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Electrical Engineering
Artificial Intelligence Day
November 19, 2020
9:00 am - 5:30 pm • Online

6G Networks:
Beyond Shannon Towards Semantic and Goal-Oriented Communications

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THE ROAD TO A GLOBAL "BRAIN"

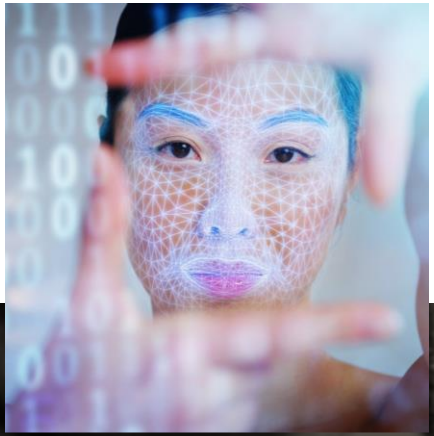
"When wireless
is perfectly applied,
the whole Earth
will be converted
into a huge brain"

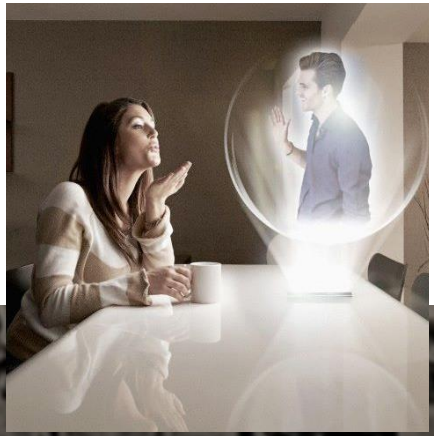
Nikola Tesla
1926

THE ROAD TO A GLOBAL “BRAIN”

By 2030, responding to fundamental **human and social needs** and based on the **expected progress in ICT,**

Tesla’s prophecy may become a reality!





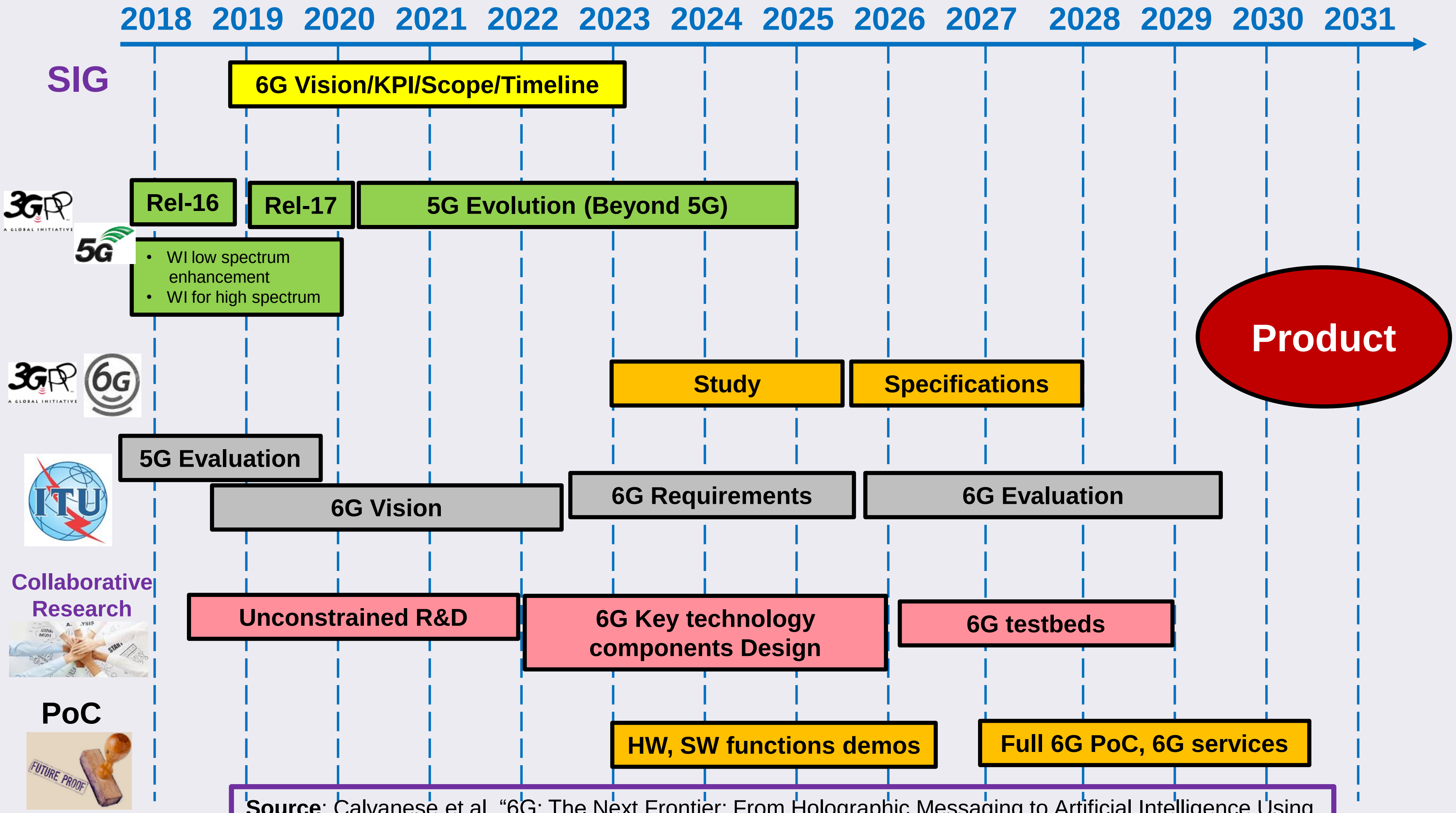
NEW SERVICES DRIVING THE BEYOND 5G EVOLUTION

5 SENSES INTERACTIVE HOLOGRAM TECHNOLOGY

INTERACTIVE HAPTIC COMMUNICATIONS

- **Low Latency** (µs-ms)
- **Self-designing Joint C4**: Communication + Computing + Caching + Control
- **Ultra-high capacity** (1-10 s Tbps)
- **Deterministic** (~~stochastic~~) **network optimization**

ROADMATO TOWARD 6G



Source: Calvanese et al.,"6G: The Next Frontier: From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication", IEEE Vehicular Magazine September 2019.

COMPARISON OF MAIN 5G & 6G KPIS

› How can we achieve them?

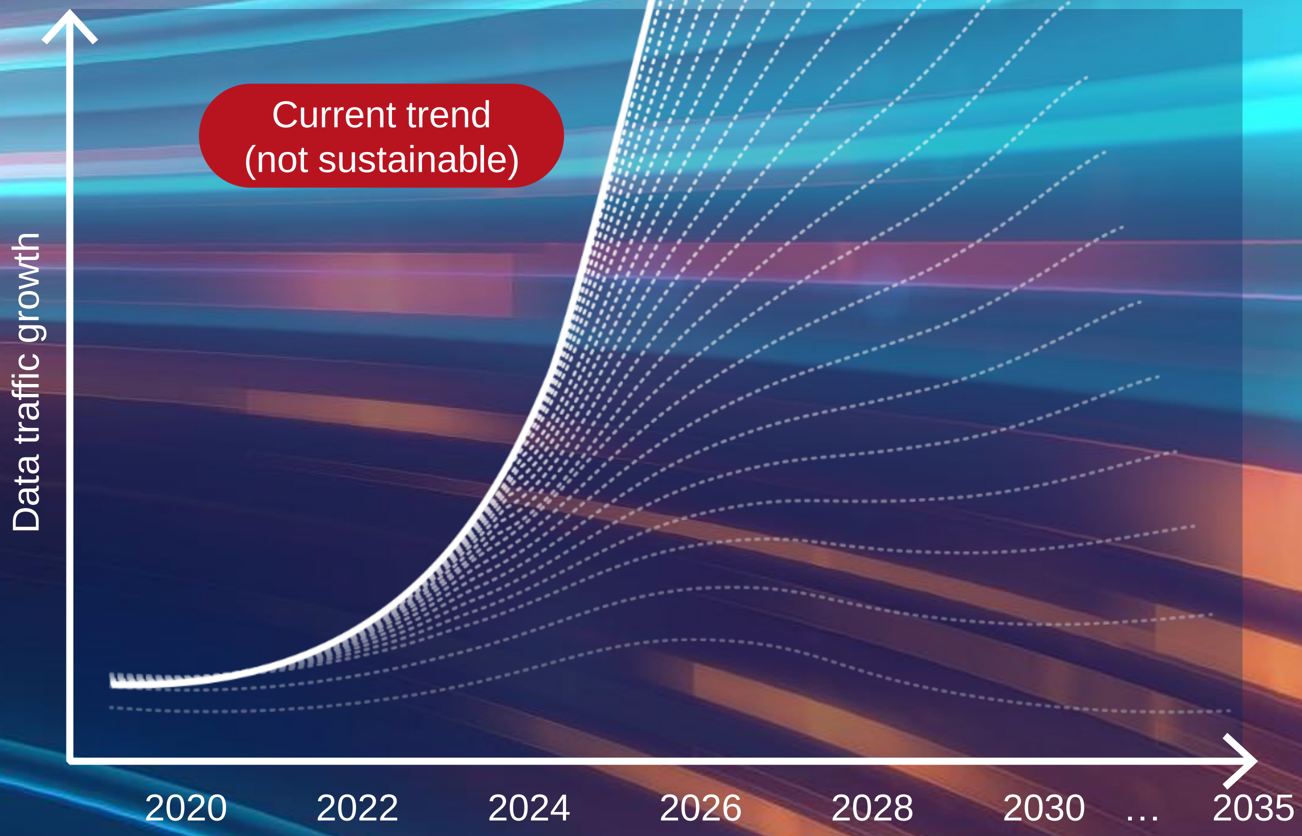
KPI	5G	6G
Traffic Capacity	10 Mbps/m^2	~ 1-10 Gbps/m^3
Data rate DL	20 Gbps	1 Tbps
Data rate UL	10 Gbps	1 Tbps
Uniform user experience	50 Mbps 2D everywhere	10 Gbps 3D everywhere
Latency (radio interface)	Up tp 1 msec	Up to 0.1 ms
Jitter	NS	1 µsec
Communication Reliability	Up to 10^{-5}	Up to 10^{-9}
Energy/bit	NS	pJ/bit
Localization precision	10 cm on 2D	1 cm on 3D

Source: Calvanese et al.,"6G: The Next Frontier: From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication", IEEE Vehicular Magazine September 2019.

