





6G Global 2023 1st- 2nd of November 2023





The Post Shannon Era Towards Semantic, Goal-Oriented & Reconfigurable Intelligent Environments aided 6G 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



COMMUNICATIONS

- Low Latency (µs-ms)
- > Self-designing Joint C4: Communication + Computing + Caching + Control
- Ultra-high capacity (1-10 s Tbps)
- > AI-Native Connect-Compute Design

MASSIVE MACHINE TYPE COMMUNICATIONS SUPPORTING DISTRIBUTED INTELLIGENCE (MMTCXDI) 6G SERVICES

Future 6G Machine-Type Communications (MTC) will enlarge the capabilities of 5G massive MTC to include pervasive distributed computation algorithms supporting the distributed intelligence of 6G networks & services

[Calvanese2020-Semantic6G] E. Calvanese Strinati and S. Barbarossa: *6G Networks: Beyond Shannon Towards Semantic and Goal-Oriented Communications*, Communication Networks Journal, Feb. 2021.





The Post Shannon Era: Towards Semantic, Goal-Oriented & Reconfigurable Intelligent Environments aided 6G Communications | E. Calvanese Strinati | 6G Global 2023 - Korea

GLOBALLY-ENHANCED MOBILE BROADBAND (GEMBB) SERVICES [CALVANANESE2020SKY6G]

6G

To expand the computation-oriented communication environment to support rate-hungry applications ... also in remote locations (oceans, rural areas and the 3D sky)

[Calvananese2020Sky6G] E. Calvanese Strinati et al., "6G in the sky: On-demand intelligence at the edge of 3D networks," ETRI Journal, vol. 10, Mai 2020. [Calvanese2020-Semantic6G] E. Calvanese Strinati and S. Barbarossa: 6G Networks: Beyond Shannon Towards Semantic and Goal-Oriented Communications,

Communication Networks Journal, Feb. 2021.



ULTRA-RELIABLE, LOW LATENCY COMPUTATIONS, COMMUNICATIONS & CONTROL (URLLCCC) 6G SERVICES

To expands the capabilities of URLLC services already supported by 5G networks, incorporating the computation services running at the edge of the network and E2E (remote or automated) control.

Now RELIABILITY targets are not only on communication aspects but also on computation & intelligence support, such as on learning accuracy or correct classification probability

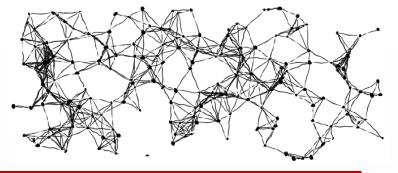
[Calvanese2020-Semantic6G] E. Calvanese Strinati and S. Barbarossa: *6G Networks: Beyond Shannon Towards Semantic and Goal-Oriented Communications*, Communication Networks Journal, Feb. 2021.





SEMANTIC 6G SERVICES

[CALVANESE2020-SEMANTIC6G]



To support all applications involving a share of knowledge between the interacting (intelligent) parties seamlessly connecting and intertwining of different kinds of intelligence (natural, artificial)

To support intelligence as a service: from connected things to connected intelligence

To induce & train reasoning and generalization skills of Al agents

[Calvanese2020-Semantic6G] E. Calvanese Strinati and S. Barbarossa: *6G Networks: Beyond Shannon Towards Semantic and Goal-Oriented Communications*, Communication Networks Journal, Feb. 2021.

