

Towards Sustainable Networks: Is Cell-Free Massive MIMO the Answer?

Ozan Alp Topal

August 21

SweWIN RA3 Workshop on Resource Management
and Orchestration

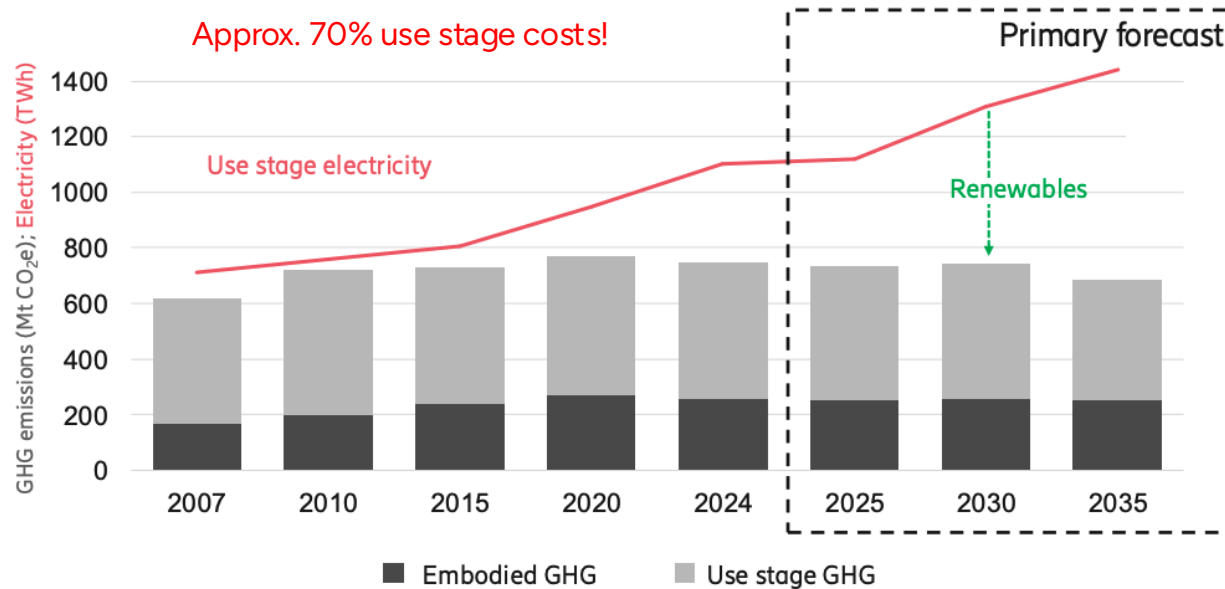


SweWIN

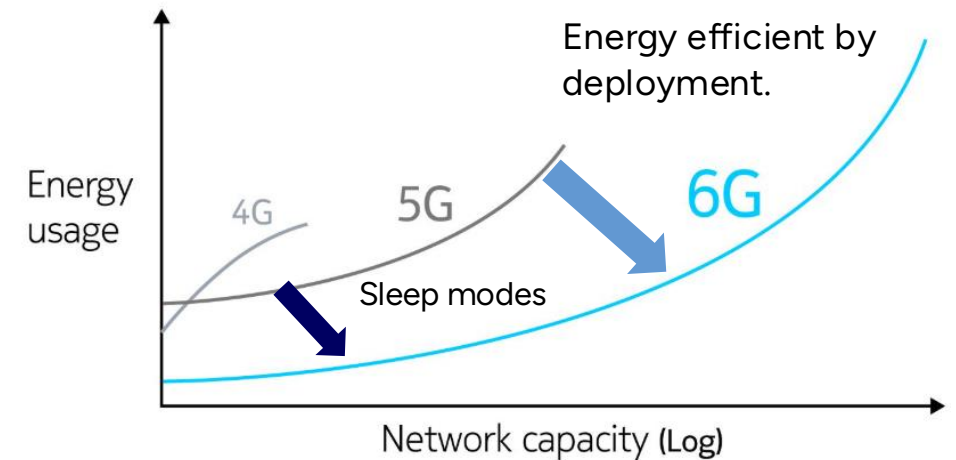
Swedish Wireless Innovation Network

Energy Consumption and Sustainability in Networks

ICT carbon footprint and electricity use until 2035, Ericsson, 2026



- Can we decouple energy consumption and high performance?
 - How to do it?



Flexible network deployment



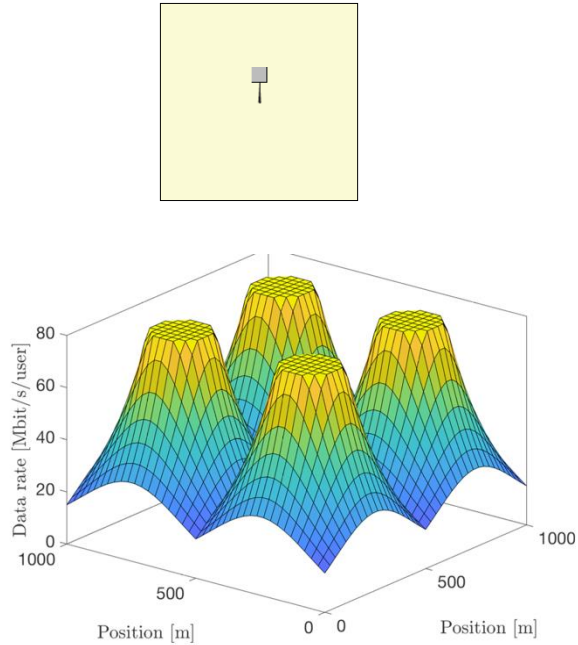
Energy-aware resource allocation

[Left-side figure] <https://www.bell-labs.com/institute/blog/in-the-6g-era-we-wont-need-to-sacrifice-sustainability-for-the-sake-of-performance>

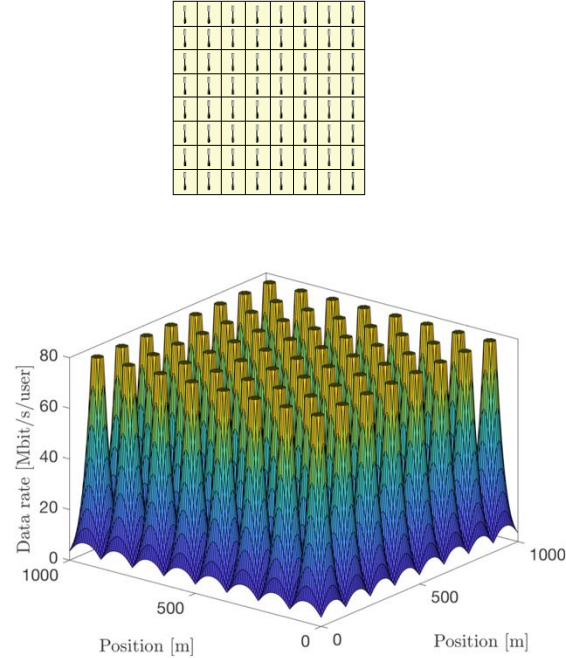
[Right-side figure] Ericsson, Electricity use and GHG emissions from the ICT sector, Presentation at SweWIN, 14 April 2026 Nina Lövehagen