EXPONENTIAL GROWTHS REQUIRES NEW ENERGY SOLUTIONS

Data will consume 20% of world’s energy

- 9 Billion of connected people on Earth
- 1 Trillion of connected devices
- Wireless communications and AI assistance will be a commodity
- The Cyber and Physical space fusion turn humans, things and events into information



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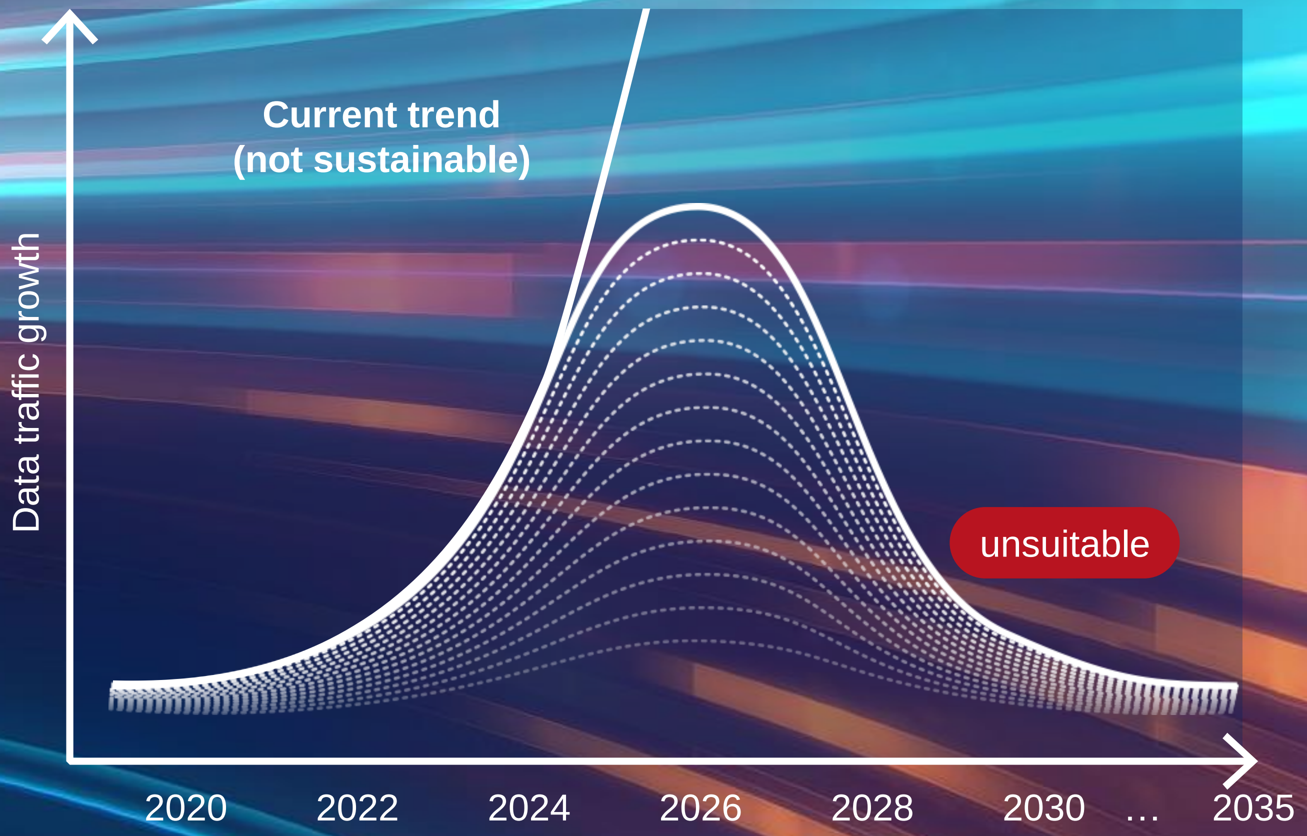

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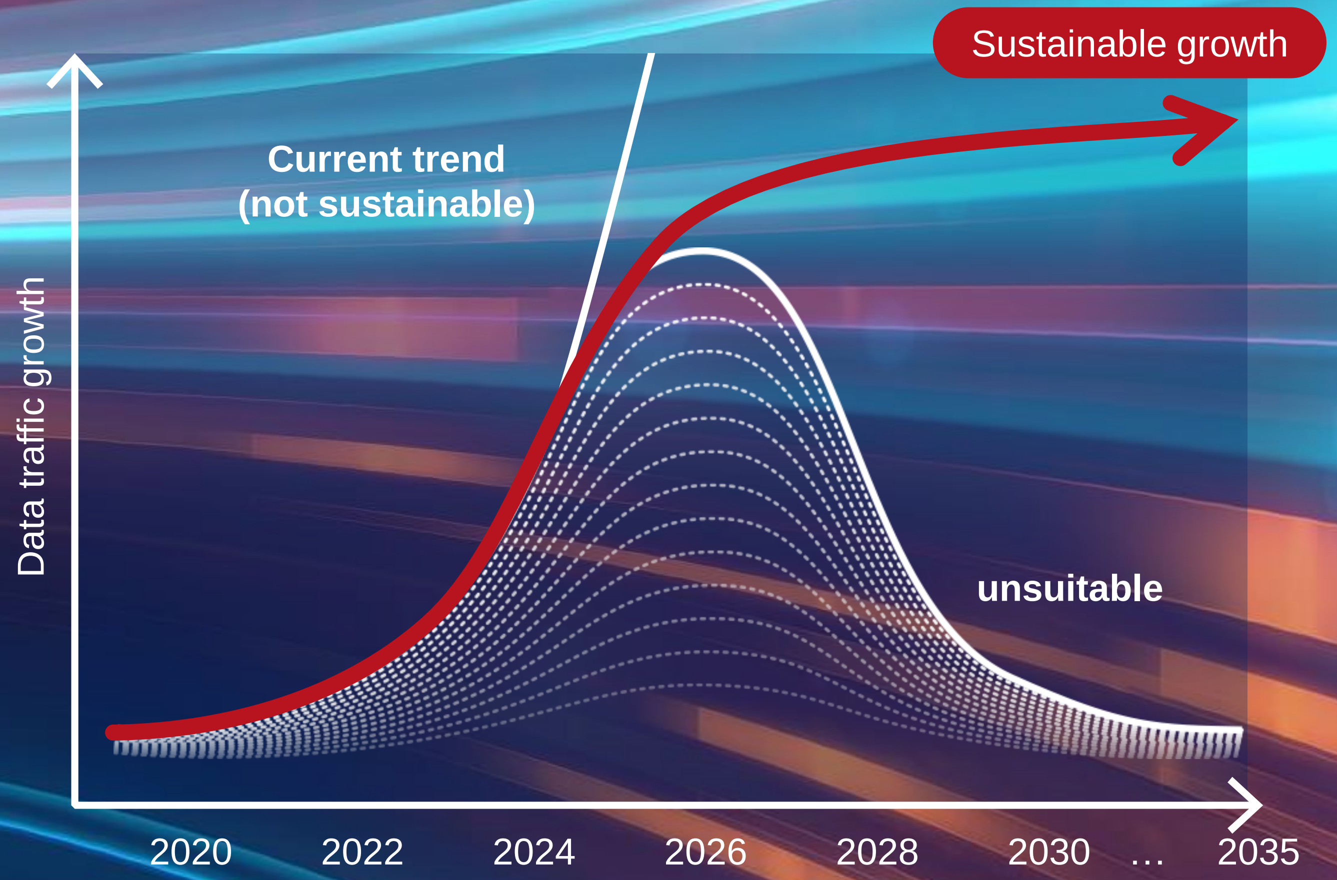
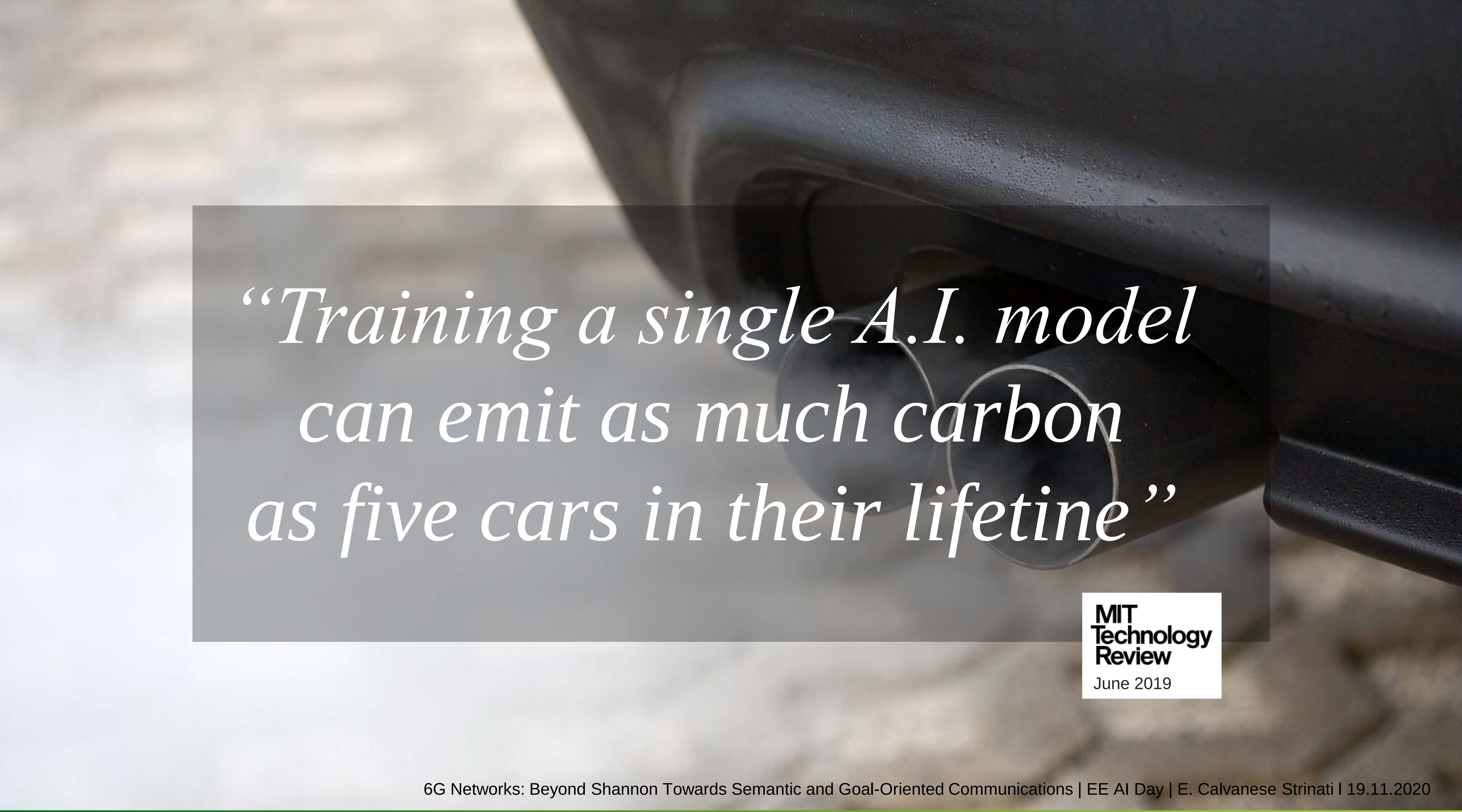
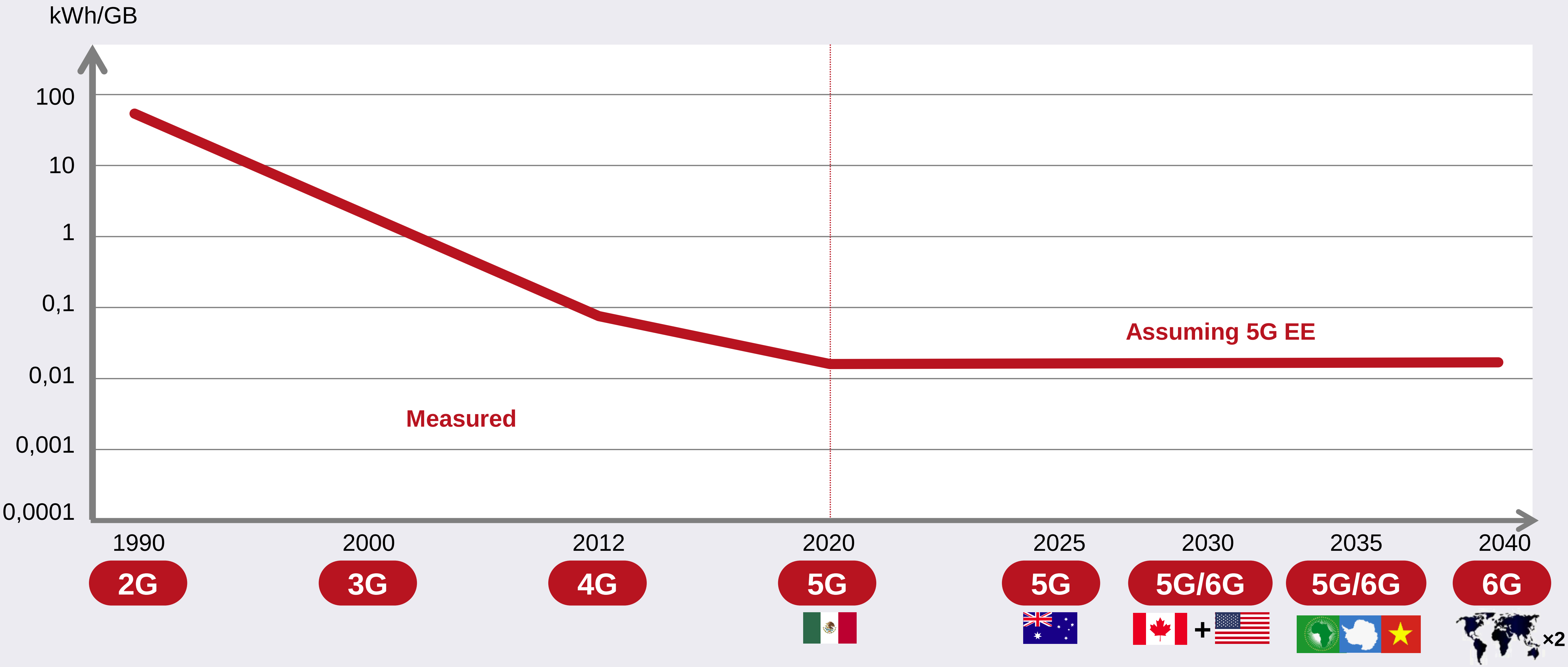



