



ETSI AI Conference 2025

EMERGING AND TRANSFORMATIVE TRENDS IN AI/ML APPLICATIONS FOR 6G NETWORKS AND SERVICES: INSIGHTS FROM ACADEMIA

Presented by:

Future Wireless Systems Scientific
and Innovation Program Director, CEA-Leti
6G-GOALS, 6G-DISAC, 6G-ARROW Coordinator

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10/02/2025



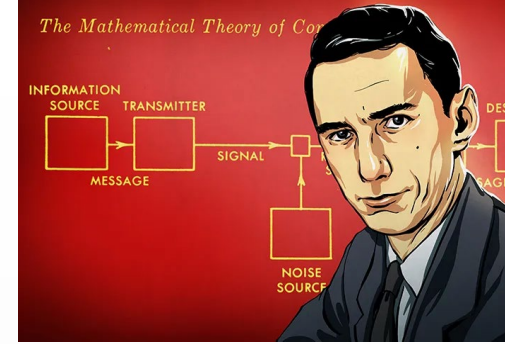
THE ROAD TO A GLOBAL “BRAIN”

*“When wireless
is perfectly applied,
the whole Earth
will be converted
into a huge brain”*

Nikola Tesla
1926

WHAT WE HAVE BEING TARGETING SINCE 2G

Shannon Channel Information Capacity



$$C = BW \times n \times \log_2 (1 + SNIR)$$

C Capacity (bits/seconds)

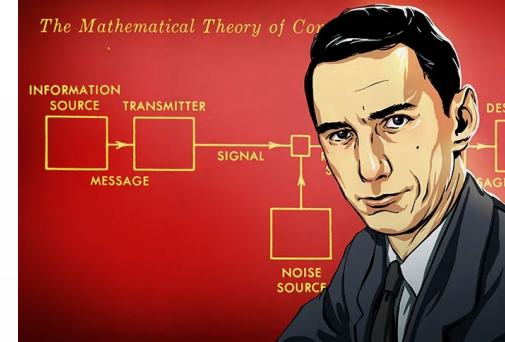
BW Radio channel Bandwidth (Hz)

n Number of uncorrelated signal paths

SNIR Signal to Noise + Interference Ratio

Note that this is the Shannon **capacity** for **single user AWGN channel** under **infinite code lengths** assumption. This formulation is not valid with other types of channels.

HOW 5G ACHIEVED THE X1000 FACTOR IMPROVEMENT



Shannon Channel Information Capacity

$$C = BW \times n \times \log_2(1 + SNIR)$$

x1000 **x10** **x10** **x10**

C = **BW** × **n** × **log₂ (1 + SNIR)**

Capacity (bits/seconds) **Radio channel Bandwidth (Hz)** **Number of uncorrelated signal paths** **Signal to Noise + Interference Ratio**

- Spectrum Management
- Carrier aggregation
- New mmW Spectrum
- (Ultra Massive) MIMO
- Network densification
- Small cells
- RIS

Spectral efficiency:

- Beamforming & high dBi antennas
- new modulations & coding schemes
- new waveforms, full-duplex
- RIS

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

GENERATIONS OF CONTENT BLIND COMMUNICATIONS



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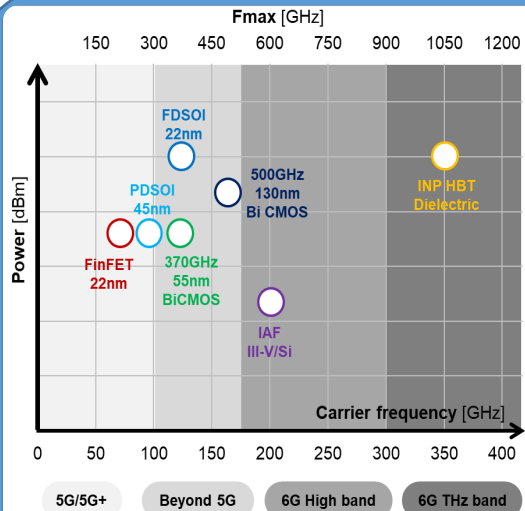
like pressing keys randomly!

TARGET: Data volume & (ultra) communication reliability



ULTRA-RELIABLE CONTENT BLIND 6G TECHNOLOGY PILLARS

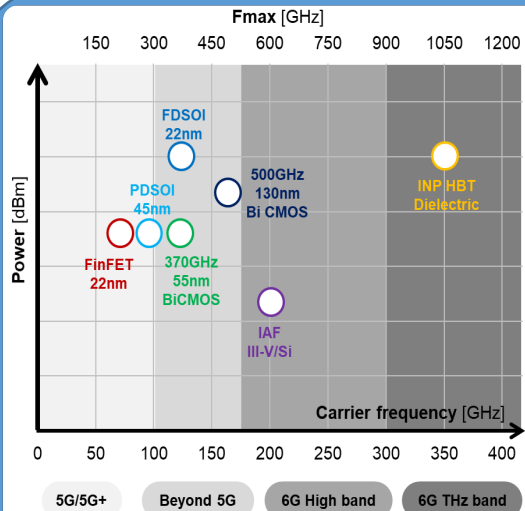
Sub-THz Communications



Calvanese Strinati, E., et al. "Toward 6G: From New Hardware Design to Wireless Semantic and Goal-Oriented Communication Paradigms". *ESSCIRC 2021*