From Massive MIMO to Cell-Free Massive MIMO

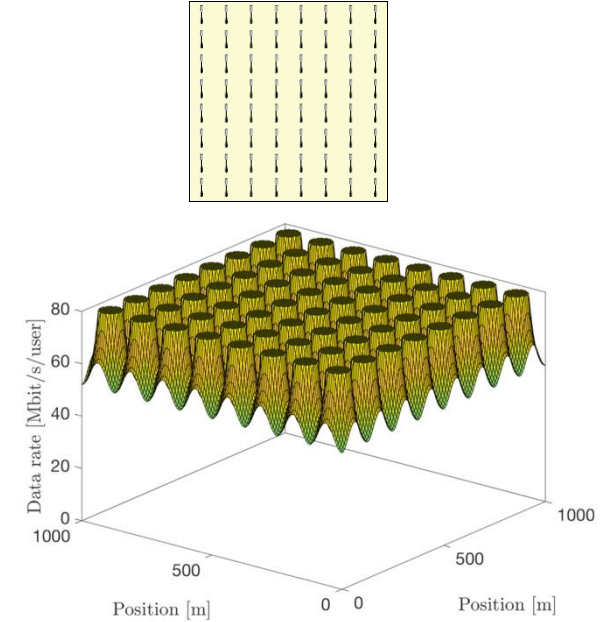
Massive MIMO (5G)



Small cell (4G-5G)

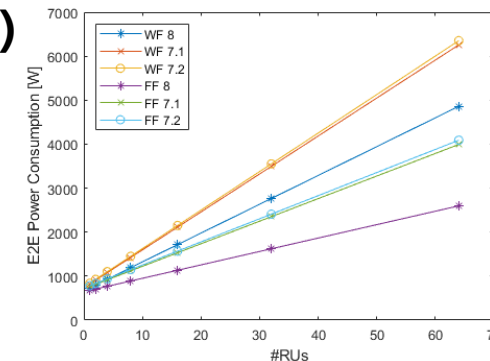


Cell-free massive MIMO (6G?)



Why cell-free is not mainstream yet? (upcoming with 6G?)

- Expensive deployment
 - **Fiber digging the ground**
 - Rental site costs,
 - Tight synchronization, expensive radio
- **Higher running energy consumption!**

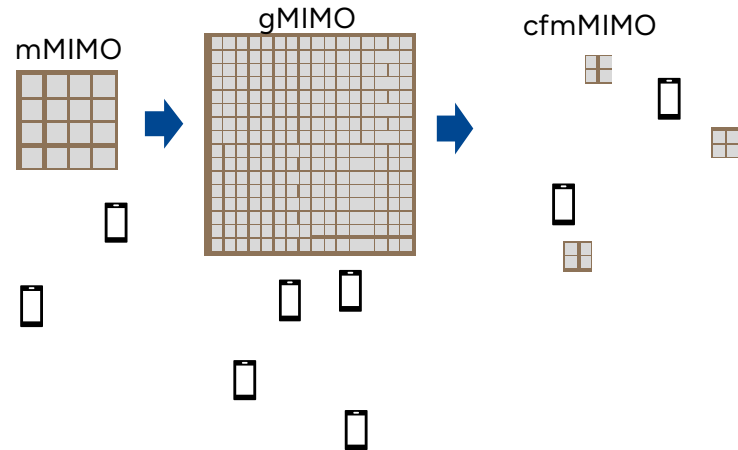


(Full-power all
RUs serving all
UEs)

Energy Consumption and Sustainability in Networks

Flexibility in the radio

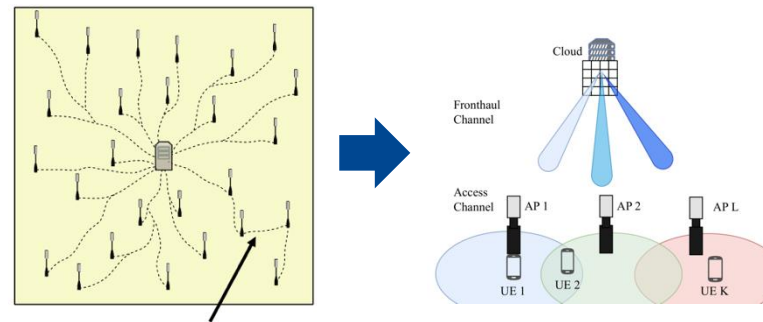
Cell-free massive MIMO



- More of the same is not a solution!
 - Cell-edge either suffers or consumes high energy
- Distributed small dense radio + coherent joint processing = cell-free massive MIMO
 - Ideally no-cell edge users → higher EE

Flexibility in the fronthaul

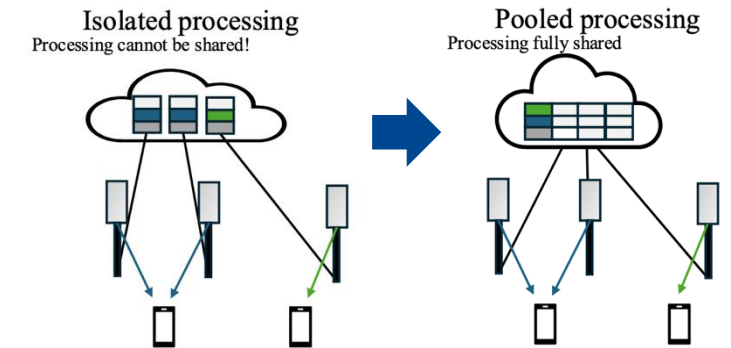
Wireless fronthaul



- Easy flexible deployment
- Fronthaul can be shared.
- Wireless connectivity → coverage issues
- Higher power consumption compared to the fiber!

Flexibility in the processing

Virtualization & cloudification



- Decouple proprietary hardware and software -> easy updates, reduced hardware footprint
- Host multiple workloads -> higher resource efficiency
- Processing pooling -> higher efficiency

Energy-aware resource allocation for radio, fronthaul and processing!!!