"Training a single A.I. model
can emit as much carbon
as five cars in their lifetine"
MIT
Technology
Review
June 2019

WIRELESS NETWORKS' ENERGY CONSUMPTION



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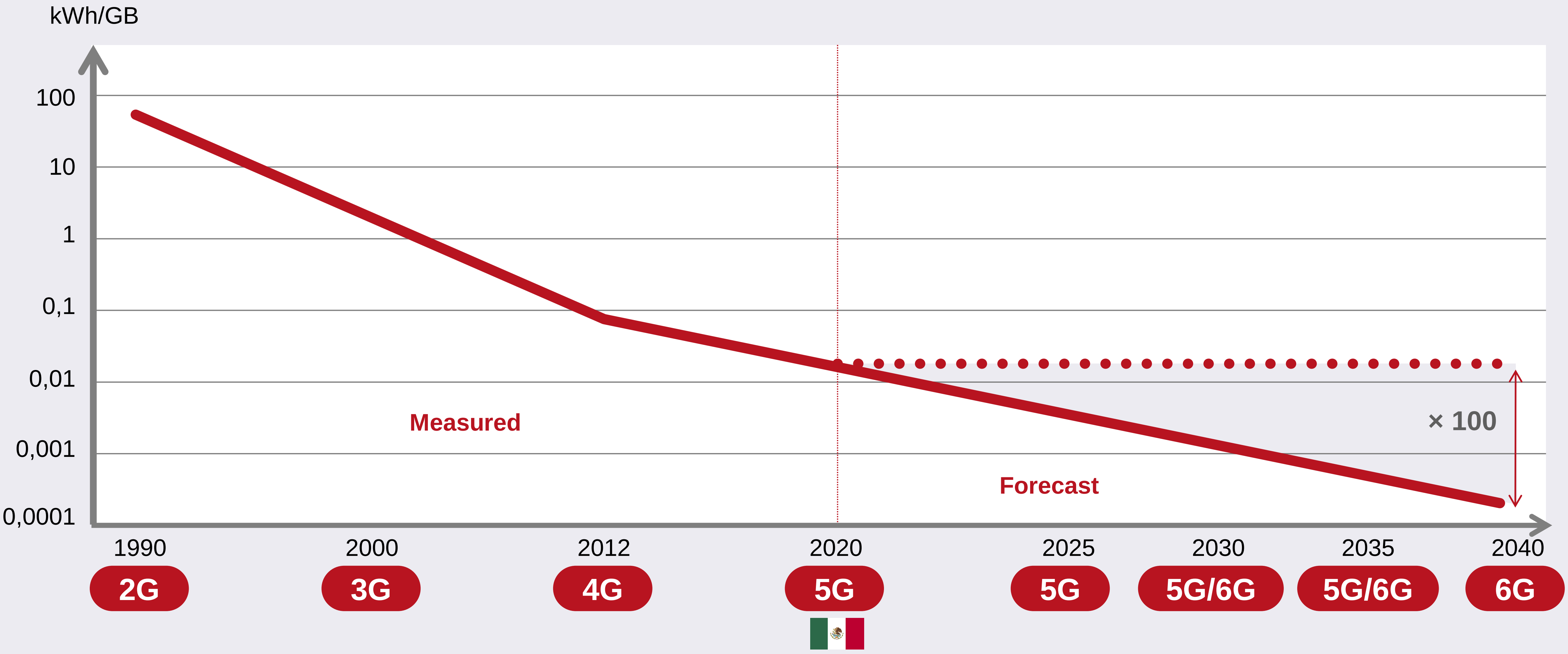

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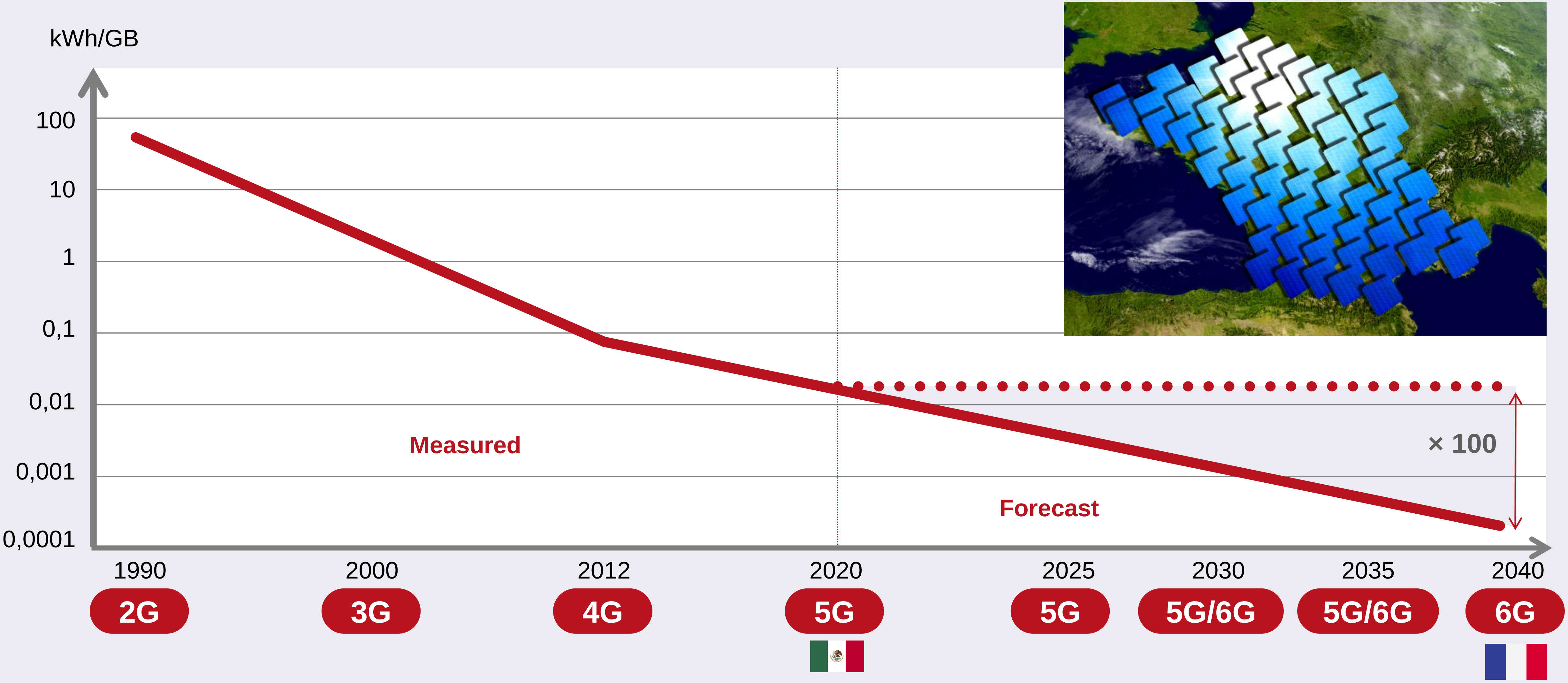
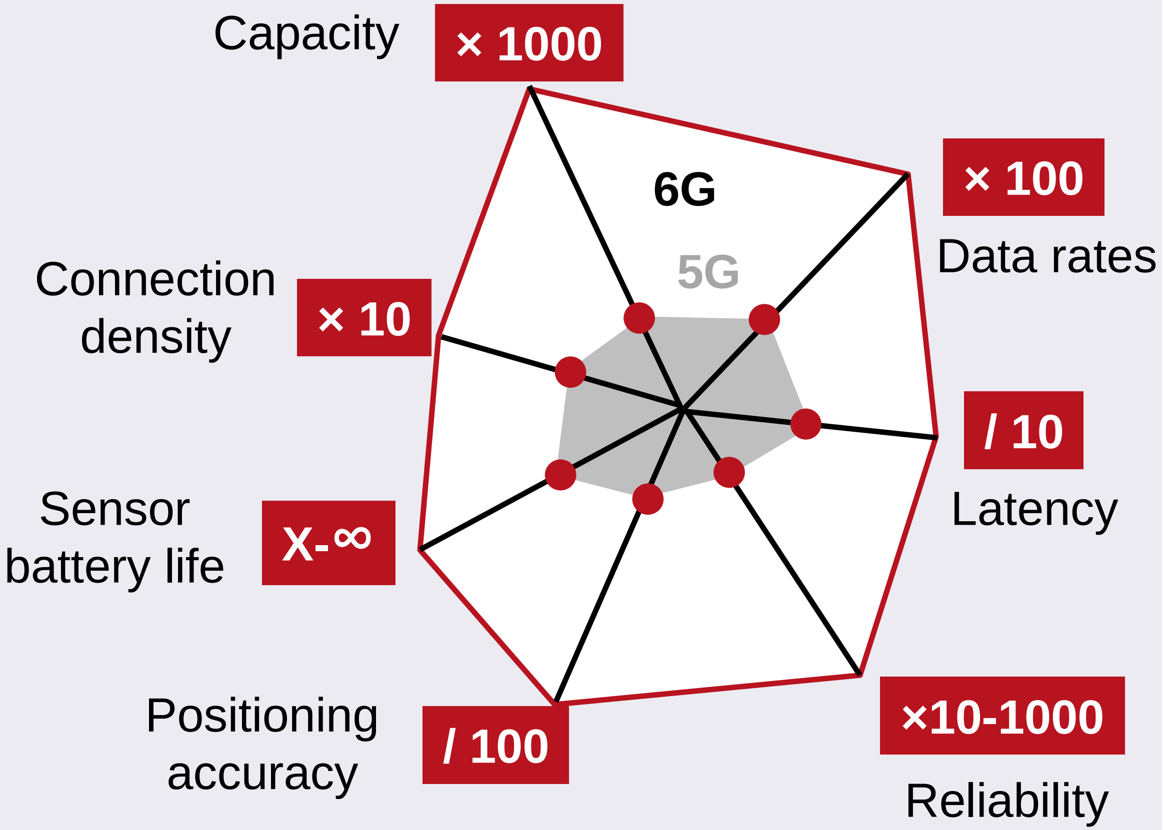
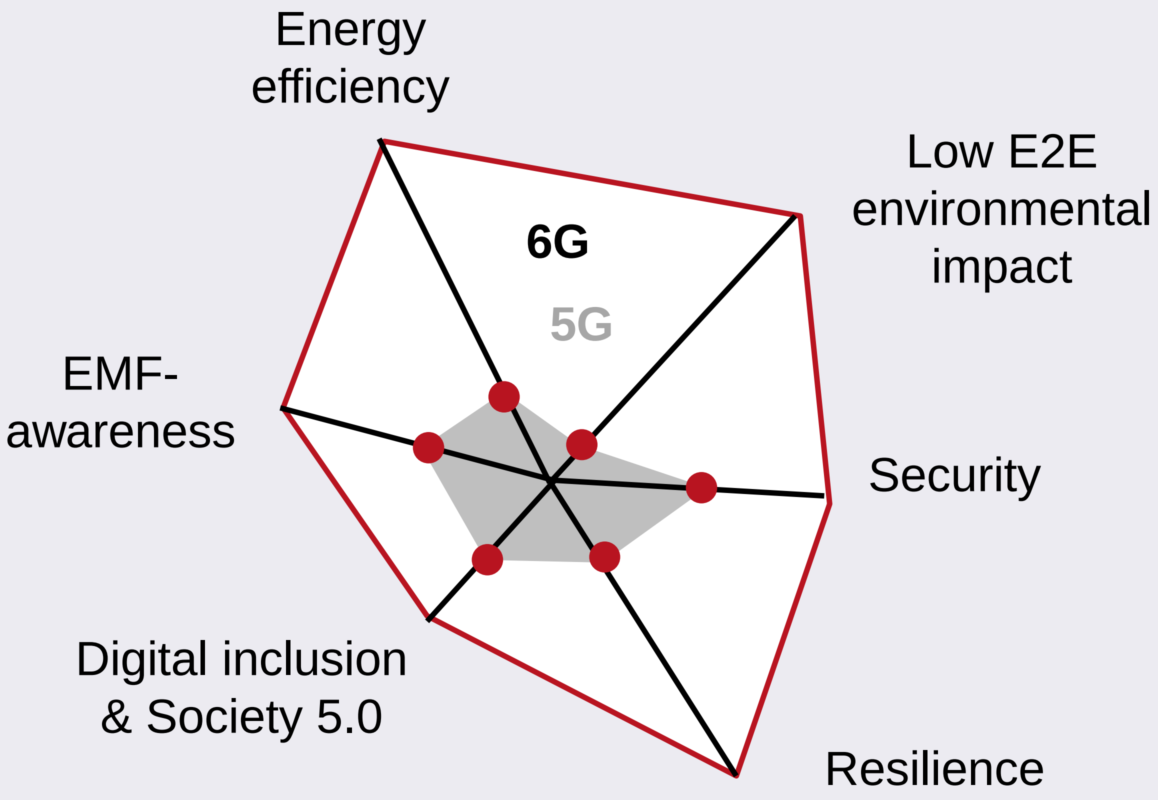


