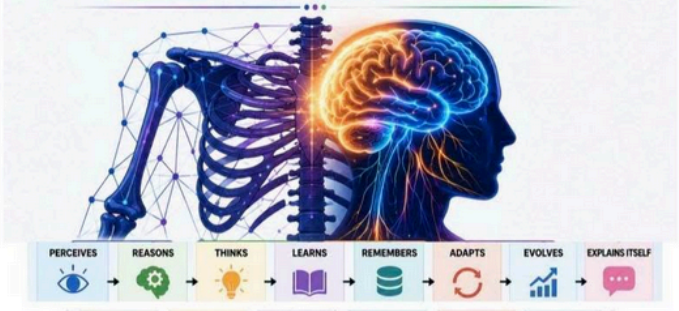
From Digital Twins to Cognitive Twins:
Closing the Metacognitive Loop for 6G & Beyond Wireless Systems



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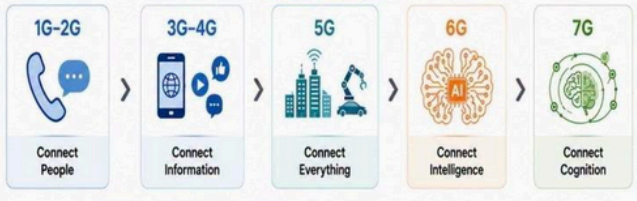
"We built the skeleton of a global network.
Now we must give it a brain and a nervous system." IFA'2026



COGNITIVE WIRELESS ERA

FROM CONNECTIVITY TO COGNITION

Each generation expanded what networks could do.



Networks are evolving from communication systems into cognitive systems.

Future systems require networks that understand intent, predict outcomes, and coordinate decisions.

THE INTELLIGENCE CLIMB OF FUTURE NETWORKS

From reactive connectivity to cognitive intelligence

COGNITIVE AI (6G/7G)
Thinks, reasons, and acts with intent.
- Reasoning
- Intent-awareness
- World models
- Multi-agent coordination

AI-NATIVE (6G)
Built for AI from the ground up.
- Single adaptive AI
- Cross-layer intelligence
- Self-healing
- Goal-driven optimization

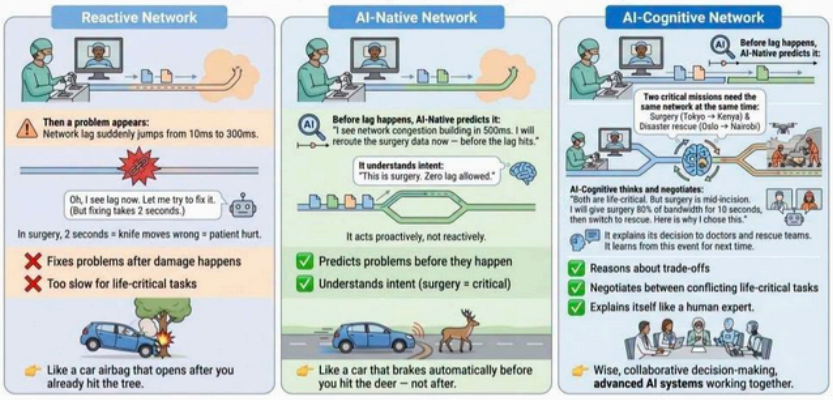
AI-ENHANCED (5G+)
Optimizes and automates network functions.
- AI as add-on
- Function optimization
- No learning across layers

REACTIVE (4G/5G)
Responds after the event with no intelligence.
- Rule-based
- No learning
- No context
- After-event response

As intelligence rises across layers, networks become more autonomous and impactful.

From Reactive to AI-Native to AI Cognitive Networks

Example: Surgeon in Tokyo operates on patient in Kenya

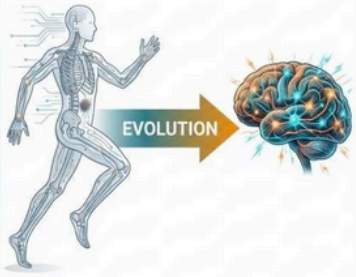


FROM AI-NATIVE TO COGNITIVE AI NETWORKS

From intelligence as a feature to intelligence as a nervous system

AI-Native Network (6G) — AI as Core
- Goal-Oriented & Context-Aware
- AI Built into All Layers (PHY to APP)
- Single Integrated Learning System (Learns from Data)
- Self-Optimizing (Latency, Reliability, Energy)
- Proactive: intent-aware, grasp human goals, causal reasoning