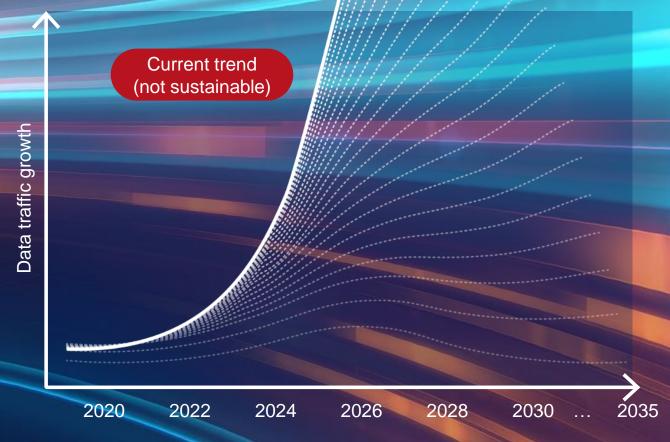




EXPONENTIAL GROWTHS REQUIRES NEW ENERGY SOLUTIONS

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

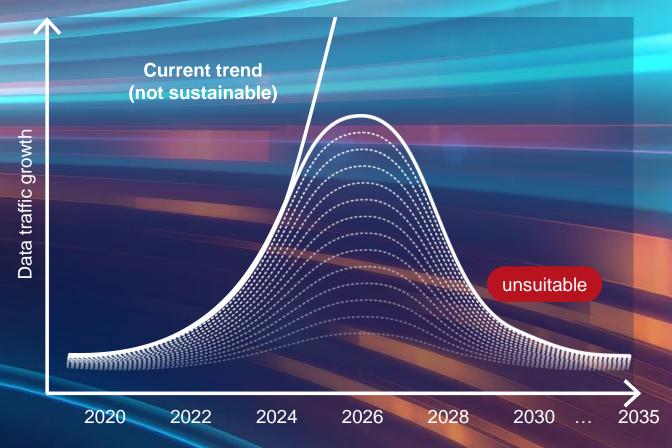




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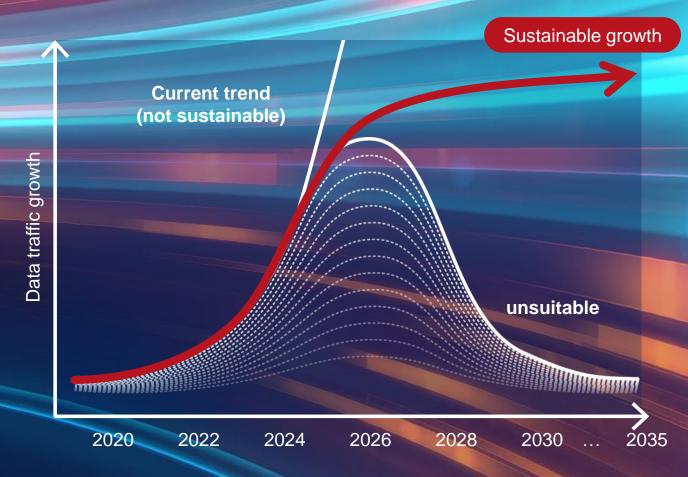




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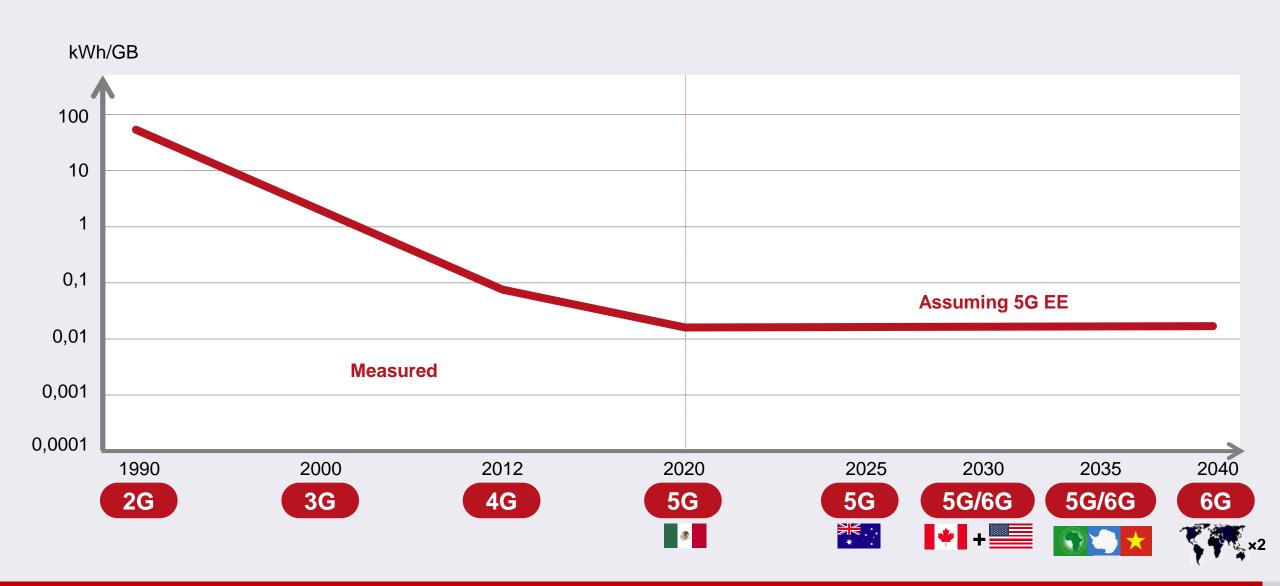
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WIRELESS NETWORKS' ENERGY CONSUMPTION



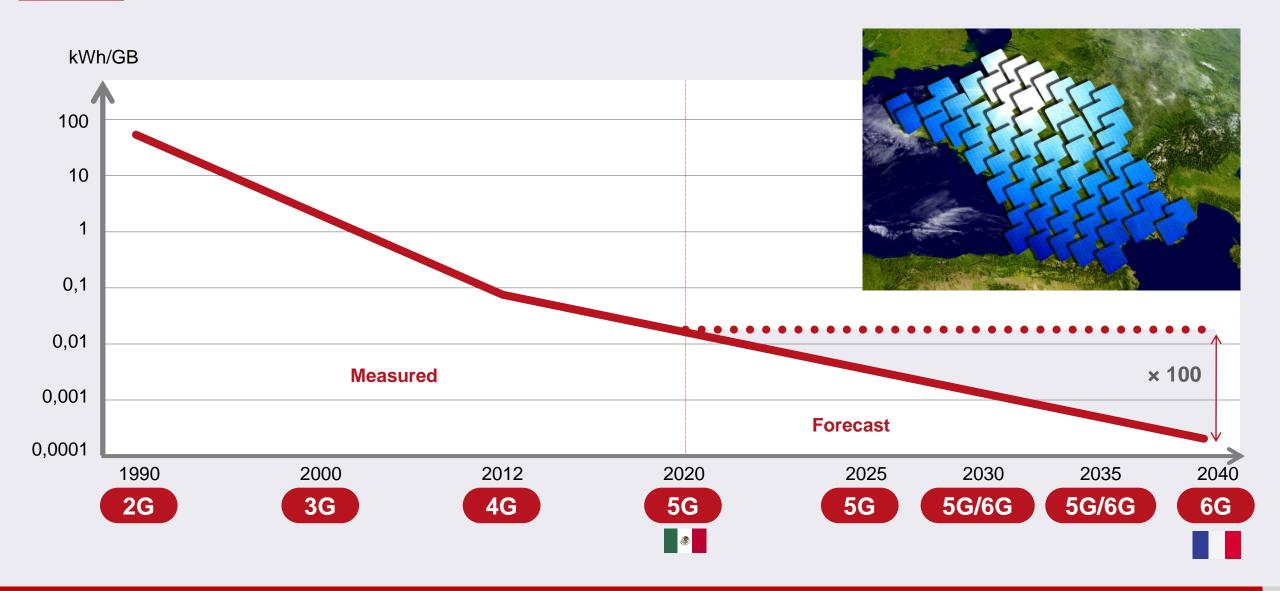


WIRELESS NETWORKS' ENERGY CONSUMPTION





WIRELESS NETWORKS' ENERGY CONSUMPTION



6G KPIS: THE SYSTEM LEVEL PERSPECTIVE

5G improved system level KPIs

- To ensure the conceptual continuity with 5G
- To extend performance requirements on already envisaged sets of KPIs (x10 x1000)

