Unlocking the Energy-Saving Potential in O-RAN Cell-Free Massive MIMO:

Joint Radio, Wireless Fronthaul, and Cloud Orchestration

Ozan Alp Topal

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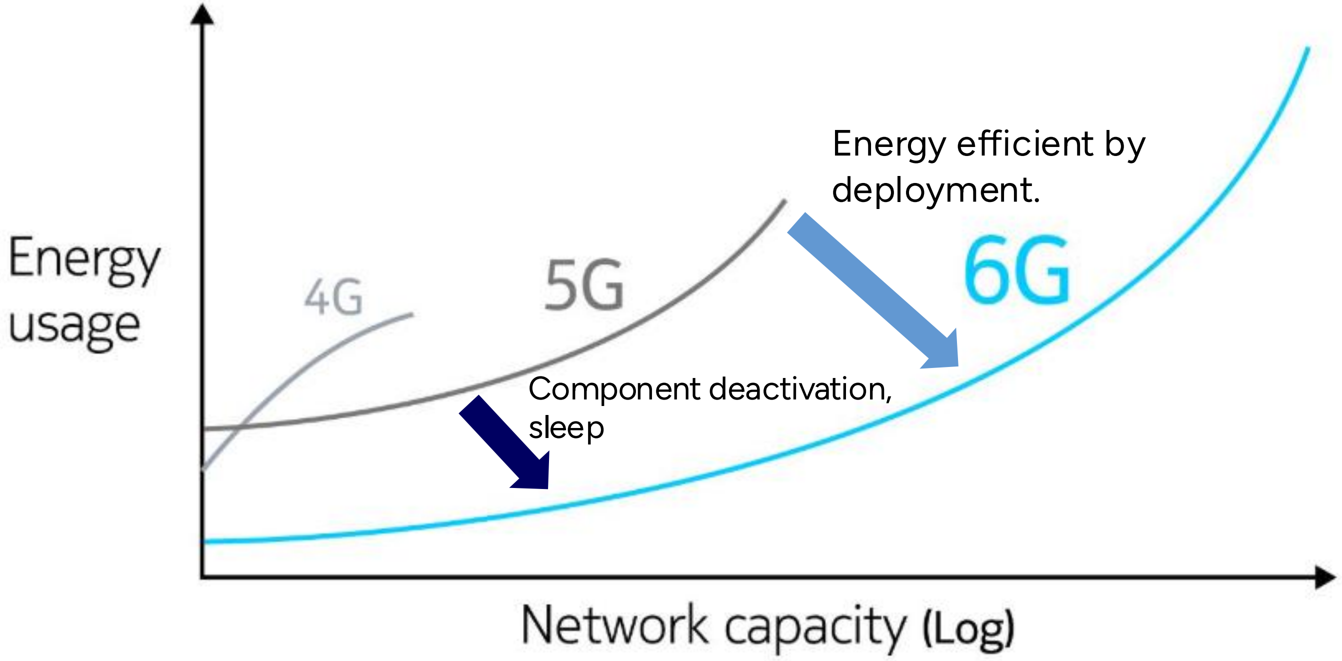
Energy Consumption and Sustainability in Networks



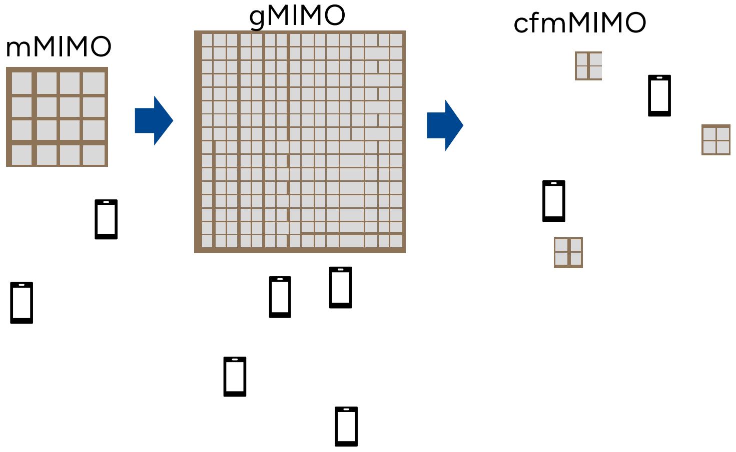
- Flexible network deployment
- Energy-aware resource allocation