AI-NATIVE: Brilliant memorization and optimization



Cognitive Wireless Network (7G) — Network as a Nervous System
- Fully Prescriptive: closes the loop (predict → prescribe → act)
- Self-Evolving Architecture: no human upgrades — rewires itself over time
- Distributed Cognition: every node thinks — no central bottleneck
- Neuro-Symbolic AI: pattern matching + logic = true reasoning
- Incremental + Meta-Learning: learns continuously, doesn't forget, learns how to learn

COGNITIVE = A nervous system that truly thinks

Self-Evolving / Distributed Cognition

NERVOUS SYSTEM OF EVERYTHING

One Cognitive Twin is a brain. Many Connected Brains = A Nervous System for the Real World



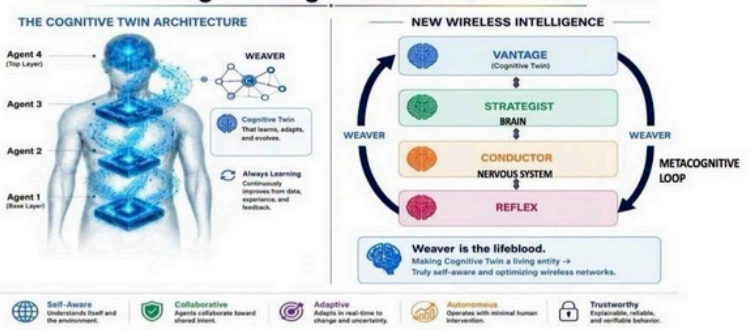
Passive long-term simulations
What-if analysis, planning, and offline evaluation

Active, thinks, learns, predicts failures, makes decisions
Real-time cognition & decisioning

Sensing, processing, and responding everywhere
Autonomous • Real-time • Scalable

From passive models → to intelligent brains → to a living nervous system of everything
Multiple cognitive twins working together as one — perceiving, understanding, reasoning, and acting in the real world.

COGENT: Cognitive Agents for Collaborative Intent



Think of this as the nervous system of a human being mapped to a network

All agents share one Metacognitive Loop —
the Weaver watches all, the Vantage remembers all, the Reflex acts on all.

I. F. Akyildiz and Tugce Bilen, "COGENT-Wireless: Hierarchical Cognitive Agents for Intent-Driven Autonom Beyond 6G Systems", submitted in June 2026.

THE FIVE COGNITIVE AGENTS

One thinking network built from five agents, five timescales, one continuous feedback loop

WEAVER — The Wisdom *(continuous, cross-agent)*
Watches every agent at once, metalearns across them, and continuously improves the whole system — the metacognitive layer that ties the network together.

VANTAGE
The Memory
HOURS – DAYS
- Simulates and predicts future network states
- Learns from historical + real-time telemetry

Feeds: Strategist & Conductor

STRATEGIST
The Brain
MINUTES – HOURS
- Turns human intent into network strategy
- Negotiates goals, SLAs & priorities

Feeds: Conductor

CONDUCTOR
The Nervous System
MS – SECONDS
- Executes strategy in real time
- Orchestrates beams, routing, handovers, slicing

Feeds: Reflex

REFLEX
The Muscle Memory
MICROSECONDS
- Reacts instantly — no reasoning involved
- Local channel, power, MCS & HARQ decisions

Closes the loop back to Conductor

Five agents, one cognitive loop — each fast enough for its job, all coordinated by Weaver.

COGENT: THE FIVE-AGENT COGNITIVE ARCHITECTURE

One architecture — five agents — five timescales — from muscle memory to strategic vision

