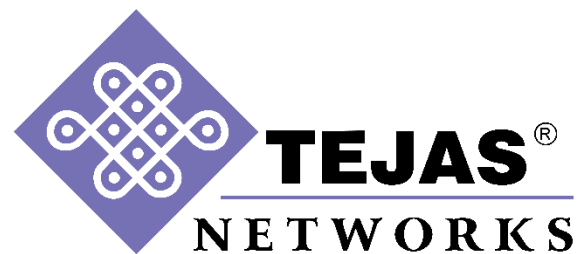




**“The Heartbeat of O-RAN:
Engineering The Synchronization at O-RU Level”**

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Tejas Networks**



Agenda

- **Foundations of O-RAN Synchronization**

- Why Sync Matters in Open RAN
- Sync Sources (PTP / SyncE / GNSS)
- How Synchronization Works End-to-End

- **Sync Architecture & Requirements**

- 3GPP Timing Requirements (TAE, TE)
- O-RAN Timing Categories (A/B/C)
- RU Sync Consumers (FPGA, RF, DDR, OS, BMC)

- **The Sync Engineering Journey**

- Clock Architecture & Planning
- Clock Tree & DPLL Design
- Bring-Up & Pre-Test (1PPS, 10 MHz, Timestamp Integrity)

- **RU Synchronization Behavior**

- RU Sync State Machine
- Wait Times & Lock Dynamics
- 1PPS → Frame/Slot/Symbol Alignment
- Carrier Deactivation & Holdover Logic

- **Validation & Integration**

- OTA Synchronization Validation
- E2E Integration with DU/CU/5GC/UE
- Certification & Compliance (O-RAN, ITU-T, 3GPP)

- **Operational Insights**

- SMO Telemetry & Closed-Loop Sync Assurance
- Field Learnings (PDV, Asymmetry, Timestamping, Drift)
- Operator Perspective: What the Network Expects from a Sync-Stable RU

Summary & Closing

Key Takeaways

The Complete RU Sync Journey

Q&A

O-RAN Basics

What is O-RAN?

O-RAN (Open Radio Access Network) is a disaggregated, open, multi-vendor architecture designed to bring modularity, programmability, and intelligence to the RAN.

• O-RU (Radio Unit)



- Handles RF transmission/reception, beamforming.
- Acts as a **timing endpoint** — must maintain phase/frequency/time alignment.
- Implements Low-PHY (7.2x split).

• O-DU (Distributed Unit)



- Executes real-time L2 & partial L1 (and parts of High-PHY) functions.
- Acts as **PTP master** or Clock Boundary for the RU.
- Hosts near-RT control loops.

• O-CU (Centralized Unit)



- Higher-layer protocols (PDCP, SDAP).
- Handles mobility, session management, and coordination.

• SMO / RIC (Intelligence & Management)



- SMO = Service Management & Orchestration (O1 interface).
- Hosts RIC (rApps/xApps) for AI-driven optimization.
- Provides sync monitoring, KPIs, and remedial actions.

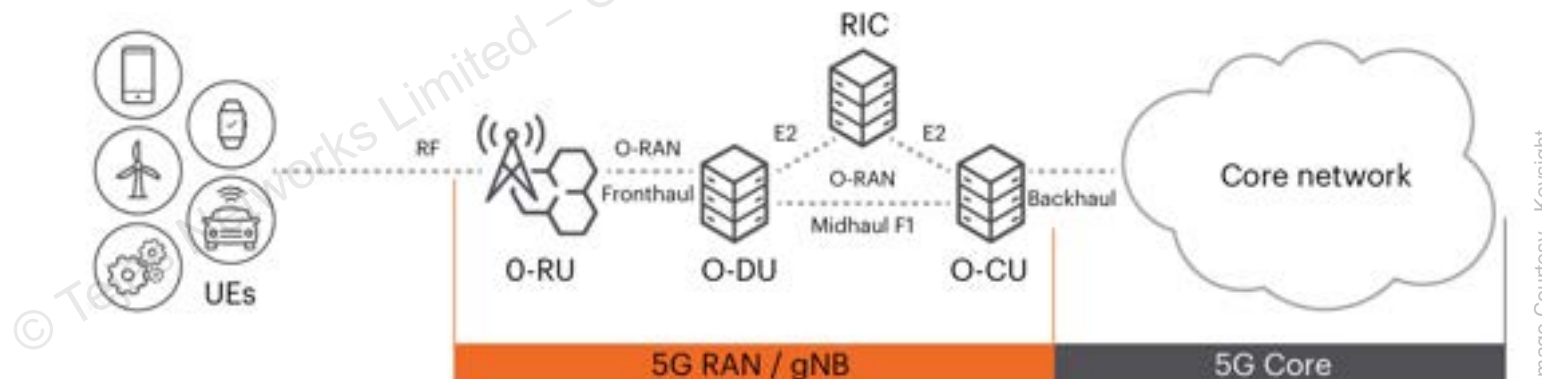


Image Courtesy - Keysight

O-RAN Fronthaul

The O-RAN Fronthaul (Split 7.2x)

The fronthaul connects the O-DU and O-RU using standard Ethernet-based interfaces, transporting:

- **User Plane (U-Plane: IQ Data)**

- Carries 7.2x split IQ samples.
- Extremely time-sensitive — requires phase/frequency alignment between DU and RU.
- Any timing error impacts EVM, MIMO, and TDD switching.