Entirely New 6G system level KPIs

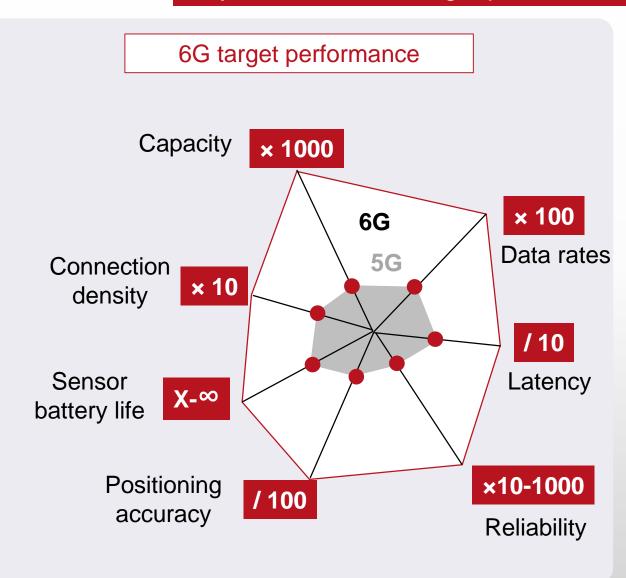
- To support a **connect-computation-intertwining of intelligence network**:
- To extend of **connect-computer-store-control** capabilities to **NTN**
- To address **sustainability** (of technology, network operation, task, inference, EMF)

	KPI	5 G	6G
٦	Traffic Capacity	10 Mbps/m²	~ 1-10 Gbps/m³
	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
	Communication Reliability	Up to 10 ⁻⁵	Up to 10 ⁻⁹
	Localization precision	10 cm on 2D	1 cm on 3D
	Jitter	NS	1 µsec
	Energy/bit	NS	pJ/bit
	Energy/goal	NS	TBD
	Inference reliability	NS	TBD
	EMF	NS	TBD

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

TECHNOLOGY EXPECTATION SHIFT AT 2035 HORIZON

System Level 6G target performance



How can we achieve them?It is not just a SW update!

5G improved system level KPIs

- > To ensure conceptual continuity with 5G
- \rightarrow To extend performance ($\times 10 \times 1000$)

Entirely New 6G system level KPIs

- > To support new functionalities and services
- To address sustainability

WHAT DETERMINES THE CAPACITY OF A NETWORK



Shannon Channel Information Capacity



Capacity (bits/seconds)

Radio channel Bandwidth (Hz) x n x

 $log_2 (1+SNIR)$

Signal to Noise + Interference Ratio

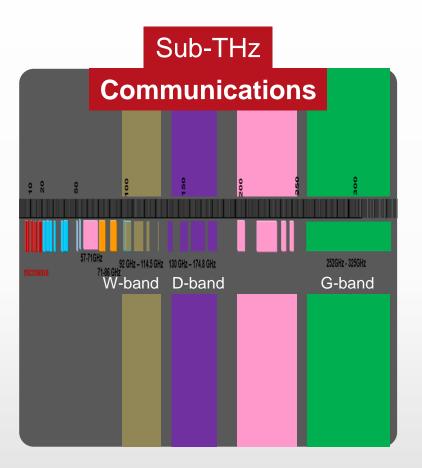
signal paths

Number of uncorrelated

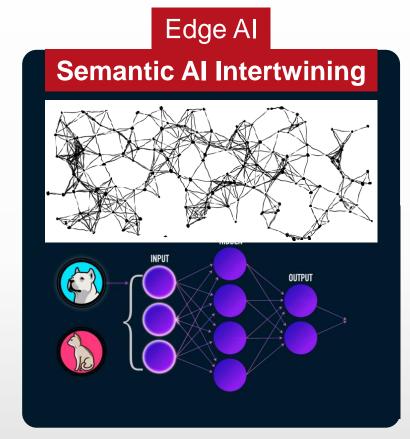
How to achieve a x1000 factor improvement in 6G?



6G TECHNOLOGY PILLARS

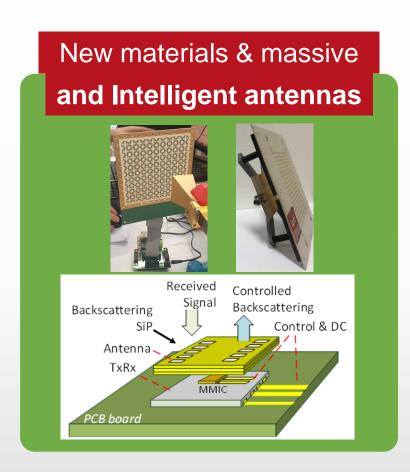


Al/ML technologies to design the next generation air interface and new compensation techniques for HW limitations



