Public Wireless Supply Chain INNOVATION FUND

Energy Efficiency Testing and Power Modeling of O-RAN Radio Units

October 28, 2025
O-RAN Dallas FTF Meeting

Zhuohuan Li, Prasanthi Maddala, N. K. Shankaranarayanan, Ivan Seskar
WINLAB at Rutgers,
The State University of New Jersey
(contact: zhuohuanli@winlab.rutgers.edu)

Sarat Puthenpura, Alexandru Stancu
ONF
Aether (LF)

Christian Nunez Alvarez, Gregg Albrecht
Keysight Technologies

RUTGERS AETHER cognizant KEYSIGHT WINLAB

Outline

- Introduction, Background & Motivation
- POET Testbed Overview
- RU Power Modeling Methodology
- Testing Platform
- Experimental Results
- Conclusions & Future Work

O-RAN Energy Efficiency Research Program

Public Wireless Supply Chain INNOVATION FUND

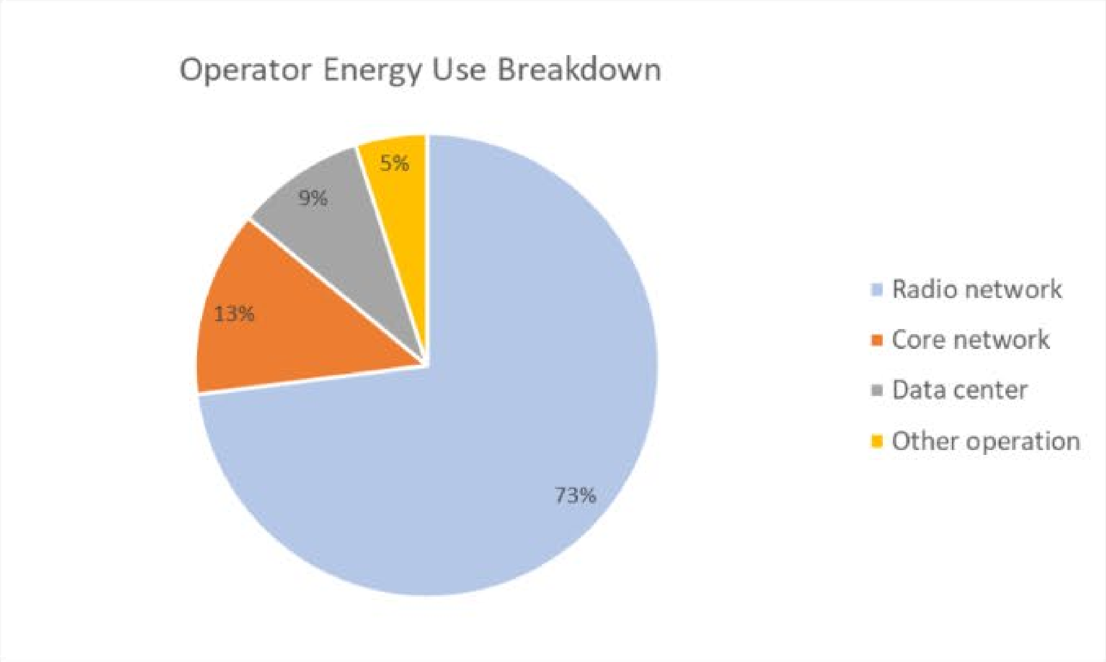
- An NTIA-funded R&D program
  - Methodology & KPIs
  - Data Collection & Predictive Models
  - Industry Standards(EE KPIs) Contribution
- O-RAN Energy Efficiency Testing (POET) testbed
  - Emulated component testing and End-to-end testing
- Power measurements for O-RUs, servers, and VNFs/CNFs
- No existing data in open literature
- Objective: Share Progress, Engaging for Collaboration & Feedback

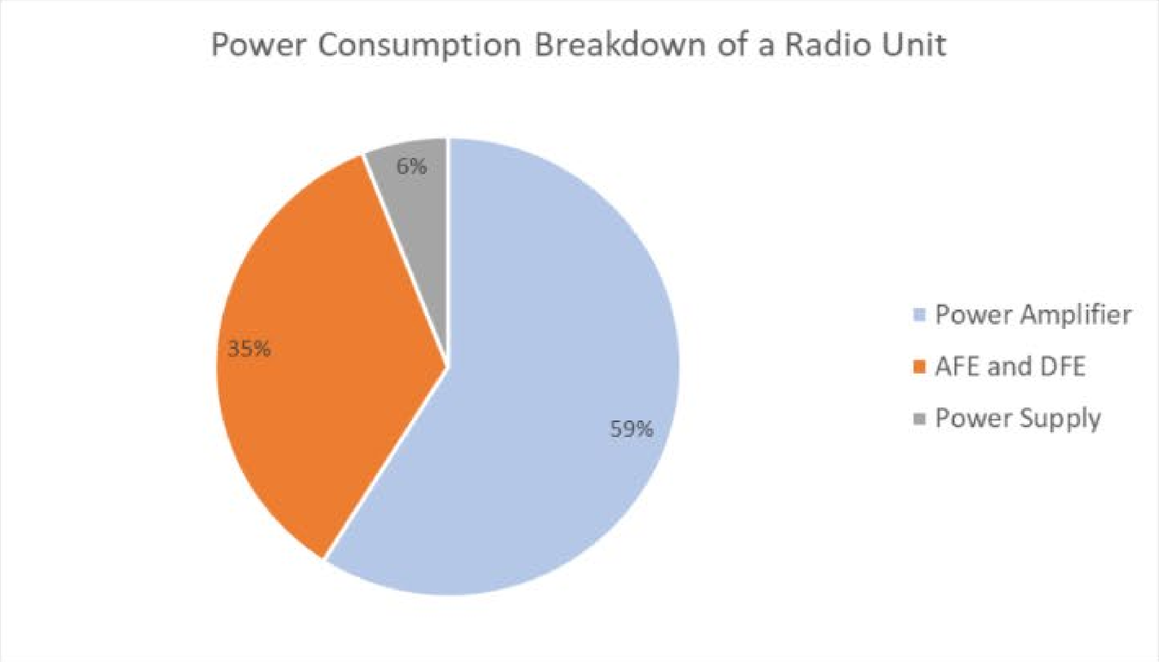
RUTGERS AETHER cognizant KEYSIGHT WINLAB

Network Energy Consumption Breakdown

Public Wireless Supply Chain INNOVATION FUND

Breakdown of power consumption of network, base station, and radio unit[1]





NGMN Alliance, "Green Future Networks – Network Energy Efficiency v1.1," December 2021