*https://www.bell-labs.com/institute/blog/in-the-6g-era-we-wont-need-to-sacrifice-sustainability-for-the-sake-of-performance

Energy Consumption and Sustainability in Networks

Flexibility in the radio

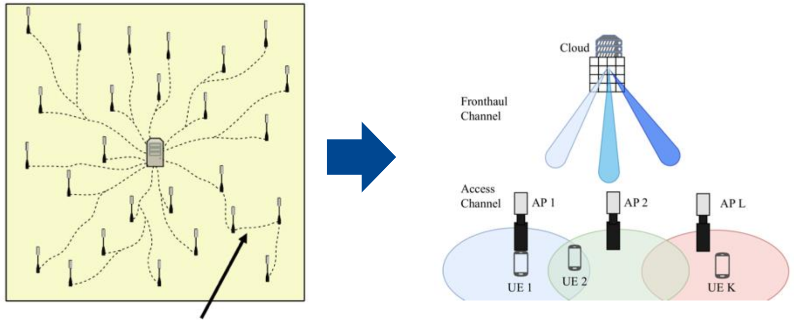
Cell-free massive MIMO



- More of the same is not a solution!
  - Diminishing returns due to correlation
  - 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

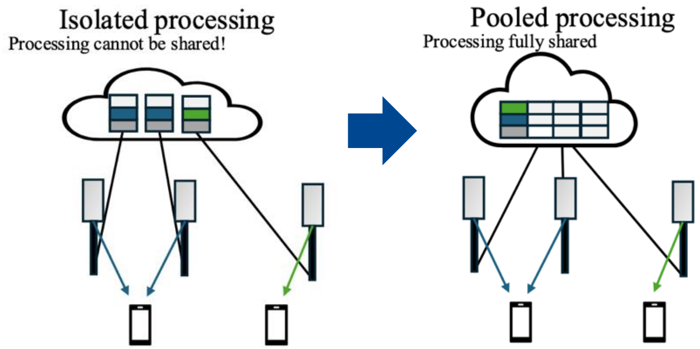
Wireless fronthaul



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

Flexibility in the processing

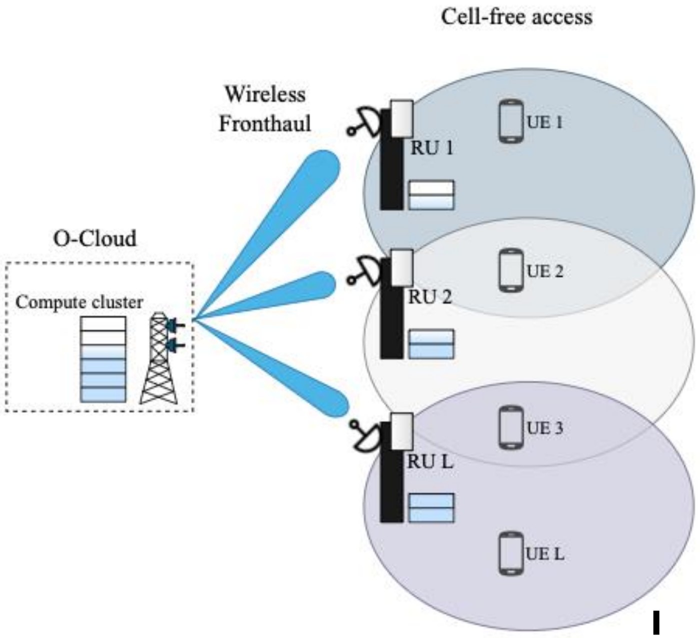
Virtualization & cloudification



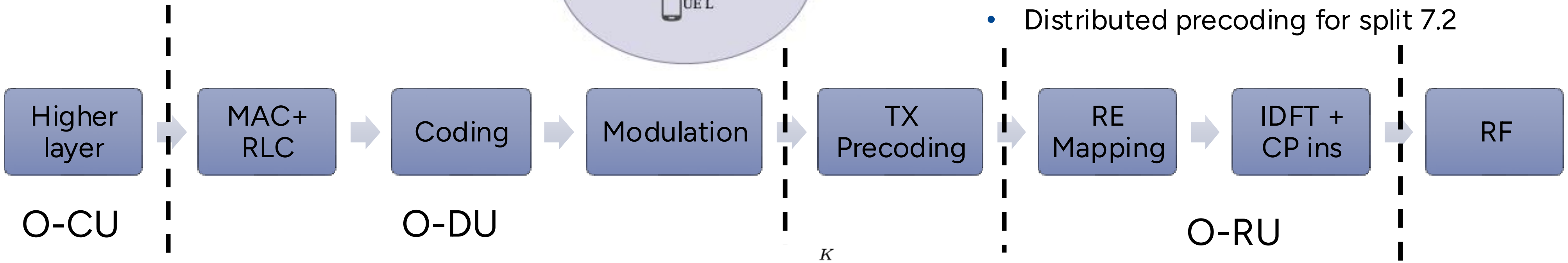
- Decouple proprietary hardware and software -> easy updates, reduced hardware footprint
- Host multiple workloads -> higher resource efficiency
- Processing pooling -> higher efficiency

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

Cell-Free Massive MIMO & Open RAN