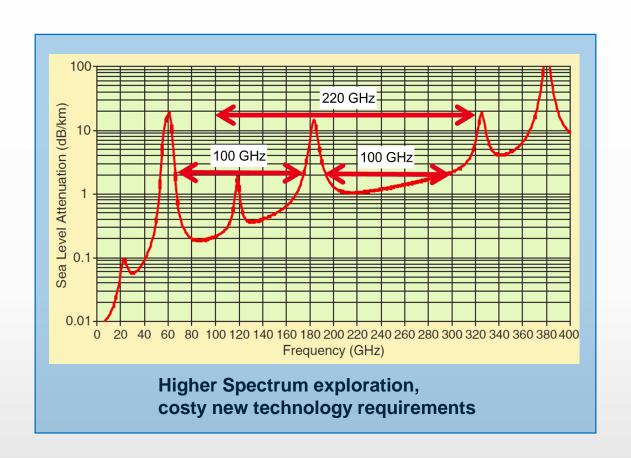
Edge Al/ML to offer processing and reasoning capability close to the applications and data

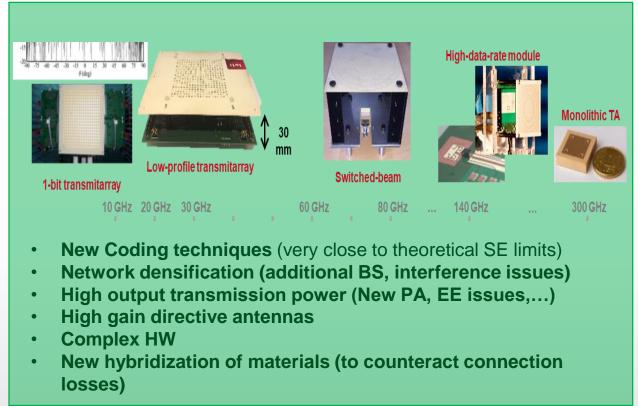
Semantic Communications to enable native Al intertwining



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

CLASSICAL PARADIGM: RACE FOR FASTER-HIGHER CAPACITY LINKS







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.

6G KPIS: THE HW PERSPECTIVES

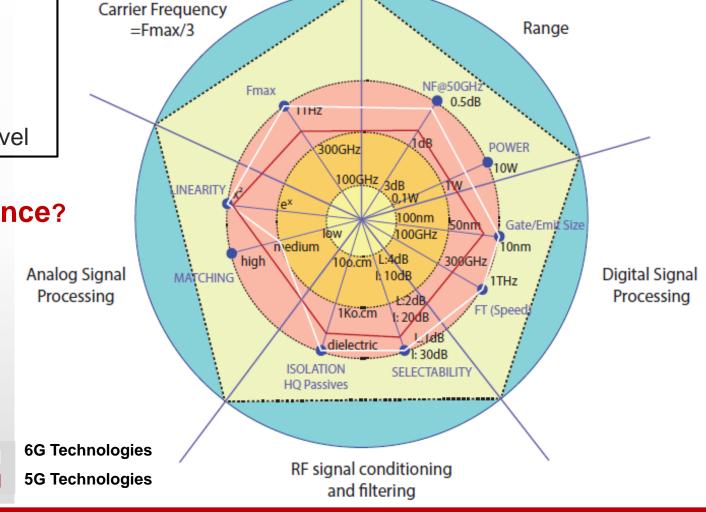
New KPIs on HW & technology

- KPIs specifying the process technologies & required HW performance
- to support effective operation KPIs at system level

How to achieve the required performance?

- High out power
- Selectability
- Isolation
- Acceptable EE (10-20%)
- High FMAX (Fmax/10 < F0 < Fmax/3)
- New Materials, new IC technologies

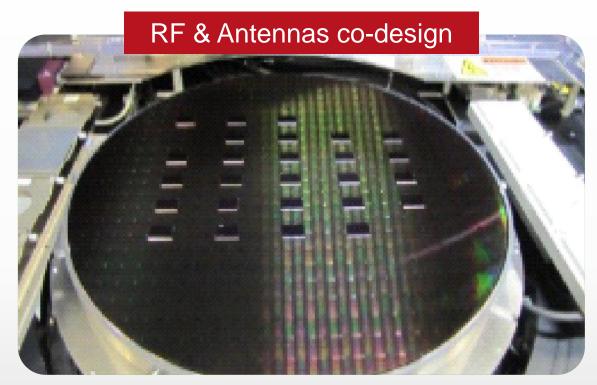
• ...



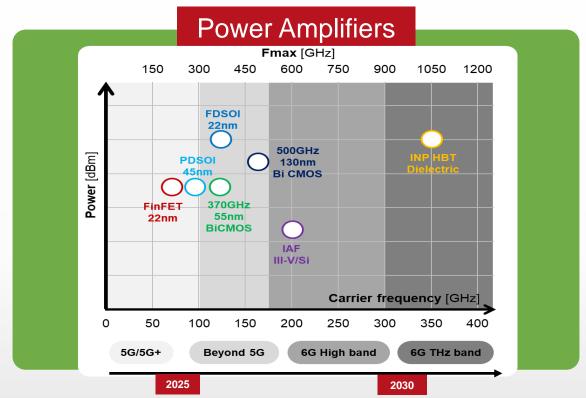
Source: E. Calvanese Strinati and et. al., "Toward 6G: From New Hardware Design to Wireless Semantic and Goal-Oriented Communication Paradigms". (invited paper) ESSCIRC Conf 2021, Sept. 2021.



SUB-THZ COMMUNICATIONS: WHY 6G HW MATTERS!



