# Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

**Submission Title:** Design of Graphene-based Nano-antennas for Terahertz Band Communication
**Date Submitted:** 13 November, 2012
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**Re:**
**Abstract:** A novel graphene-based nano-antenna that exploits the behavior of Surface Plasmon Polariton (SPP) waves in semi-finite size Graphene Nanoribbons (GNRs), is proposed, modeled and analyzed. First, the conductivity of GNRs is analytically and numerically studied by starting from the Kubo formalism to capture the impact of the electron lateral confinement in GNRs. Second, the propagation of SPP waves in GNRs is analytically and numerically investigated, and the SPP wave vector and propagation length are computed. Finally, the nano-antenna is modeled as a resonant cavity, and its frequency response is determined. The results show that graphene-based plasmonic nano-antennas which are just one-micrometer long and few-nanometer wide can efficiently operate in Terahertz Band.
**Purpose:** Design of compact graphene-based nano-antennas for Terahertz Band communication

# Design of Graphene-based Plasmonic Nano-Antennas for Terahertz Band Communication

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# Outline

- Introduction
- Conductivity of Graphene Nanoribbons
- Surface Plasmon Polariton Waves in Graphene Nanoribbons
- Frequency Response of Graphene-based Plasmonic Nano-antennas
- Conclusions

# Nanonetworks

I. F. Akyildiz and J. M. Jornet, "Electromagnetic Wireless Nanosensor Networks," Nano Communication Networks Journal (Elsevier), March 2010.

I. F. Akyildiz and J. M. Jornet, "The Internet of Nano-Things," IEEE Wireless Communication Magazine, December 2010.

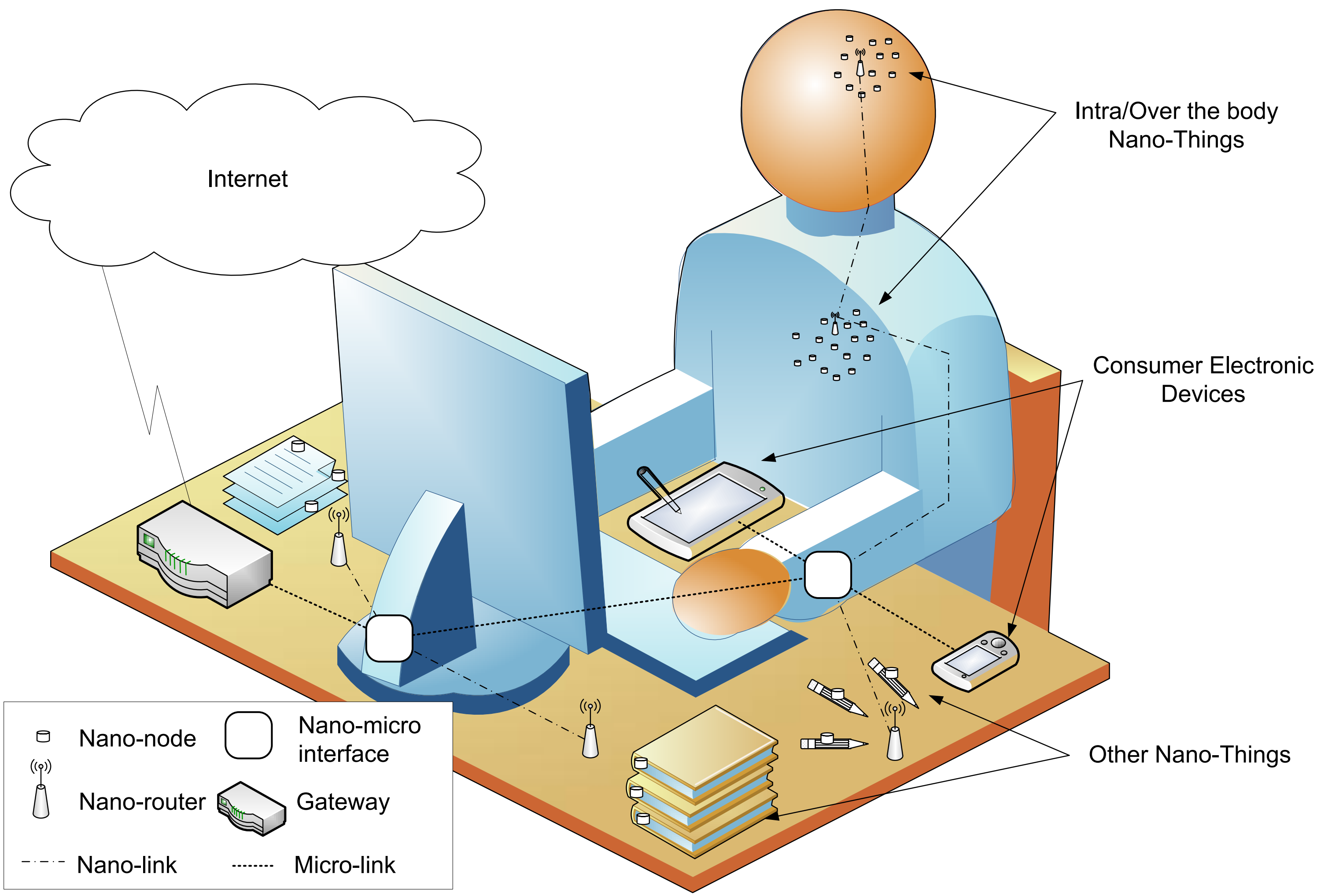
I. F. Akyildiz, J. M. Jornet and M. Pierobon, "Nanonetworks: A New Frontier in Communications," Communications of the ACM, November 2011.

