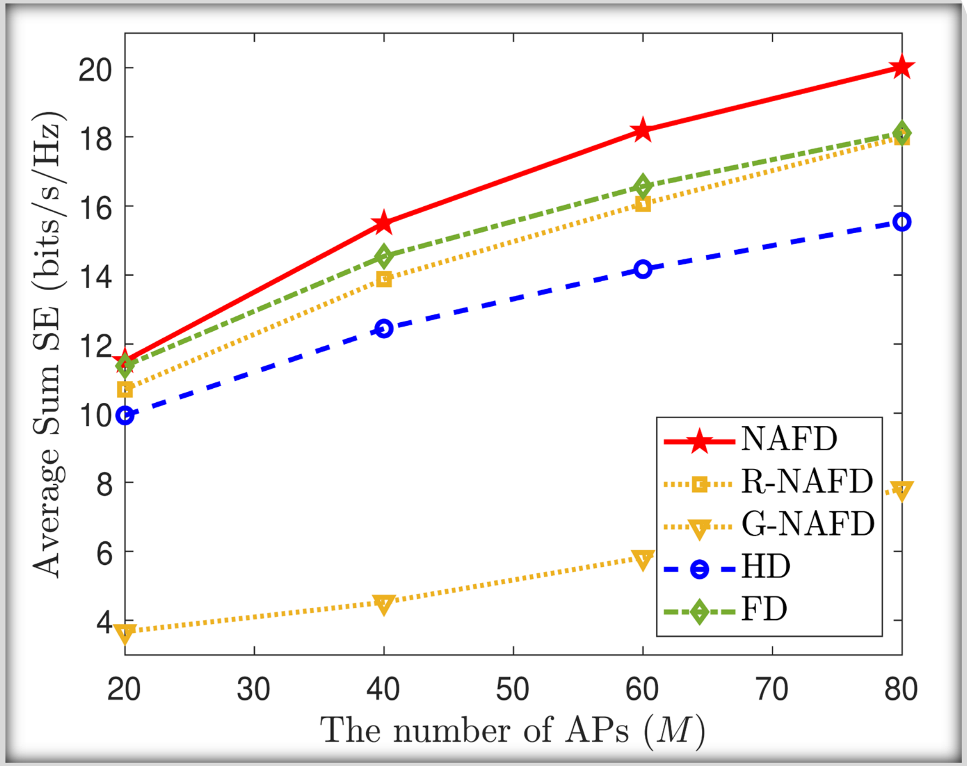
Half-Duplex cell-free massive MIMO Systems,
DL-and-UL payload data transmission phase is divided into two equal time fractions. The power coefficients and LSFD weights are optimized

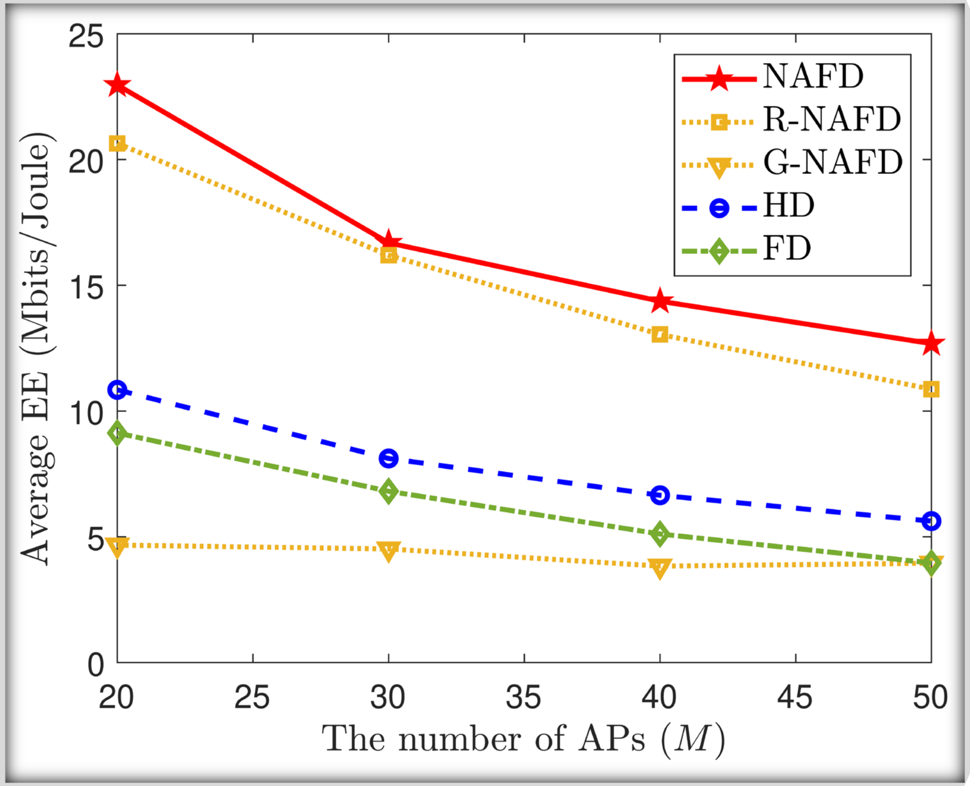
FD

Full-Duplex cell-free massive MIMO Systems,
For the sake of fairness, the FD scheme deploys the same number of antennas as the other schemes. The power coefficients and LSFD weights are optimized

