"The Heartbeat of O-RAN: Engineering The Synchronization at O-RU Level"

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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

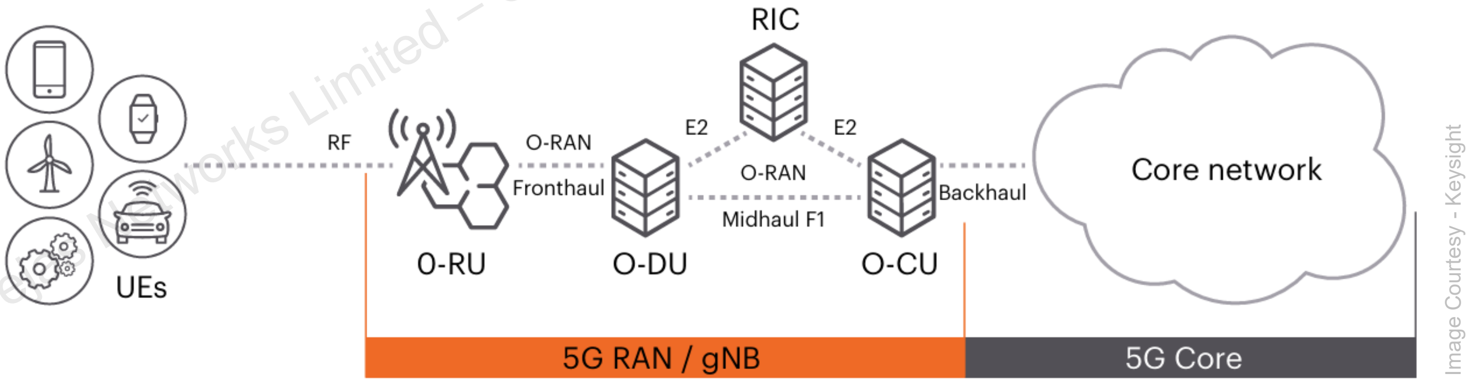
Q&A

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.



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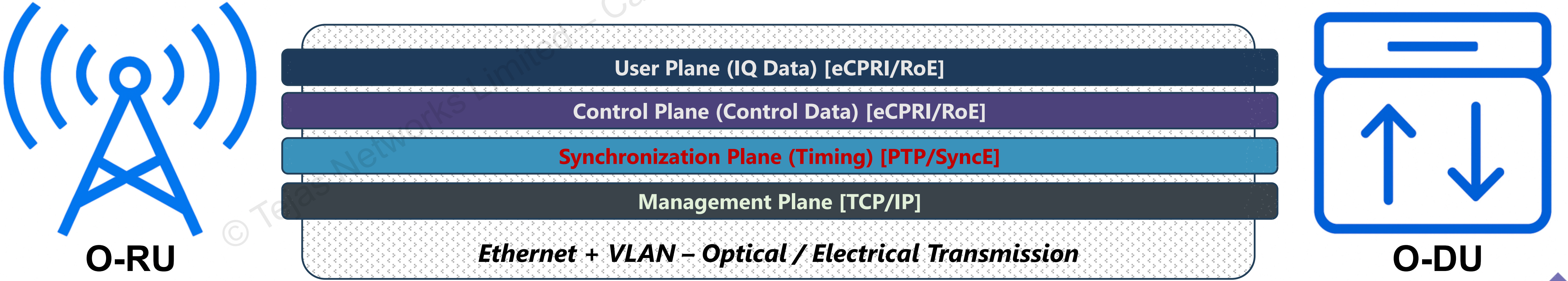
O-RAN Fronthaul

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).

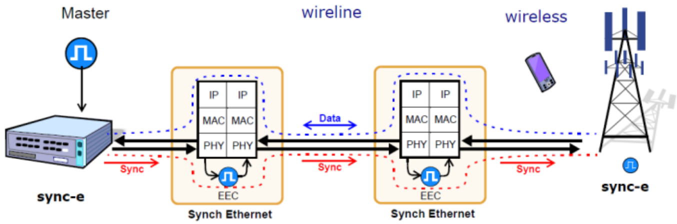


How Synchronization Works in O-RAN

Timing Sources

GNSS

PTP



SyncE

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 7.2xManagement Plane (M-Plane)**
  - The O-DU sends IQ data assuming RU's frame boundary is exact.
  - Any timing slip breaks the PHY pipeline.

