



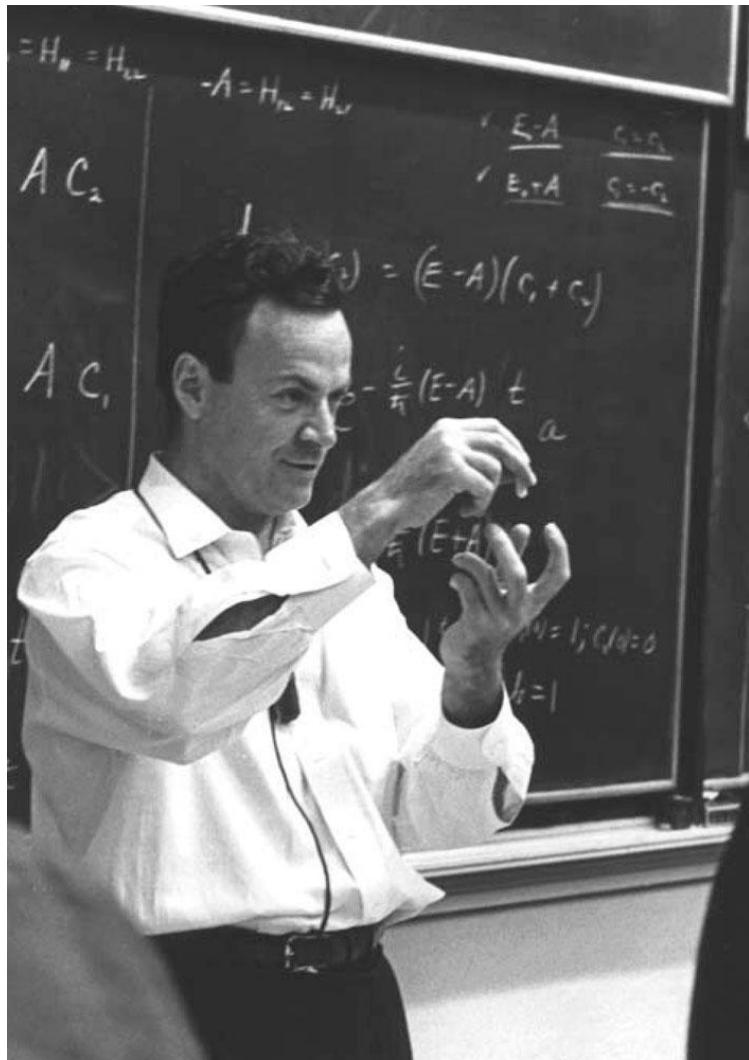
<http://www.n3cat.upc.edu>

Graphene applied to wireless nanocommunications: From networks-on-chips to reconfigurable metamaterials

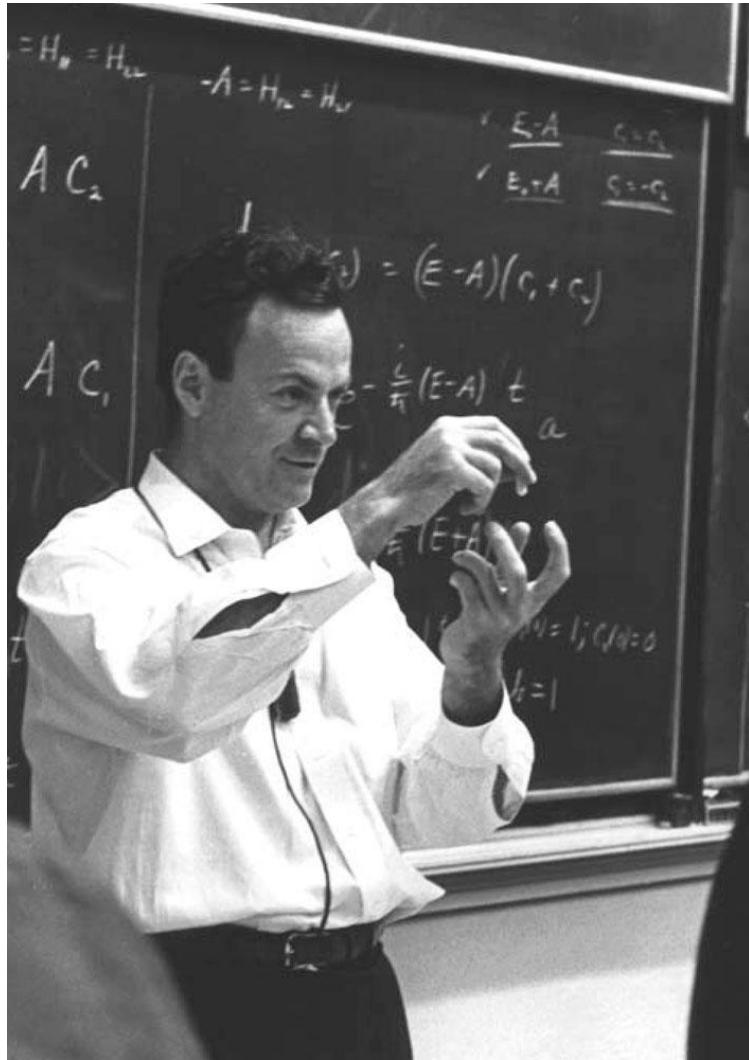
Sergi Abadal

abadal@ac.upc.edu

www.sergiabadal.com



“There’s
plenty of
room at the
bottom”



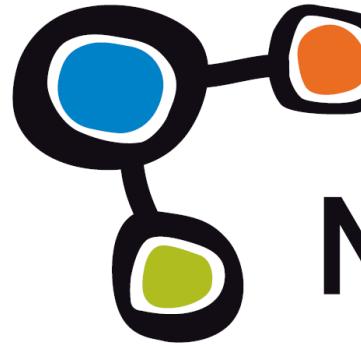
Nanotechnology:

Manipulation of matter at an atomic, molecular, and supramolecular scale

(atom: 0.15 nm)

(DNA: ϕ 2 nm)

(bacteria: 200 nm)



N3Cat

Nanonetworking Center
in Catalunya

*Research Center within UPC devoted to
investigating how nanotechnology can be leveraged
to improve current communications and networks*

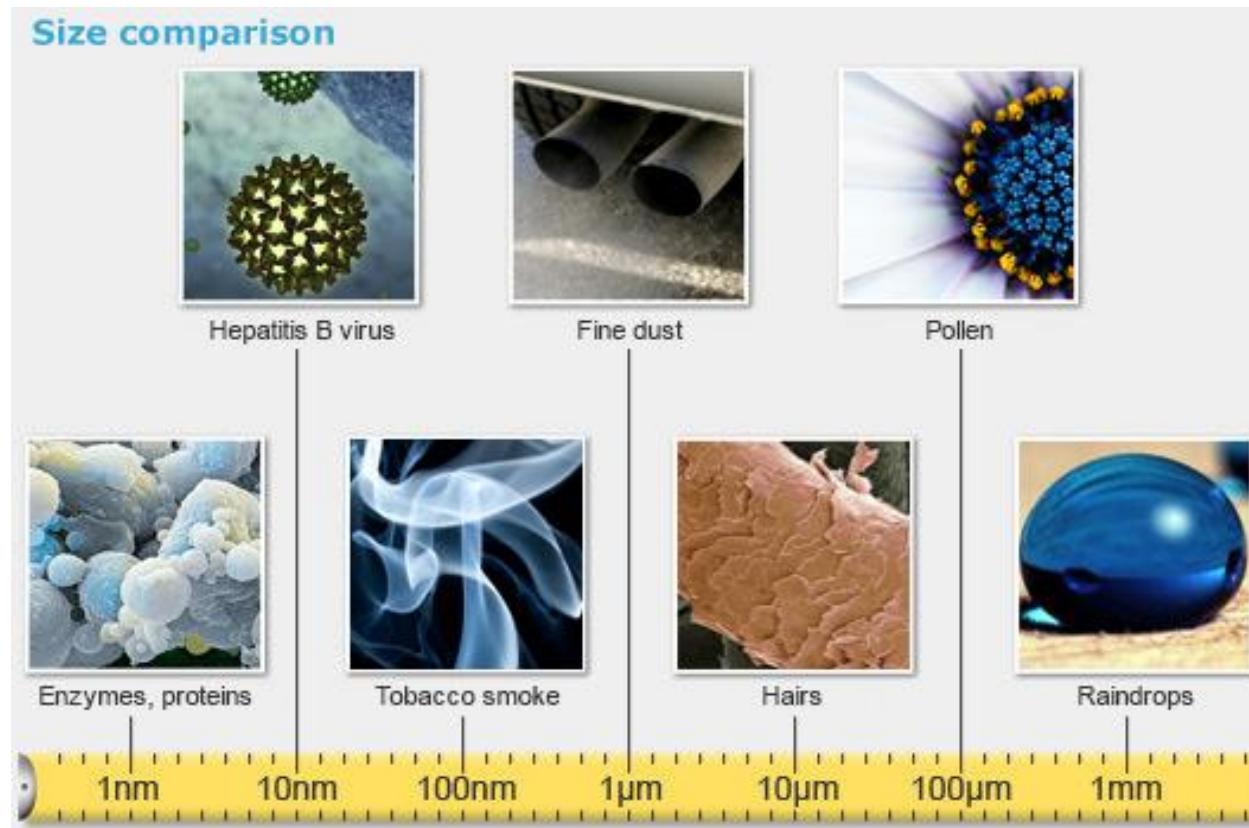


N3Cat

Nanonetworking Center
in Catalunya

NANO: working at very small sizes
and making use of nanotechnology

- Nanodevices, nanocommunications, nanonetworks: composed by elements whose dimensions are on the nanometer scale
 - 1 meter = 10^9 = 1.000.000.000 nanometers





N3Cat

Nanonetworking Center
in Catalunya

MULTIDISCIPLINARY: we need experts
in materials, telecom, computer
science, biotechnology...

- Core members in different departments at UPC

- Josep Solé i Pareta (AC)
- Albert Cabellos (AC)
- Eduard Alarcón (EE)
- Sergi Abadal (AC)



- Members in other institutions

- Universitat de Buffalo (USA)
- Universitat de Tampere (Finland)
- Koc University (Turkey)





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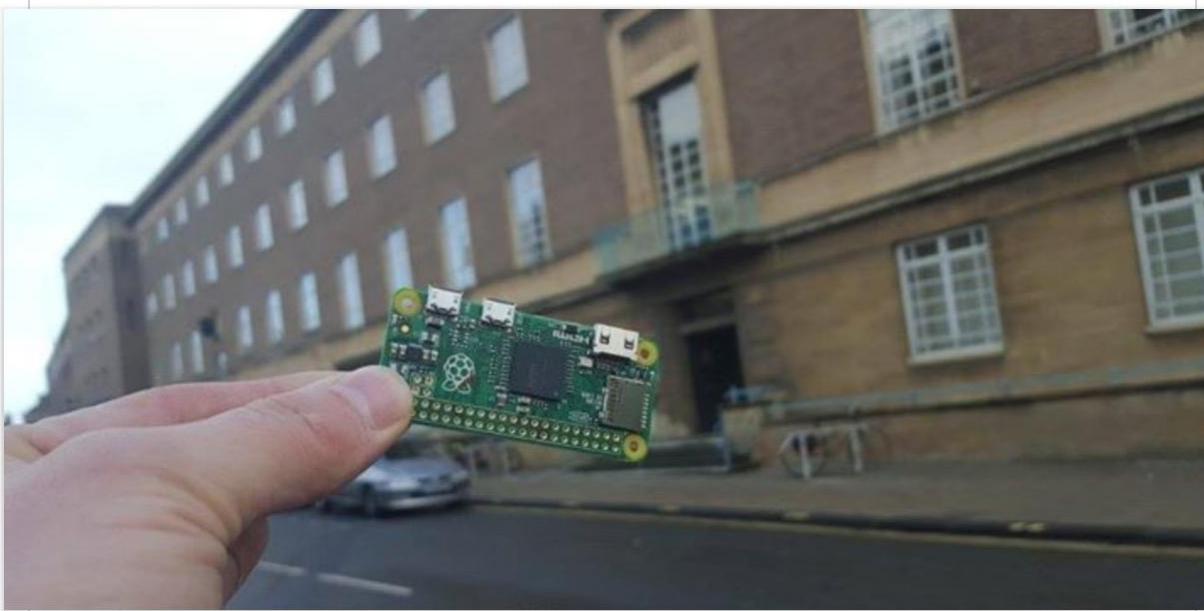
Nanonetworking Center
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DISRUPTIVE: we do not seek
incremental advances, our prospects
are (at least) 10 years from now

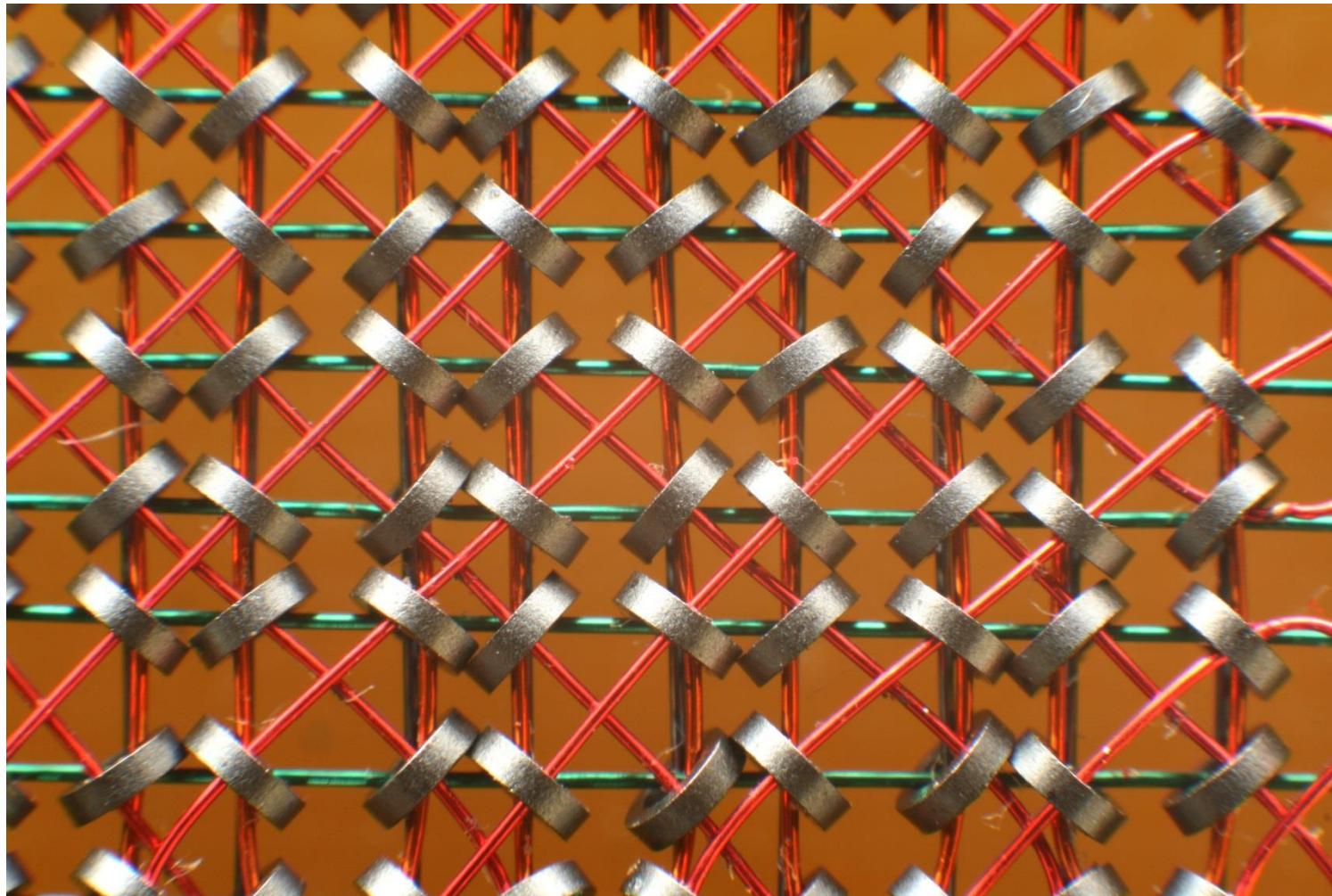
- Which is the downscaling límit of communication devices and systems? Ten years ahead and beyond



