O-RAN ALLIANCE

O-RAN nGRG WORKSHOP

February 5th, 2024

Secrets of Semantic Communications in the Era of 6G Networked Intelligence

Invited Talk by

Emilio Calvanese Strinati

CEA-Leti / 6G-GOALS, 6G-DISAC, 6GARROW

Bridging the Physical, Digital, and Cognitive Worlds with Semantic AI

GOALS

6G DISAC

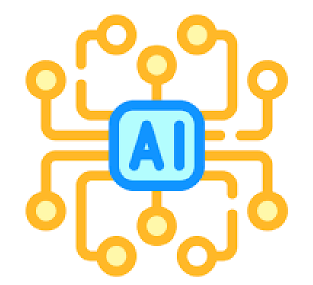
6GARROW

FRANCE 2030

cea leti

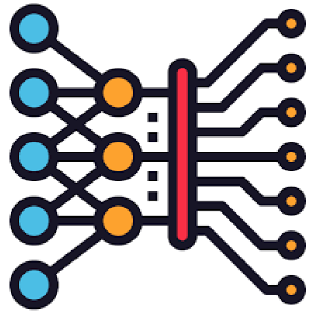
WHAT

SEMANTICS & EFFECTIVENESS: A REVOLUTION FROM THE PAST



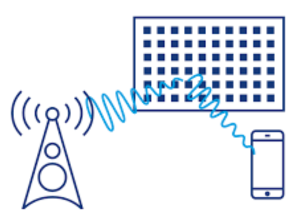
Level C: *Effectiveness*

3. **Level C:** How effectively does the received meaning affect conduct in the desired way?
   (The **effectiveness** problem)



Level B: *Semantic*

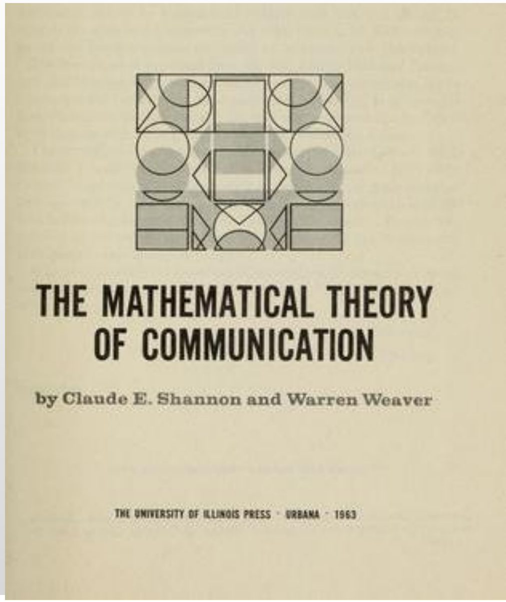
2. **Level B:** How precisely do the transmitted symbols convey the desired meaning?
   (The **semantic** problem)



Level A: *Technical*

1. **Level A:** How accurately can the symbols of communication be transmitted?
   (The **technical** problem)

The broad subject of communication can be organized into **three levels** **[Shannon, Weaver, 49]**



THE MATHEMATICAL THEORY
OF COMMUNICATION

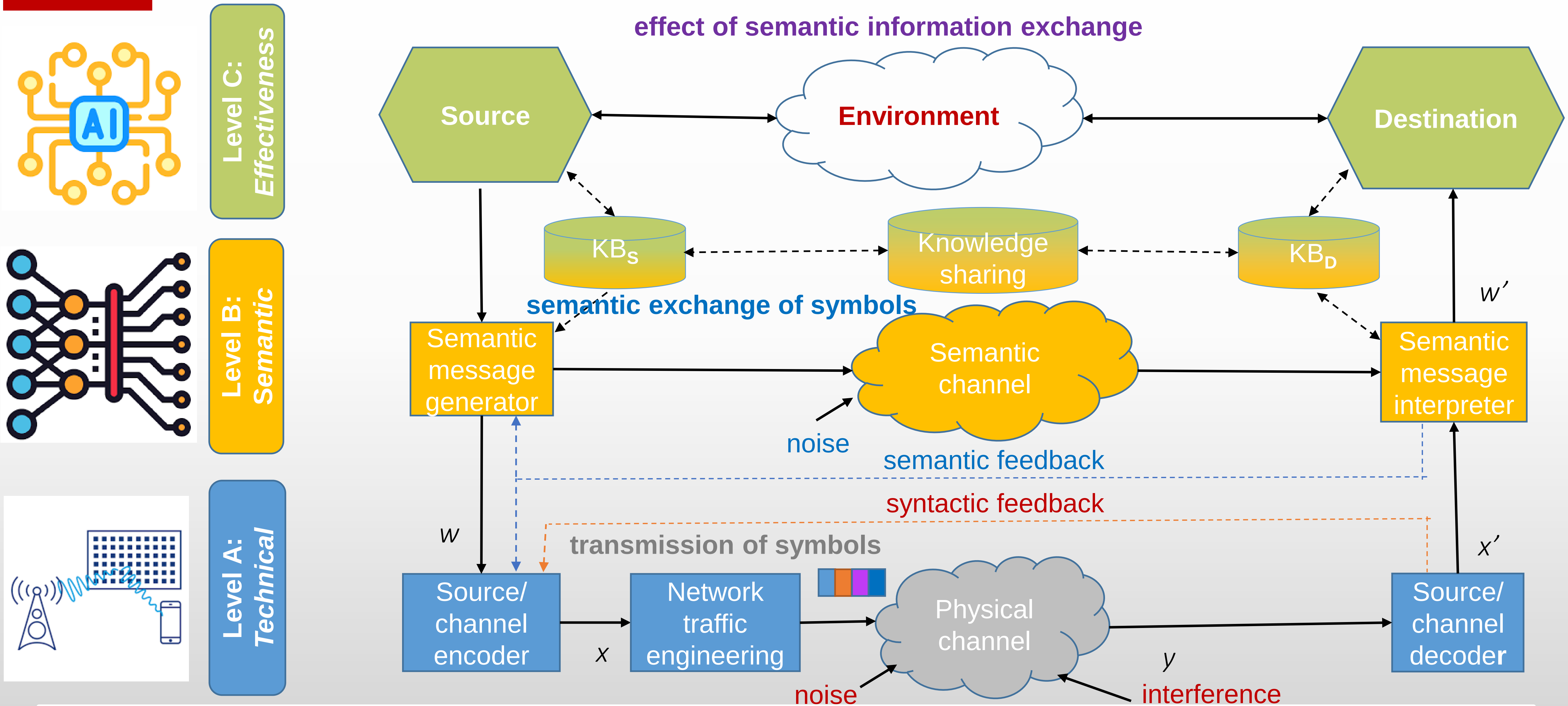
by Claude E. Shannon and Warren Weaver

THE UNIVERSITY OF ILLINOIS PRESS · URBANA · 1963

Source: E. Calvanese Strinati and Barbarossa.,"6G Networks: Beyond Shannon Towards Semantic and Goal-Oriented Communications". Computer Networks Journal, Feb. 2021.

WHAT

SEMANTICS & EFFECTIVENESS



Level C: *Effectiveness*

Level B: *Semantic*

Level A: *Technical*

effect of semantic information exchange

Source

Environment

Destination

KB_S

Knowledge sharing

KB_D

semantic exchange of symbols

Semantic message generator

Semantic channel

Semantic message interpreter

noise

W'

semantic feedback

syntactic feedback

W

transmission of symbols

X'

Source/ channel encoder

Network traffic engineering

Physical channel

Source/ channel decoder

X

Y

noise

interference

Source: E. Calvanese Strinati and Barbarossa.,“6G Networks: Beyond Shannon Towards Semantic and Goal-Oriented Communications”. Computer Networks Journal, Feb. 2021.

WHAT FROM DATA TO INSIGHTFUL INFORMATION

> *"Information is data endowed with meaning and purpose"*
> *Herbert Simon, 1971*

Semantics refers to the **meaning or interpretation of information** — ***what the data represents*** *(in a context, for a use, etc.)*, rather than the data itself.

6G **Semantics** = **WHAT** that information means (context, intent, purpose)

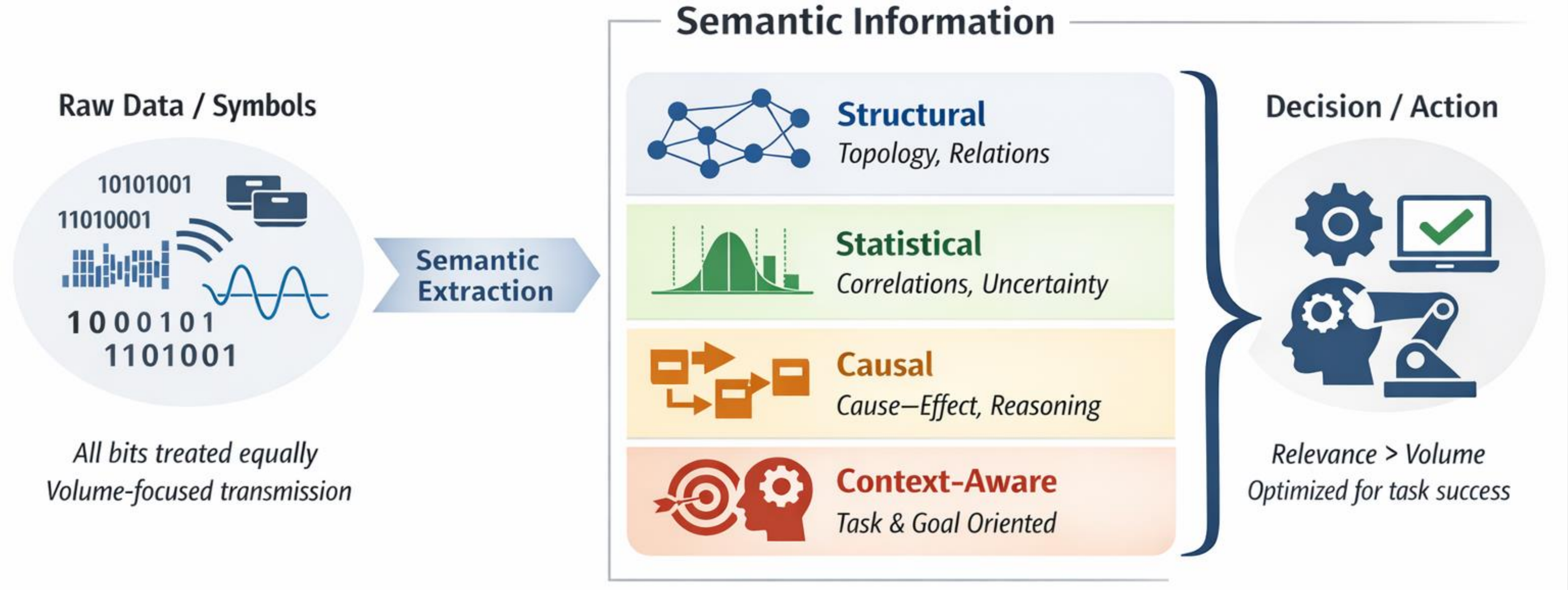
In contras: **5G** **Syntax** = **HOW** information is structured (bits, packets, symbols)

Semantics: **abstraction**, **representation** and **extraction** of meaning from data.