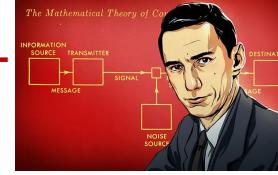
- > 100+Gbps transceivers
- > RF & Antenna co-design
- Next CMOS frontier: New transistors, new materials, hybridation



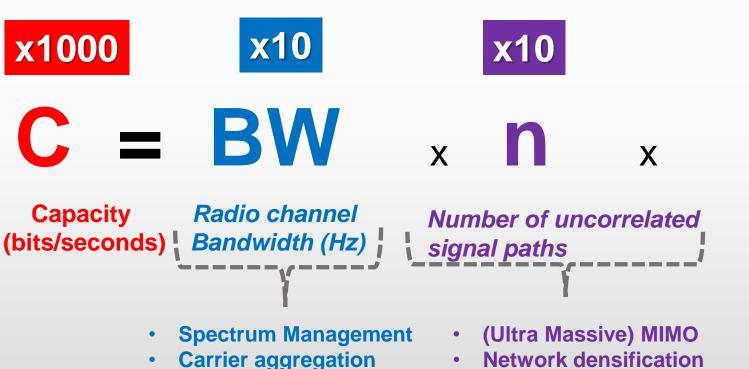
Between 200 GHz and 350 GHz today cost and energy efficient technology are still an open research and industrialization challenge!

Source: E. Calvanese Strinati and et. al., "Toward 6G: From New Hardware Design to Wireless Semantic and Goal-Oriented Communication Paradigms". (invited paper) ESSCIRC Conf 2021, Sept. 2021.

HOW 5G ACHIEVED THE X1000 FACTOR IMPROVEMENT



Shannon Channel Information Capacity



New mmW Spectrum

- log₂ (1+SNIR)
 - Signal to Noise +
 Interference Ratio

Spectral efficiency:

x10

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

Small cells

PARADIGM SHIFT #1 - TRANSMISSION EFFECTIVENESS OUTCOME

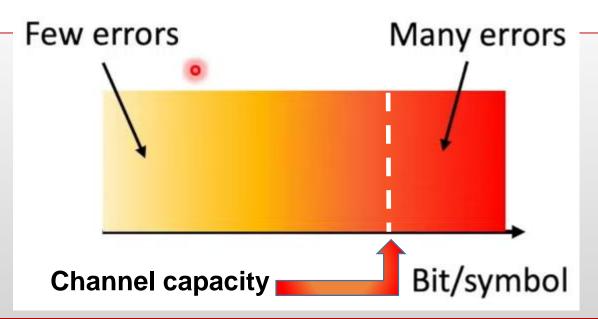
From: Spectral Efficiency of Data-oriented Communications

Send more data over the available spectrum to use it efficiently

Send the maximum volume of data per second while maintaining a target QoS.

How to? Not just more antennas and/or network densification (interference issues)

(Massive) MIMO, cell free, beamforming, new modulatoins, waveforms & coding schemes, full-duplex, etc.



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From: Spectral Efficiency of Data-oriented Communications

Send more data over the available spectrum to use it efficiently

Send the maximum volume of data per second while maintaining a target QoS.

How to? Not just more antennas and/or network densification (interference issues) (*Massive*) *MIMO*, *cell free*, *beamforming*, *new modulatoins*, *waveforms* & *coding schemes*, etc.

To: Effectiveness *per Goal* of transmission strategy outcome

Goal-oriented Communications

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

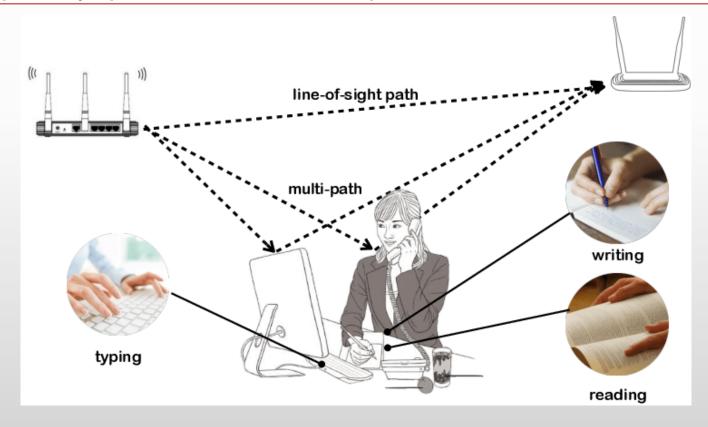
Beyond the common Shannon paradigm of guaranteeing the correct reception of each single transmitted bit, irrespective of the meaning conveyed or target goal

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

PARADIGM SHIFT #2 – COMMUNICATION ENVIRONMENT SHAPING

From: fight uncontrollable "dictated by nature" propagation environments

How to? Higher antenna gains, modulate transmission power, larger "diversity" gains (space, time, frequency, polarization, multi-paths, multi-users, codes, etc.)



PARADIGM SHIFT #2 – COMMUNICATION ENVIRONMENT SHAPING

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How to? Higher antenna gains, modulate transmission power, larger "diversity" gains (space, time, frequency, polarization, multi-paths, multi-users, codes, etc.)