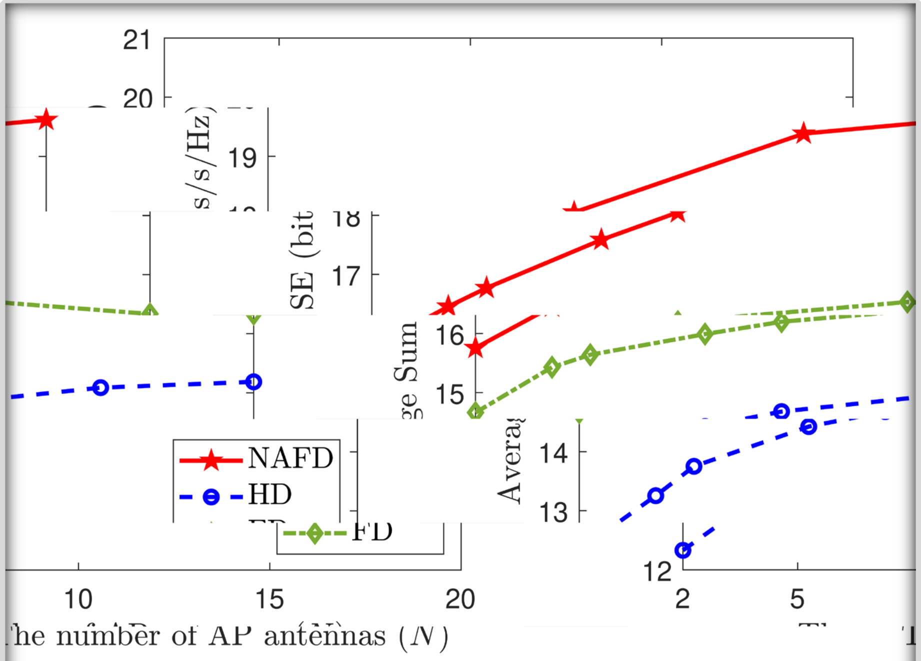
[R] A. Chowdhury, R. Chopra, and C. R. Murthy, "Can dynamic TDD enabled half-duplex cell-free massive MIMO outperform full-duplex cellular massive MIMO?" *IEEE Trans. Commun.*, vol. 70, no. 7, pp. 4867–4883, May 2022.

Impact of number of APs on SE and EE





SE versus number of AP antennas   Average EE versus individual SE



f, the number of AP antennas on the SE Fig. 4: Impact o
0, $K_d = K_u = 4, \mathcal{S}_{QoS} = 0.2$ bit/s/Hz, $\sigma_{\text{SI}}^2/\sigma_n^2 =$ ($NM = 8$
50 dB).