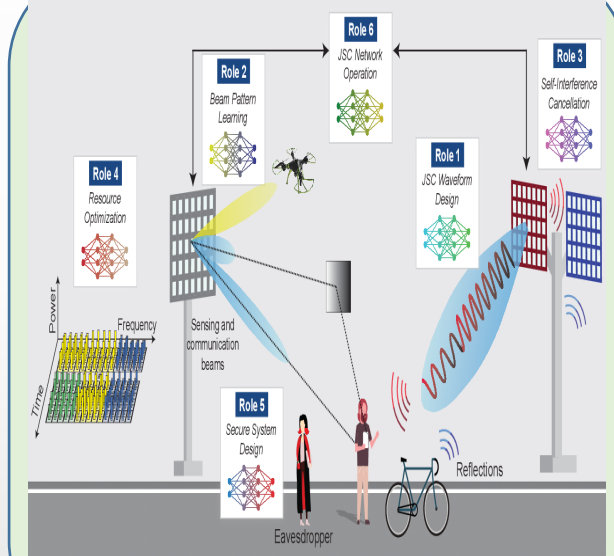
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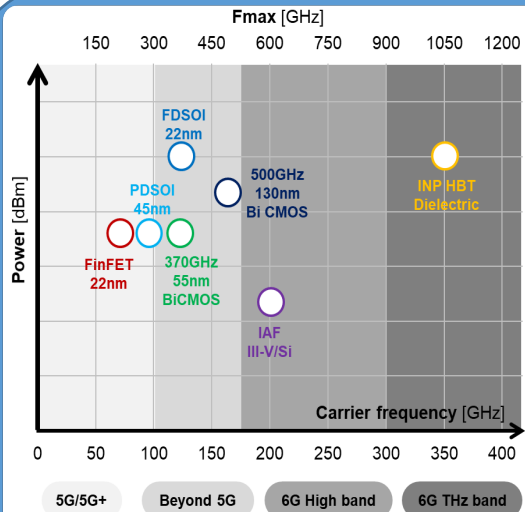
Integrated Communication & Sensing



Source: "Integrated Sensing and Communication for 6G: Ten Key Machine Learning Roles", Umut Demirhan and A. Alkhateeb, in *IEEE Communications Magazine*, 2022.

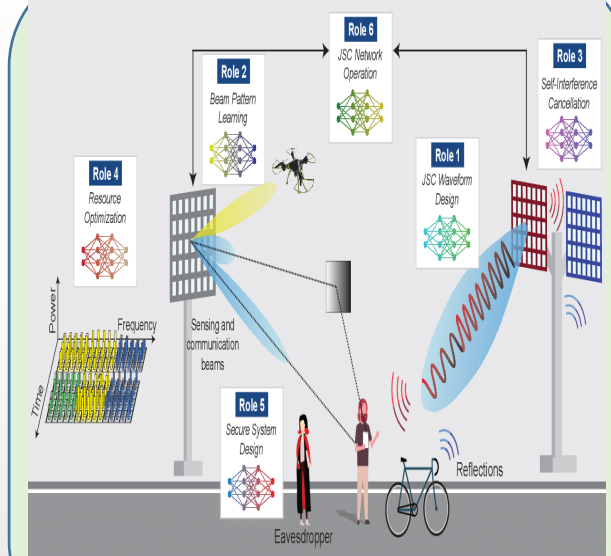
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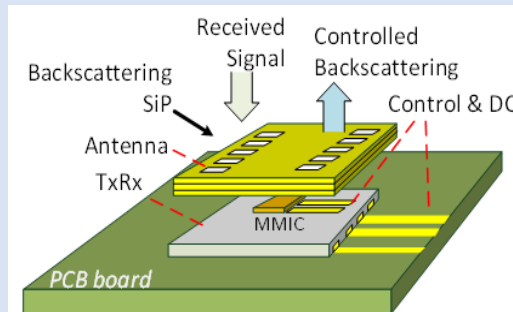
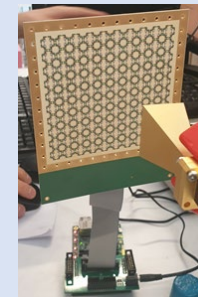
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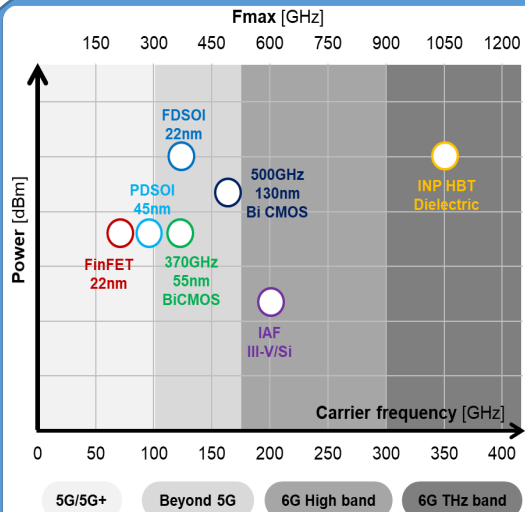
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New materials & Intelligent antennas



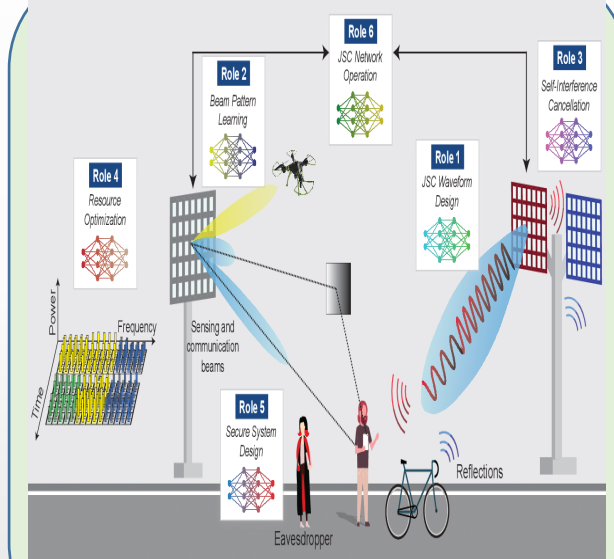
ULTRA-RELIABLE CONTENT BLIND 6G TECHNOLOGY PILLARS

