6G Semantic Communications: 6G-GOALS project

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6G-GOALS WHO

6GSNS
PHASE 2

Project Coordinator: Emilio CALVANESE STRINATI — cea leti

Runtime: 01 January 2024 – 31 December 2026

Technical Manager: Paolo DI LORENZO — cnit

11 Consortium Partners

4 EU Member States

1 Asian Affiliated partner

TOSHIBA

Imperial College London

AALBORG UNIVERSITET

Orchestrating a brighter world
NEC

cea leti

Hewlett Packard Enterprise

EURECOM
Sophia Antipolis

TIM

Hewlett Packard Enterprise

SUTD
SINGAPORE UNIVERSITY OF TECHNOLOGY AND DESIGN

cnit
consorzio nazionale interuniversitario per le telecomunicazioni

5G PPP
PUBLIC-PRIVATE PARTNERSHIP

European Commission

6G-GOALS WHY IF WE COULD SAY LESS BUT UNDERSTAND MORE?

6G-GOALS: THE SEMANTIC & GOAL-ORIENTED COMMUNICATIONS OPPORTUNITY
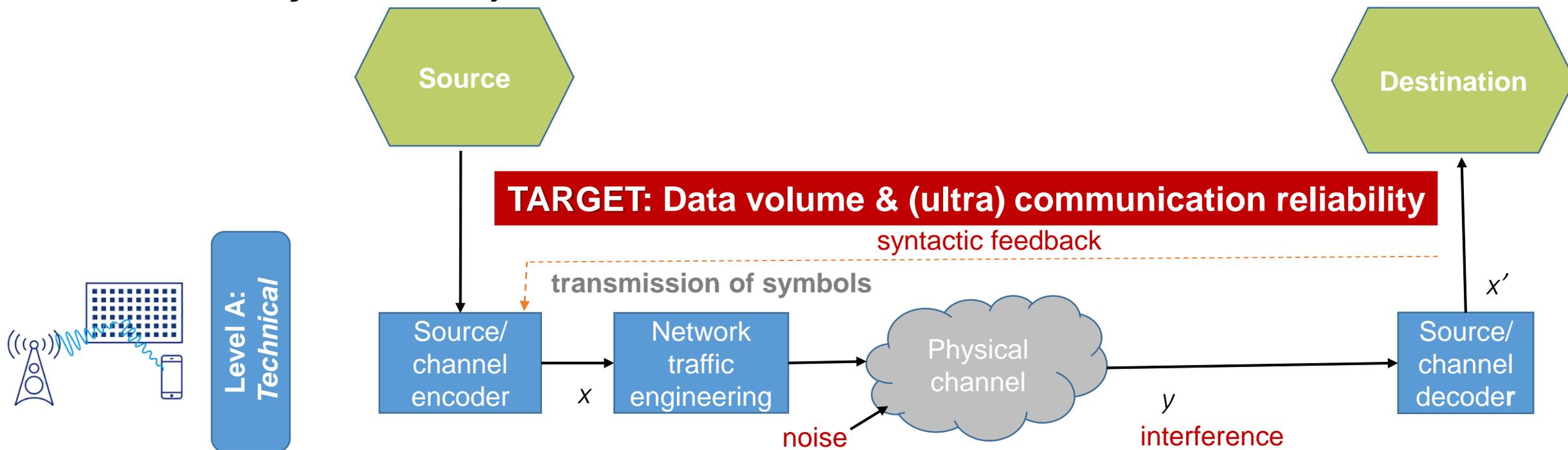
GENERATIONS OF CONTENT BLIND COMMUNICATIONS

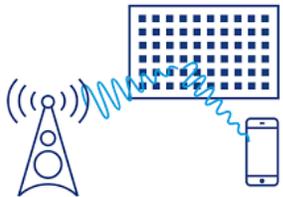**Current *content-blind transmit-without-understanding* approach**:
data is transmitted without any prior **understanding** of how informative it is (**semantic**) to the receiver or useful (**pragmatic**) for the end-goal of communications

Shannon's approach (The **technical** problem):
How **accurately** can the symbols of communication be transmitted?

TARGET: Data volume & (ultra) communication reliability

GENERATIONS OF CONTENT BLIND COMMUNICATIONS

Current fast-*content-blind transmit-without-understanding* approach:
Data is transmitted without any prior **understanding** of how informative it is (**semantic**) to the receiver or useful (**pragmatic**) for the end-goal of communications

like pressing keys randomly!
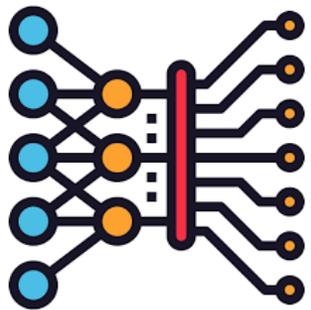
TARGET: Data volume & (ultra) communication reliability

Level A: Technical

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

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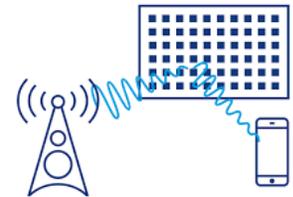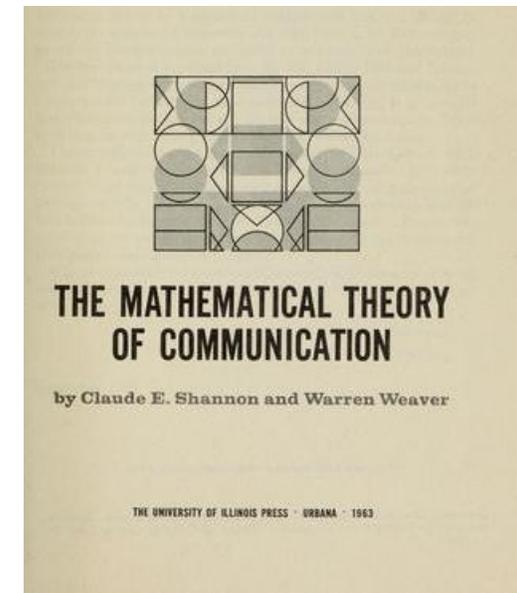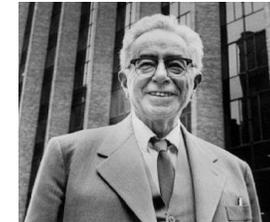
2. **Level B:** How precisely do the transmitted symbols convey the desired meaning? (The **semantic** problem)

Level A: Technical

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

THE MATHEMATICAL THEORY OF COMMUNICATION

by Claude E. Shannon and Warren Weaver

THE UNIVERSITY OF ILLINOIS PRESS · URBANA · 1963

Level C:
Effectiveness

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

Level B:
Semantic

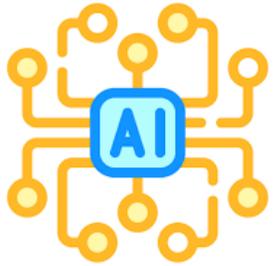2. **Level B:** How precisely do the transmitted symbols convey the desired meaning? (The **semantic** problem)