- **Control Plane (C-Plane)**

- Configures the RU for beamforming, PRACH, UL/DL switching.
- Must be synchronized with the U-Plane.

- **Synchronization Plane (S-Plane)**

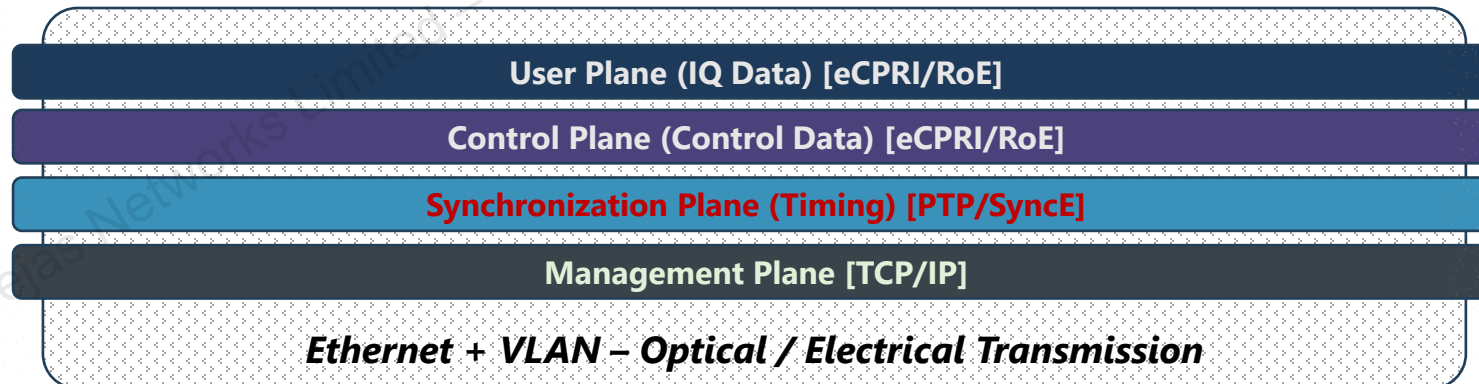
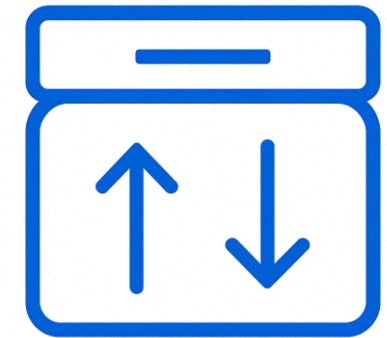
- Distributes phase/time/frequency from network → DU → RU.
- Uses SyncE + PTP (IEEE-1588v2, G.8275.x profiles).
- This is the “heartbeat delivery channel” for the radio.

- **Management Plane (M-Plane)**

- Runtime monitoring, fault management, configuration.
- Sync KPIs are sent to SMO (offsetFromMaster, sync-state, TE, Freq error).



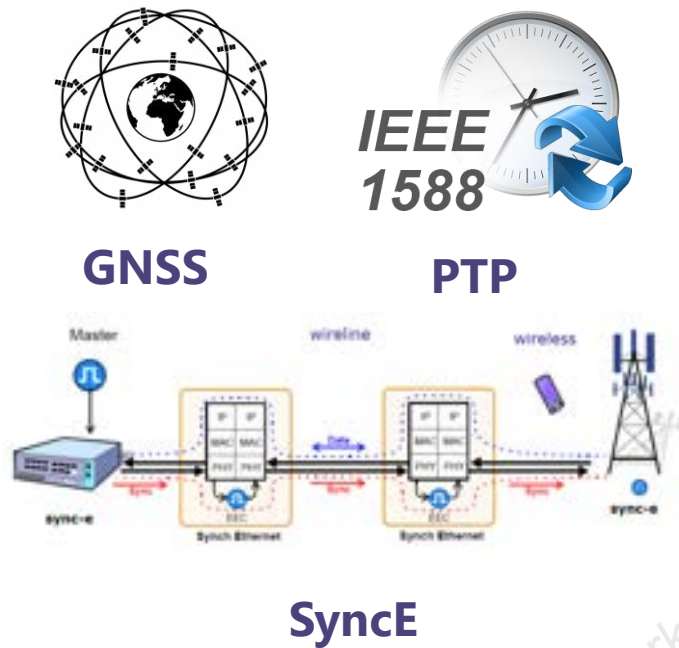
O-RU



O-DU

How Synchronization Works in O-RAN

Timing Sources



Timing Roles

• O-RU



- Consumes SyncE + PTP
- Aligns LO, sampling clocks, TDD switching, and Frame #0

• O-DU

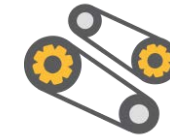


- Acts as PTP Telecom Boundary Clock
- Provides stable timing to RUs through fronthaul