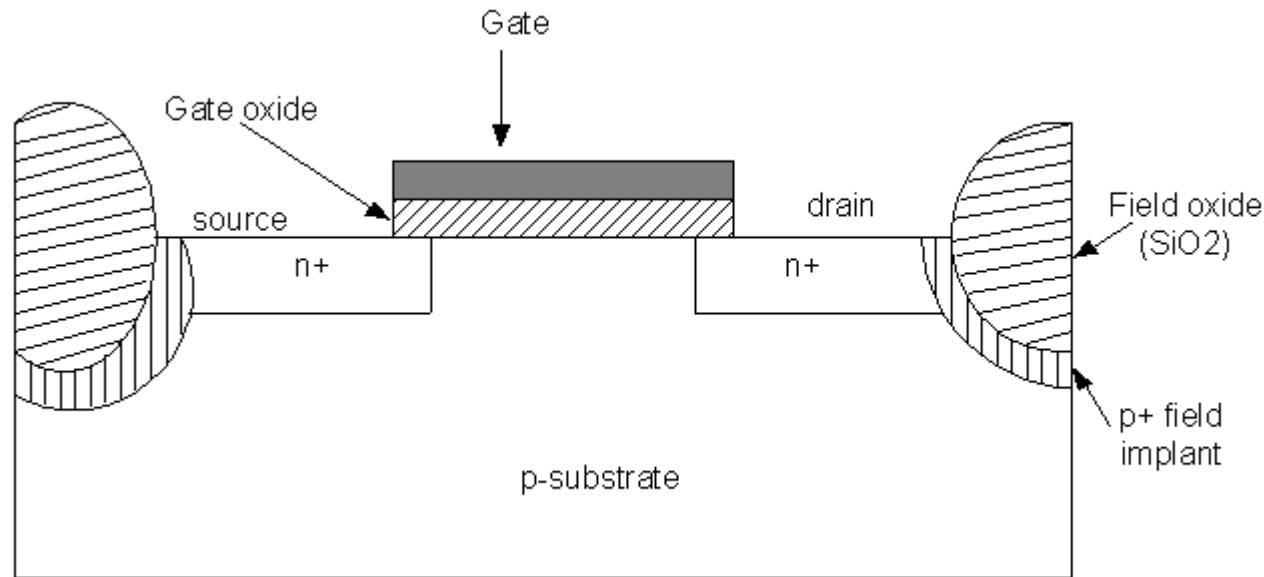
Same place, 60 years later



The beginning: Magnetic-core memories vs. pen drives



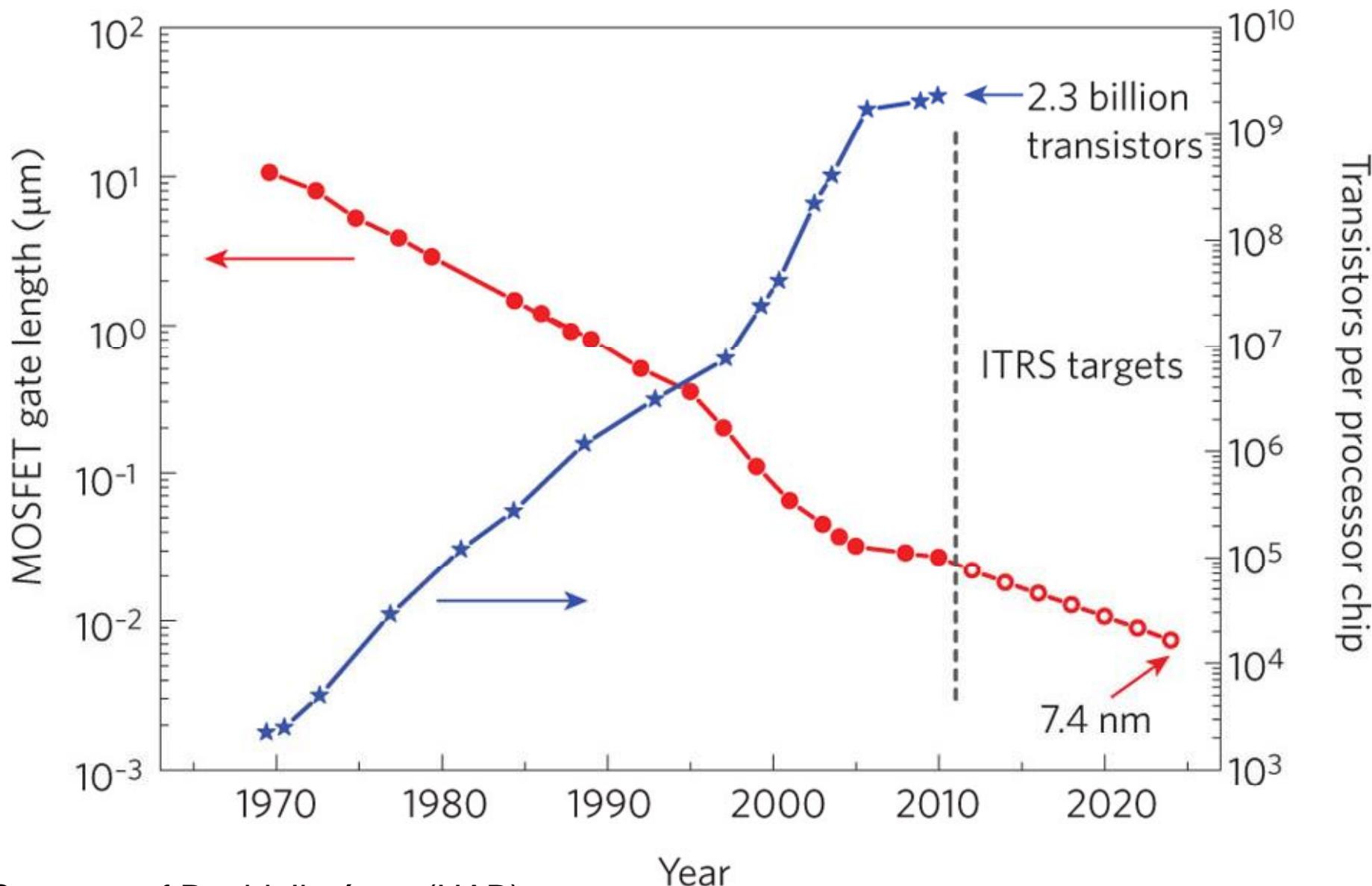
- A ferrite memory of 0.25 m^2 could hold 0.5 KB
 - PDP 11 had 128 ferrite boards for an amazing 64 KB
- Newest USB drives have surpassed the TB barrier
 - That means 12-15 orders of magnitude greater density
- **Where's the catch?**
 - The use of the right material: silicon
 - It allowed the creation of basic devices such as the transistor, the foundation of almost any electronic device today
 - Technology advances have later allowed us to make smaller, faster, more efficient transistors → Moore's Law
- **Is this going to be forever?**



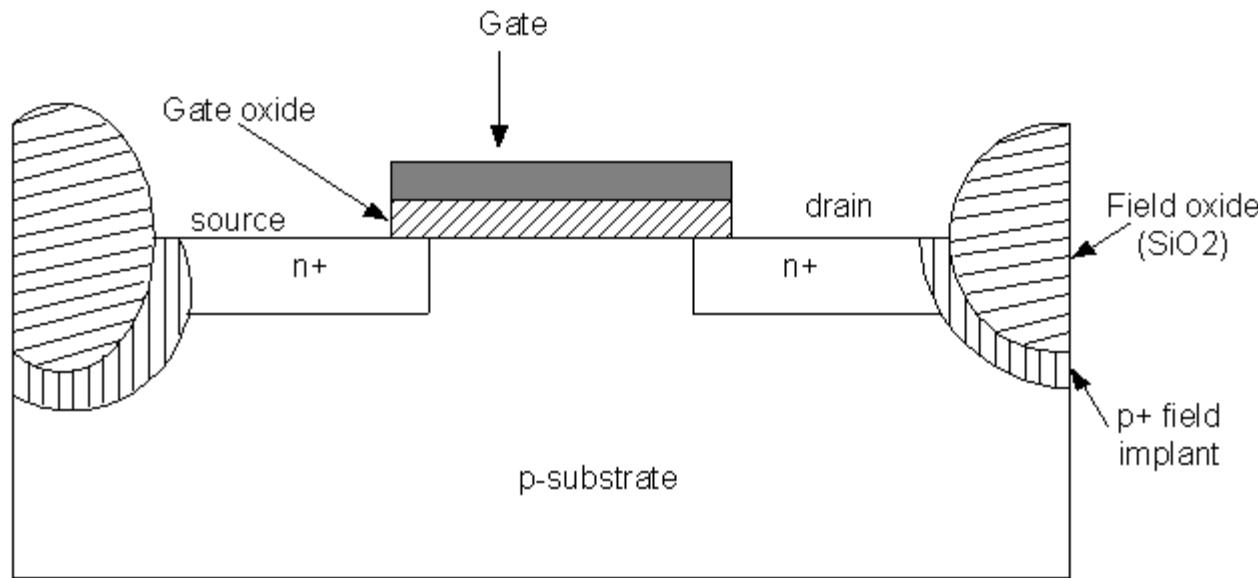
Consequences of Dennard scaling

- Smaller means, of course, higher density
- Smaller means more efficient
- Smaller means faster

Evolution of silicon transistors



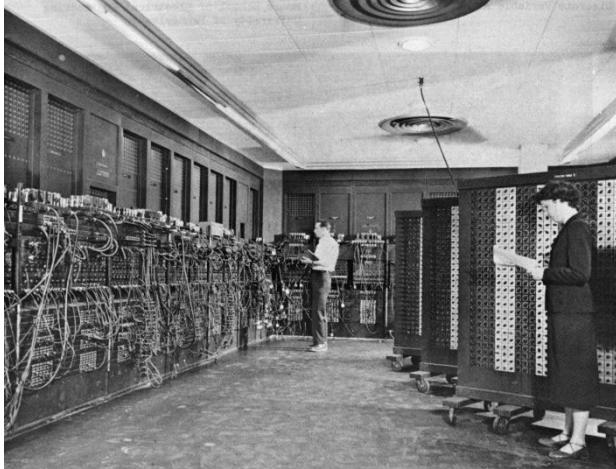
A transistor



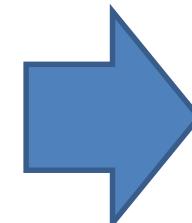
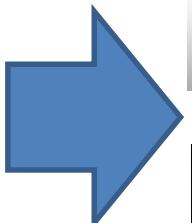
- Problem #1: it becomes increasingly difficult to avoid quantum tunneling
- Problem #2: the technology has a limit – transistors with a few atoms?

- So, is this going to be forever?
- No, we arrived pretty far with silicon, but the Moore's era will end soon
- We need a solution:
 - More Moore: desperately looking for ways to further scale down transistors
 - More than Moore: application-driven components with other architectures (accelerators), other functionalities (sensing) and, in the end, ***other materials***

First technologies



Mastering Silicon



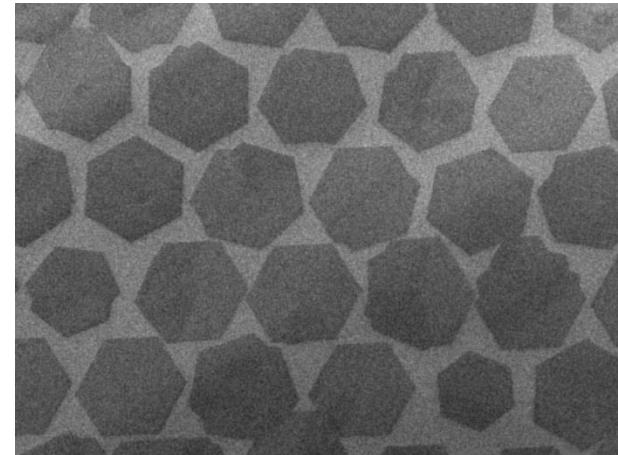
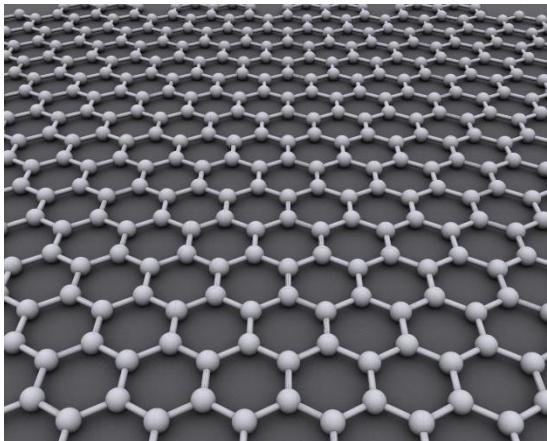


Graphene

Singular properties and applications

Graphene

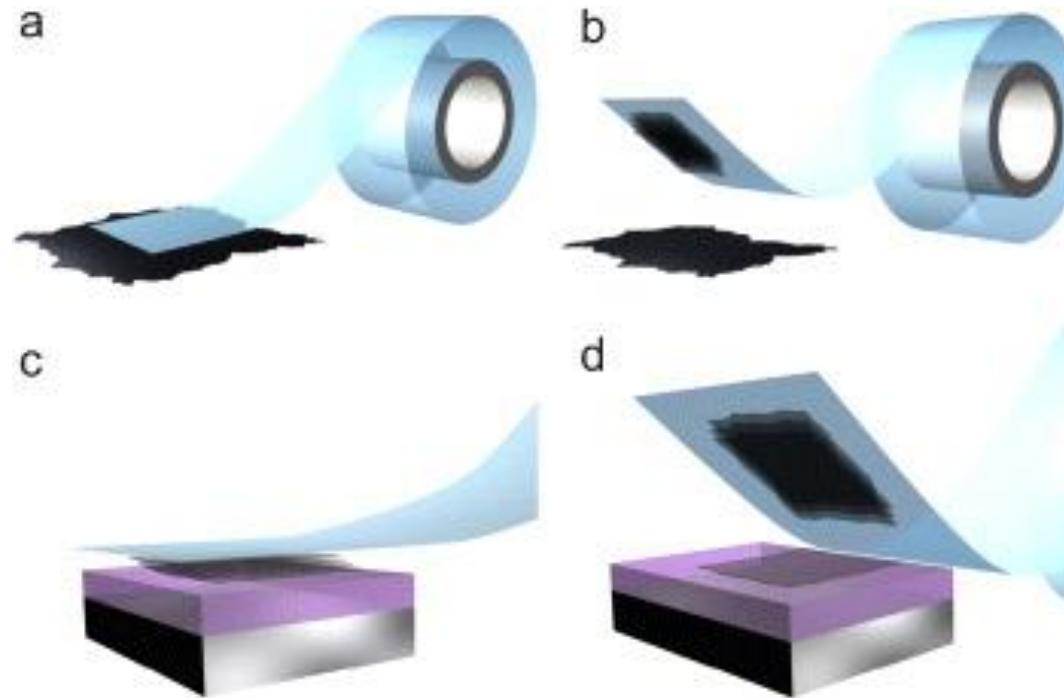
- One-atom-thick honeycomb lattice of carbon atoms (2D)
- First theorized by P. Wallace in 1947
- First isolated by A. K. Geim and K. S. Novoselov in 2004
- A. K. Geim and K. S. Novoselov are awarded with the nobel prize in physics in 2010



Graphene: How to isolate it



- Scotch tape method



- Now the challenge is how to make this at massive scales and obtain graphene with good properties

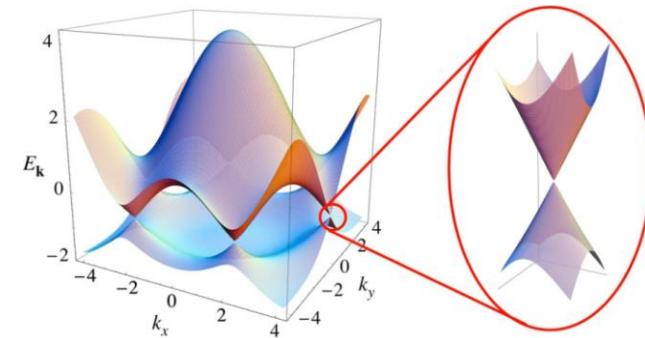
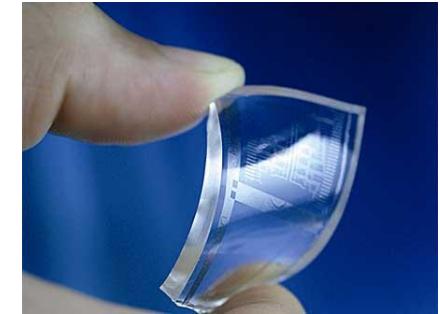
The properties of graphene



2D

What are graphene's extraordinary properties?