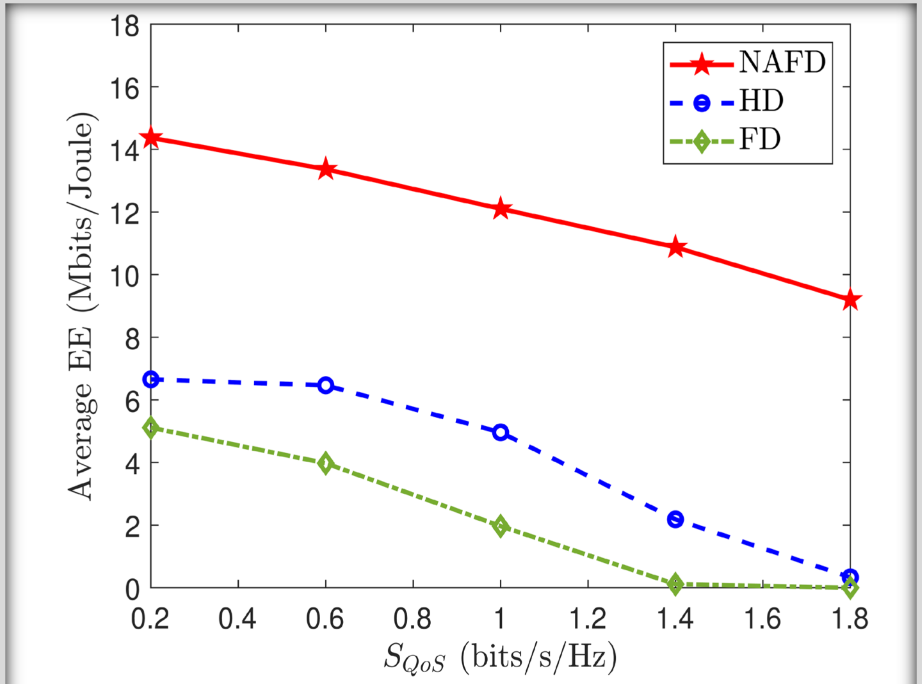


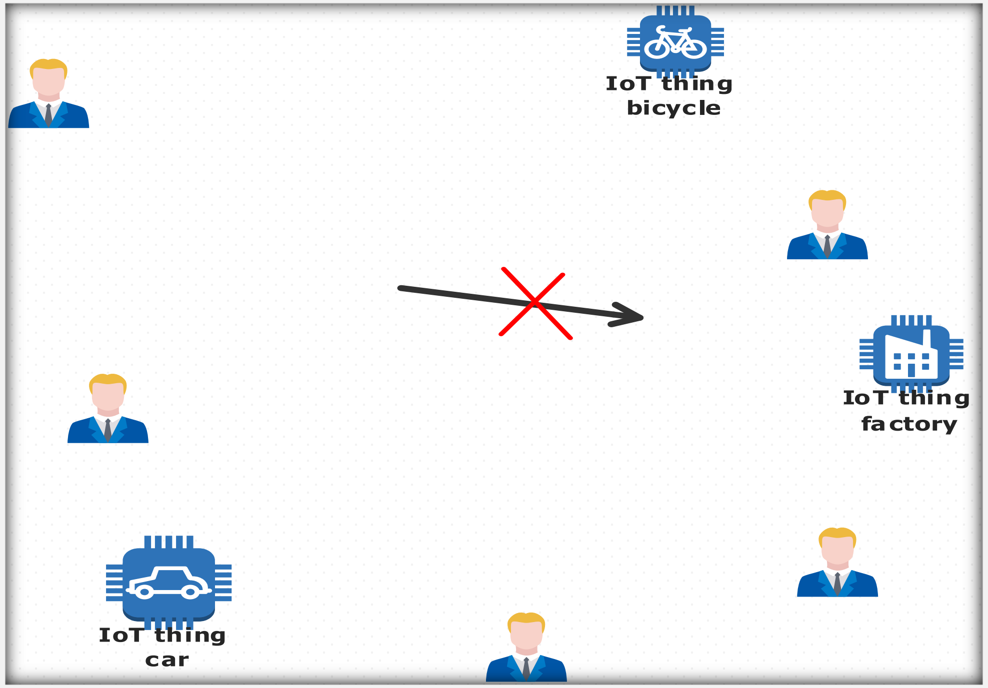
Fig. 7: Impact of individual SE requirements on EE ($M = 40, K_d = K_u = 4$ bit/s/Hz, $\sigma_{\text{SI}}^2/\sigma_n^2 = 50$ dB).

Cell-free massive MIMO

- **SWIPT-enabled Cell-free Massive MIMO**

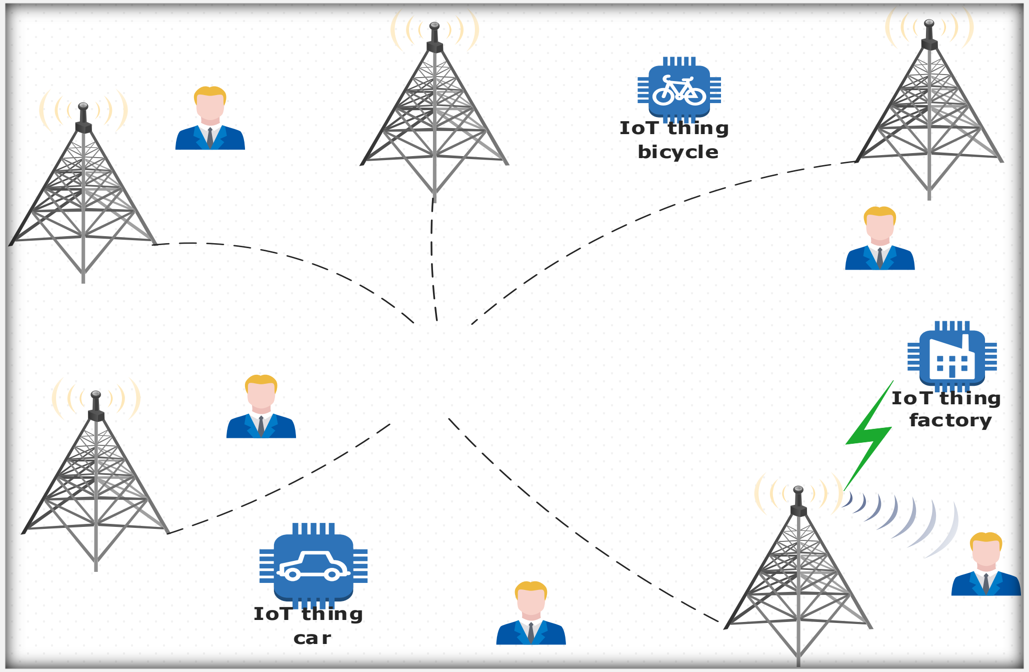
Cell-free massive MIMO and SWIPT: Basics

