N3Cat

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Campus d'Excel·lència Internacional

grau Enginyeria Fisica

Graphene antennas for nanotechnology-enabled Wireless Communications

Eduard Alarcón[1]

Ignacio Llatser[1], Sergi Abadal[1], Alberto Cabellos[1], Josep Jornet[1,2], Mario Nemirovsky[3], Max Lemme[4], Heekwan Lee[5],Tomás Palacios[6],Ian F. Akyildiz[1,2]

[1] Nanonetworking Center (N3Cat) and DEE, UPC BarcelonaTech
[2] GeorgiaTech, Atlanta, USA
[3] BSC Barcelona Supercomputing Center
[4] Royal Institute of Technology, KTH Stockholm, Sweden,
[5] Samsung Advanced Institute of Technolgy, Seoul, South Korea
[6] Massachussets Institute of Technology, MIT, Boston, USA

Team and projects

N3Cat

- " Graphene-enabled Wireless Communications" funded by the **Samsung Advanced institute of Technology** (Seoul, Korea) under the GRO gift program
- "Graphene antennas for Wireless Networks-on-chip" funded by the **Intel research**
- EU FET flagship project "Graphene"
- EU FET flagship accesit "Guardian Angels"
- EU FET flagship project "Human Brain project"

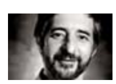
Dr. Albert Cabellos (AC)
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Ignacio Llatser
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

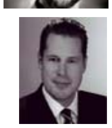
Josep Miquel Jornet (UPC, MIT)
Georgia Tech

Prof. Eduard Alarcón (EE)
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Prof. Ian Akyildiz (UPC Hon.)
Georgia Tech



Dr. Mario Nemirovski
Barcelona Supercomputing Center — icrea



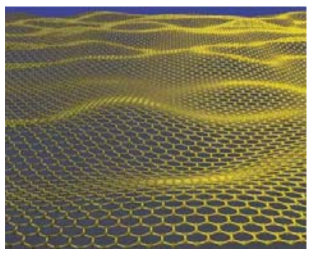
Prof. Max Lemme
KTH Royal Institute of Technology

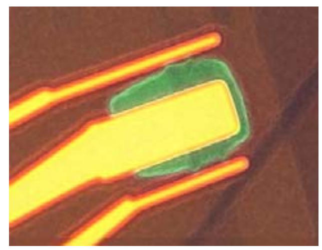
Prof. Tomas Palacios
Massachusetts Institute of Technology

Grafè

N3Cat

- Grafè
  - Capa de carboni monoatòmic (d'un sol àtom de gruix)
  - Xarxa cristal·lina en forma de niu d'abella
  - Descobert per A. K. Geim i K. S. Novoselov el 2004
  - Aquest descobriment els va valer el premi Nobel de física



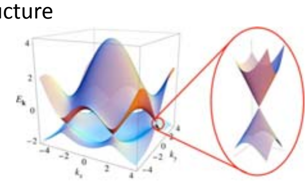


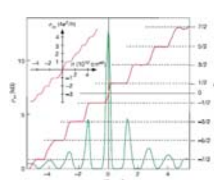
3

Grafè

N3Cat

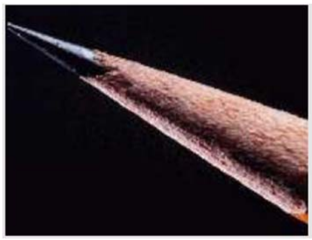
- Quines són les propietats extraordinàries del grafè que han atret l'atenció d'investigadors al voltant del món?
  - Material més fi i lleuger observat a la natura (0.3 nanometers)
  - Més dur que el diamant
  - 300 cops més resistent que l'acer (Young modulus 1 TPa (Steel ~ 0.2 TPa))
  - Condueix l'electricitat molt millor que el coure
  - Transparent (97.7% optical transparency)
  - Flexible: pot prendre qualsevol forma
  - One-atom-thick impermeable membrane
  - Gapless energy band structure



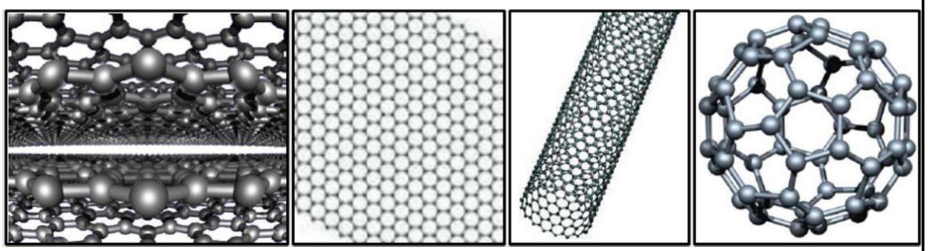


4

Production of Graphene



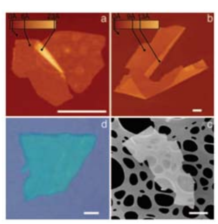
- Graphene in many dimensions
  - 3D in grahpite
  - 2D in single layer (graphene)
  - 1D in carbon nanotubes
  - 0D in fuellerenes

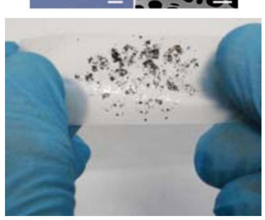


Anton Lopatin, Graphene a new Electronic Material FAU Erlangen-Nürnberg

5

Graphene Mechanical Exfoliation





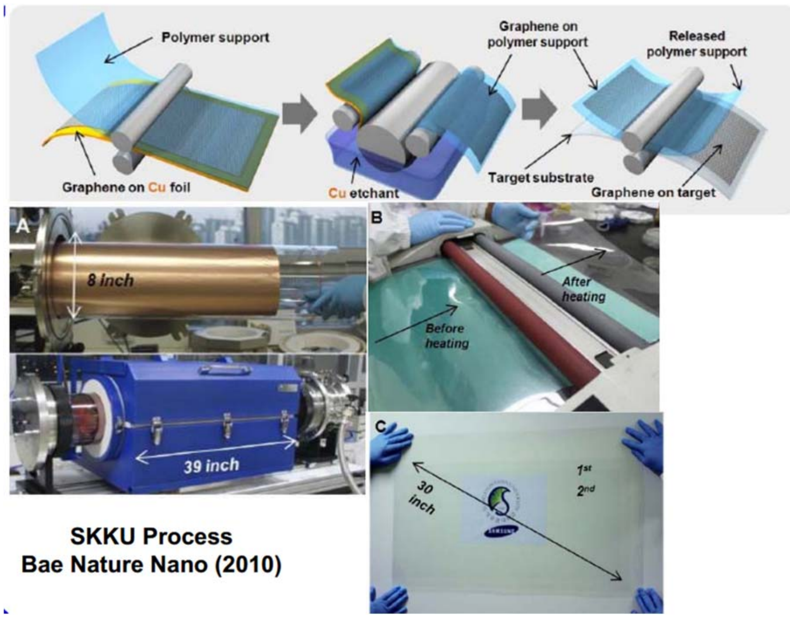
- Graphene flakes were preliminary identified with optical microscope
- Analysis with Atomic Force Microscopy
- Before it was beleived that they could not exist due to thermal instability
- *"The found class of 2D crystals offers a wide choice of new materials parameters for possible applications and promises a wealth of new phenomena usually abundant in 2D systems*."