- Thinnest and lightest material in nature
- Tougher than diamonds
- More resistant than steel (300 times)
- Impermeable
- Transparent
- Extremely flexible
- Great thermal conductor
- **Better electrical conductor than copper**



Applications of graphene



GRAPHENE FLAGSHIP

https://res.cloudinary.com/mynewsdesk-cld/image/upload/t_limit_1000/a5oqeh1zjymy5qwj7z6u.jpg

- These properties lead to a wide variety of potential applications

- Materials

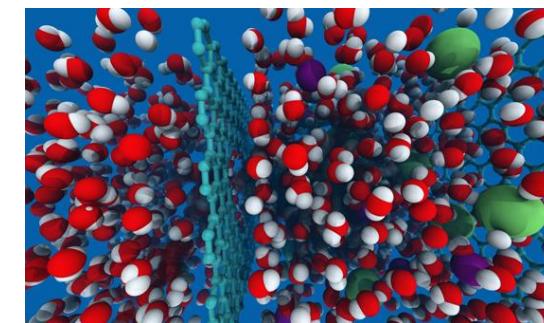
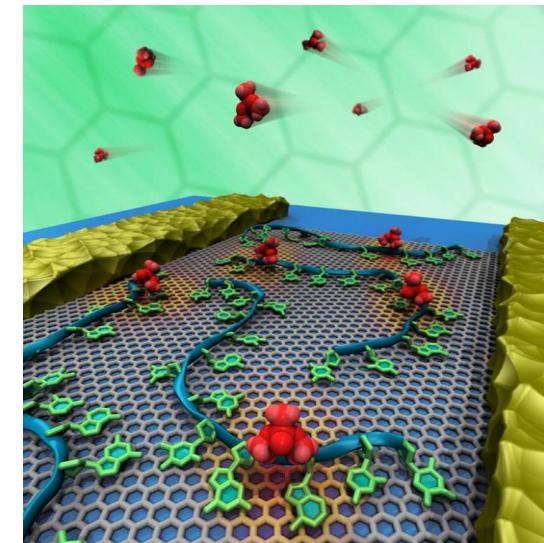
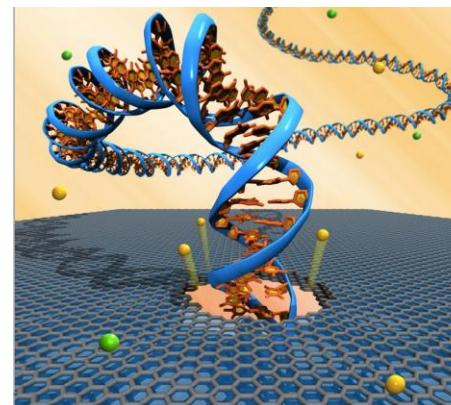
- Next generation of touch screens: dirt-repellant
 - Light but strong structures for aeronautics

- Chemistry

- Ultra-precise gas sensors
 - Filters for polluted water (radioactive)

- Bio-medicine

- Bacterium detection
 - DNA sequencing



■ Nano-electronics

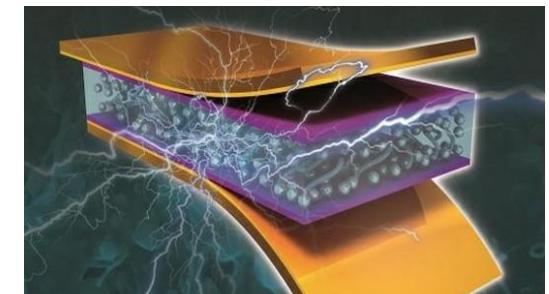
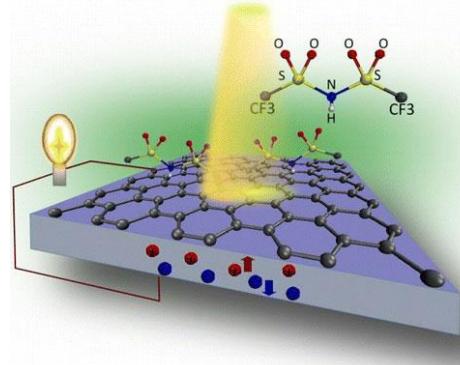
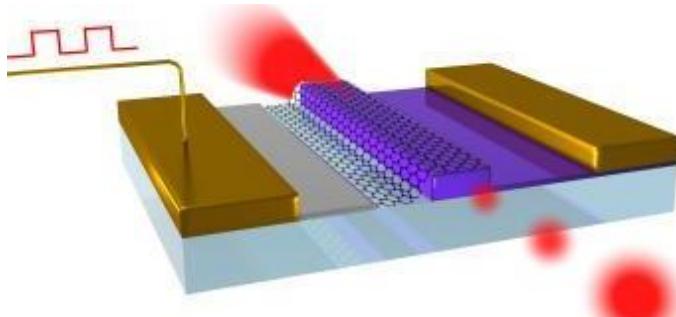
- Miniaturization of transistors and ultrafast integrated circuits
- Supercapacitors for fast-charging and long-lasting new batteries
- Piezoelectric effect at the nanoscale (nanogenerators)

■ Nano-optics

- Nano-lasers
- Optical modulators
- More efficient solar cells

■ Information and Communication Technologies

- Nanocommunication networks



The graphene-enabled future: an example



● The ***smartphone*** in 2025

- Foldable and bendable screen
- Hydrophobic materials
- Changing size and color
- Multiple sensors
- Higher autonomy
- Energy harvesting
- Haptic interface
- ***Nanoantennas???***





Nanoantennas and Nanocomunicaciones

- We just described what is graphene, which are the most important properties, and the multiple applications that it could enable
- We have also seen that this material has a huge economic potential and has opened the door to lots of opportunities in Europe and around the world
- Now, we focus on the importance of graphene in the ICT context in general and, in particular, in the development of nanocommunication networks.

■ Nano-electronics

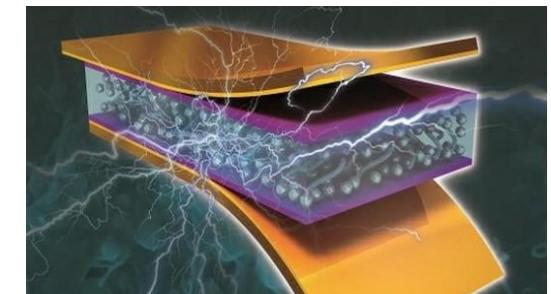
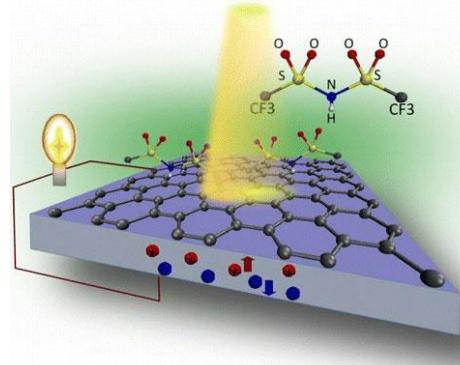
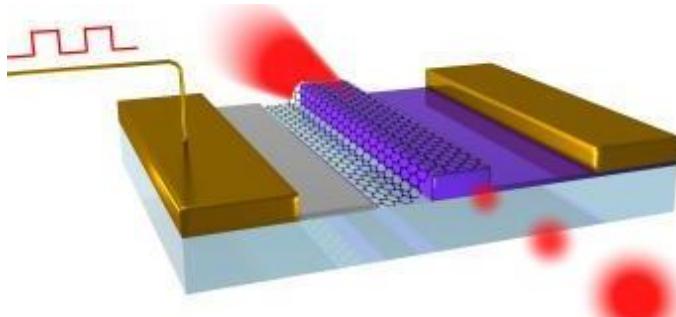
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- Piezoelectric effect at the nanoscale (nanogenerators)

■ Nano-optics

- Nano-lasers
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- More efficient solar cells

■ Information and Communication Technologies

- Nanocommunication networks



- What if we are capable of enabling wireless communication and networking among such miniaturized devices (down to a few μm , nm)?

● **How?**

- Reducing the size of the communication system: the antennas first

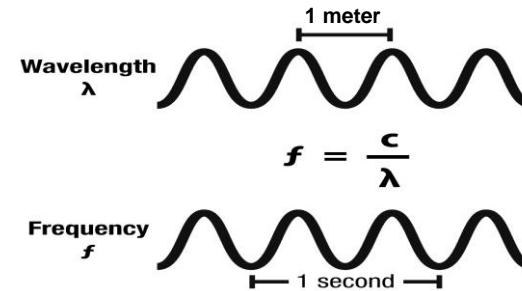
● **For what?**

- Allowing the nanodevices (or nanomachines), which are very basic functional units, to cooperate among them to perform more complex tasks
- Place antennas in complex systems, but that are extremely constrained in area

● The resonance frequency

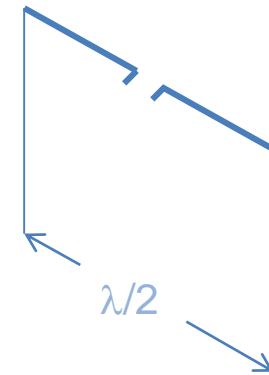
- An RF antenna is a tuned circuit that has an inductance and a capacitance, which lead to a given resonant frequency (waves oscillate constructively inside the antenna)
- This frequency is used as the transmission and reception frequency of the antenna
- The main characteristic determining the resonant frequency is the size of the antenna. The longer are the antenna elements, the lower the resonant frequency

The relation between frequency f and wavelength λ in a metallic antenna is:



● Antenna dimensions

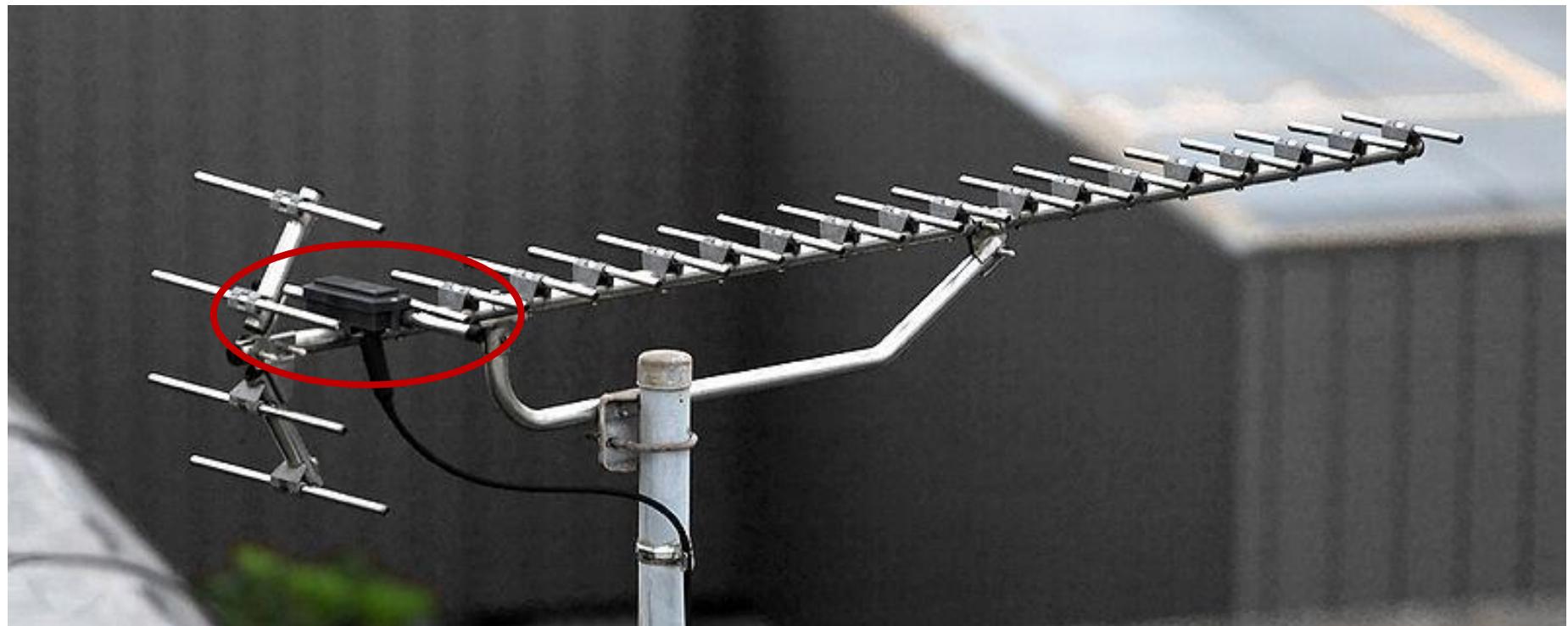
- The length a metallic antenna use to receive signals from a given frequency needs to be $\lambda/2$

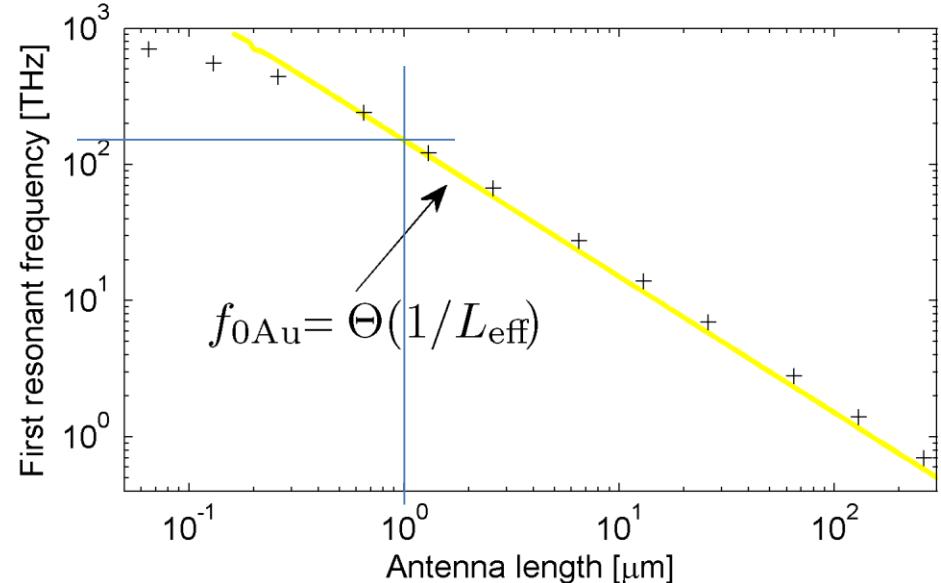
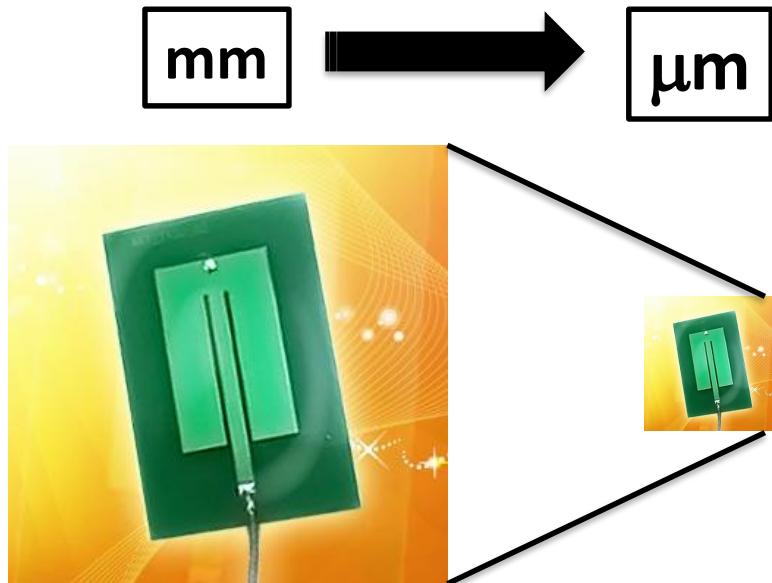


● Examples:

- VHF (Very High Frequency): 30 – 300 MHz $\rightarrow \lambda$: 10 - 1 m
- UHF (Ultra High Frequency): 300 MHz – 3 GHz $\rightarrow \lambda$: 1 – 0.1 m
 - $\lambda/2 \sim 0'30$ m (2 x 0'15 m) \rightarrow MOVIL? WIFI?

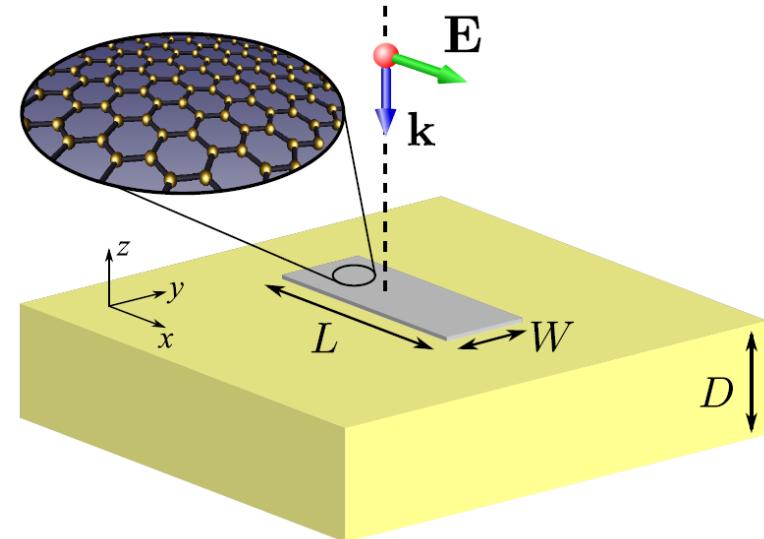
Designing antennas for nanocommunications



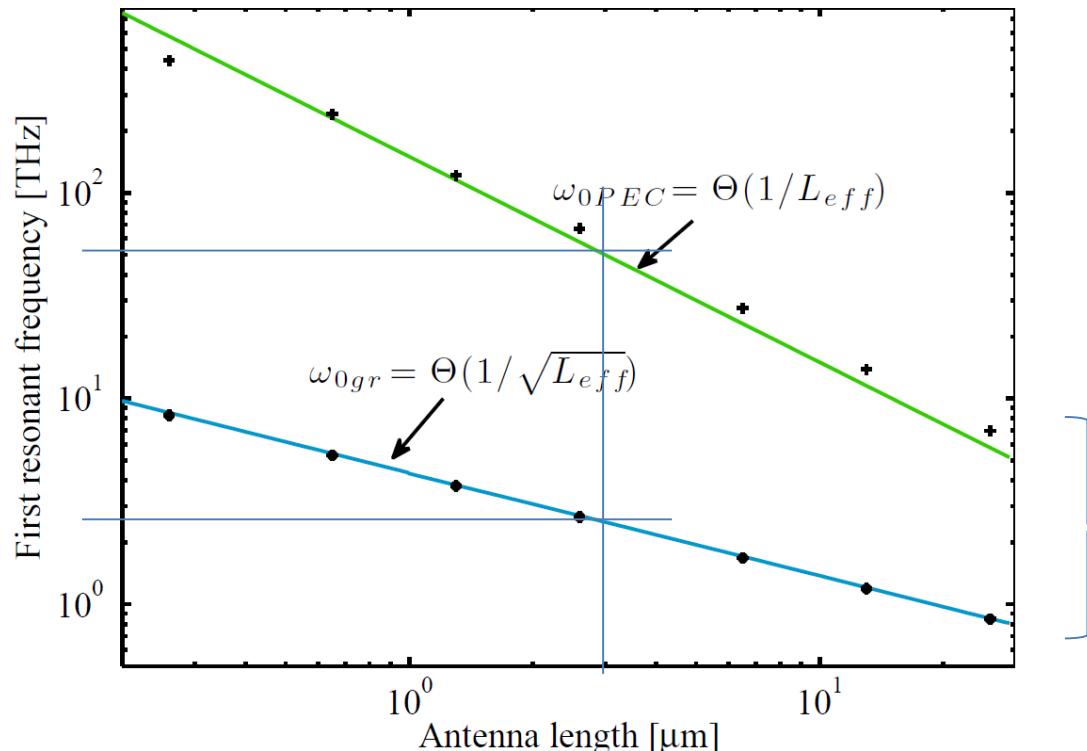


- Imagine now that we attempt to downscale our antenna to a few μm so that we can embed it in microdevices
- We just mentioned that the resonant frequency scales as $\Theta(1/L)$
- At the microscale, our metallic antenna becomes optical, which means that we need a laser to excite it (among other problems)