Level A:
Technical

1. **Level A:** How accurately can the symbols of communication be transmitted? (The **technical** problem)
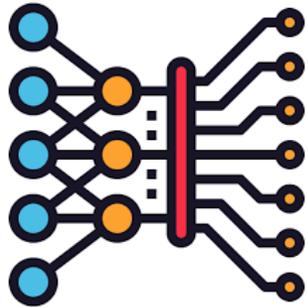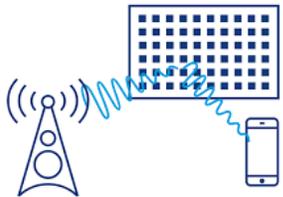
The broad subject of communication can be organized into **three levels**
[Shannon, Weaver, 49]
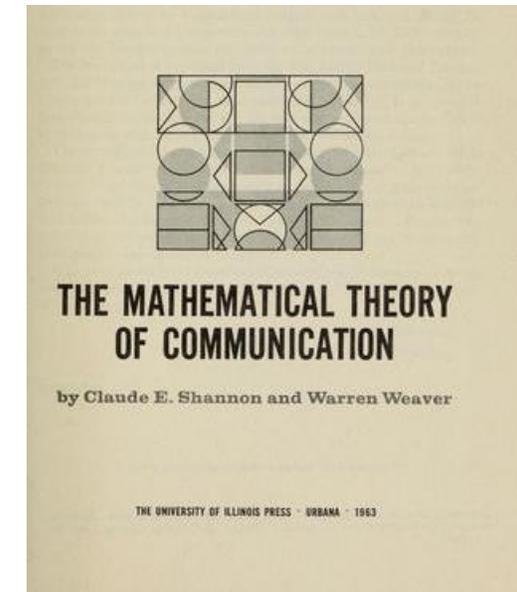
THE MATHEMATICAL THEORY
OF COMMUNICATION

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effect of semantic information exchange

Level C: Effectiveness

Source — Environment — Destination

KB$_S$ — Knowledge sharing — KB$_D$

semantic exchange of symbols

Level B: Semantic

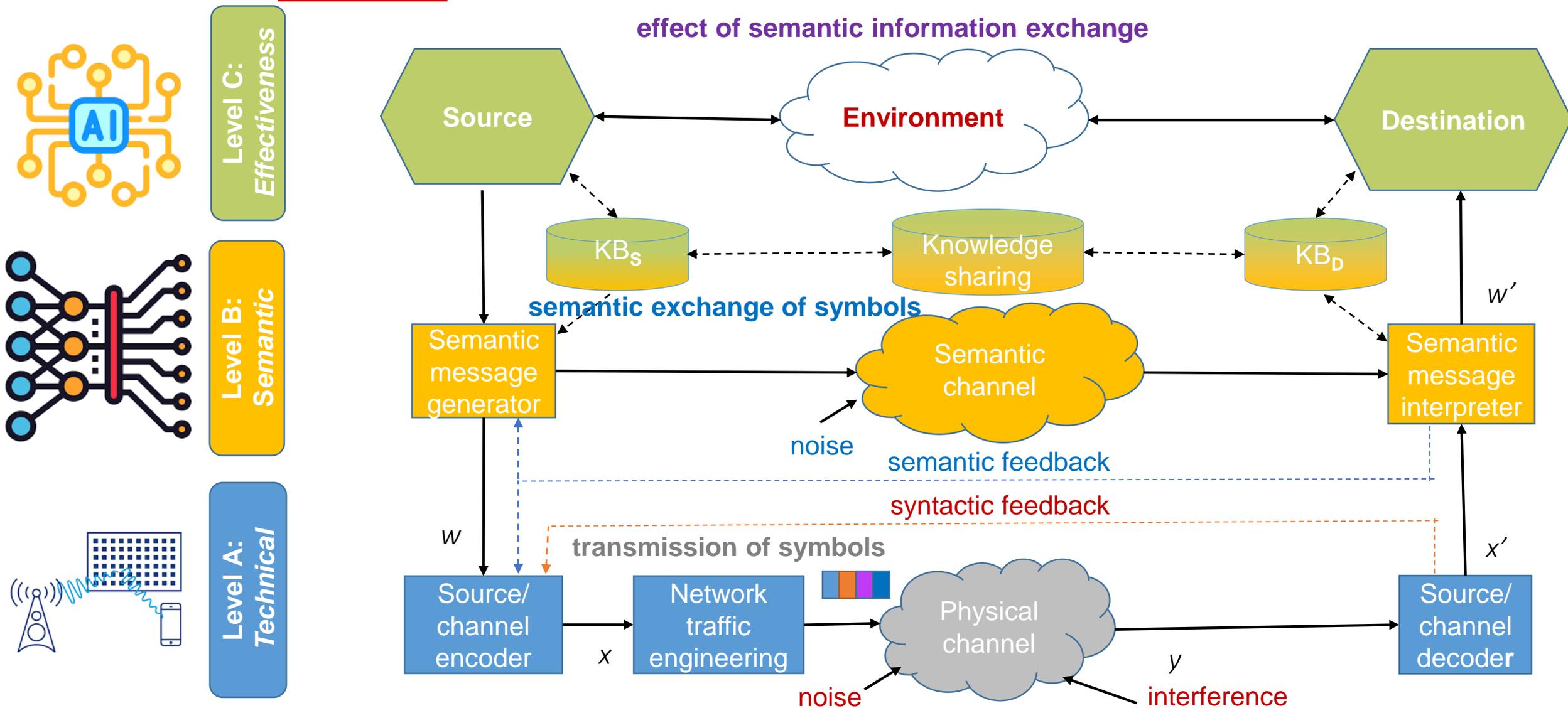Semantic message generator — Semantic channel — Semantic message interpreter

noise

semantic feedback

w'

syntactic feedback

w

transmission of symbols

Level A: Technical

Source/channel encoder — Network traffic engineering — Physical channel — Source/channel decoder

x — y — x'

noise — interference

Objective: Lay the **theoretical**, **algorithmic** and **operational foundations** of **a AI-Native semantic communication** and networking paradigms

Communicate (or protect) only what cannot be deduced or predicted by AI to:
- Send less but understand more
- Facilitate knowledge sharing, between heterogeneous/distributed AI devices
- Stimulate reasoning between AI rather than ensuring high bit accuracy of shared (raw) data

Understand-then-transmit

What if … I can Read it … can you?

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!

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When the order of words or characters changes,

your brain still **correctly interpret** sentences.

AI Semantic understanding of context and goals enable self-correction of inaccuracies & incompleteness in data and focus on meaningful informative information

#1 Goal Oriented Communications

From: Data-oriented & content-blind communications

To: Goal-oriented effective transmission where communications are shaped to achieve a goal or to accomplish a task

WHAT **6G can do it differently** – **2 paradigm shifts with AI**

#1 Goal Oriented Communications

From: Data-oriented & content-blind communications

To: Goal-oriented effective transmission where communications are shaped to achieve a goal or to accomplish a task

#2 AI-native Semantic Communications

From: Moving content-blind raw data

To: Share only what cannot be deduced or inferred by (Generative)AI (w/o GO)

➔ **identify the relevant needed information to recover the meaning intended by the transmitter(s) and/or to attain the goal at the receiver(s)**

But **focusing rather on the actual effect that the received information has on performing an action**!