• SMO (O1/Telemetry)



- Monitors offsetFromMaster, TAE, DPLL status, holdover, PPS jitter
- Enables closed-loop sync assurance



Timing Mechanism

• SyncE (Synchronous Ethernet)

- Recovers **frequency** at PHY layer
- Uses ESMC/SSM to signal quality levels
- Stabilizes the DPLL base frequency

• PTP (Precision Time Protocol)

- Provides **phase + time** alignment
- Uses timestamping for nanosecond-level precision
- Runs ITU-T G.8275.x telecom profiles

• Synchronization Hierarchy

- GM (Grandmaster) → BC (DU) → TC/BC (Transport) → RU (Slave)

| **Frequency Sync** : Aligns carrier frequencies and LO stability (SyncE) |

| **Time/Phase Sync** : Aligns transmissions across sectors and sites (PTP) |

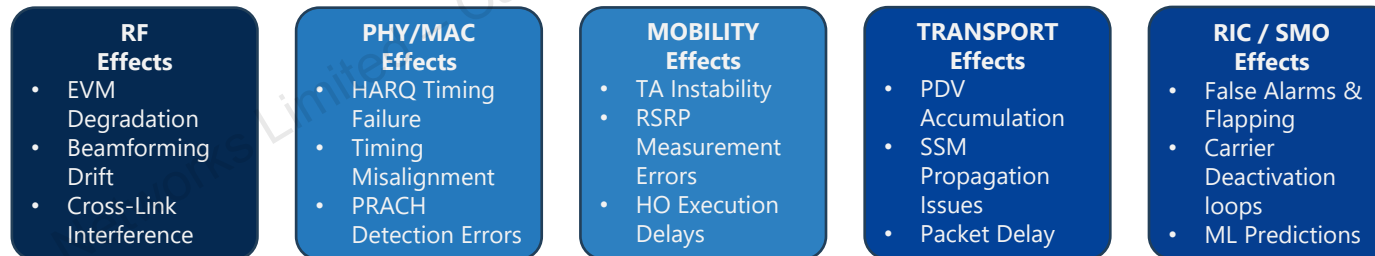
| **Frame Sync** : Aligns Frame #0, subframe, slot, and symbol boundaries inside RU |

Why Synchronization Defines the Radio Unit ?

Need of Synchronization?

O-RAN distributes radio functions across O-DU and O-RU. That disaggregation means the RU must maintain extremely tight timing alignment to ensure:

- **Correct TDD UL/DL Switching**
 - Every RU must switch UL→DL→UL at the exact same nanosecond.
 - Even ± 100 ns drift creates inter-cell interference.
- **Stable Beamforming & MIMO Coherence**
 - Phase-synchronized antennas add signals constructively.
 - Phase error increases EVM → reduces throughput.
- **Seamless Mobility & Handover**
 - Timing mismatch → poor synchronization signals → degraded handovers.
- **IQ Transport Accuracy on Split 7.2x Management Plane (M-Plane)**
 - The O-DU sends IQ data assuming RU's frame boundary is exact.
 - Any timing slip breaks the PHY pipeline.



Sync Requirements (What the O-RU Must Achieve)

- ✓ **Frequency Accuracy**

- Lock to external reference (SyncE / PTP / 10 MHz).
- Ensures stable LO generation, RF sampling, and symbol timing.

- ✓ **Phase & Time Alignment**

- Meet (e.g **±25 ns**) alignment for O-RAN conformance.
- Critical for UL/DL switching, MIMO coherence, and IQ timing.

- ✓ **Holdover Performance**

- Maintain timing during reference loss.
- OCXO/TCXO/XO + DPLL behavior under temperature/load.

- ✓ **Convergence & Lock Times**

- SyncE lock: (e.g **30–50 seconds**)
- PTP phase lock: (e.g **50–90 seconds**) (depends on PDV + servo bandwidth)

- ✓ **Frame Boundary Mapping**

- Deterministic mapping of **1PPS** → **NR Frame 0** inside FPGA/ASIC.

- ✓ **Monitoring & Telemetry**

- KPIs exported via O1/SMO:
 - offsetFromMaster,
 - syncState,
 - MTIE/TDEV trends,
 - DPLL lock flags.

