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UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

*Campus d'Excel·lència Internacional*

**Doctoral training seminars: track microelectronics**

# Emergent enabling technologies for wireless data, energy processing and communications


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## Graphene-enabled wireless comms: Team and projects

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- " 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"by **Intel research**
- EU FET flagship project "Graphene"
- EU FET flagship accesit "Guardian Angels"
- EU FET flagship project "Human Brain project"

SAMSUNG ADVANCED INSTITUTE OF TECHNOLOGY

intel LABS

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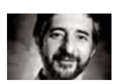

Dr. Mario Nemirovski
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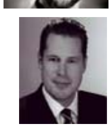
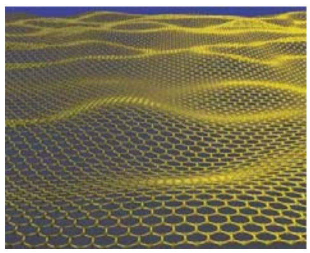


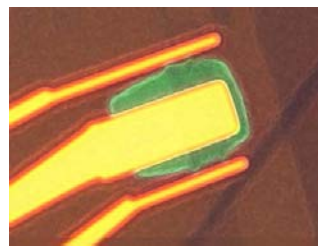
Prof. Max Lemme
KTH

Prof. Tomas Palacios
Massachusetts Institute of Technology

## *Grafè*

- 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





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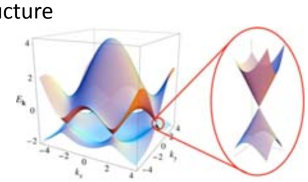
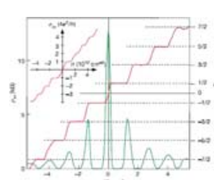
## *Grafè*

- 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





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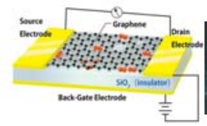
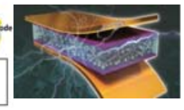
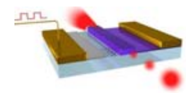
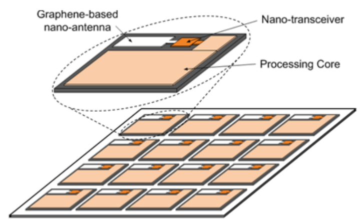
## Grafè

- 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 grafè**

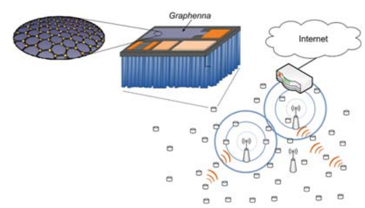







Mid-term: Graphene-based Wireless Network-on-Chip for Multi-Core processors




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.

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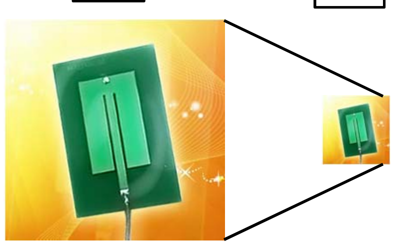
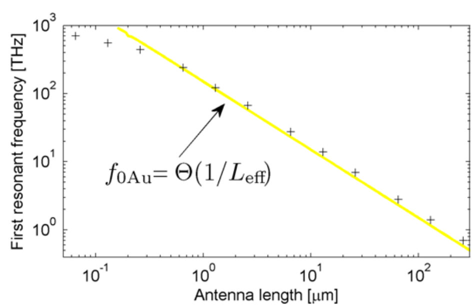
## Downscaling a traditional antenna

mm → um






- 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

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## Graphene antennas at THz band

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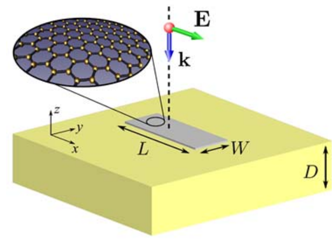
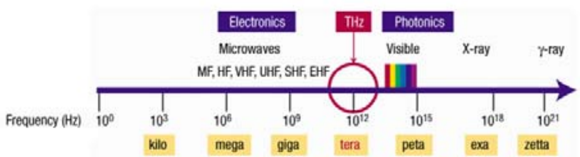
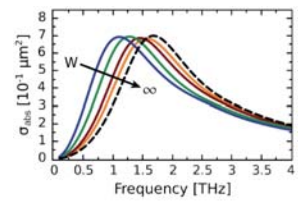
- Explore antennas that resonate
  - much lower frequency than optical regime
  - High end of the EM RF band
- Graphene-based plasmonic nano-antennas (graphennas)
  - Size in the µm range
  - Predicted to radiate in the THz band




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




- EU FET flagship project "Graphene"

GRAPHENE FLAGSHIP

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## Analysis of graphene RF plasmonic antennas

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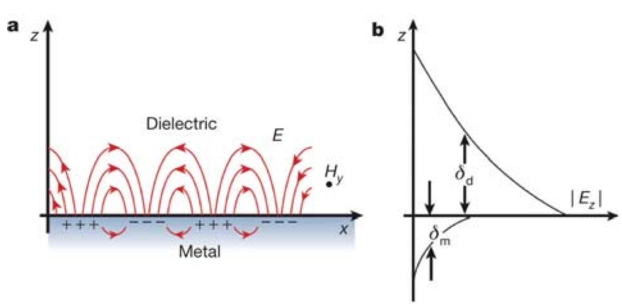
- In order to understand the behavior of graphennas, we need to study the propagation of **Surface Plasmon Polariton** (SPP) waves in graphene
  - EM waves guided along a metal-dielectric interface which are generated by an incident high-frequency radiation




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

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## Analysis of graphene RF plasmonic antennas

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- 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
$\varepsilon_0$: 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

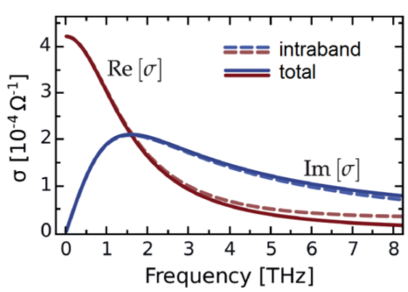
$$\sigma(\omega) = \frac{2e^2}{\pi\hbar}\frac{k_BT}{\hbar}\ln\left[2\cosh\left[\frac{\mu_c}{2k_BT}\right]\right]\frac{\mathrm{i}}{\omega + \mathrm{i}\tau^{-1}}$$

intraband contribution

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

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

interband contribution




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

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## Analysis of graphene RF plasmonic antennas