RUTGERS AETHER cognizant KEYSIGHT WINLAB

O-RAN Architecture Overview

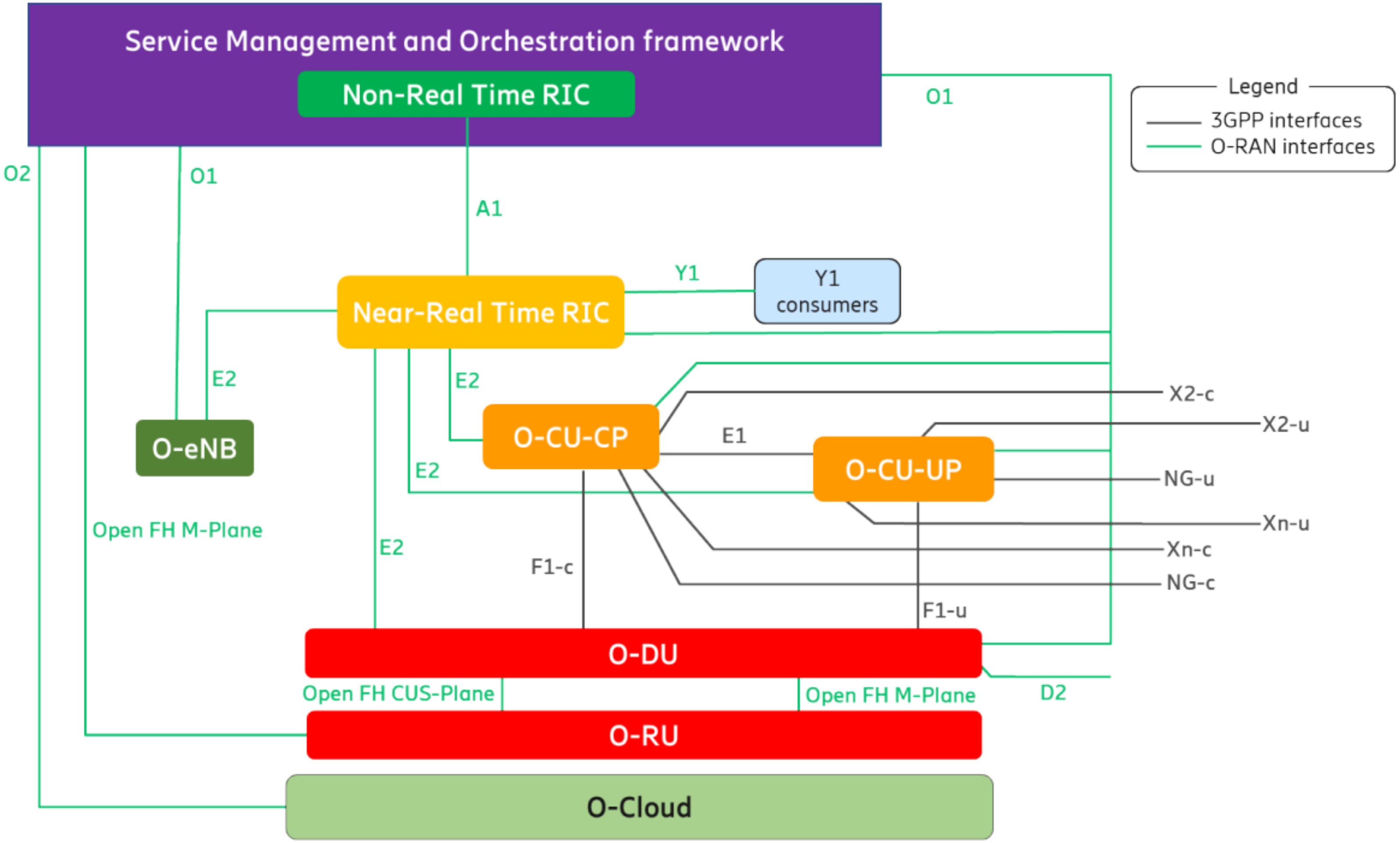


Figure 5.1-2: Logical Architecture of O-RAN

O-RAN.WG1.TS.OAD-R004-v15.00 - O-RAN Architecture Description v15.00: https://oranalliance.atlassian.net/wiki/spaces/OAH/pages/4195582093/O-RAN+Architecture+Description+v15.00

Challenges: Understanding O-RU Energy Consumption

Public Wireless Supply Chain INNOVATION FUND

- **Heterogeneous Equipment:** Lack of standardized energy metrics across different types of O-RUs (even same type has difference)
- **Complex Dependencies:** Power consumption affected by hardware efficiency, MIMO configuration, and traffic load, etc
- **Limited Data:** Few detailed measurements available in open literature
- **Optimization Gap:** Energy-saving techniques (ASM, carrier shutdown) require accurate power models

Research Objectives & Contributions

- **Our Objectives**

- **Testing Methodology:** Develop a versatile O-RU energy testing platform for comprehensive power measurements
- **Multi-Vendor Analysis:** Compare power consumption across different O-RU categories under various operational parameters
- **Power Modeling:** Parameterize and validate component-based power consumption model based on collected data

- **Key Contributions**

- **Comprehensive Dataset:** Detailed power measurements from different types of O-RUs
- **Validated Power Model:** Component-based model with empirically derived parameters
- **Power Amplifier(PA) Efficiency Analysis:** Characterization of non-linear PA efficiency curves
- **Operational Insights:** Impact of MIMO, traffic load, and RF power methods

POET: Platform for O-RAN Energy Efficiency Testing

Public Wireless Supply Chain INNOVATION FUND

Grafana Dashboards

Prometheus DB

MongoDB (Offline data)

<u>Automated Data Collection</u>

PDU power KPI (all physical equipment)

IPMI/ Redfish power KPI (all servers)

Kepler/ Scaphandre power KPI (VNF/CNF)

SMO/OAM (OFH-MP controller)

OAI, srsRAN, Amarisoft

Core ⟷ CU ⟷ DU

End-to-end testing

PTP GM Switch

RU-1

RU-2

RU-N

DU Emulator

Emulated testing

Vector Signal Analyzer

UE-Emulator

UE (Phone)

UE (Modem)

antennas

switch

cables

DC Power Supply

PDUs

RUTGERS AETHER cognizant KEYSIGHT WINLAB

Component Level Modeling: O-RU

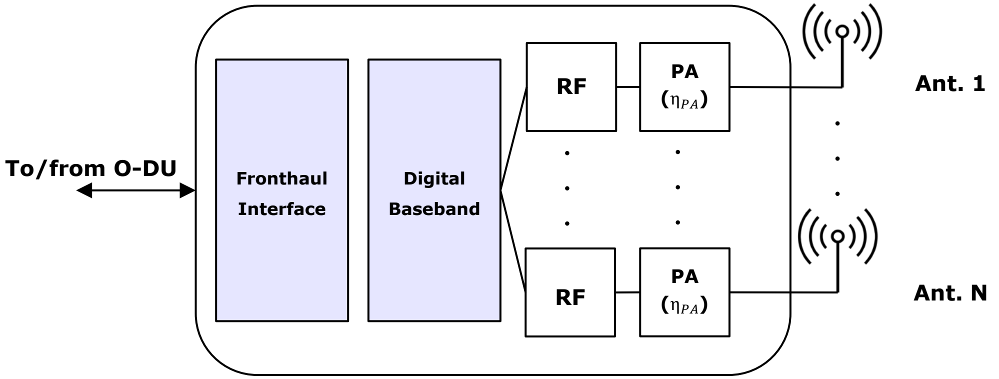
Public Wireless Supply Chain INNOVATION FUND

