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Workshop on Synchronization and Timing Systems 2026

Space-Time Synchronization Technologies as Critical Enablers of Future Public Infrastructure

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Agenda

1. Why 10–300 GHz, and Why Time Becomes the Bottleneck
2. Cell-Free Starts Here: ns Time Alignment and ps-Level Phase Stability
3. Frequency-Domain Realities: A Crystal Plateau - and an Atomic Way Out
4. From Precision to Invariance: Making Time Mean the Same
5. One Clock to Bind Them: Module + Optical + NTN + Edge

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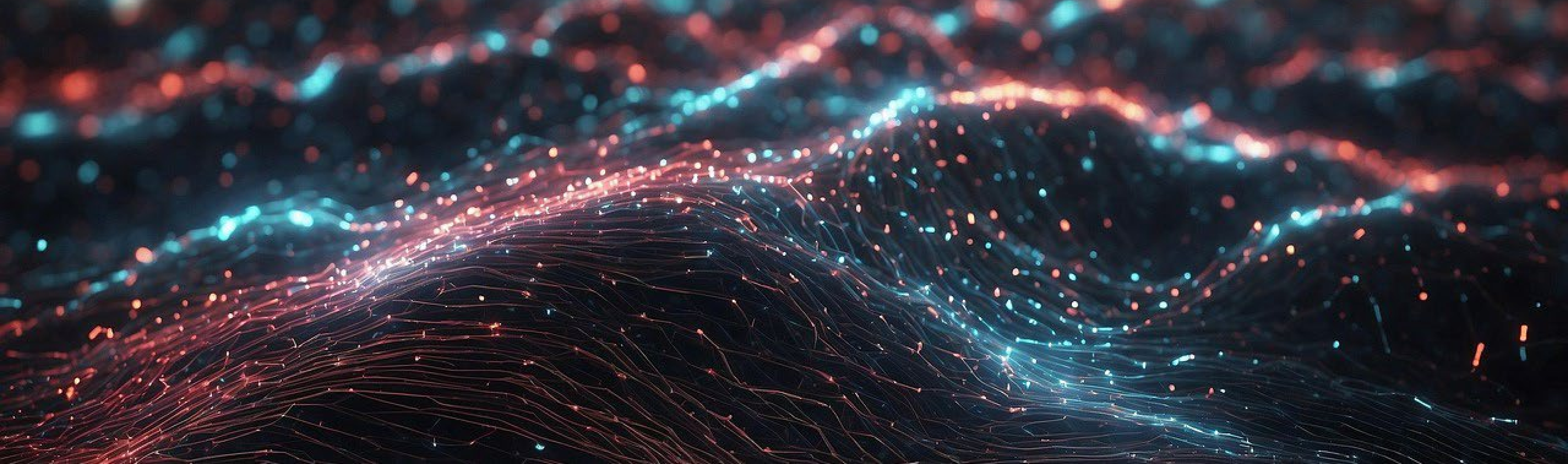
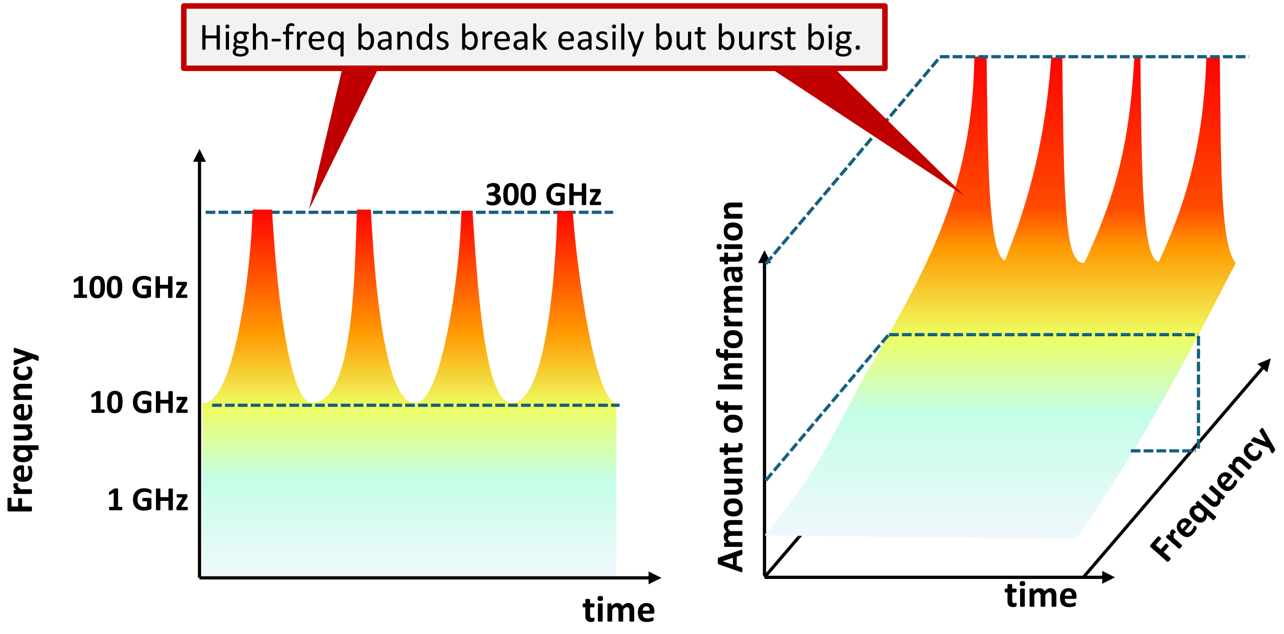
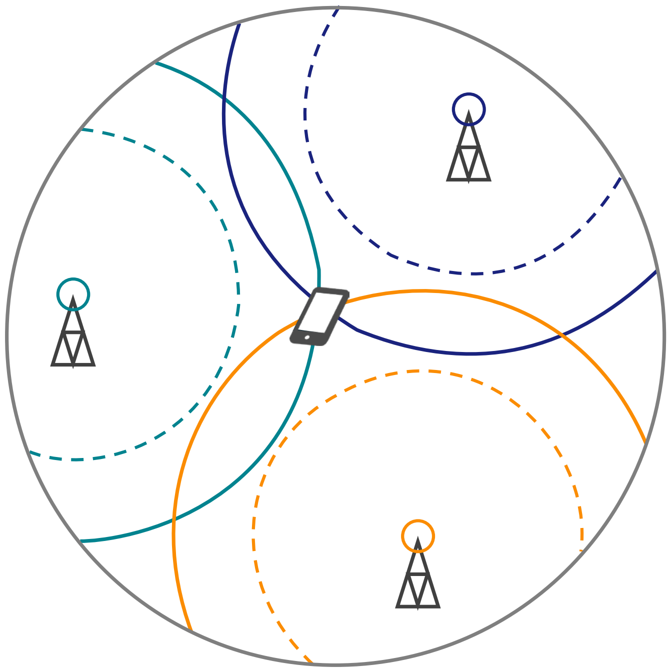