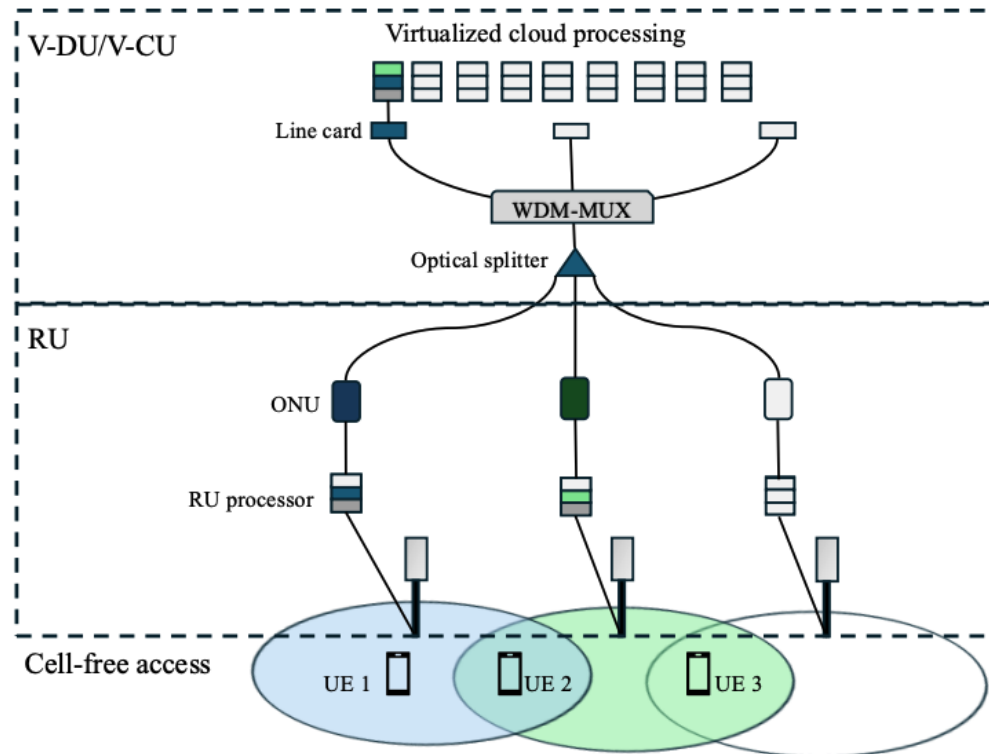
Outline

1. **Cell-free massive MIMO in Virtualized Cloud-RAN**
2. Which resources should we play with to save the most energy?
 - Energy-efficient joint radio, fronthaul, and processing allocation
3. What are the WF limitations, and how much can we overcome them?
 - Joint fronthaul & access resource allocation
4. Conclusion & Discussion

Works to be presented in this talk:

- [1] O. A. Topal, Ö. T. Demir, and C. Cavdar, "Rethinking Energy Efficiency in Cell-Free Massive MIMO: The Role of Processing and Optical Fronthaul," submitted to ICTON 2026.
- [2] O. A. Topal, Ö. T. Demir, E. Björnson, and C. Cavdar, "Joint Access and Fronthaul Resource Allocation for Cell-Free Massive MIMO with Wireless Fronthaul," submitted to SPAWC 2026.
- [3] O. A. Topal, Ö. T. Demir, E. Björnson, C. Cavdar, "Unlocking the Energy-Saving Potential in O-RAN Cell-Free Massive MIMO by Joint Orchestration of Radio, Wireless Fronthaul, and Cloud Resources", IEEE Transactions on Wireless Communications, major revision submitted July 2026

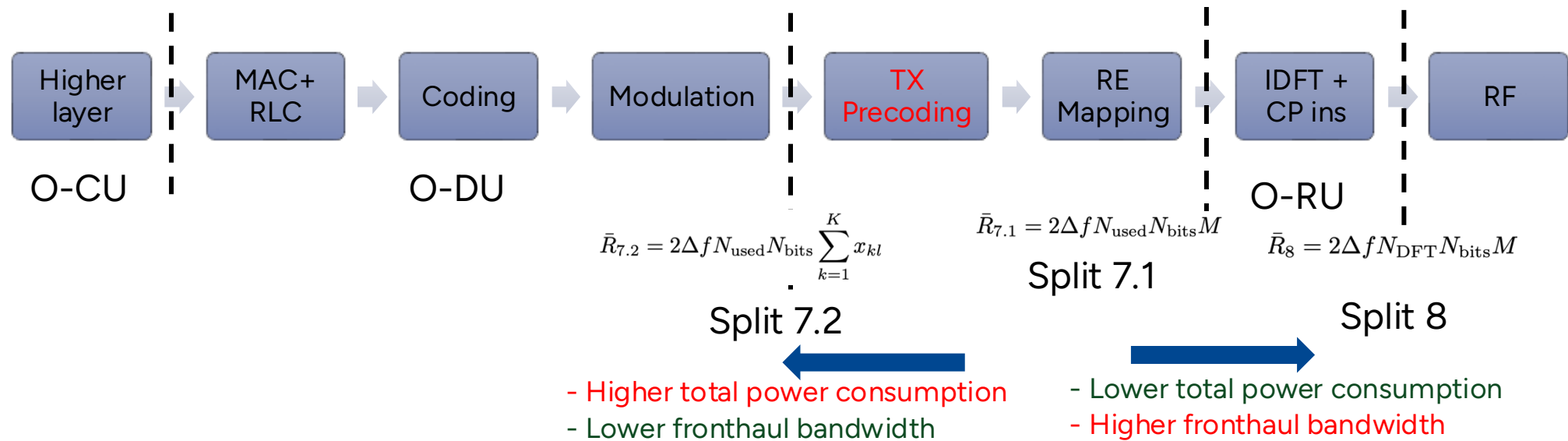
Cell-Free Massive MIMO & Virtualized Cloud RAN



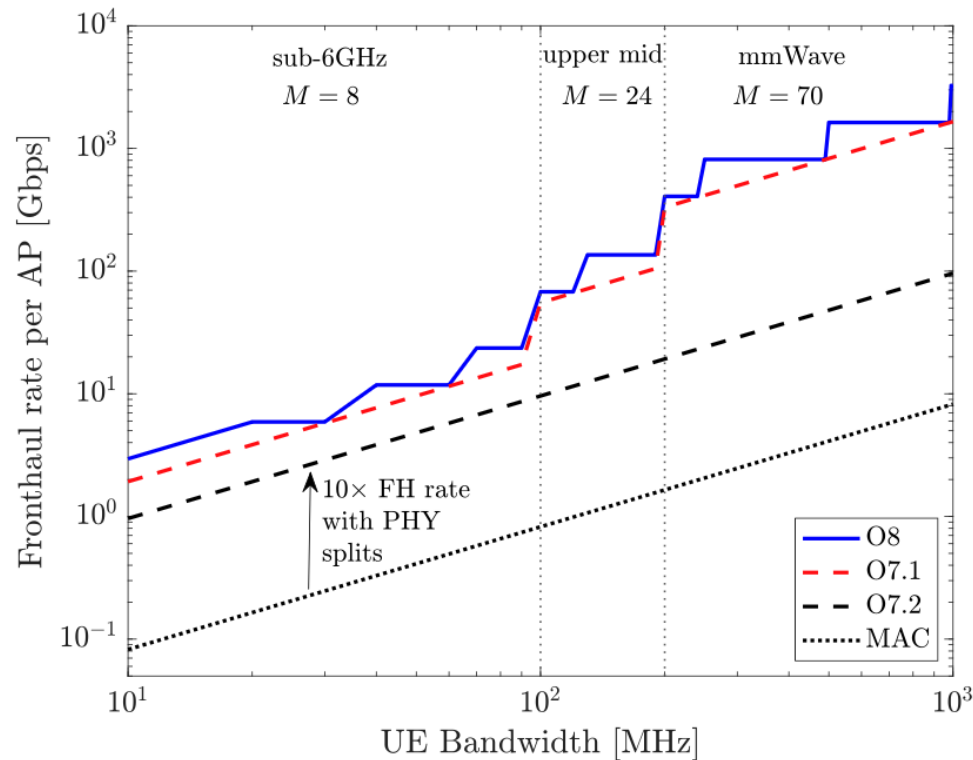
- Downlink cell-free massive MIMO system realized on top of O-RAN architecture.
- Evolved CPRI (e-CPRI) for fronthaul
- A time-and wavelength-division multiplexed passive optical network (TWDM-PON) is utilized.
 - Each line card (LC) is assigned to a wavelength.
 - Several RUs share the same wavelength with TDMA.
- Access is sub-6GHz band
- Near-RT controller can configure jointly:
 - Active circuits in radio
 - Processing cores
 - Line cards

Functional Splits and Fronthaul Rate in cfmMIMO

- Only split options 8, 7.1 and 7.2 are viable in cfmMIMO.