TECHNOLOGY EXPECTATION SHIFT AT 2035 HORIZON

6G target performance



6G 2035+ societal needs



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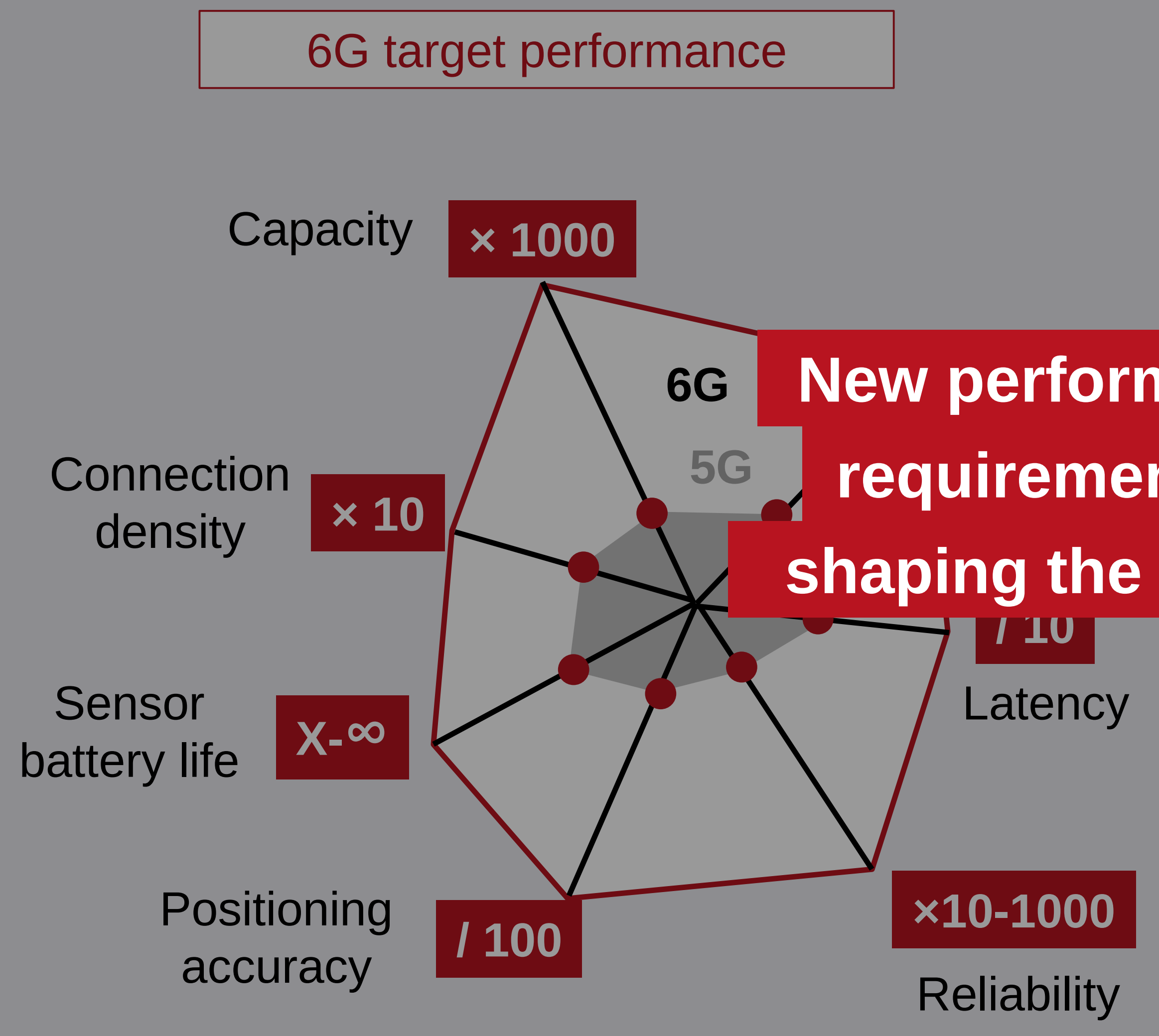
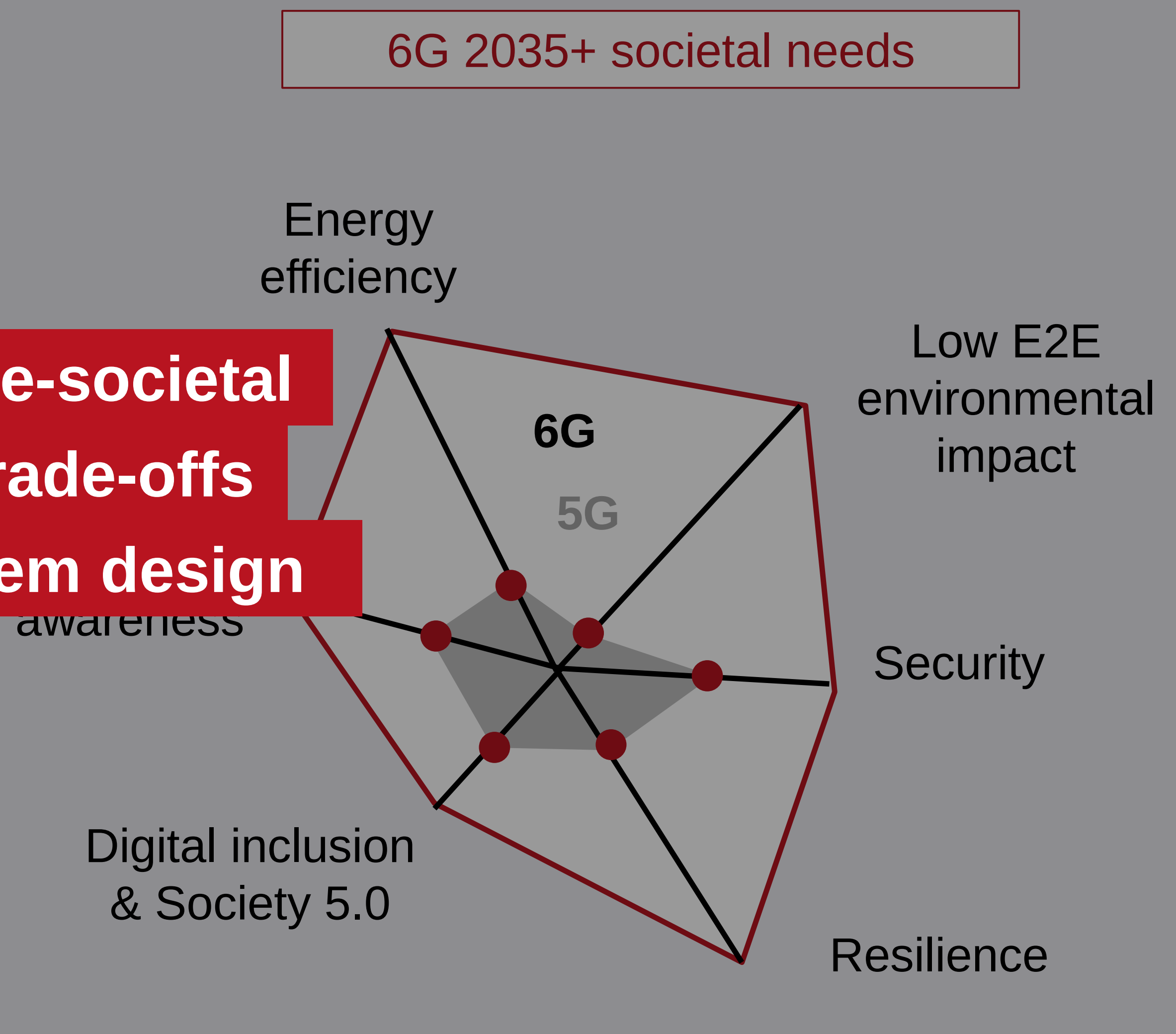




New performance-societal requirements trade-offs shaping the system design

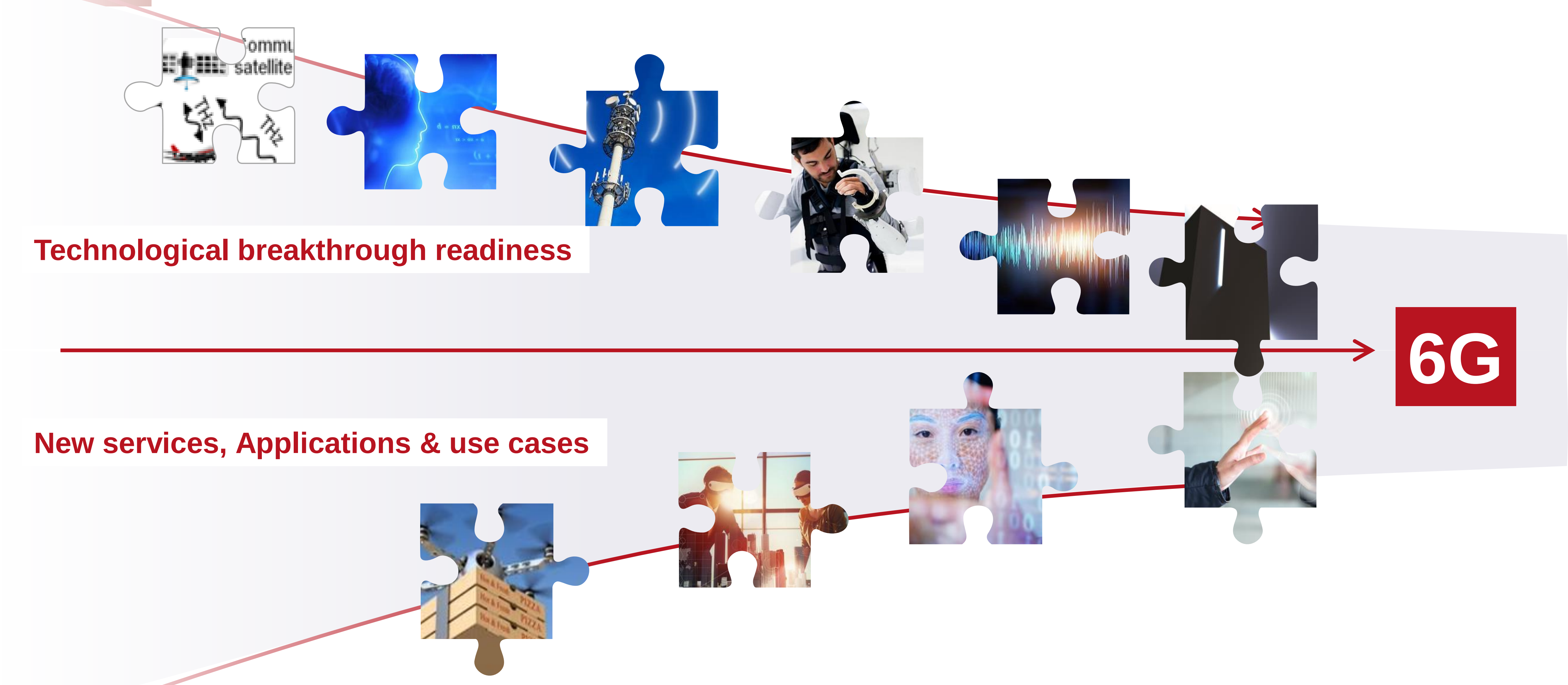
WHY WE NEED A NEW GENERATION ?