Meaning extraction is conditioned to the logic of the semantic extraction engine

WHAT SEMANTIC 101: GIVING MEANING TO DATA

*Any **structural** (topological), **statistical**, or **causal relationship** within the data to be communicated, assessed to the desired reconstruction metric or desired actions to be taken at the receiver*



Semantic Information

Raw Data / Symbols

All bits treated equally
Volume-focused transmission

Semantic Extraction

Structural
Topology, Relations

Statistical
Correlations, Uncertainty

Causal
Cause–Effect, Reasoning

Context-Aware
Task & Goal Oriented

Decision / Action

Relevance > Volume
Optimized for task success

WHAT

SEMANTIC COMMUNICATION GAINS & CHALLENGES

Opportunities & Gains

- **Energy efficiency** – transmits only relevant information, lowering power use and overhead
- **Latency reduction** – improves timeliness for real-time and goal-oriented tasks
- **Better spectrum utilization** – adaptive spectrum usage via semantic-aware protocols
- **Scalability** – supports massive IoT and machine-type communications with reduced signaling load
- **Integration with AI/ML** – enhances learning and inference tasks directly at the communication layer (train while communicating)
- **Cross-domain efficiency** – boosts performance in numerous applications
- **Interoperability** – enables compatible communication across heterogeneous networks
- **AI optimization**: new effective communication–computation–caching trade-offs

Challenges

- **Lack of established semantic information theory** – no widely accepted framework for metrics and limits
- **Knowledge, logic, representation mismatch** – different devices may interpret semantics differently
- **Complex trade-offs with AI timing** – balancing compression, fidelity, computational cost, and real-time/causal constraints is difficult
- **Standardization gap** – absence of agreed semantic interfaces, KPIs, and protocols across vendors
- **Backward compatibility** – integrating semantic layers with existing 5G architectures remains complex
- **Limited testbeds** available
- **Coexistence** between semantic and legacy systems
- **Support for O-RAN's intent-based RAN management**: how semantics enrich intent translation

HOW TO MEASURE SEMCOMS GAINS & EFFECTIVENESS?

Semantic communications metrics

20+ metrics and KPIs in 6 different areas: Information theoretic, text, image/video, timing-related, goal-oriented, secrecy **[D2.2 6G-GOALS]**

$$\begin{cases} R(D,P) \overset{\text{def}}{=} \min_{p_{\widehat{X|X}}} I(X,\hat{X}) \\ E[\Delta(X,\hat{X})] \le D \\ d(p_X, p_{\hat{X}}) \le P \end{cases}$$

Rate-distorsion-perception: low distortion alone is not enough — perception (semantic fidelity) is essential

$$\mathrm{FID} = ||\mu_{\text{real}} - \mu_{\text{generated}}||^2 + \mathrm{Tr}\left(\Sigma_{\text{real}} + \Sigma_{\text{generated}} - 2(\Sigma_{\text{real}}\Sigma_{\text{generated}})^{1/2}\right)$$

Frechet-Information Distance: Captures **semantic similarity** measuring on a learned feature space

$$\Theta(f(A), f(B)) = ||f(A) - f(B)||_2^2$$

Semantic similarity among embeddings

$$\mathrm{AoE} = \{\mathcal{S} \mid \mathcal{E}_{go}(\mathcal{S}) \geq q_{\text{th}}\}$$

Area of Effectiveness

$$\mathrm{LPIPS}(x,y) = \sum_l \frac{1}{H_l W_l} \sum_{h,w} ||\, \widehat{y^l_{hw}} - \widehat{x^l_{hw}}\, ||_2^2$$

Perceptual Image similarity (DL, GO, Heuristics)
It measures meaningful features preservation

$$s(t) = sup\{g_i \in S\colon g_i + \delta_i \le t\}$$

$$\Delta_L(t) = t - s(t)$$

Age of Loop: freshness of information when used

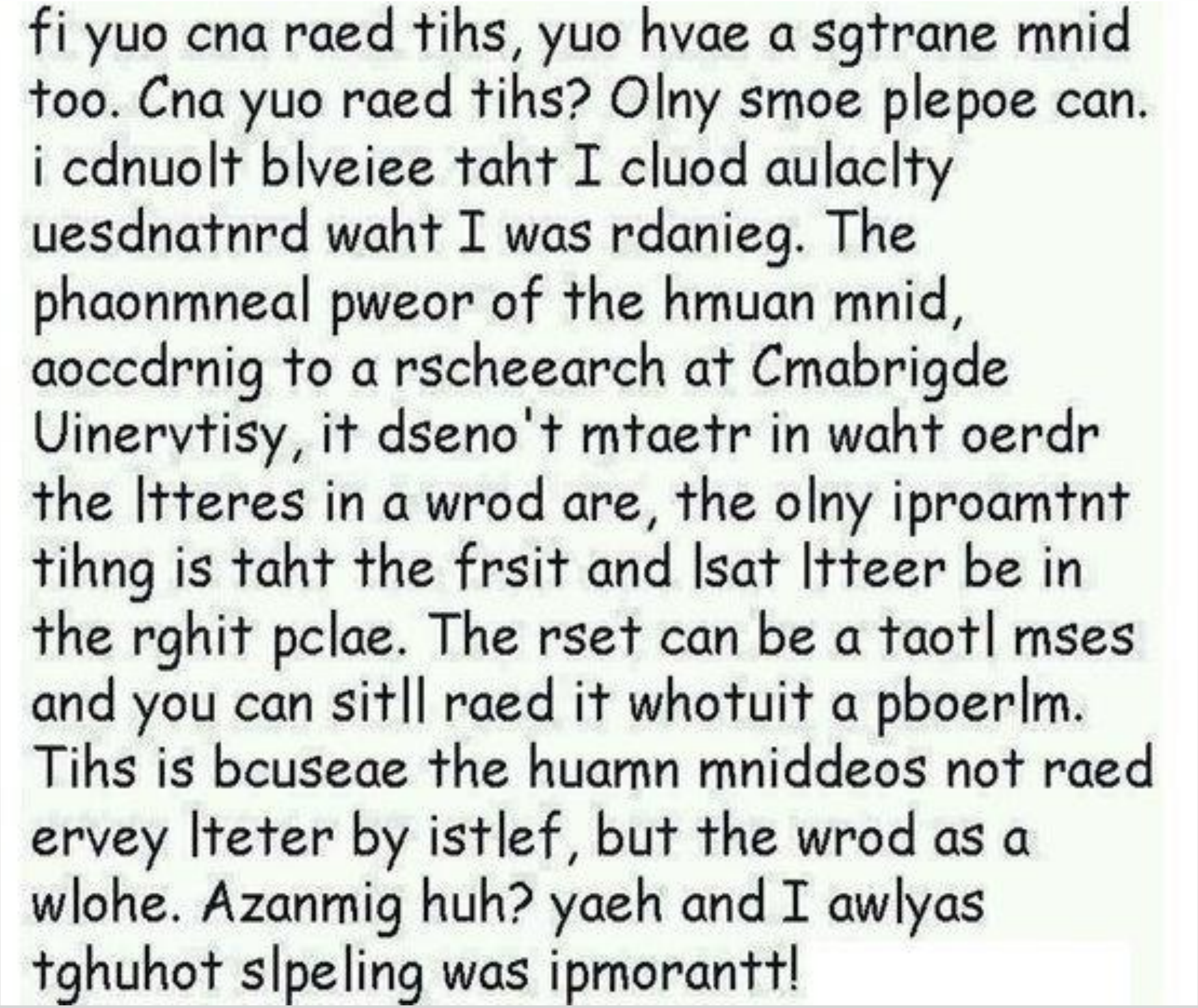
WHAT

SEMANTIC COMMUNICATION GAINS: ROBUSTNESS

Semantic robustness (Comm, Inference, Task accomplishment)

