

Graphene-enabled Wireless Communication Networks at the Nanoscale

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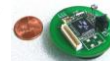
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Nanonetworks

Which is the **downscaling limit** of a communication network?




?




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Nanonetworks




- Nanonetworks
 - Wireless networks at the nanoscale
 - Expand the range of applications of nanotechnology



environmental



biomedical




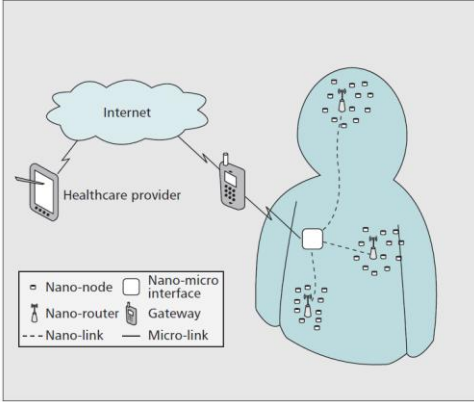
consumer goods

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Applications of Nanonetworks






Intra-body disease detection and cooperative drug delivery systems

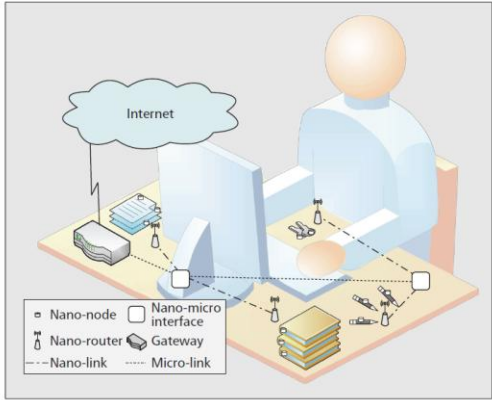
Ian F. Akyildiz, Josep Miquel Jornet, "The Internet of Nano-Things", *IEEE Wireless Communications*, 2010.

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Applications of Nanonetworks






The Internet of nano-things

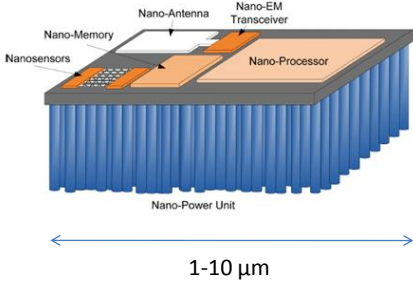
Ian F. Akyildiz, Josep Miquel Jornet, "The Internet of Nano-Things", *IEEE Wireless Communications*, 2010.

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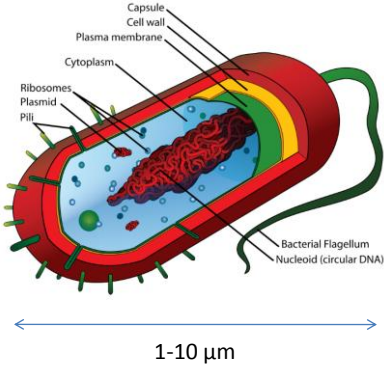
Nanomachines



Nanonetworks: interconnection of **nanomachines**



1-10 μm



1-10 μm

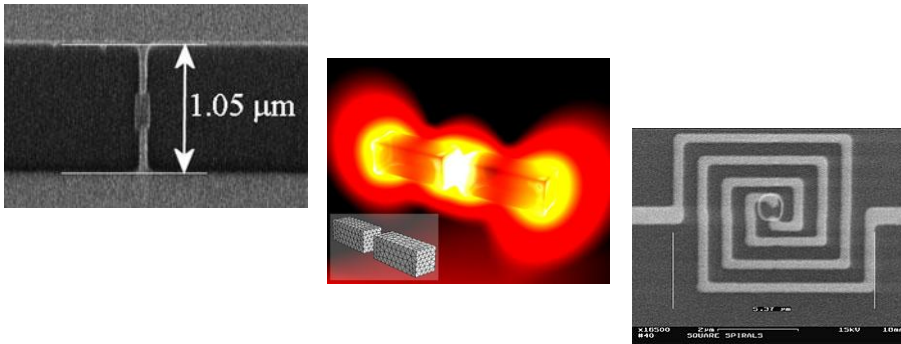
Ian F. Akyildiz, Josep Miquel Jornet, "Electromagnetic Wireless Nanosensor Networks", *Nano Communication Networks (Elsevier)*, 2010.