Sub-THz Communications



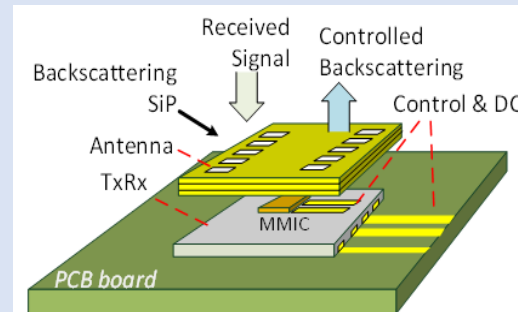
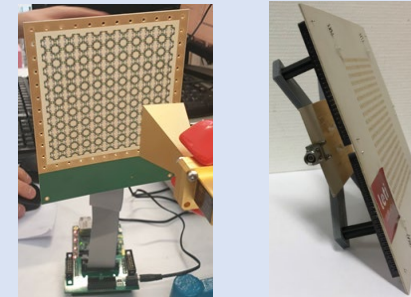
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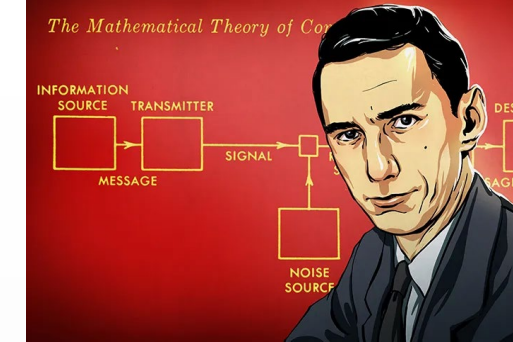
- ML/AI to optimize data processing & transmission
- network operation & orchestration

AI/ML technologies to design the next gen air interface & new compensation techniques for HW limitations

Edge AI/ML to offer processing and data fusion capability close to applications requirements

ML to optimize the use of RIS and enable on demand selective KPIs optimization (EE, secrecy, resources reuse factors, EMF ...)

WHY TO TARGET (AGAIN) THE X1000 FACTOR WITH THE AI-NATIVE 6G?



Shannon Channel Information Capacity

$$C = BW \times n \times \log_2(1 + SNIR)$$

x1000 **x10** **x10** **x10**

C = **BW** × **n** × **log₂(1 + SNIR)**

Capacity (bits/seconds) Radio channel Bandwidth (Hz) Number of uncorrelated signal paths Signal to Noise + Interference Ratio

6G technology should provide application grade **reliability**, **sustainability** & be **AI-Native**?

6G CAN DO IT DIFFERENTLY – 3 PARADIGM SHIFTS FOR 6G

#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



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#2 Wireless Communication Environment Shaping

From: Fight uncontrollable “dictated by nature” propagation environments

To: Engineer & Shape on-demand “favorable” wireless communication environments with **Reconfigurable Intelligent Surfaces**

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#3 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)



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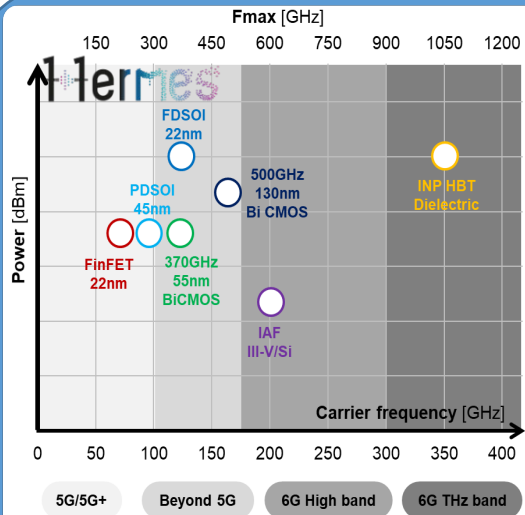


From: Moving content-blind raw data

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

AI-NATIVE SEMANTIC AWARE 6G TECHNOLOGY PILLARS

Sub-THz Semantic Communications



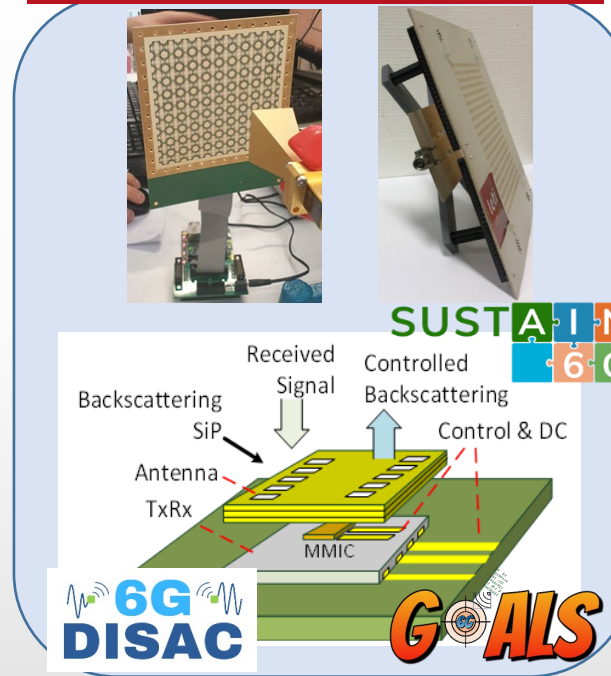
Calvanese Strinati, E., et al. "Toward 6G: From New Hardware Design to Wireless Semantic and Goal-Oriented Communication Paradigms". *ESSCIRC 2021*

Integrated Semantic Communication & Sensing



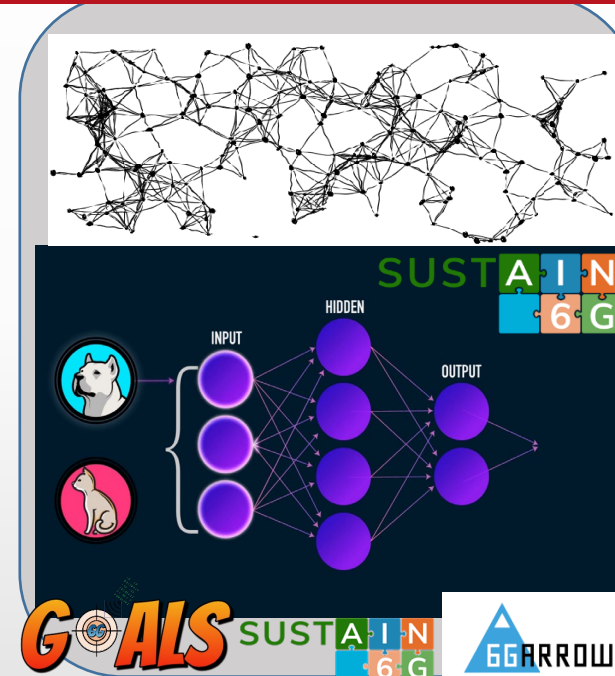
Source: Calvanese Strinati, E, et al. "Towards Distributed and Intelligent Integrated Sensing and Communications for 6G Networks. *arXiv preprint arXiv:2402.11630* <https://arxiv.org/abs/2402.11630>. 18 Feb 2024.