- Nanotechnology is providing a new set of tools to the engineering community to design and manufacture novel electronic components, which are just a few cubic nanometers in size

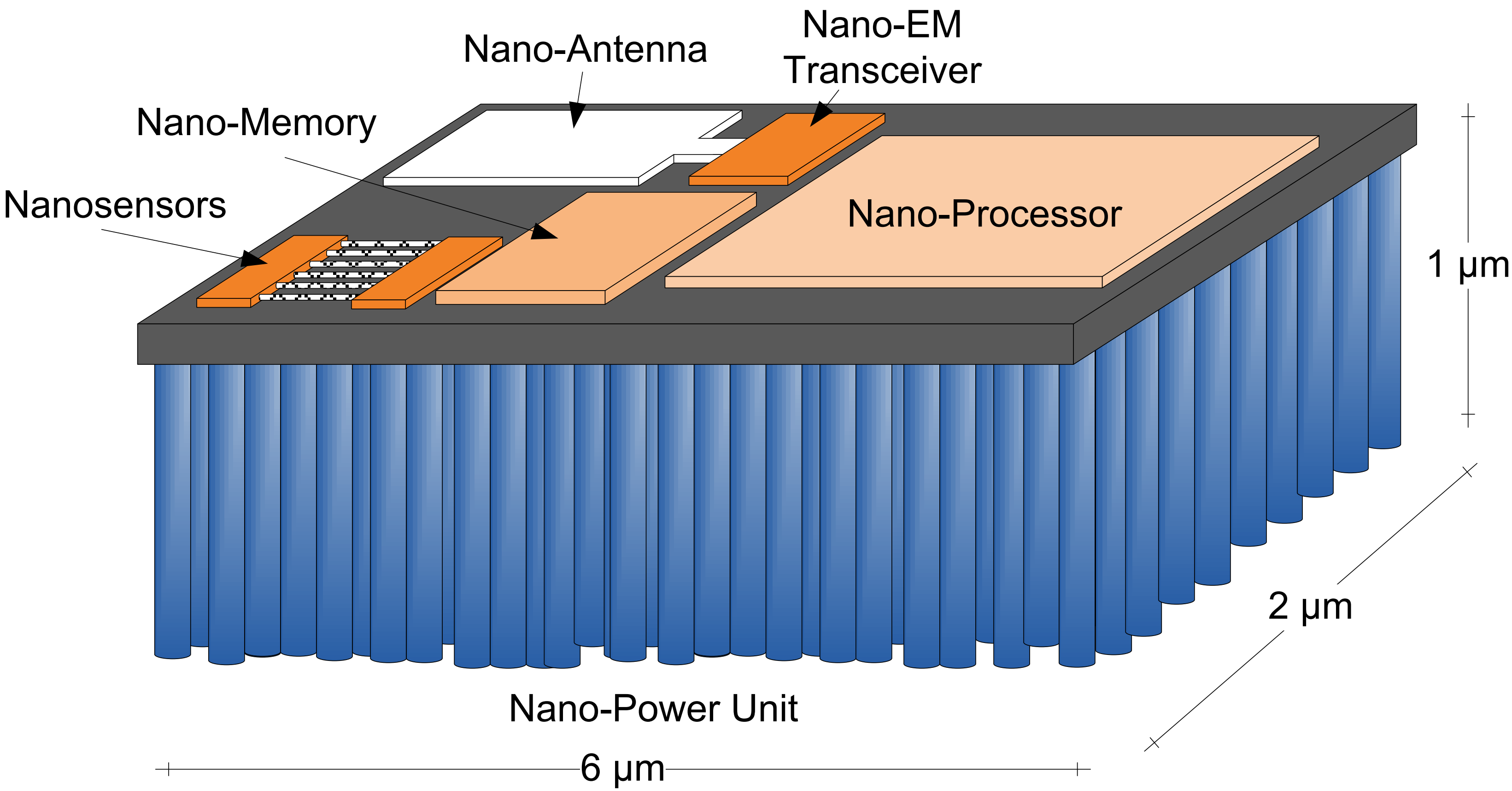
- The integration of several of these nano-components into a single entity will allow enable the development of more advanced nano-devices