- Downlink cell-free massive MIMO system realized on top of O-RAN architecture.
- Only split options 8, 7.1 and 7.2 are viable in cfmMIMO.
- Wireless fronthaul is considered. (mmWave band)
  - mmWave band with TDMA/SDMA.
  - LOS connectivity
  - Hybrid beamforming, analog combining
- Access is sub-6GHz band
  - Centralized precoding for split 7.1 and 8
  - Distributed precoding for split 7.2



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

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

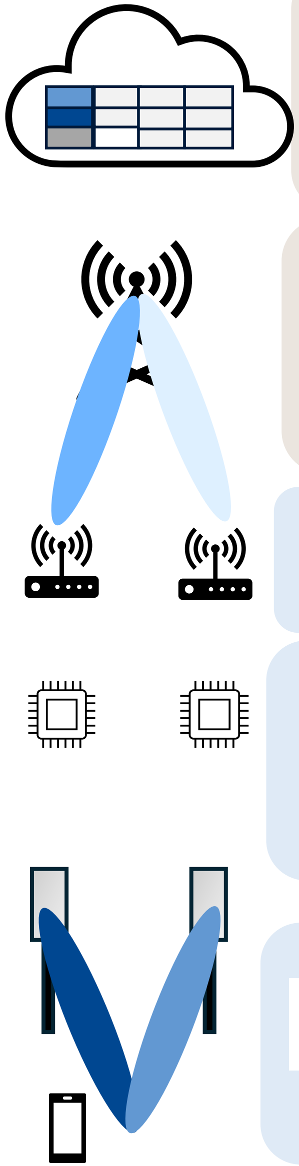
$$\bar{R}_{8} = 2\Delta f N_{\text{DFT}} N_{\text{bits}} M$$

Split 7.2 | Split 7.1 | Split 8

- Higher total power consumption
- Lower fronthaul bandwidth

- Lower total power consumption
- Higher fronthaul bandwidth

A Modular End-to-End Power Consumption Model



Cloud processing:

$$P_{\text{Cloud}}^{\text{proc}} = \frac{P_{\text{GPP},0}^{\text{proc}} W_a + \Delta_{\text{GPP}}^{\text{proc}} \frac{C_{\text{GPP}}}{C_{\text{GPP}}^{\max}}}{\sigma_{\text{cool}}}$$

