Measurement Based Time-Domain Power Saving Through Radio Equipment Deactivation on Sub-6GHz Base Station Site

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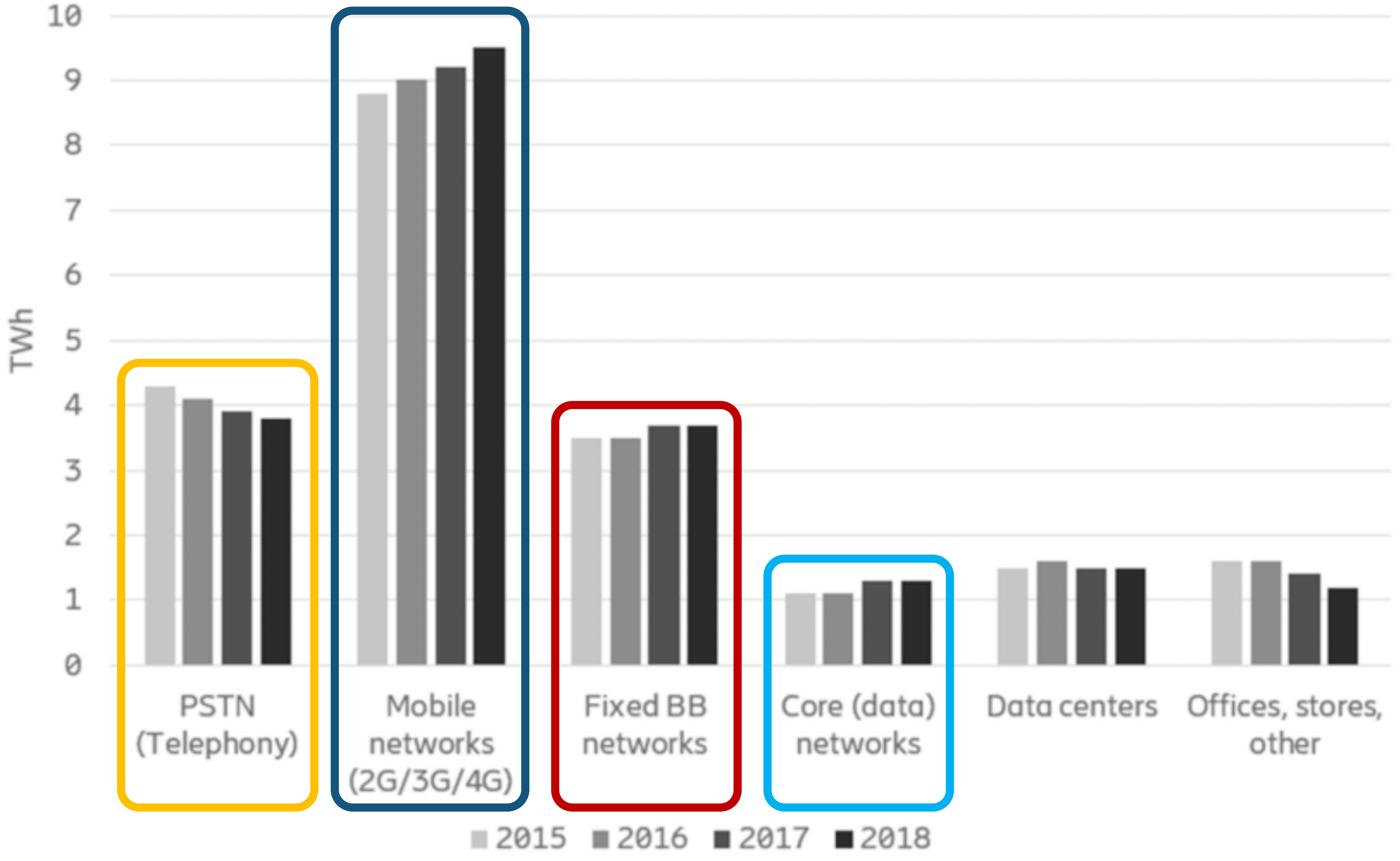
Context: Energy consumption of mobile networks

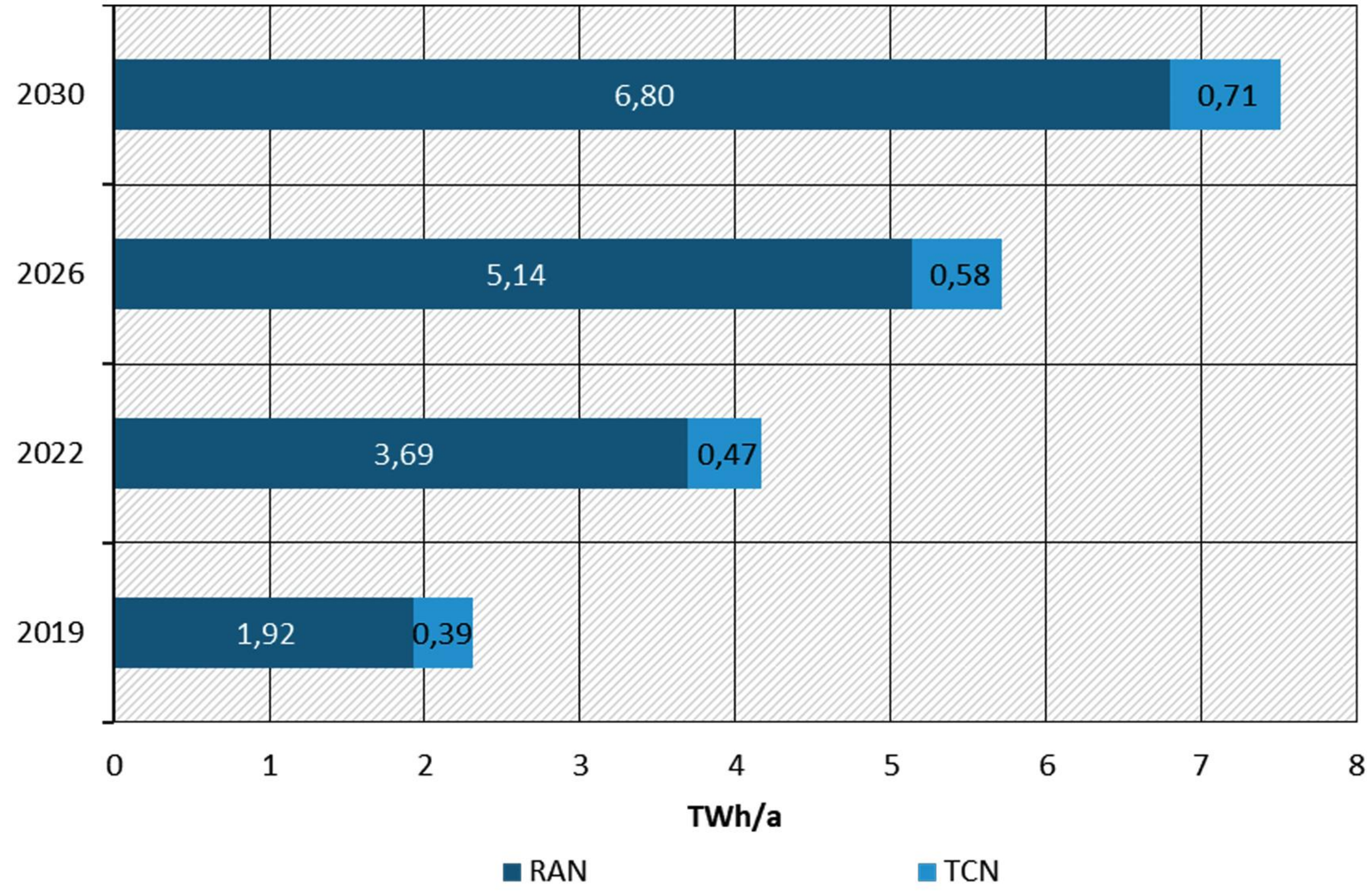
- **Energy consumption:**
  - ICT: ~ 6-7% of global electricity consumption.
  - Networks: ~ 10-30% of ICT and 80-90% of Telco's electricity consumption (2015-2018).
  - Radio Access Network (RAN): ~ 80% of mobile network (2015-2018).