1. Why 10–300 GHz, - and Why *Time* Bottlenecks it

- **Vast, underused spectrum and very wide channels** boost **area capacity** and relieve congestion in legacy bands.
- **Links are fragile** by nature at high frequencies—so we design for **bursty, beam-steered** (coherent combining) connectivity to synthesize an “always-on” experience.
- As bandwidth and distribution scale, **ns/ps-level time alignment** and **degree-level phase coherence** bound beamforming and cell-free MIMO.





2. Cell-Free Starts Here: ns Time Alignment and ps-Level Phase Stability

・Coherence threshold(assumption): To cooperate in distributed MIMO, keep carrier phase difference ≤ 15° between sites per carrier.

→ Using $\Delta\phi = 2\pi f \Delta t$, this implies ps-class timing at high carrier frequencies.

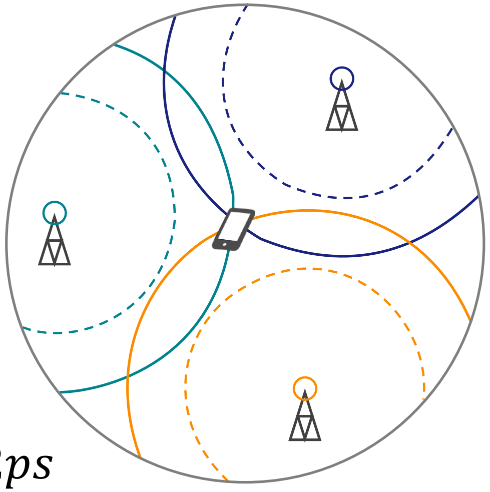
・What ps means at our bands:

10 GHz:

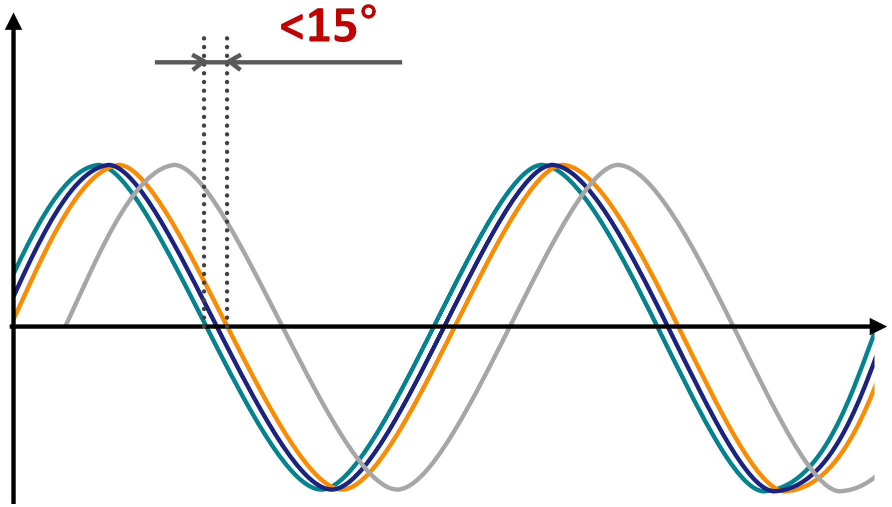
$$\Delta t \approx \frac{15°}{360°}\frac{1}{f} \approx \frac{1}{24}\frac{1}{10\ GHz} \approx 4.2ps$$