Technological breakthrough readiness

New services, Applications & use cases

6G

WHY WE NEED A NEW GENERATION ?



THE PATH TOWARD A NEW GENERATION ?

RETHINKING THE DATA-GENERATION TO USE CHAIN

Future wireless communication generation will

Not just **the X-factor** performance improvement race

new HW design, AI technologies, network management and operation…

But also **support sustainable evolution of society and economics**

SHANNON AND WEAVER, 1949

The broad subject of communication can be **organized into three levels**:

- **Level A** (***The technical problem***): How accurately can the symbols of communication be transmitted?
- **Level B** (***The semantic problem***.): How precisely do the transmitted symbols convey the desired meaning?
- **Level C** (***The effectiveness problem.)***: How effectively does the received meaning affect conduct in the desired way?

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

Shannon provided a rigorous and formal solutions to the technical problem, lying the foundation of information theory

Shannon, left deliberately aside all aspects related to semantic and effectiveness.

GENERALIZED SHANNON'S INFORMATION THEORY

Several schools of thought have proposed different alternative approaches:

- **Philosophy of information** [L. Floridi, What is the philosophy of information?, Metaphilosophy 33 (2002) pp. 123{145.]
- **Logic and information** [K. Devlin, Logic and information, Cambridge University Press, 1995.]
- **Information algebra** [J. Kohlas, Information algebras: Generic structures for inference, Springer Science & Business Media, 2012.]
- **Information flow** [J. Barwise, J. Seligman, et al., Information ow: the logic of distributed systems, Cambridge University Press, 1997.]
- **Quantum information theory** [M. A. Nielsen, I. Chuang, Quantum computation and quantum information, 2002.]
- **Algorithmic information theory** [C. S. Calude, Information and randomness: an algorithmic perspective, Springer Science & Business Media, 2013]

Semantic communication systems
addressing the problem of potential "misunderstanding" during communications

DIFFERENT INTERPRETATION OF THE WORD INFORMATION

Semantic information:

information as associated to a meaning

→ how relevant is a message to increase the knowledge level of the destination

Syntactic information (in the Shannon's sense): associated to the probabilistic model of the symbols used to encode or transmit information

→ how often a message appears

Note that if a message is more commonly true, it contains less sematic information

- Information (Winter & Rainy) >information (Rainy)
- Information (Rainy) > Information(Rainy & Cold)

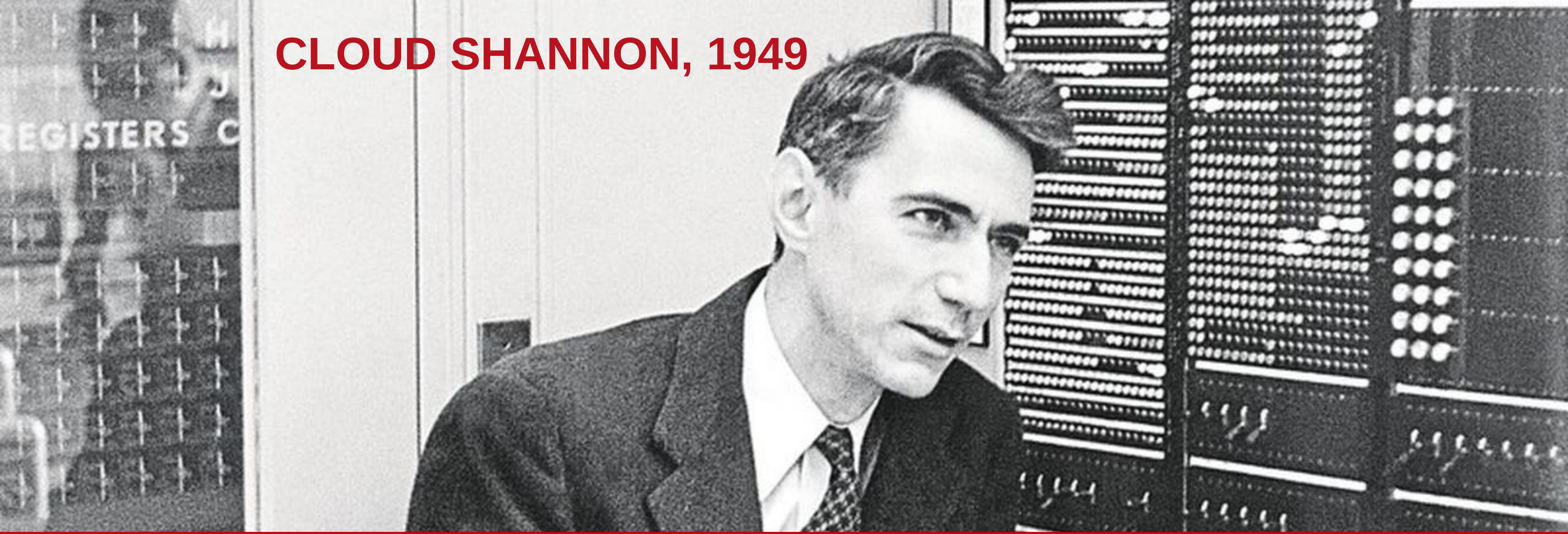
- **Semantic information is associated to the level of knowledge available at destination**

SYNTACTIC INFORMATION (SHANNON'S SENSE)

Pressing keys at random (approximately independent and uniformly distributed) generates messages with **high syntactic information**

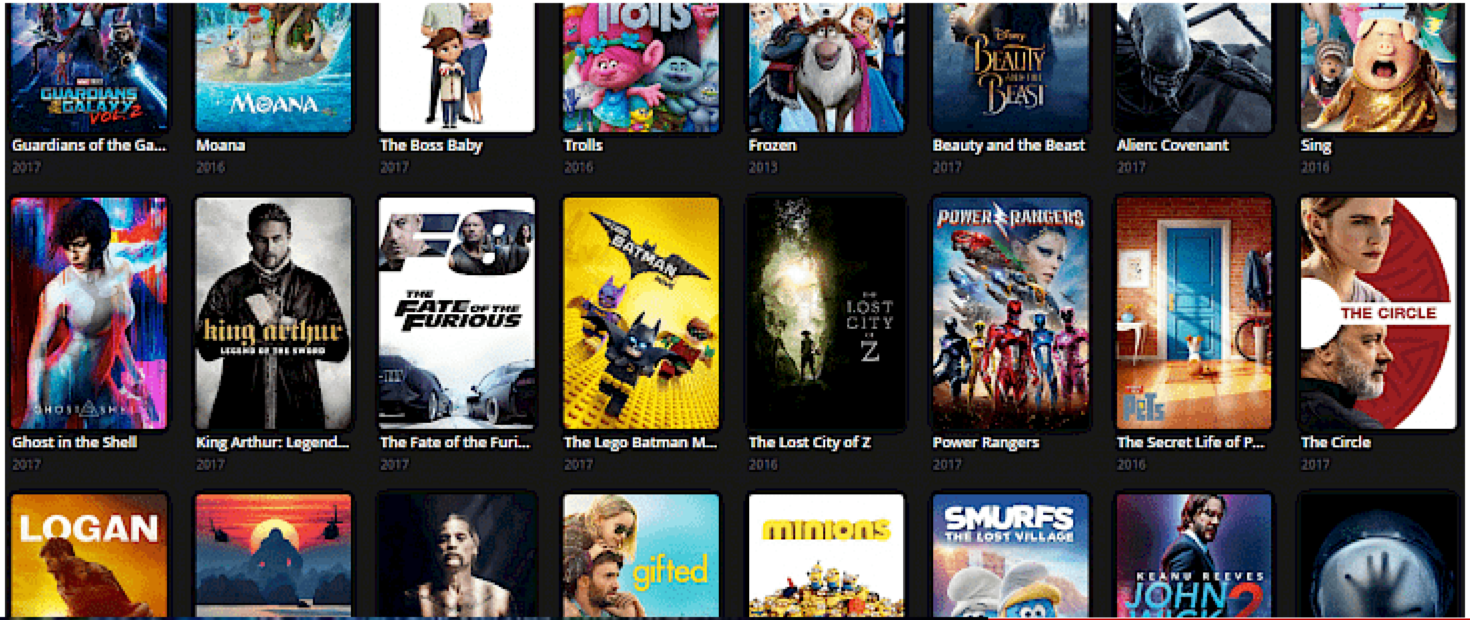
But **Z-E-R-O**
Semantic information

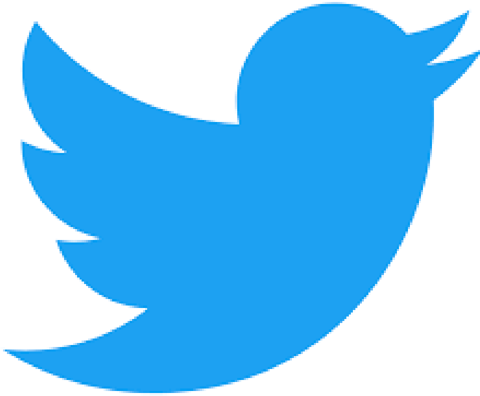
CLOUD SHANNON, 1949



'Information' is fully determined by the probability distribution on the set of possible messages, and unrelated to the meaning, structure or content of individual messages.'

BUT ARE THOSE JUST SEQUENCES OF BITS?





“These semantic aspects of communication are irrelevant to the engineering problem”

[Shannon 1949]

Is it always true?

MISUNDERSTANDING CAN BE COSTY!