K. S. Novoselov, D. Jiang, F. Schedin, T. J. Booth, V. V. Khotkevich, S. V. Morozov, and A. K. Geim "Two-dimensional atomic crystals" Proceedings of the National Academy of Sciences of the USA 2005

6

Production of large Graphene sheets

N3Cat



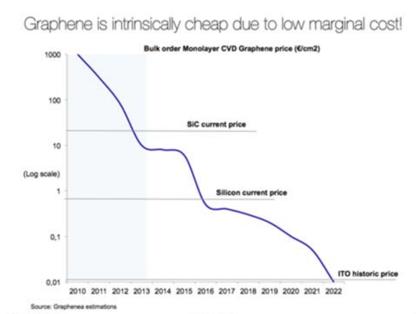
SKKU Process
Bae Nature Nano (2010)

7

Mass production of graphene

N3Cat

- Graphite is cheap ($ per kg)
- Graphene cost is related to its quality (e.g. electron mobility)
  - Graphene oxide
  - CVD Graphene
  - Mechanically exfoliated graphene
- According to the estimates graphene cost is expected to decrease



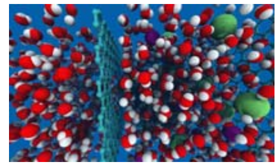
Marko Spasenovic "The Price of Graphene" Graphenea 2011

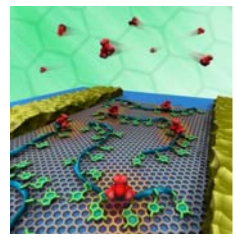
8

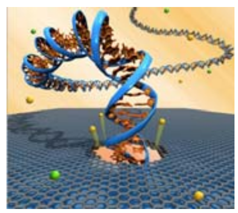
Grafè

N3Cat

- Aquestes propietats fan del grafè possibiliten avenços disruptius en múltiples àmbits de la ciència i la tecnologia:
  - Materials
    - Pantalles tàctils resistents i flexibles
    - Estructures resistents i lleugeres (aeronàutica)
  - Química
    - Sensors de gasos ultra-precisos
    - Neteja d'aigua contaminada per material radioactiu
    - Destil·lació d'alcohol a temperatura ambient
    - Dessalinització d'aigua
  - Bio-medicina
    - Detecció de bacteris
    - Seqüenciació de l'ADN





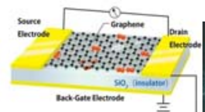


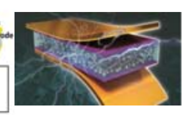
9

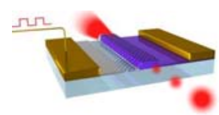
Grafè

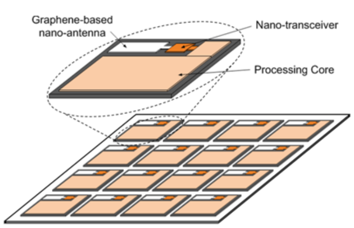
N3Cat

- Nano-electrònica
  - Transistors i circuits integrats ultra-ràpids
  - Super-condensadors (bateries)
  - Efecte piezoelèctric a la nano-escala
- Nano-òptica
  - Nano-làsers
  - Moduladors òptics
- Tecnologies de la informació i les comunicacions
  - **Comunicacions de rang ultra-curt basades en antenes de gra**

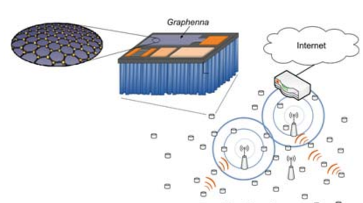








Mid-term: Graphene-based Wireless Network-on-Chip for Multi-Core processors



Long-term: Wireless Nano-Sensor Networks (WNSN)

I. F. Akyildiz, J. M. Jornet, "The Internet of Nano-Things", IEEE Wireless Communications, 2010.
S. Abadal, A. Cabellos-Aparicio, J. A. Lázaro, E. Alarcón, J. Solé-Pareta, "Graphene-enabled hybrid architectures for multiprocessors: bridging nanophotonics and nanoscale wireless communication," in Proc. of the International Conference in Transparent Optical Networks (ICTON), 2012.

10

Graphene Electronic Properties

N3Cat

- Graphene is a semi-metal or a zero-gap semiconductor
- Very high mobility for electrons: 20.000 $cm^2V^{-1}s^{-1}$ (Si 1400 $cm^2V^{-1}s^{-1}$)
  - An orders of magnitude better than Si
  - Best conductor yet discovered
- Electrons behave as massless Dirac fermions
- Very low scattering
- Very low resistivity 10^{-6} Ω·cm
- Lowest material at room temperature
- Graphene can help to obtain faster and smaller electronics

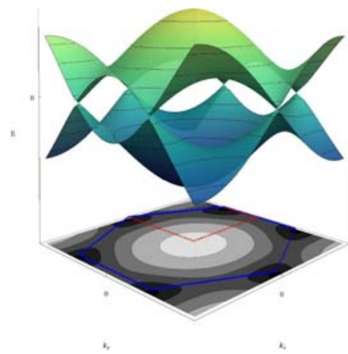
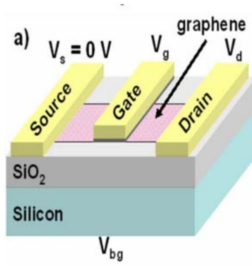


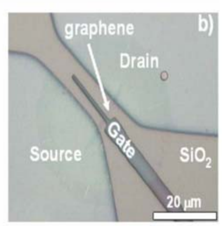
Image: Graphenea

11

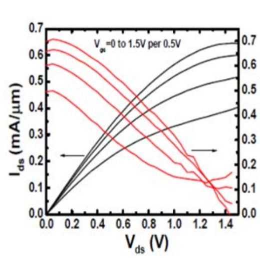
Graphene High-Frequency Transistors: Field-Effect T.

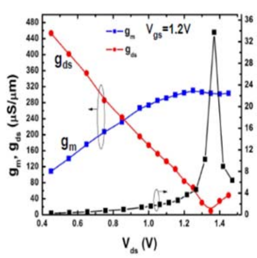
N3Cat





- Exfoliated graphene => No mass-production
- SiO_2 substrate => Mobility degraded
- No gate alingment => High access resistance
- Metal-Graphene junction => High contact-resistance





- CVD and Epitaxial GFET => Mass production
- Diamond-like carbon- substrate => Mobility improved
- Ultrathin gate-dielectric => Current-saturation improvement
- L_{ch}=40nm => f_T=350GHz

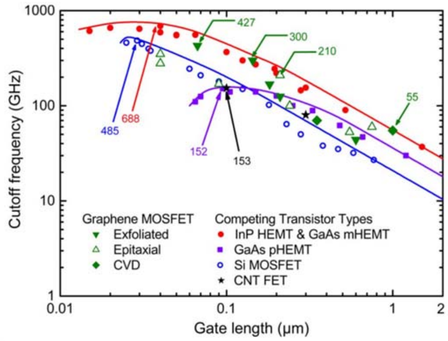
M. Lemme, "Current status of graphene transistors," Solid State Phenomena, pp. 1–11, 2010.