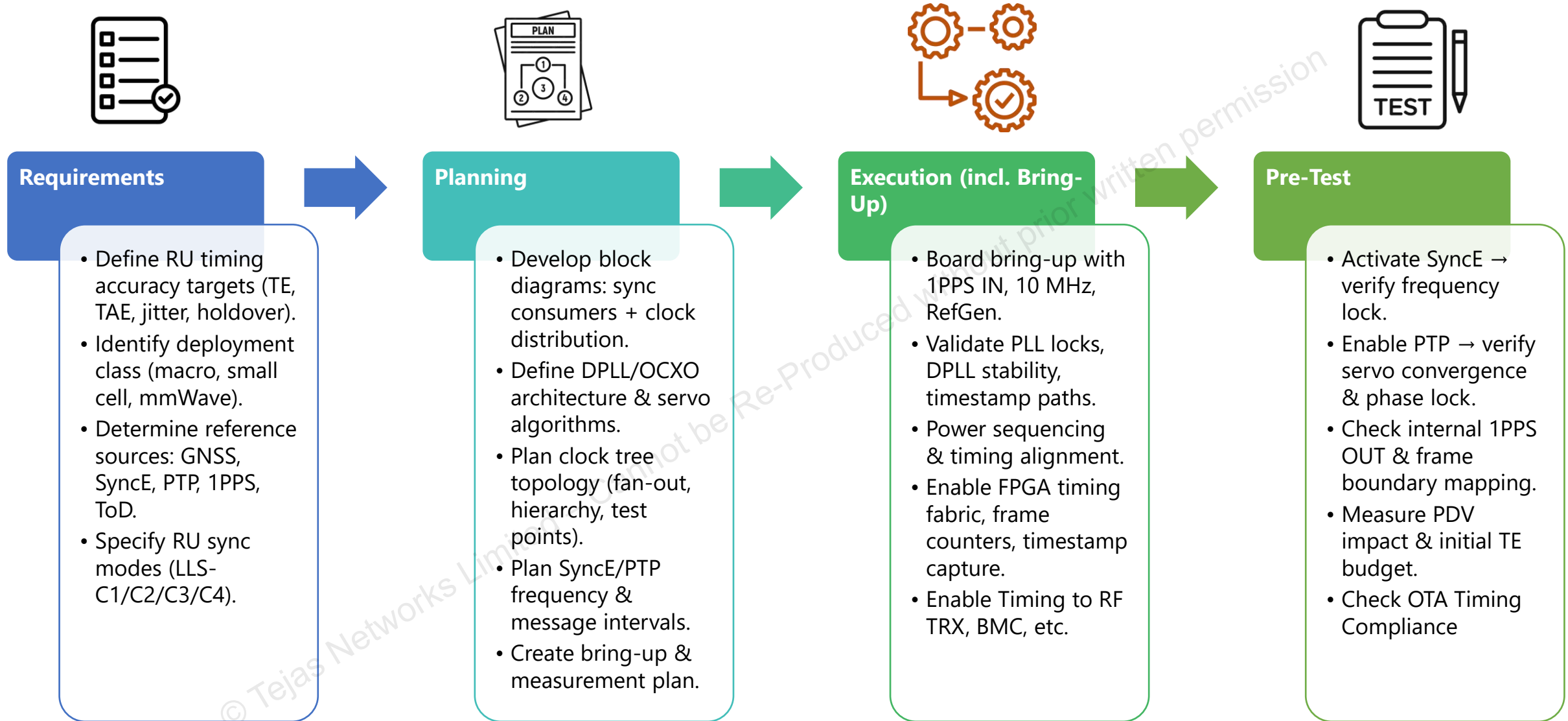
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Sync Consumers (Where Synchronization is used in O-RU ?)