Telco's electricity consumption distribution in 2015-2018 (Europe)



Malmodin and al. (2022)

Forecast of the electrical energy demand for radio (RAN) and transport core networks (TCN) for Germany 2019 to 2024.



Stobbe, Richter, UTAMO, 2023

Context: Components of a Base Station

- Previous work aimed to build a parametric power model for up-to-date commercial Base Stations (BS)
- Components of the parametric model:
  - Power amplifiers (PAs)
  - Analog front-end (AFE)
  - Digital baseband (DBB)
  - Power supply and cooling systems (PSC)
- Data sources:
  - Equipment documentation from manufacturers
  - Hourly on-site measurements over a week from MNOs
- Radio Unit's (RU) power model scales with the load:

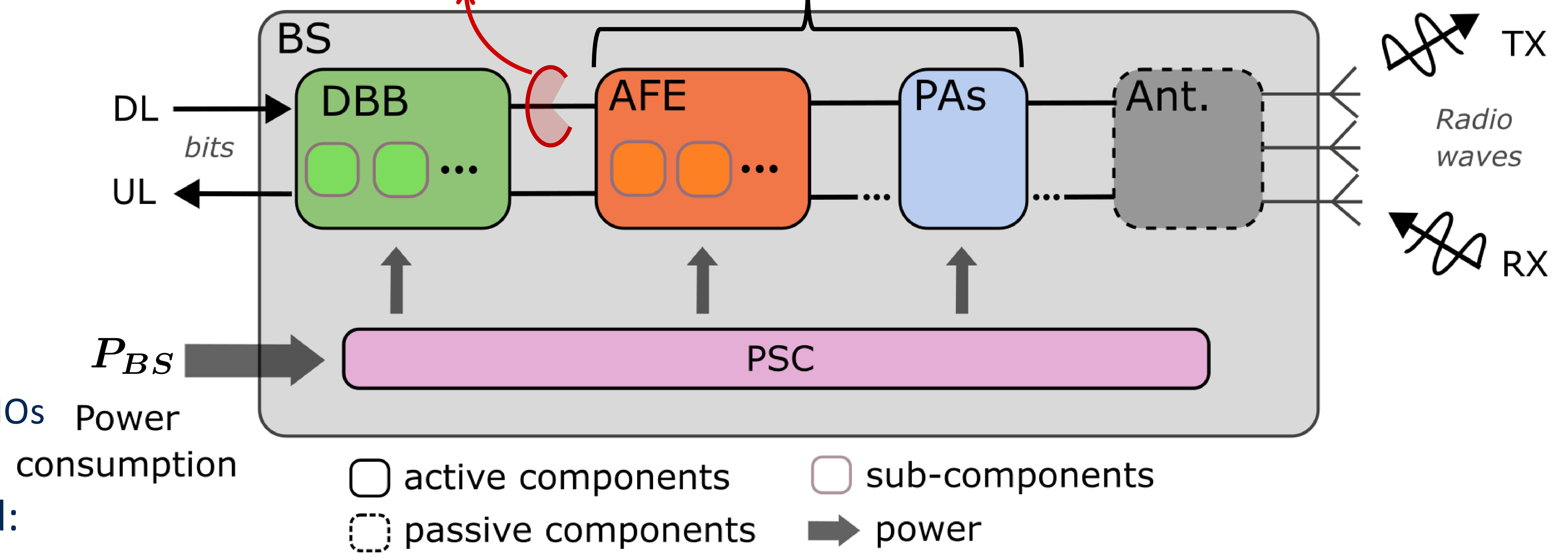
$$\overline{P}_{RU}(T_k) = \sum_{c=1}^{N_C} \underbrace{\overbrace{\alpha_c(T_k) \cdot \overline{x}_c(T_k)}^{\text{dynamic}} + \beta_c(T_k)}_{\overline{P}_{PA,c}(T_k)} + \overline{P}_{AFE,c}(T_k)$$

static: $\beta_c(T_k) + \overline{P}_{AFE,c}(T_k)$

N_C : number of cells (bands x sectors)