Cellular networks with massive antenna array



- **Highly directional** RF signal power towards energy user (EU)
- Subject to **blockage**
- **Fairness problem,** due to large path loss

Cell-free massive MIMO



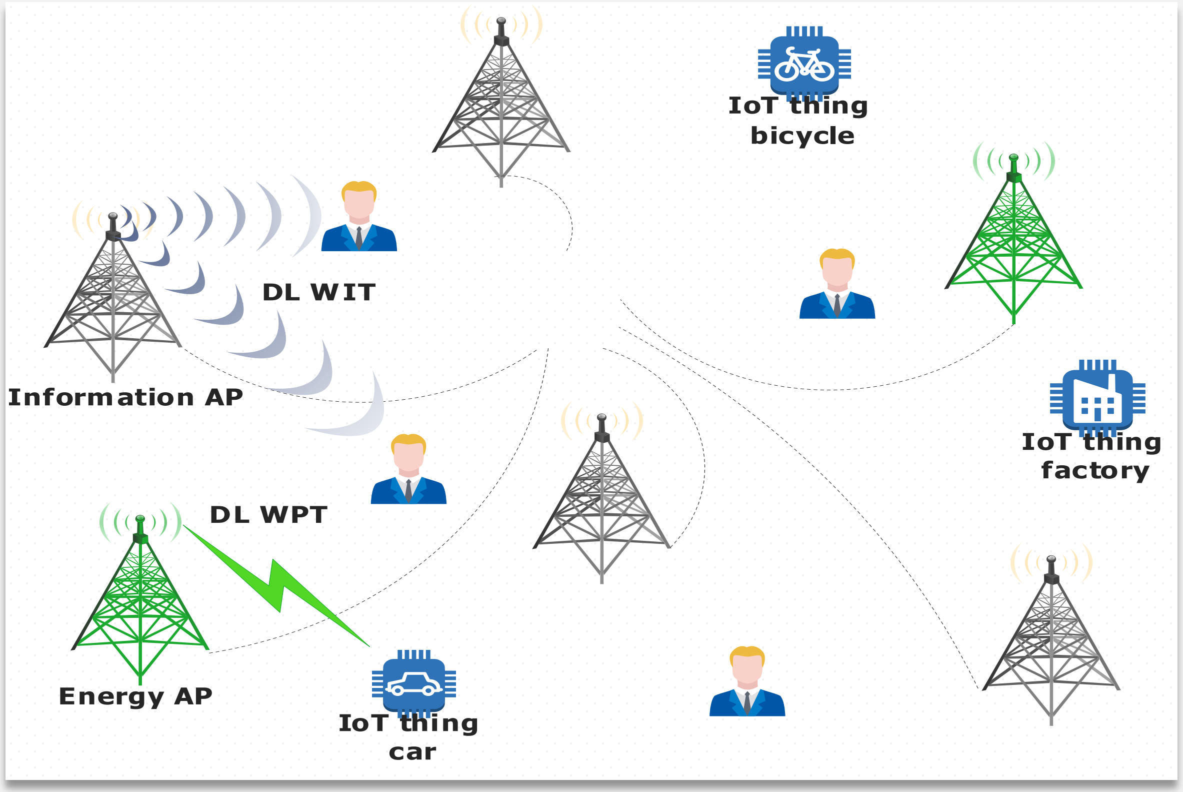
- **High macro-diversity gain and low path-loss**
- **Seamless energy harvesting energy opportunity**, for all EUs
- **Support two types of users:** EUs and information users (IUs) at the same time with specific requirements
- **Suitable for IoT and sensor networks**

Cell-free massive MIMO and SWIPT: Literature and research gap

Active research area with numerous recent research efforts, but

- **Unsatisfactory performance due to inefficient use of available resources**, HD structure with orthogonal transmission through time division between information and energy transfer phases was considered
- **Large fronthaul burden and transmit power requirement,** due to deployment of large number of APs (Dense networks) to simultaneously enhance the SE and harvested power at IUs and EUs to satisfy QoS requirements
- **NAFD structure with fixed mode assignment at APs (UL/DL transmission)** to support DL and UL users and provide EH opportunity for UL users with system level designs based on instantaneous CSI

Cell-free massive MIMO and SWIPT: Our proposal



M. Mohammadi, Le-Nam Tran, Z. Mobini, H. Q. Ngo, and M. Matthaiou, "Cell-free massive MIMO and SWIPT: Access point operation mode selection and power control," submitted to IEEE GLOBECOM 2023.