Functional Splits and Fronthaul Rate in cfmMIMO



$$\bar{R}_{7.2} = 2\Delta f N_{\text{used}} N_{\text{bits}} \sum_{k=1}^K x_{kl}$$

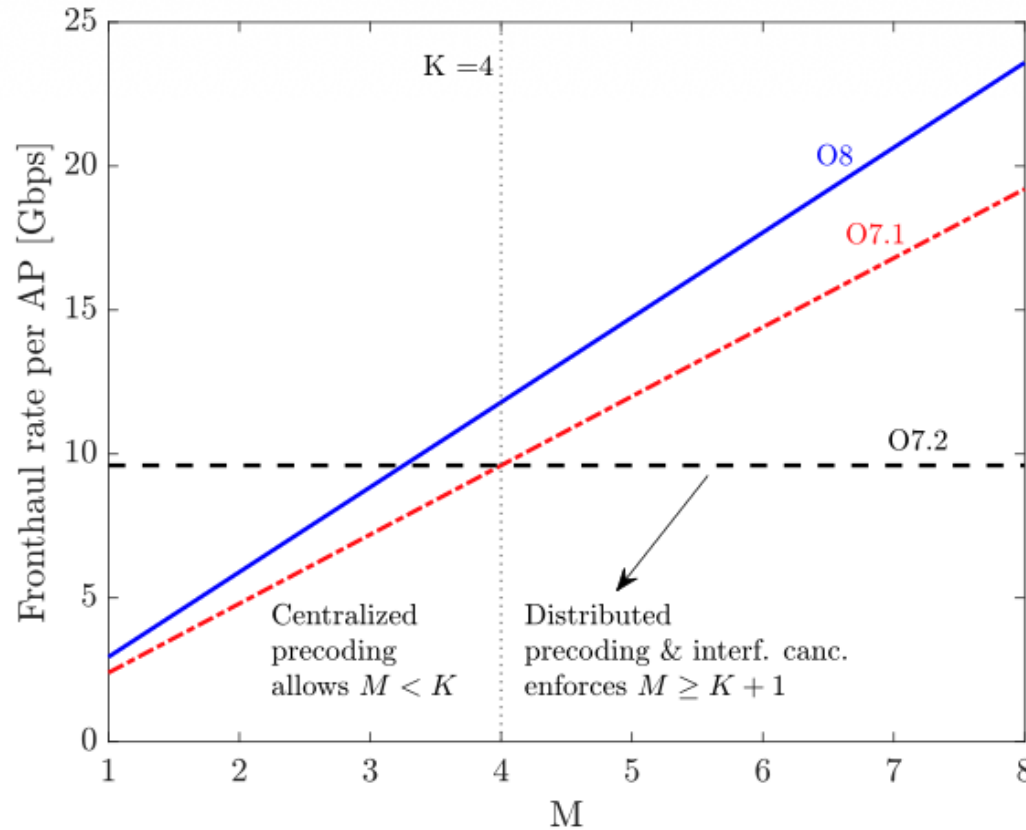
$$\bar{R}_{7.1} = 2\Delta f N_{\text{used}} N_{\text{bits}} M$$

$$\bar{R}_8 = 2\Delta f N_{\text{DFT}} N_{\text{bits}} M$$

- PHY splits require significantly high FH rate.
 - mmWave -> up to 5 Tbps data rate requirement!
- Potential solutions:
- Lowering quantization bits,
 - Array of subarrays (lowering precoding control)
- Antenna and radio turning off is necessary!

Active Antennas and Fronthaul Rate

- We let the considered AP serves 4 UEs.



Centralized precoding can act as a fronthaul data compression per radio.

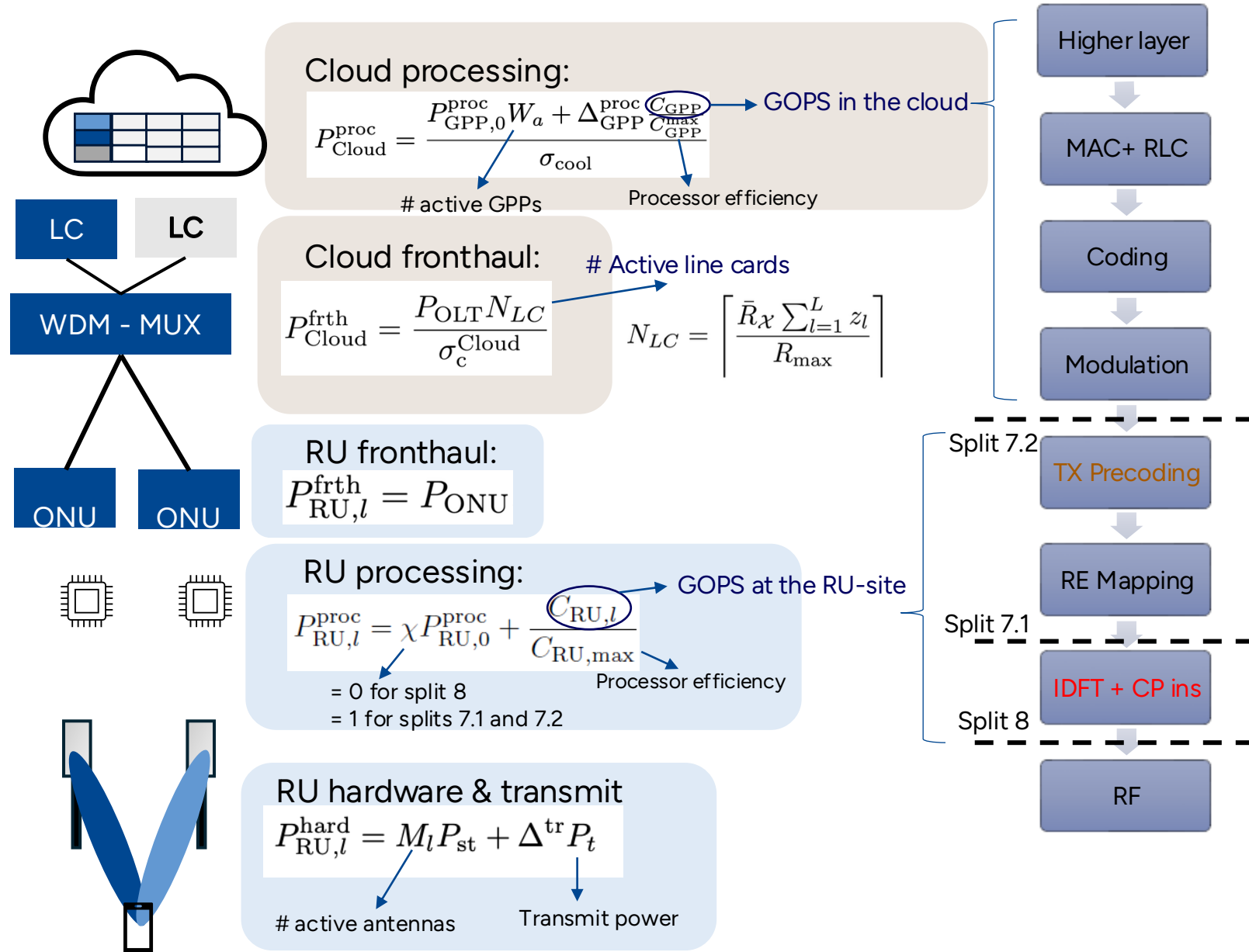
Outline

1. Cell-free massive MIMO in Virtualized Cloud-RAN
- 2. Which resources should we play with to save the most energy?**
 - **Energy-efficient joint radio, fronthaul, and processing allocation**
3. What are the WF limitations, and how much can we overcome them?
 - Joint fronthaul & access resource allocation
4. Conclusion & Discussion