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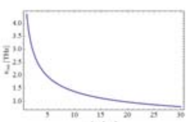
- The graphene patch acts as a Fabry-Perot resonator for SPP waves with the resonance condition

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



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## Analysis of graphene RF plasmonic antennas

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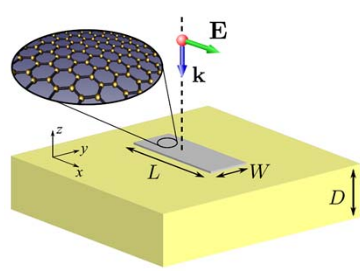
- The resonant frequency of graphennas can also be obtained by means of FEM electromagnetic simulations
  - Solve Maxwell's equations numerically with the appropriate boundary conditions
- An incident plane wave normally incident to the antenna is considered

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

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

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

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

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## Tunability of the resonant frequency in graphennas

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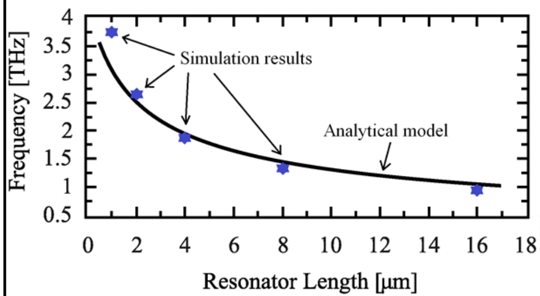
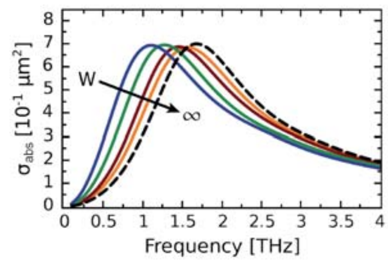
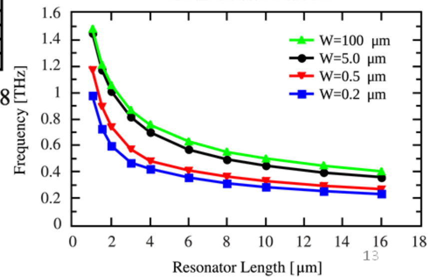
- Antenna resonant frequency as a function of its length and width

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## Comparison of graphennas and metallic antennas

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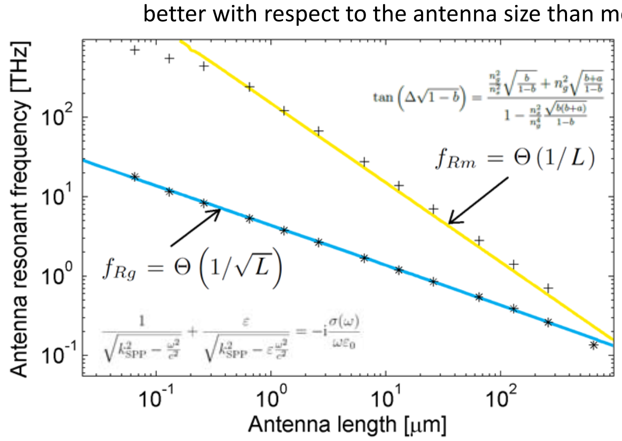
- Scalability of the resonant frequency in graphennas and metallic antennas
  - Graphennas resonate not just at a lower frequency, but they also scale better with respect to the antenna size than metallic antennas!




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.

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## Photoconductive-fed graphennas

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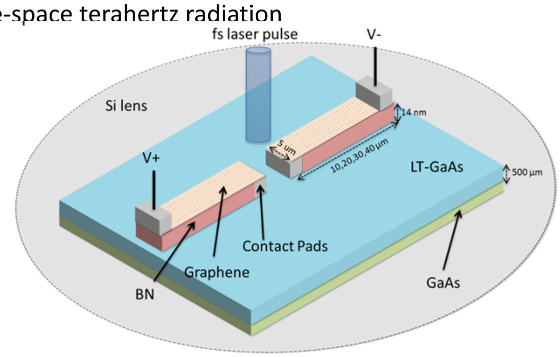
- A practical technique to feed graphennas is by means of photoconductive sources
  - Laser radiation excites photocarriers in the biased semiconductor and generates terahertz pulses
  - The excitation of SPP waves in the dipole graphenna produces a free-space terahertz radiation




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 –ECE-)



## Photoconductive-fed graphennas

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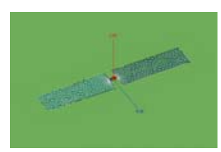
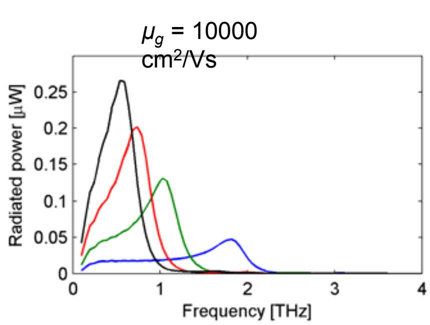
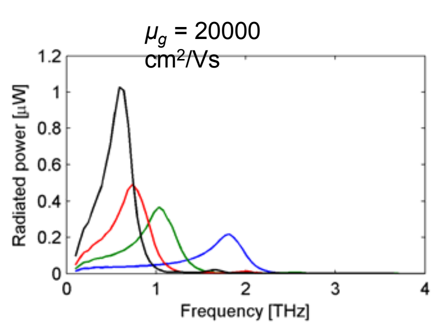
- Power radiated by the photoconductive graphenna, for different antenna lengths
  - Frequency content in the terahertz band
  - Increases with the electron mobility in graphene





## Operational range of graphene antennas

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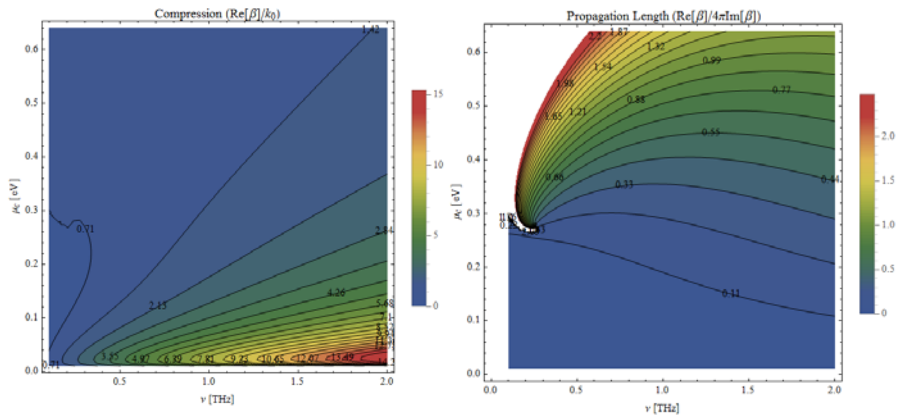
- How graphene antennas downscalability advantage compares to metallic antennas?