To: create & shape on demand smart radio environments

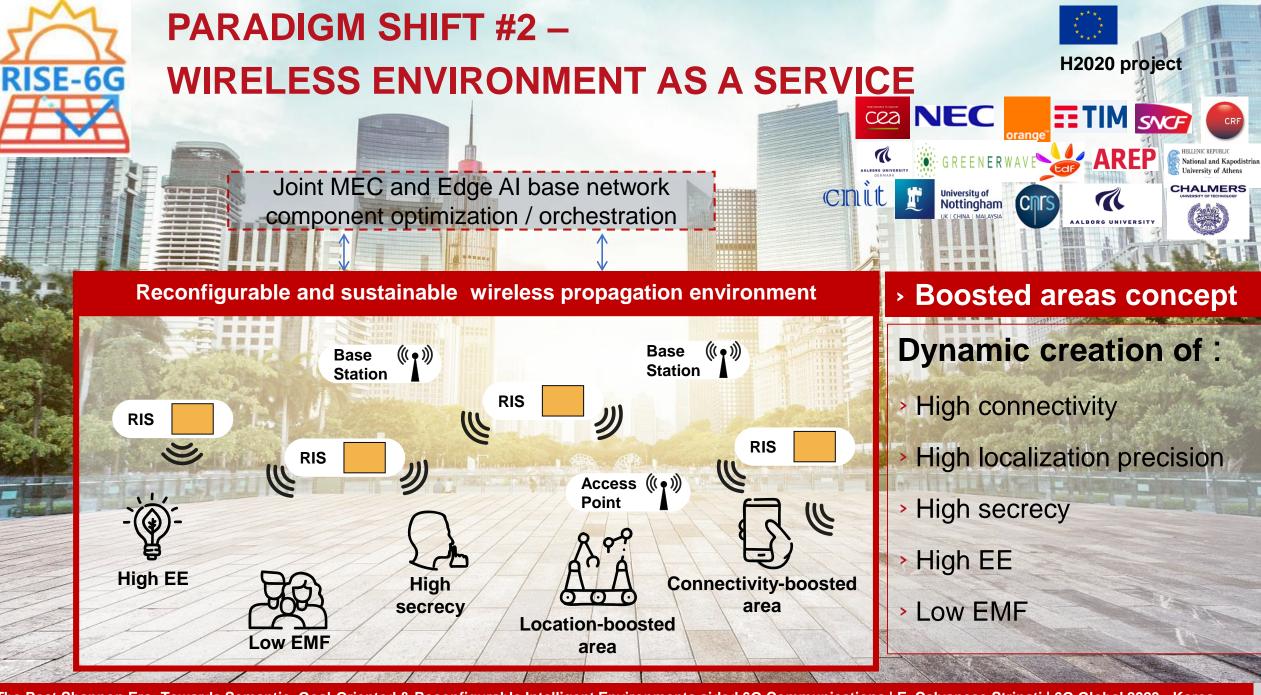
RIS assisted Communications

Controlling the reflection, scattering, and refraction characteristics of electromagnetic waves to **intentionally alter the wireless channel realization** to increase capacity or impose favorable structures to facilitate simpler communication techniques

How to?

Design of Reconfigurable Intelligent Surfaces to create & shape on demand smart radio environments where

→ wireless propagation conditions are co-engineered with the physical-layer signaling



From: Moving (raw) data to feed ML & Al is all you need!

The data PARADOX: All needs data but data needs Al.

ML/AI training, test and operation are known for insatiable appetite for data



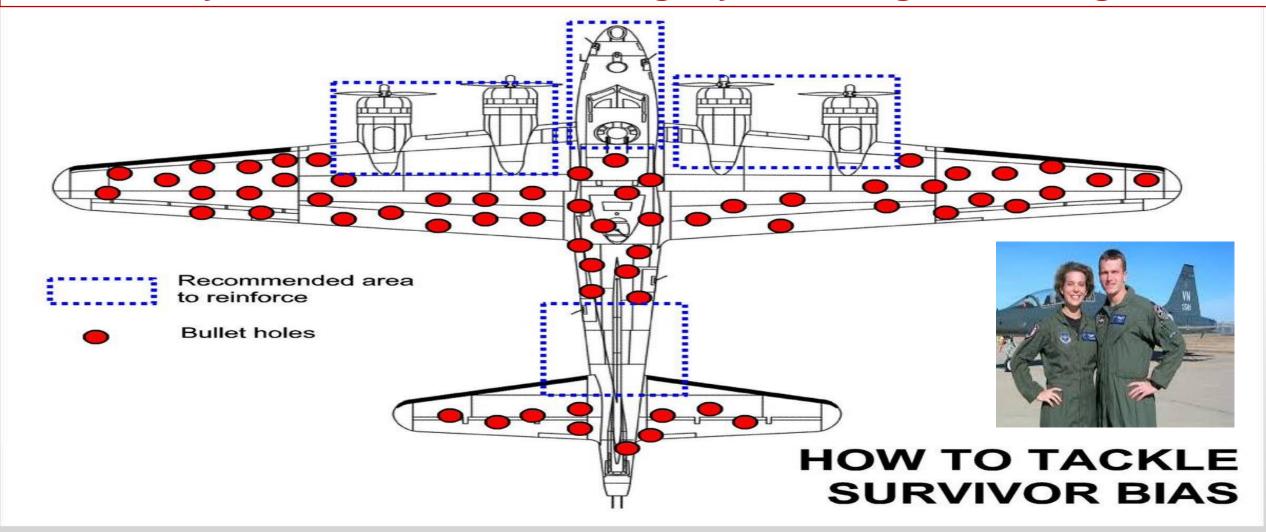
From: (Ultra) Reliable-Content-Blind-Transmit-without-Understanding