Targeting inference/intelligence reliability rather than blind bit-fidelity
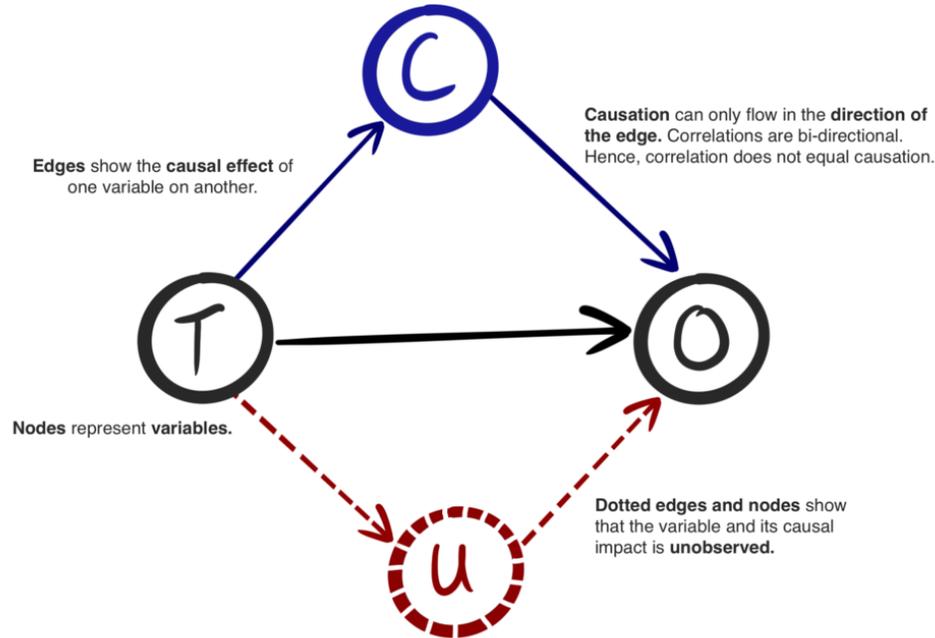
Incorporating **semantic**, **pragmatic**, and **goal-oriented** communication aspects
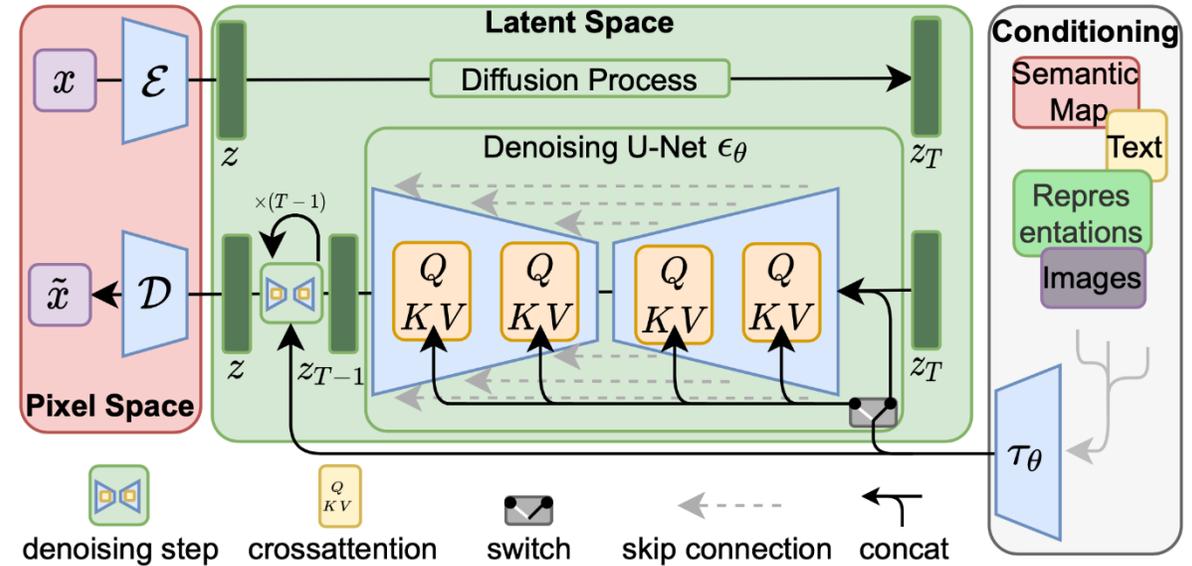
- **AI-empowered semantic data representation, sensing, compression and communication**

- **Time-sensitive communication** over wireless links

- **Sustainability** via technologies enabling new wireless services with higher efficiency

AI-native 6G system tailored for semantic and goal-oriented communications

Semantic plane that enhances both the user plane and the control plane

Open RAN to effectively handle semantic communications on a large scale

New intelligent semantic network functions responsible for semantic communication and resource management

Coexistence & **inter-operability** with semantic-agnostic systems
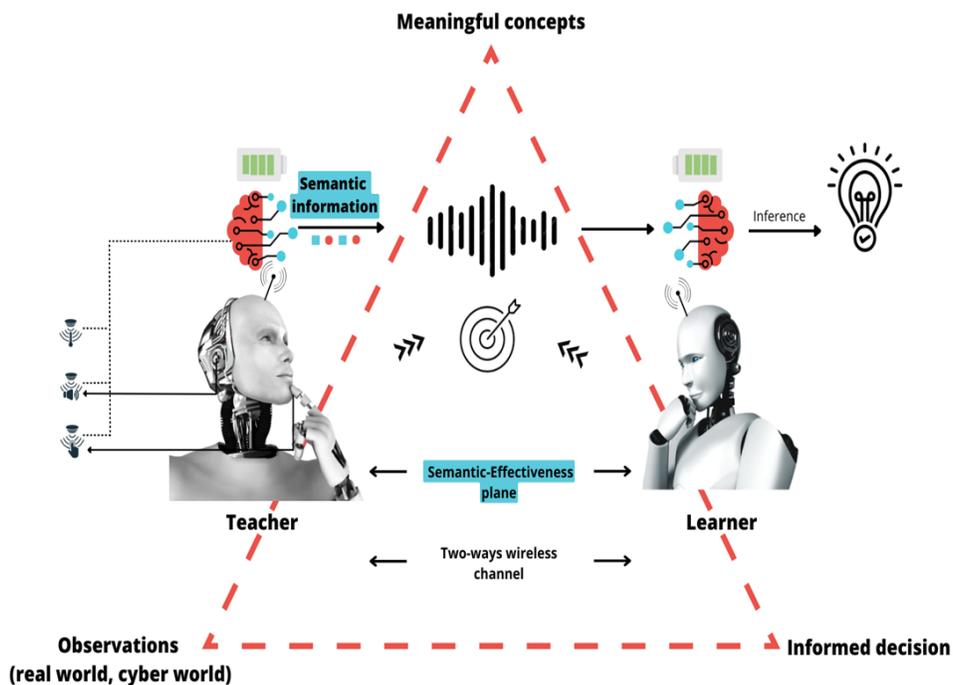
Causal representations

Generative AI

We use and study the term "semantic" in a very general sense :
any structural (topological), statistical, or causal relationship within the data to be communicated, assessed in relation to the desired reconstruction metric or desired actions to be taken at the receiver side.