Semantic Intelligent antennas



ML to optimize the **joint semantic and wireless** channels on demand selective KPIs optimization

(Edge) Generative AI & Semantic AI Intertwining



Edge AI/ML processing & reasoning close to data **Semantic Comms** to **compress** and **train** while communicating

AI/ML technologies to design the next gen air interface & new **semantic compensation** techniques for HW limitations tolerance

Edge AI/ML to offer processing and data **semantic fusion** capability close to applications requirements

WHAT IF ... I CAN READ IT ... CAN YOU?

fi yuo cna raed tihs, yuo hvae a sgtrane mnid too. Cna yuo raed tihs? Olly smoe plepoe can. i cdnuolt blveiee taht I cluod aulacly 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!

WHAT IF ... I CAN READ IT ... CAN YOU?

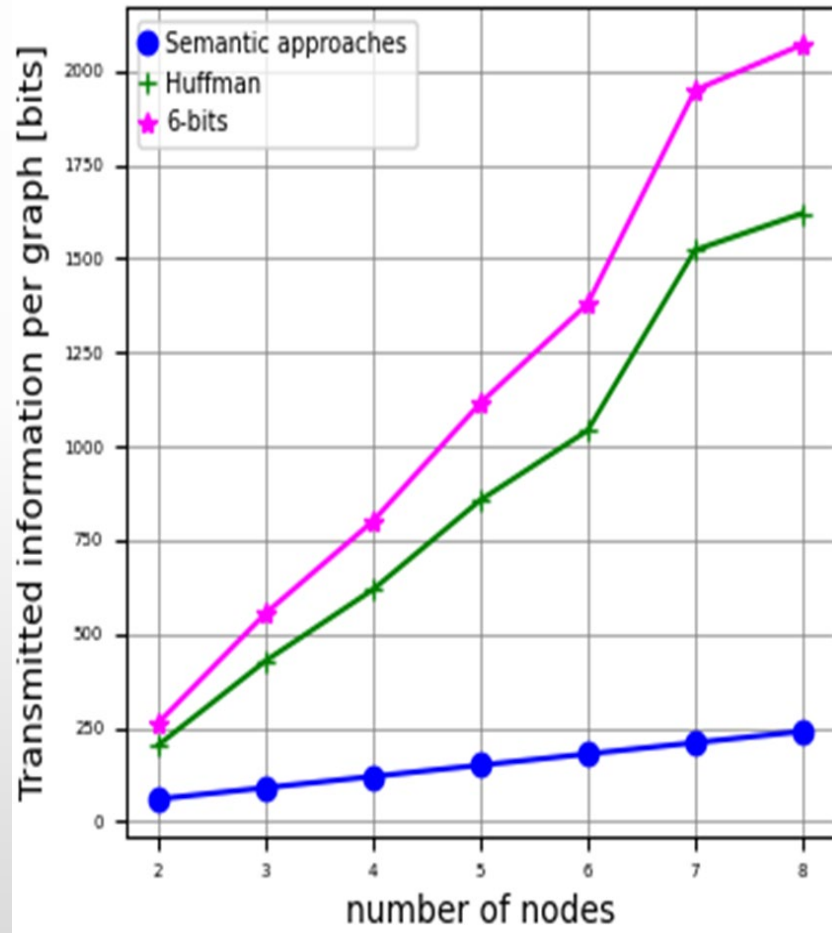
fi yuo cna raed tihs, yuo hvae a sgtrane mnid too. Cna yuo raed tihs? Olny smoe plepoe can. i cdnuolt blveiee taht I cluod aulacly uesdnatnrd waht I was rdanieg. The phaonmneal pweor of the hmuan mnid, aoccdrnig to a rscheearch at Cmabrigde Uinervtisy, it dseno't mtaetr in waht oerdr the ltteres in a 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!

When the order of words or characters changes, your brain still correctly interpret sentences.

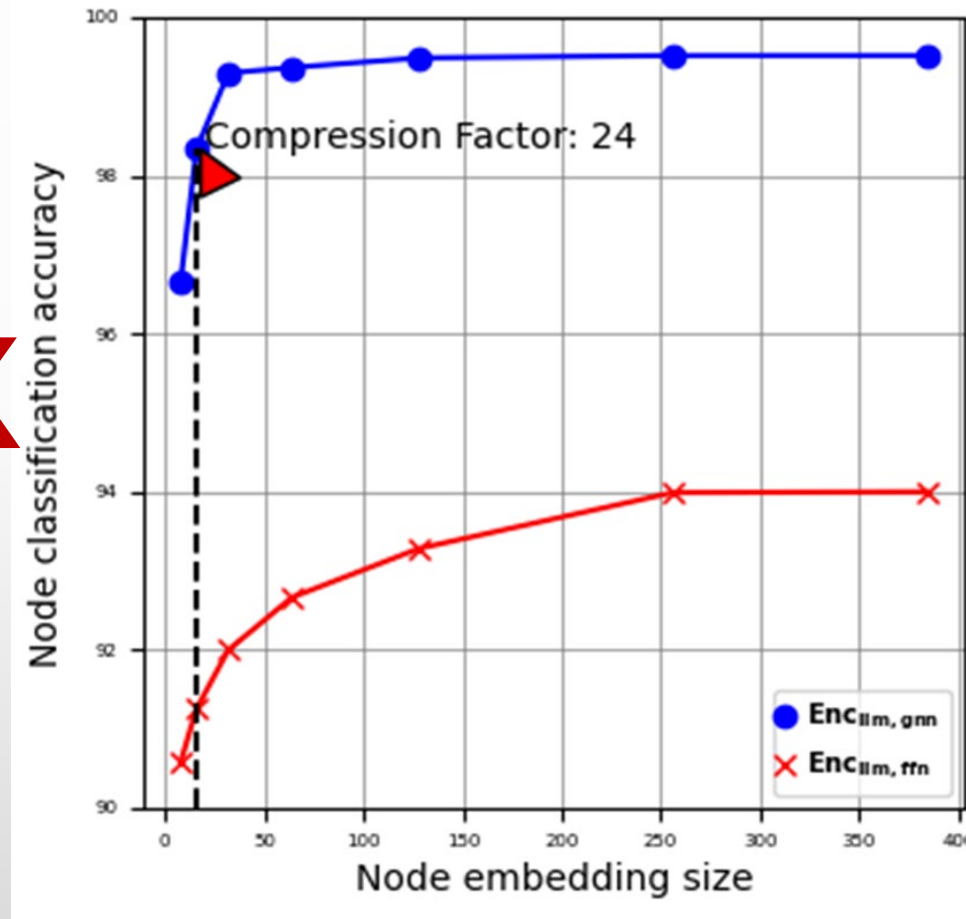
AI Semantic understanding of context and goals enable self-correction of inaccuracies & incompleteness in data and focus on meaningful informative information