REFLEX	CONDUCTOR	STRATEGIST	VANTAGE	WEAVER
The spinal cord reflex: no brain needed — fast, dumb, automatic	The cerebellum: coordinates the muscles — fast coordination	The prefrontal cortex: plans and decides — strategy	The hippocampus: memory and prediction — memory	The Metacognitive loop — learns how to learn — (self improvement)
Muscle Memory	**Nervous System**	**The Brain**	**Network Memory**	**Network Wisdom**
AI Methods: TinyML, neuromorphic computing, HW-aware AI	**AI Methods:** MARL, FL, GNNs	**AI Methods:** LLMs, intent engines, sem com models	**AI Methods:** GNNs, Transformers, generative AI, DTs	**AI Methods:** Meta-learning (MAML), online RL, anomaly detection, Page-Hinkley test
Deployment (RESIDES): RU / DU / PHY — Baseband UE Chipset — on devices	**Deployment (RESIDES):** Near-RT RIC, MEC / Edge Clusters, BSS, Domain controllers	**Deployment (RESIDES):** Non-RT RIC (Regional), Control Centers, Edge clouds or regional aggregators	**Deployment (RESIDES):** Core Cloud AI Data Centers — NWDAF	**Deployment (RESIDES):** Distributed (FL) — across cloud, edge, and devices
~0.5ms	~10ms-100ms	~100ms-1s	~seconds to hours	~hours to days

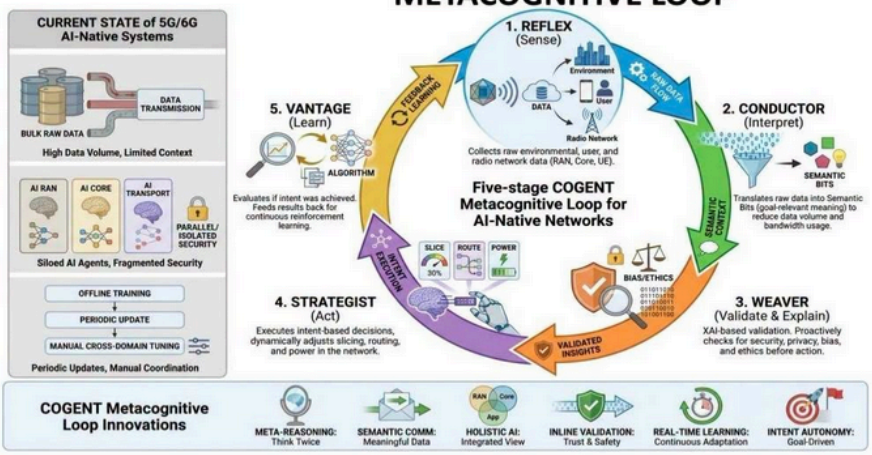
0.5ms — 10ms — 100ms — 1s — hours — days

NO OTHER ARCHITECTURE SPANS THIS RANGE: FROM A 0.5 MS REFLEX TO A MULTI-DAY LEARNING CYCLE IN A SINGLE UNIFIED COGNITIVE SYSTEM.

A HIERARCHY OF INTELLIGENCE: CLOUD THINKS. EDGE COORDINATES. HARDWARE REACTS. WEAVER LEARNS IT ALL.

COGENT UNDERSTANDS: INTENTION (WHAT USER WANTS) | SALIENCE (WHAT MATTERS NOW) | CAUSALITY (WHY THIS HAPPENED) | UNCERTAINTY (WHAT IT DOESN'T KNOW).

METACOGNITIVE LOOP



COGENT Metacognitive Loop Innovations

- **META-REASONING:** Think Twice
- **SEMANTIC COMM:** Meaningful Data
- **HOLISTIC AI:** Integrated View
- **INLINE VALIDATION:** Trust & Safety
- **REAL-TIME LEARNING:** Continuous Adaptation
- **INTENT AUTONOMY:** Goal-Driven

BEFORE: Failures & Inefficiency

- Failures = Hours of Downtime
- Static, wasteful resource allocation
- Reactive
- One giant AI model tries to do everything
- Devices need full AI capability; expensive HW upgrades

AFTER COGENT: Self-healing Autonomy & Optimization

- Self-healing autonomy (ms-secs)
- AI Optimization; energy savings
- Predictive
- Five specialized agents each with its own timescale
- Legacy device support via cognitive wrappers; no HW upgrades needed
- Lower cost, less waste, longer battery life
- Proactive security

This is not incremental improvement. This is a leap.

GRAND CHALLENGES

What must we solve to make this vision real?

THE SCALABILITY PROBLEM



Can we build AI that is fast, light, and smart enough for the real world?

THE TRUST PROBLEM



Can we trust the decisions these AI systems make?

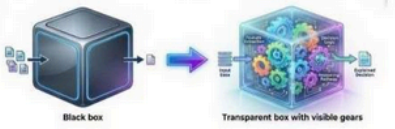
THE INTEGRATION PROBLEM



Can we weave this intelligence into the world that already exists?