100 GHz:

$$\Delta t \approx \frac{15°}{360°}\frac{1}{f} \approx \frac{1}{24}\frac{1}{100\ GHz} \approx 0.42ps$$



Sites & UE



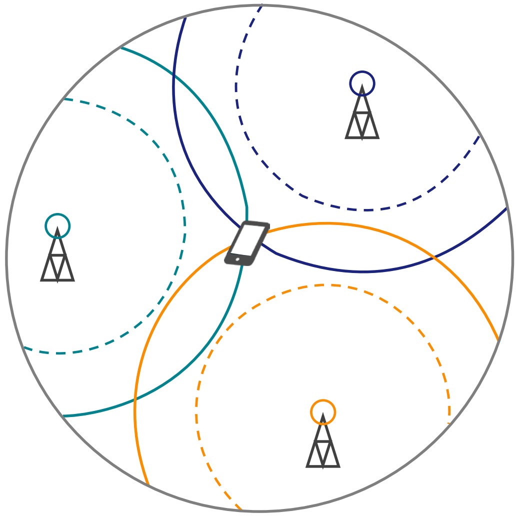
Phase (carrier)

・Operational picture: If we hold **ns-level alignment** (absolute) and **ps-level phase stability** (relative), we can **cluster sites** and operate as **cell-free MIMO.**

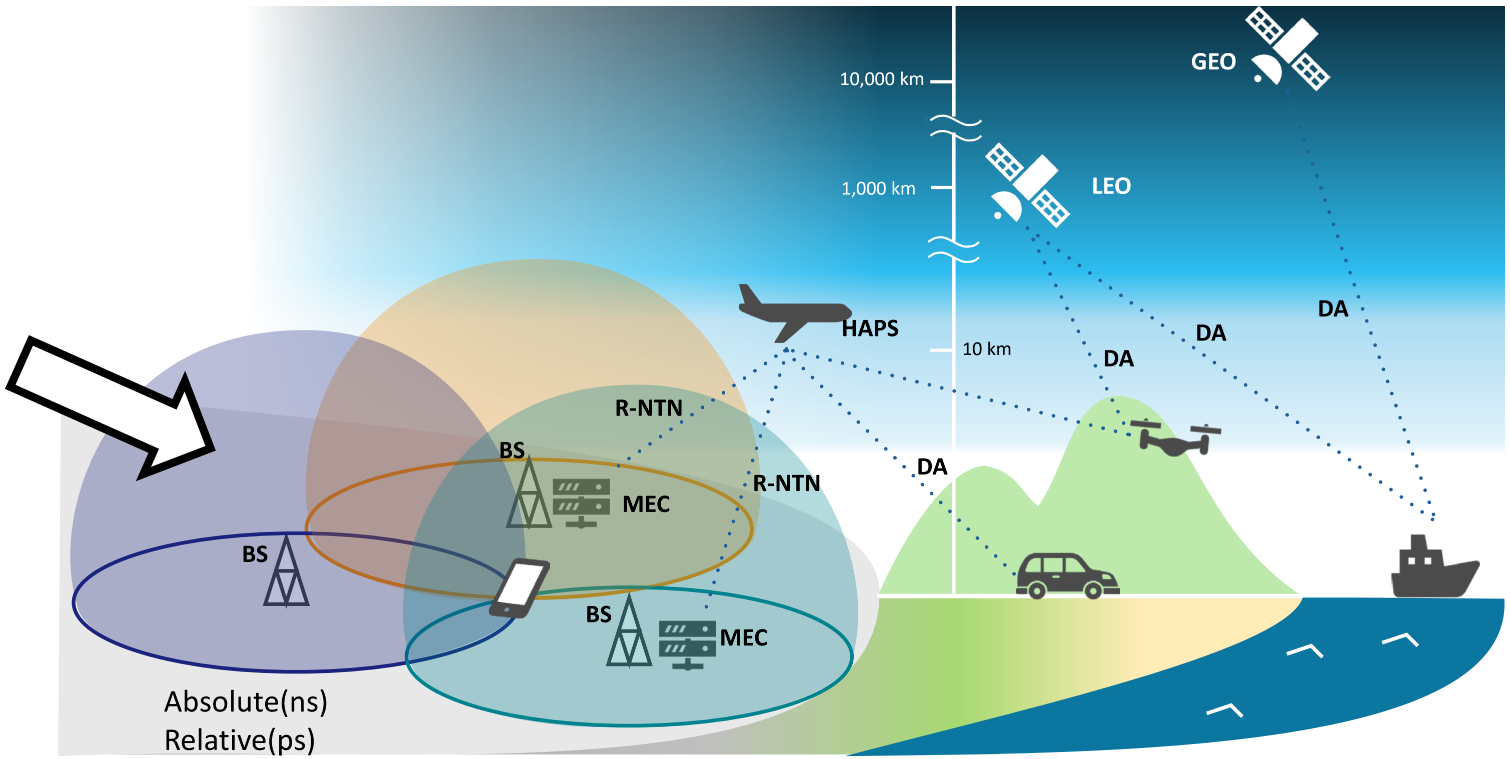
2. Cell-Free Starts Here: ns Time Alignment and ps-Level Phase Stability

- From ground to NTN: The same timing discipline enables **phase-continuous cooperation** with NTN (HAPS/LEO) once geometry/Doppler are compensated, with **MEC** (Multi-access Edge Computing/edge server) acting as the **real-time correction hub**.