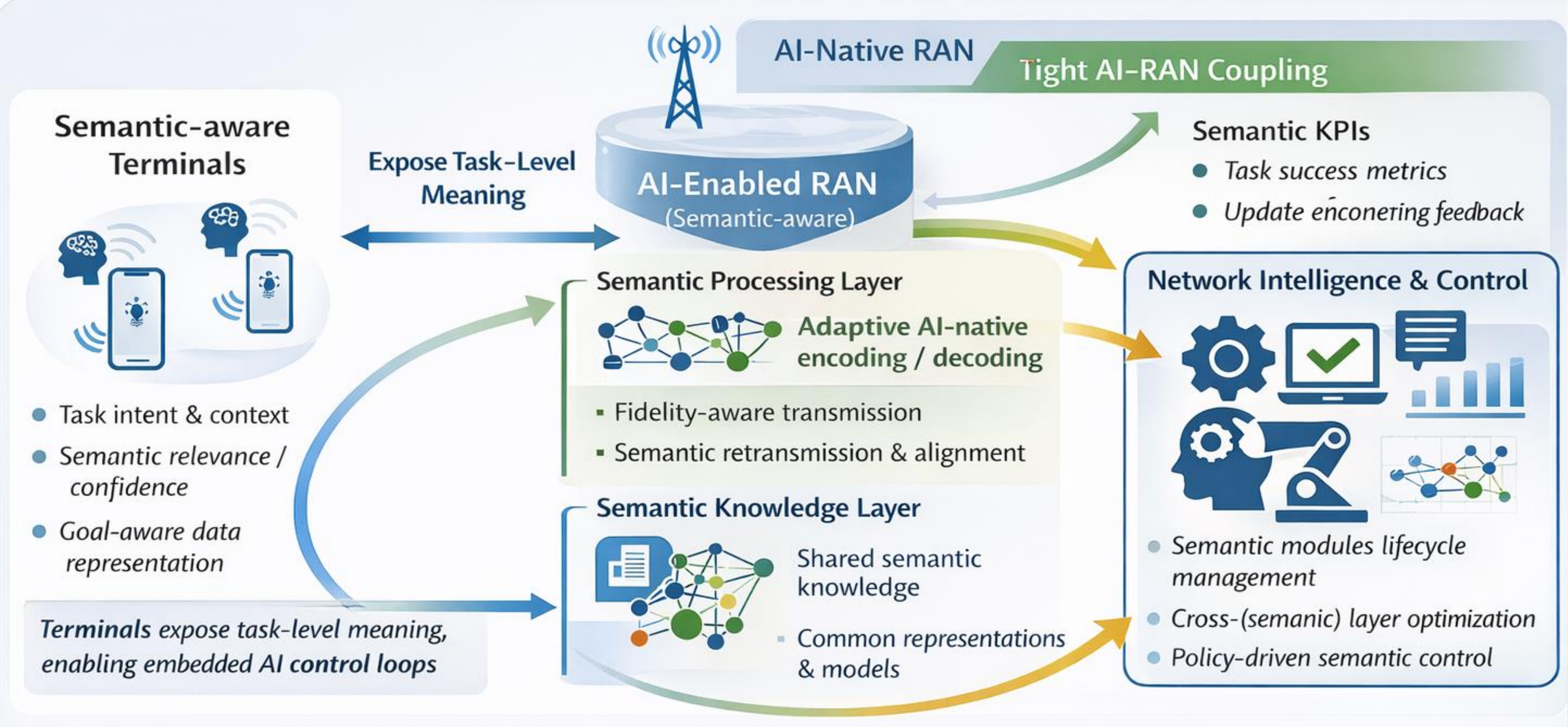
Trade-offs:

- Robustness versus ambiguity
- Robustness versus resource use (energy, processing, …)



fi yuo cna raed tihs, yuo hvae a sgtrane mnid too. Cna yuo raed tihs? Olny smoe plepoe can. i cdnuolt blveiee taht I cluod aulaclty uesdnatnrd waht I was rdanieg. The phaonmneal pweor of the hmuan mnid, aoccdrnig to a rscheearch at Cmabrigde Uinervtisy, it dseno't mtaetr in waht oerdr the ltteres in a wrod are, the olny iproamtnt tihng is taht the frsit and lsat ltteer be in the rghit pclae. The rset can be a taotl mses and you can sitll raed it whotuit a pboerlm. Tihs is bcuseae the huamn mniddeos not raed ervey lteter by istlef, but the wrod as a wlohe. Azanmig huh? yaeh and I awlyas tghuhot slpeling was ipmorantt!

WHY SEMANTIC COMMUNICATIONS NEED A NEW RAN ARCHITECTURE



Terminals** expose task-level meaning, enabling embedded **AI control loops

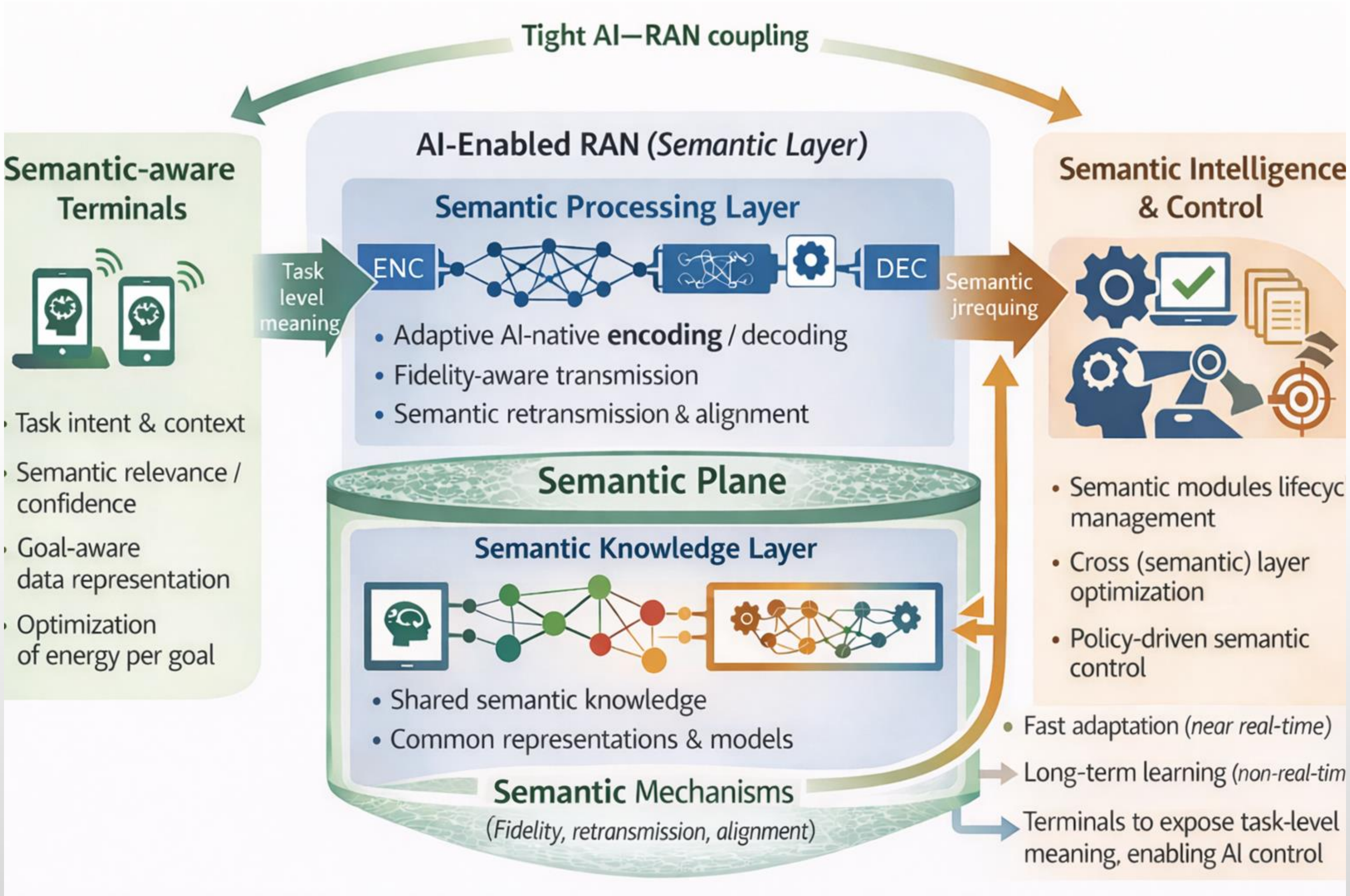
SemComs changes what we optimize : meaning instead of bits

➔ It requires intelligence inside the network and tight AI–RAN coupling

SECRET THE SEMANTIC PLANE IN AI-NATIVE 6G ARCHITECTURES

Semantic plane

- New **logical layer** to processing meaning
- To **“semantically” enhances** both the user & control planes
- **Facilitate** the delivery of **semantic services**, enable **knowledge-driven reasoning**



[D2.5 6G-GOALS]: 6G-GOALS Project, **Initial 6G-GOALS architecture and operation analysis** June 2025. https://sites.google.com/view/6ggoals/results/deliverable?authuser=0

SECRET THE SEMANTIC PLANE IN AI-NATIVE 6G ARCHITECTURES

Advantages

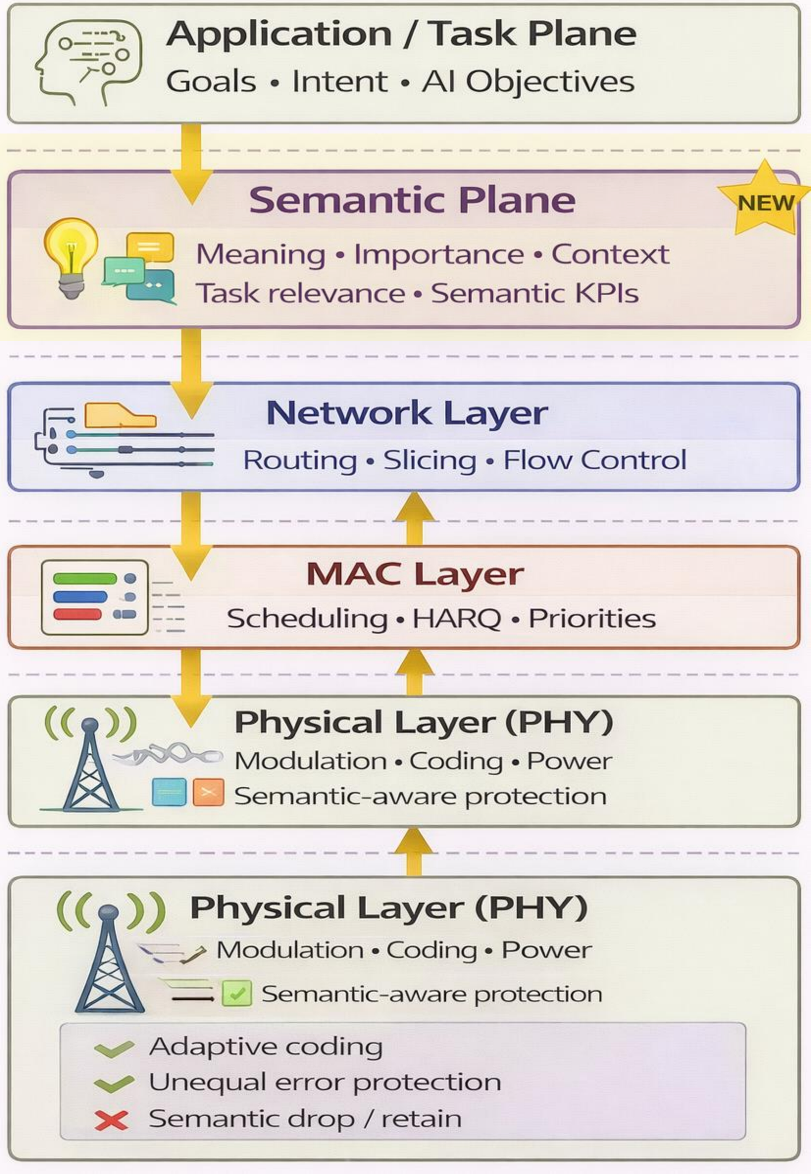
AI–Communication Convergence: Enables joint reasoning and adaptation across AI models and communication layers