Reasoning through Semantic Communications

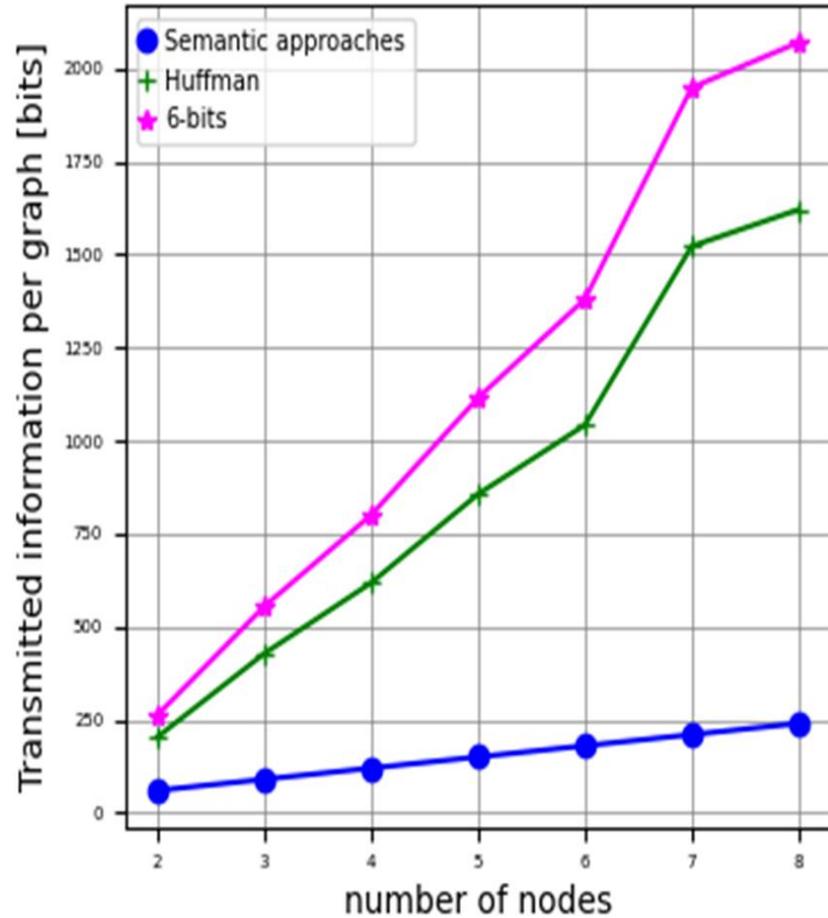## Pragmatic communications


Understand-then-Transmit
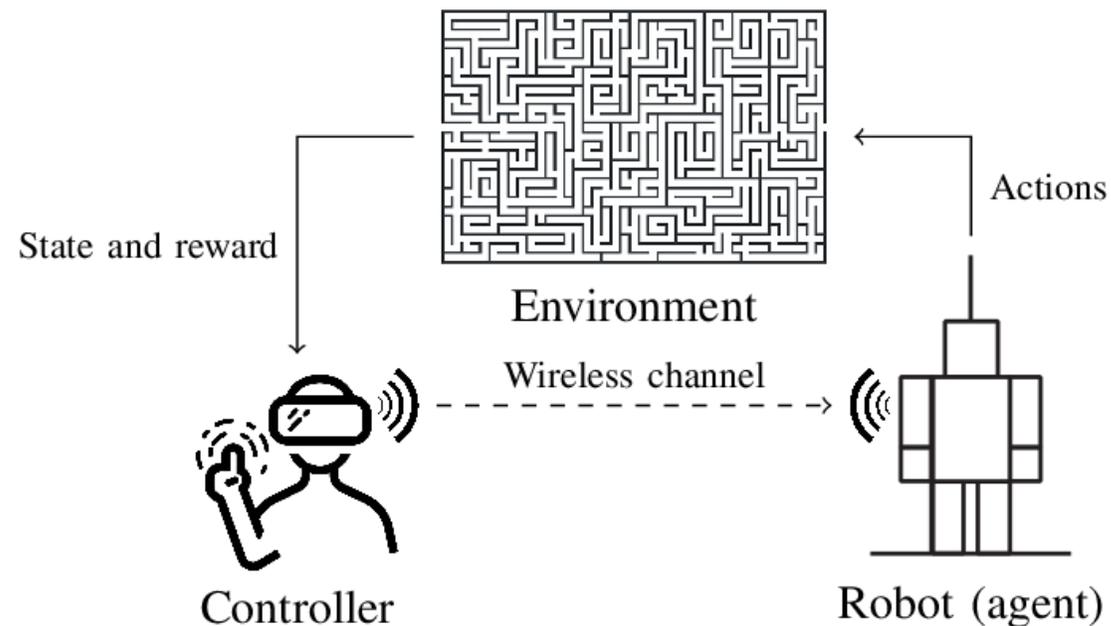
6G-GOALS : **enable learning and reasoning** via **pragmatic communications**, incorporating **causal semantic data representations**, and **considering mismatches of languages/logics/models and semantic rules** between sender(s) and receiver(s) & ensuring **backward compatibility with legacy** (data-driven) **systems**.