❑ Objective

- ✓ Simultaneous enhancement of SE at IUs and amount of harvested energy at EUs
- ✓ Support minimum individual SE requirements at IUs

❑ Proposed solution

- ✓ Joint, AP operation mode selection
  - ▪ Energy transmission or
  - ▪ Information transfer
- ✓ and power control design at APs

❑ Design criteria

- ✓ Total harvested energy maximization at EUs
- ✓ Total EE improvement

❑ Design constraints

- ✓ Maximum transmit power at APs
- ✓ Hardware and backhaul energy consumption
- ✓ Backhaul constraints

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AP mode operation selection for SWIPT: Main features

First

Efficient use of available resources

- ✓ Whole of one time slot is used for energy and information transfer towards EUs and IUs, respectively

Second

Interference management,

- ✓ Different beamforming designs can be applied at energy and information APs to manage the interference at IUs, while taking advantage of interference at the EUs

Third

Energy efficiency is significantly improved, as

- ✓ Part of APs contributing in information transmission phase and the remaining part contributing in energy transfer
- ✓ Lower backhaul is required

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Numerical results: Benchmarks

Benchmark 1

Random AP Operation Mode Selection without Power Control,
APs operation modes are randomly assigned and equal power allocation at energy APs and information APs is considered

Benchmark 2

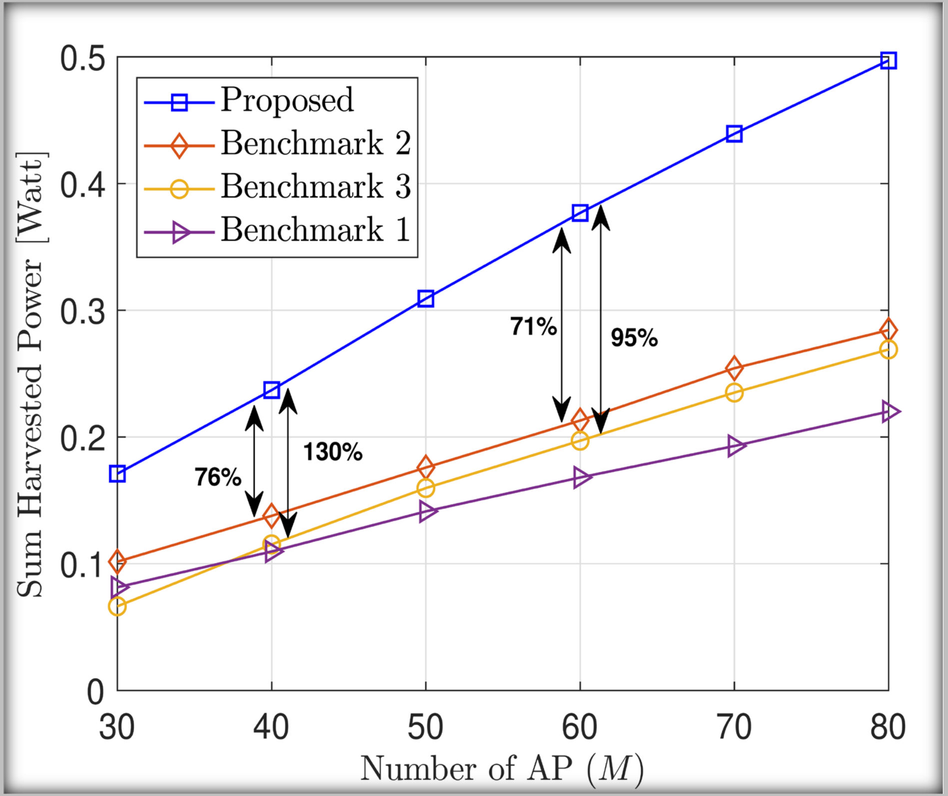
Random AP Operation Mode Selection without Power Control,
APs operation modes are randomly assigned, while the optimal DL power control coefficients at the energy and information APs are designed to support SE requirements at IUs