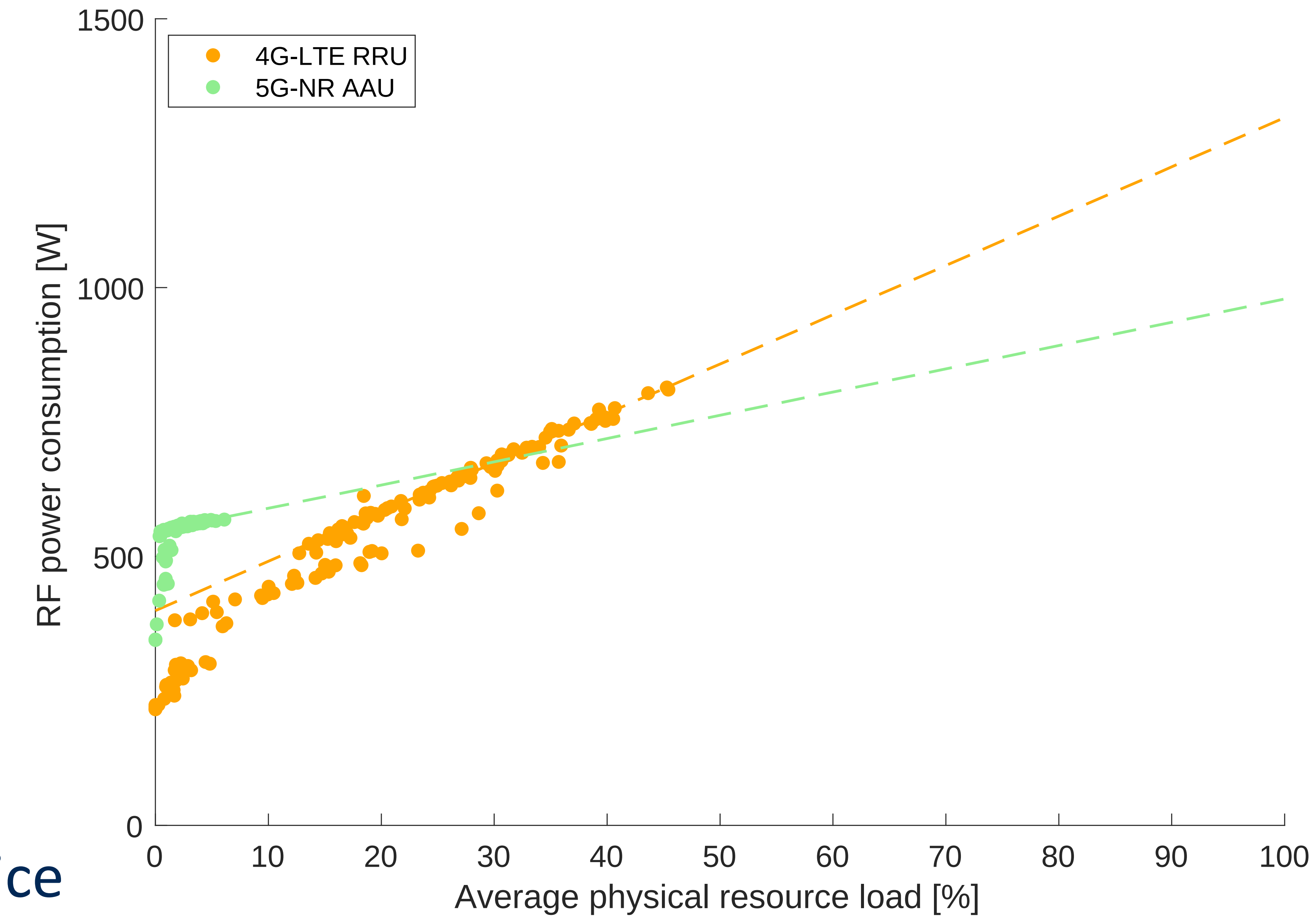
Physical resource load

$$x = \frac{X_{used}}{X_{DL}} = \frac{N_{PRB,used}}{N_{PRB}}$$



Motivations and Goal

- **Observations:**
  - Lightly loaded 5G-NR RUs, especially for AAUs
  - Higher static power for AAUs (5G-NR) compared to RRUs (4G-LTE)
  - Higher energy efficiency [symbol/J] for AAUs (5G-NR) compared to RRUs (4G-LTE)
- **Motivations:**
  - Most of the power is consumed by RUs, i.e., around 80% of the total BS power
  - Both technologies (4G and 5G) run simultaneously, targeting good Quality of Service (QoS), i.e., data rate and/or latency.
    - No discussion on how to mitigate overall power consumption <u>for given QoS</u>.
  - No clear scheduling between radio equipment based on, e.g., the data rate.



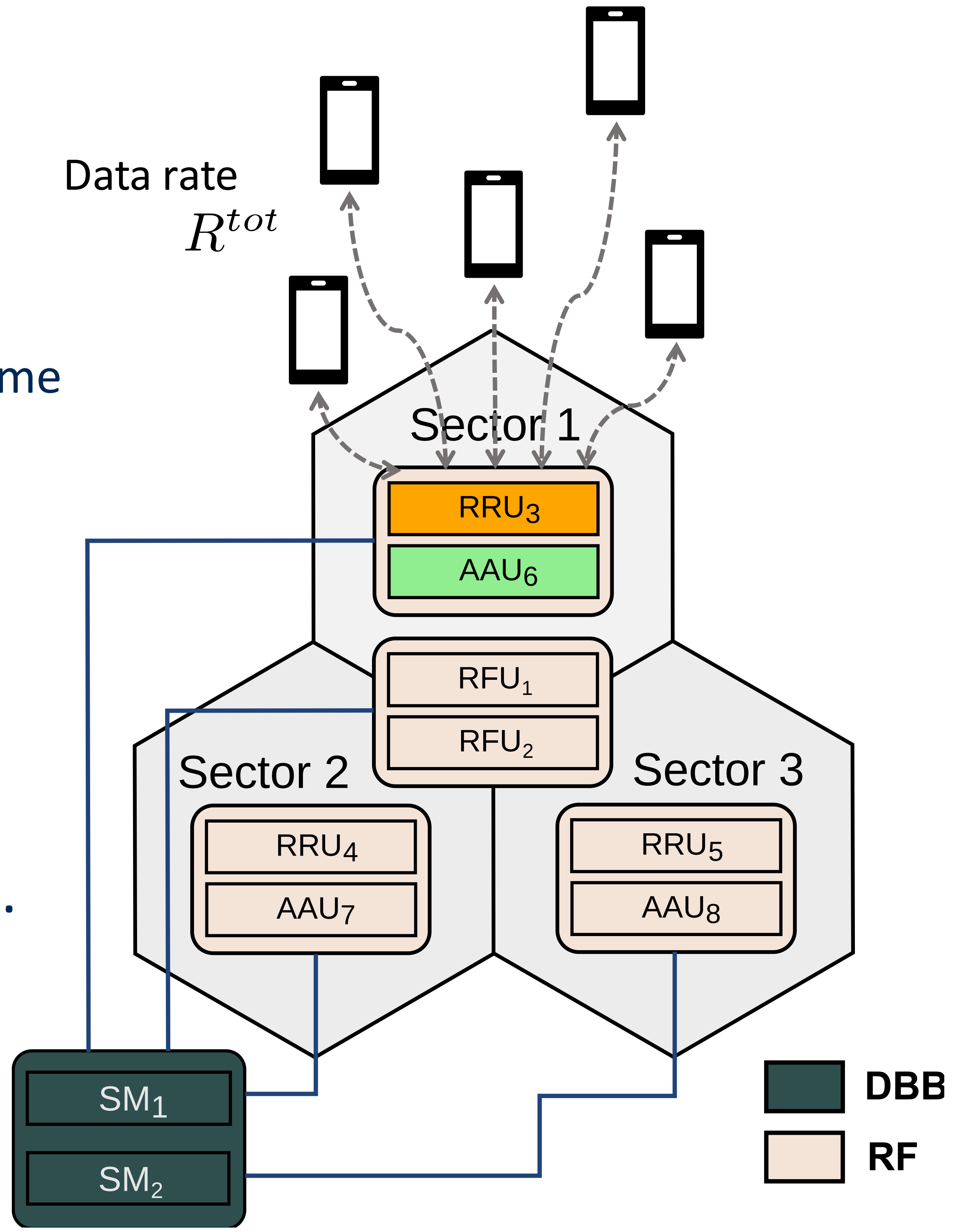
Goal: Design a scheduling algorithm that will select the most efficient Radio Unit (and deactivate the other) <u>for a given data rate</u> to mitigate the power consumption.

Outline

- Introduction
- Power saving analysis
  - Structure of the base station of interest
  - Data rate analysis
  - Deactivation methodology
  - Results
- Conclusion and future work

Structure of the Base Station of interest

- Base station:
  - 3 sectors, multi-band
  - Equipped with 3 types of RUs: RFUs, RRUs and AAUs
    - Radio Frequency Unit (RFU): is installed in the cabinet, generally serving all 3 sectors at the same time
    - Remote Radio Unit (RRU): is installed closer to passive antennas and dedicated to a specific sector
    - Active Antenna Unit (AAU): combines analog front-end, PAs and antenna elements in single unit



- RU technical specifications:
  - carrier frequency (f), bandwidth per log cell ($B_{C'}$), number of served sector (N_S), etc.

RU type	Technology	f [GHz]	$B_{C'}$ [MHz]	N_S	$N_{C'}$	$N_{L,c'}$	N_s	OH
RFU_1	LTE	0.8	10	3	6	2	84	0.11
RFU_2	NR	0.7	10	3	6	2	12	0.14
$RRU_{\{3,4,5\}}$	LTE	1.8 — 2.1	20	1	4	4—4	84	0.11
$AAU_{\{6,7,8\}}$	NR	3.5	100	1	2	4	12	0.14

Data rate analysis: Computation

- Current power models are expressed as a function of the physical resource load, not the data rate.
- Formula for the instantaneous data rate on a given cell c (:= band and sector):

$$R_c(t) = k_c \cdot \frac{N_{PRB,c}(t) \cdot N_s}{T_s}$$

$N_{PRB,c}$: Number of used Physical Resource Blocks (PRB) in cell c

T_s : Symbol duration

  - where k_c scales with Q_m, the modulation order and r, the code rate. $Q_m \cdot r$ is known as the efficiency
  - modulation order and code rates are univocally determined by the reported channel quality indicator (CQI)
  - formula assumes single efficiency factor but each UE request data with its own channel quality (~ CQI).
    - Need to consider the CQI distribution of all connected users within each hour

- Adapted average downlink data rate for a given RUi:

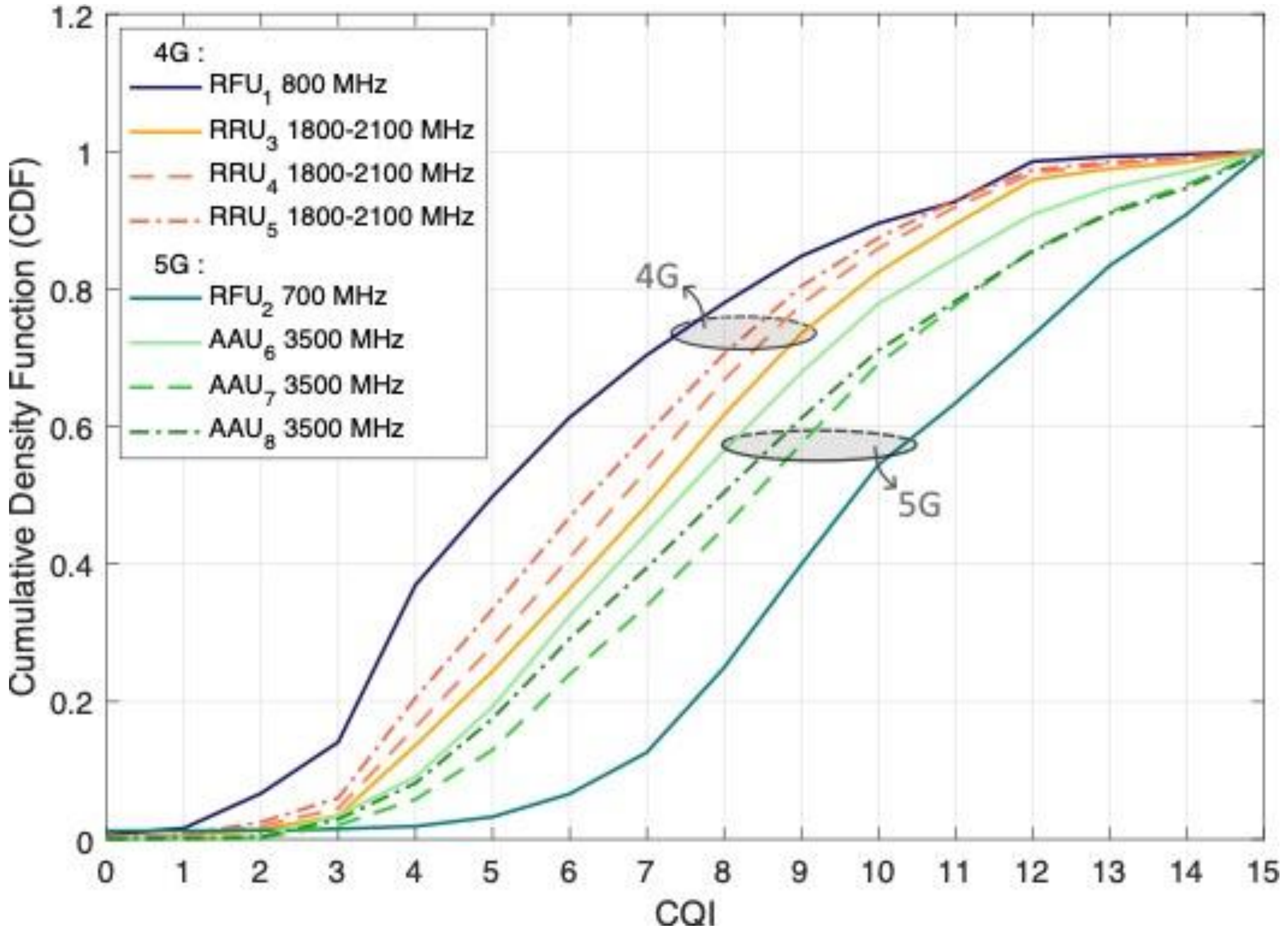
$$\overline{R}^i(T_k) = \sum_{c'=1}^{N^i_{C'}} \sum_{j=1}^{N_{CQI}} k^i_{c',j} \cdot \frac{\mathbb{P}^i_{c'}(X_j, T_k) \cdot N^i_{PRB,c'}(T_k).N^i_s}{T_k}$$

where $\mathbb{P}^i_{c'}(X_j, T_k)$ denotes the probability of having reported CQI index X_j, at hour T_k on cell c' and RU i.

where $k^i_{c',j} = N^i_{L,c'} \cdot Q^i_{m,j} \cdot r^i_j\,(1 - OH^i)$

Data rate analysis: CQI distribution

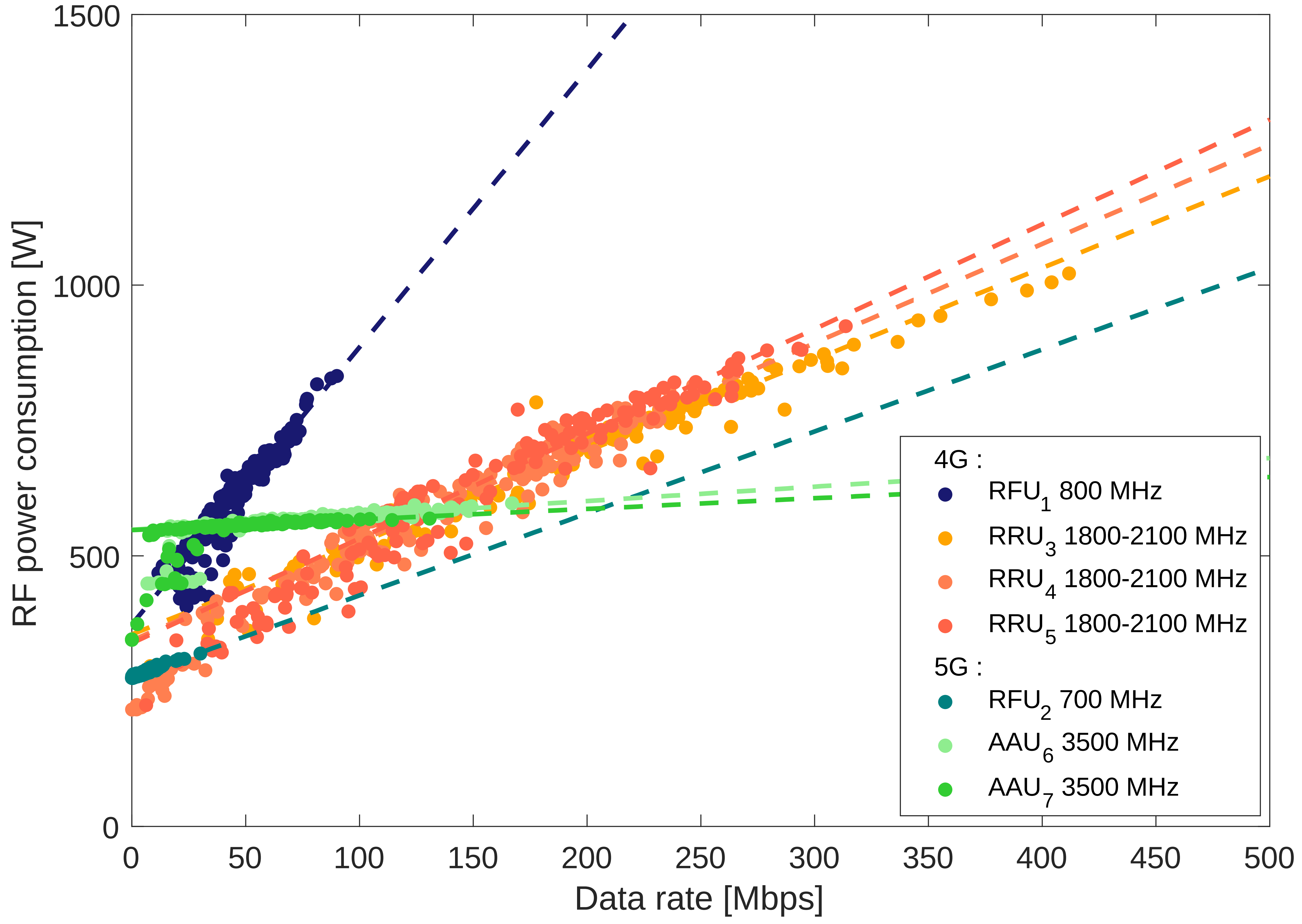
- Cumulative Density Function (CDF) of the CQI of all RUs over the week



- **Comments:**
  - UEs connected to 5G-NR radio equipment report higher CQI (in average).
    - → Higher SNR for 5G-NR users
  - Better channel quality could be due to multiple factors, e.g., proximity to the BS, better chip on the UE side, selection bias of the scheduler, etc.