RF Effects
- EVM Degradation
- Beamforming Drift
- Cross-Link Interference

PHY/MAC Effects
- HARQ Timing Failure
- Timing Misalignment
- PRACH Detection Errors

MOBILITY Effects
- TA Instability
- RSRP Measurement Errors
- HO Execution Delays

TRANSPORT Effects
- PDV Accumulation
- SSM Propagation Issues
- Packet Delay

RIC / SMO Effects
- False Alarms & Flapping
- Carrier Deactivation loops
- ML Predictions

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.

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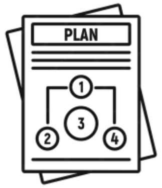
O-RU : End-to-End Sync Engineering Journey

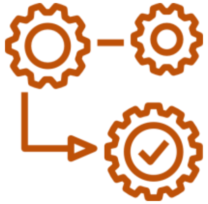
Requirements

- Define RU timing accuracy targets (TE, TAE, jitter, holdover).
- Identify deployment class (macro, small cell, mmWave).
- Determine reference sources: GNSS, SyncE, PTP, 1PPS, ToD.
- Specify RU sync modes (LLS-C1/C2/C3/C4).



Planning

- Develop block diagrams: sync consumers + clock distribution.
- Define DPLL/OCXO architecture & servo algorithms.
- Plan clock tree topology (fan-out, hierarchy, test points).
- Plan SyncE/PTP frequency & message intervals.
- Create bring-up & measurement plan.



Execution (incl. Bring-Up)

- Board bring-up with 1PPS IN, 10 MHz, RefGen.
- Validate PLL locks, DPLL stability, timestamp paths.
- Power sequencing & timing alignment.
- Enable FPGA timing fabric, frame counters, timestamp capture.
- Enable Timing to RF TRX, BMC, etc.

Pre-Test

- Activate SyncE → verify frequency lock.
- Enable PTP → verify servo convergence & phase lock.
- Check internal 1PPS OUT & frame boundary mapping.
- Measure PDV impact & initial TE budget.
- Check OTA Timing Compliance

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

Testing

- Lab testing with impairment (delay, PDV, packet loss).
- Multi-vendor interoperability test (DU ↔ RU).
- 1PPS/10 MHz distribution stability tests.
- Frame boundary accuracy (e.g < ±65 ns).
- RU state machine behavior across transitions.

Validation

- Field validation with real transport networks.
- Stability under load, temperature, and traffic bursts.
- OTA testing → EVM, beamforming coherence, CSI integrity.
- SMO telemetry verification (offsetFromMaster, TE trends).

Certification

- O-RAN WG4 conformance & interoperability.
- G.8273.x / G.8275.x sync profile compliance.
- Regulatory timing mask (spectrum leakage, ACLR).
- Operator acceptance testing (SAT).

E2E

End-to-end frame & symbol alignment across all RUs.

TDD sync across neighbor/cluster cells (< ±65 ns).