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

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## Application 1: wireless multicore processors

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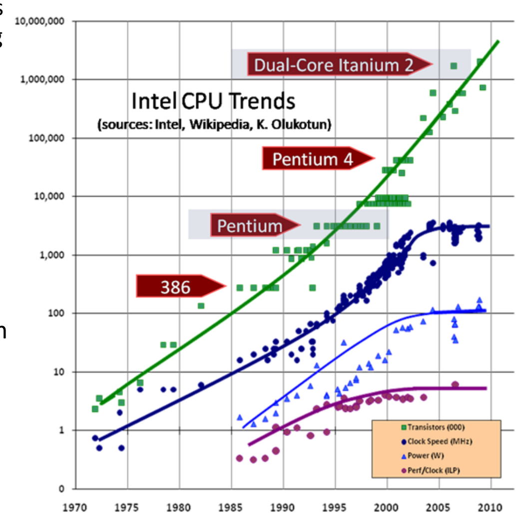
- Computer performance improvement is no longer achievable by simply increasing the operation frequency
  - Heat
  - Power consumption
  - Current leakage

➡ **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)**

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## Graphene-enabled Hybrid Optical/Wireless NoC (II)

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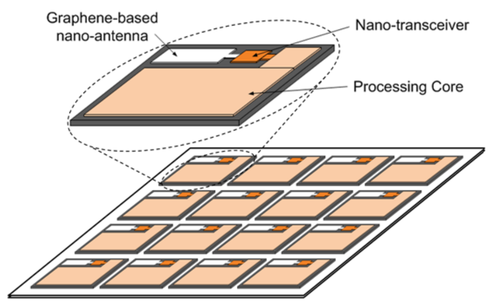
**Graphene microantennas for wireless Network-on-Chip architectures**

### 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"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## GWNOC: Feasibility Study

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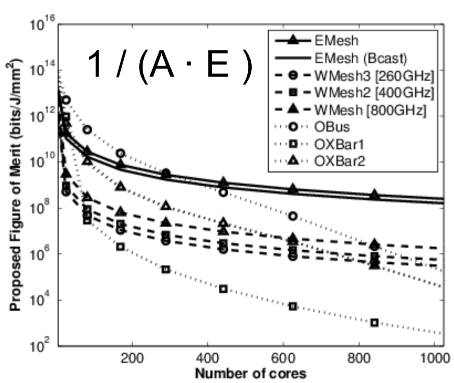
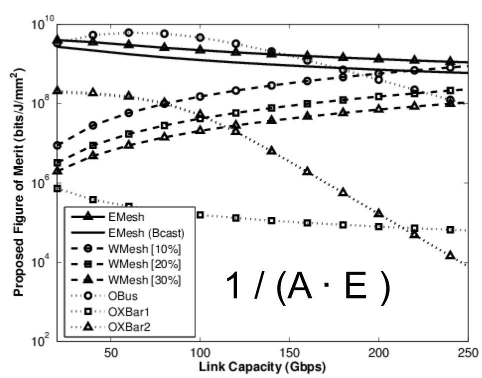
- Implementation-Communications
  - How do area (A) and bit energy (E) scale?

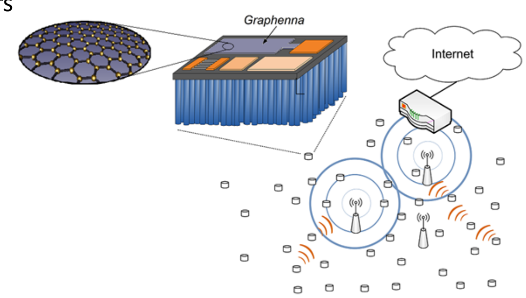



S. Abadal, M. Iannazzo, M. Nemirovsky, A. Cabellos-Aparicio, H. Lee, E. Alarcón, "**On the Area and Energy Scalability of Wireless Network-on-Chip: A Model-based Benchmarked Design Space Exploration**", submitted for publication on IEEE Transactions on Networking, Oct. 2013, revision in process.

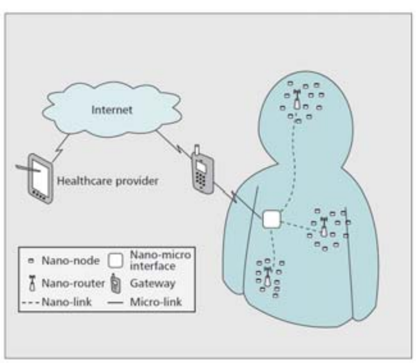
## Aplicació 2: xarxes de nano-sensors sense fils

- 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

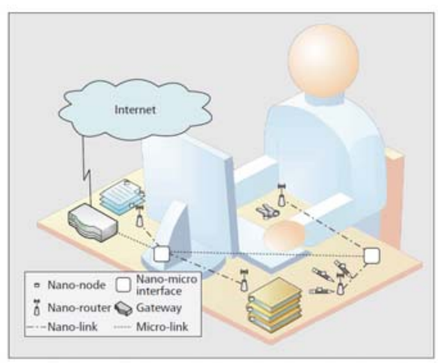



## Aplicació 2: xarxes de nano-sensors sense fils

- 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

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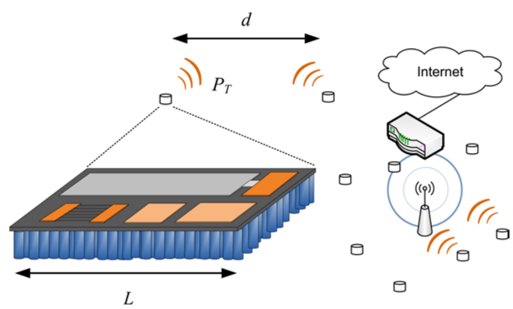
## Channel capacity in GWC