Power Consumption Model of O-RU

$$P_{O-RU} = P_{base} + N_{TX} \cdot \left(P_{idle-ch} + \frac{P_{tx-ch}(u)}{\eta_{PA}(P_{tx-ch})} + \alpha_{O-RU}(u) \right)$$

- P_{O-RU}: **Total Power:** Overall power consumption of the O-RU
- P_{base}: **Baseline Power:** Consumption when the RF section is off
- $P_{idle-ch}$: **Idle Power:** Power of a single, inactive RF chain
- P_{tx-ch}: **Transmit Power:** Power per active transmit chain
- u: **Utilization:** Resource or traffic load
- η_{PA}: **PA Efficiency:** Power Amplifier efficiency (non-linear)
- α_{O-RU}: **Processing Overhead:** Additional power from processing load
- N_{Tx} :**Transmit Chains:** Number of MIMO transmit chains

MIMO O-RU Architecture Diagram with N transmitter chain

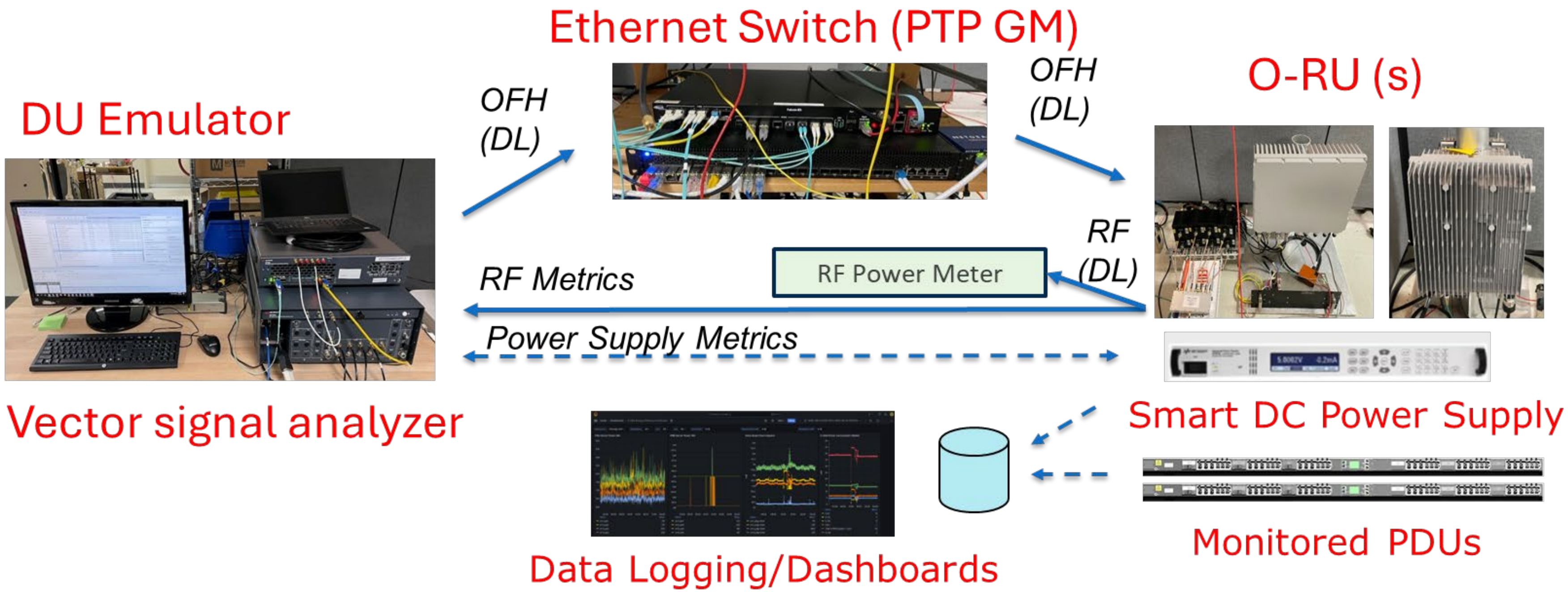


RUTGERS AETHER cognizant KEYSIGHT WINLAB

Automated O-RU Energy Testing

Public Wireless Supply Chain INNOVATION FUND

- Objective: Develop best approach to add energy efficiency testing to O-RAN conformance tests
- Research into energy tests to improve modeling and methodology
- Automated scripting of ETSI Energy Efficiency Test Case (step through Full/Busy/Medium/Low load scenarios)
- The PDU measures power with 1 W resolution, while the DCPS has 0.01 W resolution



RUTGERS AETHER cognizant KEYSIGHT WINLAB

Comparative Power Consumption of O-RUs

Public Wireless Supply Chain INNOVATION FUND

Power Measurement Details

- All O-RUs: PDU-based AC power measurement
- **O-RU B**: Additional DCPS measurements for comparison
- **PDU vs DCPS**: ~20W difference (AC adapter overhead)
- **VSA**: Measure RF Power
- Note: O-RU C & D from same vendor (similar high-power design)