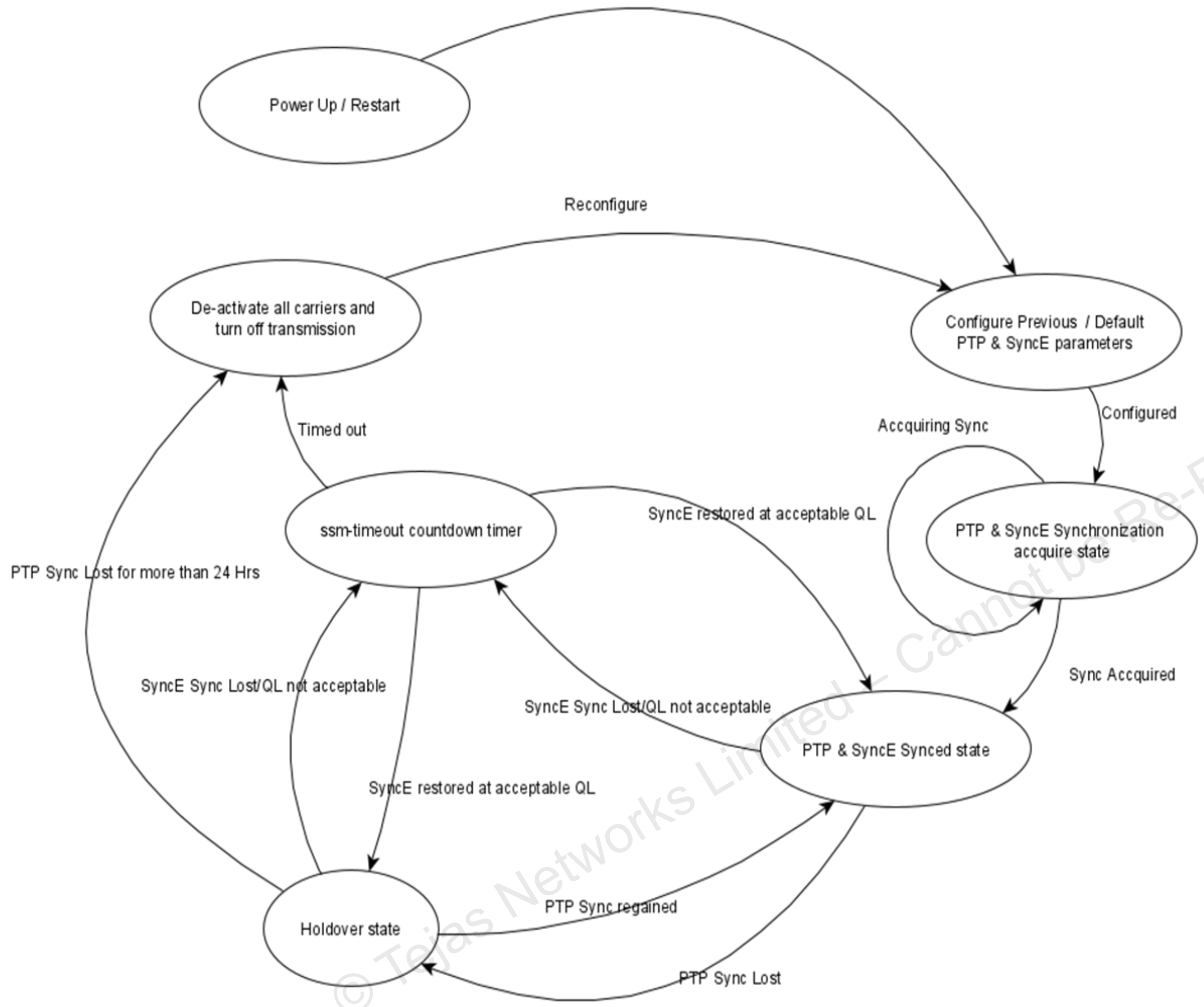
Inter-cell mobility (handover, TA stability).

CoMP / CA / MIMO coherence verification.

Timing recovery under real-world network load & jitter.

Full functional & performance KPIs with integrated timing path.

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

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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