- This problem can be solved if instead of making our antenna out of metal, we use graphene (**graphenna**)
- Graphennas can be as simple as a high-quality graphene sheet laid over a dielectric
- The particularity of graphennas is that they are plasmonic, which causes their resonance frequency to be much lower than for conventional metallic antennas.
- Graphenna example:
 - $L \sim \text{a few } \mu\text{m}$
 - $W \sim 1 \mu\text{m}$
 - $f \sim 1 \text{ THz}$



- This unique miniaturization characteristic of graphennas makes the communications system much more integrable
- We in fact discover that these antennas do scale different from the traditional $1/L$ relation of metallic antennas (blue line)



A 3- μm long *graphenna* resonates at around 2.5 THz, one order of magnitude lower than for a same-size metallic antenna

- We started with theory, we are now trying to experimentally prove that this works

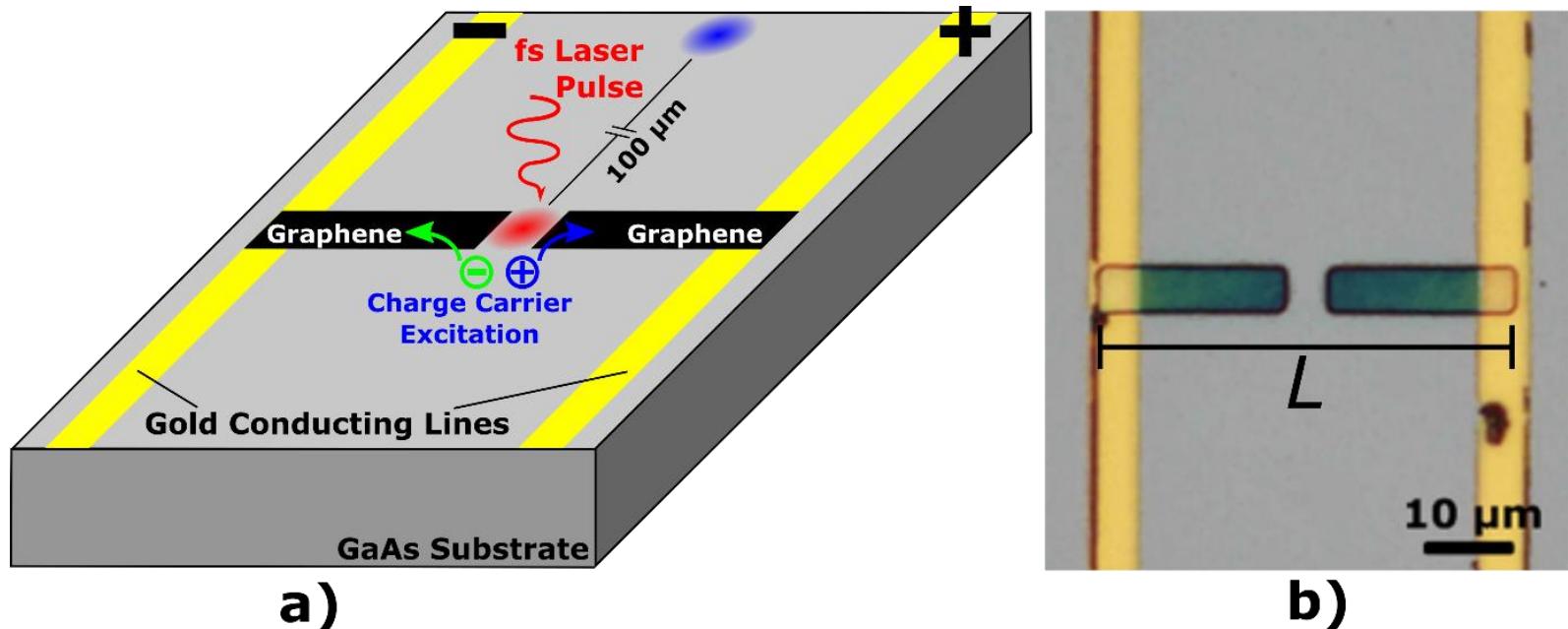
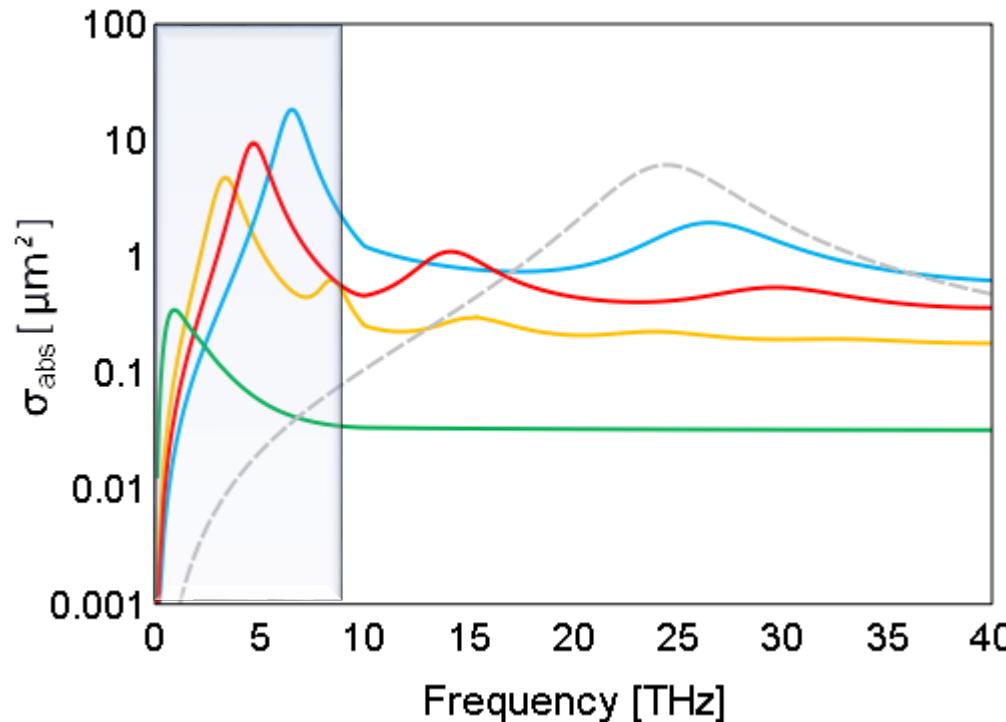
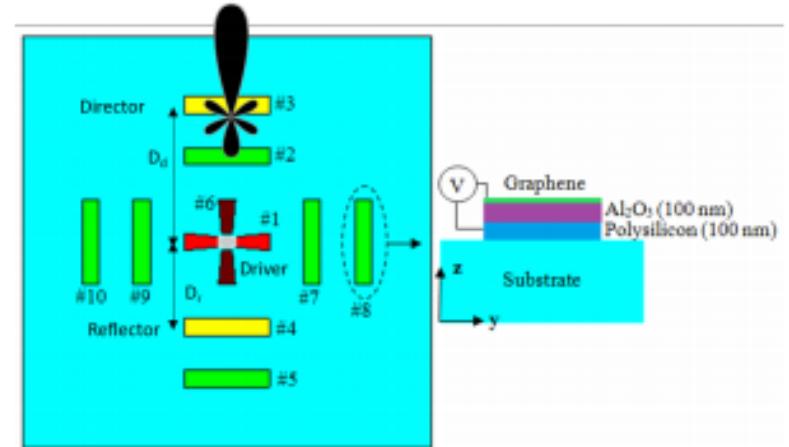
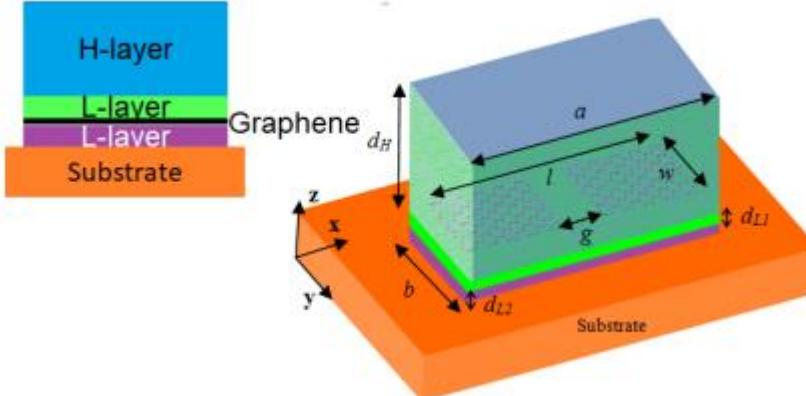
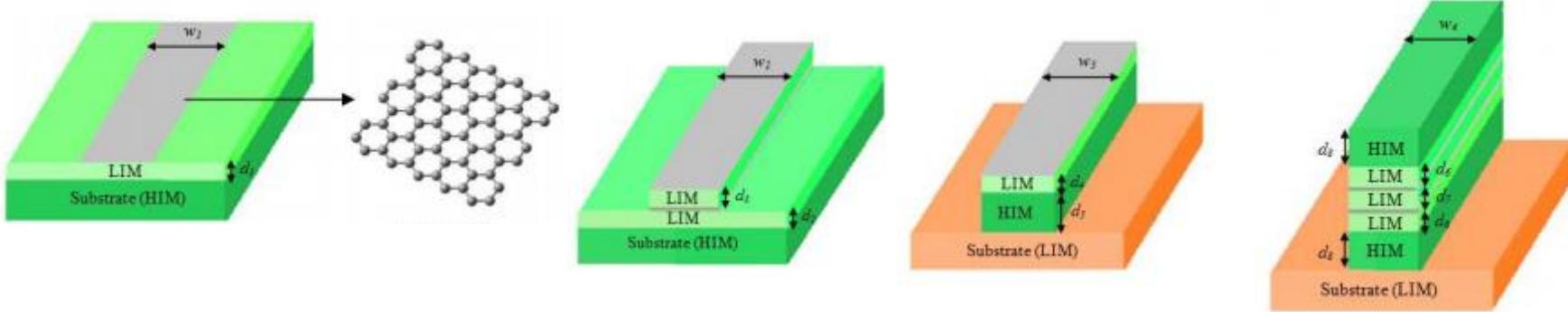


Fig. 1: a) Sample schematic. A fs-laser pulse excites charge carriers at the antenna gap. They are accelerated by the DC bias voltage applied to the gold biasing lines. The red and blue spot (not to scale) show the excitation spot at the antenna gap and 100 μm above respectively.
b) Microscopic image of the device with length $L=47 \mu\text{m}$ and PMMA resist on top.

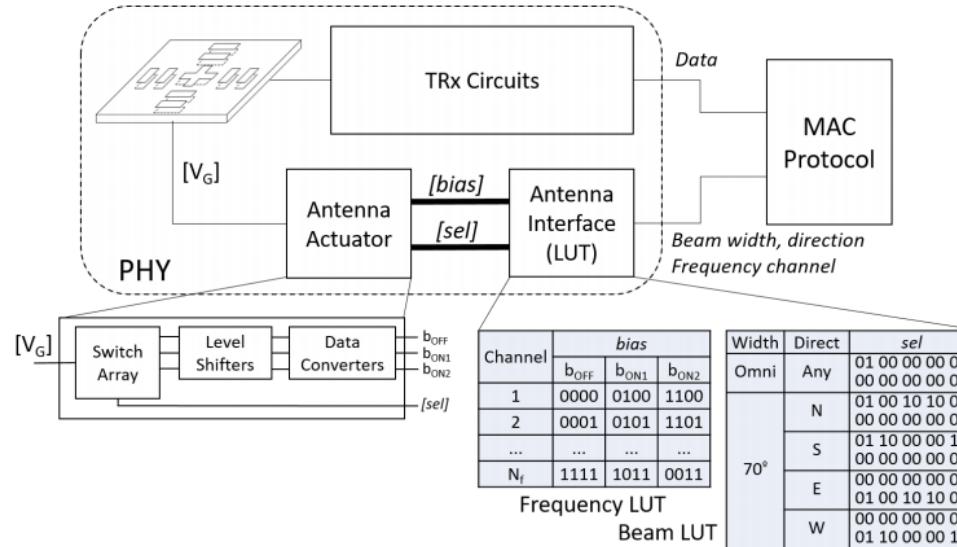
- Another compelling property of *graphennas*, compared to metallic antennas, is that its resonant frequency can be changed just changing its chemical potential (voltage, basically)



- This property offers a great flexibility when designing
 - New antennas



- ➊ This property offers a great flexibility when designing
 - 1) New antennas
 - 2) The communication protocols based on these antennas



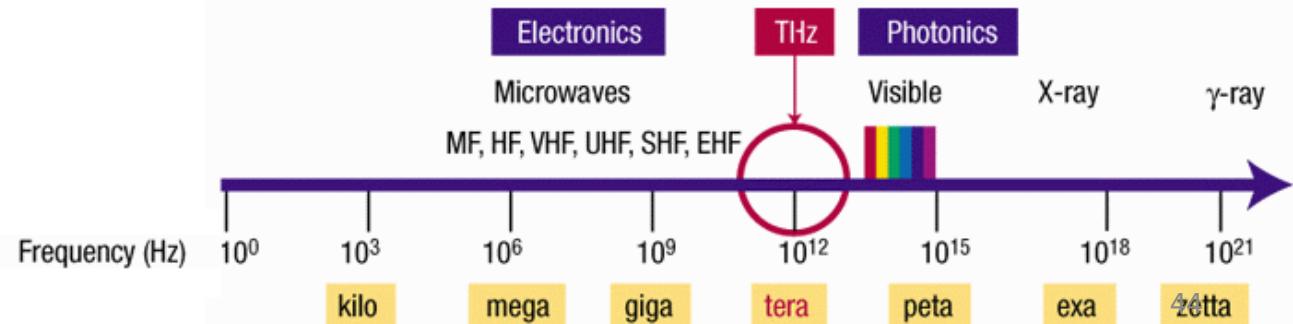
Algorithm 1 Simplified multichannel MAC protocol using the antenna controller (controller instructions in bold).

```

set(omni, any_dir, control_ch)
send(RTS, addrRX, control_ch)
{data_ch, direction} ← receive(CTS, addrRX, control_ch)
set(70°, direction, data_ch)
send(data, addrRX, data_ch)

```

- Graphennas represent a technology that allows miniaturizing wireless RF communications down to the micro and nano scales
 - 2 order of magnitude** smaller than metallic antennas
 - Radiates in the **Terahertz band** (0.1 – 10 THz)
 - The gap between the millimeter-waves (60 GHz) and the infrared-optics (100 THz) with potential for extreme speeds (~Tbps)
 - Tunable resonant frequency by just changing the voltage**
 - An unprecedented design flexibility
 - Transmission range:** from 1mm to 1m (depending on the transmission medium, the modulation, etc...)



● What if we are capable of enabling wireless communication and networking among such miniaturized devices (down to a few μm , nm)?