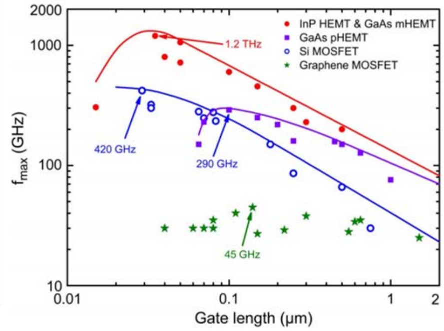
C.-Y. Sung, "Near 400 GHz World Fastest Graphene RF Transistor For High Frequency Nanoelectronics and Circuits CMOS Platform Integration", Graphene Conference 2012

12

Graphene Field-Effect Transistors: Ft and Fmax

N3Cat





- F_t = Cut-off frequency, F_{max} = Maximum frequency of oscillation, L = Gate length
- III-V-FET F_t is saturating when reducing L
- Silicon-FET F_t is slowly increasing when reducing L
- GFET F_t is increasing fast when reducing L
- GFET F_{max} is not increasing when reducing L => GFET must improve its saturation current

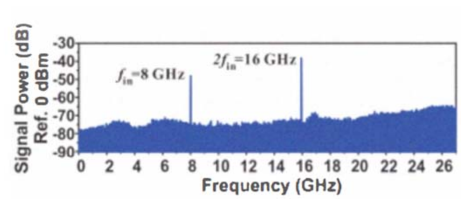
F. Schwierz, "Graphene Transistors: Status, Prospects, and Problems," vol. 101, no. 7, pp. 1567–1584, 2013.

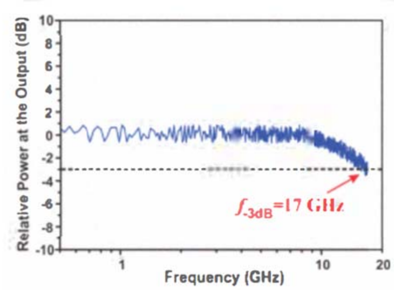
14

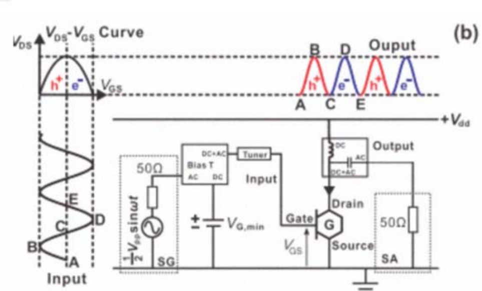
GFET 17GHz Frequency Doubler

N3Cat

- T-shape self-aligned device technology
- Ambipolar behavior => Even symmetry =>Frequency doubler
- Output spectral purity < 90%
- f_{in} = 8GHz, $2f_{in}$ = 16GHz, f_{-3dB} = 17GHz
- External Bias-T and Tuner
- Sapphire substrate







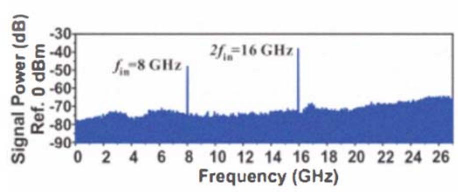
Wang, Han; Hsu, Allen; Mailly, Benjamin; Ki Kang Kim; "Towards ubiquitous RF electronics based on graphene," 2012 IEEE MTT-S International , vol., no., pp.1-3, 17-22 June 2012

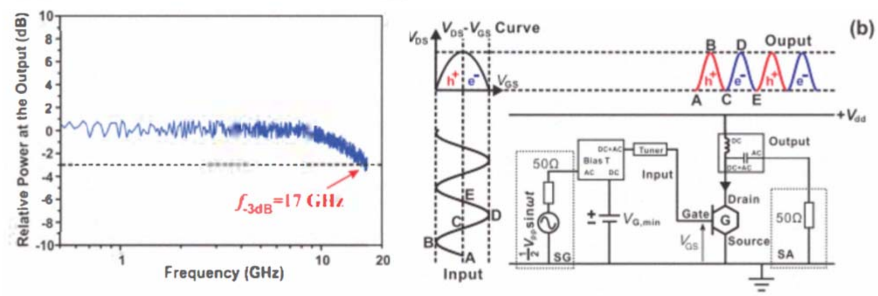
15

GFET 17GHz Frequency Doubler

N3Cat

- T-shape self-aligned device technology
- Ambipolar behavior => Even symmetry =>Frequency doubler
- Output spectral purity < 90%
- f_{in} = 8GHz, $2f_{in}$ = 16GHz, f_{-3dB} = 17GHz
- External Bias-T and Tuner
- Sapphire substrate





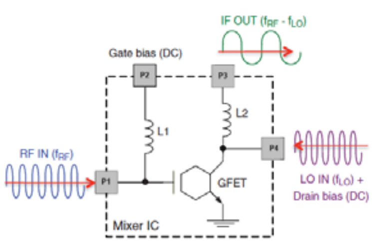
Wang, Han; Hsu, Allen; Mailly, Benjamin; Ki Kang Kim; "Towards ubiquitous RF electronics based on graphene," 2012 IEEE MTT-S International , vol., no., pp.1-3, 17-22 June 2012

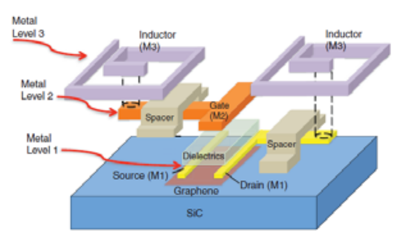
15

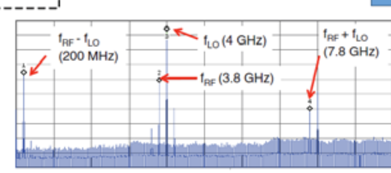
Experimental measurements of graphene devices

N3Cat

- Wafer-scale graphene integrated circuit
  - Broadband RF mixer at frequencies up to 10 GHz
  - Including a graphene FET and inductors