Semantic Communications gains: Experimental results

Factor 190+ in data compression
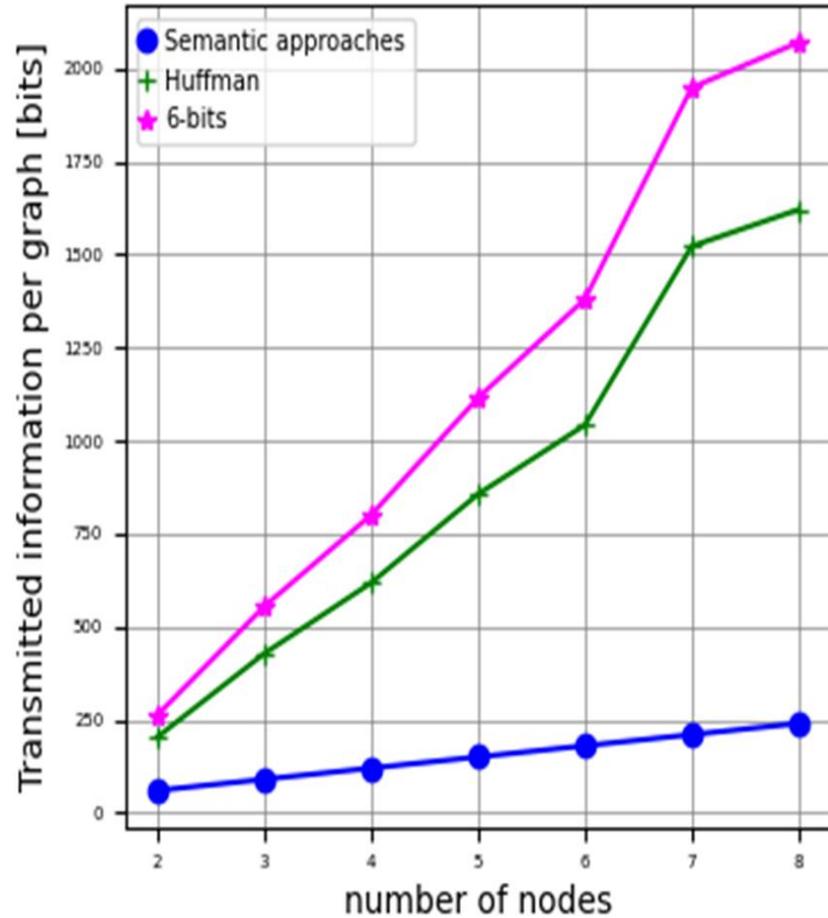
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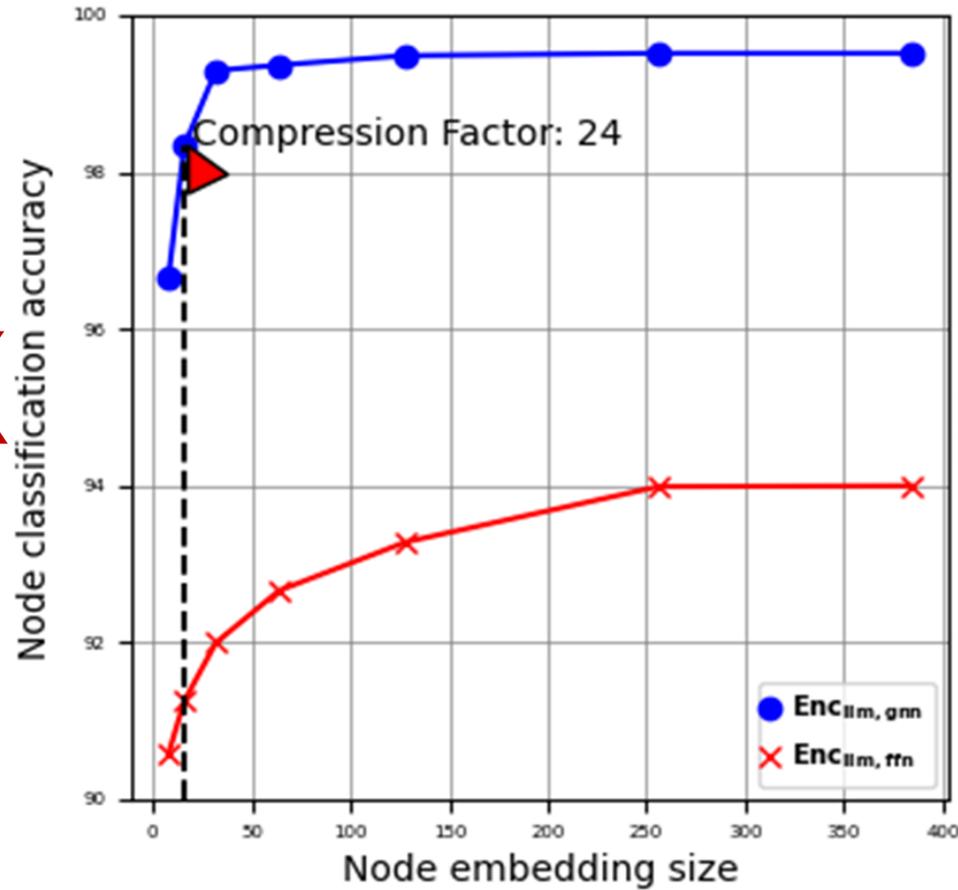
Factor 190+ in data compression

*N Hello, P Di Lorenzo, **E. Calvanese Strinati**, "Semantic Communication Enhanced by Knowledge Graph Representation Learning", IEEE SPAWC, 2024.*

Semantic Communications gains: Experimental results

Factor 190+ in data compression

Factor 23 in AI training time reduction
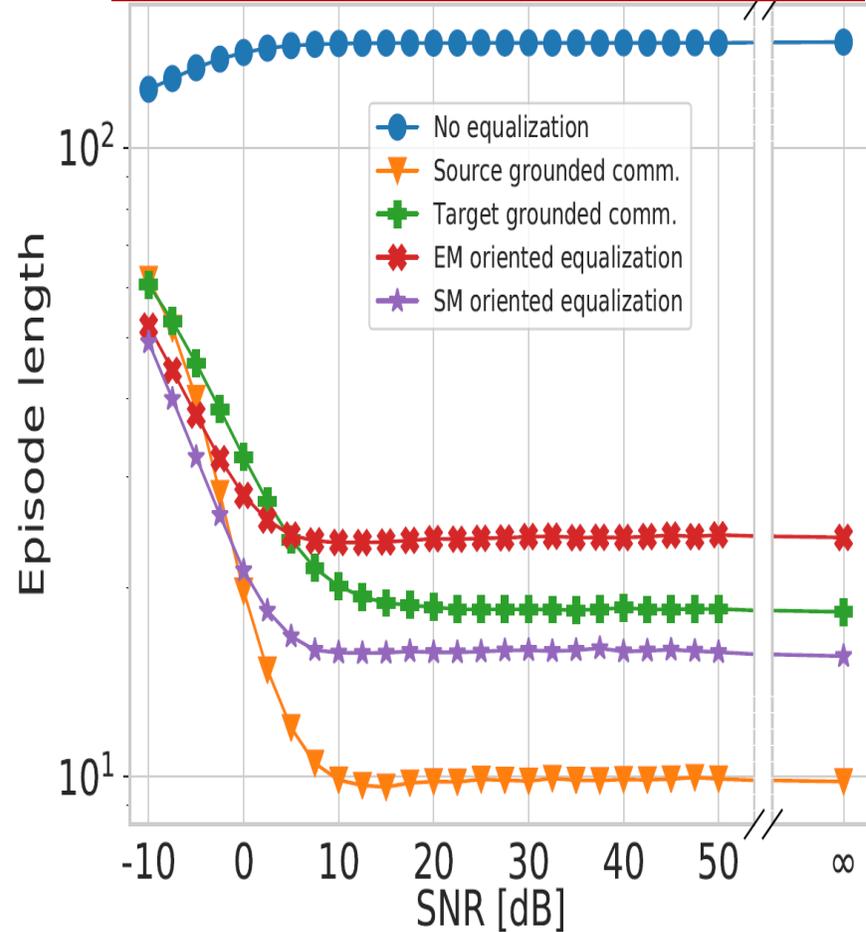
N Hello, P Di Lorenzo, **E. Calvanese Strinati**, "Semantic Communication Enhanced by Knowledge Graph Representation Learning", IEEE SPAWC, 2024.

T Huttebraucker, M Sana, **E. Calvanese Strinati,** "Latent Space Alignment for Semantic Channel Equalization", ICMLCM 2024. (**Best student poster award**).