GOPS in the cloud

active GPPs

Processor efficiency

Cloud fronthaul:

$$P_{\text{Cloud}}^{\text{frth}} = \Delta^{\text{fh}} \sum_{l=1}^{L} \bar{p}_l + M_c P_{\text{PA}} + N_c M_c P_{\text{PS}} + N_c (P_{\text{mix}} + P_{\text{DAC}})$$

FH transmit power

act. ant. for FH

act. RF chain

RU fronthaul:

$$P_{\text{RU},l}^{\text{fronth}} = P_{\text{ptp}}$$

RU processing:

$$P_{\text{RU},l}^{\text{proc}} = \chi P_{\text{RU},0}^{\text{proc}} + \frac{C_{\text{RU},l}}{C_{\text{RU},\max}}$$

GOPS at the RU-site

= 0 for split 8 and 7.1

= 1 for split 7.2

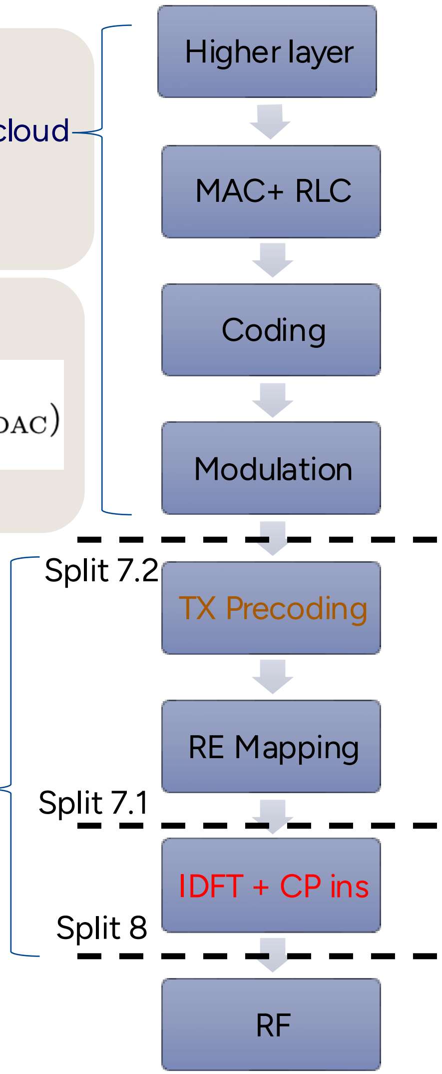
Processor efficiency

RU hardware & transmit

$$P_{\text{RU},l}^{\text{hard}} = M_l P_{\text{st}} + \Delta^{\text{tr}} P_t$$

active antennas

Transmit power



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

End to end power:

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

$$P_{\text{tot}} = \bar{P}_{\text{fixed}} + c_0 \sum_{k=1}^{K} \sum_{l=1}^{L} \rho_{kl} + c_1 \sum_{l=1}^{L} M_l + c_2 \sum_{l=1}^{L} \mathbb{I}(M_l) + c_3 \sum_{l=1}^{L} \sum_{k=1}^{K} \mathbb{I}(\rho_{kl}) + c_4 \sum_{l=1}^{L} M_l \left(\sum_{k=1}^{K} \mathbb{I}(\rho_{kl}) \right) + c_5 \sum_{l=1}^{L} \bar{p}_l$$

Following resources effect power consumption in network:

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

End to End Power Minimization

- Deployment phase: Decide #RUs, #antennas per RU, fronthaul radio equipment, processors, and functional split.
- Given deployment solve end to end power minimization problem:

$$\underset{\{M_l,\rho_{l,k},\bar{p}_l,t_i\}}{\text{minimize}} \quad P_{\text{total}} \tag{1a}$$

subject to

$$\text{SINR}_k \geq \upsilon_k, \quad \forall k \tag{1b}$$

UE SINR thresholds

$$t_i B^{\text{frh}} \log_2\left(1 + \Lambda_{il}\bar{p}_l\right) \geq O_{7.1} M_l, \quad \forall l \tag{1c}$$