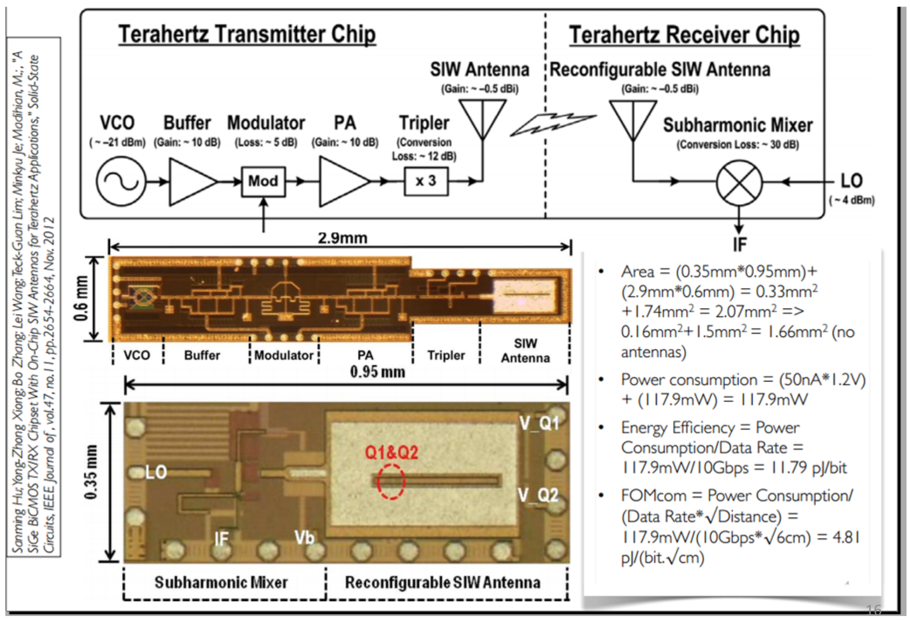




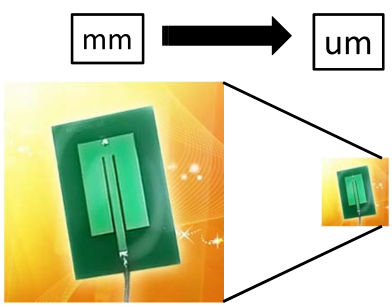
Y. Lin, A. Valdes-Garcia, S. Han, D. B. Farmer, I. Meric, Y. Sun, Y. Wu, C. Dimitrakopoulos, A. Grill, P. Avouris and K. A. Jenkins, "Wafer-Scale Graphene Integrated Circuit", Science, 2014 (IBM)

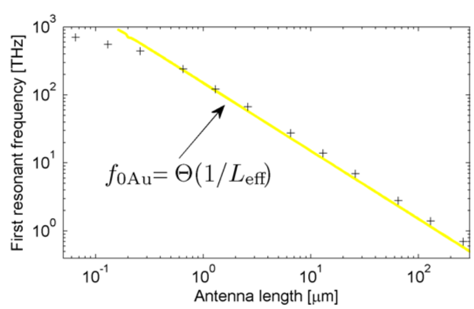
16

GFET 17GHz Frequency Doubler



Downscaling a traditional antenna





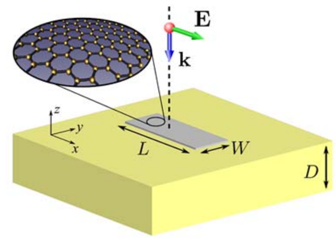
- Downscaling a traditional antenna to a few um is not possible
- Radiation frequency in the Optical Regime
- Downscalability factor: $\Theta(1/L_{eff})$

I. Llatser, C. Kremers, A. Cabellos-Aparicio, E. Alarcón and D. N. Chigrin, ***"Comparison of the Resonant Frequency in Graphene and Metallic Nano-antennas"***, in AIP Conference Proceedings, 2012

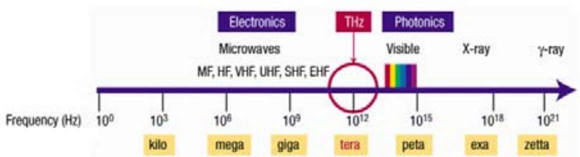
18

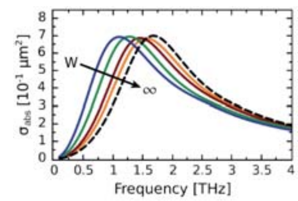
Graphene antennas at THz band

- Explore antennas that resonate
  - much lower frequency than optical regime
  - High end of the EM RF band
- Graphene-based plasmonic nano-antennas (graphennas)
  - Size in the μm range
  - Predicted to radiate in the THz band



$$\sigma(\omega) = \frac{2e^2}{\pi\hbar}\frac{k_BT}{\hbar}\ln\left[2\cosh\left[\frac{\mu_c}{2k_BT}\right]\right]\frac{i}{\omega+i\tau^{-1}}$$





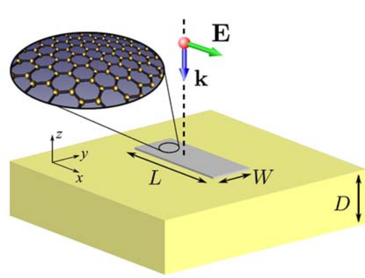
- EU FET flagship project "Graphene"

GRAPHENE FLAGSHIP

19

Graphene-enabled Wireless Communications

- **Graphene-enabled Wireless Communications (GWC)** advocate for the use of graphene RF plasmonic antennas, or **graphennas**, to communicate nanosystems
- The working principle of graphennas is as follows
  - When an EM wave irradiates the antenna, it excites the free electrons on the graphene layer
  - Surface Plasmon Polariton (SPP) waves propagate at the interface between the graphene layer and the dielectric material
  - The generated SPP waves resonate in the antenna edges

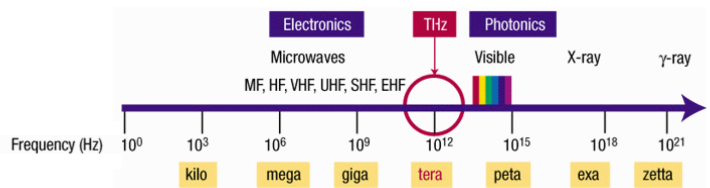


20

Graphene-enabled Wireless Communications

N3Cat

- Graphene plasmonic antennas can be developed by exploiting the propagation of SPP waves in the graphenna
- The novelty of graphennas is that they propagate SPP waves in the **terahertz band** (0.1 – 10 THz)
  - Up to two orders of magnitude below metallic plasmonic antennas
  - Comparable radiation efficiency
  - Wide tunability

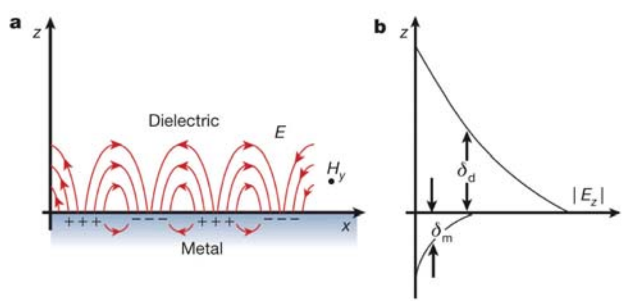


21

Analysis of graphene RF plasmonic antennas

N3Cat

- In order to understand the behavior of graphennas, we need to study the propagation of **Surface Plasmon Polariton** (SPP) waves in graphene
  - EM waves guided along a metal-dielectric interface which are generated by an incident high-frequency radiation



O. Benson, "Assembly of hybrid photonic architectures from nanophotonic constituents", *Nature*, 2011.

22

Analysis of graphene RF plasmonic antennas

N3Cat

- Current plasmonic nano-antennas
  - Made of noble metals (gold, silver)
  - Typical size ~ 10-100 nm
  - Resonant wavelength ~ 1 µm (frequency ~ 100 THz)
- Such a high frequency is not appropriate for omnidirectional wireless communications
- However, graphennas have the potential to resonate in the terahertz band
  - Graphene is able to propagate SPP waves at much lower frequencies than metallic antennas
  - Expected frequency range for future ultra-fast integrated circuits

23

Analysis of graphene RF plasmonic antennas

N3Cat

- In order to calculate the resonant frequency of graphennas, we consider their **dispersion relation**
  - Relates the wavenumber with the frequency of SPP waves propagating in a graphene layer

$$\frac{1}{\sqrt{k_{\mathrm{SPP}}^2 - \frac{\omega^2}{c^2}}} + \frac{\varepsilon}{\sqrt{k_{\mathrm{SPP}}^2 - \varepsilon\frac{\omega^2}{c^2}}} = -\mathrm{i}\frac{\sigma(\omega)}{\omega\varepsilon_0}$$