Data rate analysis: Power vs. data rate

- Hourly RU's power consumption vs. data rate over the week



- **Comments:**
  - α defines the slope and represents the energy intensity (in [J/Mb]), i.e., the inverse of the energy efficiency (in [Mb/J]),
  - 5G-NR RUs exhibit higher energy efficiency (x3-9) than 4G-LTE RUs,

  → Prefer RRUs at low data rate ($\leq 150\,Mbps$) and AAUs at higher data rate.
  - α here depends on the CQI distribution and the maximum capacity ($C = N_L \cdot B$) of the RU,

  → Cannot use this graph as such to design our scheduling algorithm because UEs should conserve their CQI index when rerouted.

RU type	Technology	α [J/Mb]	P_{stat} [W]
RFU_1	LTE	5.1	373
RFU_2	NR	1.5	275
$RRU_{\{3,4,5\}}$	LTE	1.8	345
$AAU_{\{6,7,8\}}$	NR	0.2	548

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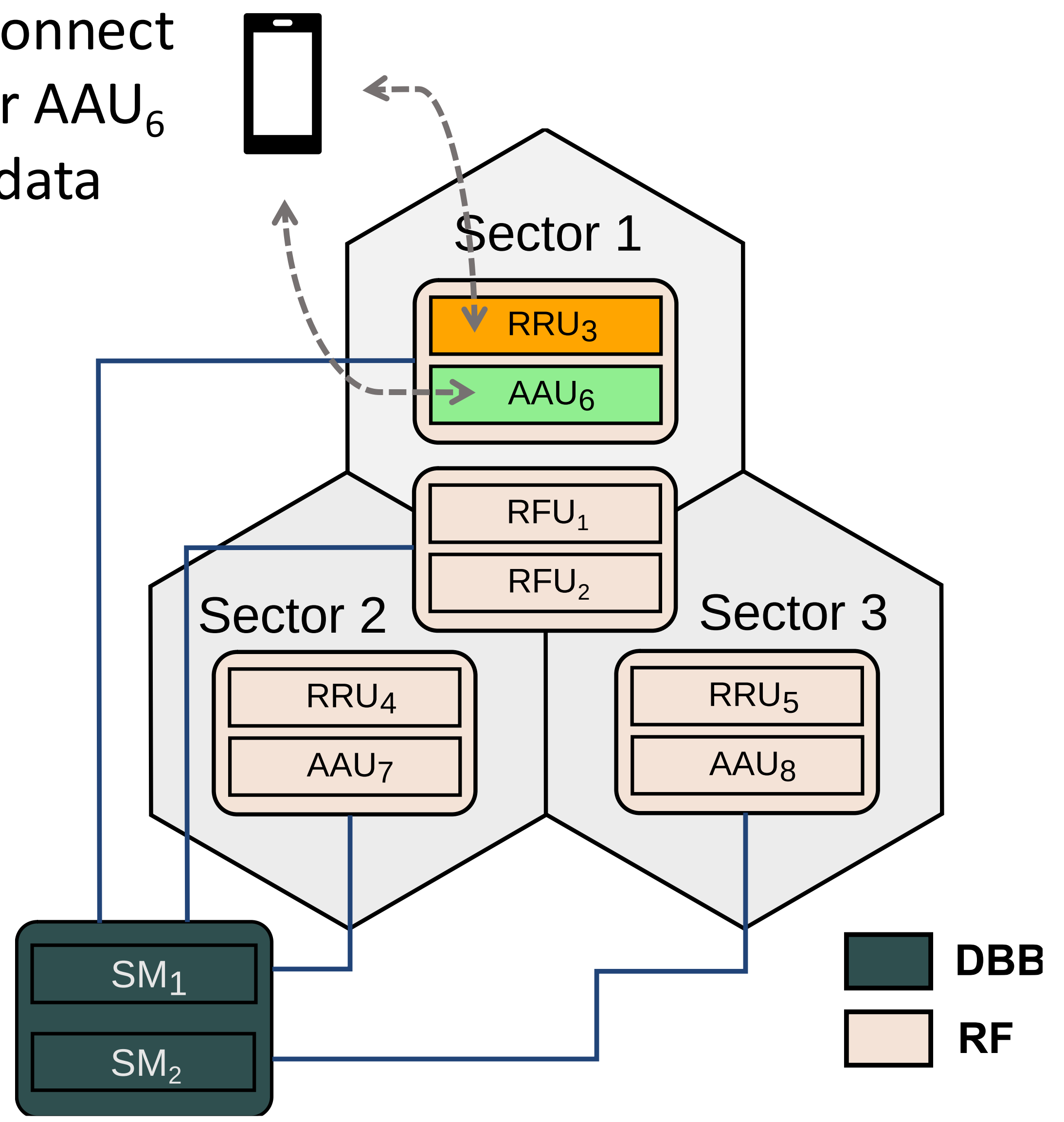
Deactivation methodology

- **Constraints and assumptions:**
  1. UE should be rerouted within the same sector,
  2. UE should remain in the same band types, i.e., coverage bands ([700, 800] MHz) or higher-bands ([1800, 2100, 3500] MHz),
  3. UE must preserve their SNR and thus their CQI when redirected,
  4. UE are assumed to be both 4G-LTE and 5G-NR compatible.



- Constraints 1 and 2 lead to the following set of paired RUs: $\mathcal{I} = \{(1,2),(3,6),(4,7),(5,8)\}$
- Constraint 3 leads to the following system to solve:

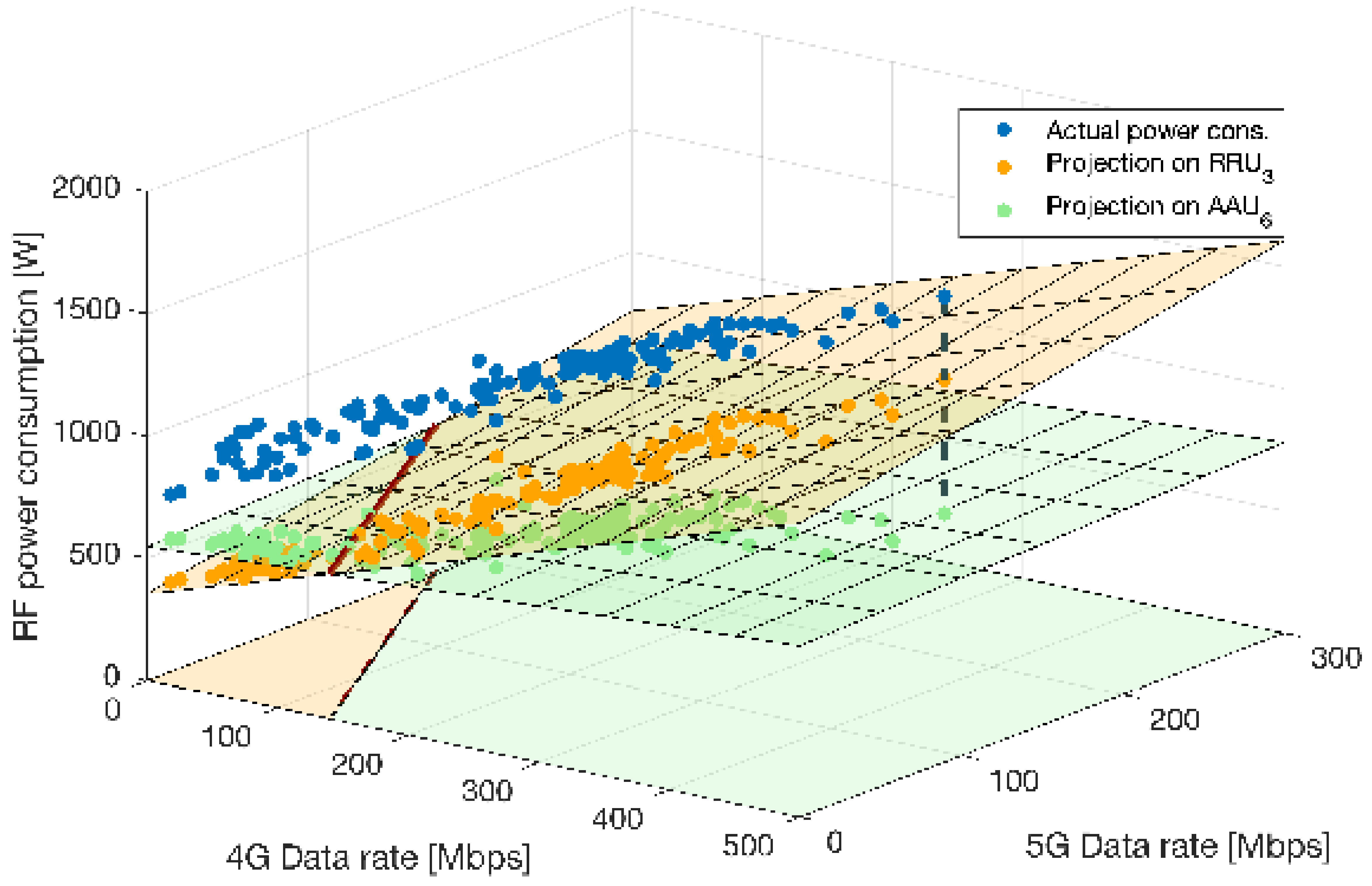
$$\begin{bmatrix} \overline{P}_{RU_i} \\ \overline{P}_{RU_j} \end{bmatrix} = \begin{bmatrix} \alpha_i(\mathbb{P}^i(\boldsymbol{X},\boldsymbol{T})) & \alpha_i(\mathbb{P}^j(\boldsymbol{X},\boldsymbol{T})) \\ \alpha_j(\mathbb{P}^i(\boldsymbol{X},\boldsymbol{T})) & \alpha_j(\mathbb{P}^j(\boldsymbol{X},\boldsymbol{T})) \end{bmatrix} \cdot \begin{bmatrix} \overline{R}^i(\mathbb{P}^i(\boldsymbol{X},\boldsymbol{T})) \\ \overline{R}^j(\mathbb{P}^j(\boldsymbol{X},\boldsymbol{T})) \end{bmatrix} + \begin{bmatrix} \overline{P}^i_{stat}(\mathbb{P}^i(\boldsymbol{X},\boldsymbol{T})) \\ \overline{P}^j_{stat}(\mathbb{P}^j(\boldsymbol{X},\boldsymbol{T})) \end{bmatrix}$$

with $\alpha_i(\mathbb{P}^j(\boldsymbol{X},\boldsymbol{T}))$ the model slope of RU_i using CQI distribution of RU_j

algorithm: Select RU_i or RU_j based on $\min\{P_{RU_i}, P_{RU_j}\}$

Deactivation methodology

- RU's power models with RU3 and RU6:



- **Comments:**
  - Previous problem reduces to solve intersection between 2 planes to find rerouting data rate threshold
  - Green (resp. Orange) region indicates where is favorable from an energy point of view to reroute users to 5G-AAU (resp. 4G-RRU).

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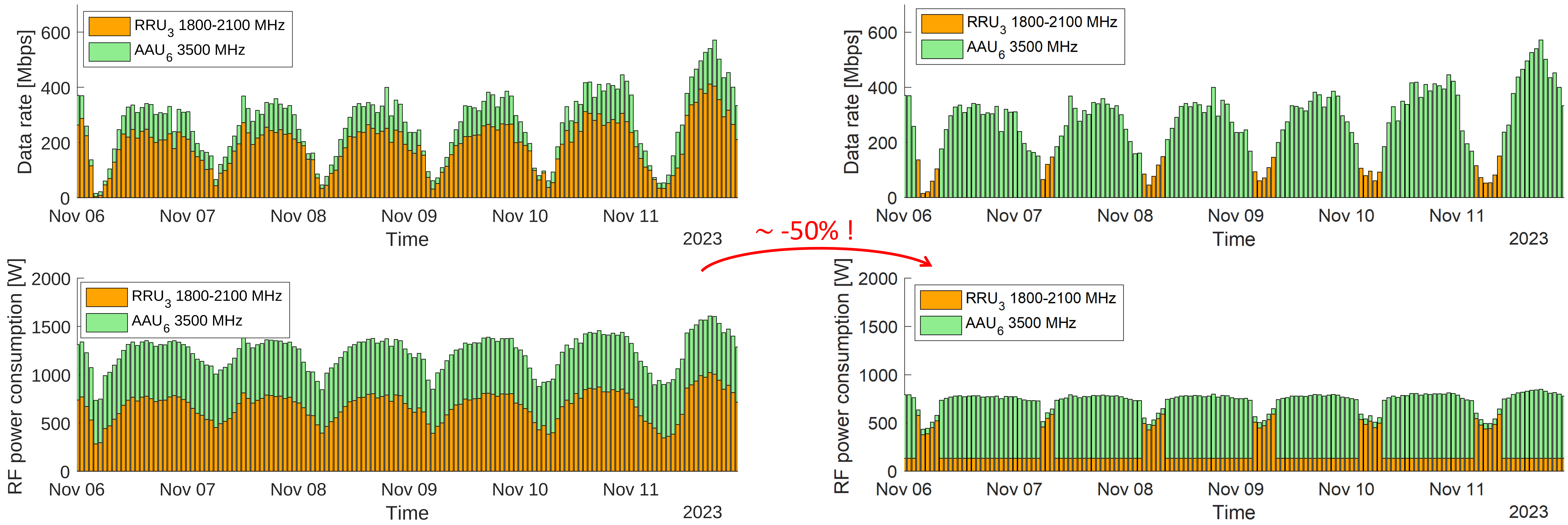
Results at the RU level