- Takeaway: **ns aligns geometry; ps preserves coherence**.
  Clustering ⇒ **cell-free on ground**, extendable ⇒ cell-free with NTN via MEC-assisted compensation.



Alignment target: Δt< 1 ns (cluster scale)
Phase stability: integrated σ_{φ} < few degree over 1-10 ms
Rule of thumb: Δt_{max} [ps] ≈41.7/f[GHz]



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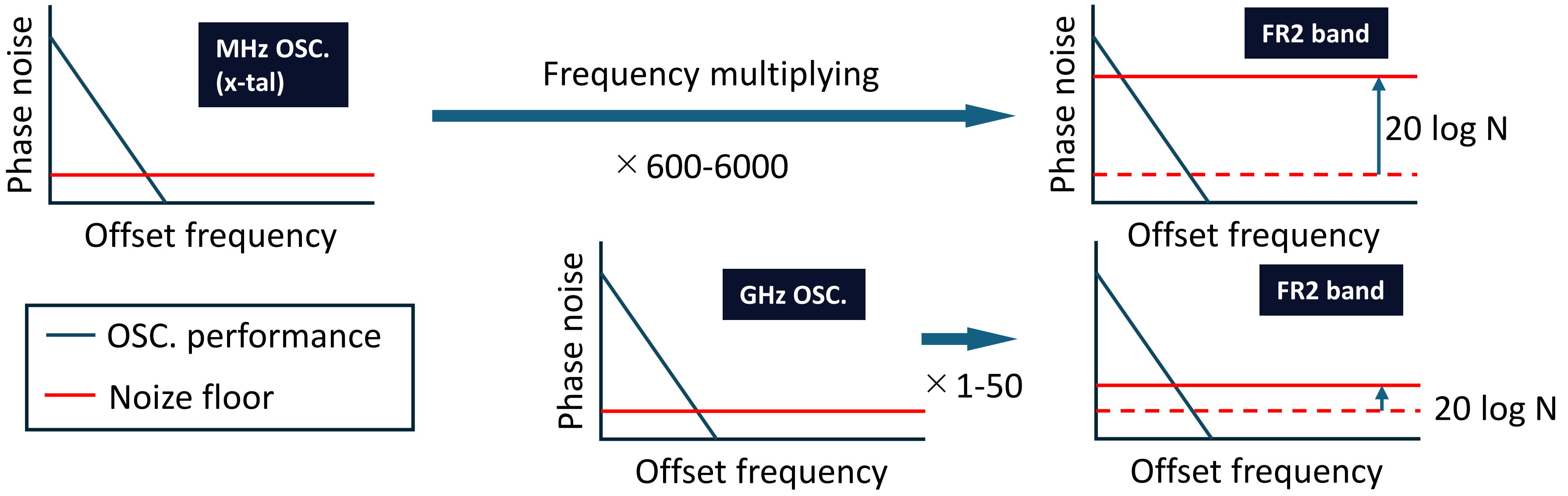
3. Frequency-Domain Realities: A Crystal Plateau - and an Atomic Way Out

- FR2 (10-300 GHz) applications makes the LO the bottleneck. With MHz-crystal-referenced × high multiplication, phase-noise scale faster than frequency, so the constellation spreads and EVM stops improving—the “crystal plateau.”

Frequency multiplies, noise multiplies faster — start with a GHz-class source that stays as stable as quartz.

- You can scale frequency; you also scale noise.
- Enough scaling, and the peak disappears into its own floor.
- The remedy: a GHz-born oscillator with the stability we expect from quartz.



3. Frequency-Domain Realities: A Crystal Plateau - and an Atomic Way Out

- Way out: Replace quartz with an **ultraminiaturized atomic clock incorporating Film Bulk Acoustic Resonator (FBAR)** to **stabilize the LO**.
  Fewer multipliers ⇒ lower integrated phase noise ⇒ lower EVM, with predictable drift under
  (Atomic-stabilized LO = one device: LO core + ultraminiaturized atomic clock inside)

	Fundamental Oscillation Frequency	Stability of oscillation frequency	Magnification of frequency multiplication ex) Target frequency: 60 GHz	Noise floor @ 60 GHz
TCXO	10~100 MHz	△	600~6000	X
OCXO	10~100 MHz	○	600~6000	X
FBAR	1~10 GHz	X	6~60	○
Atomic-stabilized FBAR (Ultra miniaturized Atomic clock)	3.417 GHz	◎	≈ 18	◎