Fronthaul rate constraints for chosen split!

$$\sum_{l=1}^{L} \alpha_{l,i}\bar{p}_l \leq P_f, \quad \forall i \tag{1d}$$

$$\sum_{i=1}^{I} t_i \leq 1 \tag{1e}$$

$$\sum_{k=1}^{K} \rho_k \leq P_t \quad \forall l \tag{1f}$$

$$M_l \in \{\tau_{S_l} + 1, \ldots, M^{\text{ac}}\}, \quad \forall l. \tag{1g}$$

(1d)–(1g): time, power, and antenna resource limitations

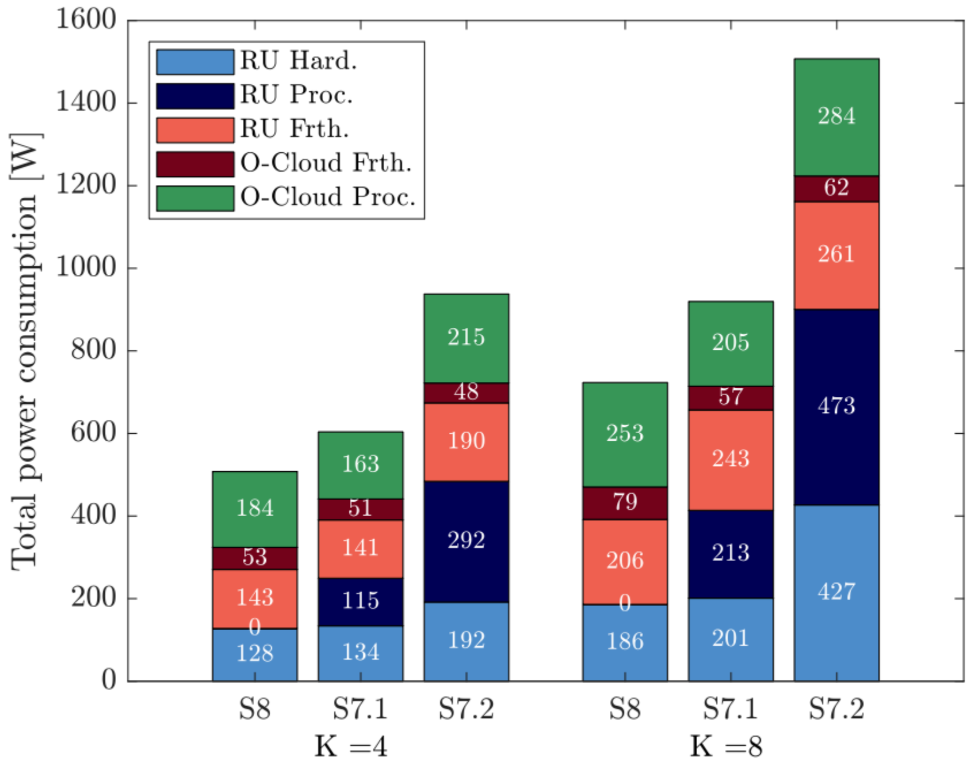
Features	8	7.1	7.2
Precoding	Centralized	Centralized	Distributed
FH rate scale	#Antennas	#Antennas	#UE streams
Algorithm	Group-sparse	Group-sparse	Block-coordinate descent

Simulation Setup

- 5G scenario, 3.5 GHz access channel, 28 GHz in wireless fronthaul
- 1 km x 1 km square region
- 16 RUs grid deployment each equipped with 8 antennas, cloud at the center.
- UEs are uniformly distributed, SE requirement is set to 2 bit/Sc/Hz.