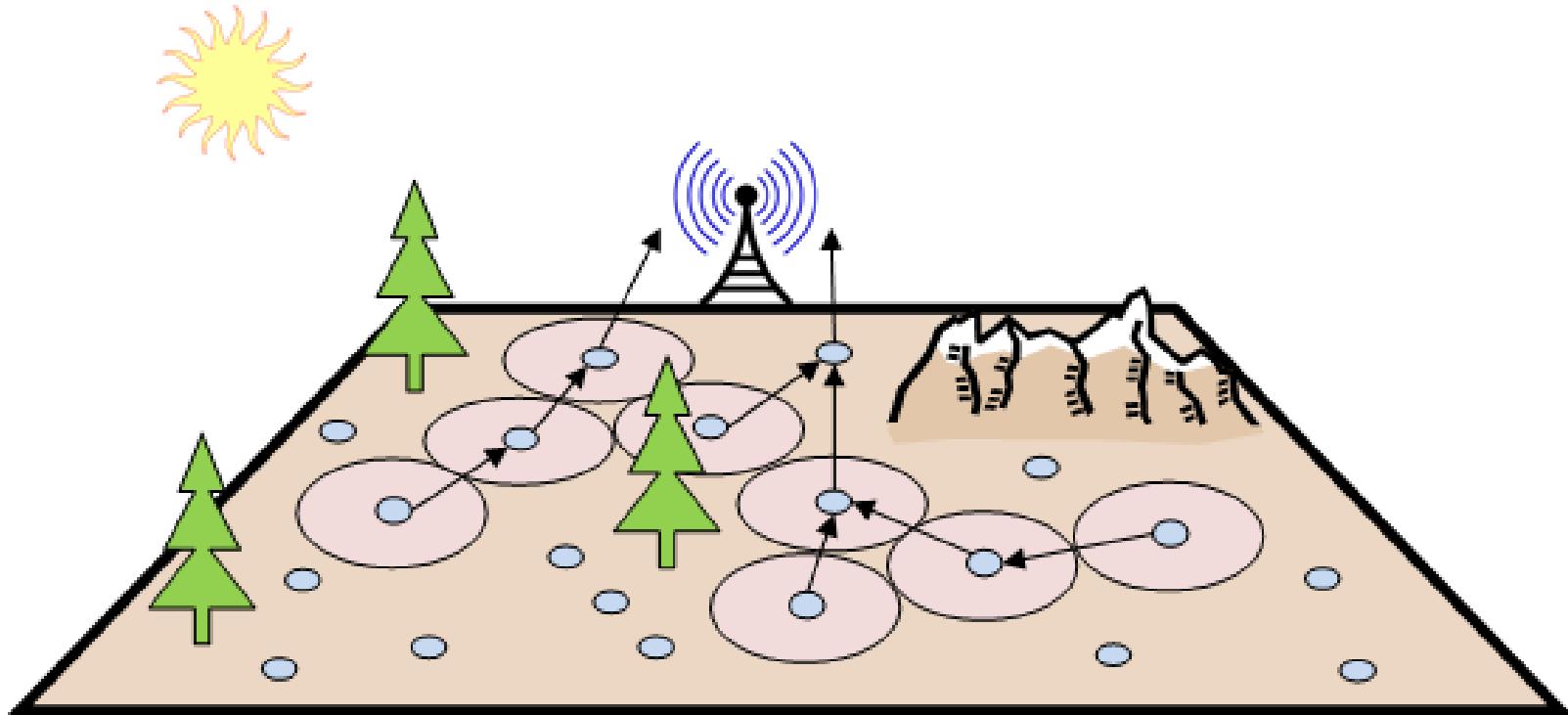
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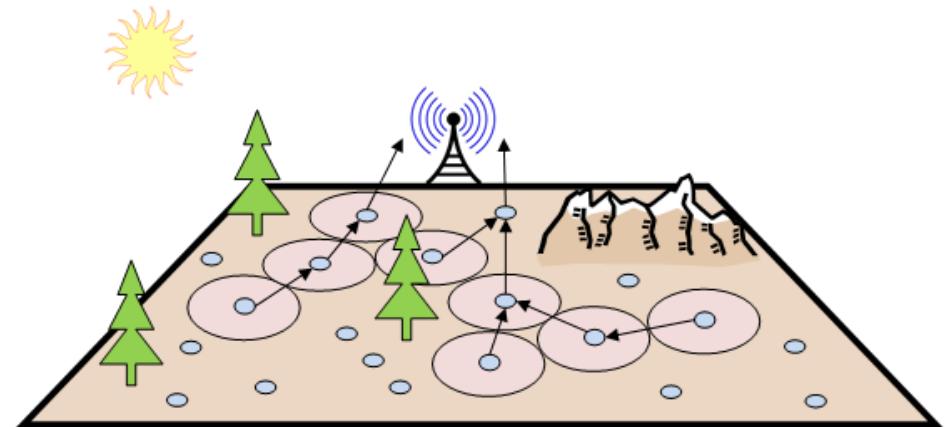
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- Place antennas in complex systems, but that are extremely constrained in area

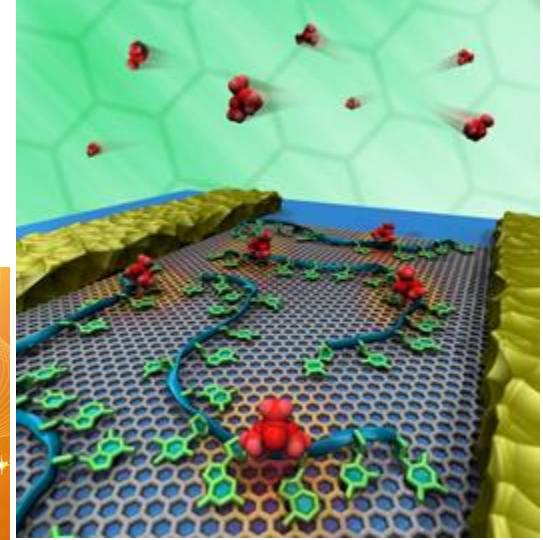
Wireless Sensor Networks and Internet of Things



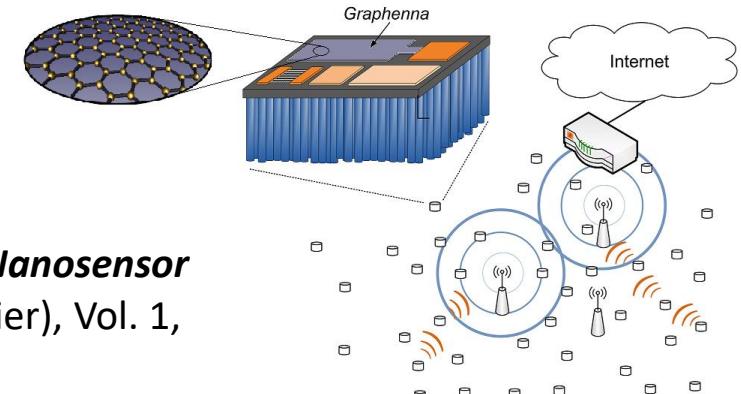
- Applications
 - Industrial IoT
 - Smart home / city / farm
 - Smart grid
 - Connected car
 - Wearables
 - ...



- **What if? Nanosensors**
 - Physical, chemical, or biological
 - Ultra-precise (single molecule)
 - Ultra-small (nano)
- **What if? Nanoantennas**

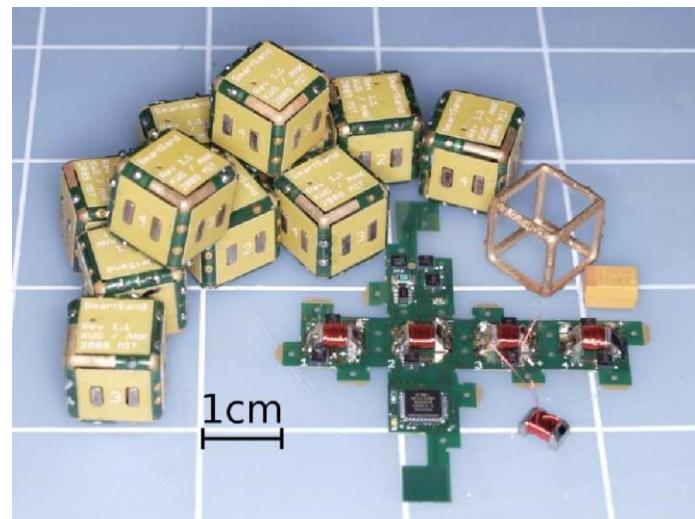
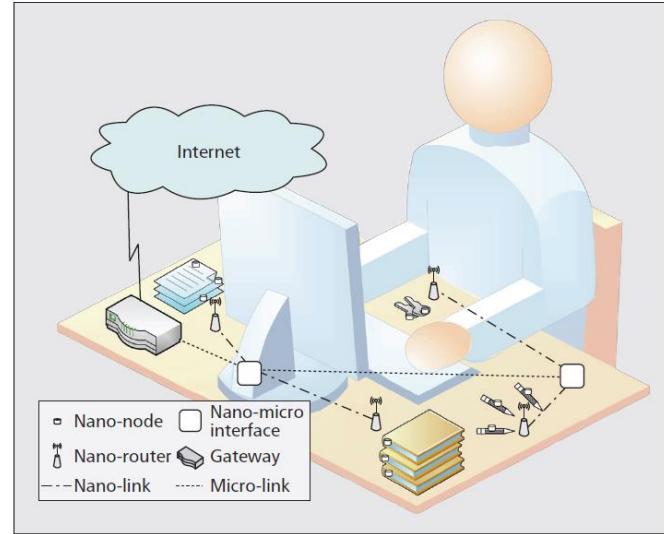


- Extension of IoT with nanosensors functionalities
 - To reach unprecedented locations
 - Concealed, implanted, scattered
 - To have unprecedented precision
 - Equipped, of course, with communication systems to reach the macroworld

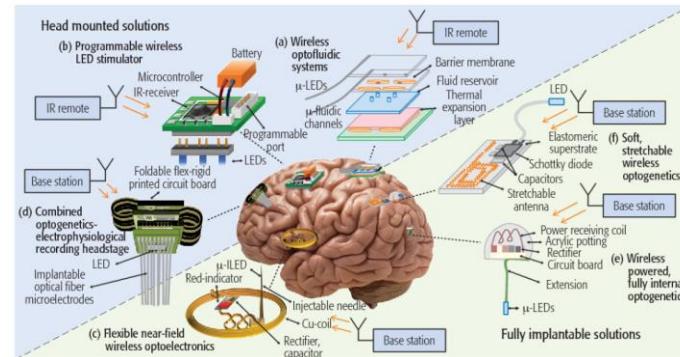
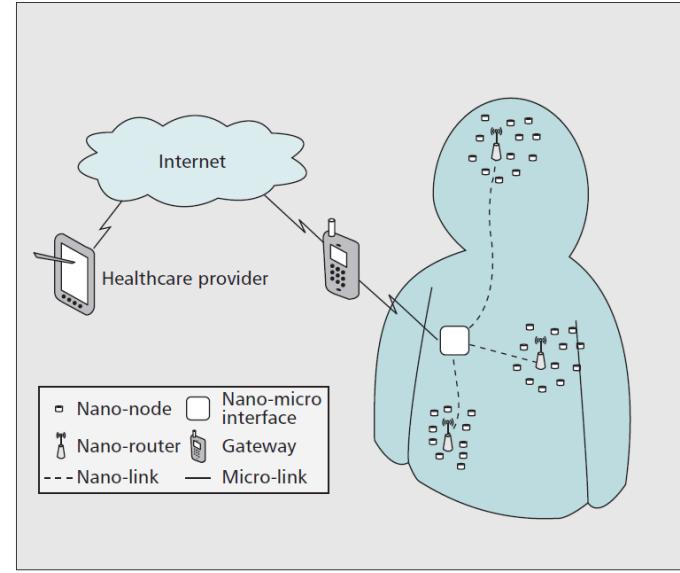


Akyildiz, I. F. and Jornet, J. M. "**Electromagnetic Wireless Nanosensor Networks**", Nano Communication Networks Journal (Elsevier), Vol. 1, No. 1, pp. 3-19, March 2010

- Interconnected office
- Smart fabrics, materials
- Programmable matter
- Haptic interfaces
- Bio-chemical defense
- Plague defeating systems
- More?



- Localized sensing
- Drug delivery (insulin)
- Ultra-precise tumor destruction
- Brain interfacing
- Functionality recovery
 - Paralysis, alzheimer



Neuralink++

● Interesting challenges

- How do we schedule transmissions to avoid interferences when we have thousands of nodes?
- How do we cope with nano-batteries, intermittent connectivity?
- How do we collectively send information to a single end-receiver?

● What if we are capable of enabling wireless communication and networking among such miniaturized devices (down to a few μm , nm)?