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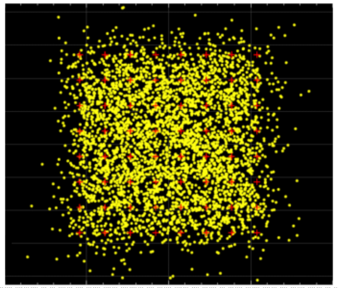
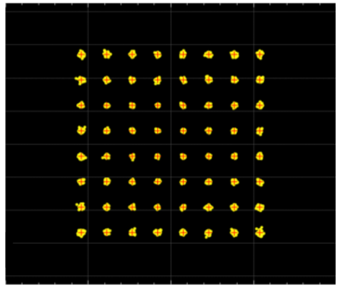
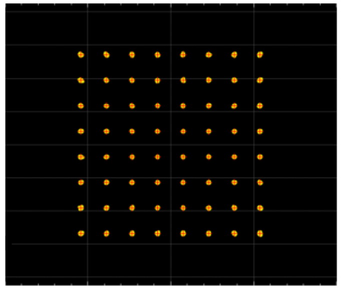
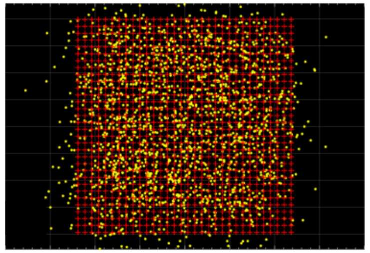
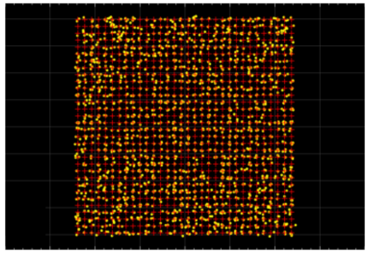
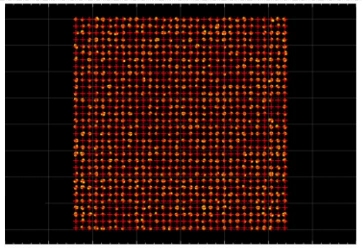
LO type on Base station (TX)			Atomic clock		
LO type on Handset (RX)			TCXO	OCXO	Atomic-stabilized FBAR (Ultra miniaturized Atomic clock)
Modulation	64 QAM	EVM	14.3	2.02	1.15
					
		BER	14.8	0.00	0.00
	1024 QAM	EVM	7.50	2.14	1.37
					
		BER	28.6	0.26	0.00314

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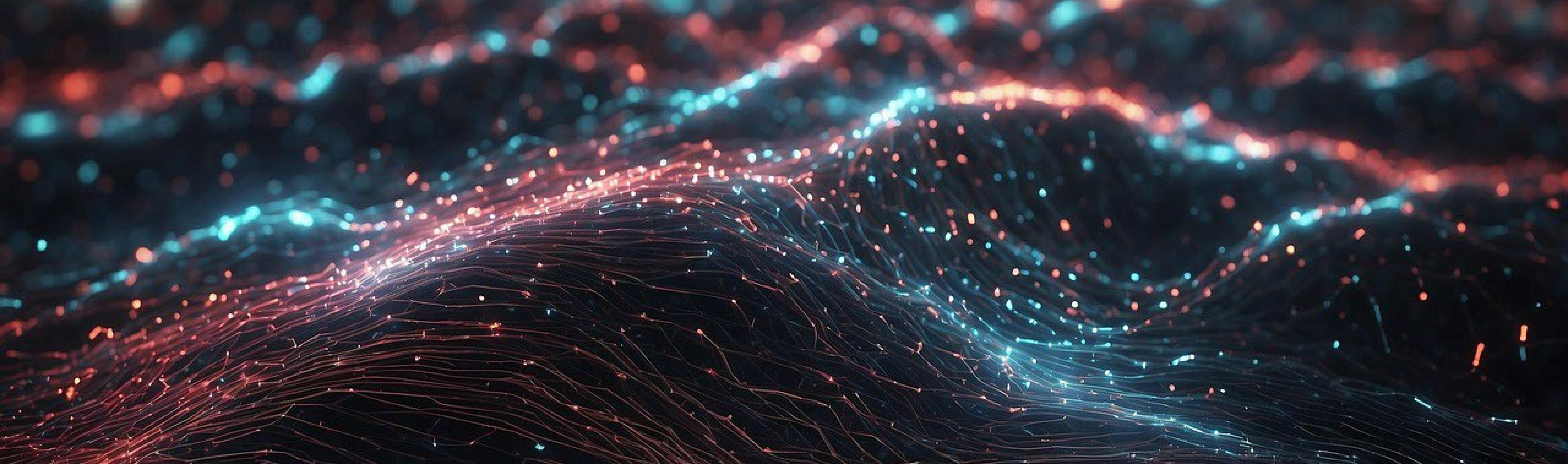


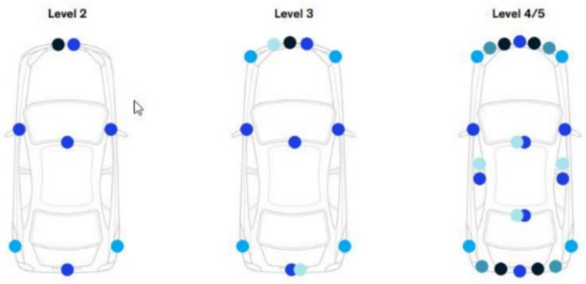
4. From Precision to Invariance: Making Time Mean the Same

- **Multi-sensor/AI workflows moving toward semantic processing and data coordination**

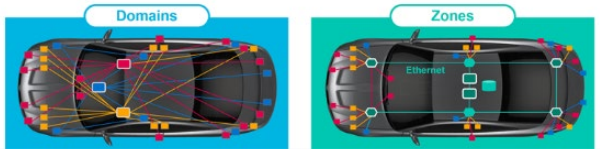
We can’t ship raw sensing to the cloud — we must ship meaning.