M^{frh}, M_c	64, 256	N_{bits}	12
f_s, B^{ac}, B^{frh}	122.88, 100, 1000 MHz	T_s	35.68 μs
P_t, P_f, pilot pow.	5, 20, 0.5 W	P_{fixed}	120 W
τ_c, τ_p	260, 6	σ_{cool}	0.9
$C_{\text{GPP}}^{\max}$, $C_{\text{RU,max}}$	360, 180 GOPS	P_{st}	6.8 W
$\Delta_{\text{RU}}^{\text{proc}}$, $\Delta_{\text{GPP}}^{\text{proc}}$	74 W	P_0^{proc}	20.8 W
N_{DFT},N_{used}	4096, 2667	P_{comp}	20.8 W
P_{optc},P_{OLT}, P_{ptp}	1.8, 20, 35 W	$\Delta_{\text{vDU}}^{\text{fh}}$	4
P_{PA}, P_{PS}, P_{mix}	25, 75, 1000 mW	P_{DAC}	3.8 W

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

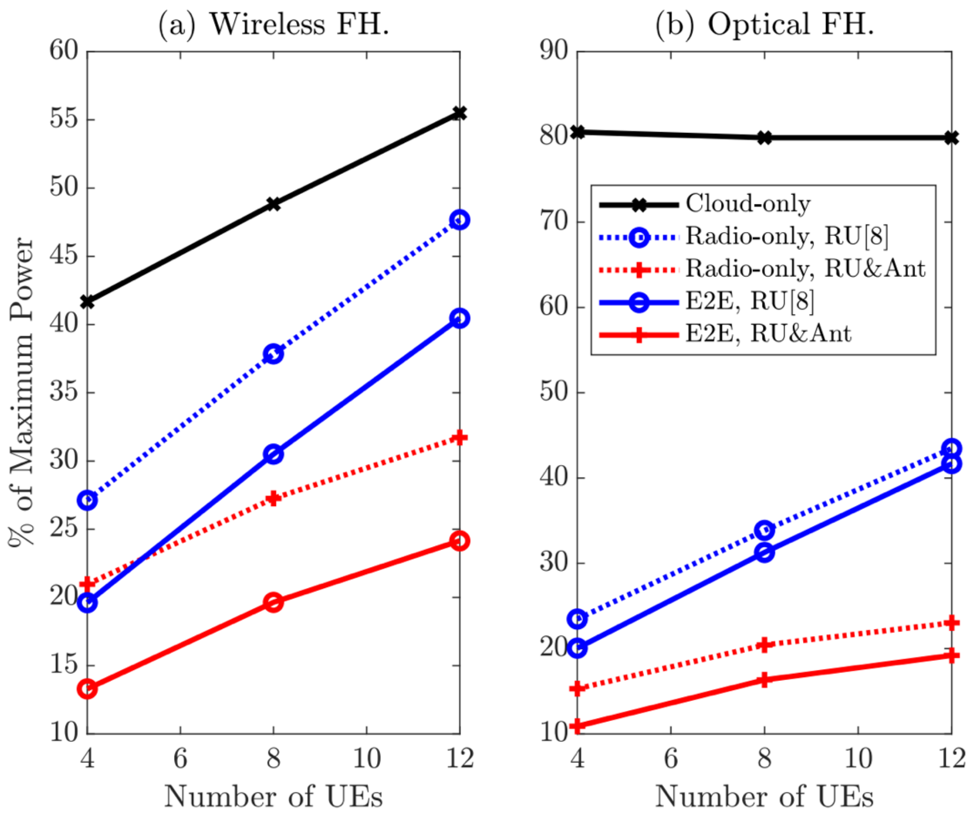
RU Fronthaul: Split 7.1 and 8 should be same but in K=8, split 8 consumes less due to more strict fronthaul rate constraint.

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

Cloud Processing: Split 7.2 consumes unnecessarily!