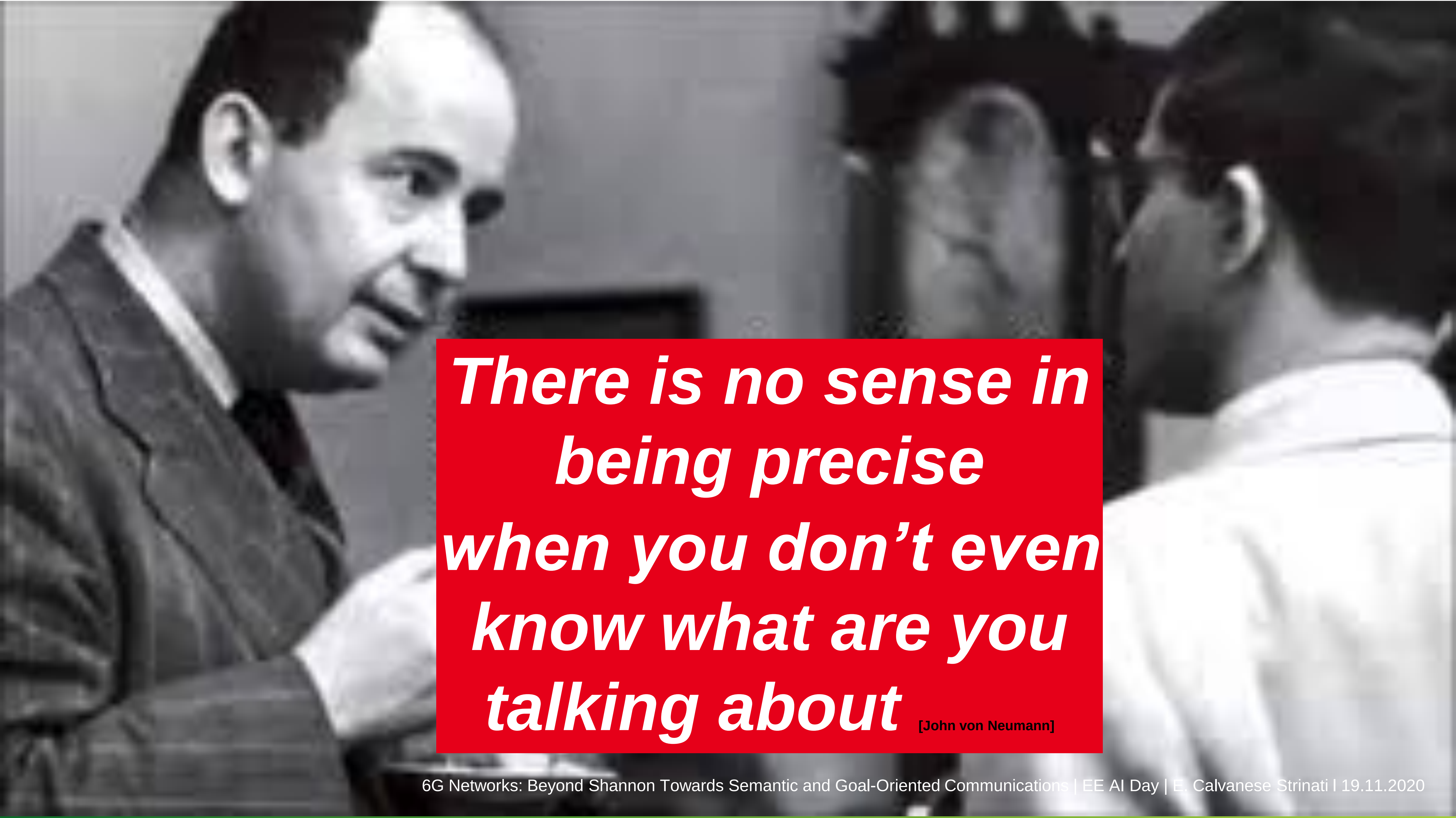
Expressed

Pounds (Lb_F)

Interpreted

Newton (N)

Mars Climate Orbited (1998-1999): mission failure costed 125 M$



There is no sense in being precise when you don’t even know what are you talking about **[John von Neumann]**

BEYOND SHANNON?

- Semantic Communications
- Goal-Oriented Communications
- Online learning-based communications
- Wireless Environment as a service

6G Networks: Beyond Shannon Towards Semantic and Goal-Oriented Communications

Emilio Calvanese Strinati[a,1,*], Sergio Barbarossa[b]

[a] *CEA Leti, 17 rue des Martyres, 38000 Grenoble, France*
[b] *Dept. of Information Eng., Electronics, and Telecomm., Sapienza Univ. of Rome Via Eudossiana 18, 00184, Rome, Italy*

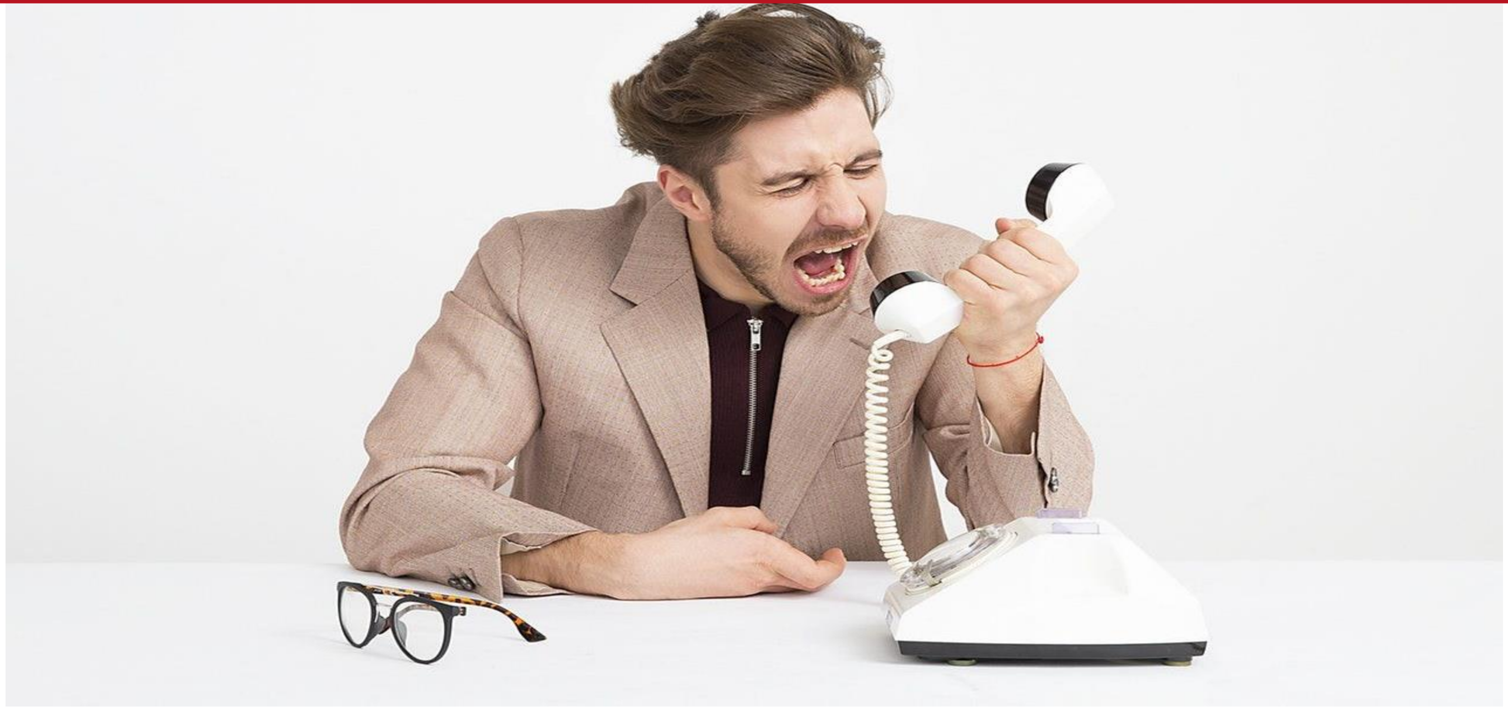
Abstract

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 packet, irrespective of the meaning conveyed by the packet. The idea is that, whenever communication occurs to convey meaning or to accomplish a goal, what really matters is the impact that the correct reception/interpretation of a packet is going to have on the goal accomplishment. 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.

SEMANTIC COMMUNICATOINS

The relevant aspect is *what* is communicated

Not *how* the message is brought to the destination



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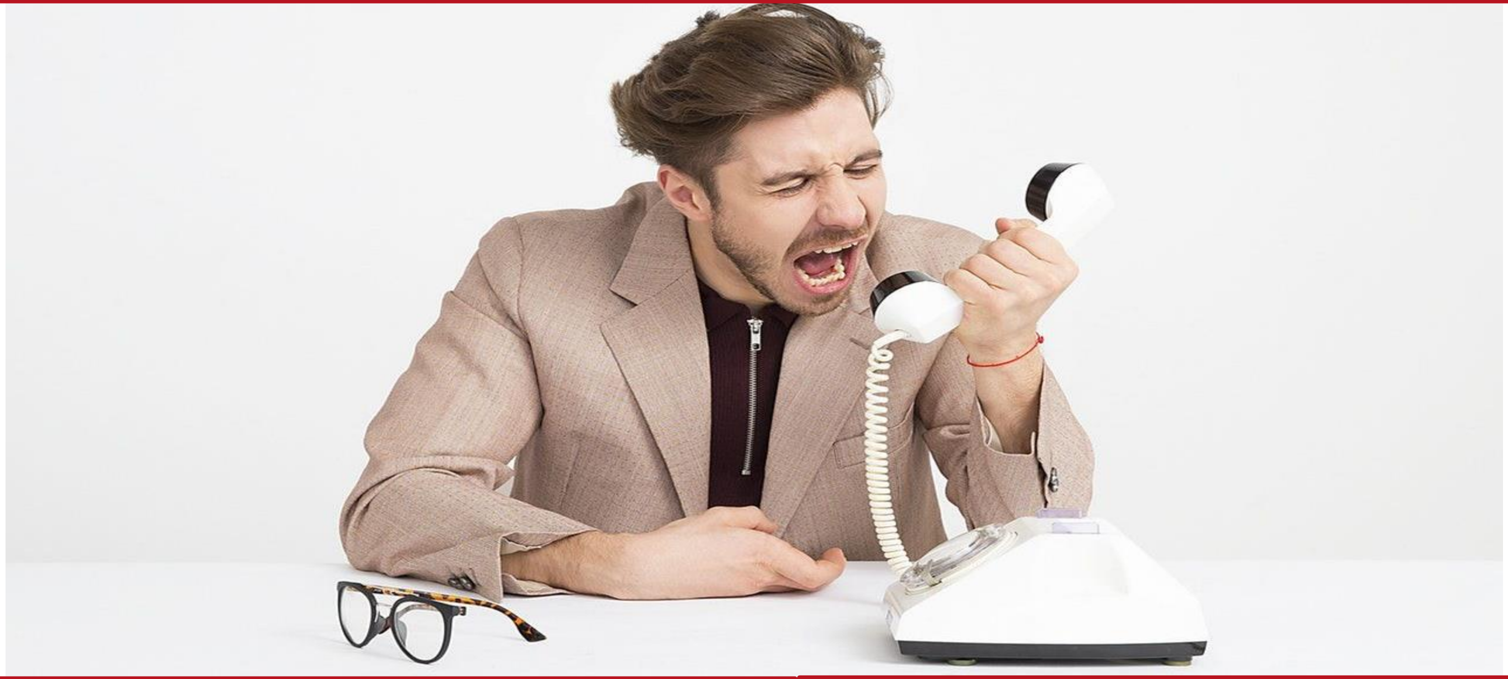
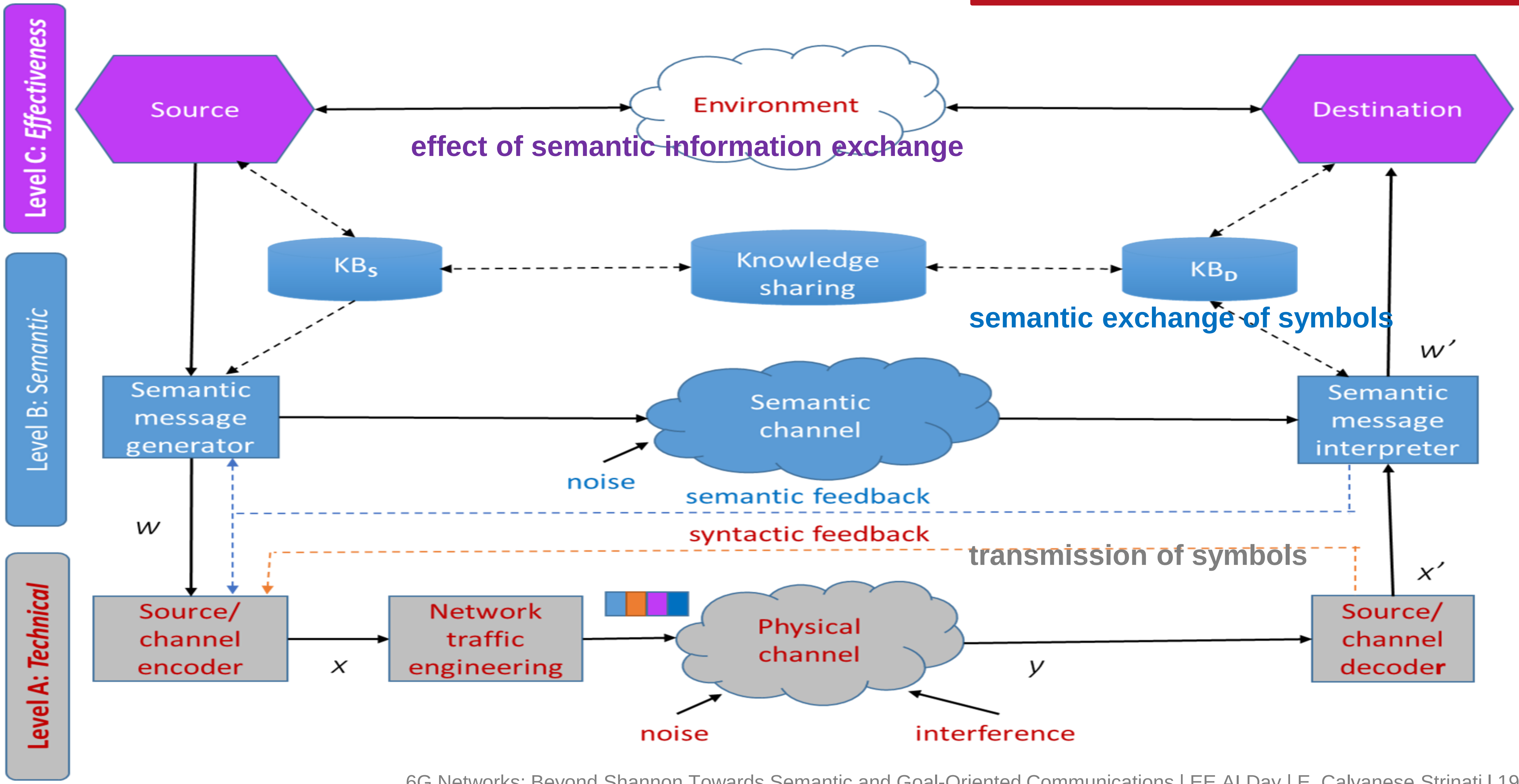