SEMANTIC COMMUNICATIONS GAINS: EXPERIMENTAL RESULTS

Factor 190+ in
data compression



X



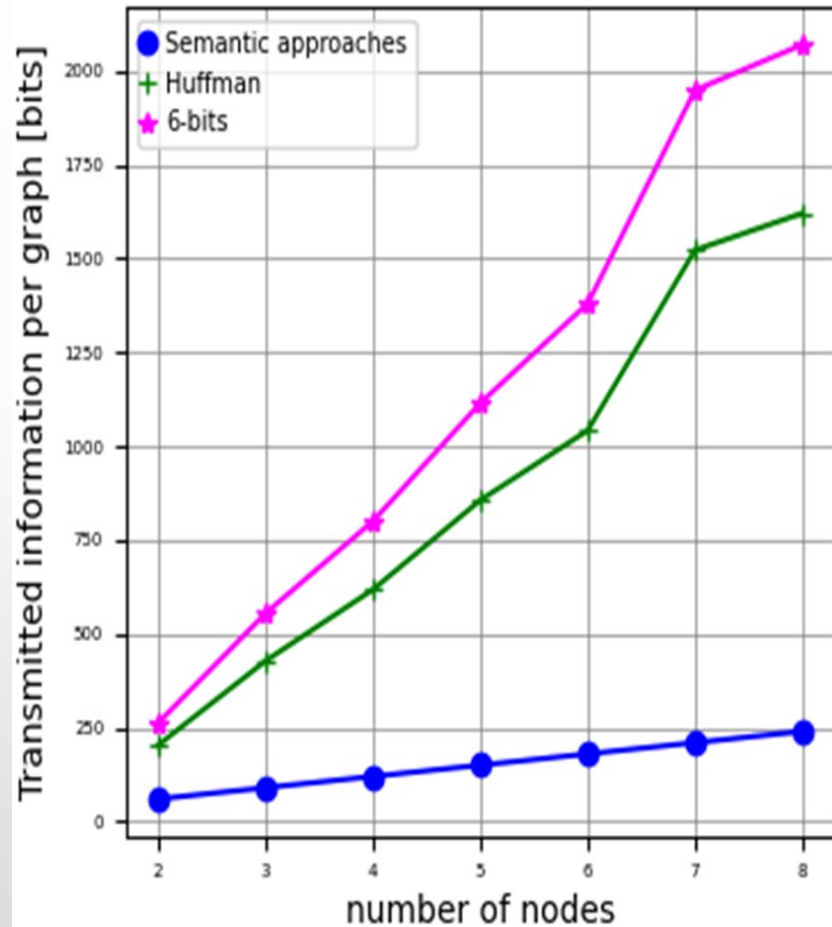
=

Factor 190+ in
data compression

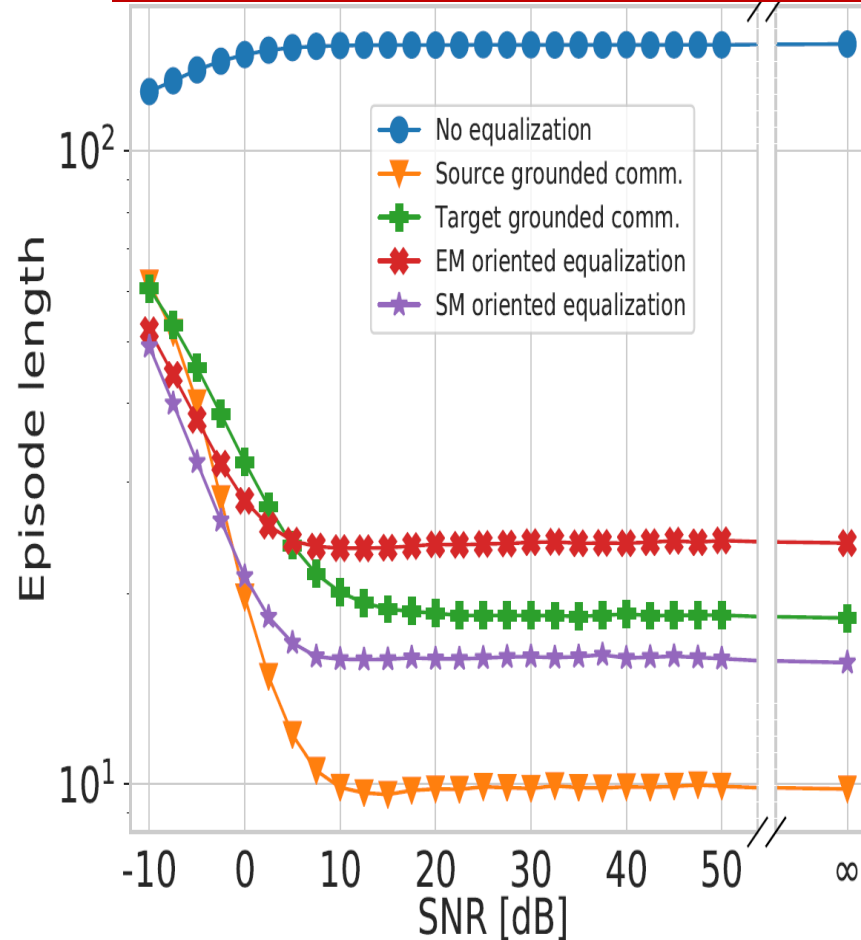
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SEMANTIC COMMUNICATIONS GAINS: EXPERIMENTAL RESULTS