- 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

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## Channel capacity in GWC

- 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

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

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## Channel capacity in GWC

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

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

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

$$C_m(L,d,P_T) = \frac{k_1}{\log(2)L}\log\left(1+\frac{c^2L^3P_T/d^2}{(4\pi)^2N_0k_1^3}\right) + \frac{c\sqrt{LP_T/d^2}}{2\log(2)\pi\sqrt{N_0k_1}}\arctan\frac{4\pi\sqrt{N_0k_1^3}}{c\sqrt{L^3P_T/d^2}}$$

$$C_g(L,d,P_T) = \frac{k_2}{\log(2)\sqrt{L}}\log\left(1+\frac{c^2L^{3/2}P_T/d^2}{(4\pi)^2N_0k_2^3}\right) + \frac{c\sqrt[4]{L}\sqrt{P_T/d^2}}{2\log(2)\pi\sqrt{N_0k_2}}\arctan\frac{4\pi\sqrt{N_0k_2^3}}{cL^{3/4}\sqrt{P_T/d^2}}$$

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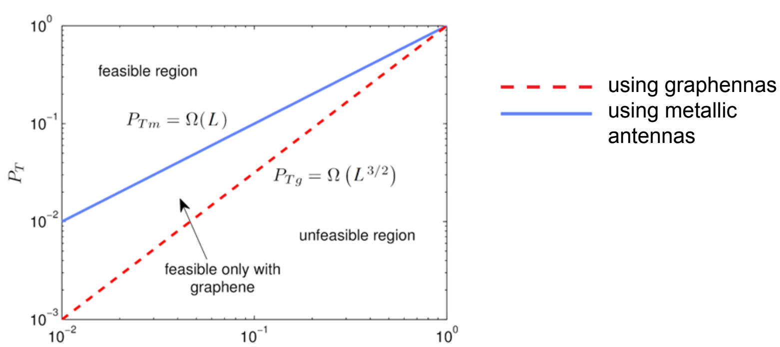
## Channel capacity in GWC

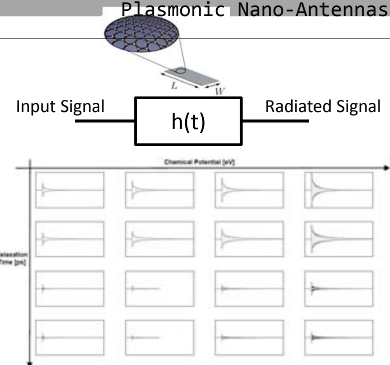
- Scalability of the transmitted power in GWC with respect to the antenna length
  - Additional feasibility condition: the network shrinks proportionally
    - Transmission distance scales proportionally to the antenna length (α=1)
  - Graphennas require less power than metallic antennas as their size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



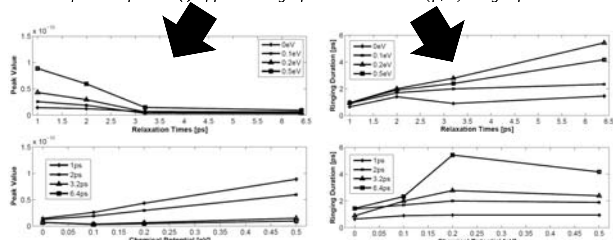

26

## Time-Domain Characterization of Graphene-based Plasmonic Nano-Antennas

N3Cat




*Impulse response **h(t)** of fixed-size graphennas within the (μ, τ) design space*



*Impulse reponse peak value [left] and duration [right] as a function of μ and τ.*

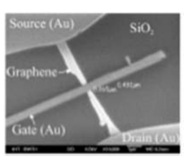
**1.** Design space exploration of the time-domain performance of graphennas of different:
- Chemical Potential (μ)
- Relaxation Time (τ)
- Dimensions (W, L)

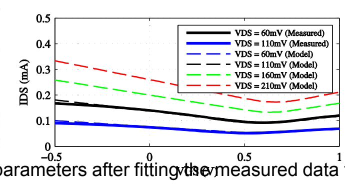
**2.** Derivation of graphenna and input signal design considerations in terms of:
- Energy
- Data Rate

*S. Abadal, I. Llatser, A. Mestres, H. Lee, A. Cabellos-Aparicio, E. Alarcón, "Time Domain Analysis of Graphene-based Nano-antennas for Chip Communication", 2013.*

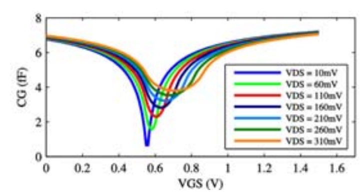
## Graphene FET model extraction oriented to device-circuit co-design methodology

N3Cat

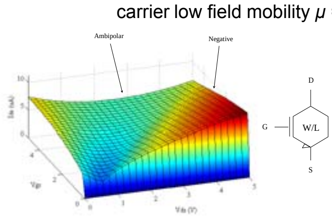


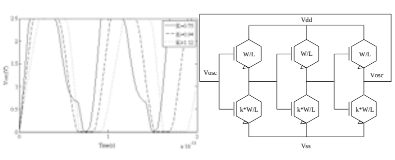

The extracted parameters after fitting the measured data to the model are: minimum sheet carrier concentration $\rho_{sh0}$ = $0.7 \times 10^{12}$ cm$^{-2}$, Dirac offset voltage $V_{GS\text{-}top0}$ = 0.5 V, and carrier low field mobility $\mu$ = 2500 cm$^2$ V$^{-1}$ s$^{-1}$.




Top gate capacitance $C_G$ vs. $V_{GS}$ for L=65nm and W=10um.




Behavioural simulation model (AMS verilog Cadence) based on large-signal physics-based model




"Design-oriented Characterization of Graphene-FET Based Ring-Oscillators: a Device-circuit Co-design Perspective", M. Iannazzo, S. Rodriguez, A. Rusu, M.C. Lemme, E. Alarcon, submitted for publication, March 2013.

"RF Performance Projections of Graphene FETs vs. Silicon MOSFETs", S. Rodriguez, S. Vaziri, M. Ostling, A. Rusu, E. Alarcon, M.C. Lemme, ECS Solid State Letters, vol. 1, no. 5, pp. Q39–Q41, Aug. 2012.