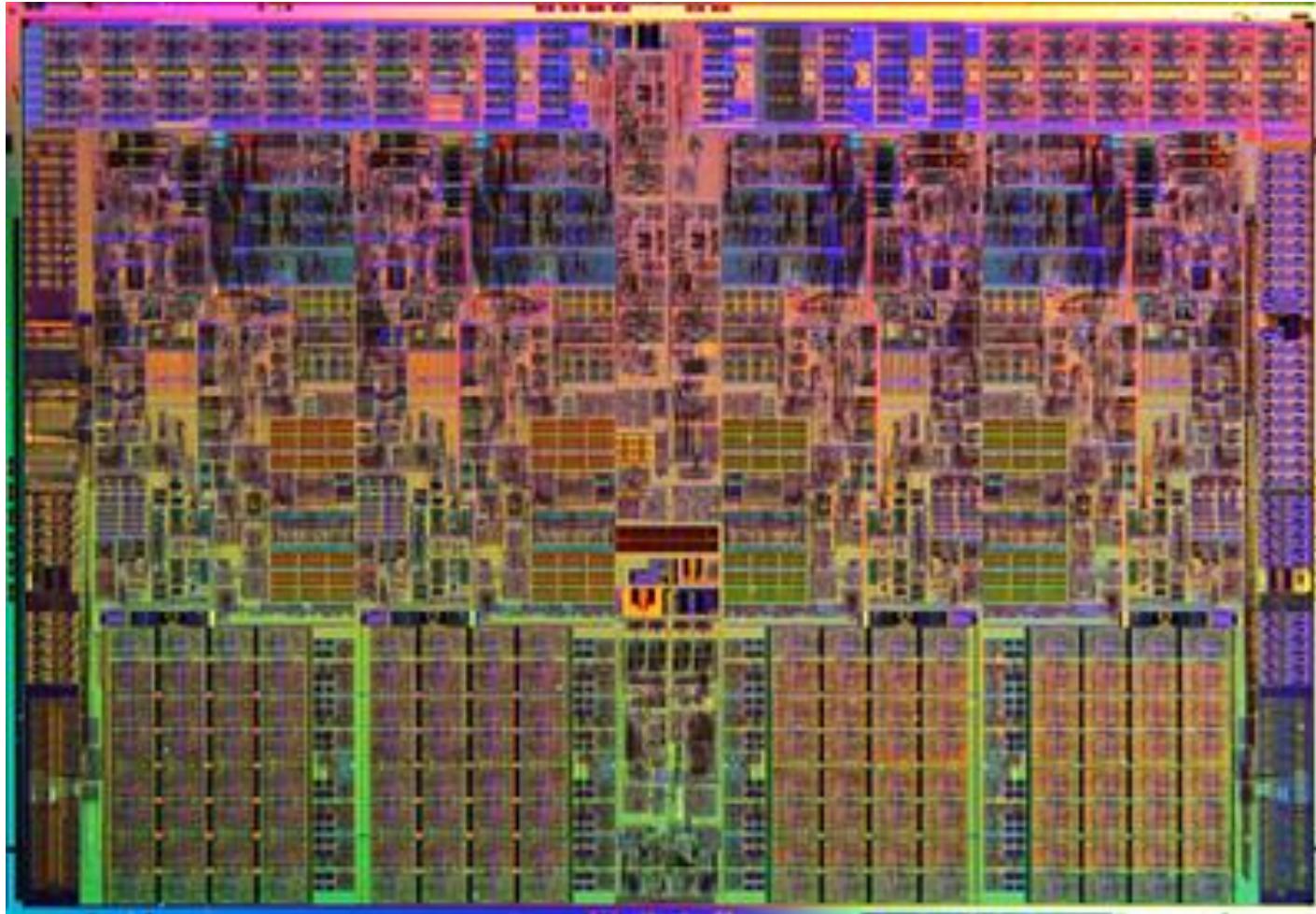
● **How?**

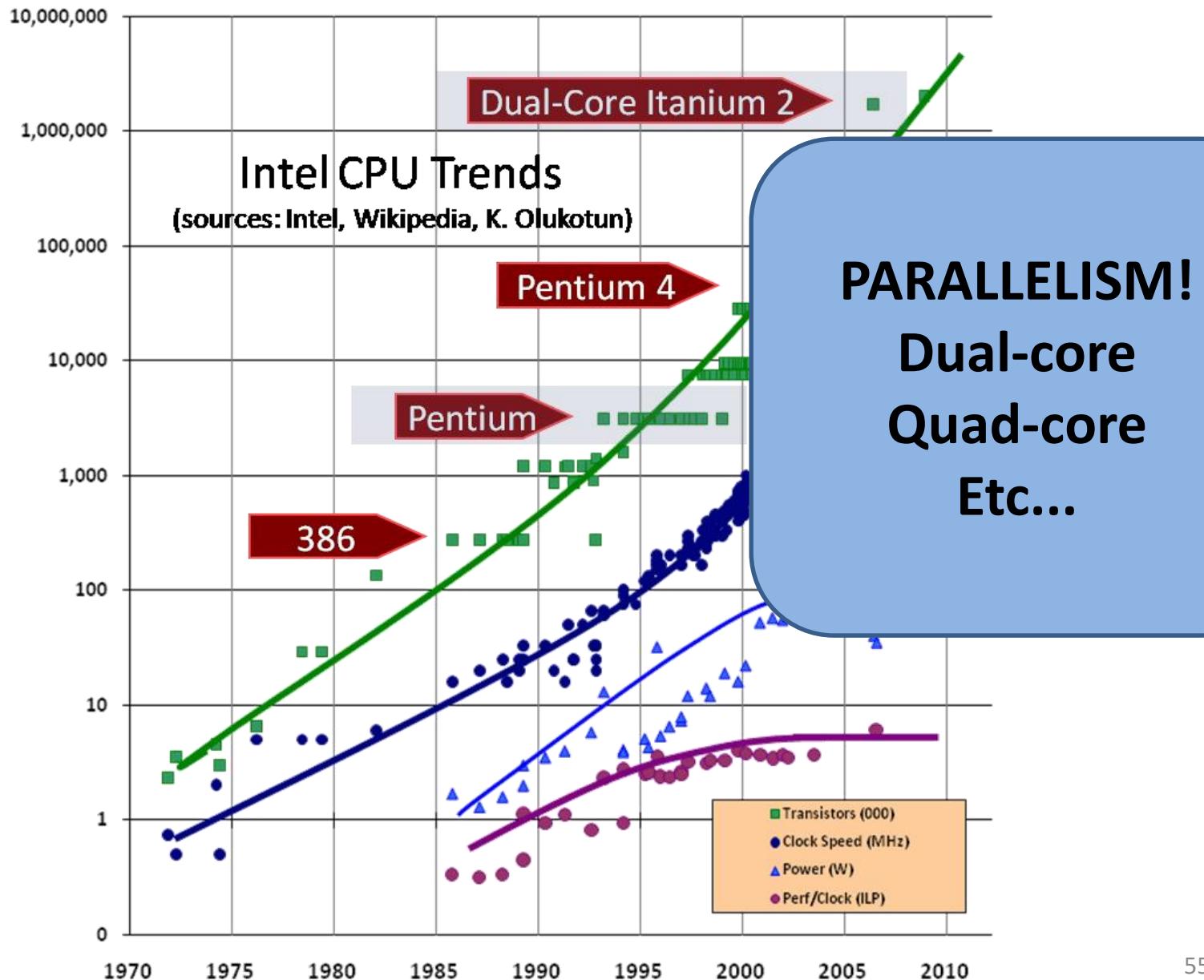
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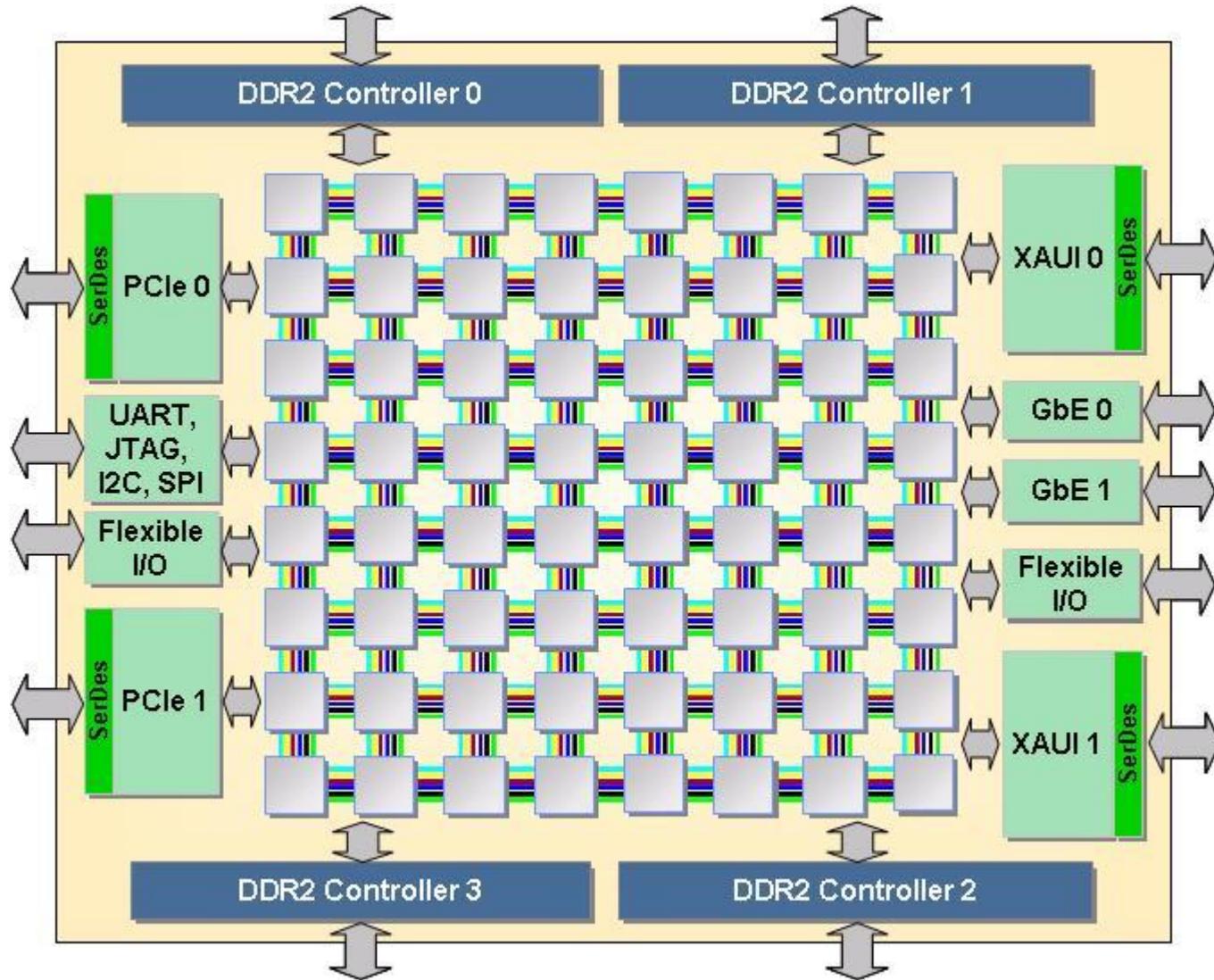
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Wireless Network-on-Chip

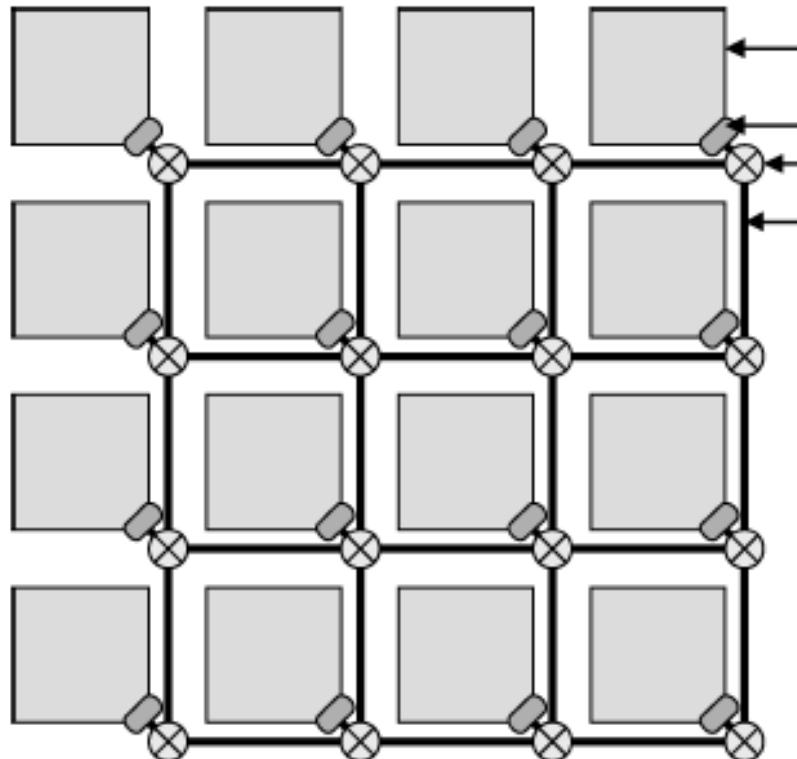




Multiprocessors that need an internal network

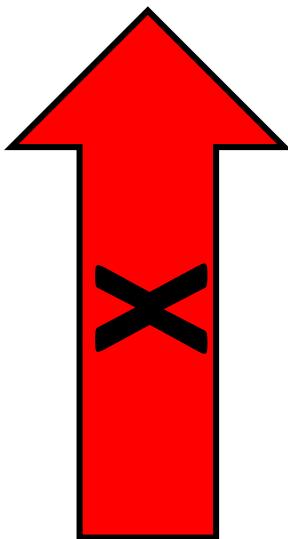


- There's literally a packet-switched network in the chip
- The cores of the processor are the clients
 - Need to communicate to share information, coordinate execution, etc...

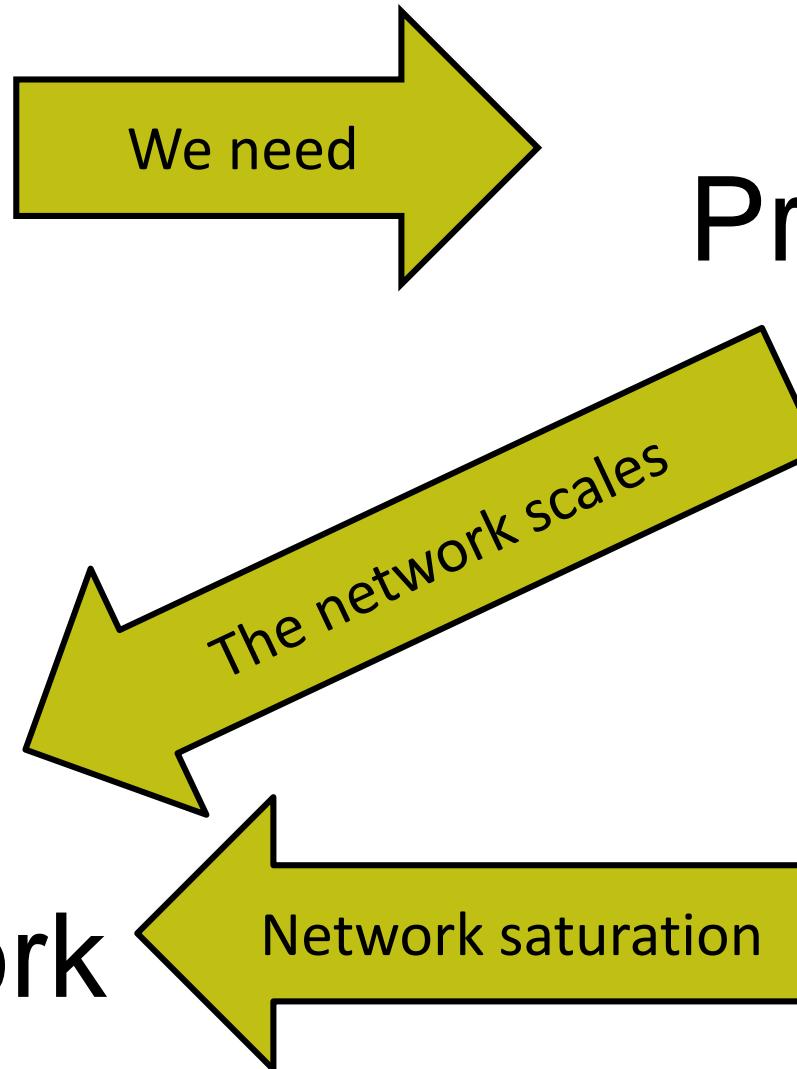


QUESTION:
**What happens if,
instead of 16, we
have 256
processors?**

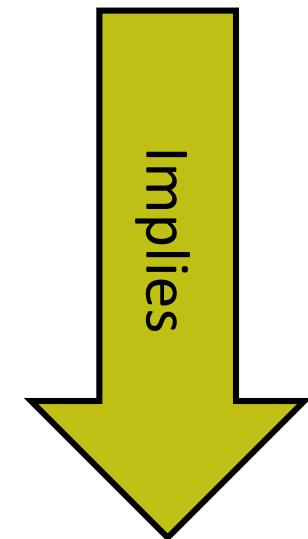
Higher speed



The network slows down

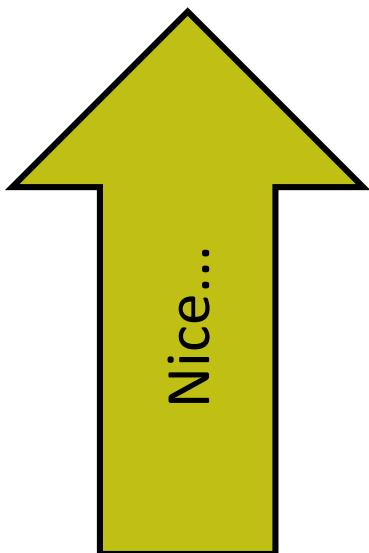


More Processors

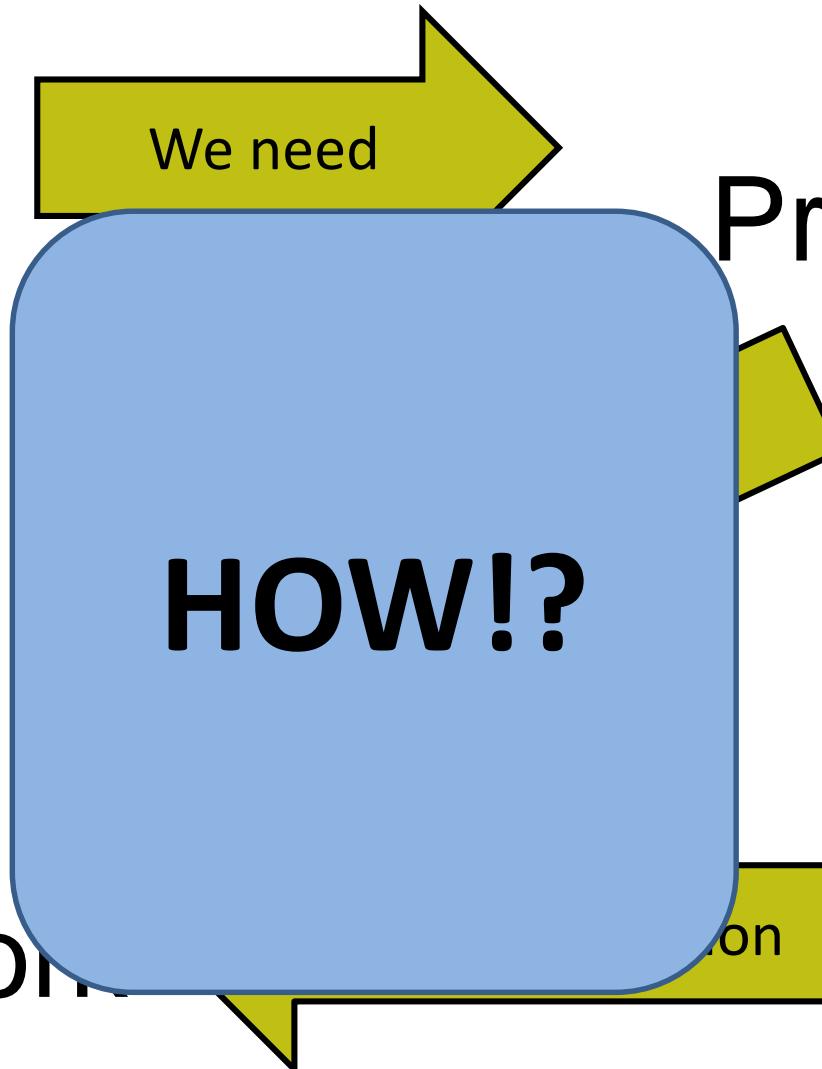


More Traffic

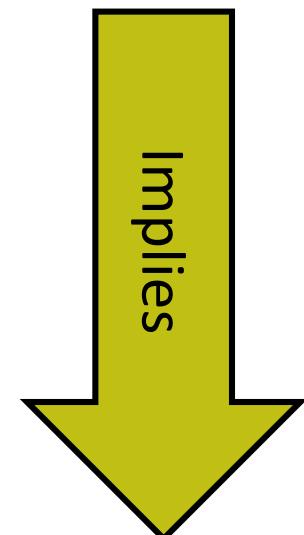
Higher speed



The network still performs

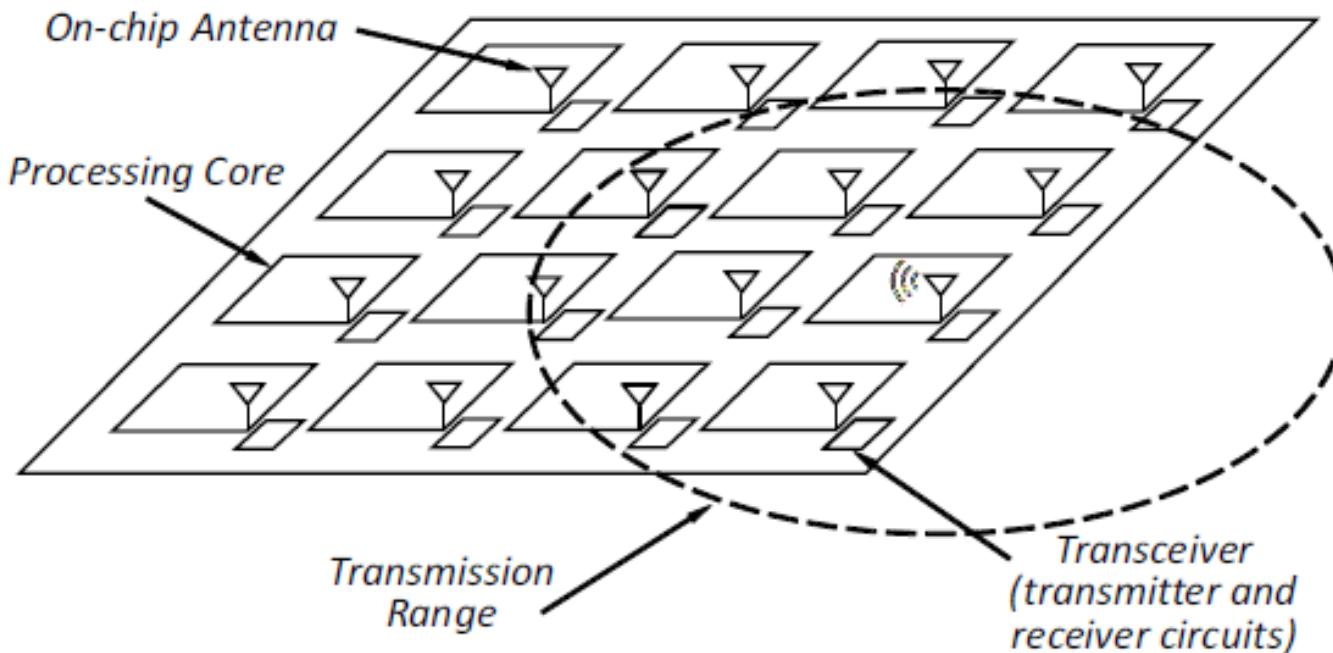


More Processors



More Traffic

- We have small antennas, let's use them
- We can reach all cores with one wireless hop, regardless of the number of cores
- Higher execution speed!