Factor 190+ in
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Factor 23 in
AI training time reduction

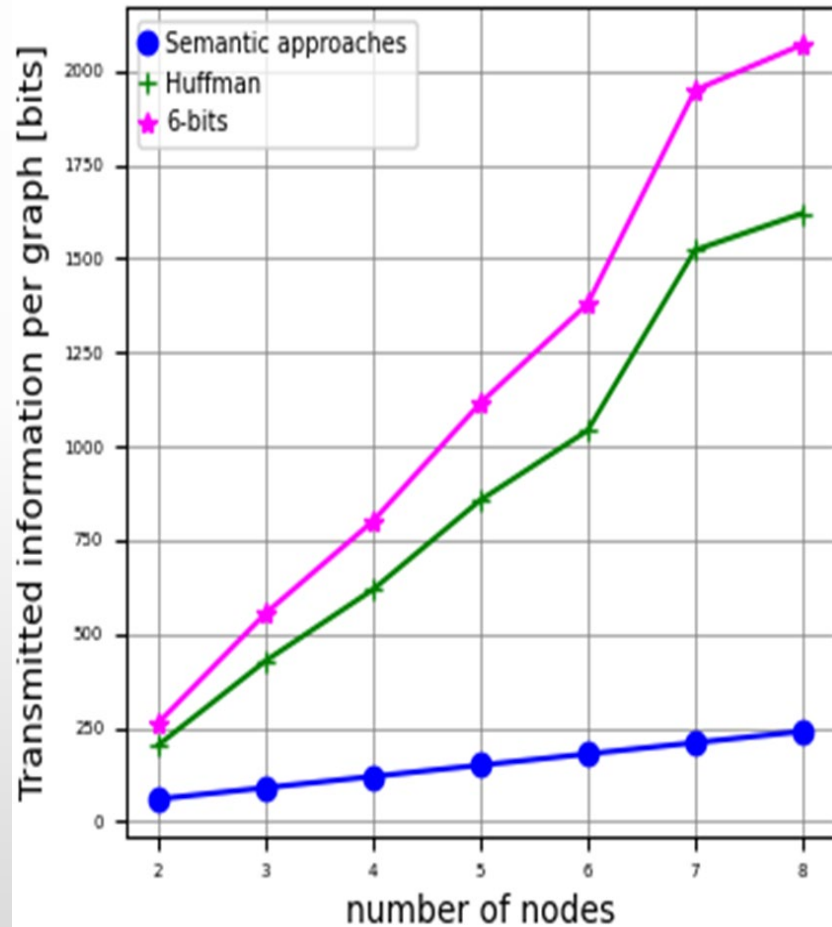


N Hello, P Di Lorenzo, E. Calvanese Strinati, "Semantic Communication Enhanced by Knowledge Graph Representation Learning", IEEE SPAWC, 2024.

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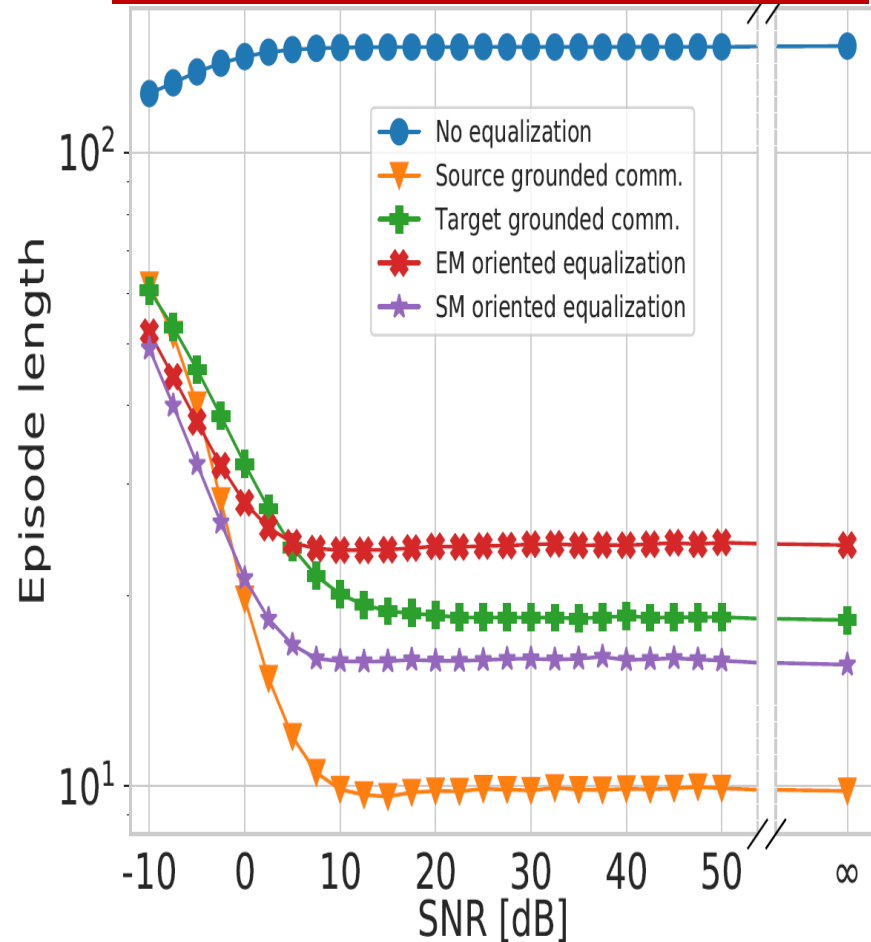
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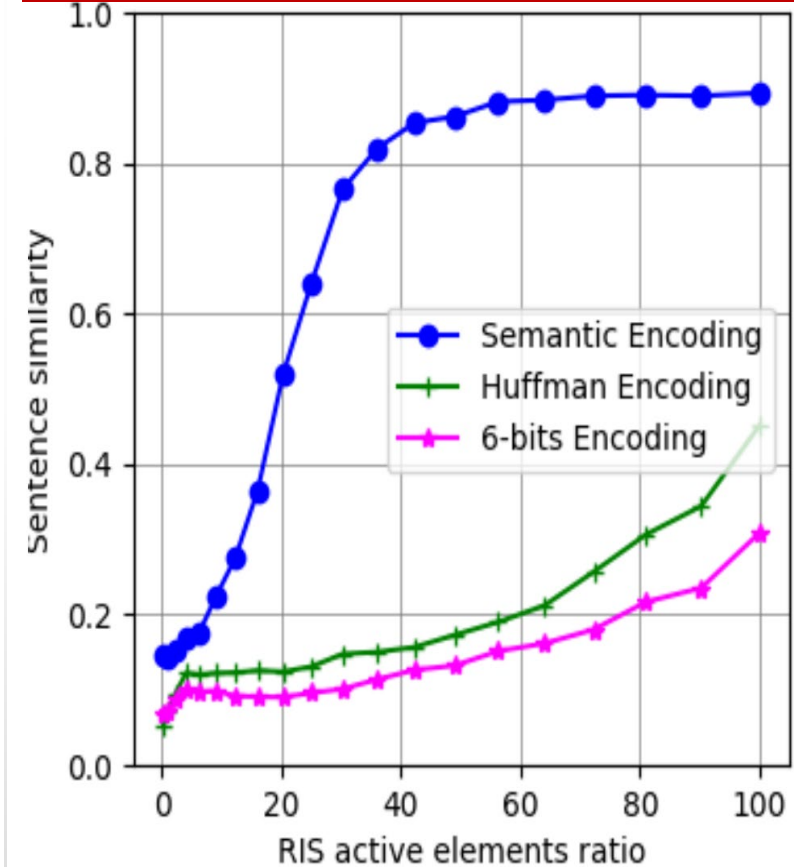
N Hello, P Di Lorenzo, E. Calvanese Strinati, "Semantic Communication Enhanced by Knowledge Graph Representation Learning", IEEE SPAWC, 2024.