- By means of communication, nano-devices will create novel nanonetworks and accomplish complex tasks in a distributed manner

# Application: The Internet of Nano-Things



# Nano-device Conceptual Architecture



# Communication in Nanonetworks

- The miniaturization of a classical metallic antenna to meet the size requirements of nano-devices would impose the use of very high resonant frequencies (well above 100 THz)

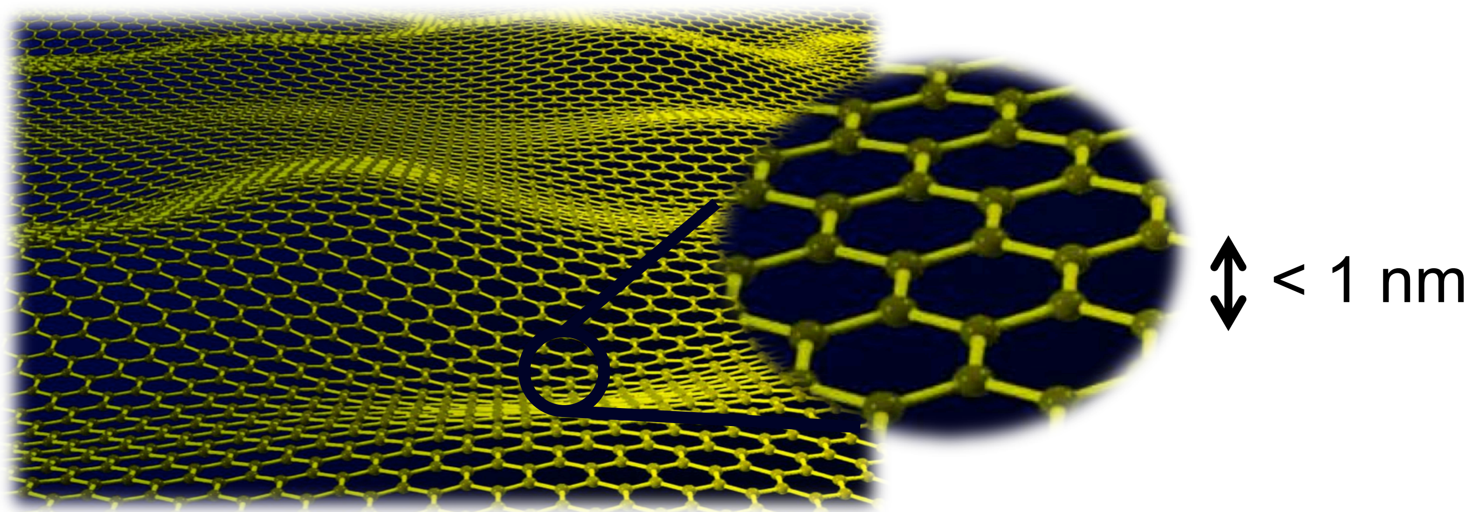
- The available transmission bandwidth increases with frequency…
  … but so does the propagation loss!!!

- The feasibility of nanonetworks would be compromised if this approach were followed due to:
  - The very limited energy and power of nano-devices
  - The lack of nano-transceivers able to operate at these frequencies
  - The *unknown* behavior of classical metals in nanostructures

- We need a new technology to enable EM communication for nano-devices!!!

# Graphene

- A one-atom-thick planar sheet of bonded carbon atoms in a honeycomb crystal lattice:
  - Many scientists had been looking for it since 1859
  - First experimentally discovered in 2004
    - Andre Geim and Konstantin Novoselov (Nobel Prize in 2010)



# Graphene

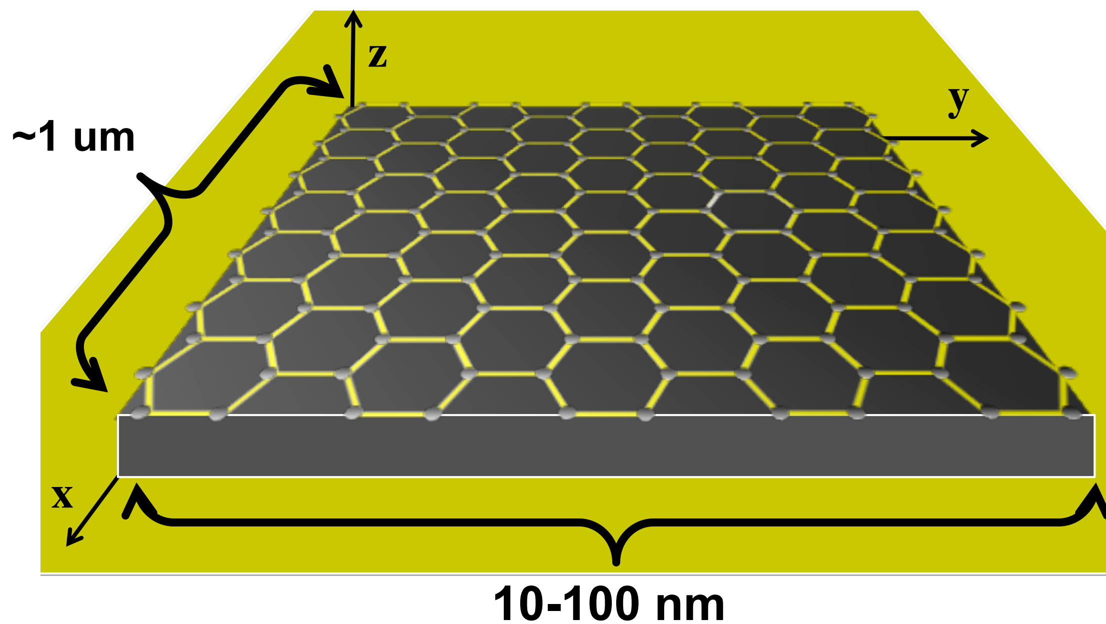
- First 2D crystal ever known to us:
  - Only 1 atom thick!!!
- World’s thinnest and lightest material
- World’s strongest material
  - E.g., harder than diamond, 300 times stronger than steel
- Bendable, i.e., takes any form you want
- Very high electron mobility at room temperature
  - E.g., much higher than copper, aluminum, silicon
- Transparent material
- Very good sensing capabilities

# Graphene-based Plasmonic Nano-antennas

J. M. Jornet and I. F. Akyildiz, "Graphene-based Plasmonic Nano-antennas for Terahertz Band Communication in Nanonetworks," submitted for journal publication, 2012.