## On-chip energy Harvesting: Team and projects

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**Project: Energy Harvesting**

**CONSOLIDER-INGENIO 2010** (Spanish Ministery of Science and Technology), "Advanced Wide Band Gap Semiconductor Devices for Rational Use of Energy (RUE)", Principal Investigator: José Millán (CNM-CSIC, Bellaterra, Barcelona,Spain), Program period: Jan 2010 – Jan 2014, Investigators: 50 (CNM, UPM, UPC, UOvi, UZ, UPV, URV), Funding: 3MEuros

**MCYT (Spanish Ministery of Science and Technology)** (TEC2007-67988-C02-01) [coordinated project], "On-chip wideband adaptive energy management of RF power amplifiers: towards efficient next-generation mobile communications RF transmitters", PI: E. Alarcon (UPC) Program period: Jan 2008 – Dec 2010. Investigators: 12 (UPC, Universidad Pública de Navarra, Universidad Rovira i Virgili, Tarragona), Total: Euro 219K

Raul Gomez, PhD candidate

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Prof. Eduard Alarcón (EE)

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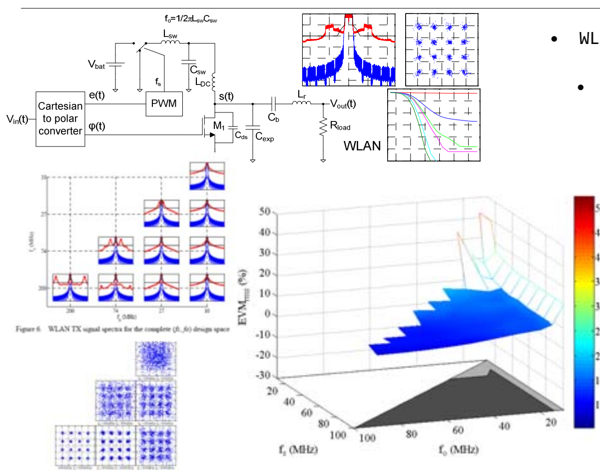
Prof. Kaushik Chowdhury (Northeastern Univ Boston)

## Device-design-oriented translayer model for tracking RF TX: *system-to-device*

N3Cat




16-QAM scatter plots for different relevant configurations within the (fs, fo) design space

16-QAM EVMrms for configurations that fulfil(solid surface) or not (mesh surface) mode 5 EVM standard requirements.

- WLAN stringent specs (BW 50 MHz)
  - Even with best topology (linear asisted multilevel) and control/modulation (nonlinear time optimal / asyn SD) efficiency is low in the available application/system-constrained design space
    - Take behavioural model down to device level to derive guidelines and FOMs for next-generation (GaN) devices in terms of Ron and Qs

J. Marchan "Device-design-oriented translayer model for Circuit/system design space characterization of EER-based transmitter for 802.11a WLAN Standard ", MSc's thesis, expected Dec 2011

*J.Marchán, E. Barba, L. Marco, D. Maksimovic and E. Alarcón "Circuit/system design space characterization of EER-based transmitter for 802.11a WLAN Standard ", IEEE International Symposium on Circuits and Systems, 2012, ISCAS 2010*

## Energy harvesting : the prehistory of a “new” concept

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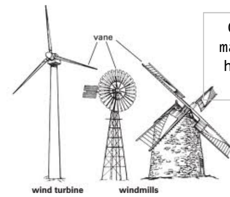
Timeline

Miniaturization (in size and power level)

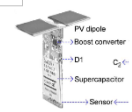
**Windmills**

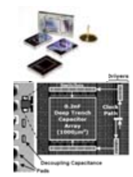



Off-shore marine wave harvesting

Kinetic wristwatch

PV cells and panels



Integrated ultra low power energy harvesters (mechanical vibration, acoustic, EM)

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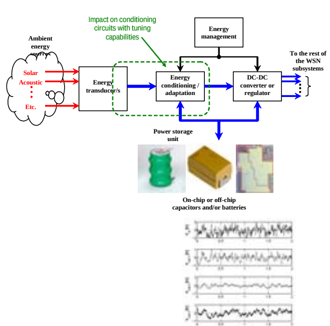
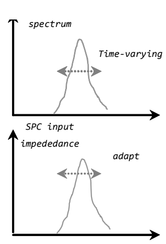
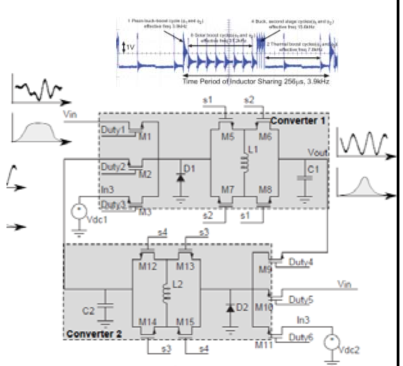
## Challenges for On-chip power management circuits targeting energy harvesting

N3Cat

- Sophisticated functionality (time-varying burst-mode energy source -and load-)
- **Adaptive power management frontend : in pursuit of instantaneous MPPT**
- Inclusion of sophisticated power processing functionality, due to the time-varying burst-mode energy harvesting source. Most of the environmental energy sources have a time-dependent energy concentration of its frequency band, as a result of the aggregation of several energy sources of the same type. In this context, there is the need to explore adaptive power management frontends in pursuit of fast wideband MPPT [3] energy tracking schemes and optimal impedance matching and energy extraction

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## Graphene-based vibration harvester

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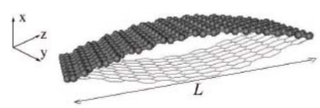
Frequency matching through nonlinear chaotic oscillation of graphene membrance mechanical harvester




Uncompressed or weakly compressed graphene membrane

$$\ddot{x} = -\frac{b}{m}\dot{x} - \frac{1}{m}\frac{\partial V}{\partial x} + \frac{\sigma^2}{m}\eta(t)$$

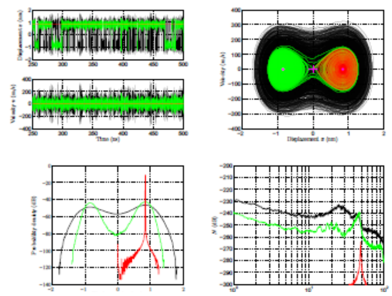


Figure 3. Dynamics of the graphene membrane under a stochastic external excitation $\sigma^2 = 1$ pN (red), $\sigma^2 = 50.5$ pN (green) and $\sigma^2 = 100$ pN (black). (a) Time series, (b) Trajectories in the phase plane $(x, v)$. Equilibrium points of the free system are also plotted. (c) Probability density function (in dB) of the displacement $x$ and (d) Smoothed FFT spectrum of the displacement $x$ and noise $\sigma^2\eta(t)$. Note that the spectrum is spread to low frequency regions when the noise intensity is sufficiently large so that the potential barrier can be crossed.