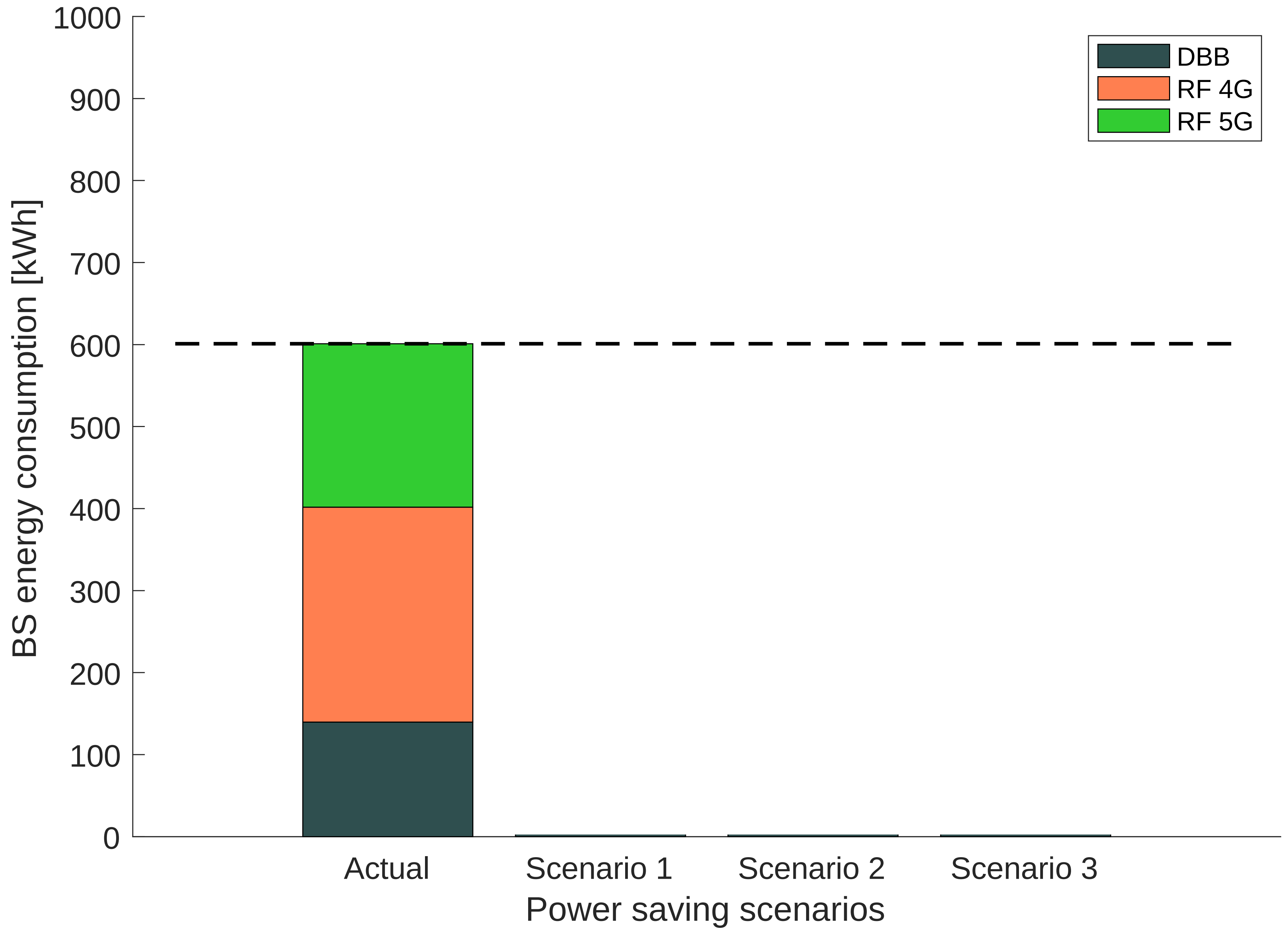
- Power and total average data rate vs. time over a week, comparison between current situation and when scheduling algorithm is applied.

Current situation (both RUs running) | Situation when designed scheduler is applied



Results at the BS level

- Power consumption breakdown at the BS level over a week
- Benchmarking of the designed scheduler with other deactivation scenarios:
    1. Actual: current situation where all RUs are running,
    2. Scenario 1: hourly deactivation of 4G-LTE Rus and redirecting data traffic of 5G-NR RUs if total reaches 80% of max 4G-LTE capacity,
    3. Scenario 2: hourly deactivation of 4G-LTE RUs and redirecting all data traffic on 5G-NR RUs,
    4. Scenario 3: hourly deactivation of 4G-LTE Rus or 5G-NR based on minimum power threshold criterion (designed scheduler).



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Conclusion and future work

- **Conclusion:**
  - We designed an energy-aware mechanism which deactivates specific RUs based on the downlink data rate, without compromising the QoS,
  - We provide a benchmark of 3 deactivation scenarios:
    - The implemented scheduling algorithm gives the highest power savings,
    - The 5G-NR RUs should be privileged over the 4G-LTE RUs, except during nighttime, i.e., 3 and 8 a.m,
    - The gain margin: 31.5% reduction in power consumption for the entire base station over a week.
- **Future work:**
  - Extend the analysis including intermediate sleep modes (TX/RX chains deactivation, μDTX, etc.),
  - Extend with more accurate QoS analysis, i.e., instantaneous throughput and latency,
  - Include the spatial distribution of the User Equipment.
  - Investigate deactivation/sleep modes of the digital baseband

End of presentation

Thank you

Non-linear behavior in measurements

- Power consumption of a given dual-band radio unit (RU) and average power model on an **hourly** basis