Correct semantic communication occurs **if** the **concept associated to the message** is **correctly interpreted** at the destination

This **does not imply** that the whole sequence of bits used to transmit the **message be decoded without errors**

WIRELESS SEMANTIC COMMUNICATIONS

*Targeting **effective tasking** rather than precise communication exchanges*



SEMANTIC EQUIVALENCE

The **meaning intended by the source** is **equivalent to the meaning understood** by its **destination**

This marks a significant departure with respect to the way information is used in Shannon's information theory, in at least 4 aspects:

1. **The amount of information conveyed by a message is associated to its semantic content,** and it is not necessarily related to the probability with which the symbols used to encode the message are generated
2. **What matters is the specific content of each message**, and not the average information associated to all possible messages that can be emitted by a source
3. The **amount of information conveyed by a message depends** not only on the message itself, but **also on the level of knowledge available at source and destination**, at the time of communication
4. Whenever communication is only an action performed to accomplish a joint goal, the **correctness of the message interpretation is associated to the effectiveness achieved in attaining the goal** thanks to the message.

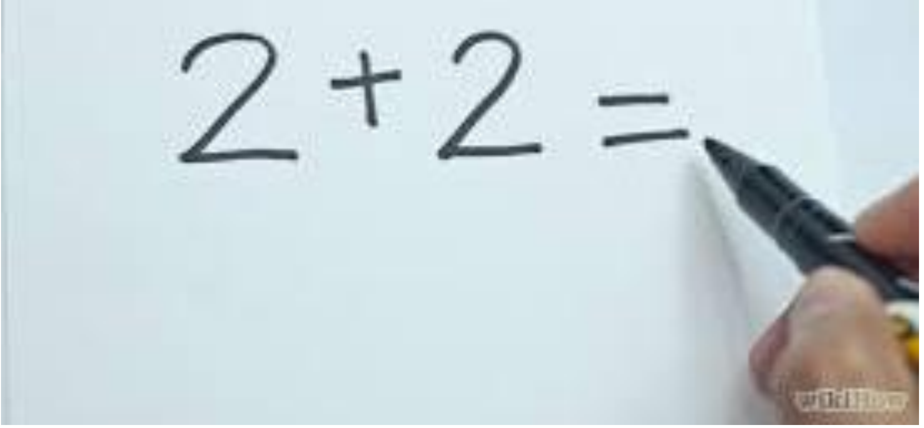
FORMAL KNOWLEDGE REPRESENTATION & REASONING

- **Correct semantic message interpretation is key to the effectiveness of semantic comms**
- **(background) Knowledge can be harvested thanks to the acquisition of a set of messages**
- **This requires to represent knowledge in a formal way**
- **[Tool] Knowledge representation:** representing knowledge by symbols and by defining the relations between symbols, in a way that makes possible the production of new knowledge
- We are investigating **how to incorporate graph-based knowledge representation in message interpretation at the receiver** [M. Chein, M.-L. Mugnier, Graph-based knowledge representation: computational foundations of conceptual graphs, Springer Science & Business Media, 2008.]

INFERENCE MADE ON SEMANTIC MESSAGES

- A **key feature of a Knowledge Based System** : **inference** made on a message should **depend only on the semantic** (meaning) of the message and **not on its syntactical form**

- **Alternative ways to encode** (Level A) **the same concept** into formally different sequences of symbols should rise to the **same semantic representation** (Level B)



→ The sound “four”

→ The symbol 4 on an image or written on a paper

The encoding mechanism and **the number of bits necessary to encode the two messages** would be **totally different,** but **the semantic information** would be **exactly the same**

SYNTACTIC VERSUS SEMANTIC ERRORS

Errors at syntactic level:

if the sequence of detected bits differs from the sequence of transmitted bits

It may occur because of the presence of random noise or interference introduced during the transfer through the channel, or because of unpredictable channel fluctuations or blocking…

Error at semantic level :

if the **meaning associated to the message at the receiver** is **not equivalent** to **what is meant at the transmitter side**

Due to **differences between the KB** systems available at source and destination nodes, or because of **some kind of semantic noise**, i.e. something that alters the concept emitted by the source, like fake news for example

MUTUAL IMPLICATION OF ERRORS

Errors at syntactic level:

An **error at the syntactic layer does not necessarily imply an error at the semantic layer**

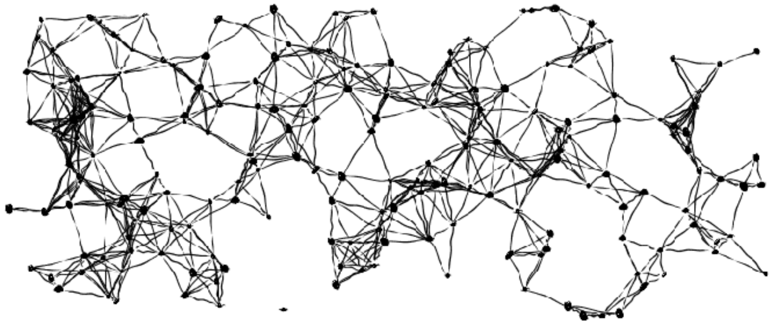
The message interpreter can in fact **recover the right content even if there are a few errors in decoding** the **received** sequence of **symbols**

Error at semantic level :

There could be errors at semantic level, even if there is no error at the syntactic level

Due to **differences of the KB's** available at source/destination, a **message that has been correctly syntactically decoded but it can be misinterpreted at the semantic level**

THE PRICE TO PAY



Additional computational complexity at the receive side

Computation caching techniques [CompCaching], advanced KB representation, exploitation of equivalent semantic should be investigated to reduce such complexity

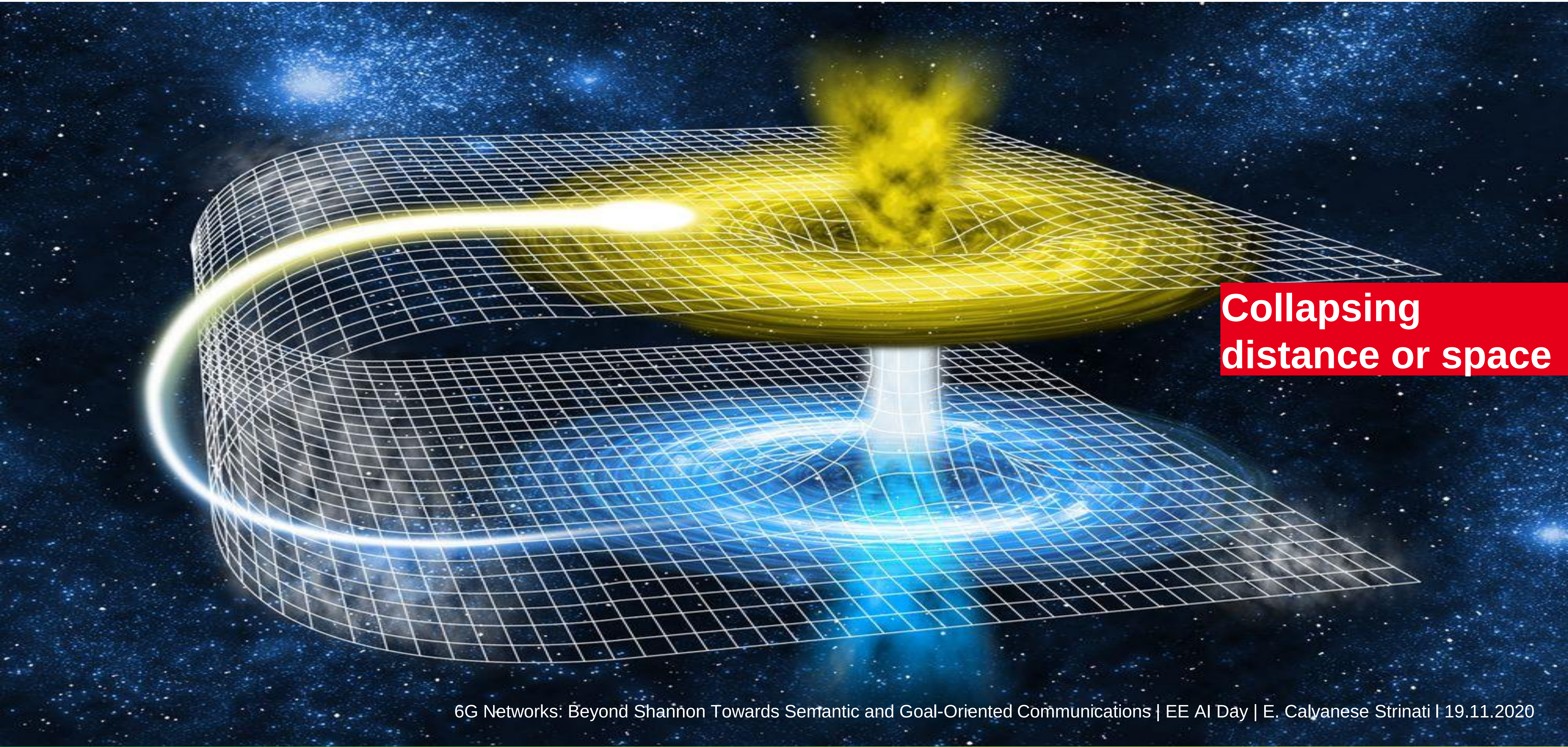
"Potentially" further delay:

The evolution of HW

Take valuable suggestions from the way our brains operate: predictive mind operation based on a mix of bottom-up and top-down operations