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Nano-antennas



Metallic nano-antennas only resonate at optical frequencies!



J. Simón, F.J. González, "Nanoantennas for polarisation division multiplexing", *Electronics Letters*, 2011.
 A.M. Kern, and O.J.F. Martin, "Surface integral formulation for 3-D simulations of plasmonic and high permittivity nanostructures", *Journal of the Optical Society of America A*, 2009.
 D.K. Kotter, S.D. Novack, W.D. Slafer, P. Pinhero, "Solar Nantenna Electromagnetic Collectors", *Proceedings of Energy Sustainability 2008*.

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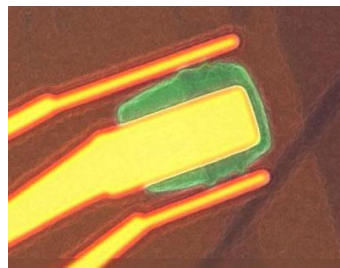
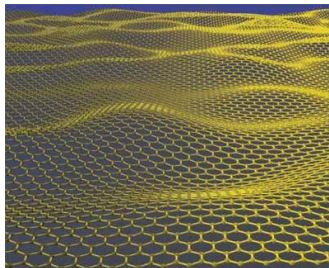
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Graphene



● Graphene

- Honeycomb lattice of carbon atoms
- 2-dimensional material
- Discovered by A. K. Geim and K. S. Novoselov




G. Liu, W. Stillman, S. Romyantsev, Q. Shao, M. Shur, A. A. Balandin, "Low-frequency electronic noise in the double-gate single-layer graphene transistors", *Applied Physics Letters*, 2009.

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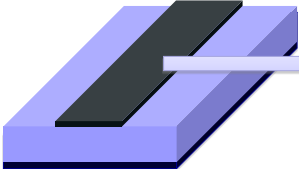
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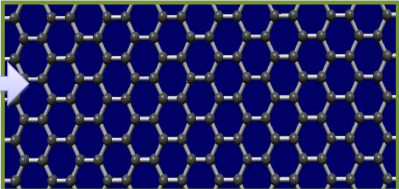
Graphene-based Nano-antennas



- Graphene-based nano-antenna
 - Quantum effects
 - Radiates at the THz band

1-10 μm




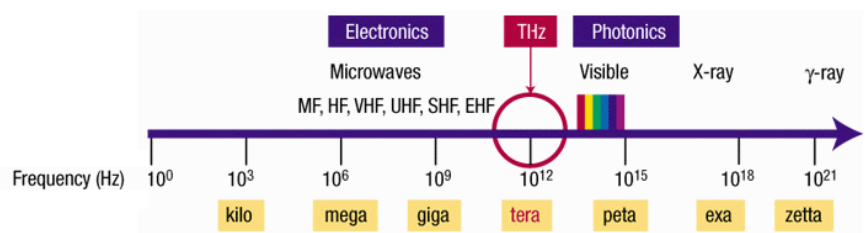


Josep Miquel Jornet, Ian F. Akyildiz, "Graphene-Based Nano-Antennas for Electromagnetic Nanocommunications in the Terahertz Band", *Proc. European Conference on Antennas and Propagation*, Barcelona, 2010 .