Semantic Cross-Layer Optimization: Injects meaning into PHY/MAC/Network decisions → new metrics, new information-communication–computation trade-offs

Resilience & Efficiency: Preserves semantic intent rather than bits, enabling importance-aware protection, drop, and resource allocation

Issues (Potential)

- **Extra latency** and **signaling** overhead
- Possible **higher energy per bit** (extra semantic processing & signaling) **but lower CUMULATIVE energy per goal** (send less bits – large semantic compression)



Application / Task Plane
Goals • Intent • AI Objectives

Semantic Plane NEW
Meaning • Importance • Context
Task relevance • Semantic KPIs

Network Layer
Routing • Slicing • Flow Control

MAC Layer
Scheduling • HARQ • Priorities

Physical Layer (PHY)
Modulation • Coding • Power
Semantic-aware protection

Physical Layer (PHY)
Modulation • Coding • Power
✓ Semantic-aware protection

- ✓ Adaptive coding
- ✓ Unequal error protection
- ✗ Semantic drop / retain

WHY O-RAN MATTERS FOR SEMCOMS: AN ARCHITECTURAL DESTINY

RICs naturally map semantic timescales

- **Near-RT RIC**: semantic-aware radio & power control
- **Non-RT RIC**: semantic training, orchestration, long-term alignment and policy learning
- **RT RIC**: semantic waveforms and ultra-fast PHY adaptation

From KPI optimization to semantic cross-layer control

- O-RAN supports rigorous cross-layer optimization beyond bit-level metrics **under multi-owner, multi-vendor** constraints : ***exactly the problem O-RAN was designed to solve***.

Open interfaces enable semantic interoperability

- Open APIs connect semantic information/metrics across components and vendors

Operationalizing semantics at scale

- Lifecycle management and orchestration make semantic modules deployable at scale.

O-RAN is structurally aligned with semantic communications, introducing: disaggregation, intelligence & open control loops

MAIN INNOVATIONS WITH RESPECT TO O-RAN (COMPATIBLE)

Semantic RIC (S-RIC)

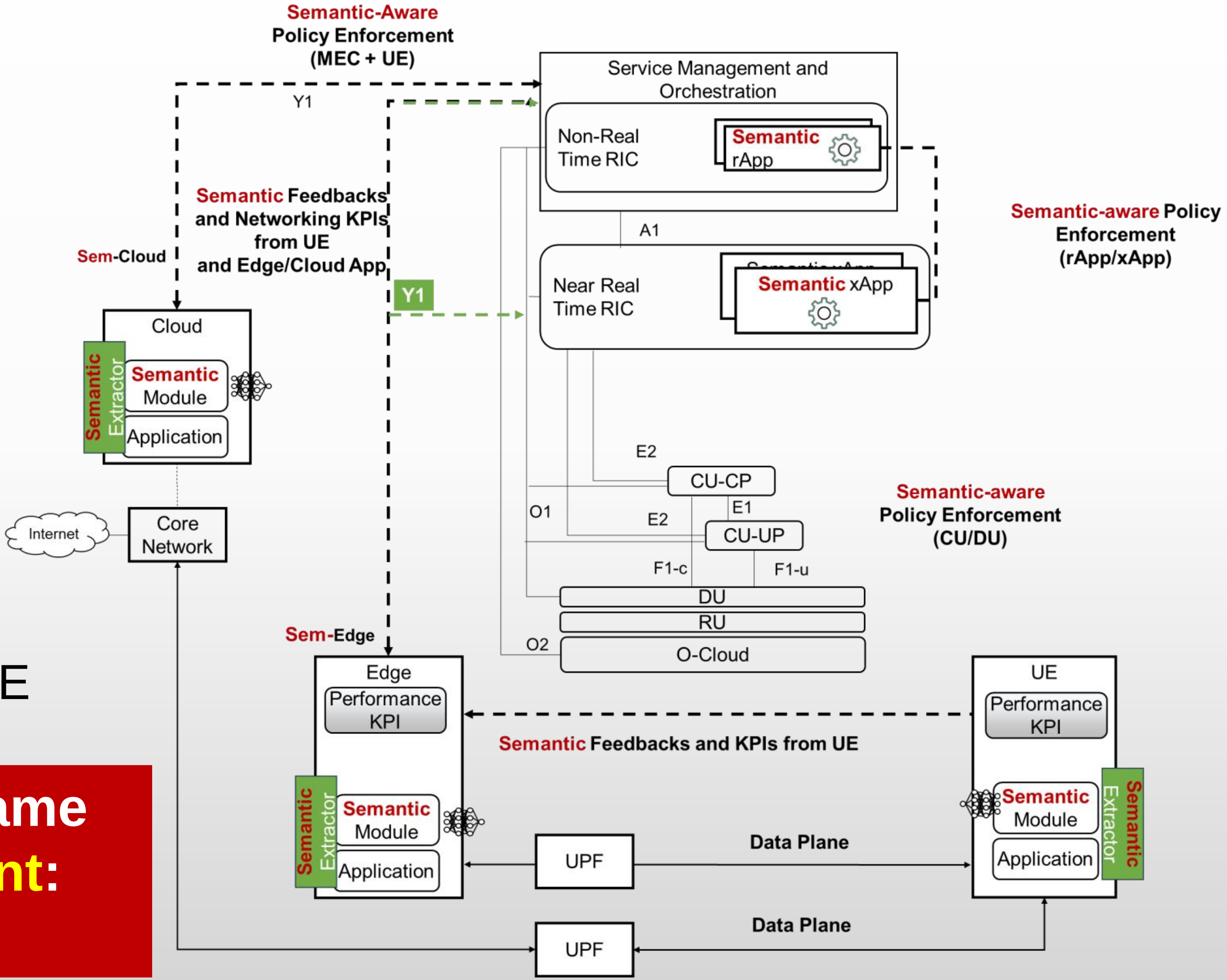
- Programmable and extensible platform for the deployment of semantic-oriented applications

Semantic module

- Extracting meaningful information from data and understanding its meaning, Semantic alignment

Semantic Interfaces

- Linking UEs to S-RIC and Sem-EDGE



O-RAN interfaces are about the same but the metrics carried are different: ex. BER → Semantic Fidelity

MAIN INNOVATIONS WITH RESPECT TO O-RAN (COMPATIBLE)

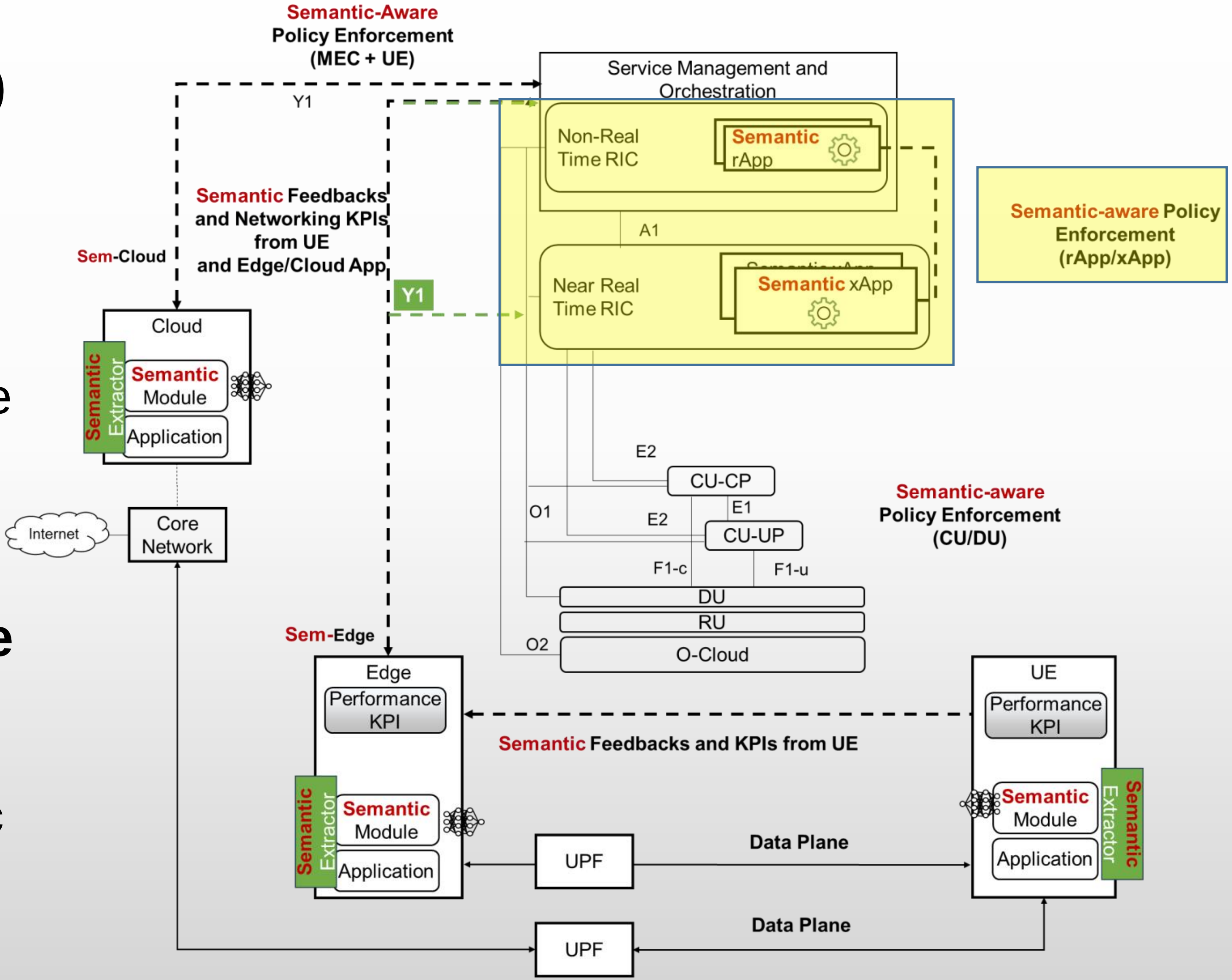
New Semantic-RIC (xApps / rApps)