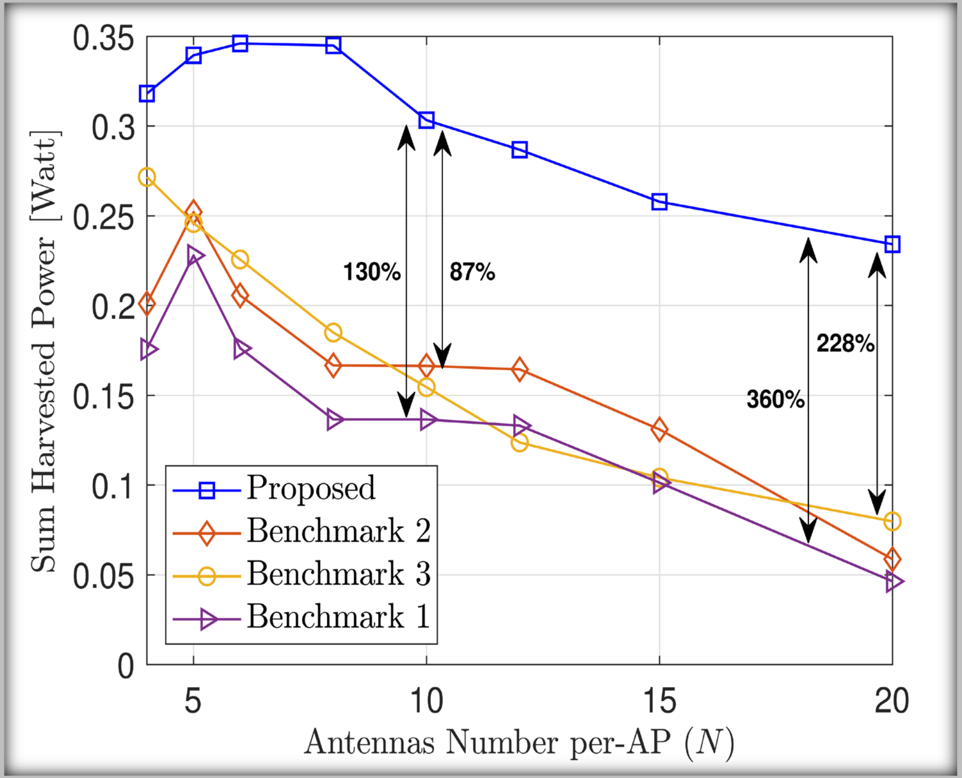
Benchmark 3

SWIPT with Orthogonal Transmission,
WIT and WPT, respectively towards IUs and EUs are performed over orthogonal time frames with equal duration [R].

[R] G. Femenias, J. Garc´ıa-Morales, and F. Riera-Palou, "SWIPT enhanced cell-free massive MIMO networks," IEEE Trans. Commun., vol. 69, no. 8, pp. 5593–5607, Aug. 2021.