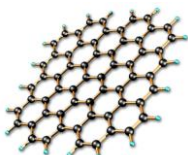
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Graphene-based Nano-antennas

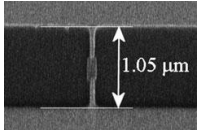




graphene-based nano-antenna

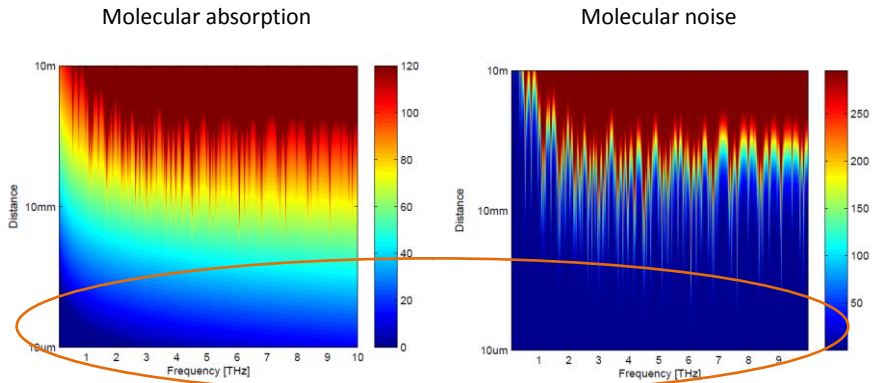


metallic nano-antenna



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Terahertz Channel at the Nanoscale



At the nanoscale, the whole frequency band is available!

Josep Miquel Jornet, Ian F. Akyildiz, "Channel Modeling and Capacity Analysis of Electromagnetic Wireless Nanonetworks in the Terahertz Band", to appear in *IEEE Transactions on Wireless Communications*, 2011.

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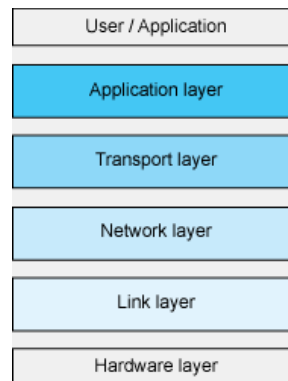
Nanonetwork Architecture



- Current network protocols **do not consider** the particularities of nanonetworks

- Very simple nodes
- Strict energy requirements
- Huge frequency band available

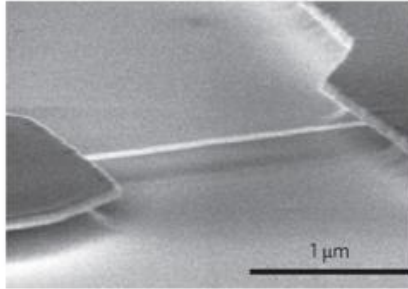
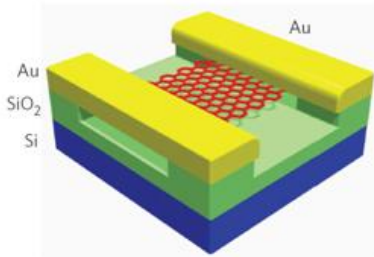
- They need to be **reinvented**



Research Challenges



- Design, develop experimental prototypes and measure novel **graphene-based nano-antennas**



Changyao Chen, Sami Rosenblatt, Kirill I. Bolotin, William Kalb, Philip Kim, Ioannis Kymissis, Horst L. Stormer, Tony F. Heinz, James Hone, "Performance of monolayer graphene nanomechanical resonators with electrical readout", *Nature Nanotechnology*, 2009.

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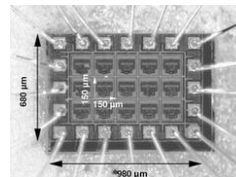
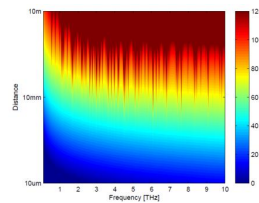
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Research Challenges