Near-RT RIC

- **Semantic context aggregation** *(CQI, latency, mobility, traffic type, SLA)*
- **Dynamic adaptation**: AMC, resource allocation, semantic drop / retain decisions

Non-RT RIC

- **Long-term semantic intelligence** *(UE behavior, semantic traffic patterns, alignment drift)*
- **Mapping task goals → semantic KPIs and policies**



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MAIN INNOVATIONS WITH RESPECT TO O-RAN (COMPATIBLE)

New functional components, procedures, and interfaces to:

UE & Semantic Edge

- **Semantic extraction/interp.**
- Collection of **application / task context, requirements, KPIs, and feedback**

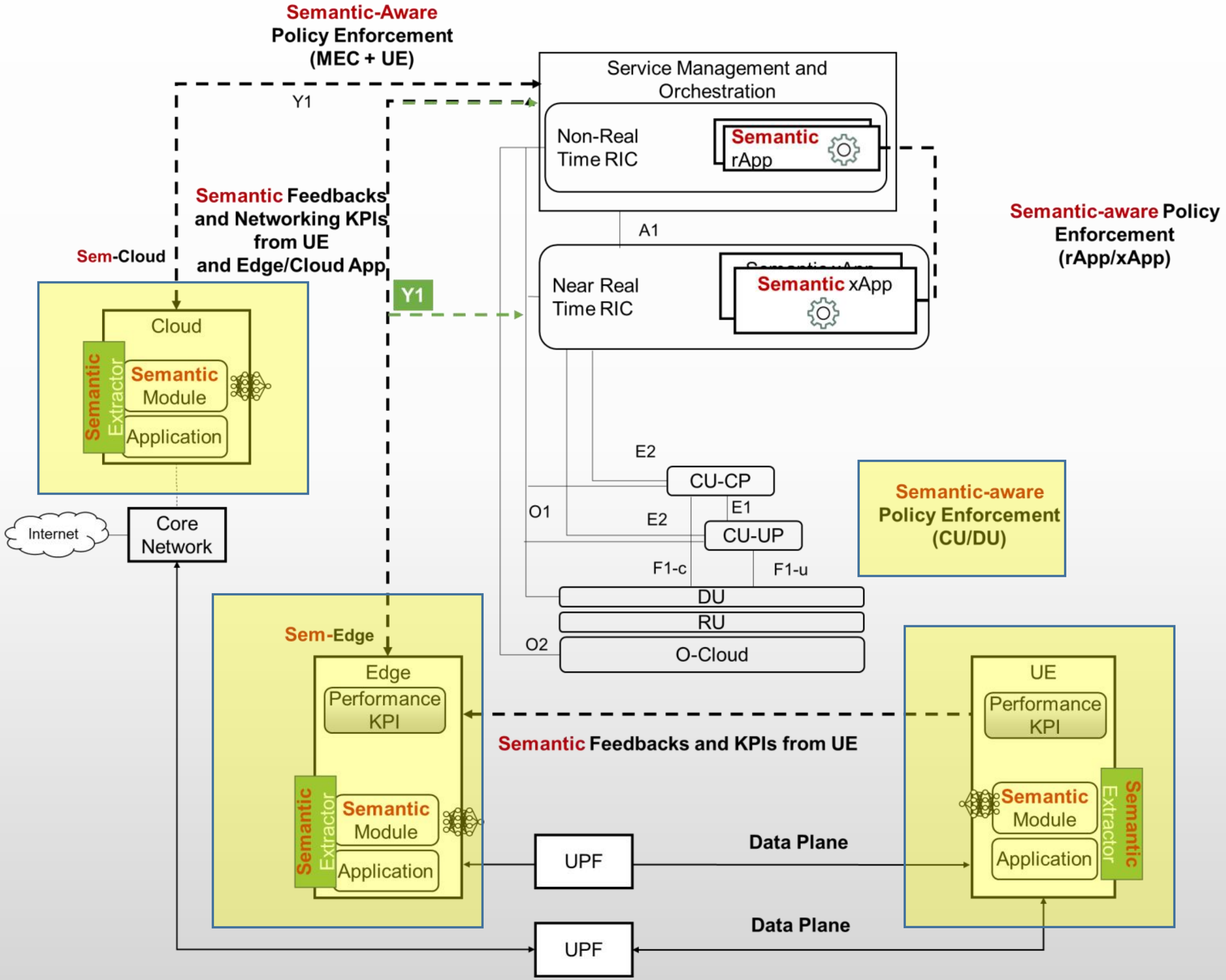
O-CU (CP / UP)

- Semantic flow differentiation and task-aware routing
- Semantic retransmission support (with O-DU)

O-DU

- Semantic-aware scheduling
- Adaptive semantic fidelity at PHY/MAC level

Interfaces (Extension): Bidirectional UE / application interaction→ Extend for semantic context and feedback exchange



MAIN INNOVATIONS WITH RESPECT TO O-RAN (NEEDS CHANGES)

Semantic RIC (S-RIC)

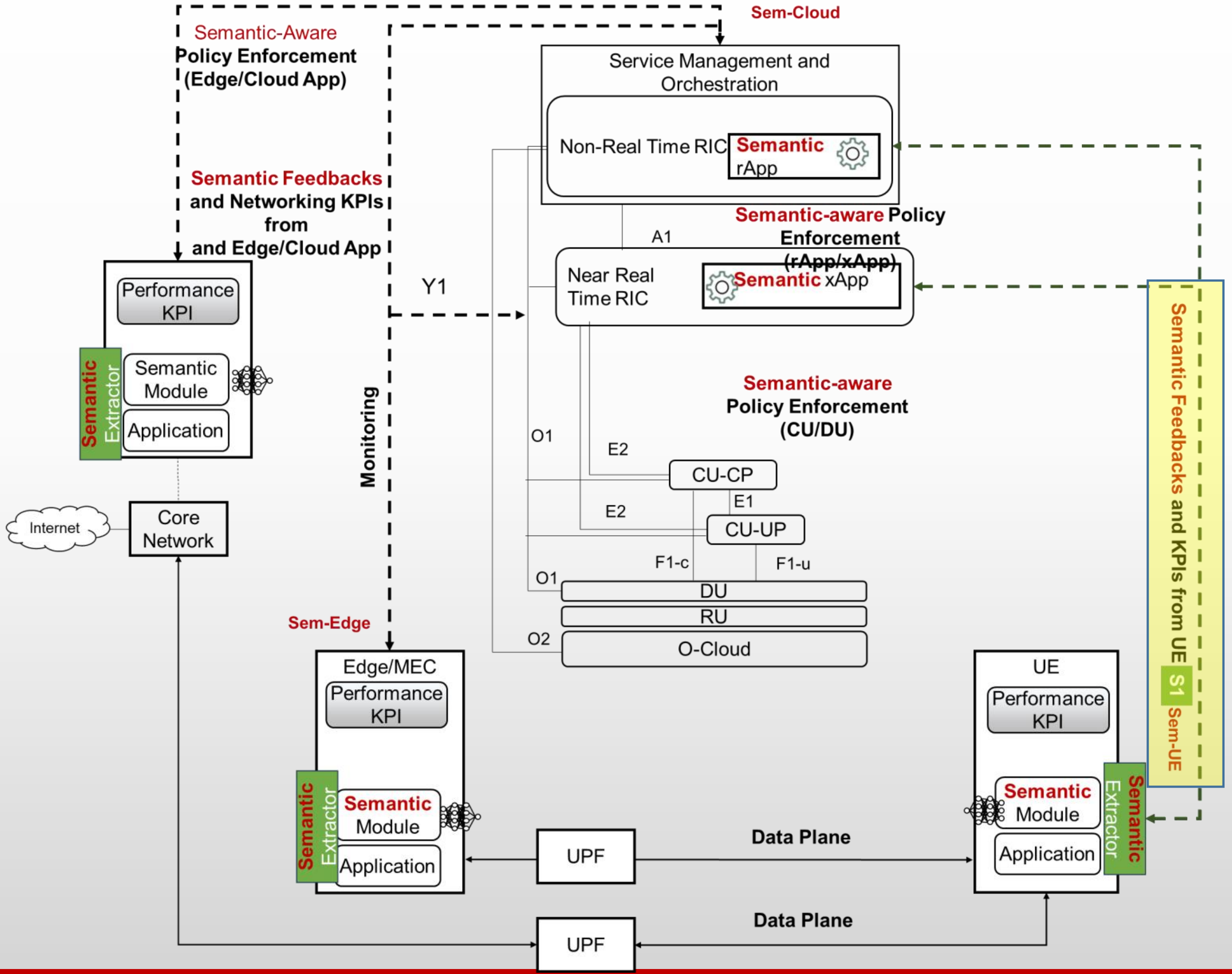
- Programmable and extensible platform for the deployment of semantic-oriented applications