ε: dielectric constant of the substrate
ε_0: dielectric constant of vacuum
β: wavenumber
ω: angular frequency
c: speed of light
σ(ω): conductivity of graphene

$$n_{\mathrm{eff}}(\omega) = \sqrt{1 - 4\frac{\mu_0}{\varepsilon_0}\frac{1}{\sigma(\omega)^2}}$$

The graphene conductivity will determine the properties of SPP in graphene

Marinko Jablan, Hrvoje Buljan and Marin Soljačić, "Plasmonics in graphene at infrared frequencies" PHYSICAL REVIEW B 80, 245435 2009 (MIT)

Analysis of graphene RF plasmonic antennas

N3Cat

- The frequency-dependent **electrical conductivity** of a graphene monolayer is obtained using the random-phase approximation

$$\sigma(\omega) = \frac{2e^2}{\pi\hbar}\frac{k_B T}{\hbar}\ln\left[2\cosh\left[\frac{\mu_c}{2k_B T}\right]\right]\frac{\mathrm{i}}{\omega + \mathrm{i}\tau^{-1}}$$

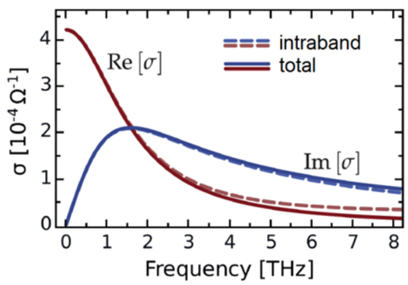
intraband contribution

$$\sigma_i(\omega) = \frac{e^2}{4\hbar}\left(H\left(\frac{\omega}{2}\right) + \mathrm{i}\frac{4\omega}{\pi}\int_0^\infty d\epsilon\,\frac{H(\epsilon) - H(\omega/2)}{\omega^2 - 4\epsilon^2}\right)$$

$$H(\epsilon) = \frac{\sinh(\hbar\epsilon/k_B T)}{\cosh(\mu_c/k_B T) + \cosh(\hbar\epsilon/k_B T)}$$

interband contribution

$\sigma(\omega)$: conductivity of graphene
ω: angular frequency
e: electron charge
$\hbar$: reduced Planck's constant
k_B: Boltzmann's constant
T: temperature
μ_c: chemical potential
τ: relaxation time



25

Analysis of graphene RF plasmonic antennas

N3Cat

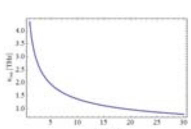
- The graphene patch acts as a Fabry-Perot resonator for SPP waves with the resonance condition

(1) $$L = L' + 2\delta L = m\frac{\lambda_{\mathrm{SPP}}}{2} = m\frac{\pi}{k_{\mathrm{SPP}}}$$

L: effective antenna length
k_{SPP}: SPP wavenumber
λ_{SPP}: SPP wavelength
m: resonance order

- By combining the resonance condition (1) with the dispersion relation in graphene (2), we can obtain the resonant frequency of graphennas as a function of their length

(2) $$\frac{1}{\sqrt{k_{\mathrm{SPP}}^2 - \frac{\omega^2}{c^2}}} + \frac{\varepsilon}{\sqrt{k_{\mathrm{SPP}}^2 - \varepsilon\frac{\omega^2}{c^2}}} = -\mathrm{i}\frac{\sigma(\omega)}{\omega\varepsilon_0}$$



26

Analysis of graphene RF plasmonic antennas

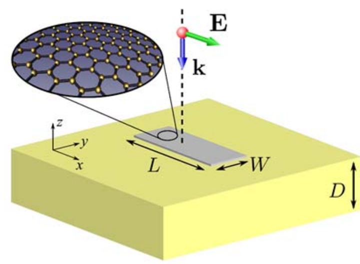
- The resonant frequency of graphennas can also be obtained by means of FEM electromagnetic simulations
  - Solve Maxwell’s equations numerically with the appropriate boundary conditions
- An incident plane wave normally incident to the antenna is considered

$$\oint \mathbf{E} \bullet d\mathbf{A} = \frac{Q}{\varepsilon_0}$$

$$\oint \mathbf{B} \bullet d\mathbf{A} = 0$$

$$\oint \mathbf{E} \bullet d\mathbf{s} = -\frac{d\Phi_m}{dt}$$

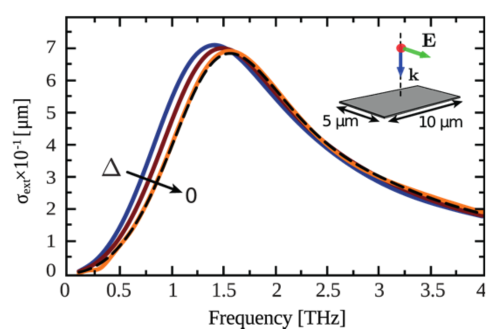
$$\oint \mathbf{B} \bullet d\mathbf{s} = \mu_0 I + \varepsilon_0 \mu_0 \frac{d\Phi_e}{dt}$$



27

Analysis of graphene RF plasmonic antennas

- Two graphenna models are considered
  - Thin slab of graphene with a finite thickness
    - Normalized effective conductivity σ/Δ
    - High mesh density $\rightarrow$ high computational cost
  - Graphene sheet as an equivalent surface impedance Z_s=1/σ
    - Current in graphene is purely superficial
    - Much lower computational cost

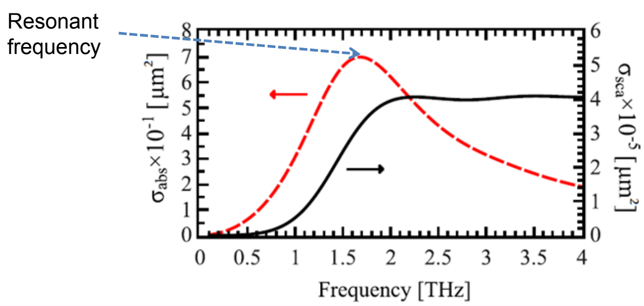


28

Analysis of graphene RF plasmonic antennas

N3Cat

- The scattering and absorption cross sections of the graphenna are numerically calculated
  - As expected in nanostructures, absorption (red line) is several orders of magnitude higher than scattering (black line)
- The **resonant frequency** is obtained as the frequency at which the absorption cross section is maximized



$$\sigma_{sca} = \frac{\oint_S d^2r\, \mathbf{S}_s \cdot \mathbf{n}}{|\mathbf{S}_{inc}|}$$

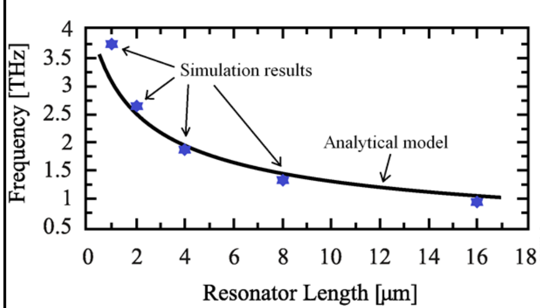
$$\sigma_{abs} = \frac{\oint_S d^2r\, \mathbf{S} \cdot \mathbf{n}}{|\mathbf{S}_{inc}|}$$