The transmitter blindly determines what to send in high symbol fidelity

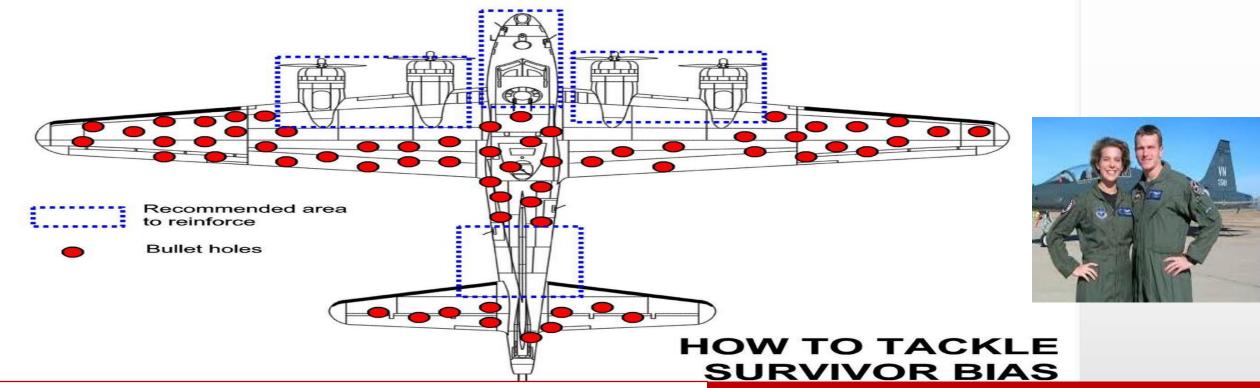
→ All data has same relevance without a specific meaning to receivers



Reliably deliver data is not enough, you need good intelligence



Reliably deliver data is not enough, you need good intelligence



Al Native Communications opportunity Sharing of pragmatically informative messages rather than "Just move" or reproduce data at spatially separated locations ... exploit the reasoning capability of Al

WHAT RELIABILITY MEANS IN THE ERA OF AI? RETHINKING THE DATA-GENERATION TO USE CHAIN

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

To: Understanding & Effectively Conveying the Intended Meaning

→ Enabling more context-aware & meaningful interactions between Intelligent Agents.

Moving beyond the exchange of raw data towards communication that is context-aware, goal-driven, and capable of preserving and conveying the intended meaning of information

Share only knowledge that cannot be reliably deduced or predicted by the receiver Al agent

Semantic communications to facilitate knowledge sharing, consensus-building & the integration of diverse perspectives, distributed reasoning & collaboration among AI systems

WHAT IS A SEMANTIC COMMUNICATION



Ask chatGPT?

As of my last knowledge update, the term "wireless semantic communications" is not an established term in the field of wireless communication.

No consistent definition of semantic communications yet : research in semantic communication is still in its infancy

• The most nucleus concern in the theory of semantic information is the meaning contained in the information.

Semantic communication goal is to stimulate reasoning rather than ensuring high bit accuracy of shared (raw) data at the receiver side.

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?

SHANNON AND WEAVER, 1949





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

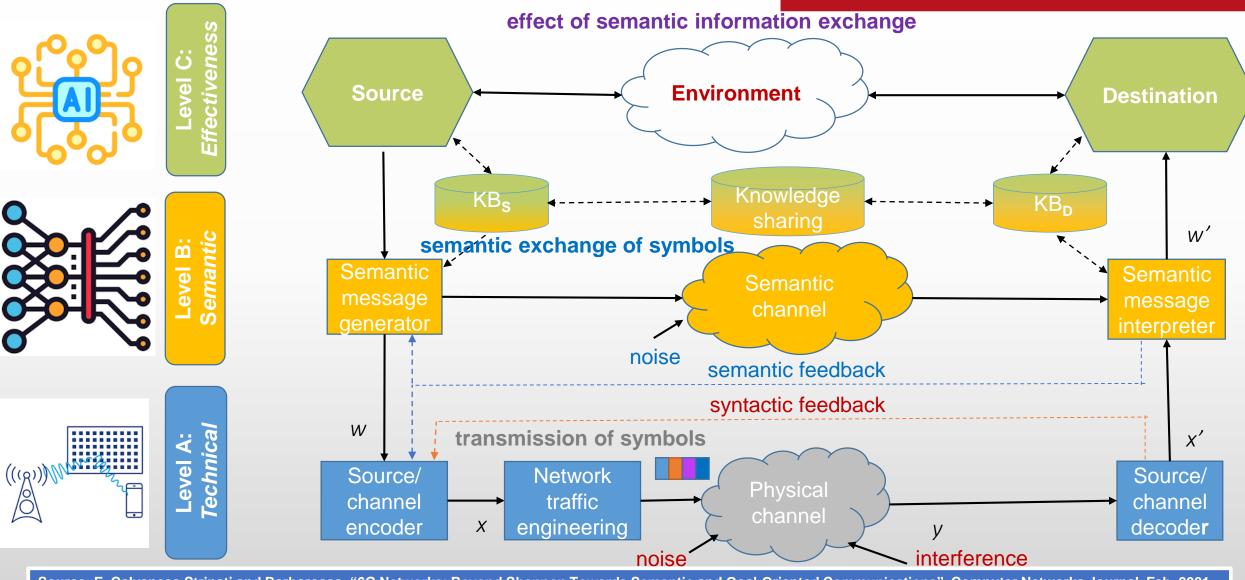
Level B (*The semantic problem*.): How precisely do the transmitted symbols convey the desired meaning?