Semantic module

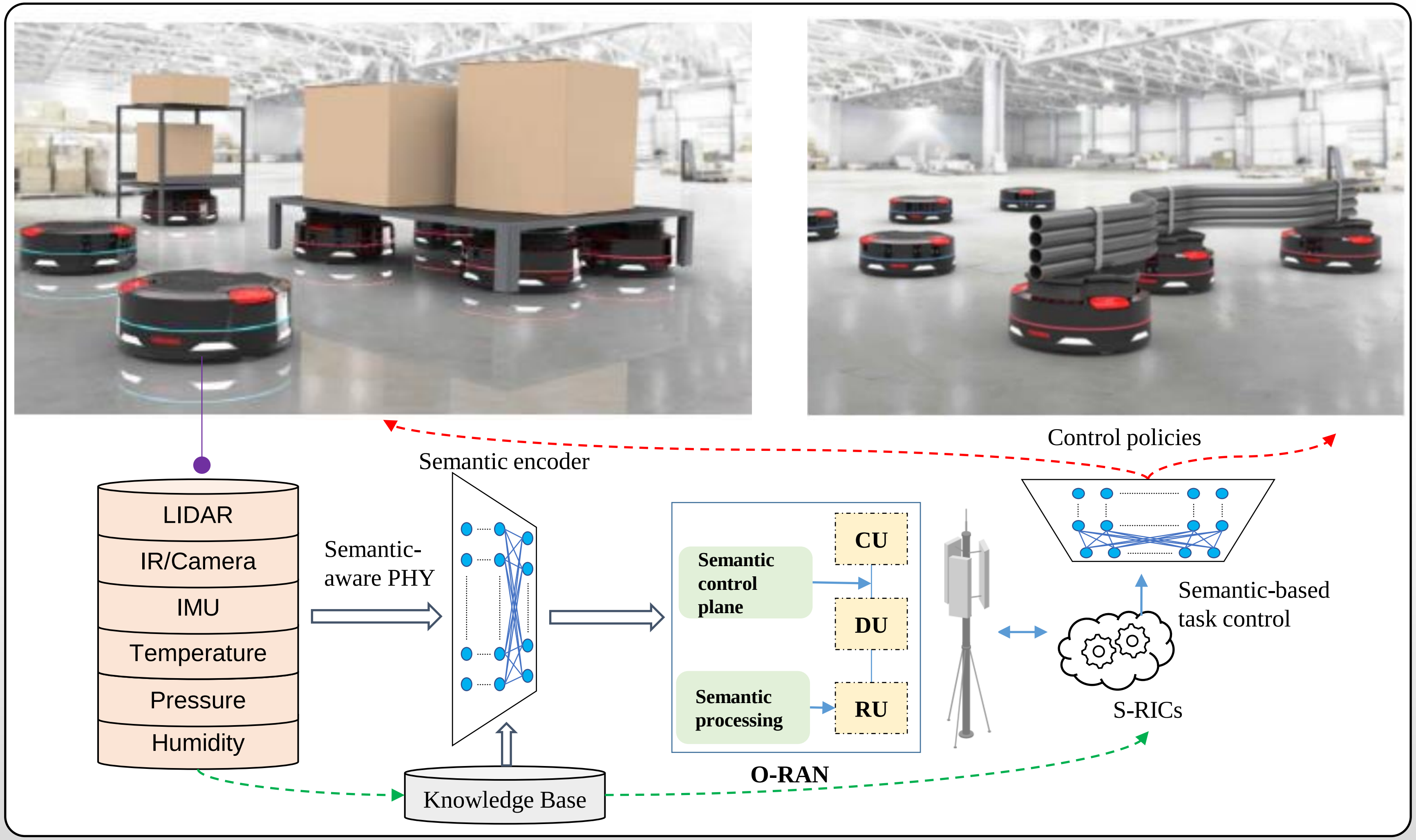
- Extracting meaningful information from data and understanding its meaning

Semantic Interfaces

- Linking UEs directly to S-RIC



O-RAN SEMCOM PROOF OF CONCEPT

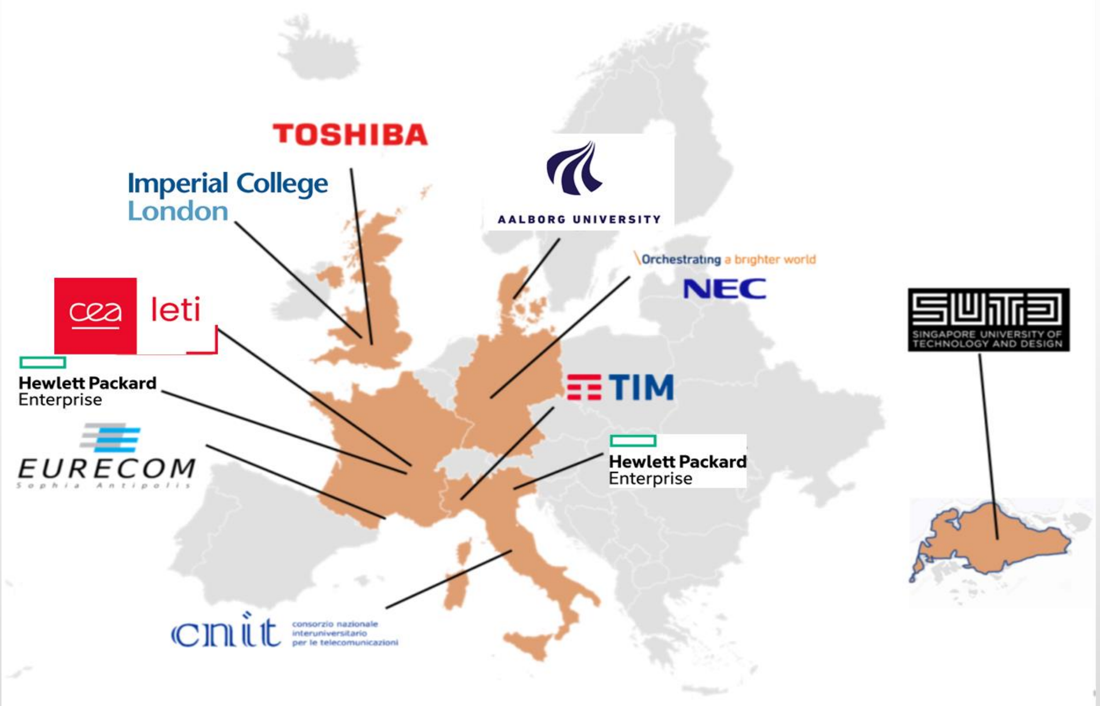


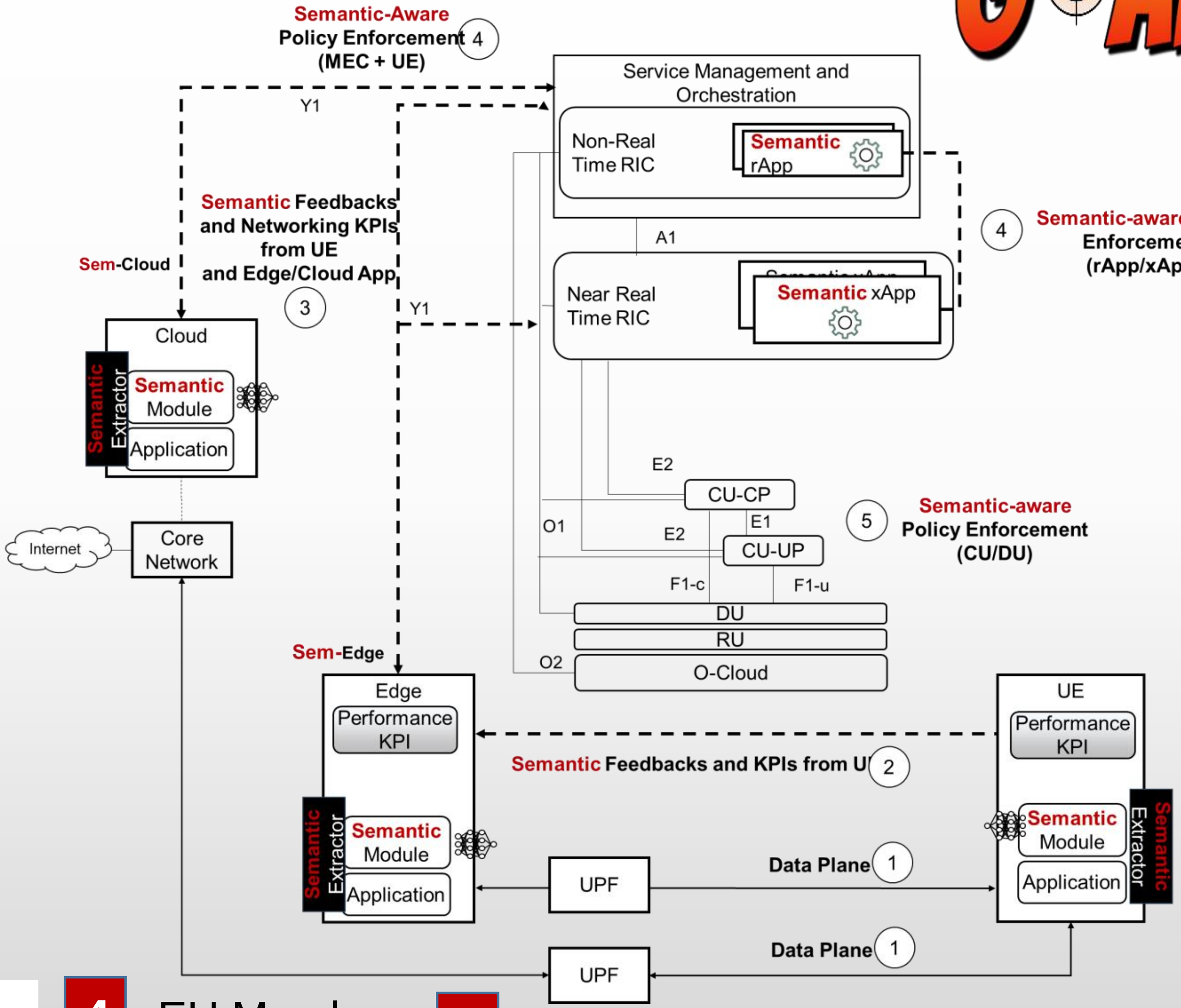
- Collaborative robot (cobot) trail under the semantic-aware Open RAN
- SemCom is designed to improve the overall operational efficiency of the cobot system
- This work is in progress (June 2026 first demos @ EUCNC)