Semantic Communications gains: Experimental results

Factor 190+ in data compression	Factor 23 in AI training time reduction	Factor 6+ in reduction of RIS active elements

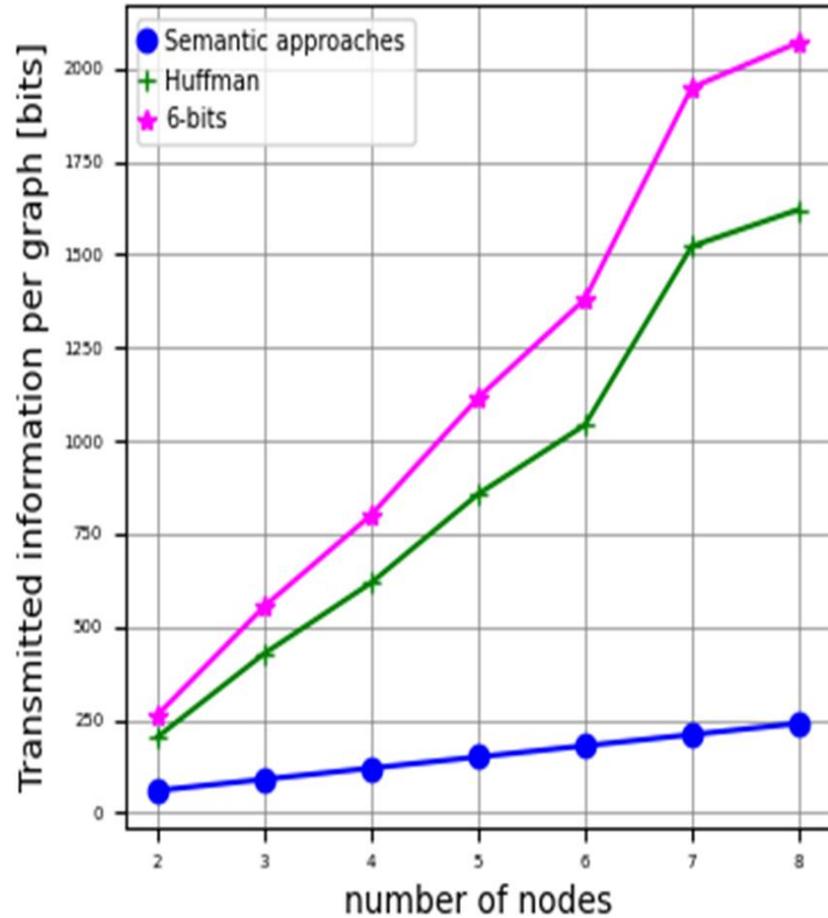(a) One bit phase quantization

N Hello, P Di Lorenzo, *E. Calvanese Strinati*, "Semantic Communication Enhanced by Knowledge Graph Representation Learning", IEEE SPAWC, 2024.
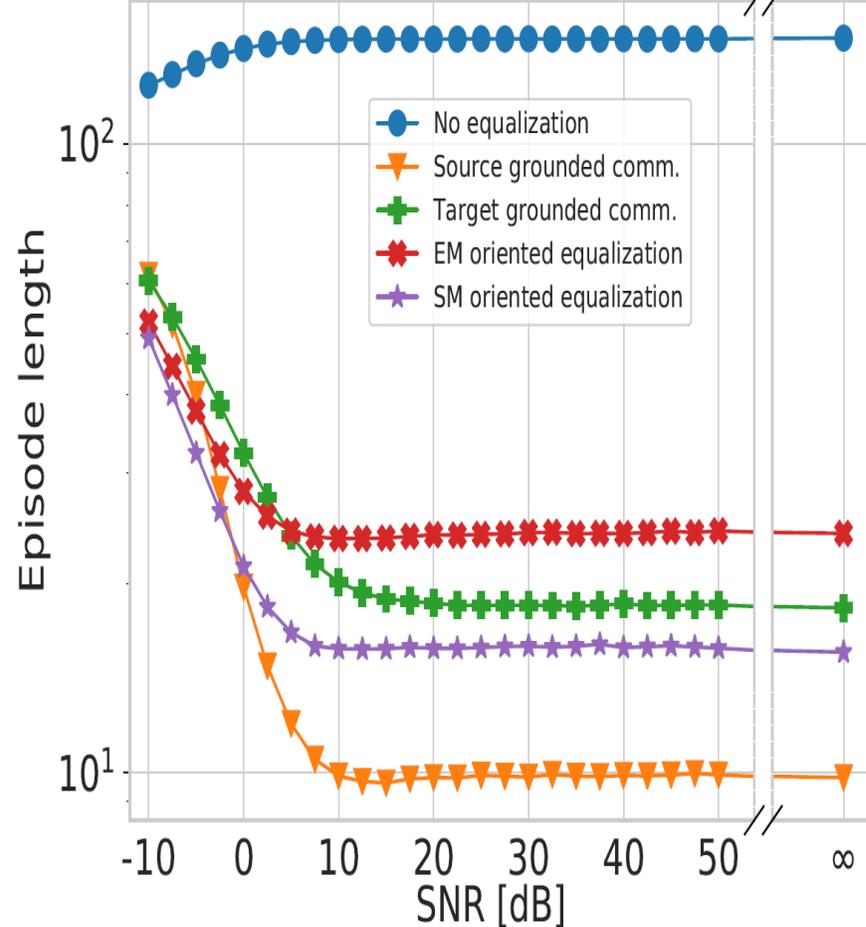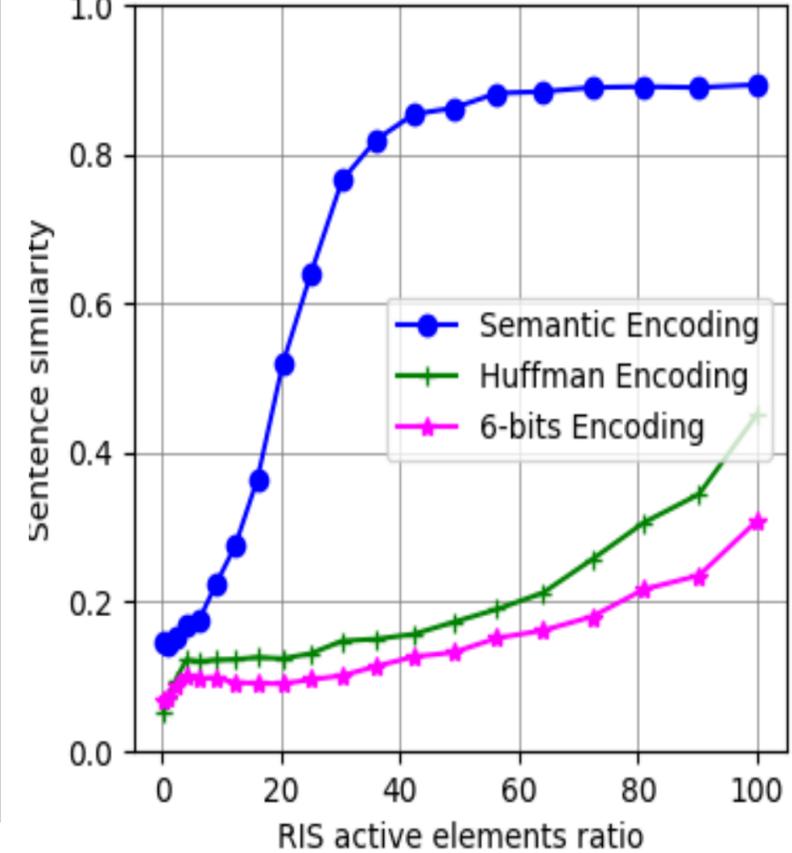
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N. Hello, M. Merluzzi, L. Sanguinetti, *E. Calvanese Strinati* , "Optimizing RIS Impairments through Semantic Communication", IEEE Globecom 2024.