Factor 23 in
AI training time reduction



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

Factor 6+ in
reduction of RIS active elements



(a) One bit phase quantization

N. Hello, M. Merluzzi, L. Sanguinetti, E. Calvanese Strinati, "Optimizing RIS Impairments through Semantic Communication", IEEE Globecom 2024.

AI-NATIVE SEMANTIC COMMUNICATION OPTIMIZATION OVER TIME

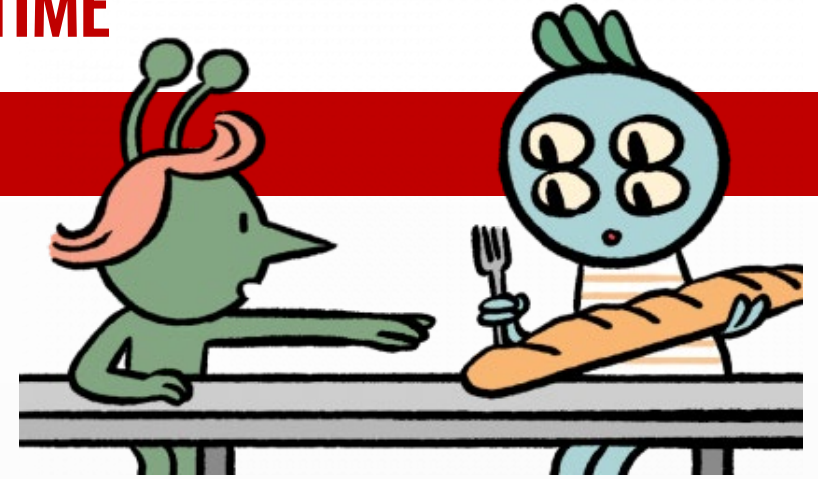
- ▶ Transmitter-receiver is like a couple experiencing a relationship
- ▶ Communication improves over time
 - ▶ Building an optimal language
 - ▶ Mutual learning and shared knowledge



First meeting

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

Communication to ask for bread



Content Blind

AI-Native

AI-NATIVE SEMANTIC COMMUNICATION OPTIMIZATION OVER TIME

- Transmitter-receiver is like a couple experiencing a relationship
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First meeting

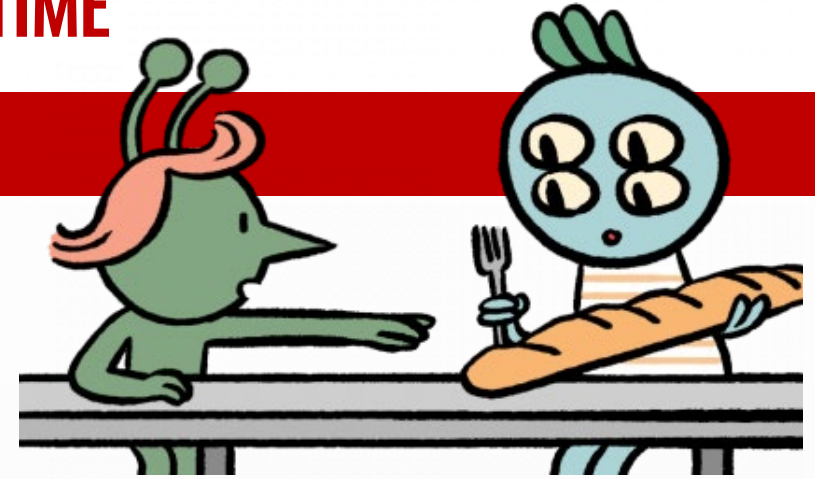
- Introduce each other
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Several months