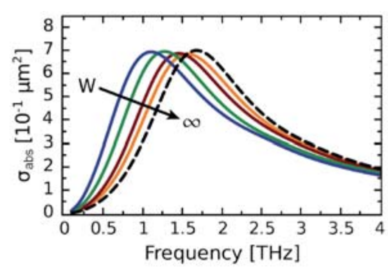
29

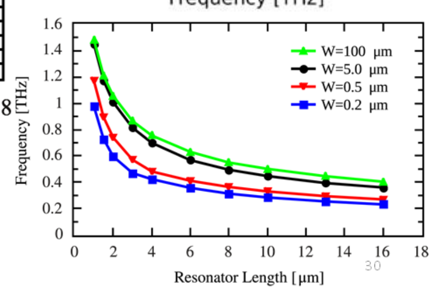
Tunability of the resonant frequency in graphennas

N3Cat

- Antenna resonant frequency as a function of its length and width





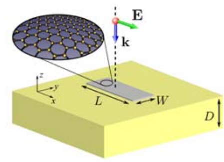


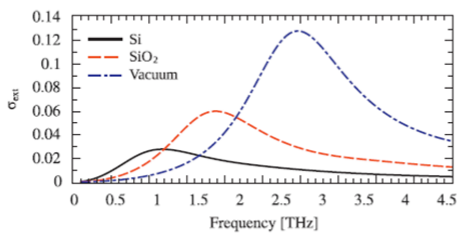
30

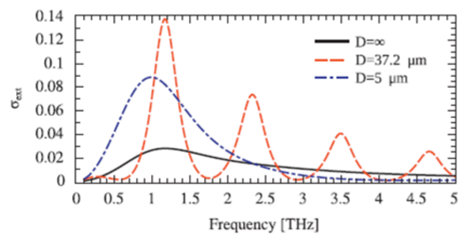
Tunability of the resonant frequency in graphennas

N3Cat

- Influence of varying the substrate material and thickness
  - The resonant frequency decreases when ε_r increases
  - By adjusting the substrate thickness, a larger resonance can be achieved





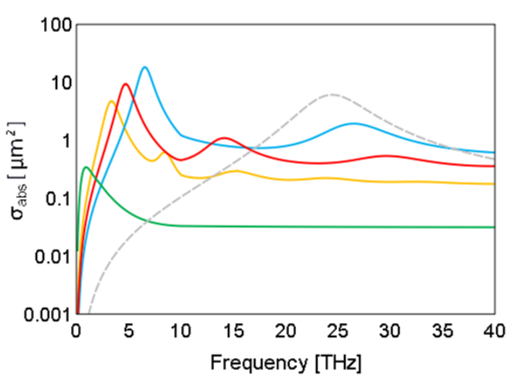


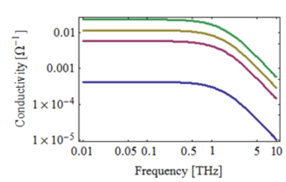
31

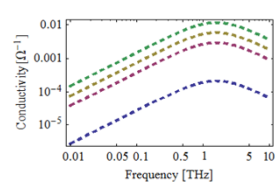
Tunability of the resonant frequency in graphennas

N3Cat

- The resonant frequency of graphennas can be tuned by changing the chemical potential
  - This can be achieved by chemical doping of the graphene layer or by applying an electrostatic bias





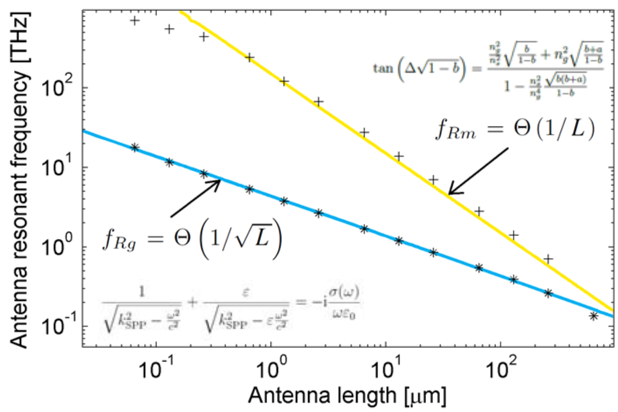


32

Comparison of graphennas and metallic antennas

N3Cat

- Scalability of the resonant frequency in graphennas and metallic antennas
  - Graphennas resonate not just at a lower frequency, but they also scale better with respect to the antenna size than metallic antennas!



Graphennas with a size of a few μm resonate in the terahertz band, 1 to 2 orders of magnitude lower than metallic antennas!

yellow line: metallic antennas
blue line: graphennas
crosses: simulation results

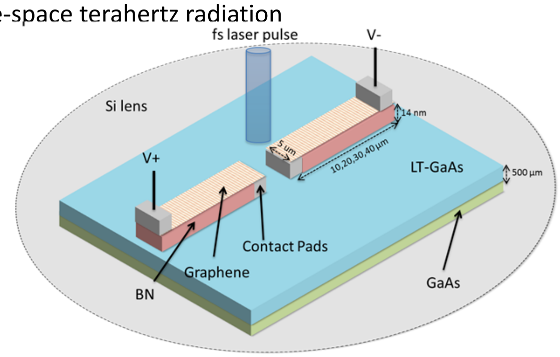
I. Llatser, C. Kremers, A. Cabellos-Aparicio, J. M. Jornet, E. Alarcón and D. N. Chigrin, ***"Graphene-based Nano-patch Antenna for Terahertz Radiation"***, Photonics and Nanostructures - Fundamentals and Applications, May 2012.

33

Photoconductive-fed graphennas

N3Cat

- A practical technique to feed graphennas is by means of photoconductive sources
  - Laser radiation excites photocarriers in the biased semiconductor and generates terahertz pulses
  - The excitation of SPP waves in the dipole graphenna produces a free-space terahertz radiation



A. Cabellos-Aparicio, I. Llatser, E. Alarcón, A. Hsu and T. Palacios, **"*Use of THz Photoconductive Sources to Characterize Graphene RF Plasmonic Antennas*"**, IEEE Transactions on Nanotechnology (UPC / MIT)

34

Photoconductive-fed graphennas

N3Cat

- A model of the photoconductive antenna allows deriving the voltage of the generated terahertz pulses
  - The power radiated by the graphenna is obtained by considering the antenna impedance, radiation efficiency and mismatch loss pulses

$$\frac{dn(t)}{dt} = -\frac{n(t)}{\tau_c} + G(t)$$

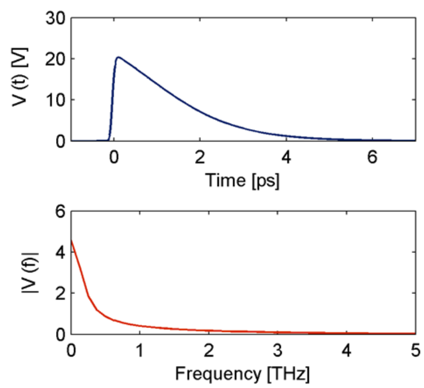
$$\frac{dv(t)}{dt} = -\frac{v(t)}{\tau_s} + \frac{e}{m}E_{loc}$$

$$\frac{dP_{sc}(t)}{dt} = -\frac{P_{sc}(t)}{\tau_r} + j(t)$$

$$V(t) = Z_a \cdot j(t)\beta \cdot V_c(t)$$

$$P = V^2/Z_a$$

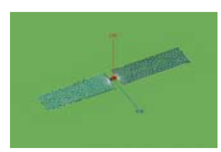
$$P_{rad} = M_L \cdot \varepsilon_R \cdot P$$