6G-GOALS `HOW` PROOF OF CONCEPTS #1:
IN-LAB DEMOS FOR SEMANTIC-ORIENTED COMMUNICATION
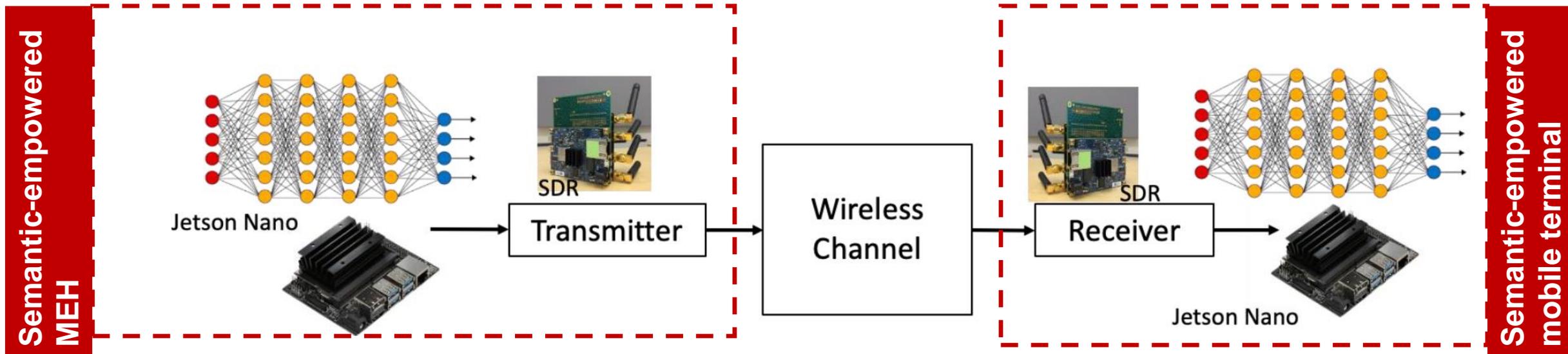
PoC implementation of the **delivery of large deep neural network** models over wireless links

- **Point-to-point scenario**:
  - the **transmitter** models the **edge server wherein the trained model is available**
  - the **receiver** (a **mobile terminal**): requests to download the model on-demand to carry out inference tasks locally within desired latency & energy budgets
- The In-LAb PoC will bring technology to a **TRL 4 maturity**

Goal: the recovered model can still serve its intended inference goal with high accuracy (robustness)

6G-GOALS HOW PROOF OF CONCEPTS #2: SEMANTIC & GOAL-ORIENTED ENABLED COLLABORATIVE ROBOTS
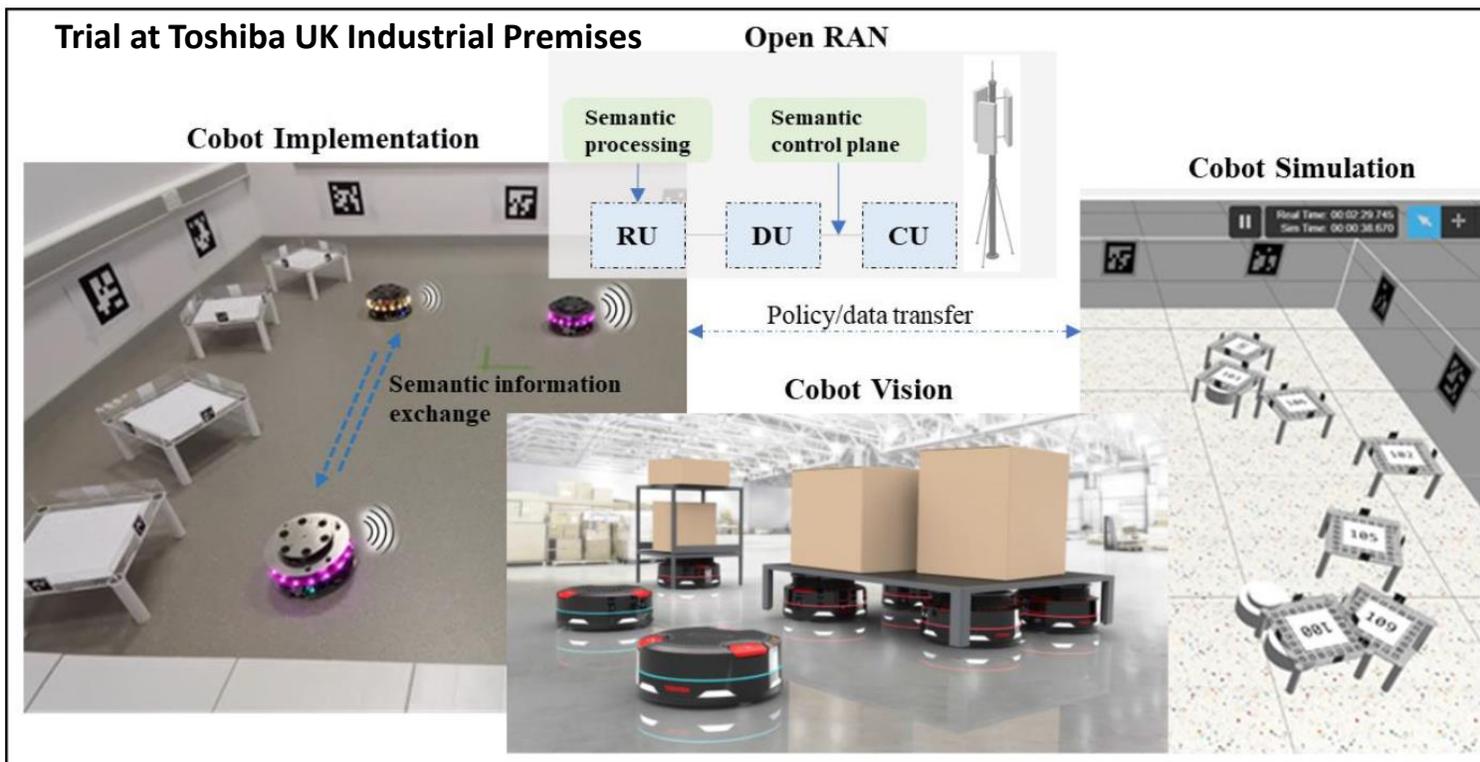
Goal: To develop E2E robot control techniques that **use semantic communication to exchange sensing data**, and allocate tasks with a Goal-Oriented approach

Target: to reduce communication overhead while improving energy efficiency

The demo trial will bring technology to a **TRL 5 maturity**

AI-Native Semantic Communication optimization over time

- Transmitter-receiver is like a couple experiencing a relationship

- Communication improves over time
  - Building an optimal language
  - Mutual learning and shared knowledge