Average harvested power versus number of APs and per-AP antenna





Massive MIMO RIS-Aided SWIPT

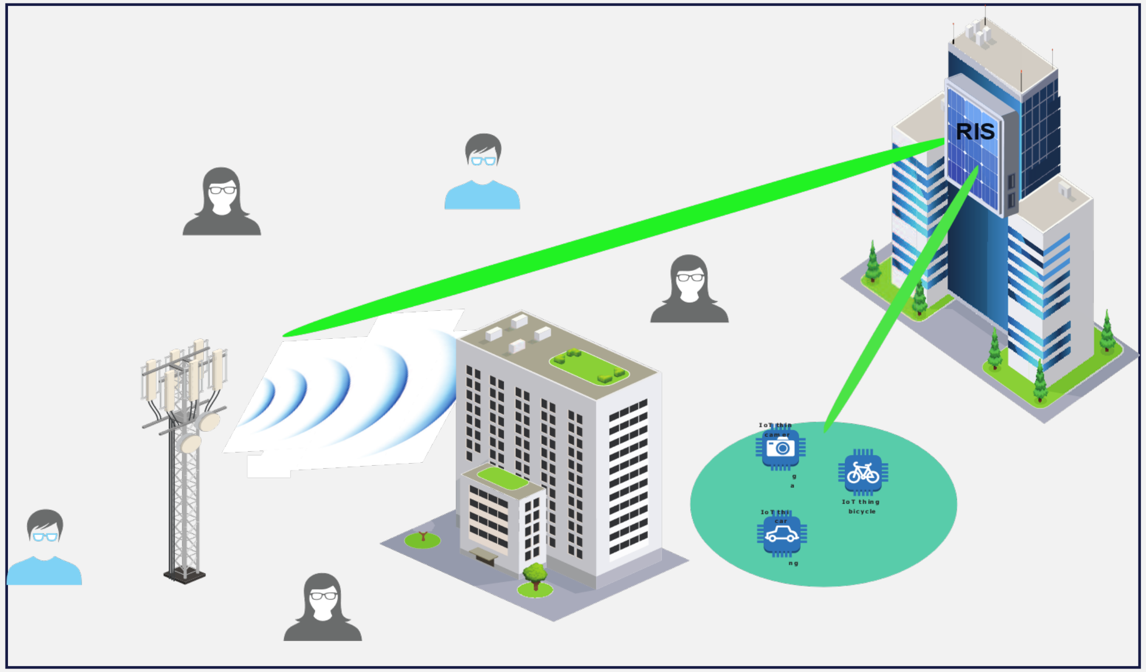
- ❑ **Massive MIMO RIS-Aided SWIPT**

Massive MIMO RIS-Aided SWIPT: Basics

Cellular networks with massive antenna array

- Subject to **blockage**

Cellular networks with massive antenna array and RIS



- For users in blockage, **RIS can be deployed**
- **RIS link is LOS,** but subject to the double path loss!

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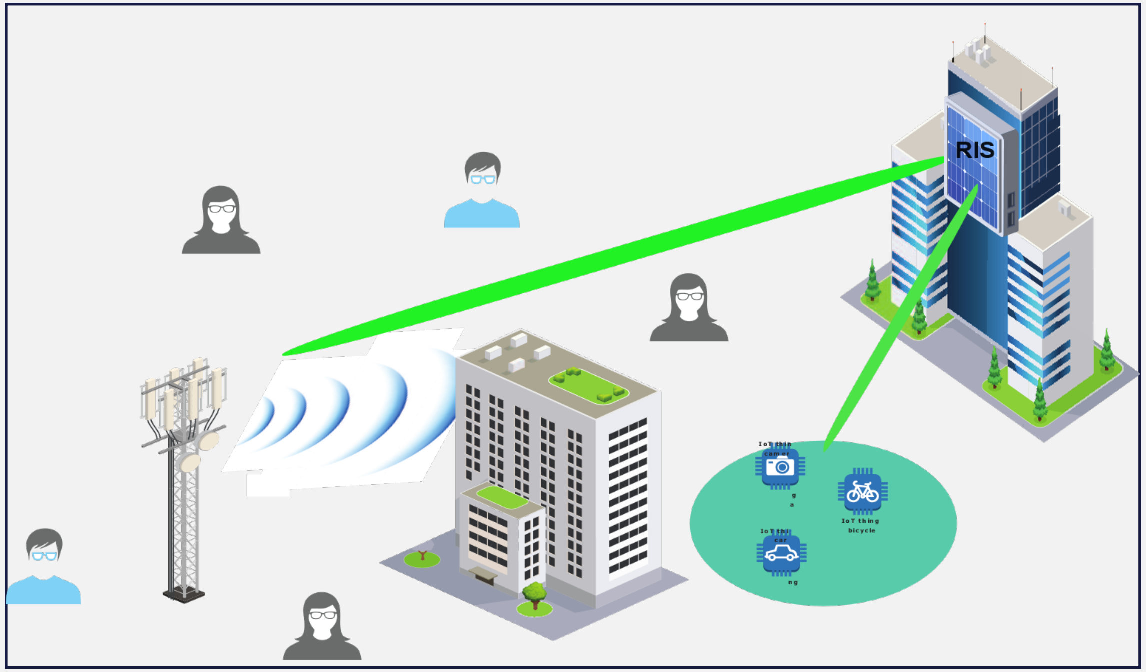
Massive MIMO RIS-Aided SWIPT : Literature and research gap

Active research area with numerous recent research efforts, but

- **Potential of the massive MIMO with low-complexity linear precoding designs, has yet not been exploited.** Traditional multi-antenna BS has been considered.
- **Perfect channel state information of the aggregated RIS-aided channels was assumed,** and the impact of the channel estimation errors and pilot overhead on the system performance are still unknown.
- **Digital and passive beamformer at the BS and RIS are designed relying on the instantaneous CSI.** Estimation of the cascade channels, however, incurs prohibitively large pilot overhead, proportional to the RIS elements.

Massive MIMO RIS-Aided SWIPT: Our Proposal



M. Mohammadi, Z. Mobini, H. Q. Ngo, and M. Matthaiou, "Integration of massive MIMO and RIS to serve energy and information users " in *Proc. IEEE ICC*, May 2023.