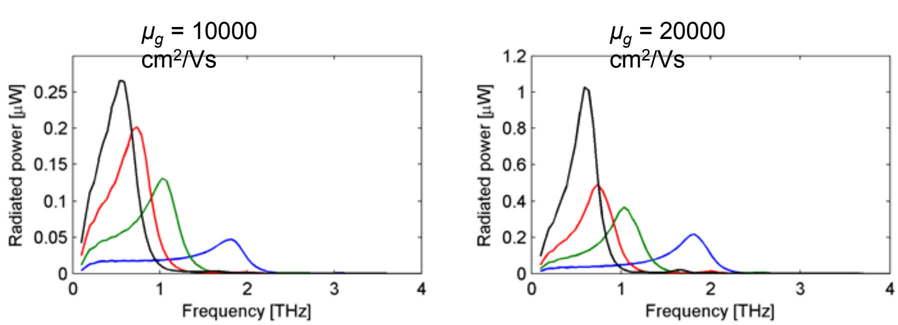


Photoconductive-fed graphennas

N3Cat

- Power radiated by the photoconductive graphenna, for different antenna lengths
  - Frequency content in the terahertz band
  - Increases with the electron mobility in graphene

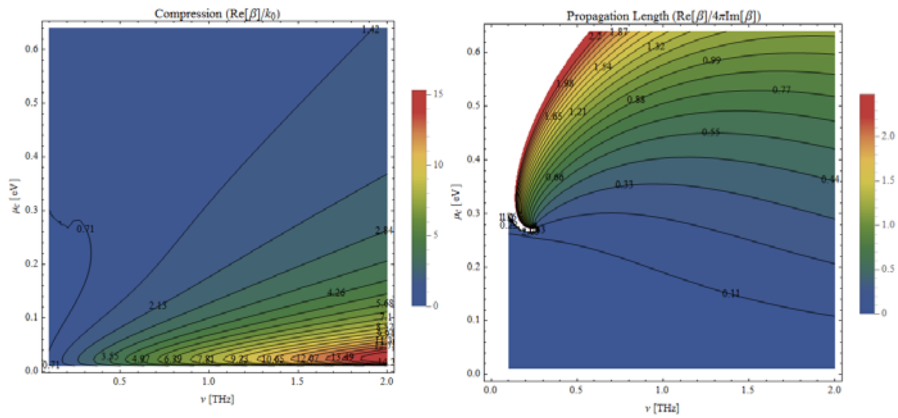




Operational range of graphene antennas

N3Cat

- How graphene antennas downscalability advantage compares to metallic antennas?



A. Cabellos,I. Llatser, E. Alarcón,A. Hsu, and T. Palacios, Max Lemme, Mikael Östling
B. (UPC / MIT / KTH / Ericsson)

37

Application 1: wireless multicore processors

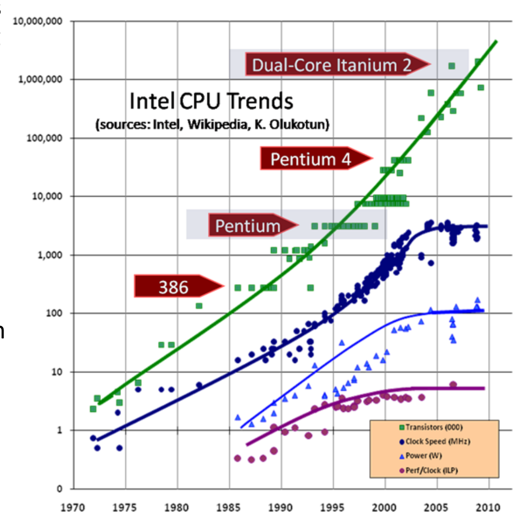
N3Cat

- Computer performance improvement is no longer achievable by simply increasing the operation frequency
  - Heat
  - Power consumption
  - Current leakage

➡ **Emergence of manycore processors**

- The performance bottleneck of multicore processors has shifted from clock frequency to inter-core communication capabilities.
  - Need of new scalable communication techniques

➡ **Comms Network-on-Chip (NoC)**



38

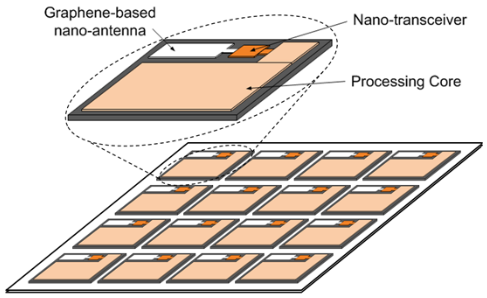
Graphene-enabled Hybrid Optical/Wireless NoC (II)

N3Cat

Graphene microantennas for wireless Network-on-Chip architectures

WHY WIRELESS for NOC?

- Multi-user shared RF medium
- Latency
- Reconfigurability
- **Inherent broadcast and multicast**
- **3D FFT supercomputers and**
- **Big Data (Google)**



PhD Candidate Sergi Abadal "Intel Doctoral Student Award"

"Graphene-enabled Wireless Communications for Manycore Architectures"

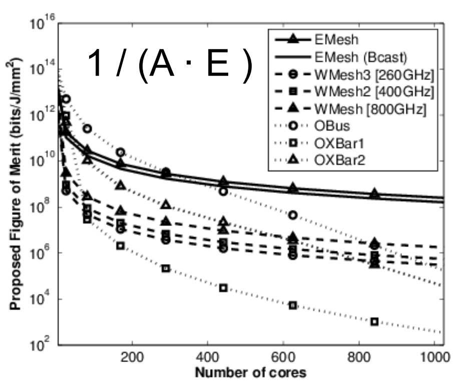
- EU FET flagship project "Human Brain project"

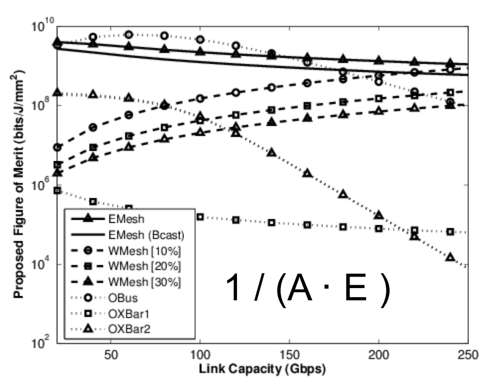
39

GWNOC: Feasibility Study

N3Cat

- Implementation-Communications
  - How do area (A) and bit energy (E) scale?