● Interesting challenges

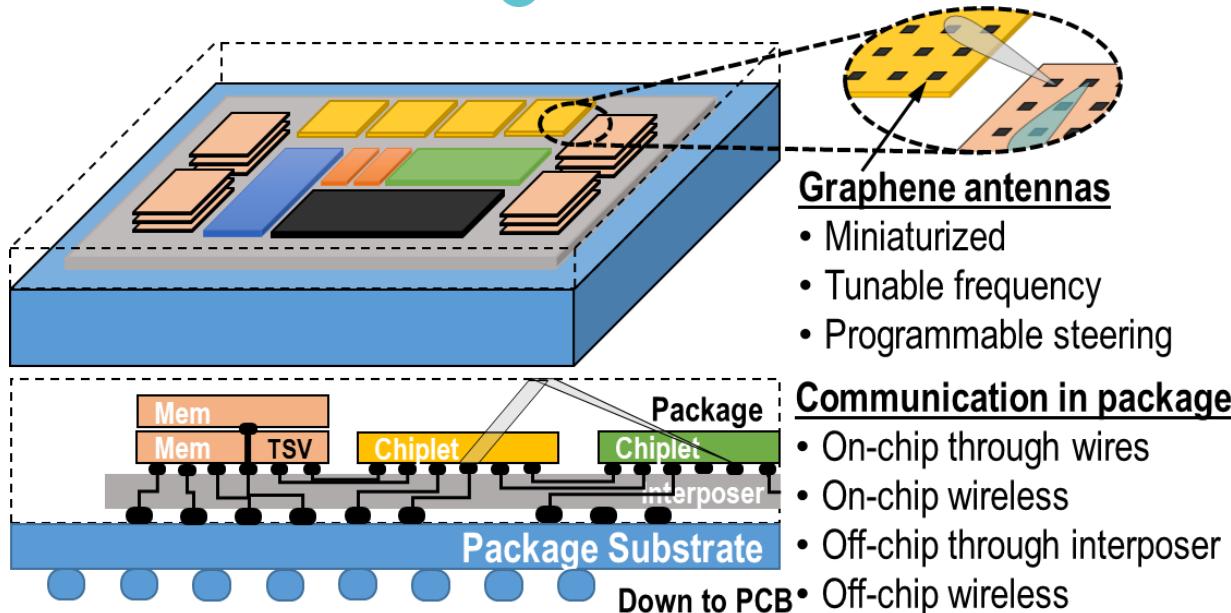
- How can we maximize the benefit of introducing a wireless network?
 - Which types of processors will benefit most from the addition of a wireless network?
- How do we leverage knowledge on the application at the MAC layer?
- How do we orchestrate the wired and wireless networks?

Wireless Plasticity for Massive Heterogeneous Computer Architectures

- Multiple chiplets
- AI Accelerators



WiPLASH



● What if we are capable of enabling wireless communication and networking among such miniaturized devices (down to a few μm , nm)?

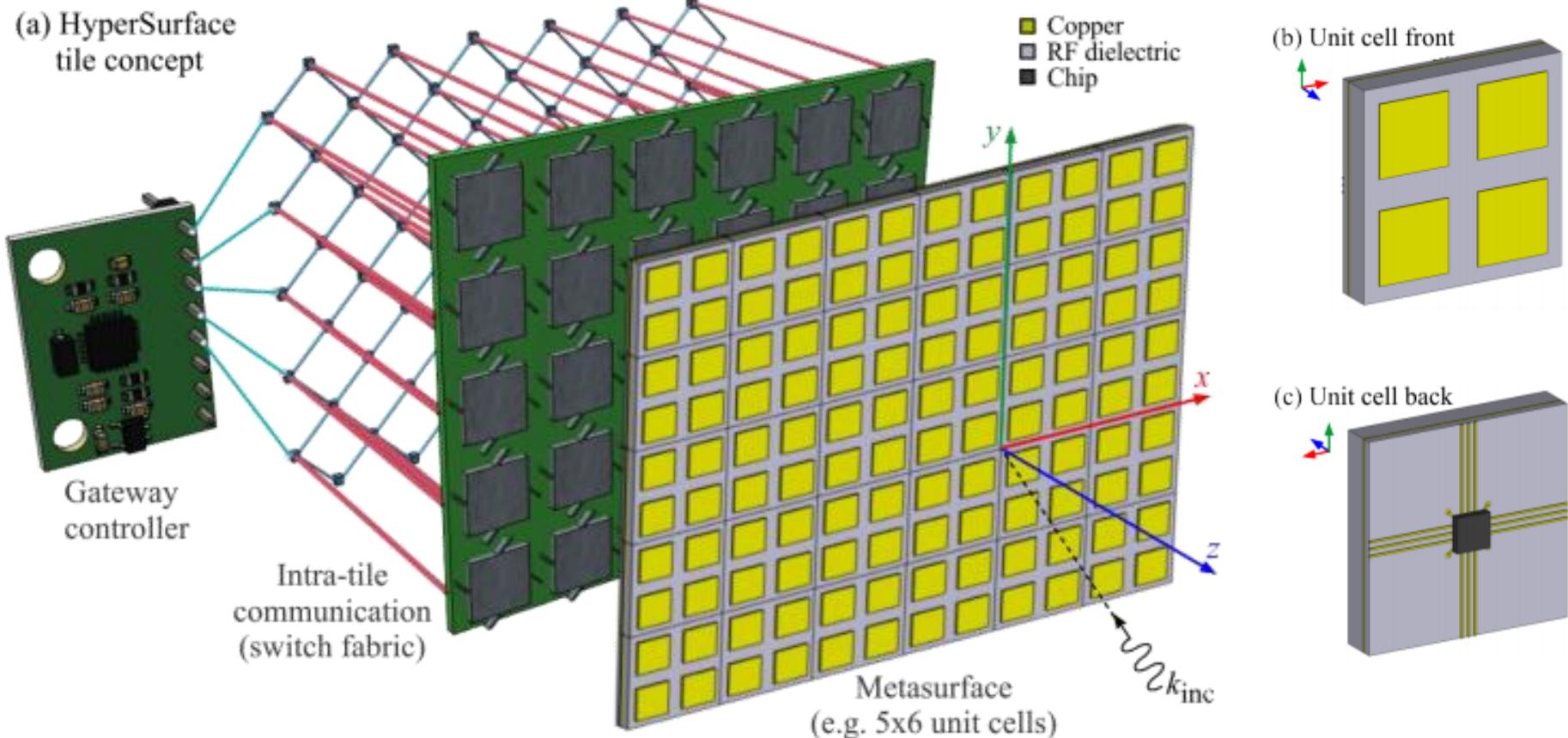
● **How?**

- Reducing the size of the communication system: the antennas first

● **For what?**

- Allowing the nanodevices (or nanomachines), which are very basic functional units, to cooperate among them to perform more complex tasks
- Place antennas in complex systems, but that are extremely constrained in area

Reconfigurable Metamaterials



S. Abadal, C. Liaskos, A. Tsoliariidou, S. Ioannidis, A. Pitsillides, J. Solé-Pareta, E. Alarcón, and A. Cabellos-Aparicio, “**Computing and Communications for the Software-Defined Metamaterial Paradigm: A Context Analysis**,” *IEEE Access*, vol. 5, 2017.

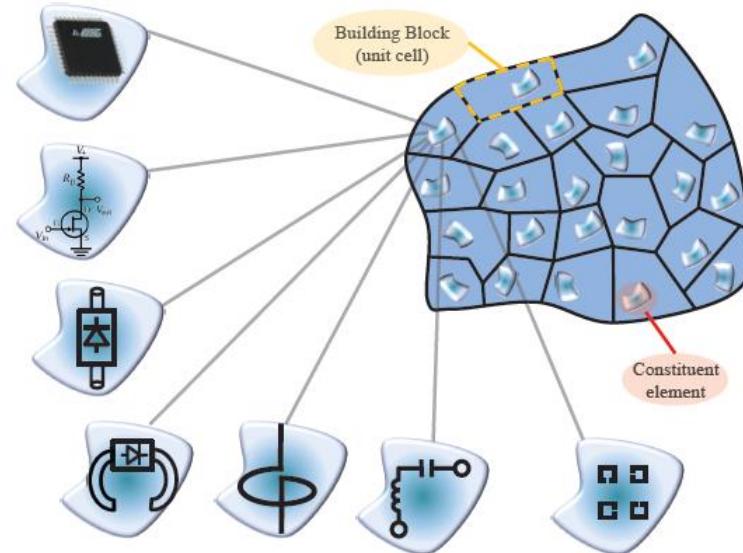
Reconfigurable Metamaterials

What does meta- mean?

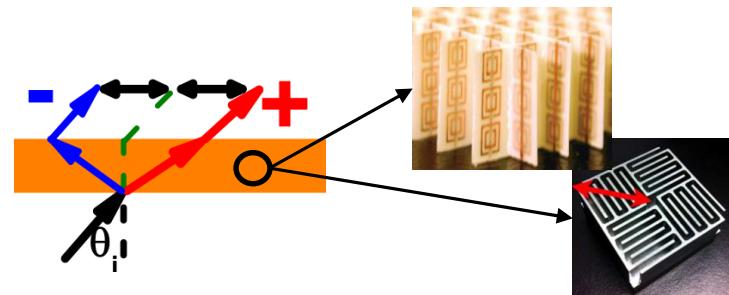
Ordinary materials



Metamaterials and metasurfaces

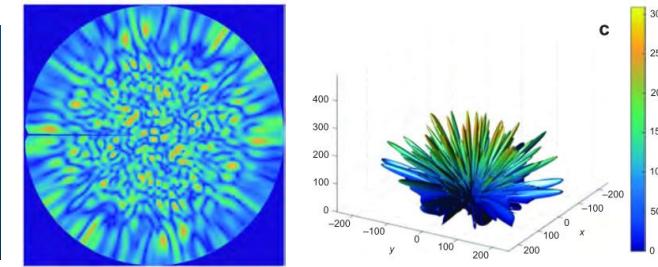
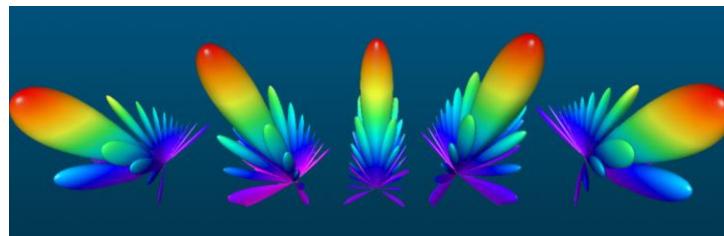
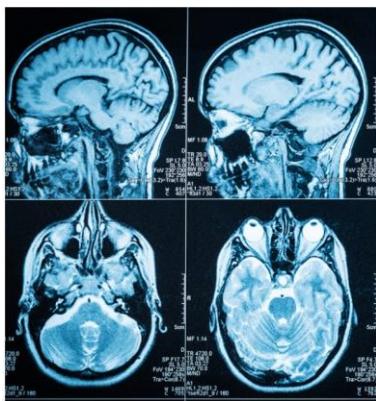
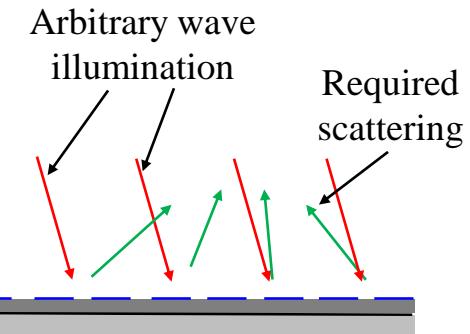
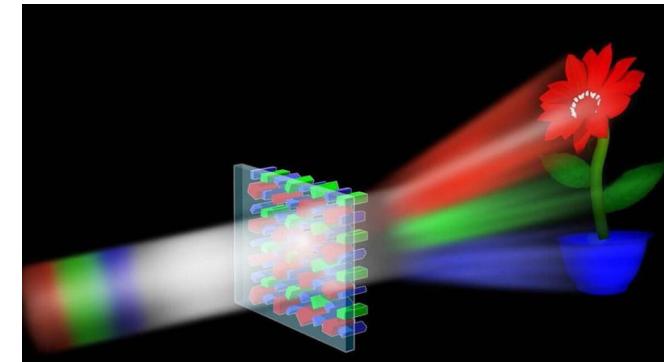
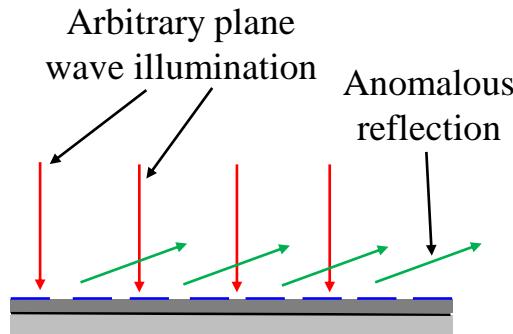
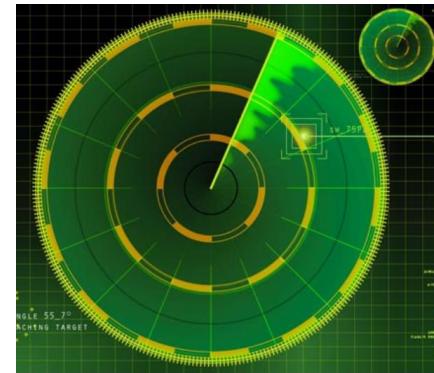
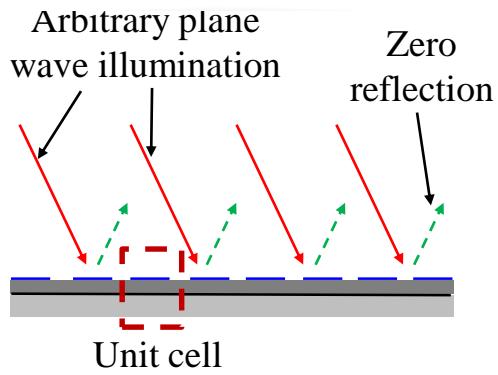


- Artificially structured materials
 - Elements, structures, devices ...
- Subwavelength size and spacing
- Unusual properties for wave control
 - e.g., negative refraction



R. A. Shelby, et al., *Science* **292**, 77 (2001)
Sci. Rep. **3**, 1614 (2013)

Applications of metamaterials



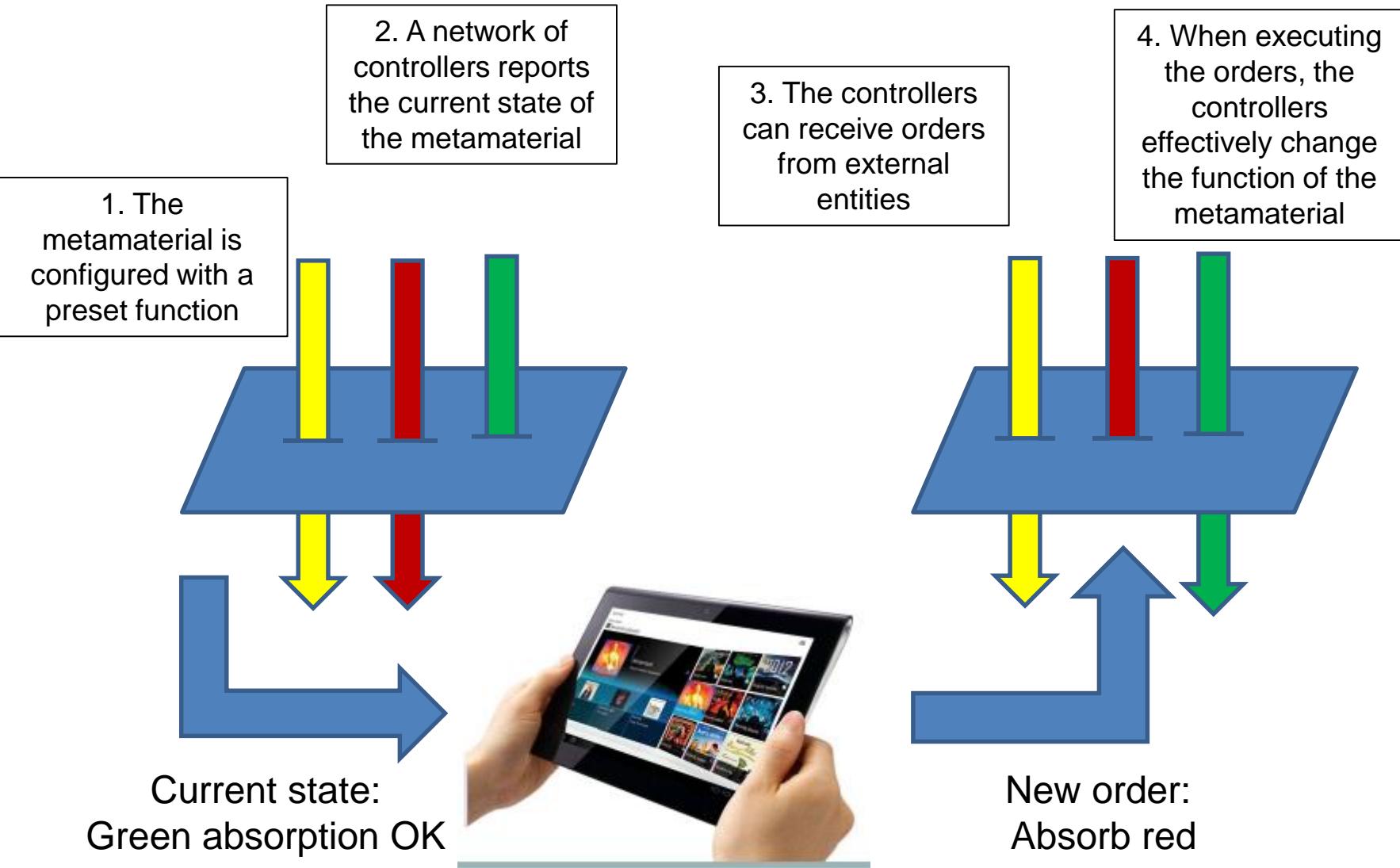
● Issues of metamaterials

- They can only be designed by experts
- They are expensive due to their complexity
- They are bound to a single functionality once designed
- It is near-to-impossible to modify certain parameters within the function for which it has been designed
- They are completely isolated