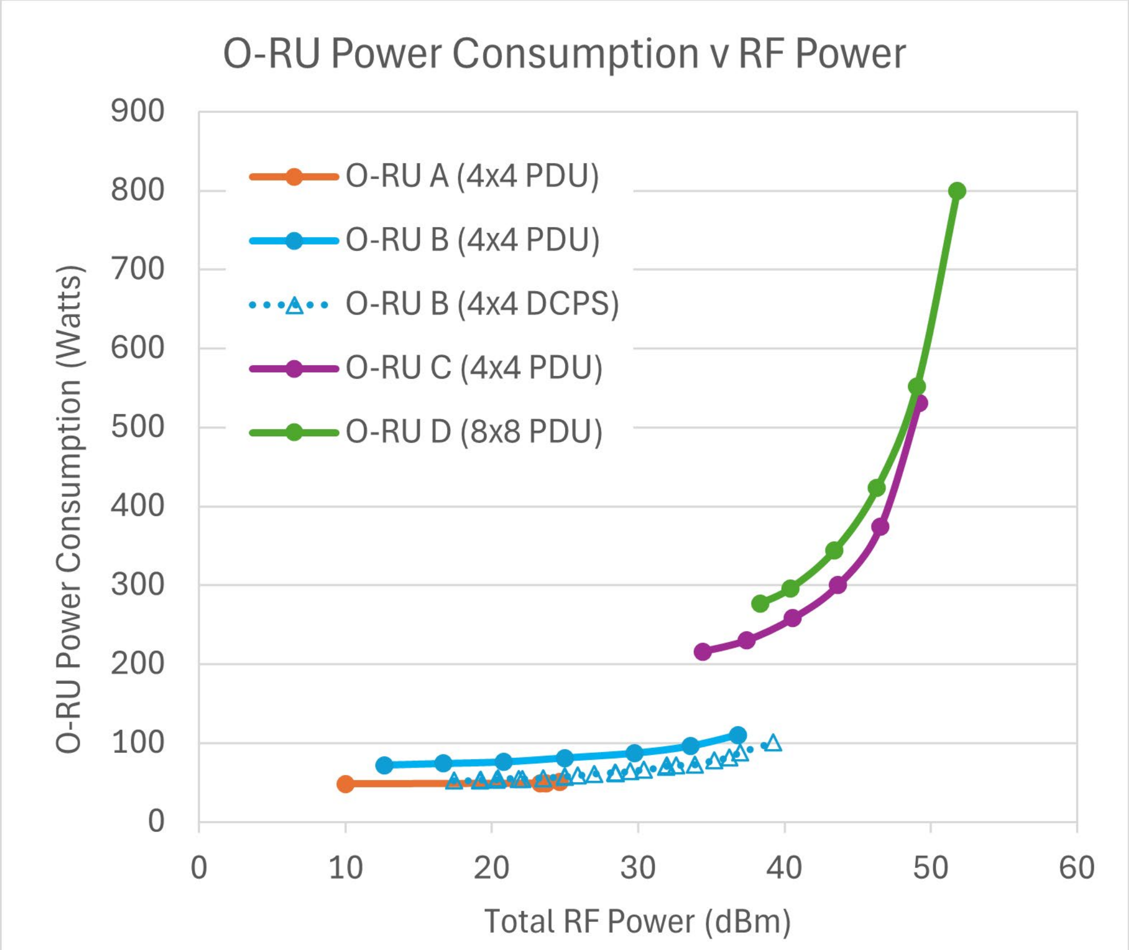
O-RU	Category	Duplex/BW/ Frequency	RF Power per Chain	Total RF Power	Antennas	Power Range
O-RU A (PDU)	Low Power	TDD / 100 MHz/ 3.6GHz	24 dBm (0.25 W)	0 - 0.5 W	4(4×4)	38 - 51 W
O-RU B (PDU)	Medium Power	TDD / 100 MHz/3.6GHz	12 - 37 dBm	0 - 10 W	4 (4×4)	72 - 110 W
O-RU B (DCPS)	Medium Power	TDD / 100 MHz/3.6GHz	17 - 39 dBm	0 - 10 W	4 (4×4)	52 - 100 W
O-RU C (PDU)	High Power	FDD / 10 MHz/3.6GHz	47 dBm (50 W)	0 - 100 W	4 (4×4)	197 - 531 W
O-RU D (PDU)	High Power	TDD / 100 MHz/3.6GHz	47 dBm (50 W)	0 - 150 W	8 (8×8)	227 - 800 W

RUTGERS AETHER cognizant KEYSIGHT WINLAB

Comparative Power Consumption of O-RUs

Public Wireless Supply Chain INNOVATION FUND

- **Power Consumption Classification:**
  - Low power (43-50W): O-RU A
  - Medium power (50-110W): O-RU B
  - High power (200-800W): O-RU C and D
- **Test Configurations on Full Load:**
  - O-RU A,B and C → 4x4
  - O-RU D → 8x8
- **Configuration Impact Factors:**
  - Number of antenna ports (4x4 vs 8x8) has significant impact on power consumption
- Underscores the importance of dynamic power management strategies and adaptive RF power control to optimize the performance-to-power consumption ratio in practical network deployments

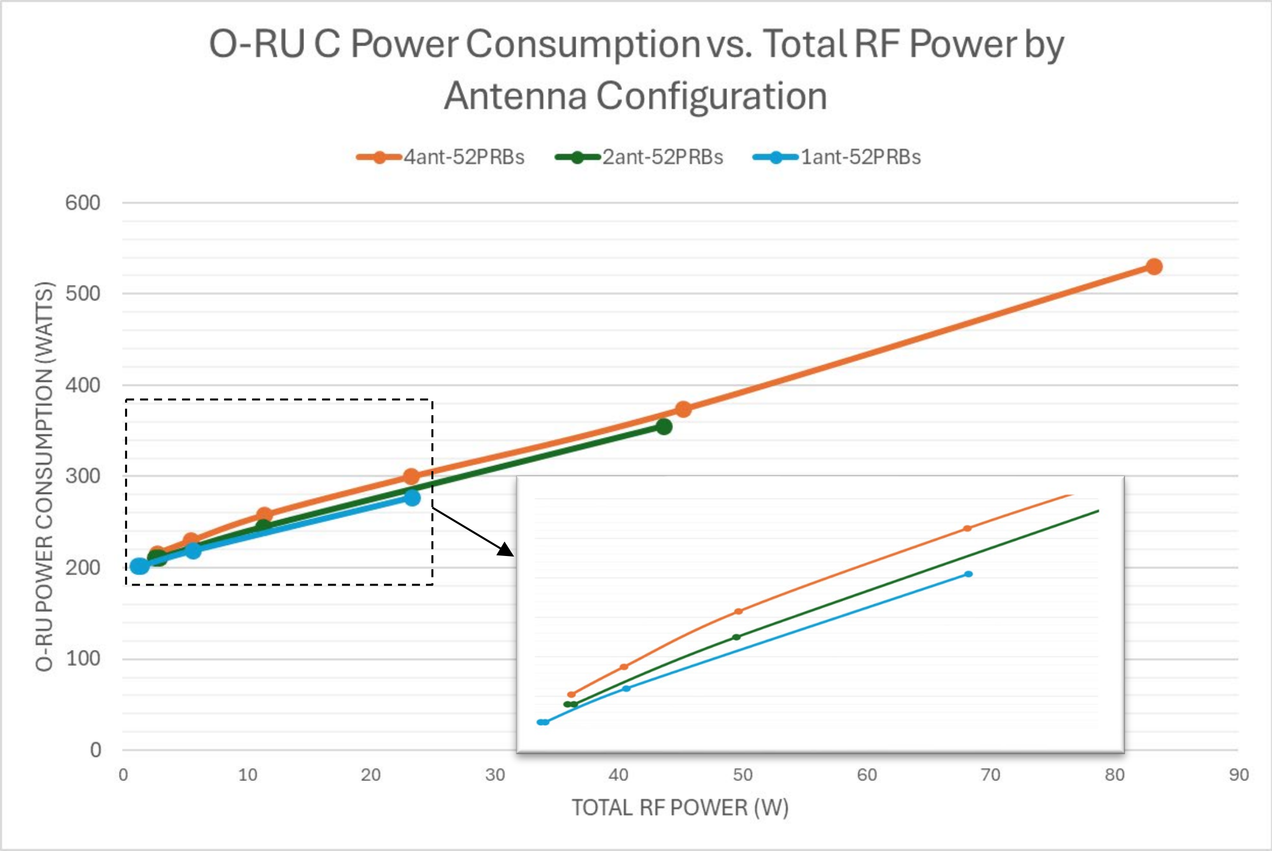


RUTGERS AETHER cognizant KEYSIGHT WINLAB

Testing different MIMO configurations under Full Load

Public Wireless Supply Chain INNOVATION FUND

- Configure MIMO mode in RU (e.g., 2x2, 4x4), and number of DL streams from DU Emulator (e.g., 1, 2, 4)
- RF cable options
  - Use individual cable outputs
  - Combine RF outputs via combiner
- VSA RF power measurement
  - use 4 ports to measure each ant.
  - includes power correction
  - included in automated EE testing
  - similar to conformance test setup
- RF power meter
  - manual or automated
  - Combined RF -> simple test