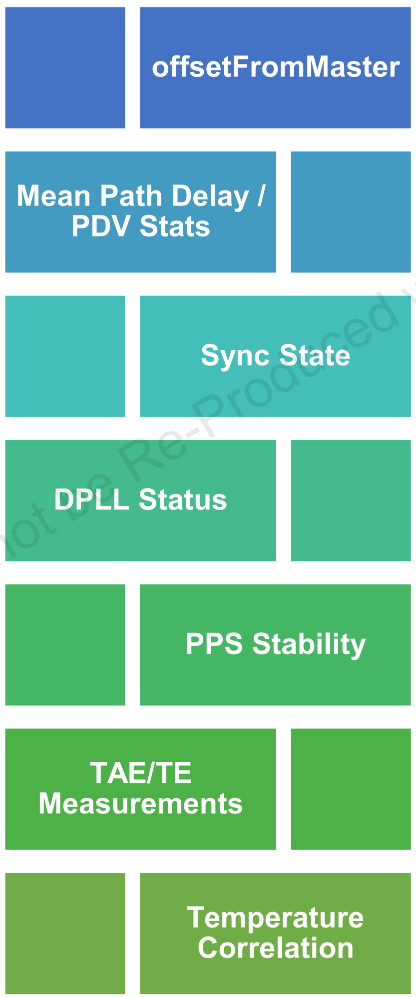
✓ Monitoring timing behavior over long durations

✓ 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

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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 µs-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

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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.*

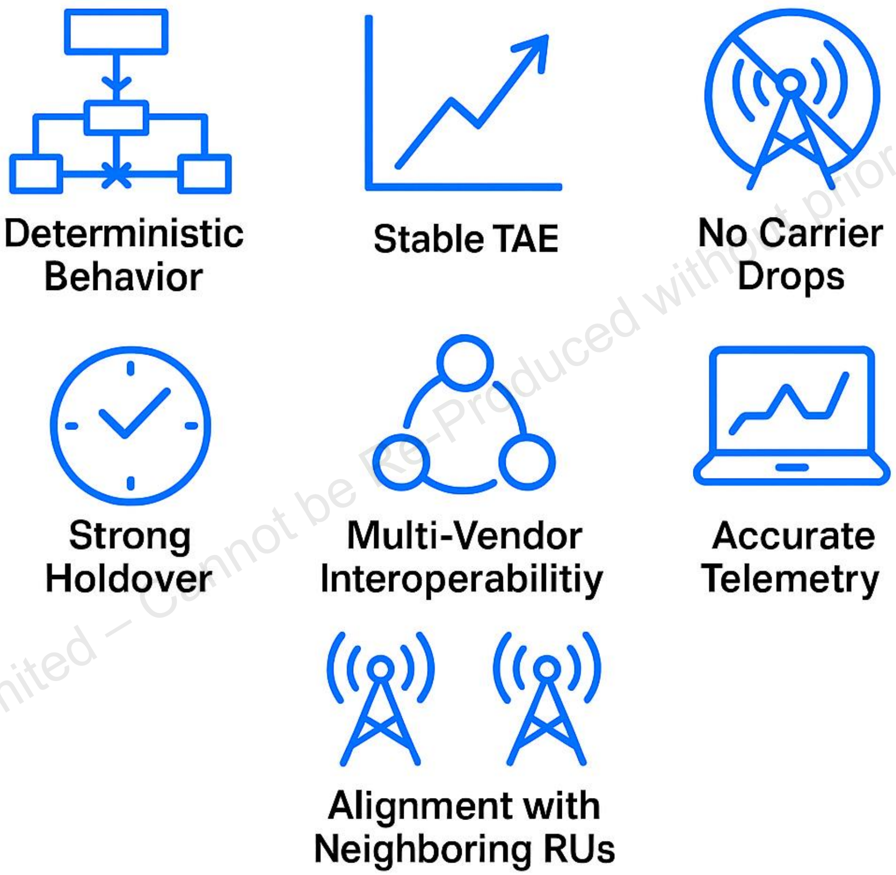
Stable TAE / TE Under Real Traffic

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

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.



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**.

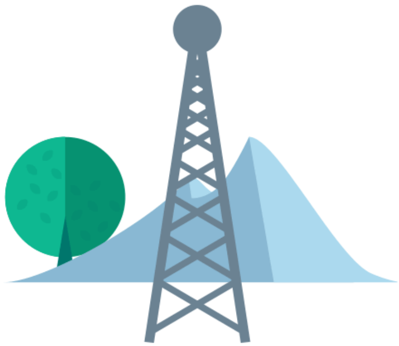
Accurate, Actionable Telemetry

• 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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