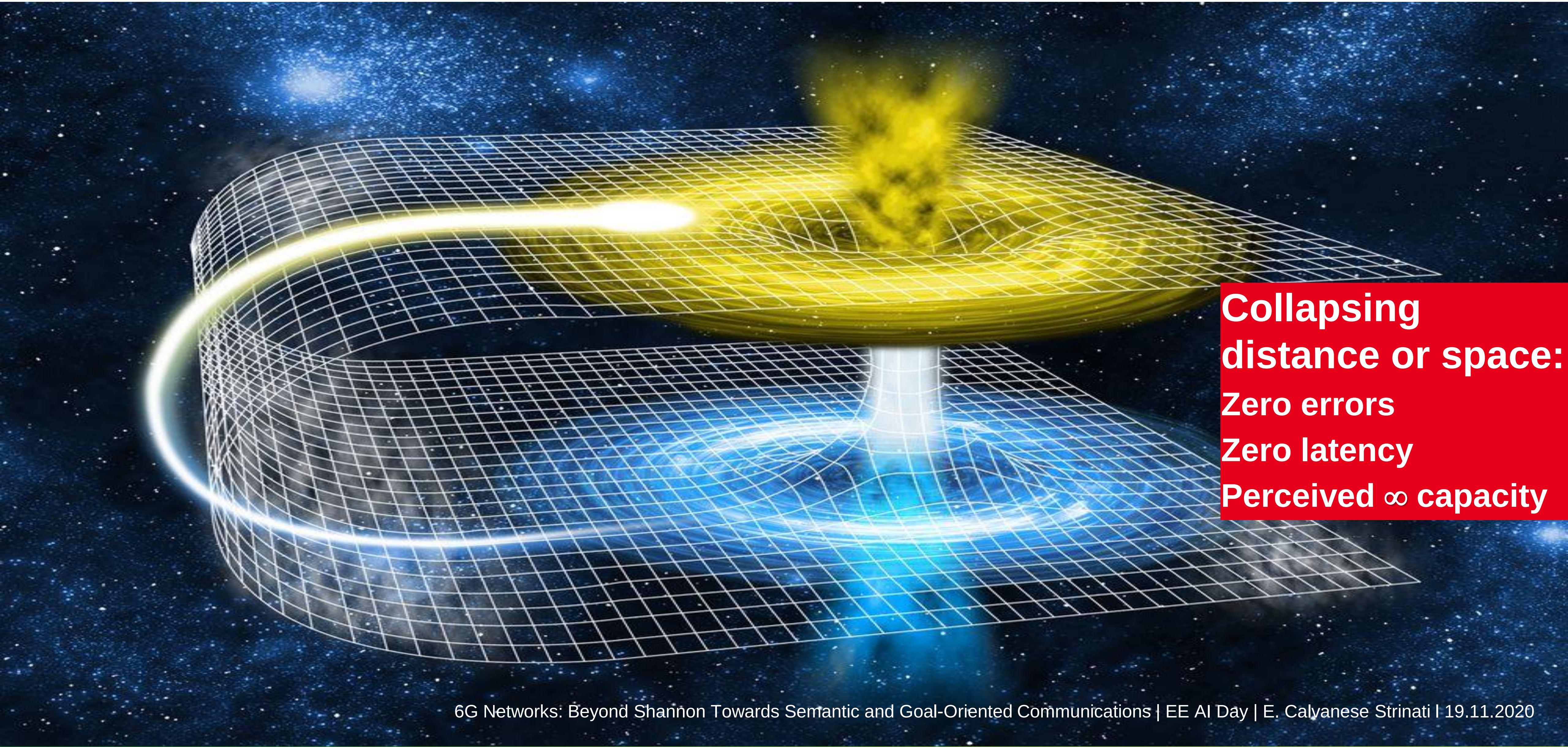
[CompCaching] N. Di Pietro and E. Calvanese Strinati, "An Optimal Low-Complexity Policy for Cache-Aided Computation Offloading," in *IEEE Access*, vol. 7, pp. 182499-182514, 2019,

GOAL OF WIRELESS COMMUNICATIONS?



Collapsing distance or space

GOAL OF WIRELESS COMMUNICATIONS?



Collapsing distance or space:

Zero errors

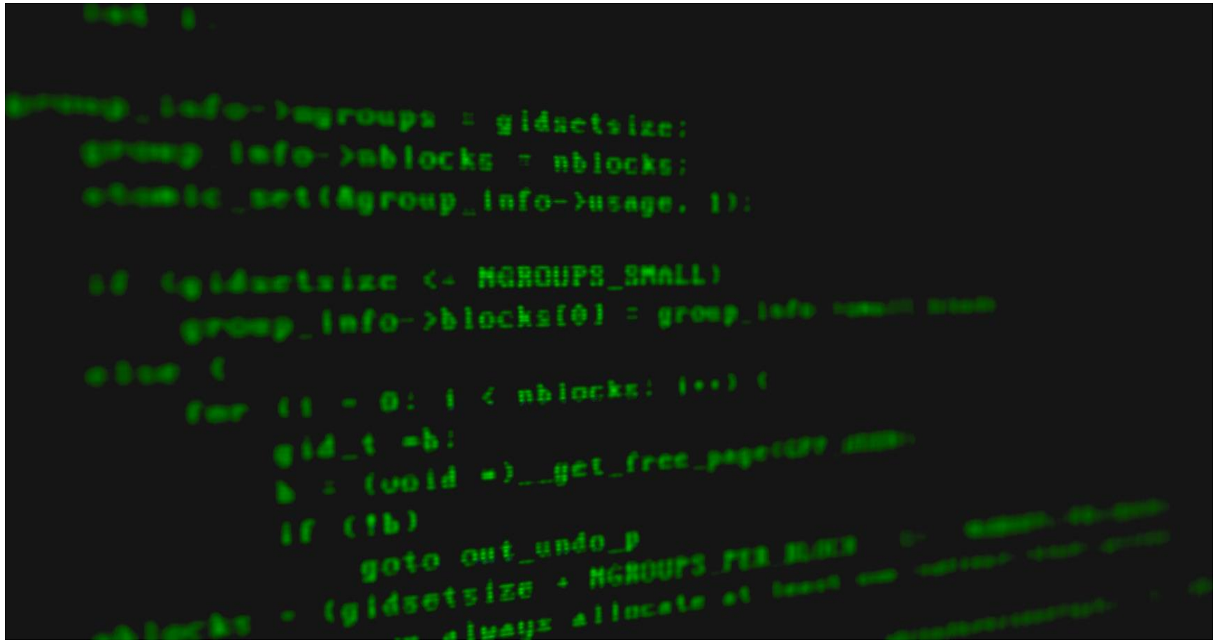
Zero latency

Perceived ∞ capacity

GOAL-ORIENTED COMMUNICATIONS

Communication is not an end in itself, but **a means for achieving shared goals** between the communicating parties

All information not strictly relevant to the fulfillment of the goal can be neglected



GOAL-ORIENTED COMMUNICATIONS

Scope

Communication has a well identified scope: Contribute to a goal achievement

Performance

Specified by the degree of fulfillment of the given goal

Effectiveness in the fulfillment of the goal **given the amount of resources** used to attain it.

Bits are not all equally informative,

…but **it is the goal that highlights** which **bits are more relevant to the goal accomplishment**

EXAMPLE OF GOAL-ORIENTED COMMUNICATIONS

- The goal of the system is to learn a set of parameters θ from a set of observations X_i

- i=1, …, N
- $X := \{x_i\}_{i=1}^{N}$ is the set of measurements
- θ is a set of deterministic parameters

- The observations x_i are outcome of a vector random variable with a probability density function $p(x; \theta)$, with vector parameter θ

- The Goal-Oriented communication system requires **sensors collect the data-set X and send the data to a fusion center**.

EXAMPLE OF GOAL-ORIENTED COMMUNICATIONS

- The **goal of the fusion center** is to **estimate the parameter vector θ from X** … with a target accuracy level
- It might **not** be **necessary to send all** the vectors X
- What is necessary is to send **T(X)**
- **T(X)** is a function of X, such as the accuracy in the estimation of θ from T(X) is the same as that achievable using the observation X directly

Does exist a **T(X) that guarantees no accuracy loss** & provides **some gain in the communication setup**?

SUFFICIENT STATISTICS OF X

- **From basic statistical signal processing, we know that T(x) is a sufficient statistics for θ, given x, if the pdf p(x; θ) can be factorized as:**

$$p(x;\theta) = g_\theta[T(x)]\,h(x)$$

- There **might exist more than one sufficient statistic**
- It is important to **identify the *minimal sufficient statistics*.**
- **A statistic T(x) is a *minimal sufficient statistic* relative to p(x; θ) if:**
  - It is sufficient
  - it is a function of every other sufficient statistic

A ***minimal sufficient statistic* maximally compresses the information** about the vector parameter **θ** in the observed samples

EXAMPLE OF SUFFICIENT STATISTICS

- **If the parameter vector is a multivariate random vector θ**
- **I(θ; x) is the mutual information between θ and x**

➔ **I(θ; T(x)) is the mutual information between θ and a sufficient statistic T(x)**

There is **no loss of information** in sending T(X) instead of X if the **goal of communication** is **estimating the parameter vector θ from the observation** of a data-set X if:

$$I(\theta; x) = I(\theta; T(x))$$

WHAT IS THE ADVANTAGE?

- **The entropy of T(X) can be much smaller than the entropy of X**
- **➔ the number of bits necessary to encode T(X) may be much smaller than the number of bits to be used to encode X**
- **➔ The number of bits to be transmitted can be significantly decreased, with no losses in terms of inference**

In general:

*if the **goal of communication is to perform some inference on the data**, it is **not necessary to transmit the data as they are,** but **it is more convenient to transmit a function of the data, which depends on the goal of the inference***

➔ ***We send only what is really relevant** for the action to be performed at the receiver side*

➔ ***Data can be significantly compacted** while leaving unaltered the performance of the inference method*

RELIABILITY WITH SEMANTIC & GOAL-ORIENTED COMMUNICATIONS

- The bottleneck, traditionally represented by the unreliability of the communication medium, is drifting towards **the reliability of decision mechanisms supporting the intelligent interaction between humans, machines and the environment**.

- Shifting the perspective to semantics and goal-oriented communications, **different bits may have different relevance in conveying information or in fulfilling a desired goal** within a time constraint

- Reliability constraints might vary depending on their significance and the goal of communication

- There is no single number for KPI on **inference reliability**, as they will depend on the specific services

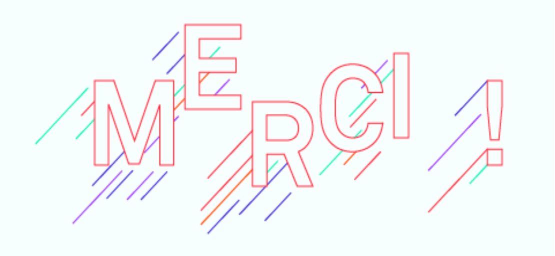
CONCLUSIONS

- Communication has been the basic commodity of every wireless generation.
- The boundary between computer science, artificial intelligence and telecommunications is disappearing
- Society and industry are becoming more and more data-centric, data-dependent, and automated
- The Cyber and Physical space fusion turn humans, things and events into information
- Shannon's model has pushed a never-stopping race for broader bandwidths, thus exploring higher frequency bands
- We need disruptive concepts to attain the sustainability targets at the horizon 2030-2040

CONCLUSIONS

- We promote the idea that **including semantic and goal-oriented aspects in future 6G networks to** attain a leap forward in terms of **system effectiveness and sustainability**
- **Communications aims to convey meaning or to accomplish a goal:**
  - what matters is the **impact that the correct reception/interpretation** of a packet **on the goal accomplishment**
- **The key idea of goal-oriented communication is to transmit only the R-E-L-E-V-A-N-T information wrt the the goal**
- **A key open challenge is to identify the relevant information and its effective semantic representation**
- **We target to distil the data that are strictly relevant to convey the information needed to attain a predefined goal**
- **Distilling the data to transmit reduces the amount of data significantly, well beyond conventional source encoding(saving BW, energy, delay)**

Thank you!



고맙습니다

ALOHA

Grazie!

6G Networks: Beyond Shannon Towards Semantic and Goal-Oriented Communications

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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 packet, irrespective of the meaning conveyed by the packet. The idea is that, whenever communication occurs to convey meaning or to accomplish a goal, what really matters is the impact that the correct reception/interpretation of a packet is going to have on the goal accomplishment. 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.

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With its ability to provide a single platform enabling a variety of services, such as enhanced mobile broadband communications, virtual reality, automated driving, and the Internet of Things, 5G represents a breakthrough in the design of communication networks. Nevertheless, considering the increasing requests for new services and predicting the development of new technologies within a decade, it is already possible to envision the need to move beyond 5G and design a new architecture incorporating innovative technologies to satisfy new needs at both the individual and societal levels.

The goal of this article is to motivate researchers to move to a sixth generation (6G) of mobile communication networks, starting from a gap analysis of 5G and predicting a new synthesis of near-future services like holographic communications, high-precision manufacturing, a pervasive introduction of artificial intelligence (AI), and the integration of new technologies, such as subterahertz or visible light communication (VLC), in a truly 3D coverage scenario. Such a framework will incorporate terrestrial and aerial radio access points to bring cloud functionalities *where and when needed on demand*.

The Road to a Global "Brain"

In 1926, the visionary Nikola Tesla stated, "When wireless is perfectly applied, the whole Earth will be converted into a huge brain." By 2030, responding to fundamental human and social needs and based on the expected progress in information and communication technologies

6G: THE NEXT FRONTIER

From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication