An Electromagnetic and Quantum Theory Perspective for Nano-scale Communication in the Terahertz Band

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Why are EM waves apparently not suitable for Nanocommunications?

- Complexity and size of existing EM transceivers:
  - Nano-machines are meant to be simple.
  - The expected maximum total size of a nano-device is just a few tenths of μm.
    - 45 nm transistor technology is already on the market.
    - 32 nm technology is around the corner but…
      - …the scaling limit of silicon-based transistors is being reached.

Why are EM waves apparently not suitable for Nanocommunications?

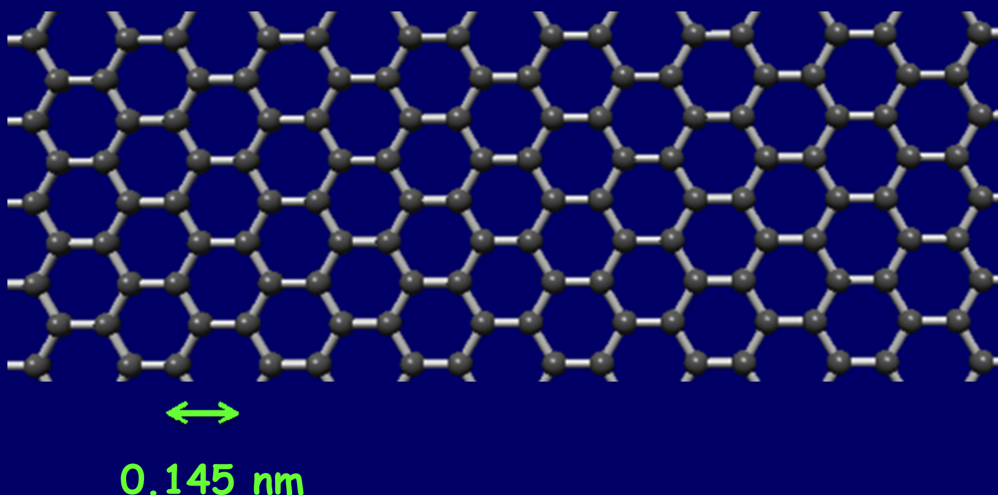
- **High Power Consumption:**
  - Available electrical power sources (batteries, energy harvesting mechanisms) are highly inefficient…
  - …specially when compared to chemical power sources for Molecular Nano-machines.

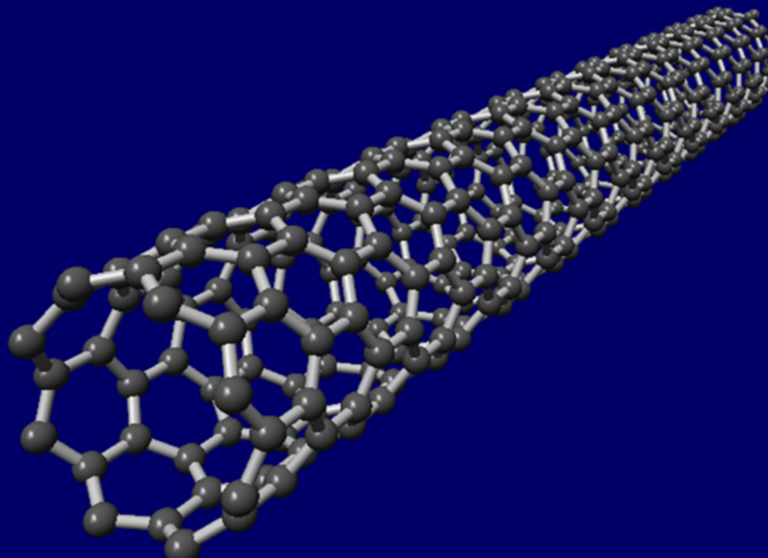
All these are "just" technological limitations, not limits imposed by Physics Laws!

Our tools are too large… but Nanotechnology is moving on!

Nanomaterials: Graphene, Carbon Nanotubes & Nanoribbons

- **Novel materials implicitly lying in the nano-scale:**
  - Graphene: a one-atom-thick planar sheet of bonded carbon atoms in a honeycomb crystal lattice.
    - Graphene Nanoribbons (GNR): a thin strip of graphene.
    - Carbon Nanotubes (CNT): a folded nanoribbon.





Nanomaterials: Graphene, Carbon Nanotubes & Nanoribbons

- Their electrical and optical properties pose new opportunities for device-technology: nano-transistors, logical nano-circuitry, nano-memories, nano-batteries.

We believe that an EM approach can still be used for the nano-scale in the Terahertz Band

Why in the Terahertz Band?

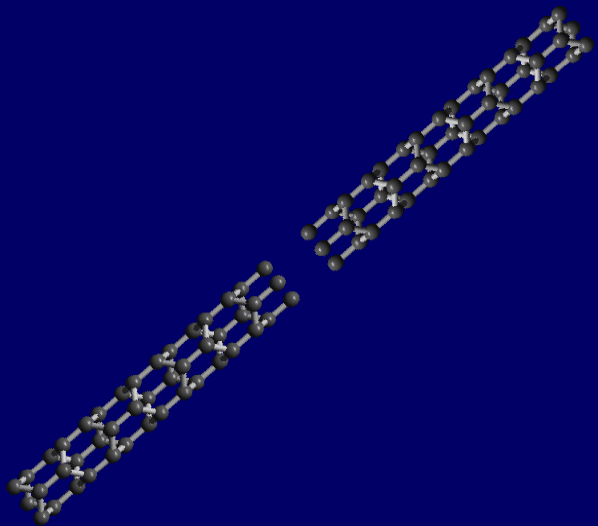
[1] J.M. Jornet and I.F. Akyildiz, "A nano-patch antenna for electromagnetic nanocommunications in the terahertz band", submitted for publication, May 2009.

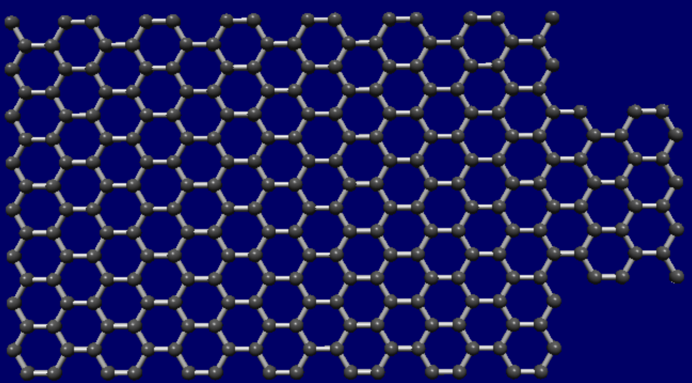
- A new set of tools: Quantum Mechanics
  - Starting from the Schrödinger equation we can obtain the electronic and optical properties of graphene in its different forms (Contact Resistance, Quantum Capacity, Kinetic Inductance, Electrons Velocity, Line Impedance).
- Some numbers:
  - The world smallest transistor is based on a thin strip of graphene just 1 atom x 10 atoms (1 nm transistor!) – Obtained in a top-down approach.
  - The predicted switching delay for GNR transistors is on the order of 0.01 ps (100 THz).
  - For a maximum antenna size on the order of a few hundreds of nanometers, a nano-antenna will be able to radiate EM waves in the Terahertz band (0.1-10~THz) [1].

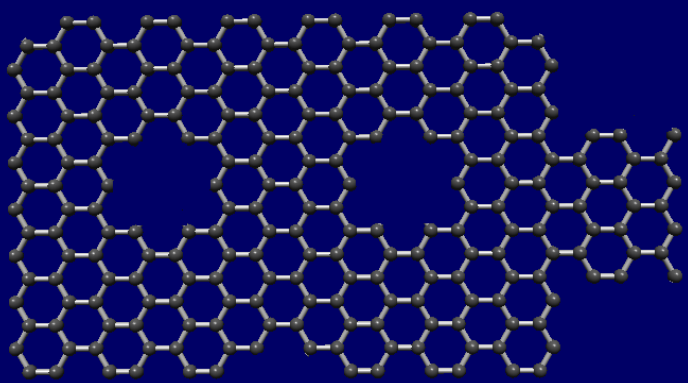
Graphene Nano-Antennas for Terahertz Communications

J.M. Jornet and I.F. Akyildiz, "A nano-patch antenna for electromagnetic nanocommunications in the terahertz band", submitted for publication, May 2009.

- Graphene can be used to build antennas:
  - Using a single Carbon Nanotube (or a set of them): a nano-dipole.
  - Using a single Graphene Nanoribbon: a nano-patch.
  - What about atom-defined antennas?