- We extract people, obstacles, intent — not pixels.
- We fuse camera, LiDAR, radar, IMU — not files.
- And to fuse anything correctly, their timelines must align.

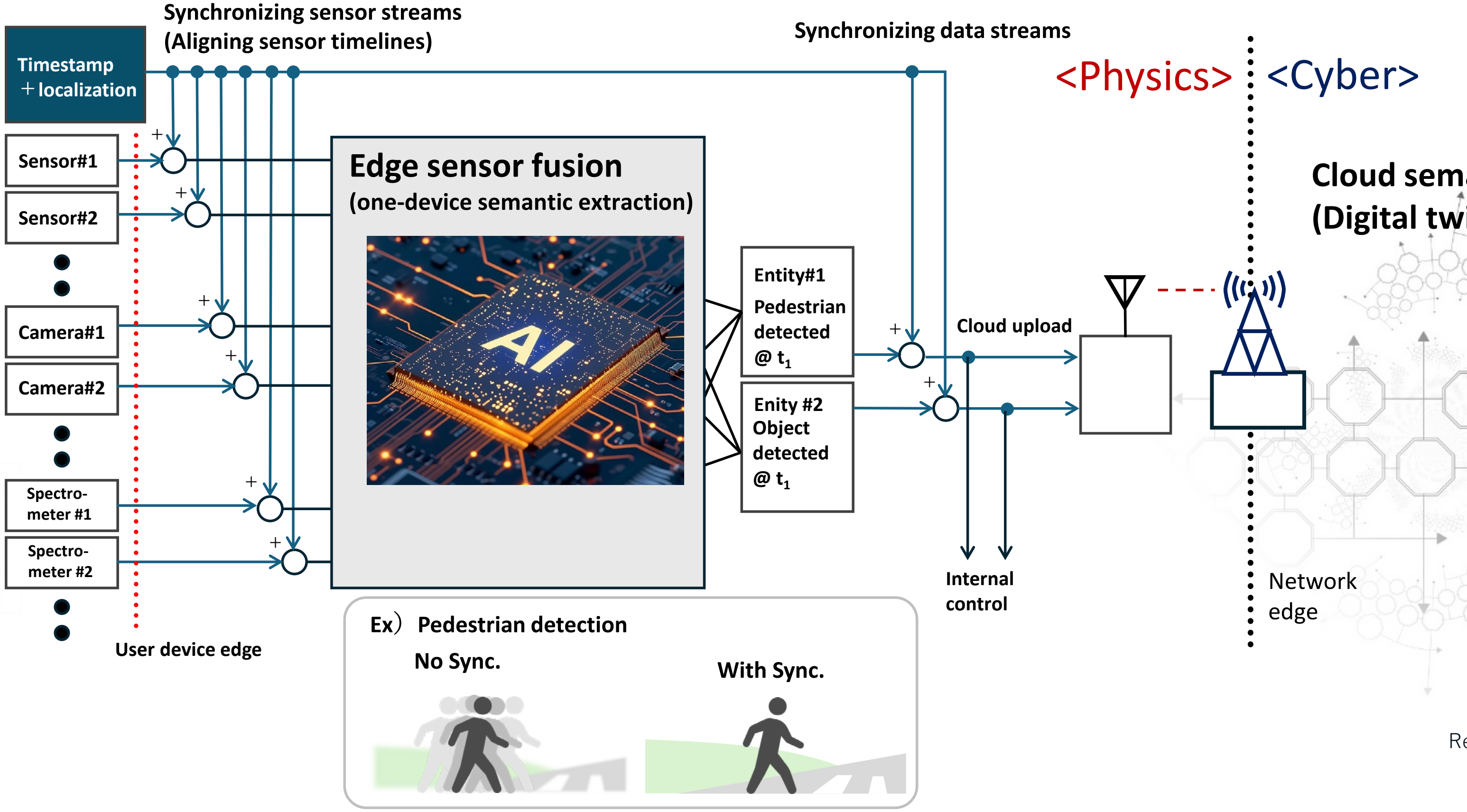
No shared time, no true fusion.

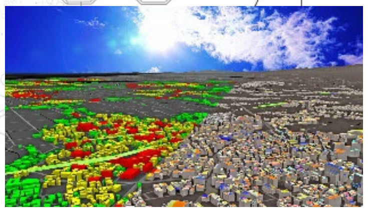


WSTS2024 Analog devices



Data Center on Wheels:Power System Design
https://mrvl.co/4h8VWrC





Coherent digital twin
Ref) PLATEAU supported by MLIT

4. From Precision to Invariance: Making Time Mean the Same

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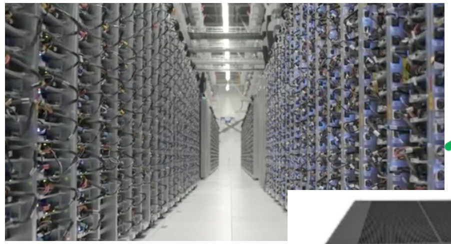
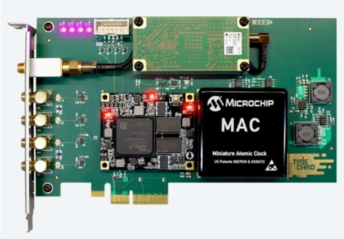
High-precision, disciplined time already underpins hyper-scaled data centers.