*"Nonlinear Dynamics in a Nanostructured Graphene Device for Energy Harvesting Applications", E. Alarcon et al, IEEE ISCAS 2013 Beijing, special session*

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## Ambient Energy model with dynamics separation and spatiotemporal correlation

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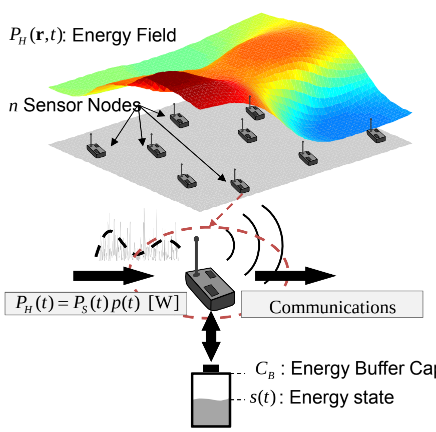
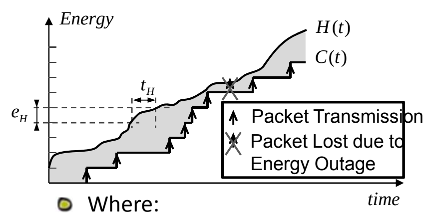
- Spatio-Temporal Correlation of the Energy Field




- The Energy Path




- Where:

$$H(t) = \int_0^t P_H(\tau)d\tau + s(0) \qquad C(t) = \int_0^t P_C(\tau)d\tau$$

Shaded area = s(t)

- We discretize the state equation:

$$s^{k+1} = e_H^k - e_C^k + s^k$$

Subject to: $0 \le s^{k+1} \le C_B$

- Where:

$$e_H^k = \int_{t_k}^{t_{k+1}} P_H(t)dt$$

$e_C^k$ = Provided by the application

- *"Scalability of Network Capacity in Energy-Harvesting-Enabled Wireless Sensor Networks", Raul Gomez Cid-Fuentes, Albert Cabellos, Eduard Alarcon, IEEE Transactions on Netwotking, 2014.*

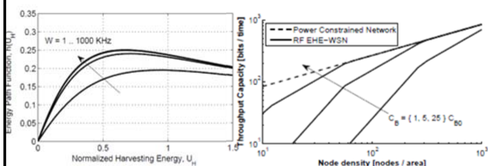
## Using the Ambient Energy model: temporal storage dimensioning and network capacity scalability

N3Cat

- Scalability
  - Define Energy Path Function:

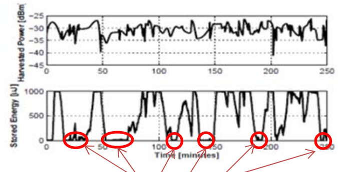
$$U_C = \frac{E_C}{C_B} = h\left(\frac{E_H}{C_B}\right) = h\left(U_H\right)$$

  - It is found that the network scales as: $\tilde{\Theta}\left(h\left(n^{-\alpha/2}\right)n^{\alpha-1/2}\right)$
  - RF Example:



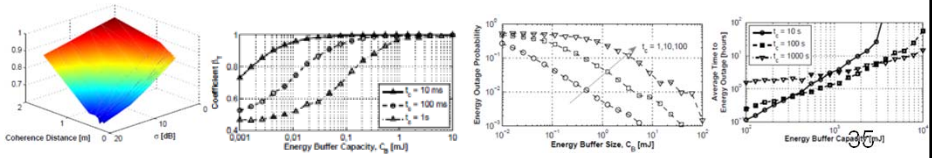

  - Spatio-Temporal Correlation

- Energy Buffer Dimensioning
  - The energy buffer must store energy to overcome slow fadings in the energy harvesting.
  - RF Example with Rayleigh Channel:




**Energy Outage**

  - Time-varying evaluation of the Energy Outage (*no steady state*):




## Wireless power transfer: Team and projects

N3Cat

- **Project: Resonant Inductive Near-field Generation System (RINGS)**

**Sponsors:**
Defense Advanced Research Projects Agency (DARPA)
National Aeronautics and Space Administration (NASA)
**Collaborators:** David Miller (Co-I), Peter Fisher, Alex Buck, Greg Eslinger (MIT)
John Merk (Co-I), Roedolph Opperman (Aurora Flight Sciences)
Elisenda Bou (UPC Barcelona Tech)

**Project proposals:**
Google Inc

Elisenda Bou, PhD candidate

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Dr. Ray Sedwick

University of Maryland

Prof. Eduard Alarcón (EE)

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Prof. Peter Fisher (MIT Dept Physics)

Massachusetts Institute of Technology

## Energy Harvesting concept extension: active energy mothership

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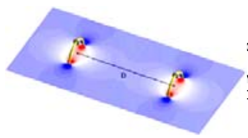
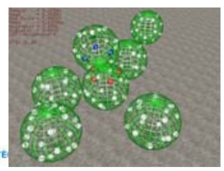
- Artificially **increase ambient** energy through active generation/radiation of a single energy source (energy **broadcast**):
  - EH-enables sensor node structure is intact, but feasible
  - Options like Resonant Wireless Power Transfer become appealing

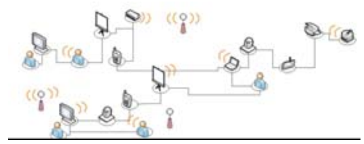


Coupled resonant non-radiative near-field antennas for WPT.

Notable efficiencies can be obtained (60%) for distances larger (4/5x) than the coils size.

  - Enables applications as **claytronics and IoT**





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## UPC work on Resonant inductive coupling WPT

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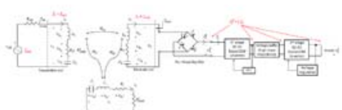
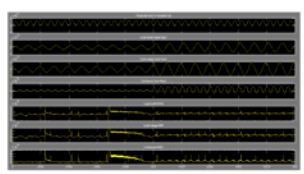
**Open challenges in Resonant inductive coupling wireless power transfer:**

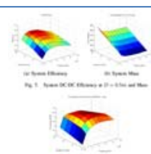
- Distance-insensitive WPT power link: *adaptive high-effiency impedance matching*

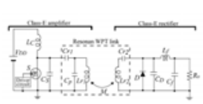




- *"Automatic Impedance Matching Proposal Based on Power Factor Correction For a Wireless Power Transfer Resonant Inductive Coupling Link", Nuria Egidos, Raymond Sedwick E. Bou-Balust and E. Alarcon*