GRAND CHALLENGE: The Trust Problem

Can we trust the decisions these AI systems make?



Explainable AI (XAI)

Build AI that can explain and justify the decisions

Improve transparency of black box models

Privacy

Implement FL and differential privacy

Trustworthy AI for Security & Robustness

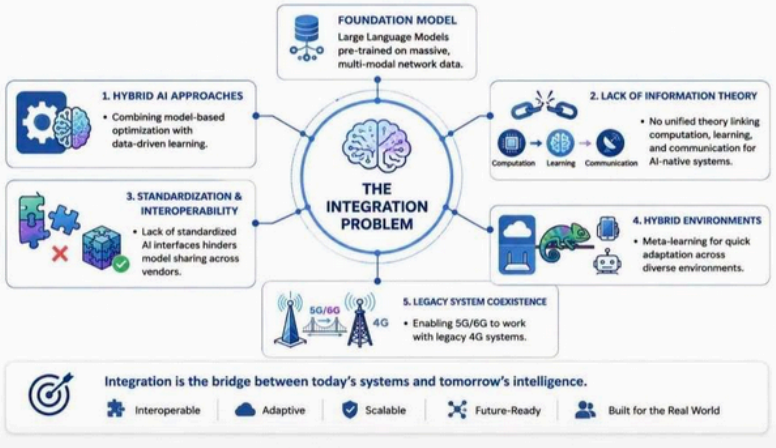
Protecting ML systems against adversarial attacks

Ethics & Fairness

Addressing bias, fairness & accountability in AI –driven systems

GRAND CHALLENGE: The Integration Problem

Can we weave this new intelligence into our existing world?



ETHICS & STANDARDS

REGULATORY REALITY CHECK FOR COGNITIVE NETWORKS

1. EU AI ACT

HIGH-RISK AI SYSTEMS



Purpose: Ensure safe, transparent and accountable AI in the EU.

2. STANDARDS GAP

NO STANDARD TODAY

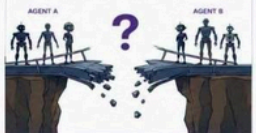


Goal: Create open, interoperable and secure standards for cognitive networks.

3. LIABILITY & GOVERNANCE

LIABILITY GAP

If two agents disagree and a packet drops, who is legally responsible? The carrier? The AI vendor? No answer today.



No legal framework for multi-agent decisions.

KEY OPEN QUESTIONS

- How do we ensure human oversight without killing autonomy and speed?
- How do we design standards that are future-proof, global and technology-neutral?
- How do we define liability in a world of autonomous AI agents?
- How do we align innovation speed with regulatory readiness?

Cognitive networks are advancing faster than the regulatory systems designed to govern them.

COGENT ROADMAP

Phase 1: Foundation (2025–2028)

- Single-domain **COGENT**
- **VANTAGE + REFLEX** prototype
- **WEAVER** overlay for monitoring
- O-RAN integration: **STRATEGIST** as rApp, **REFLEX** on O-DU

Standardization

3GPP Rel. 19/20 · O-RAN WG11

Phase 2: Integration (2028–2032)

- Full five-agent hierarchy
- **Metacognitive Loop** fully operational
- Multi-domain pilot (terrestrial + satellite)
- O-RAN enhancement: **CONDUCTOR** as xApp, cross-RIC **WEAVER**

Standardization

3GPP Rel. 21/22 · ITU-R IMT-2030

Phase 3: Maturity (2032–2040)

- Full sea-to-space **COGENT**
- UDA, NPT, Shared Cognitive Ontology
- **Foundation Model for Wireless Networks**
- O-RAN cognitive extension standardized

Standardization

ITU-R WRC-27 · CCSDS · 3GPP Rel. 23+

A FINAL THOUGHT

We have built the skeleton of a global network.
Now, we must give it a brain and a nervous system.

THE SKELETON:

- Fiber optics across oceans
- Cell towers on mountains
- Satellites in orbit
- Undersea cables in the deep



THE NERVOUS SYSTEM:

- AI that learns and adapts
- Digital twins that simulate and predict
- Semantic understanding that captures meaning
- Metacognitive loops that evolve

When we connect skeleton to nervous system, we create something new: a living, thinking digital world.

> *We built the network to connect people. Now we must teach it to think; not because it's cool, but because the world is too fast, too deep, and too complex for us to manage alone.* — IFA'2026