- Google Spanner. It keeps external consistency across regions — thanks to TrueTime. Bounded-uncertainty clocks. Ordered commits. Consistent reads.
- Meta. It runs sub-microsecond sync across whole data centers — with PTP and Time Card. Hardware timestamps. Time at scale.
- Open blueprints. The Time Appliances Project shares designs from NIC PHCs to grandmasters. End-to-end, open, deployable.

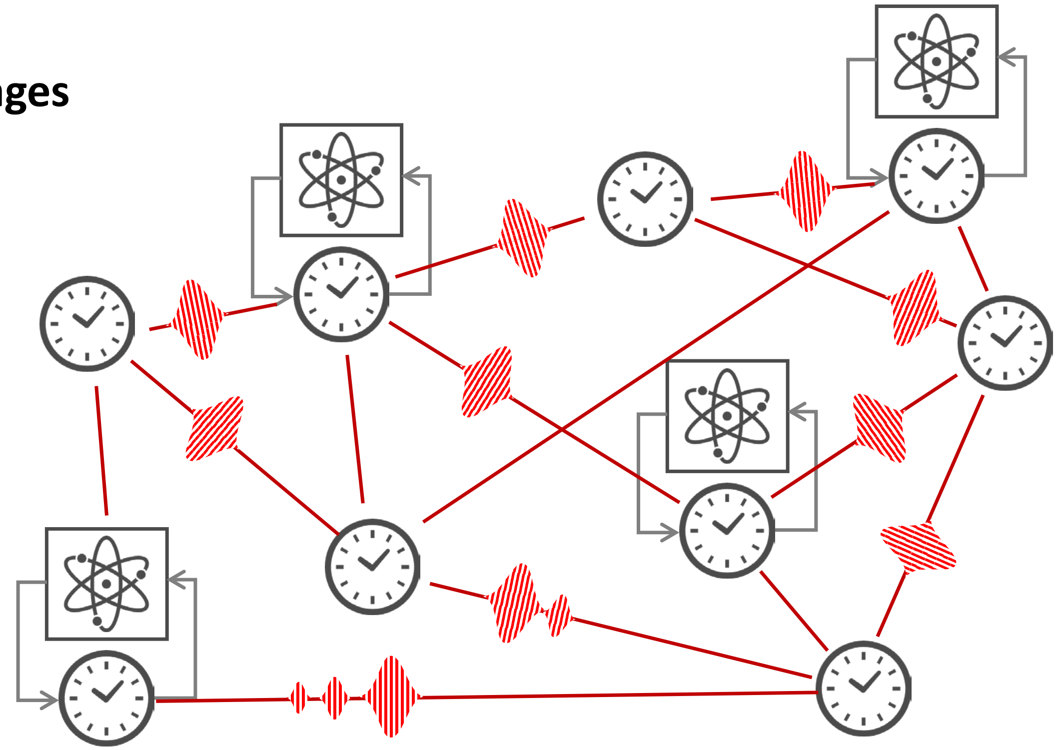
You know the micro-device we need to bring this discipline to the edge.

OPEN Compute Project®



4. From Precision to Invariance: Making Time Mean the Same

- **Not just precision**—we need **time that means the same everywhere.**
- **Timestamp invariance** = identical semantics across **devices / sites / days**.
- **Anchor to physics & traceability**:
  - – **UTC-traceable distribution** (optical / PTP / Sync-E / WR)
  - – **Ultraminiaturized atomic-clock-based holdover** for long-term stability
  - – **Edge discipline**: hardware timestamping, path-delay/asymmetry & thermal compensation
- With invariance:
  fusion error ↓, AI reproducibility/transferability ↑, GNSS-denied outages still keep time meaningful → **faster re-sync**.
- **Precision = fineness; Invariance = sameness.**