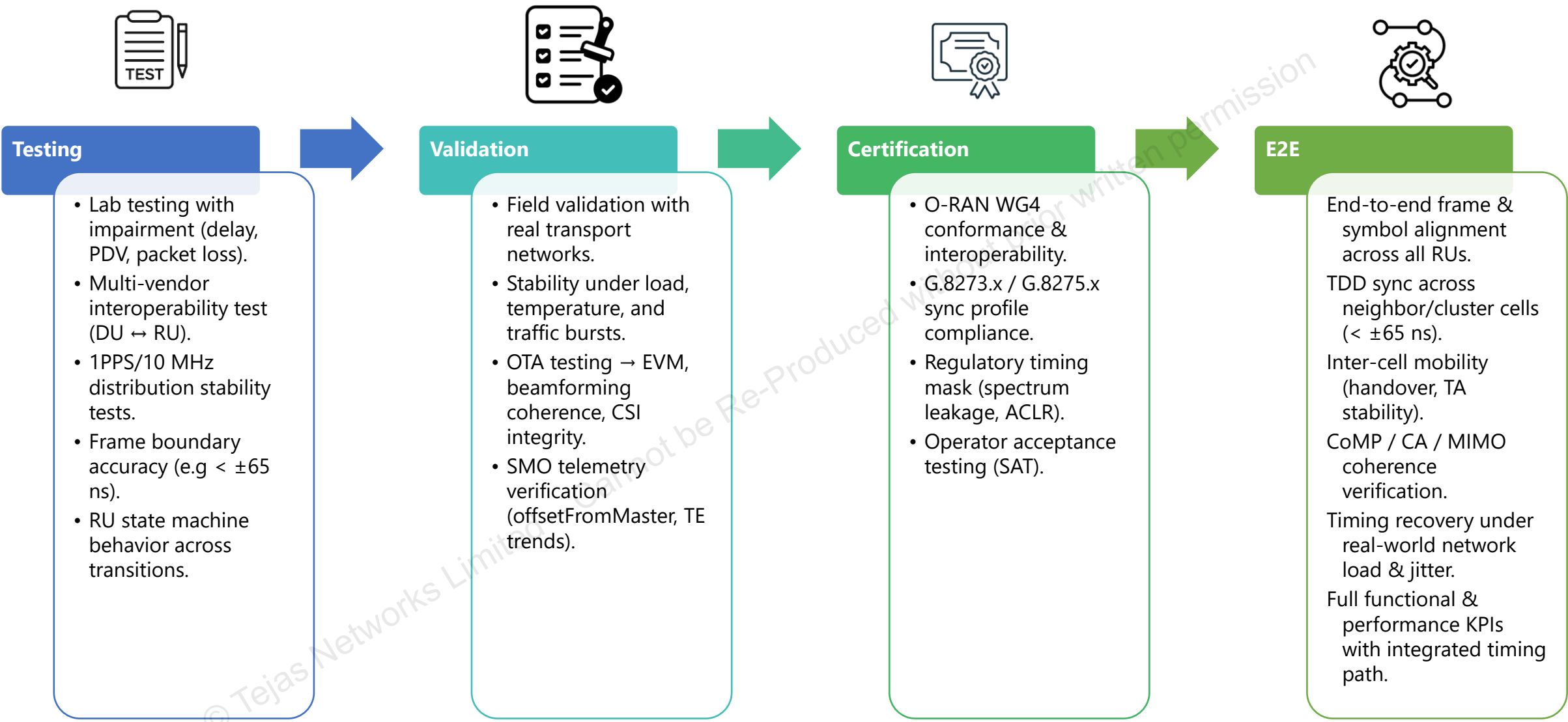
- ✓ **FPGA / ASIC Timing Fabric**
 - Slot/symbol counters, timestamp logic.
 - NCOs and digital PLL loops.
- ✓ **RF Transceiver (ADC/DAC + LO)**
 - Sampling clocks, TDD switching, phase alignment.
 - Critical for beamforming and CSI accuracy.
- ✓ **PHY Interfaces (Ethernet MAC + SyncE PHY)**
 - Hardware timestamping for PTP.
 - SyncE clock recovery and SSM propagation.
- ✓ **Memory Interfaces (DDR / LPDDR)**
 - Tight timing windows require clean, jitter-free clocks.
- ✓ **BMC / System Controller**
 - Time-based sequencing and event logging.
 - Dependency for deterministic power and reset flows.
- ✓ **SMO / Telemetry Interfaces**
 - Sync KPIs for RAN analytics & automated corrective actions.
- ✓ **OS / Operating System**
 - Uses accurate **Date/Time synchronization** for:
 - System logs, fault correlation
 - Application timestamping
 - Security protocols (TLS, certificates)
 - Inter-process timing
 - SMO/OAM reporting consistency
 - Often driven by **ToD (Time of Day)** derived from PTP/1PPS.
- ✓ **1PPS & 10 MHz Output**
 - Needed for debugging, DU sync, and test & measurement.