Works to be presented in this talk:

- [1] O. A. Topal, Ö. T. Demir, and C. Cavdar, "Rethinking Energy Efficiency in Cell-Free Massive MIMO: The Role of Processing and Optical Fronthaul," submitted to ICTON 2026.
- [2] O. A. Topal, Ö. T. Demir, E. Björnson, and C. Cavdar, "Joint Access and Fronthaul Resource Allocation for Cell-Free Massive MIMO with Wireless Fronthaul," submitted to SPAWC 2026.
- [3] O. A. Topal, Ö. T. Demir, E. Björnson, C. Cavdar, "Unlocking the Energy-Saving Potential in O-RAN Cell-Free Massive MIMO by Joint Orchestration of Radio, Wireless Fronthaul, and Cloud Resources", IEEE Transactions on Wireless Communications, major revision submitted July 2026

A Modular End-to-End Power Consumption Model



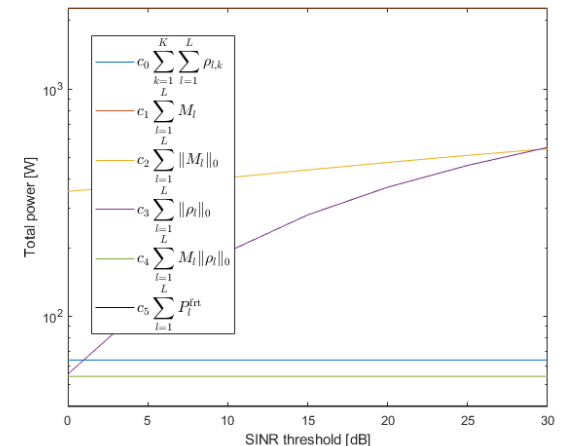
!Key assumption: Turned-off part consumes no idle power

End to end power:

$$P_{\text{tot}} = \sum_{l=1}^L (P_{\text{RU},l} + P_{\text{RU},l}^{\text{frth}}) + P_{\text{Cloud}} + P_{\text{Cloud}}^{\text{frth}}$$

Following resources effect power consumption in network:

1. Transmit power
2. **#Active antennas**
3. **#Active RUs**
4. RU-UE association
5. #Active fronthaul antennas



End to End Power Minimization

- Deployment phase: Decide #RUs, #antennas per RU, fronthaul radio equipment, processors, and functional split.
- For a given deployment, and large-scale fading coefficients solve end to end power minimization problem:

$$\begin{aligned}
 & \underset{\{M_l, \rho_{l,k}, \bar{p}_l, t_i\}}{\text{minimize}} && P_{\text{total}} \\
 & \text{subject to} && \\
 & \text{SINR}_k \geq v_k, \quad \forall k && \text{UE SINR thresholds} \\
 & \sum_{k=1}^K \rho_k \leq P_t \quad \forall l && \text{Transmit power limit} \\
 & M_l \in \{\tau_{S_l} + 1, \dots, M^{\text{ac}}\}, \quad \forall l && \text{Active \#antennas per RU}
 \end{aligned}$$

Features	8	7.1	7.2
Precoding	Centralized	Centralized	Distributed
FH rate scale	#Antennas	#Antennas	#UE streams
Algorithm	Group-sparse	Group-sparse	Block-coordinate descent

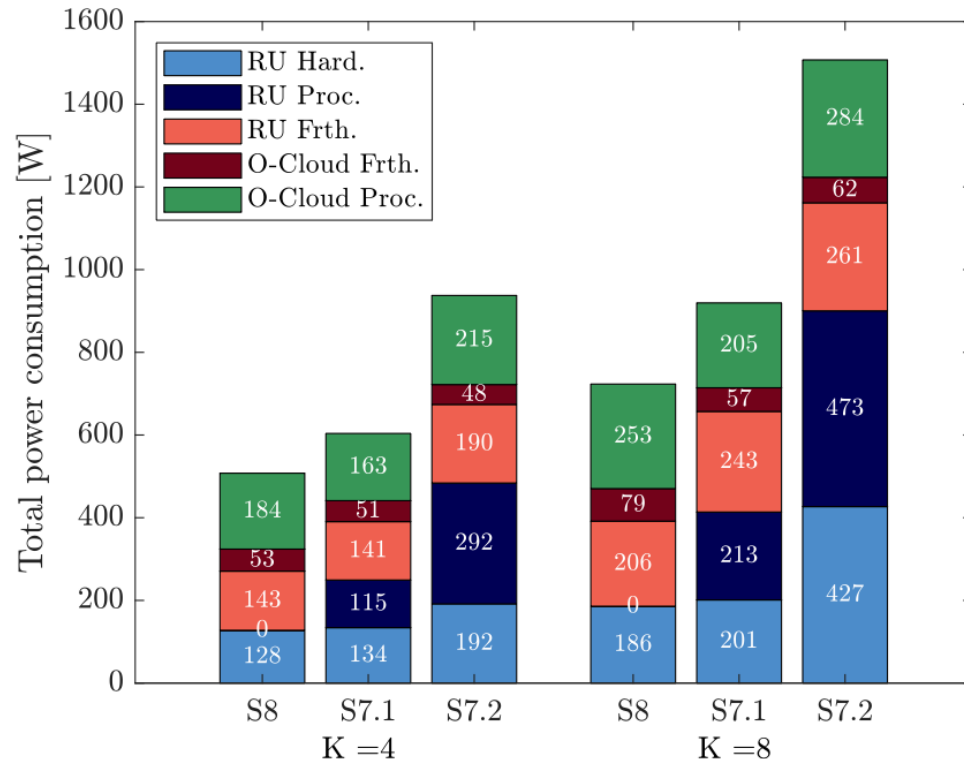
- After solving the problem, check fronthaul, turn off any unnecessary RF chain or antennas.
- Turn off processors that are not utilized.

Simulation Setup

- 5G scenario, 3.5 GHz access channel.
- 1 km x 1 km square region
- RUs grid deployment each equipped.
- UEs are uniformly distributed, SE requirement is set to 2 bit/Sc/Hz.

f_s, B^{ac}	122.88, 100 MHz	T_s	35.68 μs
P_t , pilot pow.	5, 0.5 W	P_{fixed}	120 W
$\sigma_c^{\text{Cloud}}, \sigma_c^{\text{RU}}$	0.9, 1	τ_c, τ_p	260, 6
$C_{\text{GPP}}^{\text{max}}, C_{\text{RU}}^{\text{max}}$	360, 180 GOPS	P_{st}	6.8 W
$P_{\text{OLT}}, P_{\text{ONU}}$	20, 1.8 W	Δ_r, Δ_c	74 W
$N_{\text{DFT}}, N_{\text{used}}$	4096, 2667	N_{bits}	12
$P_{\text{RU},0}^{\text{Proc}}, P_{\text{GPP},0}^{\text{Proc}}$	20.8 W	Δ^{tr}	4

Power Consumption vs Functional Splits



In cfmMIMO, processing and fronthaul dominates!