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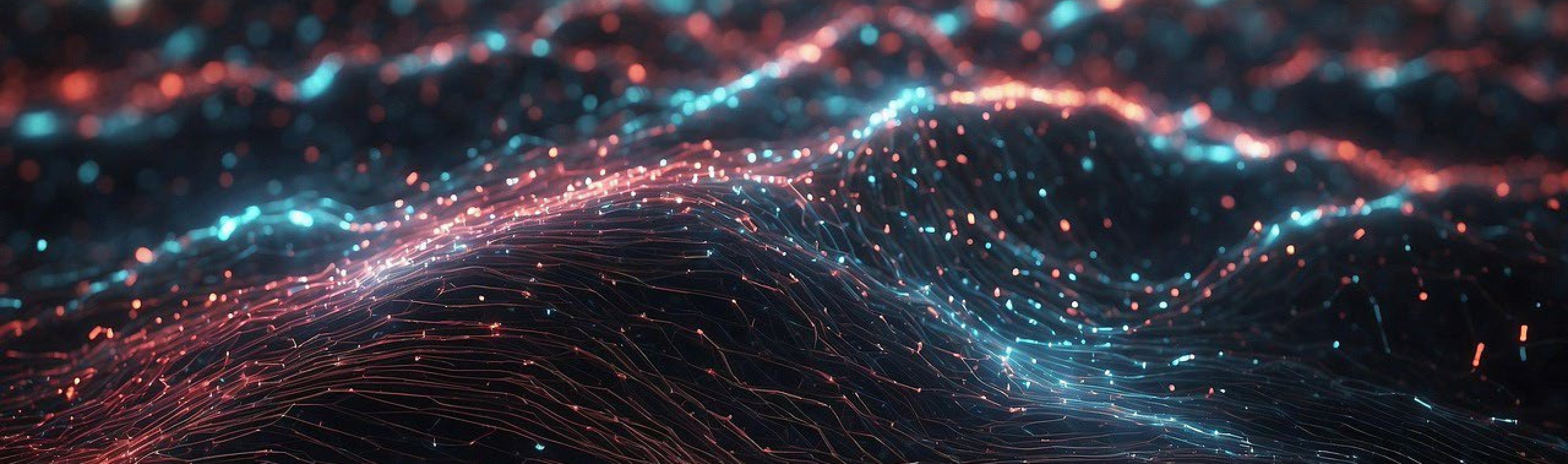

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Unified Timing Module and Cross-Layer Integration

Core Concepts Behind the Unified Timing Module

Multi-source Timing Inputs

The module integrates timing inputs from optical networks, PTP systems, and GNSS for flexible synchronization.

Ultra-miniaturized Atomic Clock

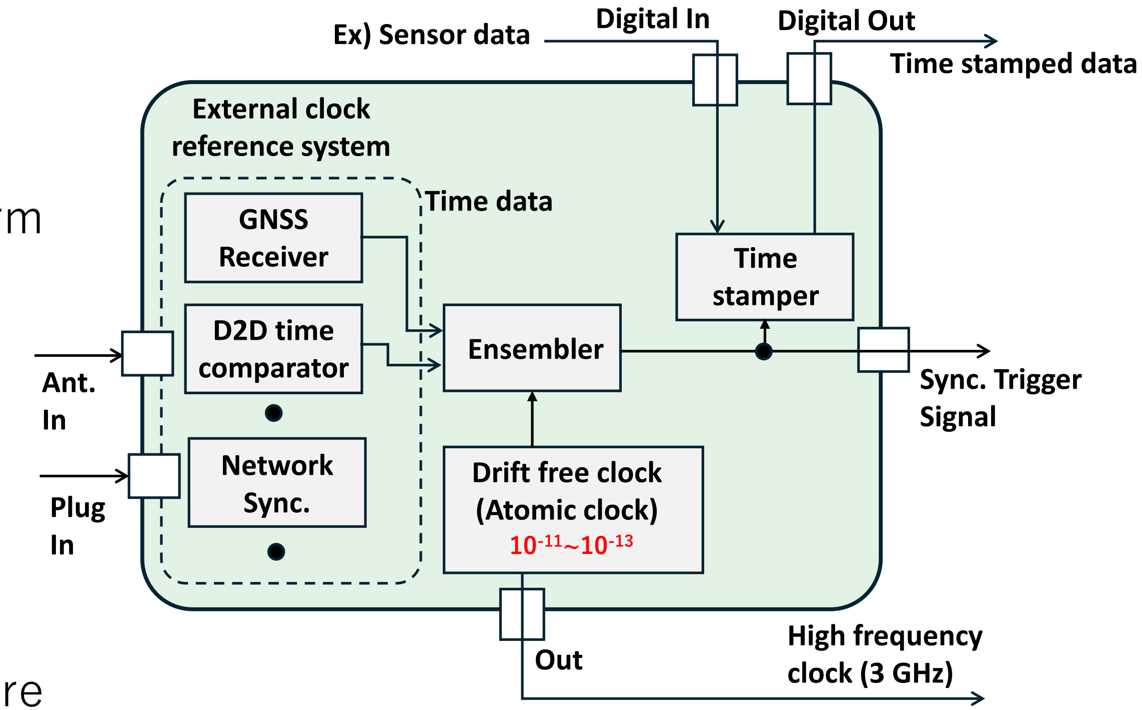
An ultra-miniaturized atomic clock ensures long-term stability during reference signal loss or degradation.

Low Phase Noise Oscillator

GHz-class local oscillator with multiplier chain reduces phase noise for cleaner timing signals.

Precise Phase Tracking & Compensation

Picosecond resolution phase tracking with hardware timestamping and compensation techniques ensures accuracy.



Unified Timing Module and Cross-Layer Integration

System Guarantees and Performance Outcomes

Precision Timing Benefits

Nanosecond alignment and picosecond stability preserve high array gain and signal quality in MIMO clusters.

Phase-Noise and Thermal Stability

Phase-noise mitigation and thermal drift control improve communication performance under varying conditions.

Timestamp Invariance for Data Fusion

Consistent timestamps across devices enable lower data fusion errors and enhance AI model reliability.

Resilient NTN Cooperation

Unified timing supports continuous phase cooperation with NTN systems and operational resilience during outages.

Thank you for your attention

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