6G-GOALS HORIZON PROJECT

Project Coordinator:
Emilio CALVANESE STRINATI

Technical Manager:
Paolo DI LORENZO





Semantic-Aware Policy Enforcement (MEC + UE) ④

Service Management and Orchestration

Non-Real Time RIC

Semantic rApp

Near Real Time RIC

Semantic xApp

Semantic-aware Policy Enforcement (rApp/xApp) ④

Semantic Feedbacks and Networking KPIs from UE and Edge/Cloud App ③

Sem-Cloud

Cloud

Semantic Extractor

Semantic Module

Application

Internet

Core Network

Y1

A1

E2

CU-CP

E1

CU-UP

O1

F1-c

F1-u

DU

RU

O2

O-Cloud

Semantic-aware Policy Enforcement (CU/DU) ⑤

Sem-Edge

Edge

Performance KPI

Semantic Extractor

Semantic Module

Application

Semantic Feedbacks and KPIs from UE ②

UE

Performance KPI

Semantic Module

Semantic Extractor

Application

UPF

Data Plane ①

UPF

Data Plane ①

5G PPP PUBLIC-PRIVATE PARTNERSHIP

6G SNS

PHASE 2

11 Consortium Partners

4 EU Member States

1 Asian Affiliated partner

6G-DISAC HORIZON PROJECT

Project Coordinator:
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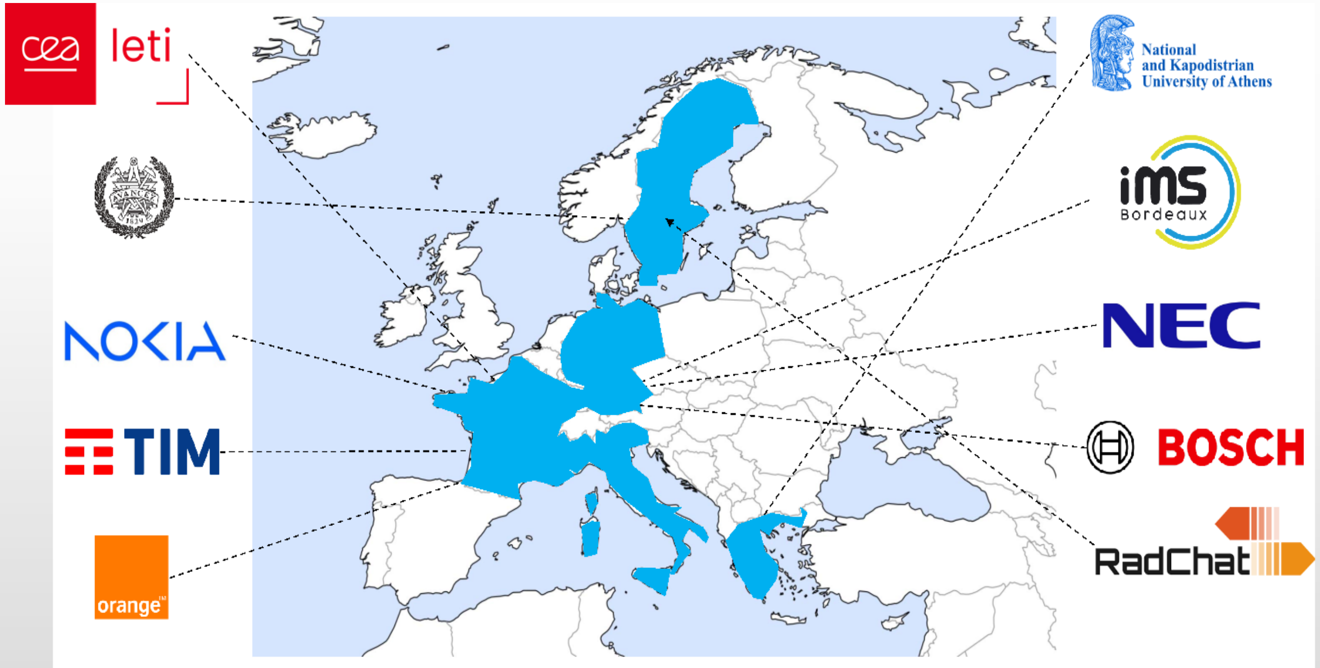
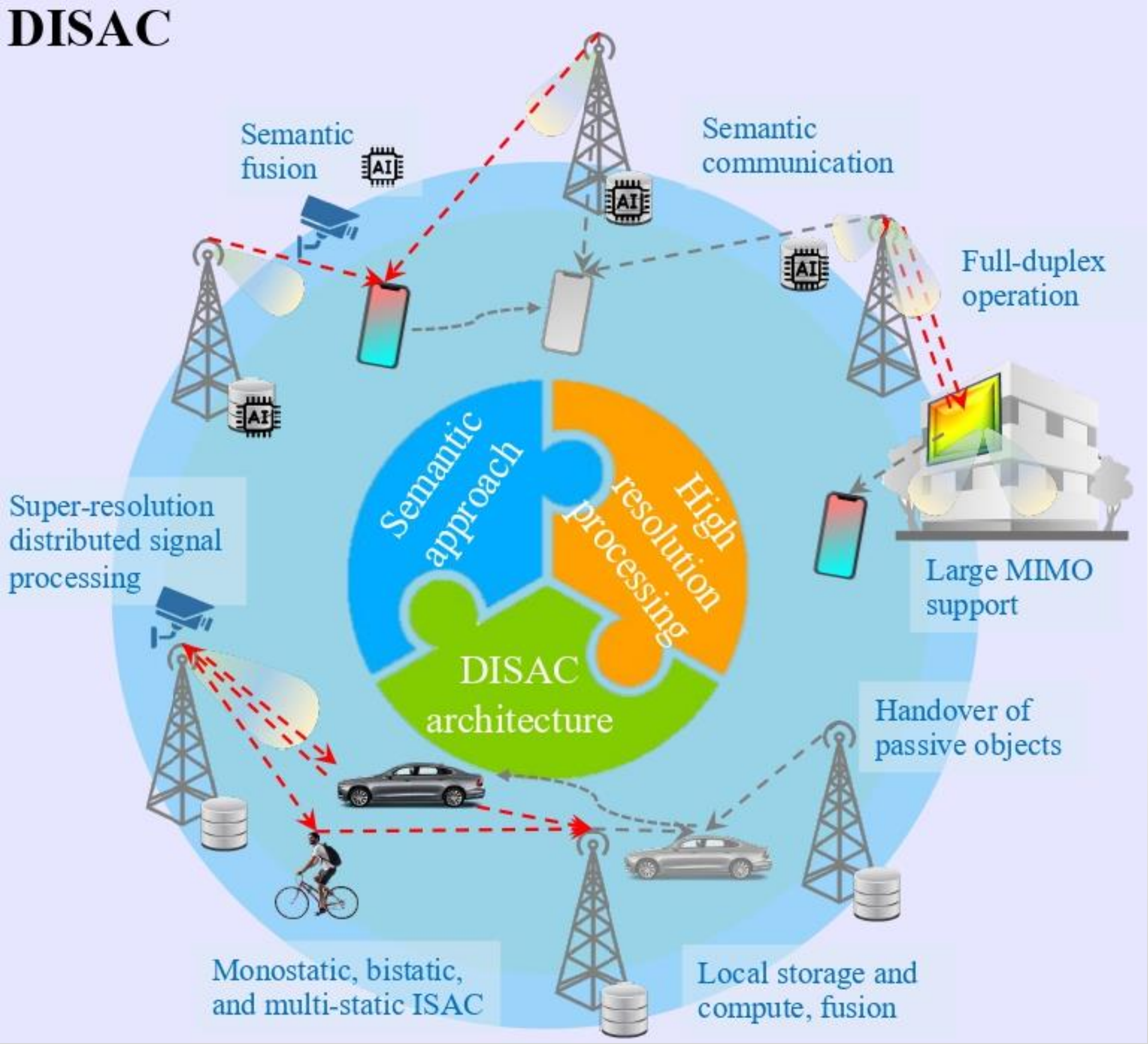


5G PPP PUBLIC-PRIVATE PARTNERSHIP

6GSNS PHASE 2

10 Consortium Partners

5 EU Member States



6GARROW

6GARROW EU-KR HORIZON PROJECT

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cea leti

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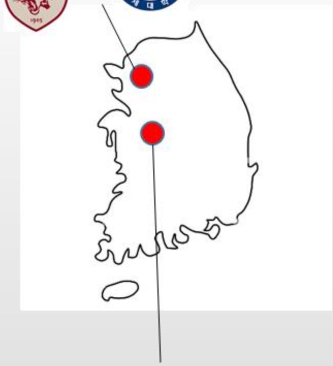
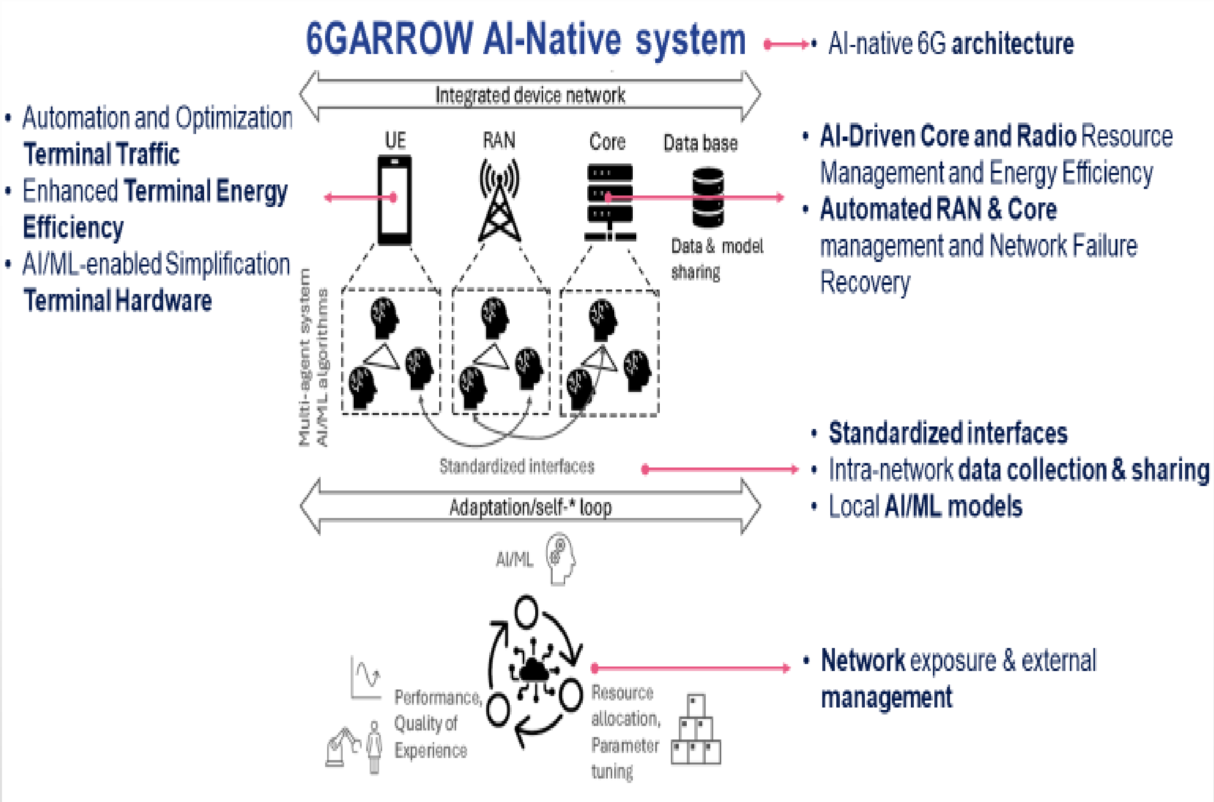
Aalto University

Project Coordinator KR
Prof. Seong-Lyun Kim





6GARROW AI-Native system

- AI-native 6G architecture

Integrated device network

- Automation and Optimization **Terminal Traffic**
- Enhanced **Terminal Energy Efficiency**
- AI/ML-enabled Simplification **Terminal Hardware**

- **AI-Driven Core and Radio** Resource Management and Energy Efficiency
- **Automated RAN & Core** management and Network Failure Recovery
- **Standardized interfaces**
- Intra-network **data collection & sharing**
- Local **AI/ML models**
- **Network** exposure & external **management**

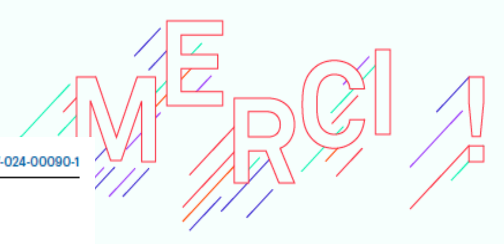
5G PPP PUBLIC-PRIVATE PARTNERSHIP

6GSNS

13 Consortium Partners

4 EU Member States + Korea

Thank you!