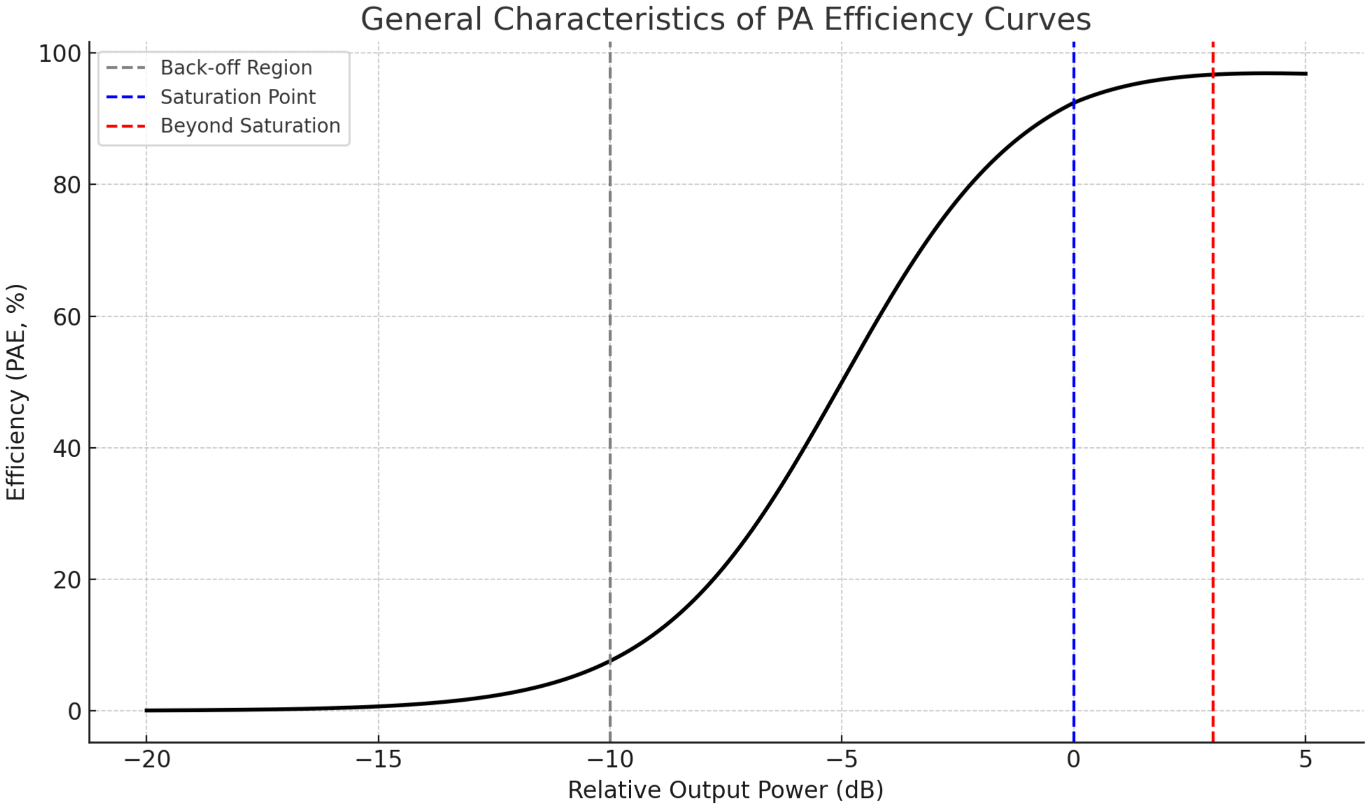


- Detailed View: Non-Overlapping curves at lower Tx power range

RUTGERS AETHER cognizant KEYSIGHT WINLAB

General Characteristics of PA Efficiency Curves

P_{AE} is **NOT linear** across the entire output power range



- **Low Efficiency at Low Output Power (Back-off):** When a PA operates significantly below its maximum (saturated) output power
- **Peak Efficiency Near Saturation:** The highest efficiency near its maximum (saturated) output power.
- **Roll-off Beyond Saturation:** Pushing beyond saturation (compression) increase output power at cost of linearity (signal distortion) and drop in efficiency (can no longer effectively convert DC power).

- LTE & 5G NR have a high Peak-to-Average Power Ratio (PAPR) -> average power much lower than the peak power.
- PAs must handle the peak power, but most of their time at much lower average power -> poor average efficiency.

Estimating PA Efficiency(ηPA)

- Key Assumption
  - To isolate the PA impact, we assume the power consumed by digital signal processing overhead is negligible:

$$\alpha_{O-RU} \approx 0$$

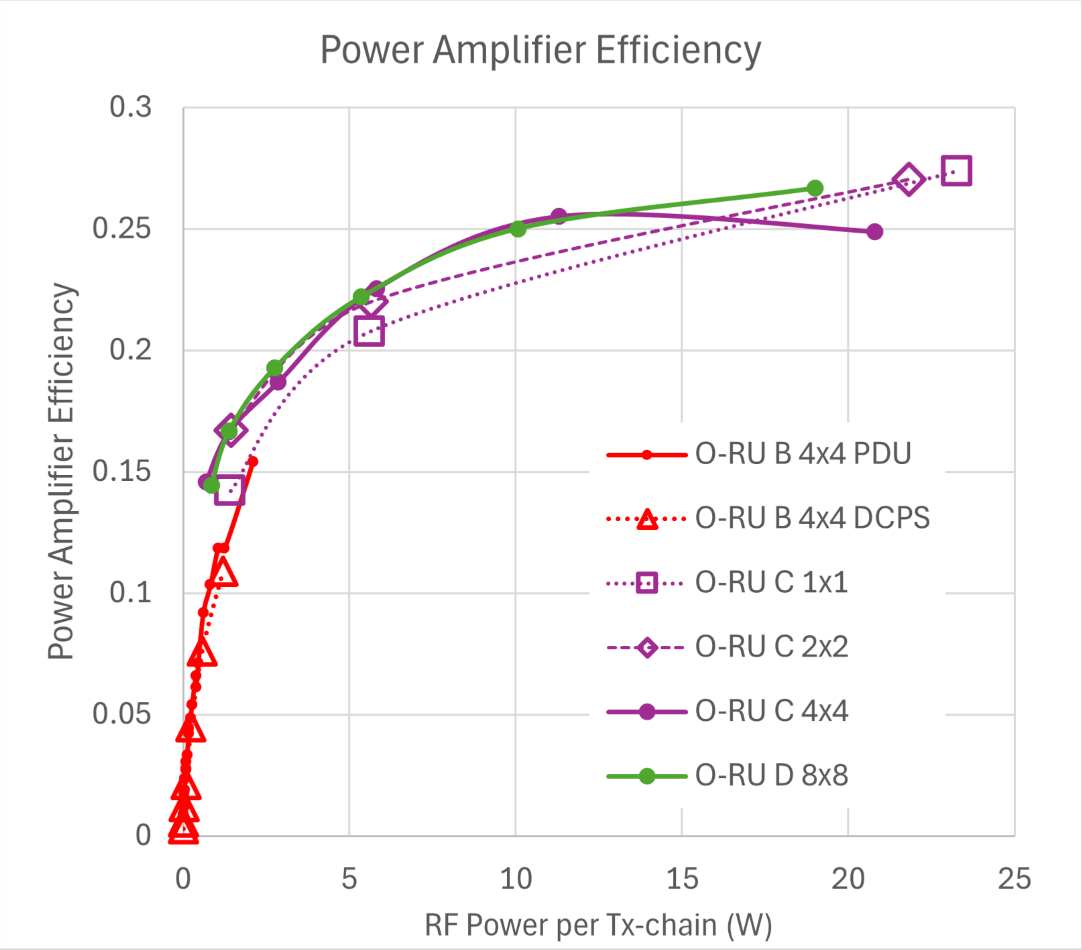
- Methodology
  - The power consumed solely by the PA is estimated by subtracting the known idle power from the total measured power of the O-RU
- η_{PA} Formula
  - This allows us to approximate the PA efficiency using the following formula:

$$\eta_{PA} \approx \frac{P_{out}}{P_{O-RU} - P_{idle}}$$

  - Where:
    - η_{PA} : The estimated PA efficiency
    - P_{out} : Measured RF output power per chain
    - P_{O-RU} : Total measured O-RU power consumption
    - P_{idle} : Measured idle power of the O-RU

Power Amplifier Efficiency Analysis

- Non-Linear: PA efficiency strongly dependent on output power level
- Inefficiency at Low Power: Efficiency often <15% at per-antenna RF output <2.5W
- High-Power O-RUs: C & D achieve ~28% peak efficiency (advanced design)
- Medium-Power O-RU B: Lower peak efficiency (~15%)
- Similar Design: O-RU C (4×4) & D (8×8) have nearly identical PA efficiency curves
- PDU vs DCPS: Same PA efficiency (additive overhead cancelled in calculation)

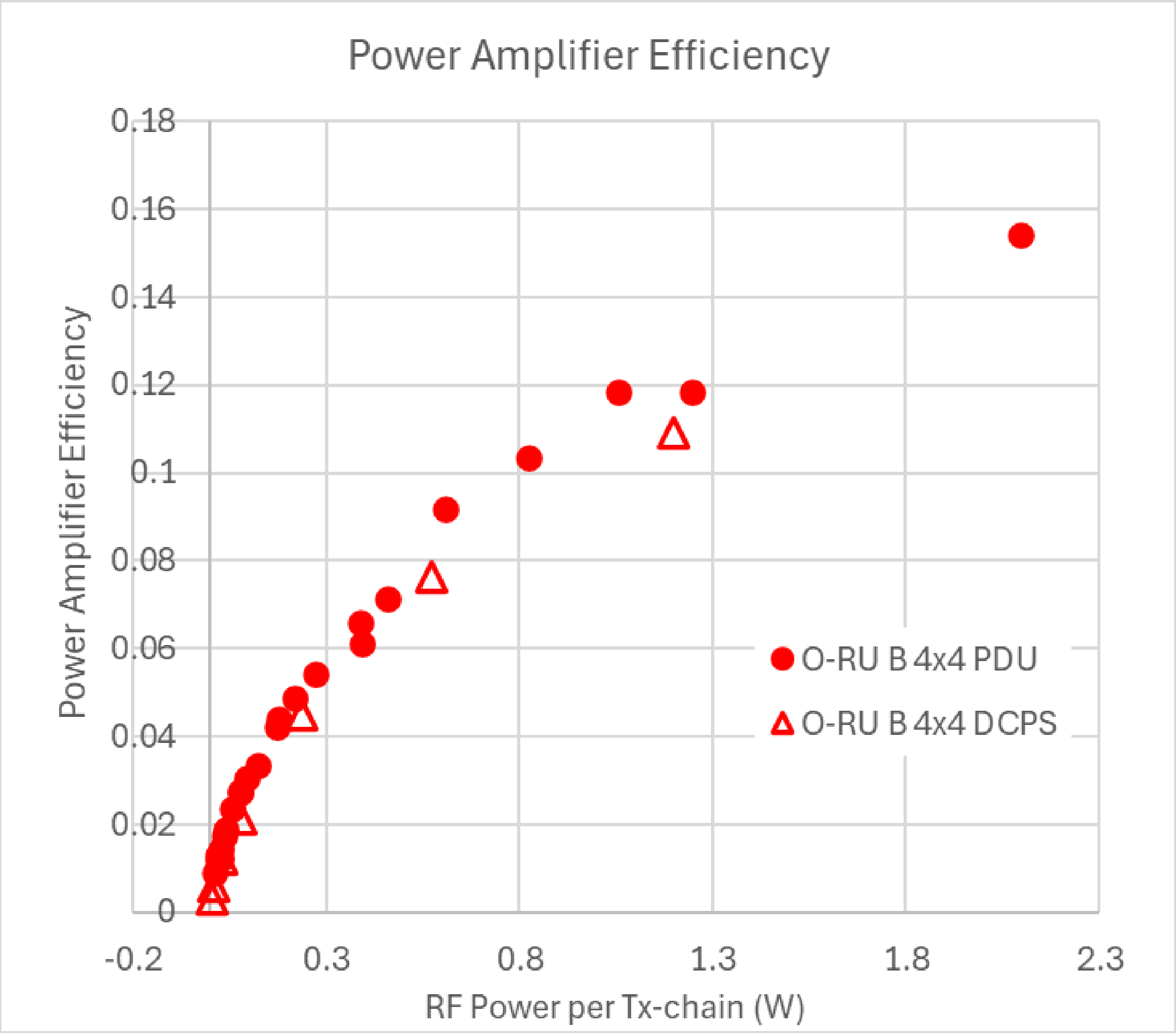


Public Wireless Supply Chain INNOVATION FUND

RUTGERS AETHER cognizant KEYSIGHT WINLAB

PA Efficiency PDU vs DCPS

Public Wireless Supply Chain INNOVATION FUND



RUTGERS AETHER cognizant KEYSIGHT WINLAB

ETSI Static Measurement Method

- ETSI has static measurement method for EE calculation, based on ETSI ES 202 706-1