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

Communication to ask for bread



Content Blind

AI-Native

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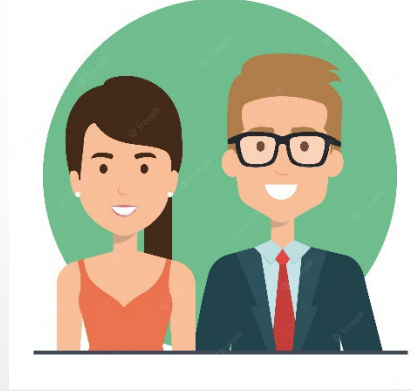
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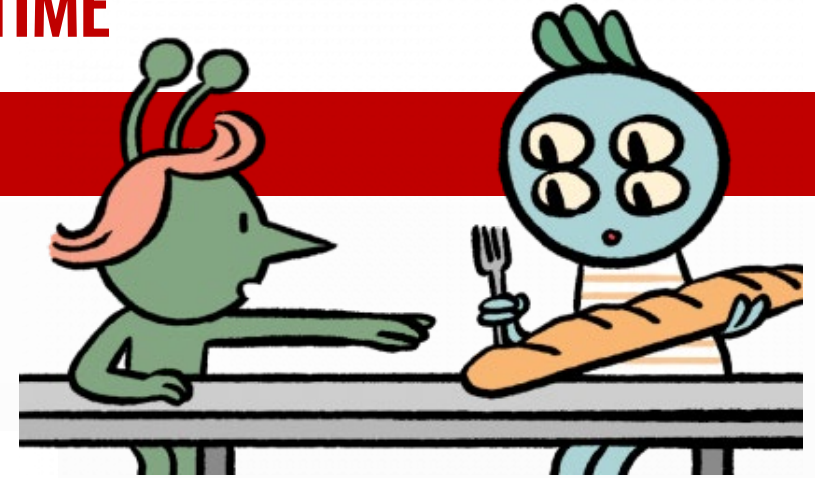
- ▶ Know each other / brief introduction
- ▶ Ask with described request
- ▶ Brief thanks



Several years

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

Communication to ask for bread



Content Blind

AI-Native

AI-NATIVE SEMANTIC COMMUNICATION OPTIMIZATION OVER TIME

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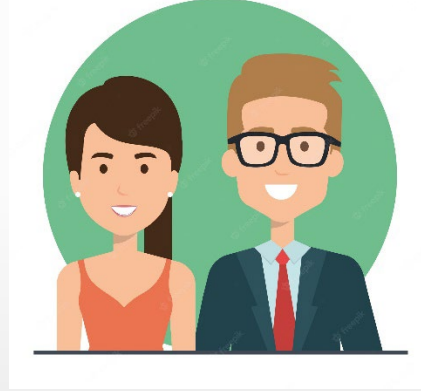
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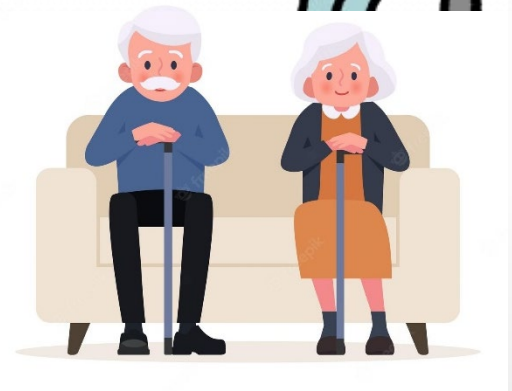
Several months

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



Several years

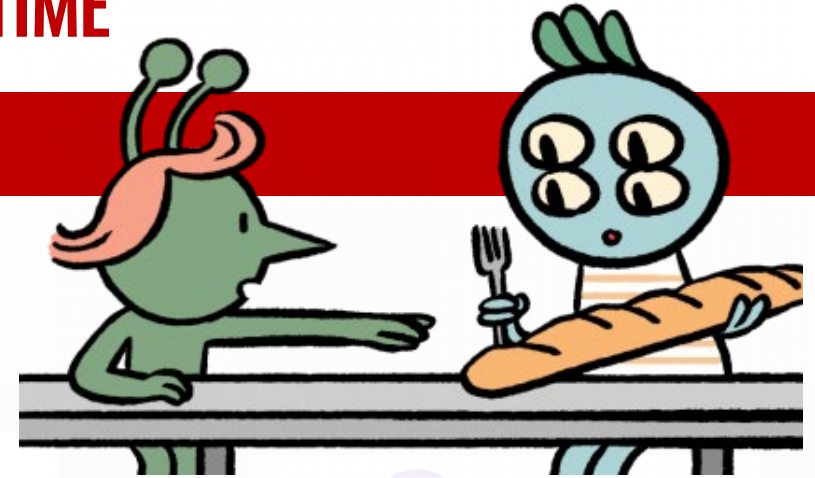
- ▶ No introduction
- ▶ Expect the other one to do the action
- ▶ Ask with short request
- ▶ No thanks



A whole life

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

Communication to ask for bread



Content Blind

AI-Native



Thank you!

MERCI!

謝謝

ALOHA

Grazie!



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Computer Networks

journal homepage: www.elsevier.com/locate/comnet



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 achievement, moving towards artificial general

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 video, which can then be semantically analyzed³. In addition, semantic

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

Emilio Calvanese Strinati^{a,*}, Sergio Barbarossa^b

^a CEA Leti, 17 rue des Martyres, 38000 Grenoble, France

^b Dent. of Information Eng., Electronics, and Telecomm., Sapienza Univ. of Rome, Via Eudossiana 18, 00184, Rome, Italy

ACCEPTED FROM OPEN CALL

Reconfigurable, Intelligent, and Sustainable Wireless Environments for 6G Smart Connectivity

Emilio Calvanese Strinati, George C. Alexandropoulos, Henk Wymeersch, Benoît Denis, Vincenzo Sciancalepore, Raffaele D'Errico, Antonio Clemente, Dinh-Thuy Phan-Huy, Elisabeth De Carvalho, and Petar Popovski

ABSTRACT

Various visions of the forthcoming sixth generation (6G) networks point toward flexible connect-and-compute technologies to support future innovative services and the corresponding use cases. 6G should be able to accommodate ever evolving and heterogeneous applications, future regulations, and diverse user-service- and loca-

es stemming from respective trends. A number of key performance indicators (KPIs) have been discussed recently [1], including up to 10 Gb/s/m³ capacity, 100 ms latency, 1 Tb/J energy efficiency, and 1 cm localization accuracy in 3 dimensions (3D). Depending on future application and service needs, these KPIs will not all have to be achieved simultaneously and on all occasions, but rather locally in space and time

Various visions of the forthcoming sixth generation (6G) networks point toward flexible connect-and-compute technologies to support future innovative services and the corresponding use cases of should be able to

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[†],

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 Merluzzi¹, Miltiadis C. Filippou², Leonardo Gomes Baltar², Emilio Calvanese Strinati¹