고맙습니다

ALOHA

Grazie!

Nature reviews


https://doi.org/10.1038/s44287-024-00090-1

6G: the catalyst for artificial general intelligence

Emilio Calvanese Strinati

Check for updates

6G might integrate 5G and AI to merge physical, cyber and sapience spaces, transforming network interactions and enhancing AI-driven decision-making and automation. The semantic approach to communication will train AI while selectively informing on goal achievement, moving towards artificial general intelligence, presenting new challenges and opportunities.

Although 5G is not yet fully deployed, there is already disagreement as to what 6G will be. The mainstream vision of 6G today is that it is a combination of 5G and artificial intelligence (AI), making it the main gateway to artificial general intelligence. However, even the link between AI and 6G is controversial. Existing AI systems are still stochastic parrots[1], mimicking or repeating sequences without any true understanding of the training data or their own output. Massive amounts of scattered data are capillary fed to AI by 5G networks with this 'content-blind transmission without understanding' approach. Thus, data are teleported without any prior understanding of how informative, valuable or timely the data are, and then the data are used to train and feed AI, with the aim of inducing reasoning and adaptation to various operational environments. As a result, AI algorithm outcomes remain limited to sophisticated pattern recognition and statistical correlations. Some algorithms generate responses on the basis of learned data, but without true understanding, interpretation or reasoning of the underlying meaning and nuances of the information processed. 6G needs more from AI and can offer more to AI. The hope is that 6G could make AI less artificial, connecting the biological world and AI, thus bridging the gaps between physical, cyber (digital) and sapience spaces. Meanwhile, AI is expected to hone reasoning skills, enabling reliable self-synthesizing networking and full automation of network management, thus eliminating the need for manual intervention (zero-touch networking).

6G can connect and entangle the physical, cyber and sapience spaces to radically change the system's perception of the foundational concepts of space, time, information and reliability.

Specifically, the shift from 5G to 6G marks a profound transformation in how networks and technologies interact with humans across physical and cyber spaces, creating intelligent environments that are responsive to the presence of both humans and machines. 5G is not AI native[2]: data are essential to feed AI reasoning engines; data are gathered, transferred and processed from scattered sources to update models, accumulate knowledge and attain goals. Still, 5G enhanced connectivity is designed to transport raw data rather than AI-understandable knowledge.

In contrast, 6G aims to create a deeply integrated, intelligent and
immersive ecosystem. This ecosystem fus
real-world interactions and events occur, t
interactions and activities take place, an
humans and AI can combine their cognitiv
edge meaningfully. The Integrated comn
advanced localization techniques of 6G
and fusion of contextualized multimodal
video, which can then be semantically anal
communications[4] will support AI by selecti
representing knowledge to make continu
possible. AI will thus be able to make inforn
underlying objective of the communicatio
and to distinguish between correlation ar

As for time, chronological measurem
nant in 5G. Instead, the focus is on the late
sion and its reliable reception. 5G end-to
managed mainly to limit and regulate da
transmission latency within the wireless a
the cumulative contributions of processing
specific limitations. With 5G, this trans
transfer speeds and guaranteed synchro
applications and services. Nevertheless
challenging. As of today, the physical limi
munication are being reached, making it
solutions at higher-spectrum bands. The s
considered in 6G, targeting even smaller ti
ing strictly controllable 'time jitters' to ser
with similar physical and hardware limit
for new spectra is increasingly difficult. T
the conceptual understanding of time in
different from that in 5G systems. Time is
munication, processing, reasoning, mem
use of information, such as inference, c
6G, time is not just about latency, nor is
and ordering boundaries for the physical
experienced differently, owing to disentan
physical, cyber and sapience spaces. 6C
the sapience space, where time is under
within and between the physical and cyb
ing reasoning, decision-making and the d
and wisdom.

In the sapience space, time causality
ceived, and digital synchronicity differs
simultaneity. Interactivity and the illusi
the perceptible time granularity. This g
spaces and agents (biological or artifici
their methods of collecting, modeling, p
external stimuli. Timing is governed by d

nature reviews electrical engineering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Computer Networks

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ELSEVIER

6G networks: Beyond Shannon towards semantic and goal-oriented communications

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ARTICLE INFO

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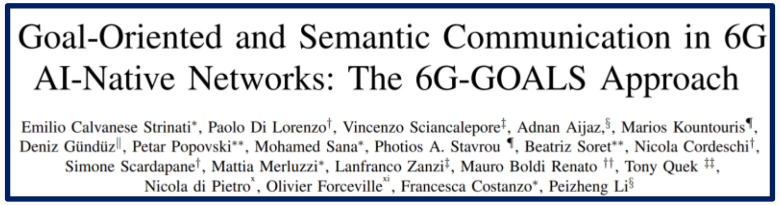
MEC
Semantic communications
Semantic learning
Goal oriented communications
Sustainability
Green communications

ABSTRACT

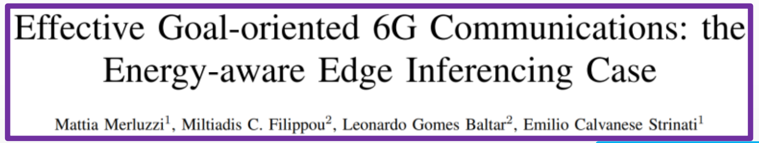
The goal of this paper is to promote the idea that including semantic and goal-oriented aspects in future 6G networks can produce a significant leap forward in terms of system effectiveness and sustainability. Semantic communication goes beyond the common Shannon paradigm of guaranteeing the correct reception of each single transmitted bit, irrespective of the meaning conveyed by the transmitted bits. The idea is that, whenever communication occurs to convey meaning or to accomplish a goal, what really matters is the impact that the received bits have on the interpretation of the meaning intended by the transmitter or on the accomplishment of a common goal. Focusing on semantic and goal-oriented aspects, and possibly combining them, helps to identify the *relevant information*, i.e. the information strictly necessary to recover the meaning intended by the transmitter or to accomplish a goal. Combining knowledge representation and reasoning tools with machine learning algorithms paves the way to build semantic learning strategies enabling current machine learning algorithms to achieve better interpretation capabilities and contrast adversarial attacks. 6G semantic networks can bring semantic learning mechanisms at the edge of the network and, at the same time, semantic learning can help 6G networks to improve their efficiency and sustainability.


Goal-Oriented and Semantic Communication in 6G AI-Native Networks: The 6G-GOALS Approach

Emilio Calvanese Strinati*, Paolo Di Lorenzo†, Vincenzo Sciancalepore‡, Adnan Aijaz,§, Marios Kountouris¶, Deniz Gündüz‖, Petar Popovski**, Mohamed Sana*, Photios A. Stavrou ¶, Beatriz Soret**, Nicola Cordeschi†, Simone Scardapane†, Mattia Merluzzi*, Lanfranco Zanzi‡, Mauro Boldi Renato ††, Tony Quek ‡‡, Nicola di Pietro[x], Olivier Forceville[xi], Francesca Costanzo*, Peizheng Li§


Pragmatic Goal-Oriented Communications under Semantic-Effectiveness Channel Errors

Tomás Hüttebraucker, Mohamed Sana, Emilio Calvanese Strinati


Effective Goal-oriented 6G Communications: the Energy-aware Edge Inferencing Case

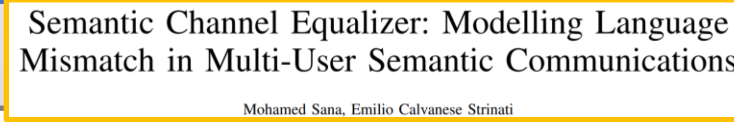
Mattia Merluzzi[1], Miltiadis C. Filippou[2], Leonardo Gomes Baltar[2], Emilio Calvanese Strinati[1]


Learning Semantics: An Opportunity for Effectiv 6G Communications

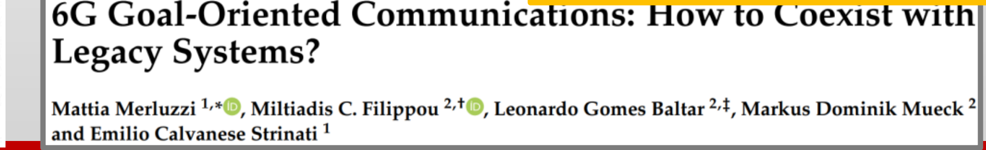
Mohamed Sana[1], Emilio Calvanese Strinati[1]


GOAL-ORIENTED COMMUNICATIONS FOR THE IOT: SYSTEM DESIGN AND ADAPTIVE RESOURCE OPTIMIZATION

Paolo Di Lorenzo, Mattia Merluzzi, Francesco Binucci, Claudio Battiloro, Paolo Banelli, Emilio Calvanese Strinati, and Sergio Barbarossa


Semantic Channel Equalizer: Modelling Language Mismatch in Multi-User Semantic Communications

Mohamed Sana, Emilio Calvanese Strinati


6G Goal-Oriented Communications: How to Coexist with Legacy Systems?

Mattia Merluzzi [1,*], Miltiadis C. Filippou [2,†], Leonardo Gomes Baltar [2,‡], Markus Dominik Mueck [2] and Emilio Calvanese Strinati [1]