● Objectives for reconfigurable metamaterials

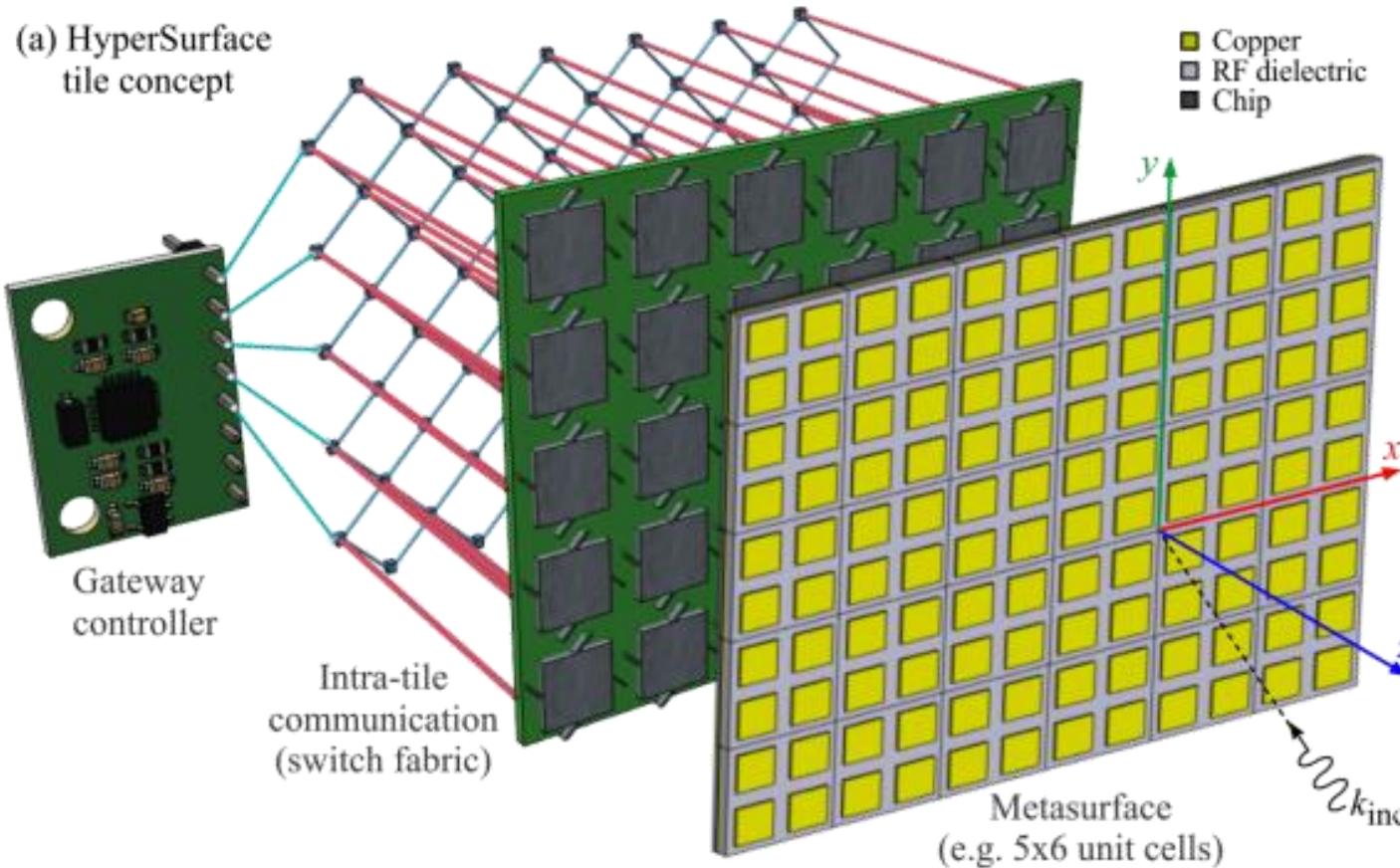
- Carrying out different functions
- Being able to change their parameters at will or depending on the state of the surroundings
- Being able to easily coordinate different metamaterials
- Exposing reconfigurability to the non-expert (API)

Reconfigurable Metamaterials

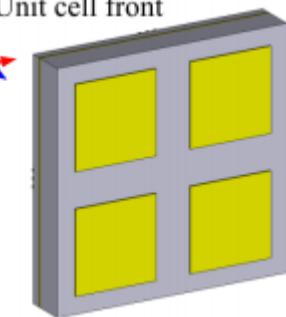


Why do we need antennas here?

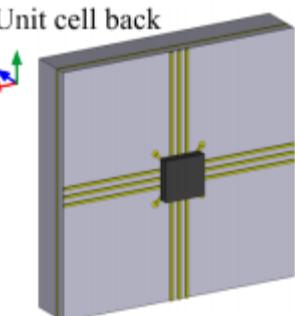
(a) HyperSurface tile concept



(b) Unit cell front

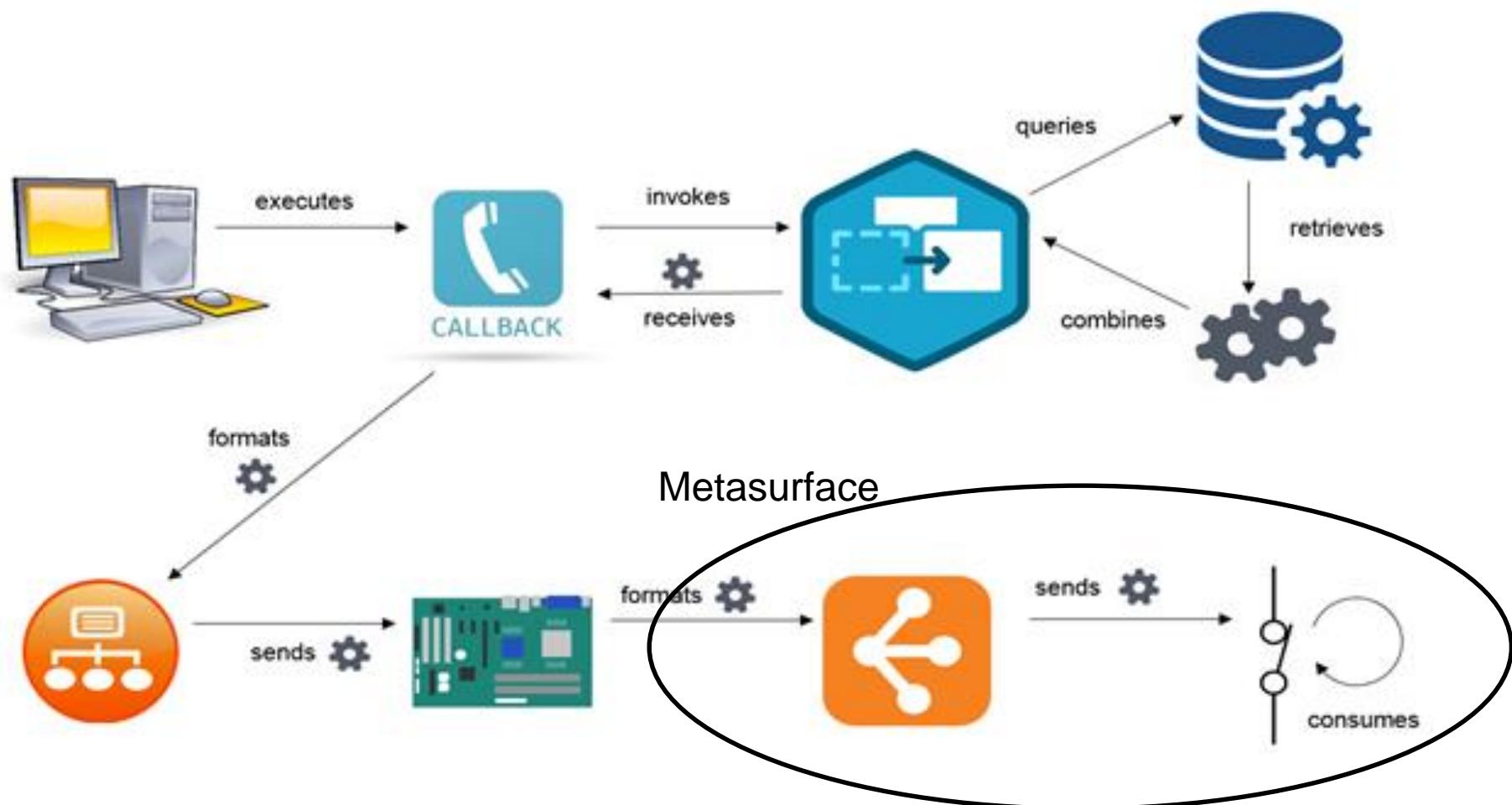


(c) Unit cell back



S. Abadal, C. Liaskos, A. Tsoliariidou, S. Ioannidis, A. Pitsillides, J. Solé-Pareta, E. Alarcón, and A. Cabellos-Aparicio, “**Computing and Communications for the Software-Defined Metamaterial Paradigm: A Context Analysis**,” *IEEE Access*, vol. 5, 2017.

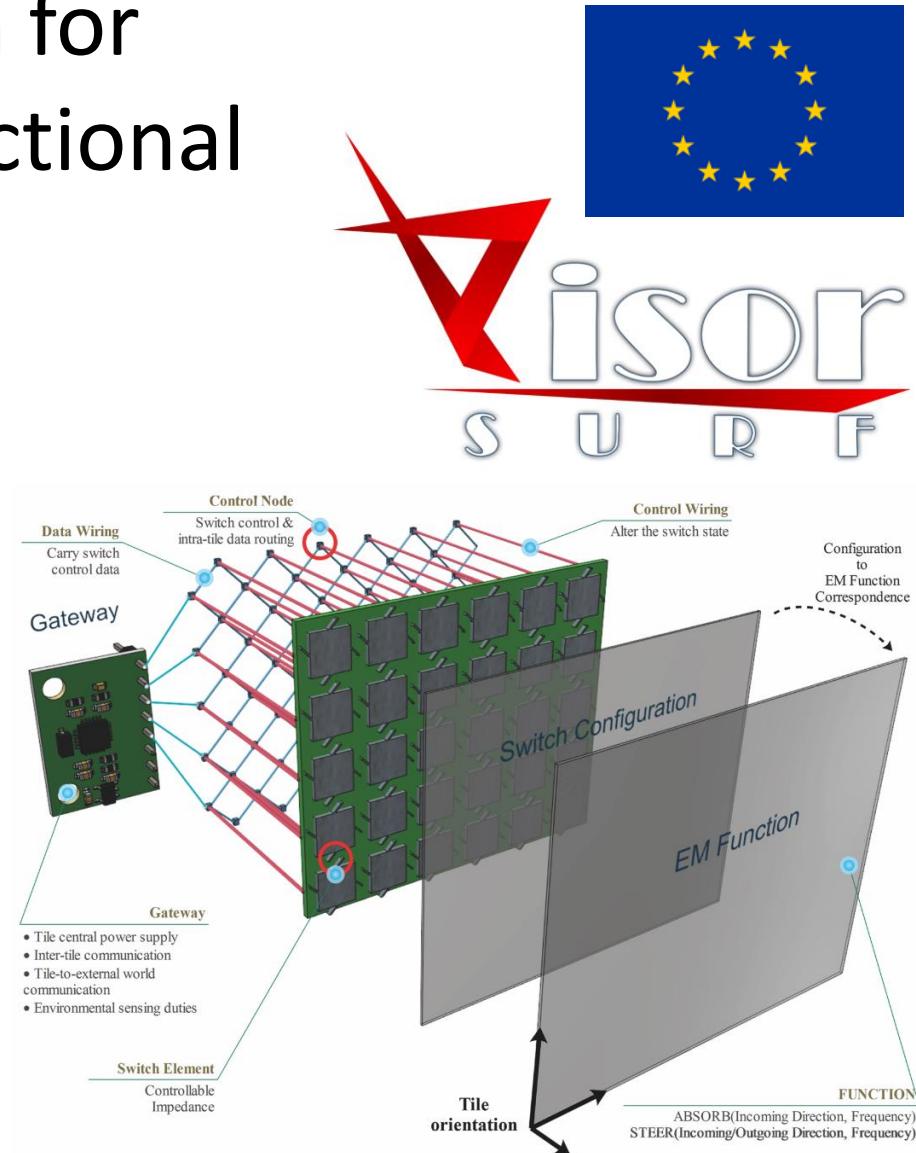
○ Why do we need antennas?



● Interesting challenges

- How many bits of memory do we need at each controller?
- How do we, given a target EM behavior, know the state of each metallic patch?
- Should we design the network to be slow and low-power, or fast and intermittent?
- How much traffic should it support?

- A Hardware Platform for Software-driven Functional Metasurfaces
- Multifunctional prototype at 5 GHz



Conclusions

- Graphennas may be a key enabler of miniaturized wireless communications
 - Miniaturization of up to two orders of magnitude
 - Wide tunability → Novel communication protocols
 - Efficiency issues exist → need to explore tradeoffs
- New area-constrained applications are possible thanks to this new technology
 - They have different performance/cost requirements
 - New communication challenges arise

We gratefully acknowledge support from the European Commission through grants:

- WIPLASH: Wireless Plasticity for Massive Heterogeneous Computer Architectures (H2020-863337)
- VISORSURF: A Hardware Platform for Software-driven Functional Metasurfaces (H2020-736876)

MSc thesis at N3Cat

- Contact Prof. Pareta or myself if you would like to do your MSc thesis on:
 - Programmable Metamaterials
 - Wireless Communications for Manycore Processor Systems and Big Data
 - Communication Analysis and Design of AI Accelerators (including GNNs)
 - Communication in quantum computers
 - Collision detection and protocol design for applications beyond 5G

Graphene applied to wireless nanocommunications: From networks-on-chips to reconfigurable metamaterials

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- What is Graphene : <http://www.graphene-flagship.eu>
http://www.youtube.com/watch?feature=player_embedded&v=dTSnnlTsVg
- The Graphene Flagship project: <http://www.graphene-flagship.eu>
http://www.youtube.com/watch?feature=player_embedded&v=3CoPVmWKral
- Nokia Morph Project: <http://research.nokia.com/morph>
http://www.youtube.com/watch?feature=player_detailpage&v=Zto6aTZM9t0
- Guardian Angels Flagship: www.ga-project.eu
- Six ways graphene could make the world a greener place , “The Guardian”, January 28, 2015
http://www.theguardian.com/sustainable-business/2015/jan/28/graphene-six-ways-wonder-material-improve-world-sustainability?CMP=new_1194
- I. Llatser, A. Cabellos-Aparicio, E. Alarcón, J. M. Jornet, H. Lee and J. Solé-Pareta, **“Scalability of the Channel Capacity of Graphene-enabled Wireless Communications to the Nanoscale”**, IEEE Transactions on Communications (to be published).
- I. Llatser, C. Kremers, D. N. Chigrin, J. M. Jornet, M. C. Lemme, A. Cabellos-Aparicio and E. Alarcón, **“Radiation Characteristics of Tunable Graphennas in the Terahertz Band”**, Radioengineering Journal, December 2012.
- J. M. Jornet and I. F. Akyildiz, **“Channel Modeling and Capacity Analysis for Electromagnetic Wireless Nanonetworks in the Terahertz Band”**, IEEE Transactions on Wireless Communications, 2011.

La **ràdio** és la transmissió de senyals mitjançant la modulació d'ones electromagnètiques amb freqüències per sota de les de la llum visible.

La radiació electromagnètica es propaga per mitjà de camps electromagnètics oscil·lants que travessen l'aire i el buit de l'espai. [Viquipèdia]

Camp elèctric oscil·lant