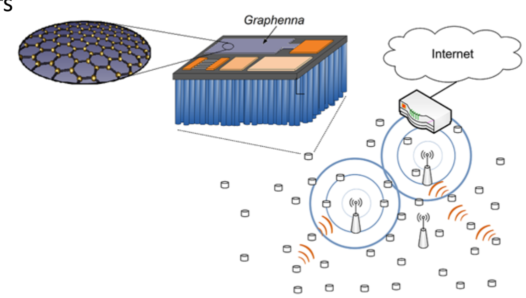




S. Abadal, M. Iannazzo, M. Nemirovsky, A. Cabellos-Aparicio, H. Lee, E. Alarcón, "**On the Area and Energy Scalability of Wireless Network-on-Chip: A Model-based Benchmarked Design Space Exploration**", submitted for publication on IEEE Transactions on Networking, Oct. 2013, revision in process.

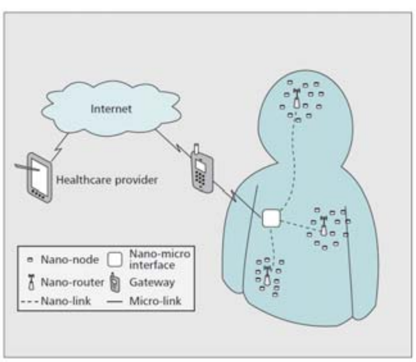
Aplicació 2: xarxes de nano-sensors sense fils

- Nano-sensor
  - Nanodispositius d'una dimensió de uns quants (pocs) micròmetres
  - Capacitat de mesurar, processar i emmagatzemar informació
  - I de recol·lectar l'energia que necessita per sensar i processar (*energy harvesting*), per exemple amb nanofils de zinc
  - Equipats amb antenes de grafè per comunicar-se (via ràdio) amb d'altres nano-sensors

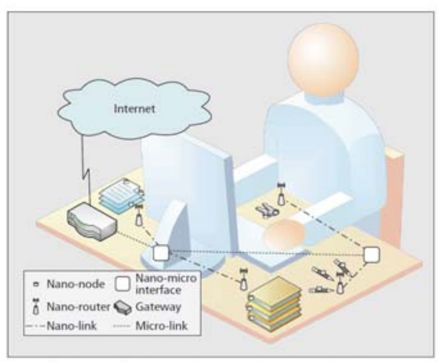


Aplicació 2: xarxes de nano-sensors sense fils

- Algunes aplicacions de les xarxes de nano-sensors:



Sistema de detecció de malalties i administració cooperativa de medicaments (Intrabody networks)



Internet de les nano-coses (Internet of nano-things)

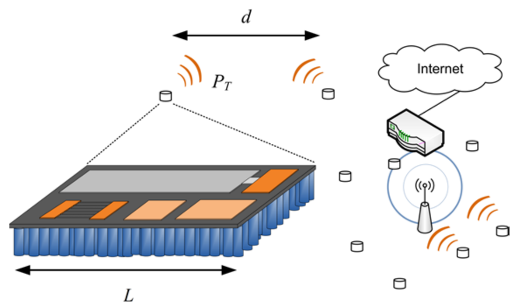
- EU FET flagship project "Guardian Angels"

Guardian Angels
for a smarter life

Channel capacity in GWC

N3Cat

- The scalability of the channel capacity in GWC is studied as a function of three scale parameters
  - Antenna length *L*
  - Transmission distance *d*
  - Transmitted power P_T
- The results using graphennas and metallic antennas are compared



43

Channel capacity in GWC

N3Cat

- The channel capacity is obtained with the Shannon-Hartley theorem, integrated over the whole terahertz band

$$C = \max_{S(f): \int_B S(f)df \leq P_T} \int_B \log_2 \left(1 + \frac{S(f)}{A(f)N(f)}\right) df$$

Transmitted power spectral density

$$S(f) = \begin{cases} P_T/B & \text{if } 0 < f < B, \\ 0 & \text{otherwise.} \end{cases}$$

Noise power spectral density

$$N(f,d) = k_B(T_{sys} + T_{mol}(f,d))$$

$$T_{mol}(f,d) = T_0(1 - e^{-k(f)d})$$

$$T_{sys} = T_0 = 293 \text{ K}$$

Channel attenuation

$$A = A_{spread}A_{abs}$$

$$A_{spread} = \left(\frac{4\pi f d}{c}\right)^2$$

$$A_{abs} = \frac{1}{\tau_m} = e^{k(f)d}$$

Bandwidth

$$B_m = \frac{k_1}{L} \qquad B_g = \frac{k_2}{\sqrt{L}}$$

44

Channel capacity in GWC

- Expression of the channel capacity in GWC
  - The factor P_T/d^2 will have a key role

$$C(B,d,P_T) = \int_0^B \log_2\left(1 + \frac{P_T/B}{\left(\frac{4\pi f d}{c}\right)^2 N_0}\right) df$$

$$= \frac{B}{\log 2}\log\left(1 + \frac{c^2 P_T}{(4\pi d)^2 B^3 N_0}\right) + \frac{c\sqrt{P_T}}{2\log(2)\pi d\sqrt{N_0 B}}\arctan\frac{4\pi d B^{3/2}\sqrt{N_0}}{c\sqrt{P_T}}$$

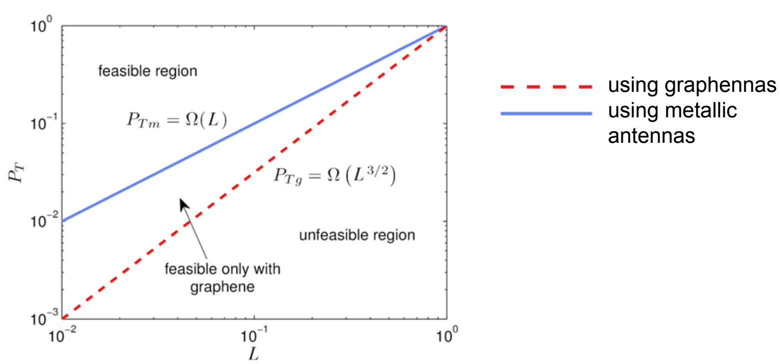
$$C_m(L,d,P_T) = \frac{k_1}{\log(2)L}\log\left(1 + \frac{c^2 L^3 P_T/d^2}{(4\pi)^2 N_0 k_1^3}\right) + \frac{c\sqrt{LP_T/d^2}}{2\log(2)\pi\sqrt{N_0 k_1}}\arctan\frac{4\pi\sqrt{N_0 k_1^3}}{c\sqrt{L^3 P_T/d^2}}$$

$$C_g(L,d,P_T) = \frac{k_2}{\log(2)\sqrt{L}}\log\left(1 + \frac{c^2 L^{3/2} P_T/d^2}{(4\pi)^2 N_0 k_2^3}\right) + \frac{c\sqrt[4]{L}\sqrt{P_T/d^2}}{2\log(2)\pi\sqrt{N_0 k_2}}\arctan\frac{4\pi\sqrt{N_0 k_2^3}}{cL^{3/4}\sqrt{P_T/d^2}}$$

45

Channel capacity in GWC

- Scalability of the transmitted power in GWC with respect to the antenna length
  - Additional feasibility condition: the network shrinks proportionally
    - Transmission distance scales proportionally to the antenna length (α=1)
  - Graphennas require less power than metallic antennas as their size is reduced to the nanoscale



46

Thanks

N3Cat

Nanonetworking Center in Catalunya

www.n3cat.upc.edu

47