- Physical channel model for **THz-band communications** at the very short range and its experimental validation

$$\begin{aligned}
 H = & \sum_{\mathbf{k}, \sigma} \epsilon_{\mathbf{k}} a_{\mathbf{k}, \sigma}^{\dagger} a_{\mathbf{k}, \sigma} + \left(\gamma + \frac{\epsilon_b}{2} \right) b^{\dagger} b \\
 & + \frac{U_a}{V_a} \sum_{\mathbf{k}, \mathbf{k}'} a_{\mathbf{k}, \uparrow}^{\dagger} a_{-\mathbf{k}, \downarrow}^{\dagger} a_{-\mathbf{k}', \downarrow} a_{\mathbf{k}', \uparrow} \\
 & + \frac{U_{ab}}{V_a} \sum_{\mathbf{k}, \sigma} a_{\mathbf{k}, \sigma}^{\dagger} a_{\mathbf{k}, \sigma} b^{\dagger} b + \frac{U_b}{V_b} b^{\dagger} b^{\dagger} b b \\
 & + \frac{gV_b}{V_a^{3/2}} \sum_{\mathbf{k}} \left(b^{\dagger} a_{-\mathbf{k}, \downarrow} a_{\mathbf{k}, \uparrow} + a_{\mathbf{k}, \uparrow}^{\dagger} a_{-\mathbf{k}, \downarrow}^{\dagger} b \right)
 \end{aligned}$$



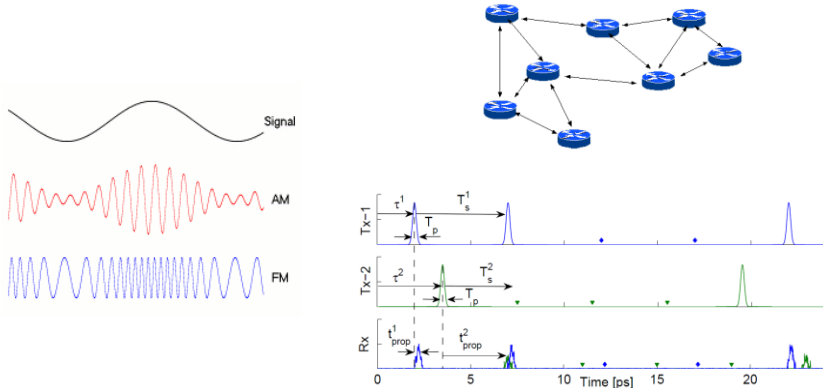
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Research Challenges



- **Novel modulations, protocols and techniques** specifically suited for nanonetworks



Joan Capdevila Pujol, Josep Miquel Jornet, Josep Solé-Pareta, "PHLAME: A Physical Layer Aware MAC Protocol for Electromagnetic Nanonetworks", in *Proc. 1st IEEE International Workshop on Molecular and Nano Scale Communication*, 2011.

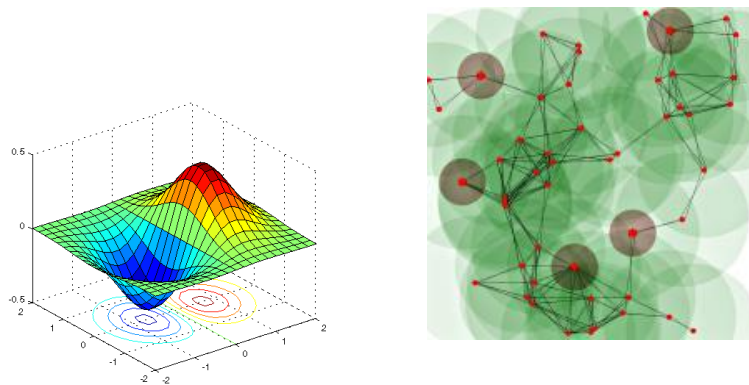
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Research Challenges



- Physical-level and network-level **simulation frameworks** for nanonetworks



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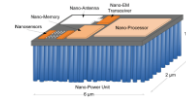
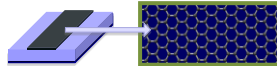
Summary



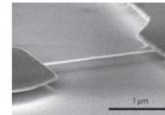
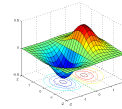
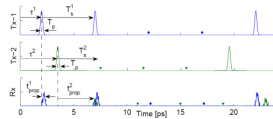
- **Nanonetworks** will greatly expand the range of applications of nanotechnology



- **Graphene-based nano-antennas** will allow the implementation of nanonetworks



- Nanonetworks will require **radically different** solutions from those in current wireless networks



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Thank you for your attention



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