- Overall system efficiency



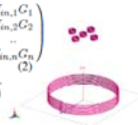


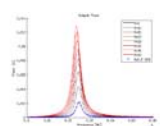
MIMO ºWPT system

- *"Class E2 Resonant Non-Radiative Wireless Power Transfer Link: A design-oriented joint circuit-system co-characterization approach", Elisenda Bou-Balust, Tomoharu Nagashimay, Hiroo Sekiyay, Eduard Alarcon*

$$\begin{pmatrix} I_1 \\ I_2 \\ .. \\ I_n \end{pmatrix} = \begin{pmatrix} 0 & G_{21}G_1 & .. & G_{n1}G_1 \\ G_{12}G_2 & 0 & .. & G_{n2}G_2 \\ .. & .. & .. & .. \\ G_{1n}G_n & G_{2n}G_n & .. & 0 \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ .. \\ I_n \end{pmatrix} + \begin{pmatrix} V_{in,1}G_1 \\ V_{in,2}G_2 \\ .. \\ V_{in,n}G_n \end{pmatrix} \quad (2)$$

$$\eta_{N,pp} = \frac{|I_j|^2 R_{L,j}}{\sum_{i=0}^{i=N_T} |I_{i,T}|^2 \Re(Z_i) + \sum_{i=0}^{i=N_R} |I_{i,R}|^2 \Re(Z_i)}$$





$$\eta_{pp} = \frac{G_r G_t G_{tr}^2}{4G_r^2 G_{tr}^2 - G_r(4G_{rr} - (N-1)G_{tr}^2 G_t) + 1}$$

- *" Scalability Analysis of SIMO Non-Radiative Resonant Wireless Power Transfer Systems based on Circuit Models", Elisenda Bou-Balust, Raymond Sedwick and Eduard Alarcon*

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## Chaotic nonlinear dynamics in RIC-WPT

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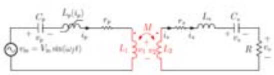
Chaotic oscillation of RIC-WPT with nonlinear saturable inductors

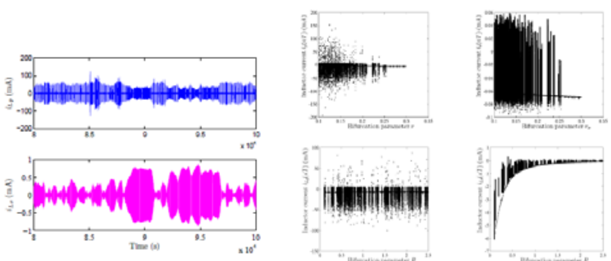


$$x(t) = e^{A_i(t-t_i)}x(t_i) + \int_{t_i}^{t} e^{A_i(t-\tau)}B_i(\tau)d\tau := \Phi_i(t-t_i)x(t_i) + \Psi_i(t,t_i)$$

$$\dot{x} = A_i x + B_i := f_i(x)$$

$$A_i = \begin{pmatrix} \frac{\mathcal{L}_s r_p}{\Delta(i_p)} & \frac{MR}{\Delta(i_p)} & \frac{\mathcal{L}_s}{\Delta(i_p)} & \frac{M}{\Delta(i_p)} \\ \frac{M r_p}{\Delta(i_p)} & \frac{\mathcal{L}_p(i_p)R}{\Delta(i_p)} & \frac{M}{\Delta(i_p)} & \frac{\mathcal{L}_p(i_p)}{\Delta(i_p)} \\ \frac{1}{C_p} & 0 & 0 & 0 \\ 0 & \frac{1}{C_s} & 0 & 0 \end{pmatrix}$$

$$B_i = \begin{pmatrix} \frac{V_{in}\mathcal{L}_s}{\Delta(i_p)}\sin(\omega_f t) \\ \frac{V_{in}M}{\Delta(i_p)}\sin(\omega_f t) \\ 0 \\ 0 \end{pmatrix}, \quad x = \begin{pmatrix} i_p \\ i_s \\ v_p \\ v_s \end{pmatrix}$$



*"Unveiling Nonlinear Dynamics in a Resonant Inductively Coupled Wireless Power Transfer Circuit", E. Bou-Balust, A. el Aroudi, P. Fisher, E. Alarcon, IEEE ISCAS 2014 Melbourne, special session (UPC / MIT / URV)*

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## Embedding energy processing frontends in RIC-WPT

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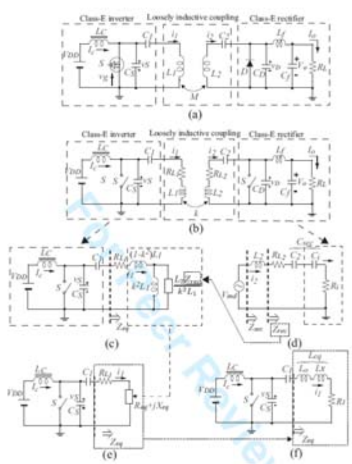
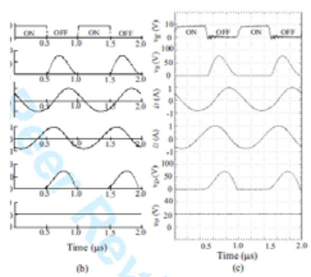
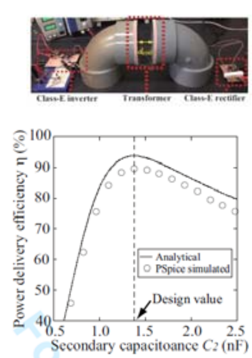
Resonant Inductive Coupled Wireless Power Transfer
With Class-E2 DC-DC Converter for high efficiency





$$v_S(2\pi) = 0 \quad \text{and} \quad \left.\frac{dv_S}{d\theta}\right|_{\theta=2\pi} = 0.$$

$$\eta_{max} = \frac{k^2\omega^2 L_1 L_2 R_i}{R_{L1}(R_i + R_{L2})^2 + k^2\omega^2 L_1 L_2 (R_i + R_{L2})}.$$



$$C_S = \frac{2\sin(\pi D_S)\cos(\pi D_S + \phi_S)\sin(\pi D_S + \phi_S)[(1-D_S)\pi\cos(\pi D_S) + \sin(\pi D_S)]}{\omega\pi^2(1-D_S)R_1}.$$



*"Analytical Design Procedure for Resonant Inductively Coupled Wireless Power Transfer With Class-E2 DC-DC Converter", Tomoharu Nagashima1, Kazuhide Inoue, Xiuqin Wei, Elisenda Bou-Balust, Eduard Alarcon, Marian K. Kazimierczuk, and Hiroo Sekiya, submitted to IEEE Journal on Emergent topics in Power (Chiba and Fukuoka Universities, Japan, Wrigth Univ. OH, UA and UPC)*