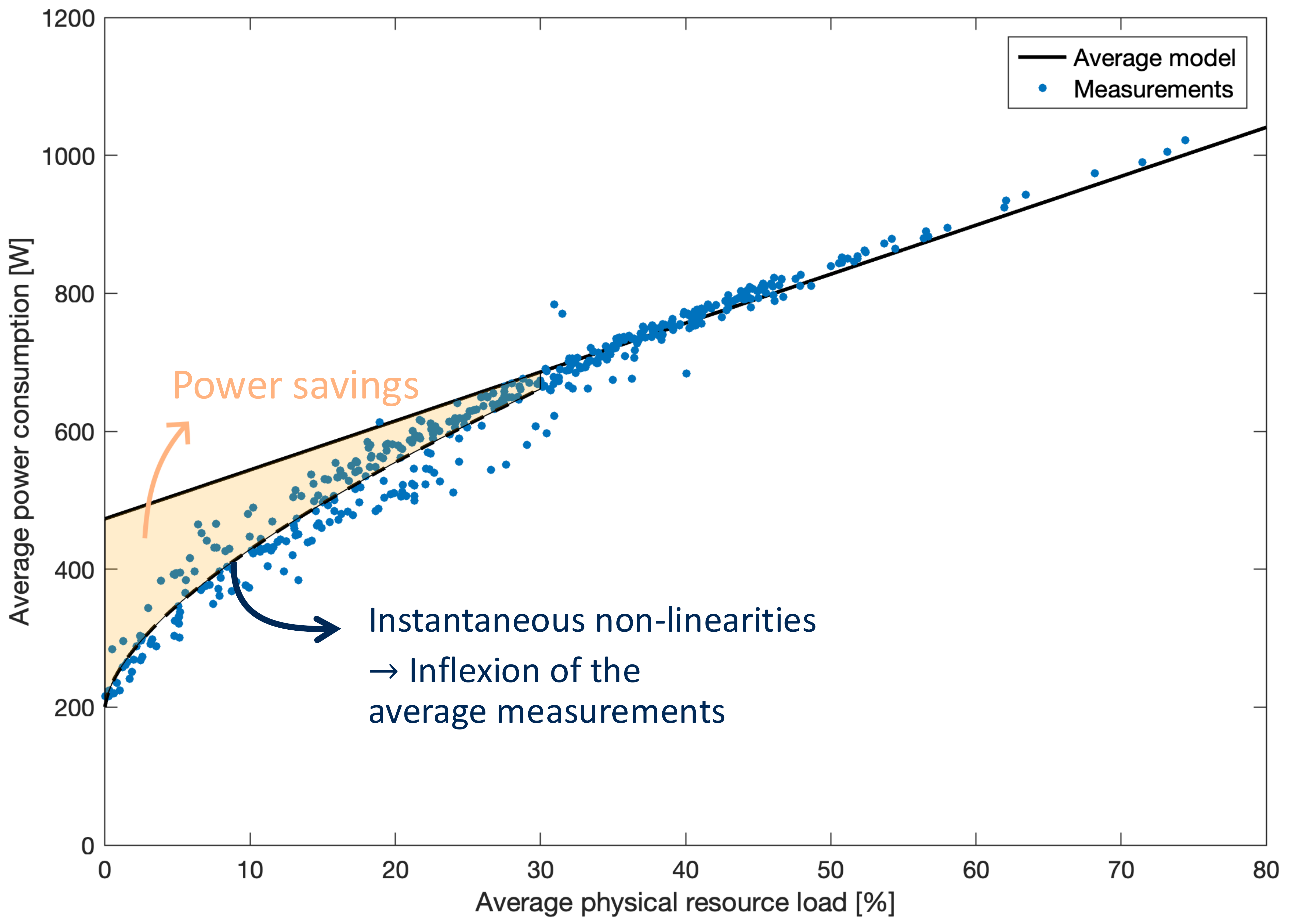
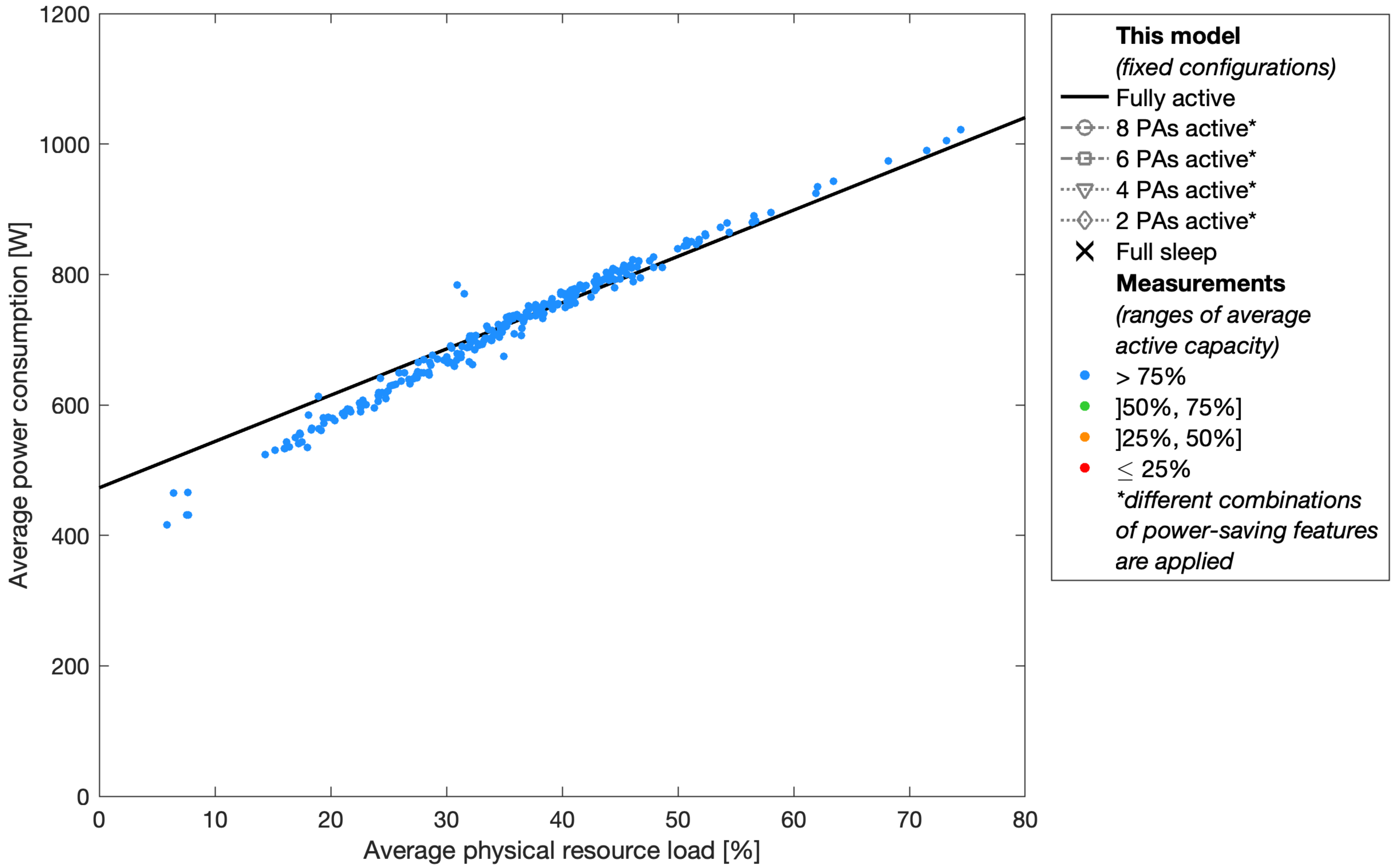
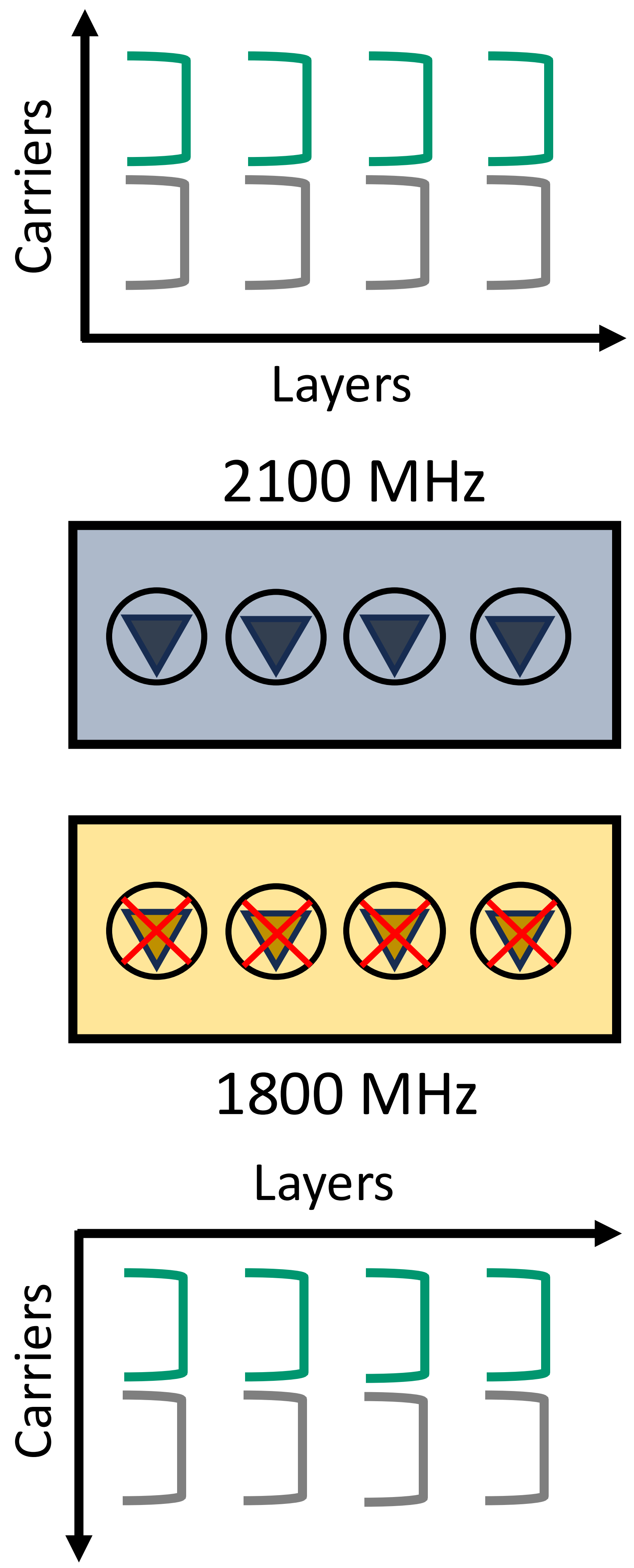


Illustration of power saving features

- Power consumption of a given dual-band radio unit (RU) and average power model (**hourly**)





LTE radio resource frame