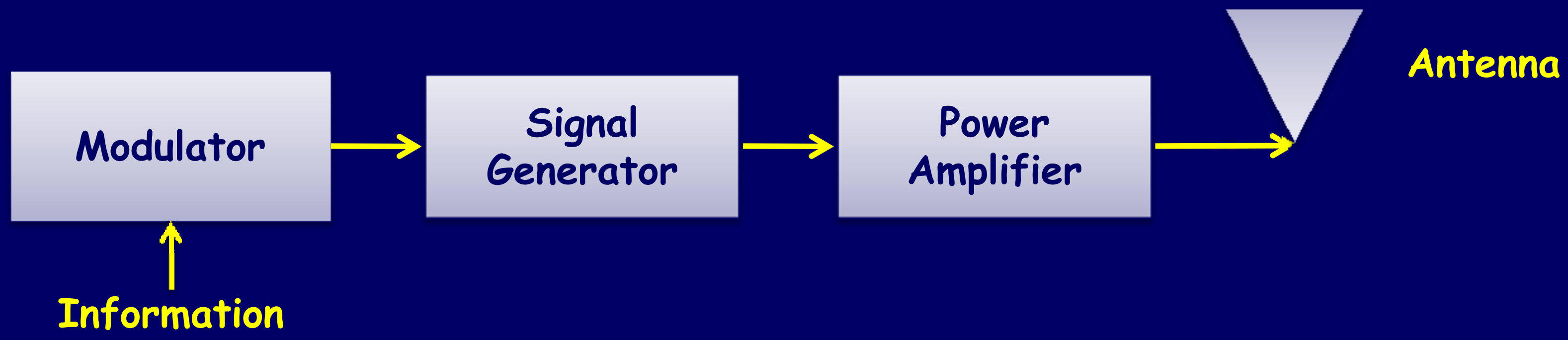






Graphene EM Nano-Transmitter

J.M. Jornet and I.F. Akyildiz, "A physical channel model for EM nanocommunications in the Terahertz Band", in preparation, 2009.



- A fully-graphene EM transmitter is not only possible but also desirable:
  - Relatively low speed of electrons → We deal with nano-scale dimensions but we still have feasible resonant frequencies.
  - Large mean free path → Back scattering of electrons is reduced, increasing the device efficiency (almost no losses within the nano-scale).
  - Total integration → Single "chip" manufacturing, there is no impedance matching problem.
  - Atomic precision device.

Terahertz Propagation in the Nano-Scale

J.M. Jornet and I.F. Akyildiz, "A physical channel model for EM nanocommunications in the Terahertz Band", in preparation, 2009.

The Terahertz Band (0.1 – 10 THz):

- Proposed for short range ultra-broadband communications.
  - We were not looking for it, we simply "physically" ended up there…
- Terahertz Waves have not been studied too much so far:
  - They can be understood as very high frequency microwaves.
  - They can be studied as low frequency infrared light.
- The main propagation effects that can be observed are:
  - Spreading Loss (Friis)
  - Molecular Absorption Loss (Beer-Lambert Law + Schrödinger equation, again).
- Always keeping in mind that we are in an ultra-short range.

Graphene EM Nano-Receiver

J.M. Jornet and I.F. Akyildiz, "A physical channel model for EM nanocommunications in the Terahertz Band", in preparation, 2009.

- Similarly to the transmitter, a fully-graphene receiver is desirable.
- Noise:
  - Molecular Noise: the energy absorbed by the molecules in the medium is re-radiated, thus increasing the received noise.
  - Device noise: Large mean free path → Back scattering of electrons is reduced, clearly improving the noise factor of graphene-based transistors.

Open Challenges and Future Work

- Further transceiver analysis from the device perspective:
  - Novel transceivers design, electronic simulation tools for nano-devices, nano-antenna measurements, prototype development.
- More complete channel models accounting for NLOS transmission, interference, nano-obstacles, etc.
- Novel networking protocols accounting for ultra-short distance ultra-broadband communications.
- So far, we are assuming that there is a considerable amount of "available" electrons travelling through a certain amount of carbon atoms, so we can still use classical EM theory:
  - If these number is decreased and we cannot longer think of EM waves → We should start thinking in terms of photons → Particle Theory → The Standard Model of Physics.