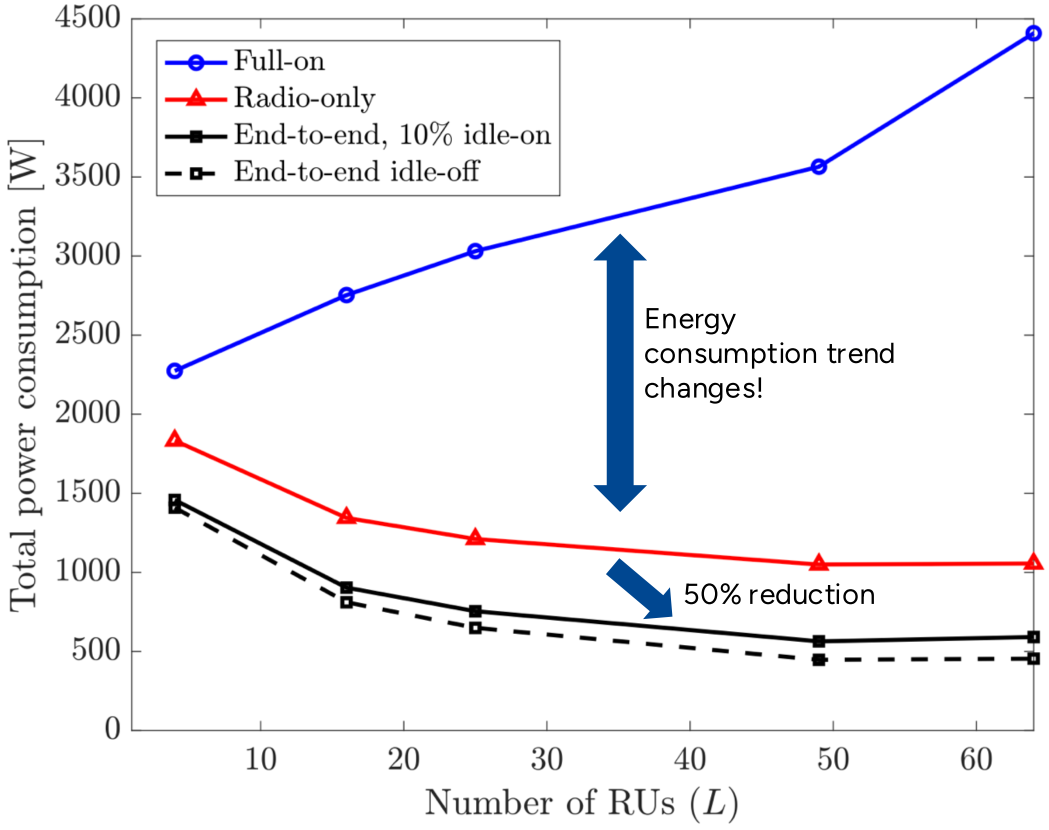
Centralized precoding pays off!

Benchmarking



- Approx. 70% energy can be saved with the proposed method!
- 10% further gain by fronthaul postprocessing.