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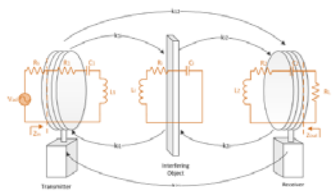
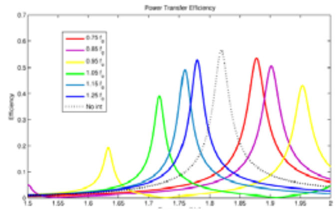
## Interference analysis in RIC-WPT

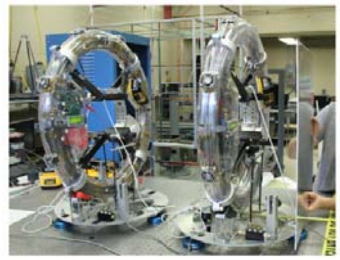
N3Cat

Model predicting effect of interfering objects on frequency detuning






$$\eta = \frac{(\omega M_{12})^2 Z_L Z_i}{Z_1(Z_2+R_L)^2 Z_i + (\omega M_{12})^2 (Z_2+R_L) Z_i + (\omega M_{1i})^2}$$



Backplane metallic object.
RING testbed for WPT/FF
oriented to ISS

- *"Interference analysis on Resonant Inductive Coupled Wireless Power Transfer Links", Elisenda Bou-Balust, Eduard Alarcon , Raymond Sedwick and Peter Fisher, IEEE ISCAS 2013 Beijing, (UPC/Maryland/MIT)*

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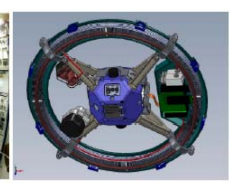
## UPC work on Resonant inductive coupling WPT

N3Cat

**On-going applications:**

- Fractionated spacecrafts / nanosatellite constellation / flight formation

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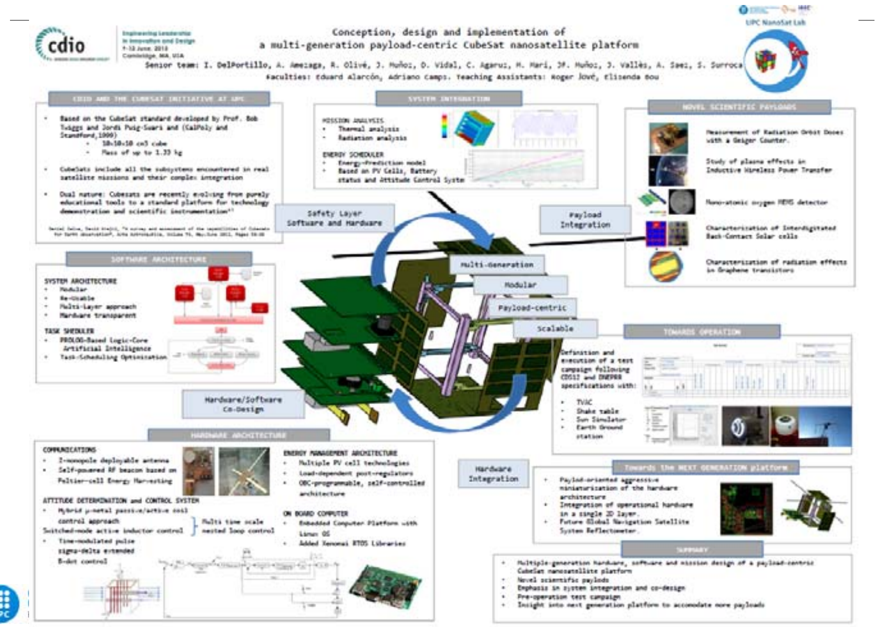
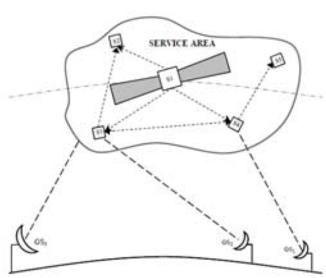
## UPC nanosatellite project (nanosat lab)




## On scalability of nanosat distributed architectures

**Project:** 2013. Google Faculty Research Award "Android Beyond the Stratosphere". PIs: Prof. Eduard Alarcon, Prof. Adriano Camps. Team: Elisenda Bou-Balust (UPC), Adria Recasens (MIT), Íñigo del Portillo (MIT), Daniel Selva (MIT)

Google




$$\begin{pmatrix} \eta_{1,d(t_1)} p_{1,d(t_1)}^{R,t_1} & \cdots & \eta_{N_s,d(t_1)} p_{N_s,d(t_1)}^{R,t_1} \\ \vdots & \ddots & \vdots \\ \eta_{1,d(t_{N_t})} p_{1,d(t_{N_t})}^{R,t_{N_t}} & \cdots & \eta_{N_s,d(t_{N_t})} p_{N_s,d(t_{N_t})}^{R,t_{N_t}} \end{pmatrix} \begin{pmatrix} R_1^R \\ \vdots \\ R_{N_S}^R \end{pmatrix} = \begin{pmatrix} R_{obt}^{R,t_1} \\ \vdots \\ R_{obt}^{R,t_{N_t}} \end{pmatrix}$$

$$[MAX]\, z = \sum U_t p_t = \sum U_t \prod p_t^R = \sum U_t \prod \frac{R_{obt}^R}{R_{need}^R}$$

s.t.:

$$R_{need}^R \geq \left((T \cdot \eta^R) \circ p^R\right) R_s^R$$

$$\underline{1} \geq (p^R)^T \underline{1}$$

$$p_{ij}^{R,t} \geq 0$$

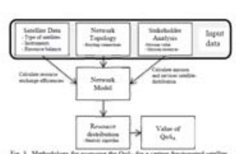
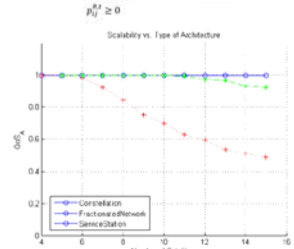


Fig. 3. Methodology for assessing the $QoS_R$ for a certain fractionated satellite network configuration.




- *"On Scalability Limits of Resource Constrained General Purpose Fractionated Satellite Network Architectures " Iñigo del Portillo, Elisenda Bou-Balust, Marc Sanchez, Daniel Selva, Eduard Alarcón, (UPC / MIT AeroAstro), submitted to ACTA ASTRONAUTICA, 2014*

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