Channel / Condition	Low Load (Idle)	Medium Load	Busy Hour Load	Full Load
Broadcast & Sync (PBCH, PSS, SSS, RMSI)	✅ Always Transmitted	✅ Always Transmitted	✅ Always Transmitted	✅ Included in All RBs
Data Channel (PDSCH)	❌ Not Transmitted	**30%** of PRBs transmitted	**50%** of PRBs transmitted	**100%** of All Resource Blocks (RBs) are transmitted
Control Channel (PDCCH)	❌ Not Transmitted	**30%** of resources (~2 PRBs/slot)	**50%** of resources (~3 PRBs/slot)	**100%** of resources (~6 PRBs/slot)

Two Approaches to Implement Standard Load Levels:

Frequency-Based Loading

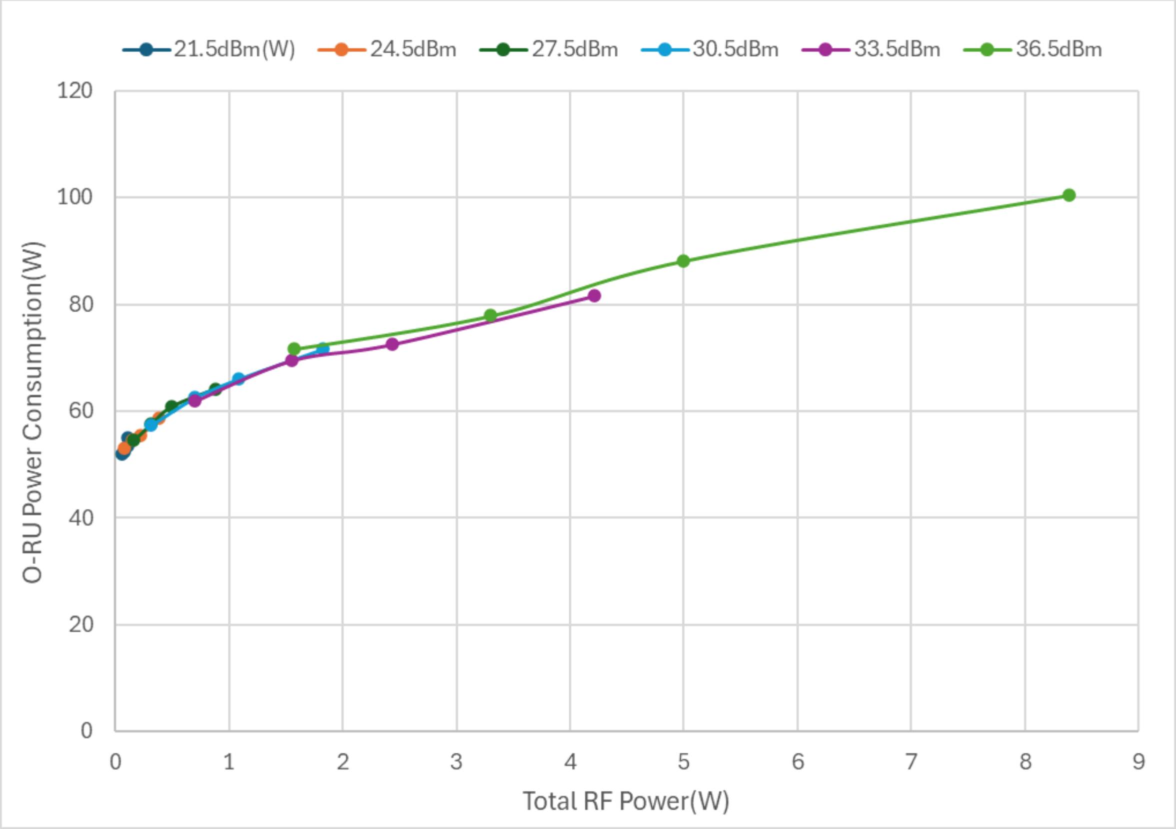
- Vary number of PRBs
- What changes: Bandwidth of transmitted signal
- What stays same: Transmission time and slots
- Real-world scenario: Different number of users served in same time window

Time-Based Loading

- Vary number of time slots
- What changes: Duration or time slots where transmission occurs
- What stays same: PRB allocation per slot
- Real-world scenario: Intermittent transmission or dynamic scheduling

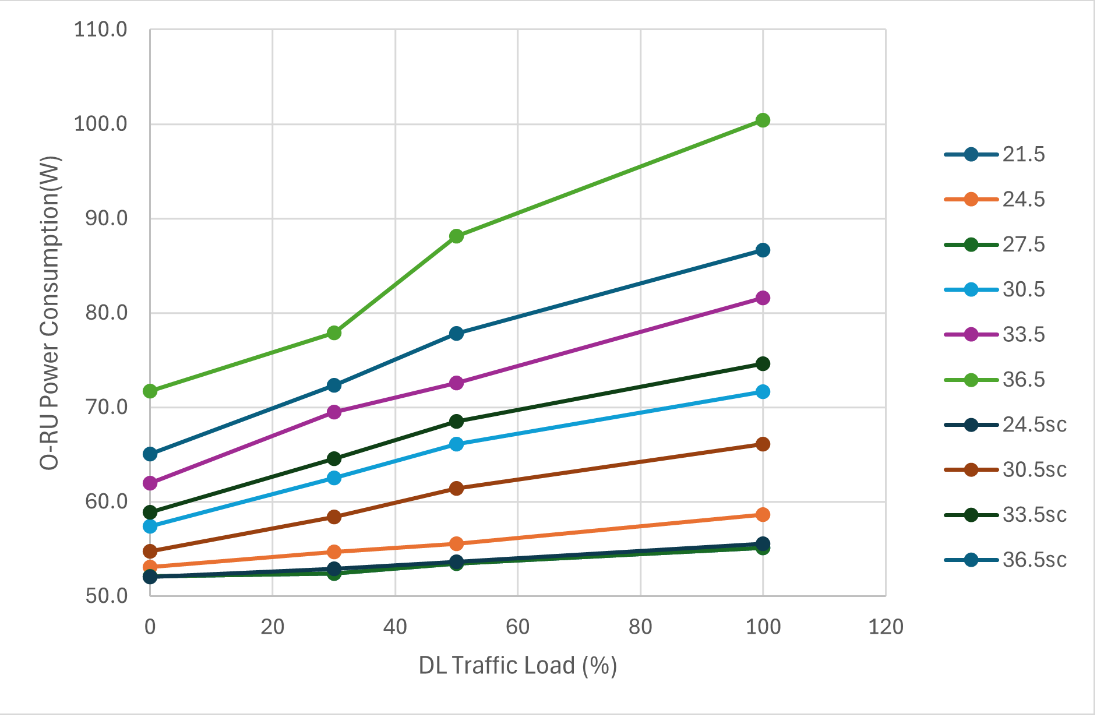
Testing multiple Tx gains and Utilization