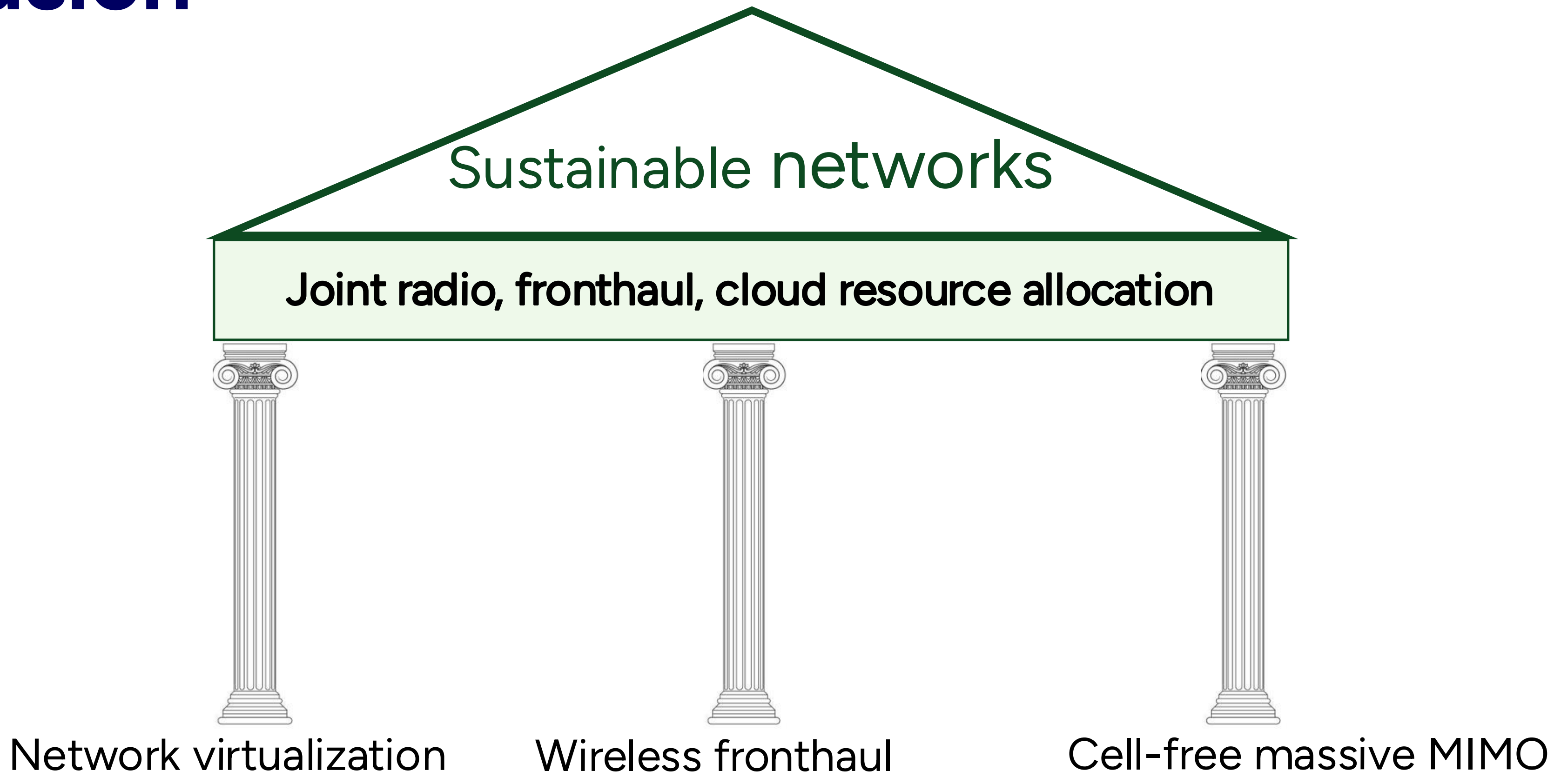
Power Consumption vs Deployment



Denser deployment –> higher energy consumption

Denser deployment + intelligent control –> lower power consumption

Conclusion



- Split 7.1 strikes a good balance between wireless FH and power consumption.
- Further fronthaul resource allocation required to lower the rate requirements.

Q&A

Thanks for listening!

oatopal@kth.se

[1] O. A. Topal, Ö. T. Demir, E. Björnson, and C. Cavdar, “Unlocking the energy-saving potential in O-RAN cell-free massive MIMO by joint orchestration of radio, wireless fronthaul, and cloud resources,” arXiv preprint arXiv:2604.04073

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

[3] Z. Ge, O. A. Topal, I.A. Meer, P. Xiao, and C. Cavdar, “EARL: Energy-Aware Adaptive Antenna Control with Reinforcement Learning in O-RAN Cell-Free Massive MIMO Networks,” in ICC 2026.