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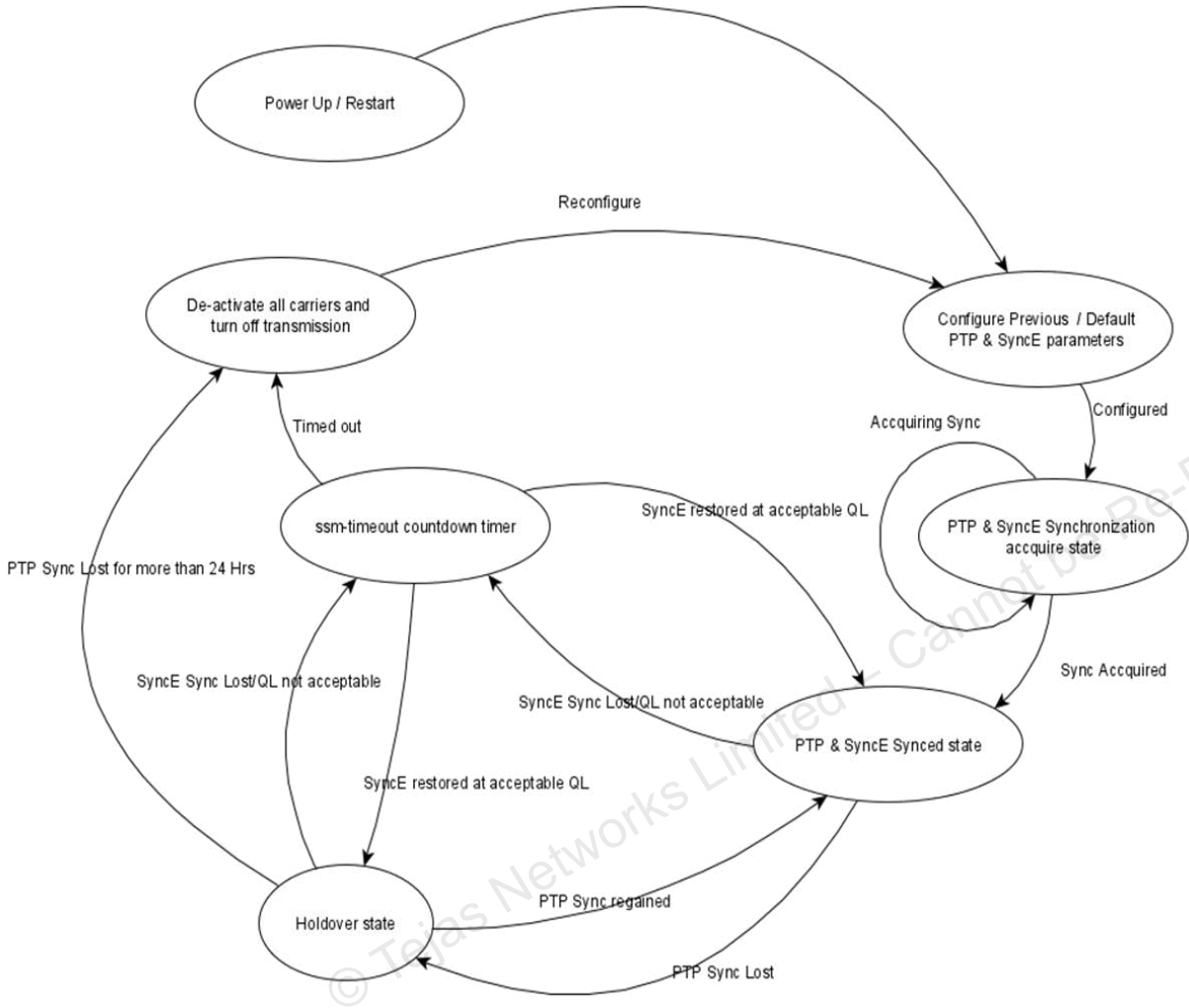
O-RU : End-to-End Sync Engineering Journey



O-RU : End-to-End Sync Engineering Journey



O-RU Synchronization State Machine



- **Initial State:** Power Up / Restart → Configure PTP & SyncE.
- **Acquire Sync:** Enter synchronization acquire state.
- **Normal Operation:** PTP & SyncE synced at acceptable quality.
- **Sync Loss Handling:**
 - Enter Holdover if sync lost.
 - Use internal oscillator for limited time.
- **Timeout Action:** If sync loss > 24 hrs → deactivate carriers.
- **Recovery:** Re-lock to PTP & SyncE when restored.

State Transition	
Original State (Free Run/Acquiring/ Synchronised/Holdover)	New State (Free Run/Acquiring/ Synchronised/Holdover)
Free Run	Free Run
Free Run	Acquiring
Acquiring	Synchronised
Synchronised	Holdover
Holdover	Free Run

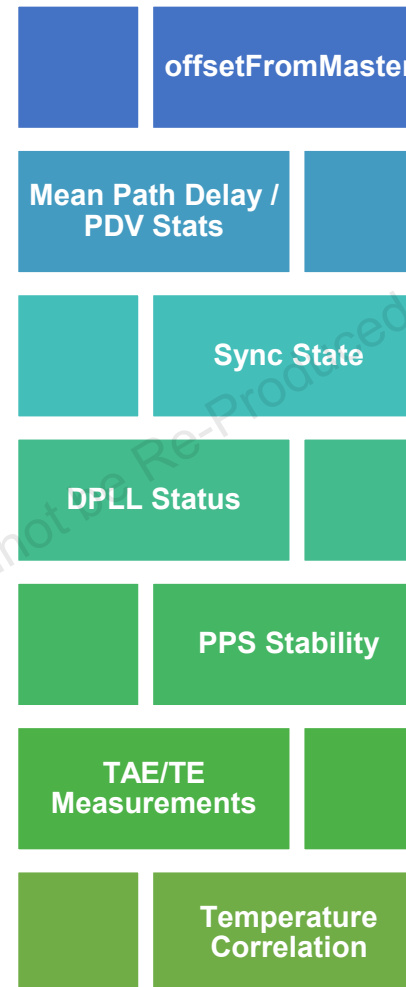
SMO Integration, Telemetry & Closed-Loop Sync Assurance

- **Role of the SMO**

- (Service Management & Orchestration)**

- The SMO ensures end-to-end sync quality by:
 - ✓ Collecting sync KPIs from all RUs
 - ✓ Monitoring timing behavior over long durations
 - ✓ Triggering actions when drift, jitter, or loss is detected
 - ✓ Providing visibility across thousands of radios
 - ✓ O-RAN O1 interface carries all sync telemetry.