Communication to ask for bread

First meeting

- Introduce each other
- Ask kindly with properly described request
- Thanks the other one

Content Blind ⟶ **AI-Native**
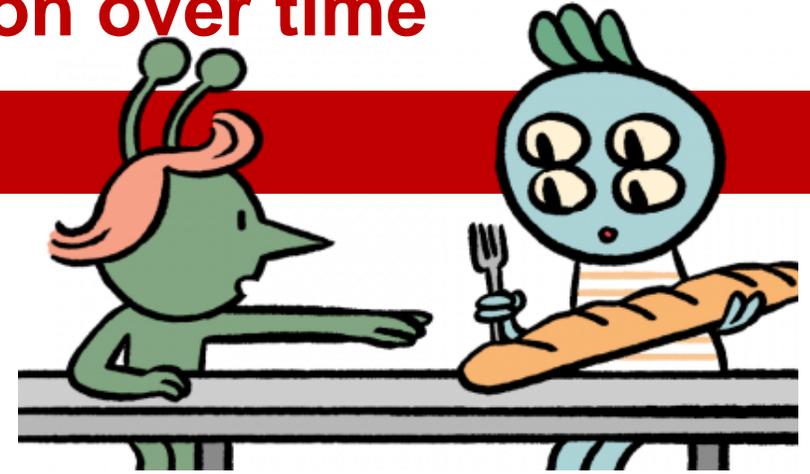
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Several months

- Know each other / brief introduction
- Ask with described request
- Brief thanks

Content Blind → **AI-Native**

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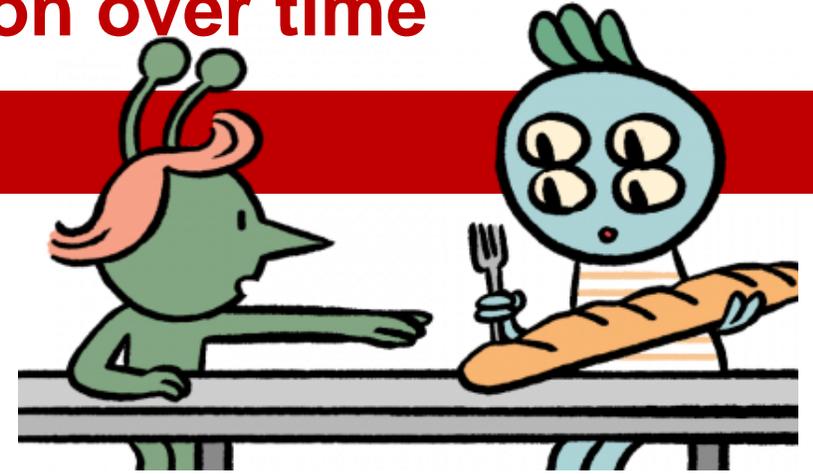- Introduce each other
- Ask kindly with properly described request
- Thanks the other one

Several months
- Know each other / brief introduction
- Ask with described request
- Brief thanks

Several years
- No introduction
- Expect the other one to do the action
- Ask with short request
- No thanks

Content Blind → **AI-Native**
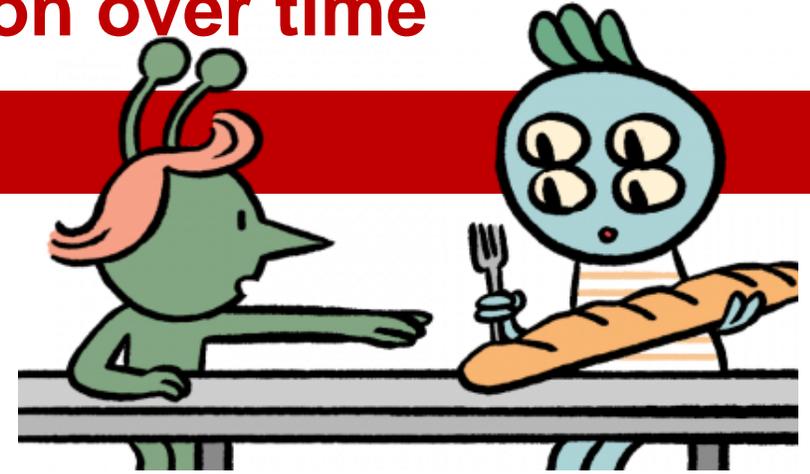
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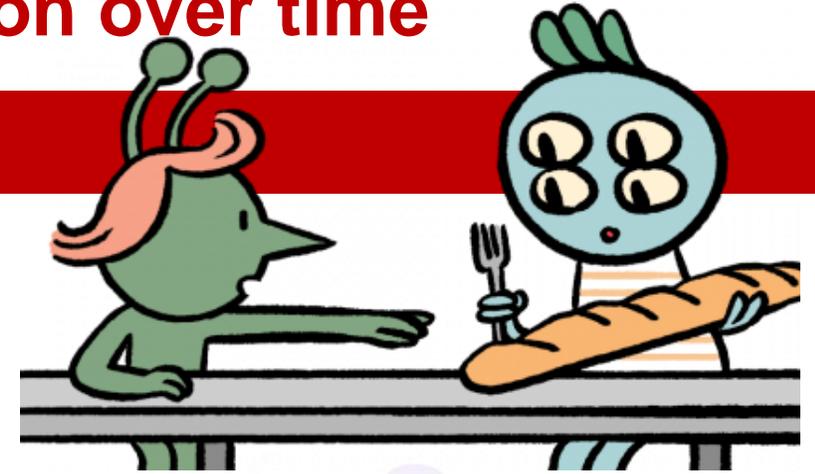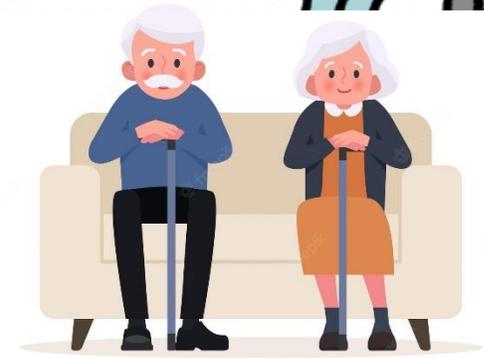- Ask with short request
- No thanks

A whole life
- Just able to hear the other one
- Ask with a quick eye contact
- No thanks
- Wait for the next eye contact

Content Blind → training the model INCREMENTALLY over time → **AI-Native**

Thank you! MERCI! 謝謝 고맙습니다 Grazie!

ALOHA

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†,

Comment

nature reviews electrical engineering
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

In contrast, 6G aims to create a deeply integrated, intelligent and immersive ecosystem. This ecosystem fuses the physical space, where real-world interactions and events occur, the cyber space, where digital interactions and activities take place, and the sapience space, where humans and AI can combine their cognitive capabilities to apply knowledge meaningfully. The integrated communication and sensing and advanced localization techniques of 6G will allow the incorporation and fusion of contextualized multimodal data, such as text, image and

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

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]

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Website:
www.6g-goals.eu

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