RU Hardware: Split 7.2 higher radio hardware PC: **Distributed precoding is inefficient, more antennas active!**

RU Processing: In higher splits, more processing is done in the RU site --> high power consumption

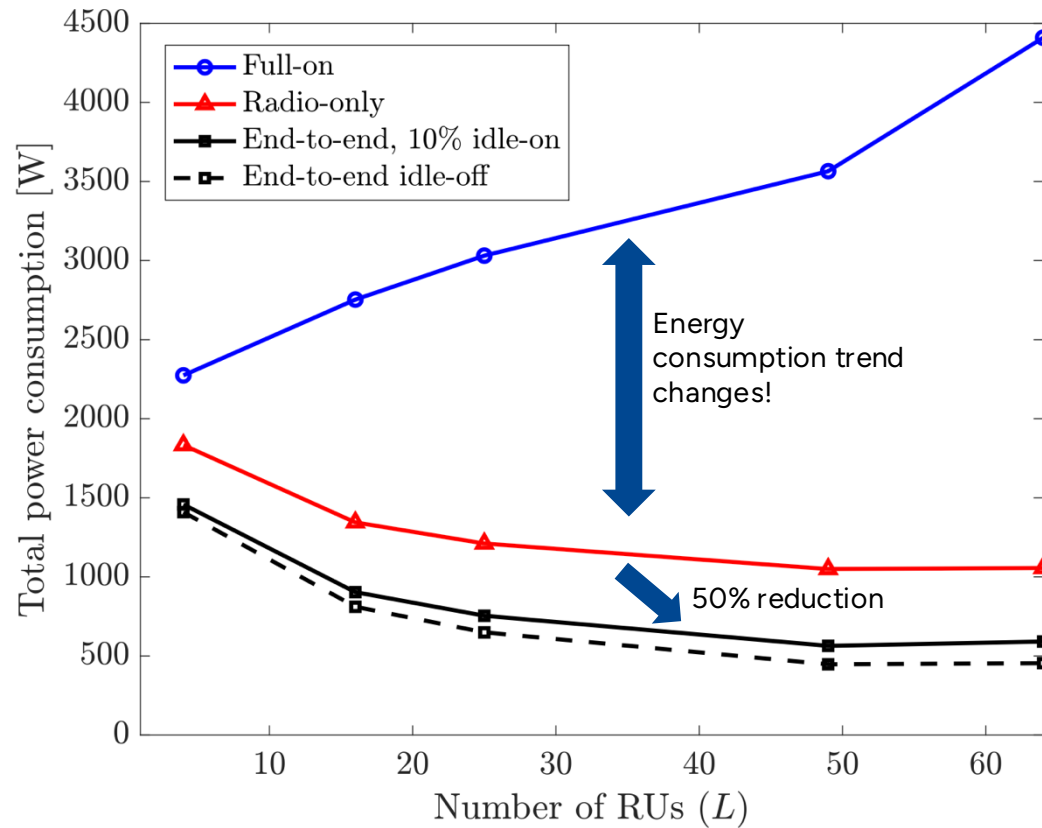
RU Fronthaul: Split 7.1 and 8 should be same but in K=8, split 8 consumes less due to more strict fronthaul rate constraint.

Cloud Fronthaul: Split 7.2 consumes unnecessarily for K=8.

Cloud Processing: Split 7.2 consumes unnecessarily!

Centralized precoding pays off!

Power Consumption vs Deployment

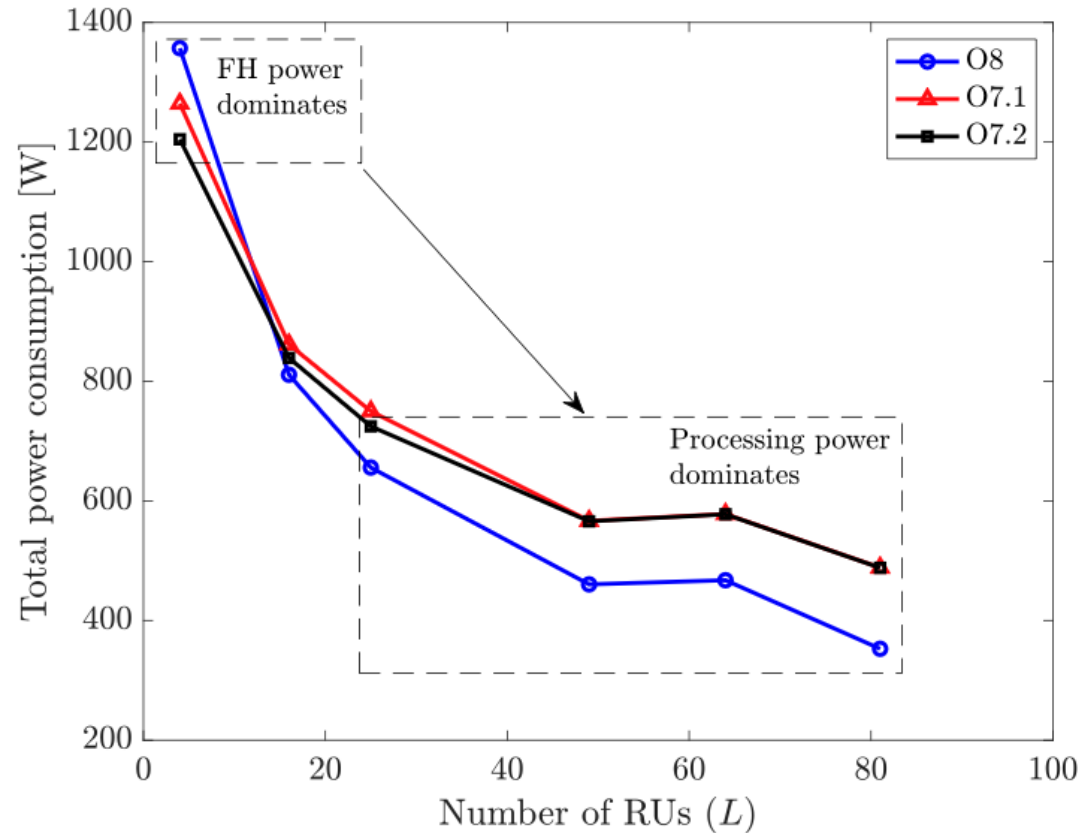


Denser deployment → higher energy consumption

Denser deployment + intelligent control → lower power consumption

[A simpler heuristic is implemented, split 8 is considered.]

Functional Split vs Deployment



[A simpler heuristic is implemented.]