Typical Sync KPIs



- **Multi-Layer Correlation**

- Sync telemetry is correlated with:
 - EVM, RSRP/RSRQ anomalies
 - HO failures
 - TA instability
 - PDV spikes in transport
 - Temperature and power events
 - This turns sync monitoring into a **network-wide timer health dashboard**.

- **Why This Matters**

- Prevents sync-related outages
 - Improves beamforming and MIMO reliability
 - Ensures high QoS and VoNR performance
 - Keeps cluster-level timing coherent
 - Reduces field-debugging time by 10×
 - Moves RAN toward self-healing sync loops

Certification & Compliance for SYNC-Ready O-RUs



- **O-RAN WG4 Conformance (CUS-Plane)**
- Confirms that the RU meets all fronthaul sync requirements:
 - **✓ Timing Categories (A / B / C)**
 - Phase/Time alignment
 - Frequency accuracy
 - TE/TAE thresholds
 - 1PPS → Frame alignment
 - **✓ PTP/SyncE Behavior**
 - Correct processing of Sync, Follow_Up, Delay_Req/Resp
 - Correct correctionField handling
 - SSM/ESMC propagation
 - SyncE priority selection
 - **✓ State Machine Compliance**
 - INIT → WAIT → FREQ-LOCK → TIME-LOCK → HOLDOVER → FAULT
 - Correct transitions and timers



- **ITU-T Sync Profile Compliance**
- Must meet global timing standards:
 - **✓ ITU-T G.8275.1 / G.8275.2 (PTP Telecom Profiles)**
 - Message intervals
 - BMCA behavior
 - PDV tolerance
 - Transparent Clock / Boundary Clock interoperability
 - **✓ ITU-T G.8262 / 8264 (SyncE)**
 - Jitter and wander performance
 - ESMC/SSM priority correctness
 - **✓ ITU-T G.8273.x (PTP Slave Clock Performance)**
 - TE, TDEV, MTIE thresholds
 - Holdover requirements
 - Jitter limits under PDV

Certification & Compliance for SYNC-Ready O-RUs



- **3GPP Conformance**

- Ensures RU meets radio-side timing expectations:

- **✓ TAE (Time Alignment Error) Requirements**

- CA (FR1/FR2)
 - MIMO & Tx diversity
 - DC / TDD / inter-band CA
 - Must meet XXX ns or μ s-level targets

- **✓ RF Performance Metrics**

- EVM
 - ACLR
 - SEM
 - SSB timing accuracy
 - Beamforming & CSI stability
 - These all indirectly validate sync quality.

- **Regulatory Certification**

- Sync affects RF emissions:

- **✓ Emissions Under Timing Drift**

- If timing drifts, spectral leakage increases
 - Must stay within FCC/ETSI masks

- **✓ Clock Stability During Frequency Drift**

- Stability under voltage/temp variation
 - Regulatory acceptance depends on LO stability → Sync quality

- **Interoperability Certification (Plugfests)**

- Performed in O-RAN plugfests and operator labs:

- **✓ DU ↔ RU Timing Interop**

- PTP packet formats correction
 - Field behavior, Startup ordering
 - Frame mapping consistency

- **✓ Multi-Vendor Scenarios**

These are true test of O-RU readiness.

Field Learnings & Practical Challenges in O-RU Sync

- **PDV Is the No.1 Timing Killer**

- Transport networks introduce **non-uniform PDV**, not seen in lab setups.
- Burst PDV (microbursts) causes servo oscillations.
- Most timing instability traces back to transport jitter, not the RU.

- **Learning:**

- Tune DPLL bandwidth conservatively; avoid overly aggressive phase correction.

- **Asymmetry Is More Common Than Expected**

- Sources of asymmetry discovered in the field:
- Different fiber lengths.
- Unequal switch paths.

- **Learning:**

- Always measure asymmetry during site acceptance; correct at transport layer.

- **Timestamp Integrity Issues**

- Field failures often traced to:
- Incorrect PHY timestamp configuration.
- FPGA variable-latency paths.
- Inconsistent correctionField behavior from intermediate BC/TC nodes.

- **Learning:**

- Validation of timestamp path is *mandatory* before deployment.

- **Timing Drift in Real Temperature Cycles**

- RUs exposed to outdoor conditions (40–70°C).
- Drift rate increases significantly at extremes.
- Holdover degrades faster than lab expectations.