- Configure RU Tx gain to control RU Tx Power output
- Configure automated Energy Efficiency test in DU emulator
- ETSI 202 706 1 Static Energy Test Load profiles (full, busy, medium, low)
- Utilization loading can use frequency (PRBs) or time resources (slots)
- Enables collection of multiple data points for modeling



RU Power Consumption v. PRB utilization

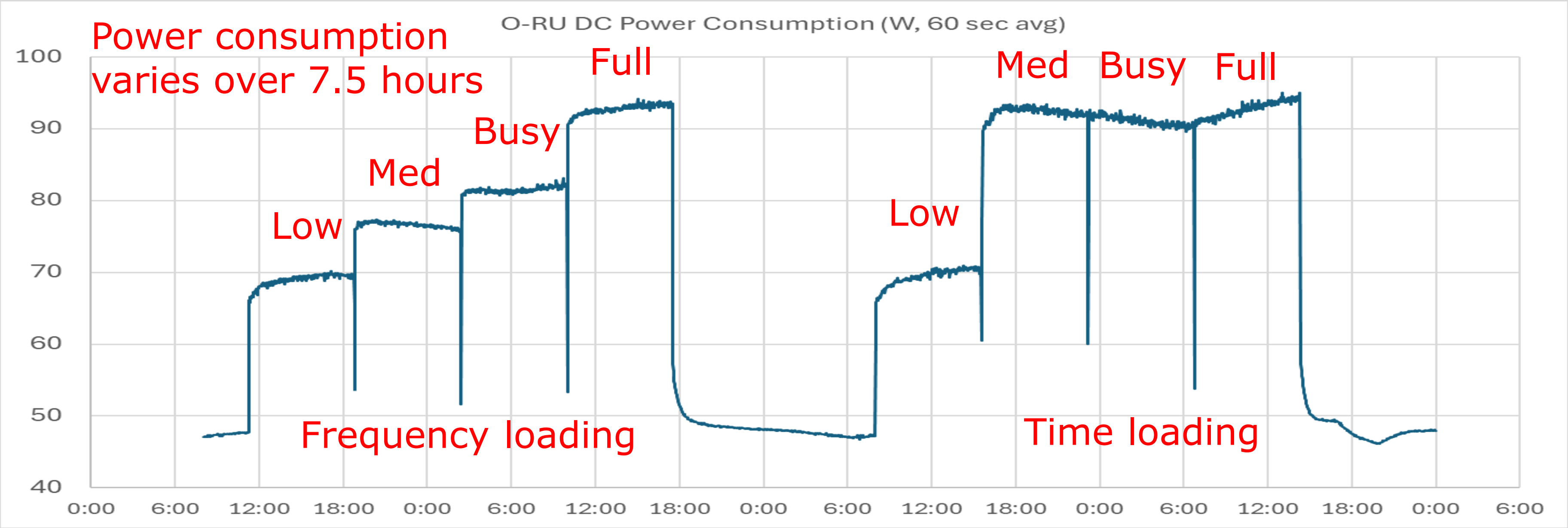
- Modeling for utilization is significant for operations teams
- Configure RU Tx gain to control RU Tx Power output(Each line represents Tx Power in dBm)
- Configure automated Energy Efficiency test in DU emulator
- ETSI 202 706 1 Static Energy Test Load profiles (full, busy, medium, low)

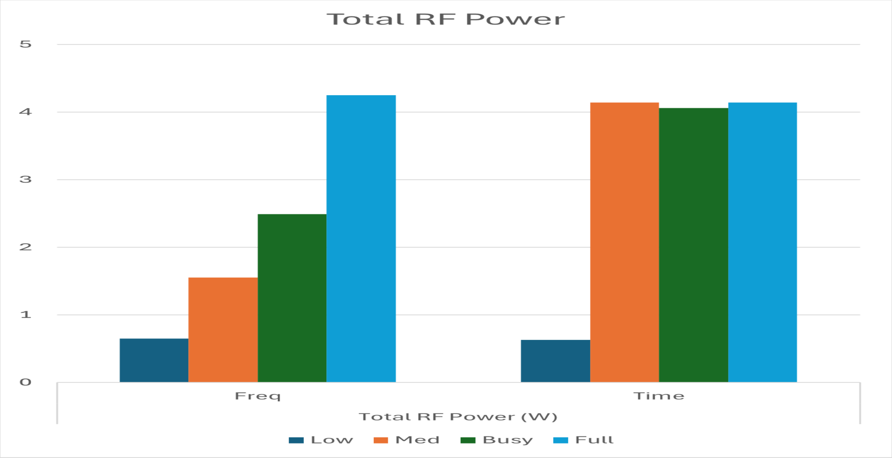


RUTGERS AETHER cognizant KEYSIGHT WINLAB

O-RU Power Consumption: Long-duration load tests

- Multiple O-RU loading as per ETSI Static Test
- Low/Medium/Busy/Full
- Frequency (PRB) load variation & Time (slot) load variation
- 7.5 hours at each load level
- Time-based loading has different Power consumption – depends on O-RU





RUTGERS AETHER cognizant KEYSIGHT WINLAB

Conclusion

Public Wireless Supply Chain INNOVATION FUND

Comprehensive Dataset

Detailed, multi-vendor O-RU power measurements **NOT available in open literature**

- Different O-RUs tested
- Multiple MIMO configurations
- Various traffic loads and RF power levels

Validated Power Model

Component-based model accurately reflects hardware behavior

- Empirically derived parameters
- Non-linear PA efficiency characterized

Critical Insights

- Idle power dominates for some Mid/Low Power O-RUs
- Key performance matrices like non-linear PA Efficiency

Practical Impact

- Foundation for energy-saving algorithms
- Guidelines for equipment selection
- Network planning optimization
- Sustainable O-RAN deployment strategies

RUTGERS AETHER cognizant KEYSIGHT WINLAB

Future Work

Public Wireless Supply Chain INNOVATION FUND

- **Extended Dataset**
  - **NTIA-funded ORCID T&E Lab** measurements with more O-RUs
  - **Multi-band O-RUs** in field-deployment scenarios

- **ML Optimization**
  - **ML Algorithms** for adjusting parameters dynamically
  - **Predictive analytics** for network-wide optimization

- **Model Refinement**
  - **Enhanced accuracy** with expanded operational scenarios
  - **Dynamic traffic** modeling

- **Simulator Integration**
  - **Network planning tools** for deployment analysis
  - **Digital twin** for virtual testing and validation

THANK YOU