- Power consumption reduction trend occurs in all splits.
- Distribute radio + centralize processing + energy-aware resource allocation:
 - Reduced fronthaul load
 - Reduced processing power due to less processors active
 - Flexible radio activation based on demand

Outline

1. Cell-free massive MIMO in Virtualized Cloud-RAN
2. Which resources should we play with to save the most energy?
 - Energy-efficient joint radio, fronthaul, and processing allocation
3. **What are the WF limitations, and how much can we overcome them?**
 - **Joint fronthaul & access resource allocation**
4. Conclusion & Discussion

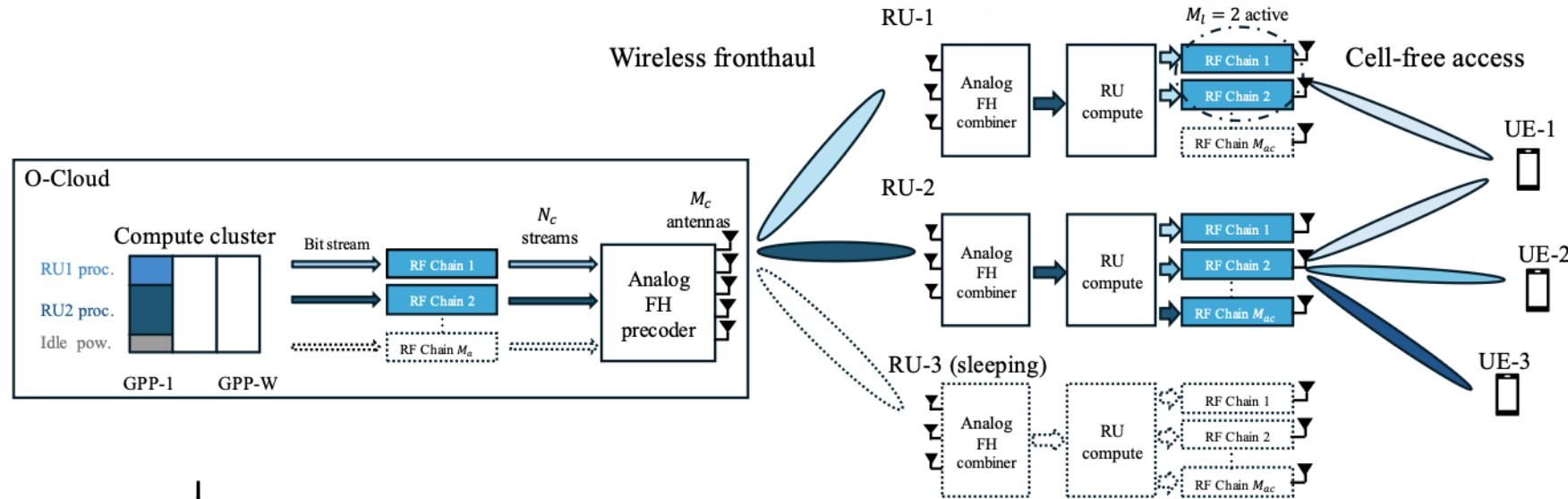
Works to be presented in this talk:

[1] O. A. Topal, Ö. T. Demir, and C. Cavdar, "Rethinking Energy Efficiency in Cell-Free Massive MIMO: The Role of Processing and Optical Fronthaul," submitted to ICTON 2026.

[2] O. A. Topal, Ö. T. Demir, E. Björnson, and C. Cavdar, "Joint Access and Fronthaul Resource Allocation for Cell-Free Massive MIMO with Wireless Fronthaul," submitted to SPAWC 2026.

[3] O. A. Topal, Ö. T. Demir, E. Björnson, C. Cavdar, "Unlocking the Energy-Saving Potential in O-RAN Cell-Free Massive MIMO by Joint Orchestration of Radio, Wireless Fronthaul, and Cloud Resources", IEEE Transactions on Wireless Communications, major revision submitted July 2026

Wireless Fronthaul in Cell-Free Massive MIMO



How to jointly allocate fronthaul and access resources to maximize the minimum UE performance?

Fronthaul link:

- mmWave band
- LOS channels, perfect CSI
- Full SDMA
- N_c RF chains, M_c antennas
- Hybrid beamforming, analog combining
 - ZF precoder for digital part, phase matching for analog precoder, combiner

$$R_l^f = B^{\text{frh}} \log_2 (1 + G_l \bar{p}_l)$$

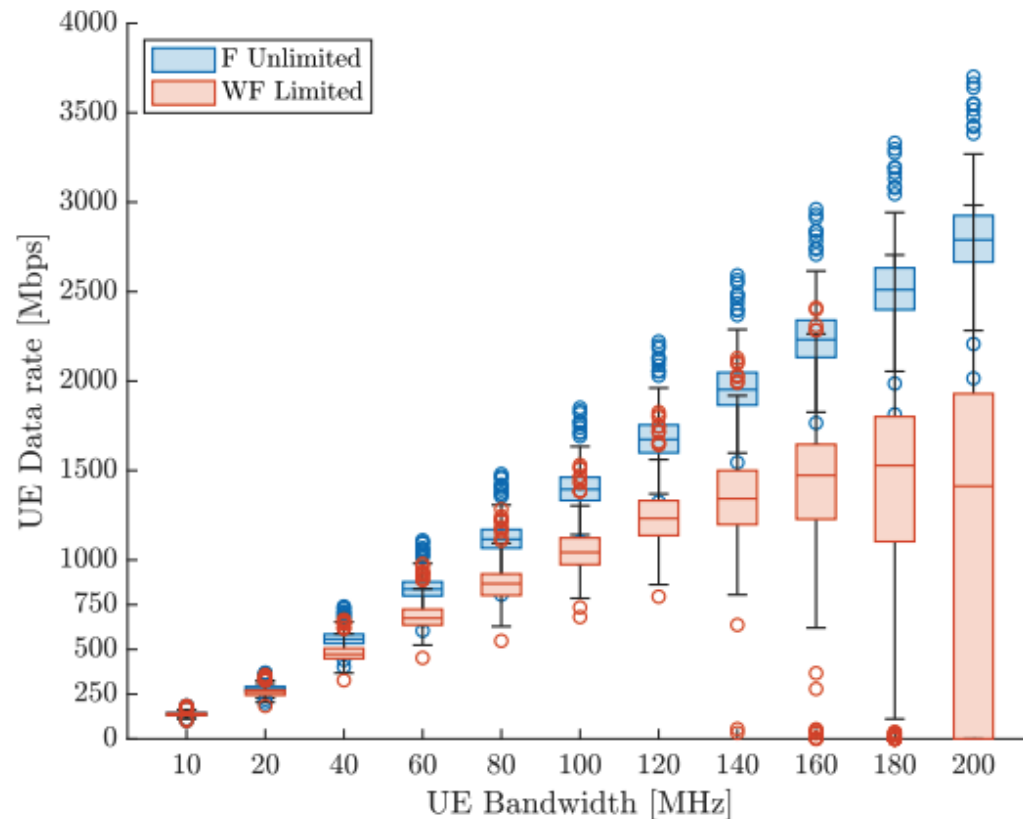
$$\max_{M_l, \bar{p}_l} \min_k SINR_k$$

subject to:

$$R_l^f \geq O_x M_l, \forall l$$

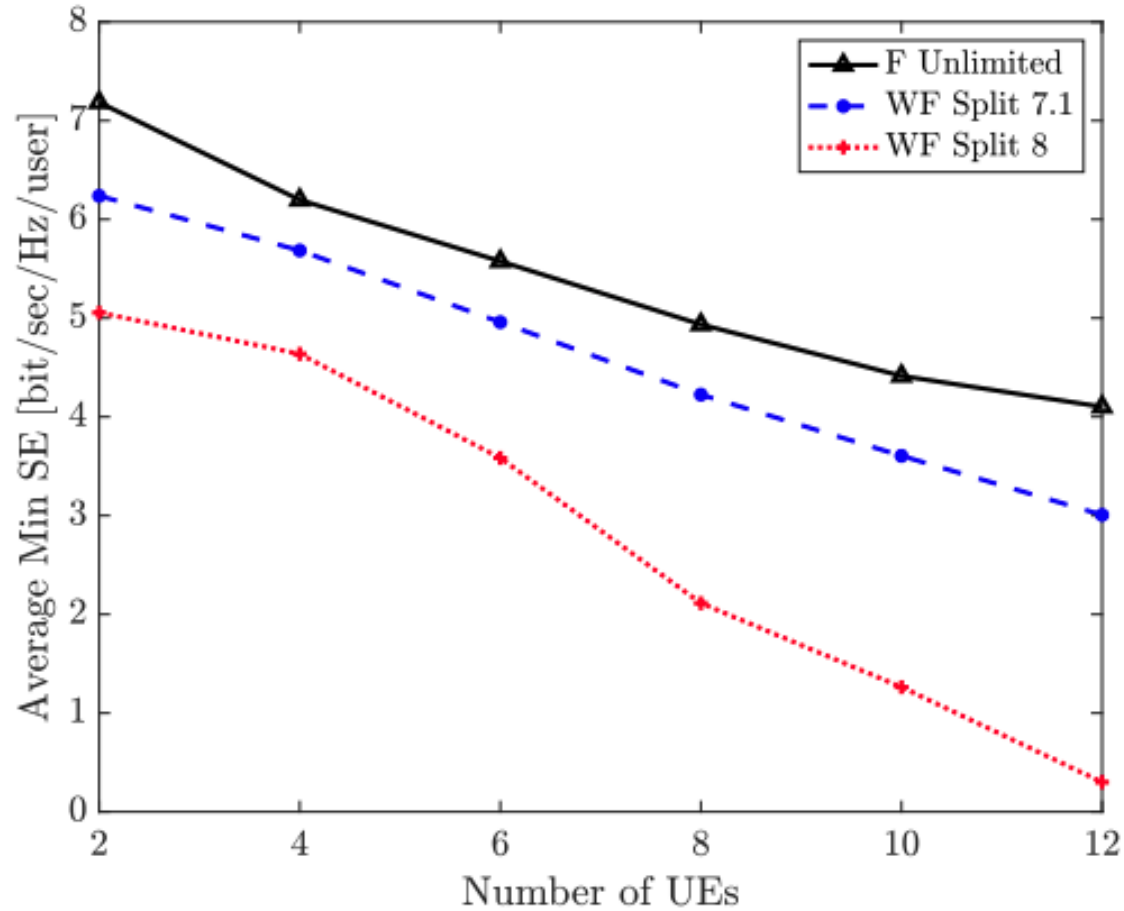
$$\sum_{l=1}^L \bar{p}_l \leq P_t$$

Single-UE Case



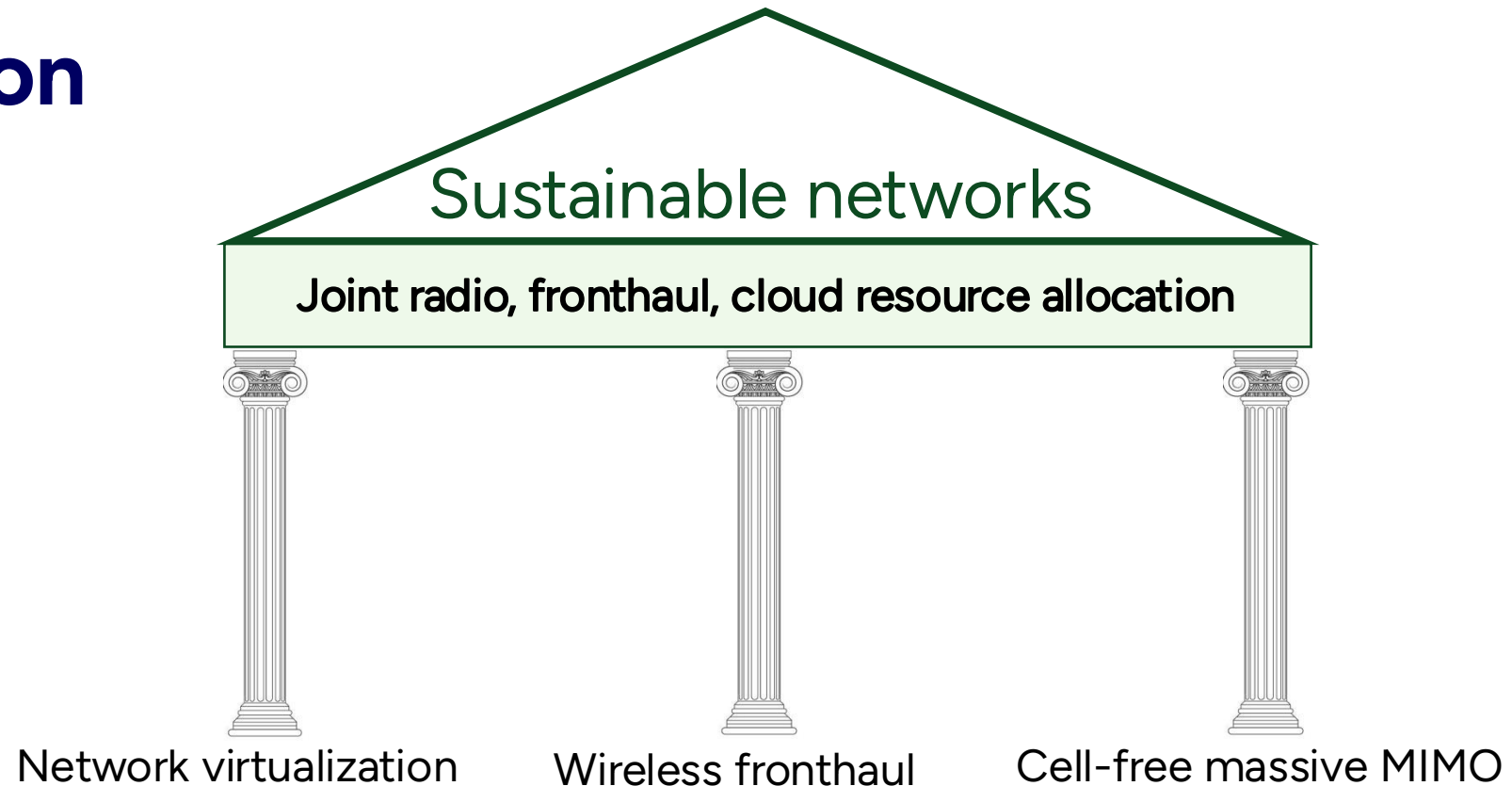
- 1 km x 1km region, 25 RUs with 8 antennas each
- 5 GHz access, 28 GHz for fronthaul links
- 200 MHz BW for fronthaul.
- WF limitation both:
 - Reduces UE performance after some bandwidth.
 - Creates inequality between different UE locations.

Multi-UE Case



- Split 8 limits performance severely.
 - The shift from 6 to 8 UEs are due to pilot contamination
- Split 7.1 overall performs close to unlimited case.

Conclusion



- Fronthaul design, and energy consumption trends are different than massive MIMO systems:
 1. **Fronthaul & processing consumes as much power as radio hardware.**
 2. **Using lower splits can lower the fronthaul load per radio, and save energy --> centralized operation**
 3. **Centralizing processing with split 7.1 seems ideal in many cases.**



Q&A

Thanks for listening!

ootopal@kth.se