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

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

WIRELESS SEMANTIC COMMUNICATIONS

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



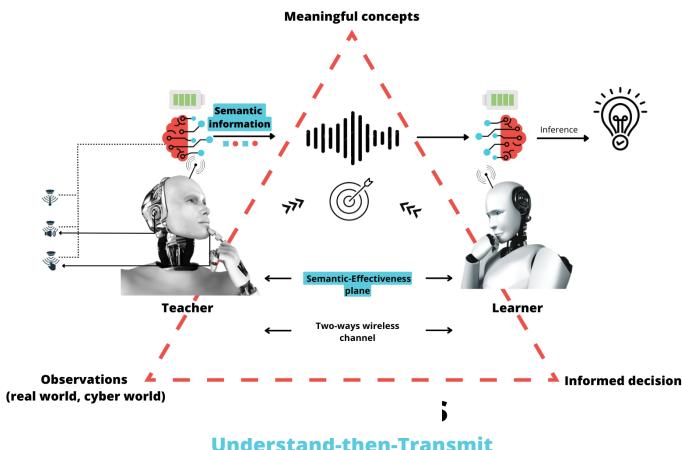
Source: E. Calvanese Strinati and Barbarossa., "6G Networks: Beyond Shannon Towards Semantic and Goal-Oriented Communications". Computer Networks Journal, Feb. 2021.

HOW TO DEFINE THE SEMANTIC COMMUNICATION PROBLEM?

Signals carry information on the physical world.

Concepts describe concrete objects and their relations in the physical world.

Languages describe signals and goals, allowing both the world and theories about the world to be symbolized and abstracted (though semantic representations).



Understand-then-Transmit

The Semantic problem accurate generation, processing & transmission of the *intended meaning* rather than individual bits and symbols (Level A)

SEMANTIC COMMS GAINS

Data Compression (Comm & Processing gain): x 1000 factor

Robustness (Comm, Inference, Task accomplishment)

Robustness versus ambiguity trade-off



Inducing AI Reasoning (at transmitter and receiver)

- Handling and planning exceptions
- Outliner data detection/pruning

Al Energy cost reduction & Sustainability of the full data-to-intelligence chain

- Less data sensed, transmitted, processed, stored
- Smaller memories and less layers in NN to achieve inference reliability

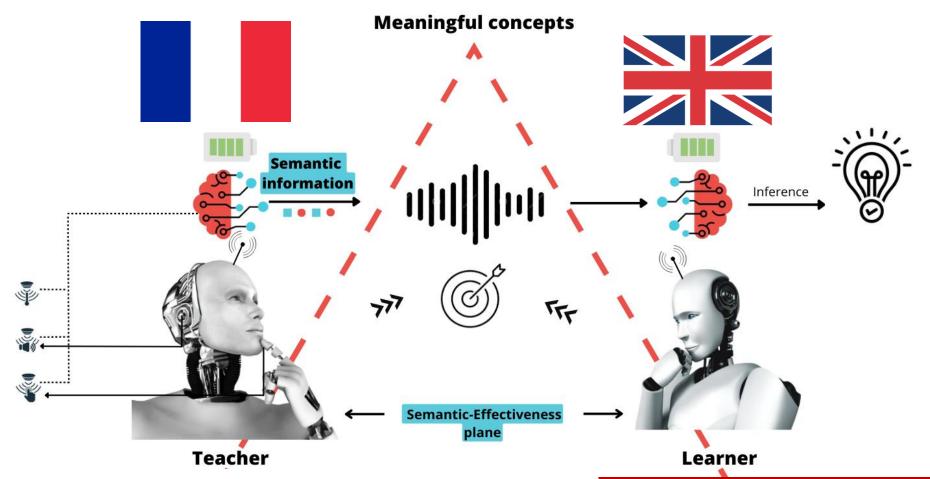
Reduced Communication Networks Resource Use (spectrum, RIS, relays,...)

SEMANTIC COMMUNICATIONS: NOT JUST JOINT SOURCE CHANNEL CODING

Source coding data Compression is the process of encoding, restructuring or otherwise modifying data in order to reduce its size.

Semantic Communications extract and learn knowledge structure, reuse it and infer logical decision based on the language that organize information and maps observed data points into corresponding symbolized semantic representations.

Fi you cna raed tihs, yuo hvae a sgtrane mnid too. Cna you 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 rschearch at Cmabridge Uinervtisty, it dseno't mtaetr in waht oerdr the Itteres in a wrod are, the only improamtnt tihng is taht the frsit and Isat Itteer be in the rghit pclae. The rset can be a taotl mses and you can sitll raed it whotuit a phoerim. Tihs is bcuseae the huamn mniddeos not raed ervey Iteter by istlef, but the wrod as a wlohe. Azanmig huh? yaeh and I awlyas tghuhot slpeling was iprnorantt!



Understanding / Reasoning differently

When teacher and learner do not use the same language (logic), the mapping between raw data bits and their selected semantic representation might differ, causing semantic ambiguity, thus errors!

Understand-then-Transmit

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



Several months

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

Communication to ask for bread



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

Shannon

Weaver

CONCLUSIONS

- Semantic Communications build a common understanding model
- Communication should be pragmatic: it is not about how the teacher (sender) thinks but how the learner (receiver) should understand
- It is how the language the teacher speaks shapes the way the learner thinks
- Semantic communications are about what "concepts" and their relations (knowledge evolution) the teacher intends to create at the learner
- Information versus Knowledge: Semantic as an universal way to communicate, to transfer knowledge
- Semantic Information as the intentional minimal representation of required knowledge for the learner to "understand" and reason about received information

There are many open challenges: contact me if you want to discuss it in details!













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Networks

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

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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

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

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 blueiee taht I cluod aulacity uesdnathrd 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 olay iproamtnt tihng is taht the frsit and Isat Itteer be in the rghit pclae. The rset can be a taotl mses and you can sitll raed it whotuit a phoerlm. Tihs is bouseae the huamn mniddeos not raed ervey Iteter by istlef, but the wrod as a wlohe. Azanmig huh? yaeh and I awlyas tghuhot slpeling was ipmorantt!