- **Massive MIMO array** provides sharp energy beam towards an intended energy receiver
- **ZF and (protective) MRT** are near-optimal precoding designs for simultaneous information and energy transmission and manage the inter-user interference
- **Two-timescale scheme** is applied to address the large pilot overhead and complexity of the instantaneous CSI assisted beamforming design
  - ✓ BS beamforming is designed based on the instantaneous aggregate CSI, while the RIS phase shifts are optimized based on **long-term statistical CSI**
- **Resource allocation** between the energy and information users is performed, by taking the pilot estimation error into account

Average harvested power versus number of BS antennas

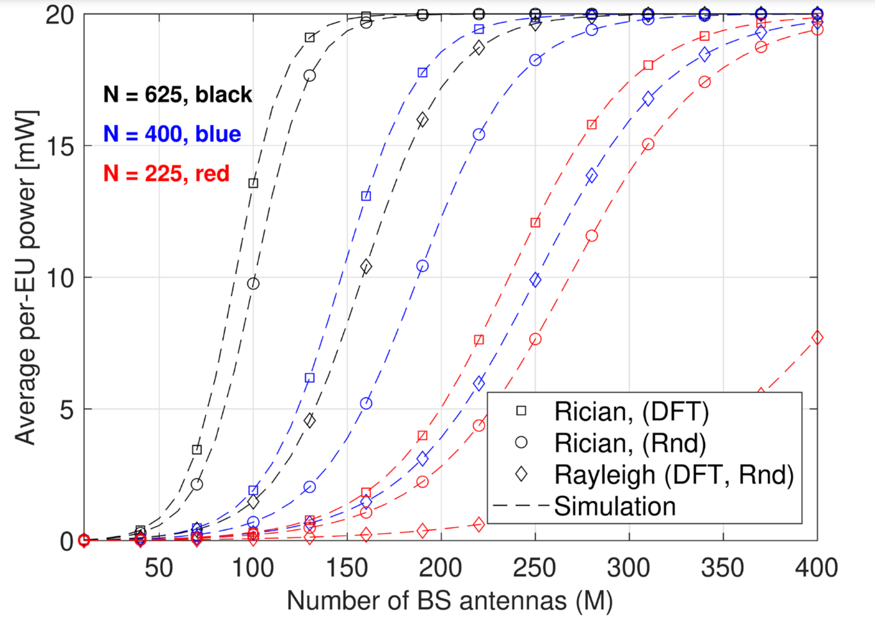


Fig. 2: Average harvested power ($K_I = 5$, $K_E = 3$).

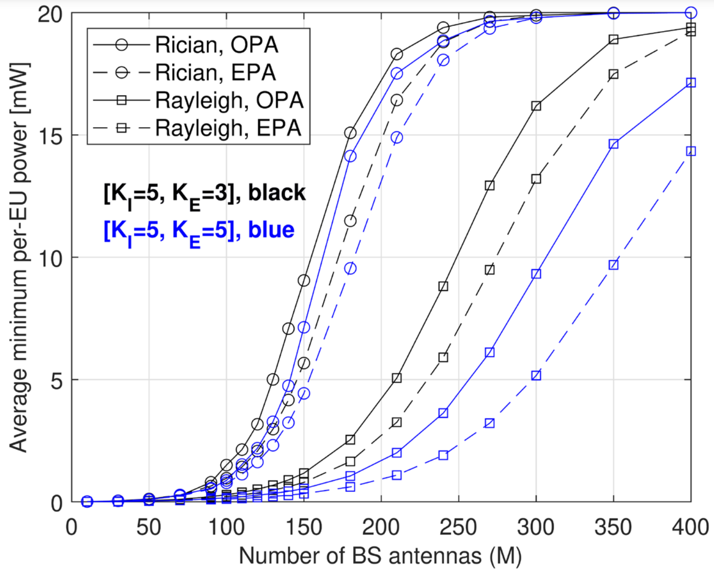


Fig. 3: Average minimum per-UE harvested power with equal and optimal power allocation ($N = 400$).

Relevant publications

- M. Mohammadi, H. Q. Ngo, and M. Matthaiou, "Cell-free massive MIMO meets OTFS modulation," *IEEE Transactions on Communications*, vol. 70, no. 11, pp. 7728–7747, Nov. 2022.
- M. Mohammadi, H. Q. Ngo, and M. Matthaiou, "Cell-free massive MIMO with OTFS modulation: Statistical CSI-based detection," *IEEE Wireless Communication Letters*, vol. 12, no. 6, pp. 987–991, June 2023.
- M. Mohammadi, T. T. Vu, H. Q. Ngo, and M. Matthaiou, "Network-assisted full-duplex cell-free massive MIMO: Spectral and energy efficiencies," *IEEE Journal on Selected Areas in Communications*, 2023.
- M. Mohammadi, L.-N. Tran, Z. Mobini, H. Q. Ngo, and M. Matthaiou, "Cell-free massive MIMO and SWIPT: Access point operation mode selection and power control," submitted to *IEEE GLOBECOM 2023*.
- M. Mohammadi, Z. Mobini, H. Q. Ngo, and M. Matthaiou, "Integration of massive MIMO and RIS to serve energy and information users," in *Proc. IEEE ICC*, May 2023.

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