- **Learning:**

- Deploy RUs with auto temperature compensation & SMO drift monitoring

Field Learnings & Practical Challenges in O-RU Sync

- **GM Switchovers Are Disruptive**

- Observed in the field:
- GM change → short PTP instability → RU drop to HOLDOVER.
- Some DU vendors generate inconsistent Announce messages temporarily.

- **Learning:**

- Use controlled GM switchover + dampened DU algorithms.

- **Multi-Vendor Integration Pitfalls**

- Not all DUs implement PTP correction Field correctly.
- Vendor-specific PTP stacks behave differently under PDV.
- SyncE priority handling mismatches are common.

- **Learning:**

- Interoperability tests MUST include real DU + transport combinations.

- **Frame Boundary Drift Under Load**

- Real-world observation:
 - High UL traffic loads → timestamp jitter variation
 - RF LO temperature rise → micro phase drift

- **Learning:**

- Continuous PPS→Frame0 monitoring is essential; SMO analytics must correlate drift with load & temperature.

- **Operators Prefer Stable Over Fast Lock**

- RUs that lock quickly but oscillate are worse than slow-but-stable lock.
- Production networks prefer fewer state transitions, even if slower.

- **Learning:**

- Tune servo bandwidth for stability > speed.

Operator Perspective:

Yes – Its Bonus Slide! 😊

What the Network Expects from a Sync-Stable RU?

Predictable & Deterministic Behavior

- RU must follow a **deterministic state machine**: INIT → WAIT → FREQ-LOCK → TIME-LOCK → OPERATIONAL.
- No unexpected transitions or oscillations.
- Startup lock times consistent across temperature & load.



Deterministic Behavior



Stable TAE



No Carrier Drops

Stable TAE / TE Under Real Traffic

- Timing alignment must remain stable under:
 - Full UL/DL load
 - Scheduling pressure
 - Beamforming activation
 - Temperature swings
- Operators **prioritize stability over fast lock**.



Strong Holdover



Multi-Vendor Interoperability



Accurate Telemetry

Cluster-Level Timing Consistency

- Neighbor RUs must remain aligned for:
 - TDD UL/DL switching
 - MIMO/beamforming
 - CA/DC operation
 - Mobility & HO stability
- Operators expect < **±65 ns** drift between RUs in a sector.



Alignment with Neighboring RUs

No Surprise Carrier Drops

- Carriers should deactivate **only** when absolutely required.
- RU should handle:
 - GM switchover
 - PTP burst errors
 - Short SyncE glitches without unnecessary drop.

Strong Holdover Behavior

- Maintain tight timing during:
 - PTP loss
 - Fiber cut
 - DU restart
- Drift must be controlled (good OCXO/TCXO performance + DPLL tuning).
- Smooth recovery—**zero phase jumps**.

Accurate, Actionable Telemetry

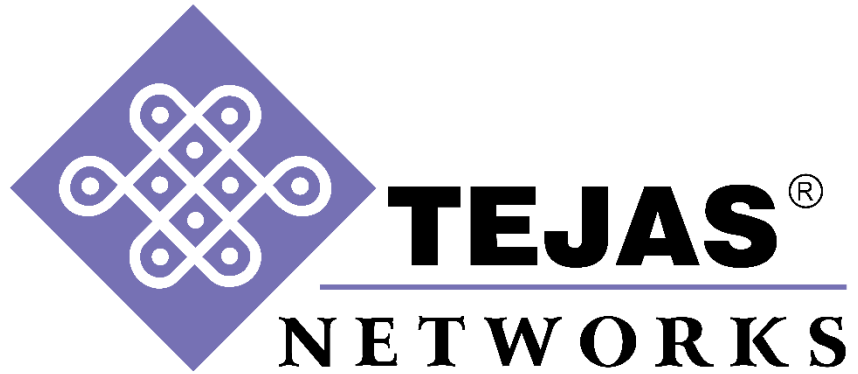
- SMO/RIC must receive:
 - offsetFromMaster
 - syncState
 - TE/TAE trends
 - PPS jitter
 - DPLL status
- KPIs must support **closed-loop automation**.

The Heartbeat of O-RAN: Key Takeaways

- ✓ Synchronization is the **foundation** of RU performance — **not an add-on!**.
- ✓ Tight alignment drives **MIMO, beamforming, CA, and TDD stability**.
- ✓ RU design must start with a **sync-centric clock architecture** and deterministic timing fabric.
- ✓ PTP + SyncE + DPLL (Network Synchronizer) tuning define **lock performance and robustness**.
- ✓ OTA + E2E validation confirm real-world stability under **PDV, load & temperature**.
- ✓ SMO telemetry enables **closed-loop correction** and network-wide sync assurance.
- ✓ Field learnings show that **PDV, asymmetry, timestamp integrity, and temperature** drift are the real challenges.
- ✓ A deployable RU passes **O-RAN, ITU-T, 3GPP and regulatory timing** compliance.



“Synchronization is not a feature — it is the operating system of O-RAN.”



Thank you!

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