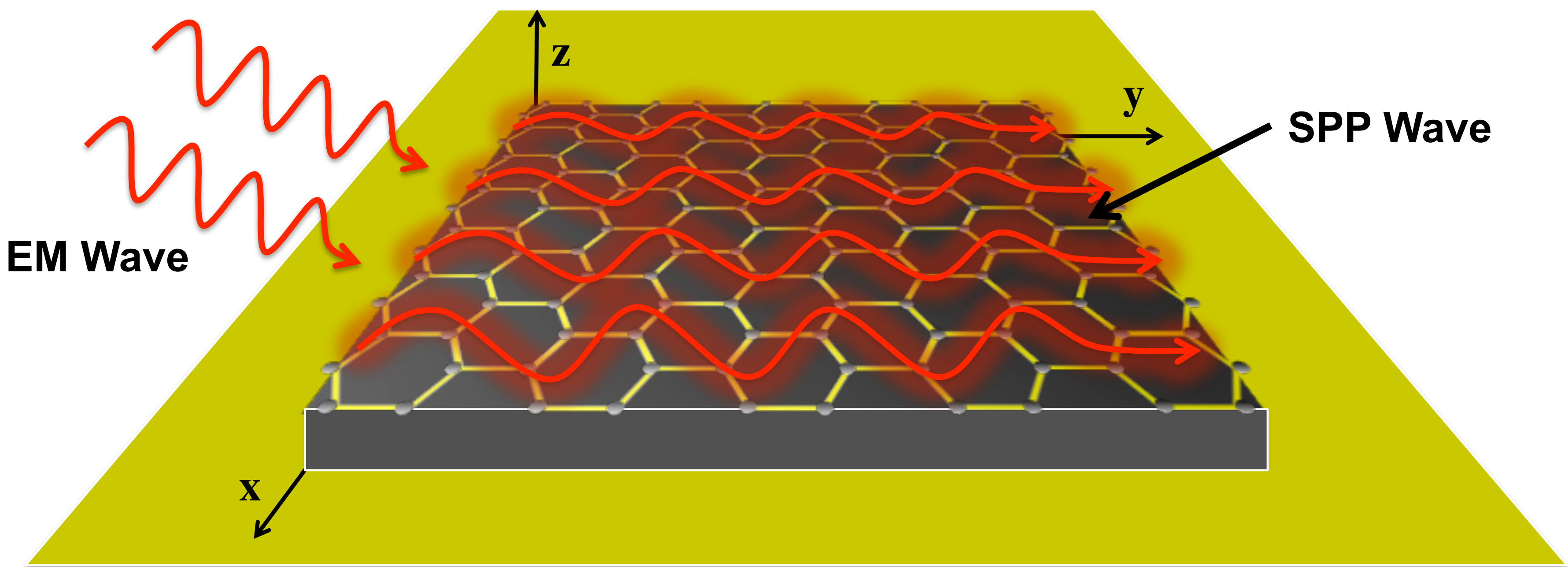
Preliminary work in 4th European Conference on Antennas and Propagation (EUCAP), Barcelona, Spain, April 2010.

- Graphene-based nano-antennas can radiate at much lower frequencies than metallic nano-antennas…
- … by exploiting the behavior of plasmons in graphene



# Graphene Plasmonics

- Graphene supports the propagation of Surface Plasmon Polariton (SPP) waves at frequencies in the Terahertz Band (0.1-10 THz):
  - Global oscillations of electric charge at the interface between graphene and a dielectric material



# Characterization of Graphene-based Plasmonic Nano-antennas

- The response of graphene-based plasmonic nano-antennas

- Depends on the dynamic complex wave vector of SPPs in graphene

- Depends on the dynamic complex conductivity of graphene

- Depends on the energy band-structure of the graphene structure

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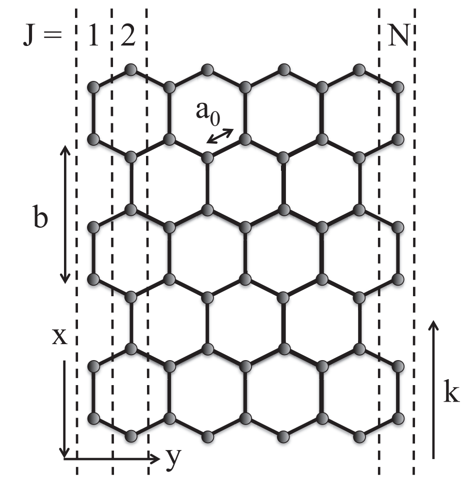
# Conductivity of Graphene Nanoribbons

- We use the Kubo formalism to compute the dynamical complex conductivity of graphene
  - I.e., we count all the allowed electron transitions in the energy band structure of finite-size graphene nanoribbons




- The energy band-structure of graphene is given by:

$$\varepsilon^{s}(k,\theta) = s\gamma_0\sqrt{1+4\cos^2\theta+4\cos\theta\cos\left(\frac{kb}{2}\right)}$$

where

$s \in \{-1,1\}$ = band index

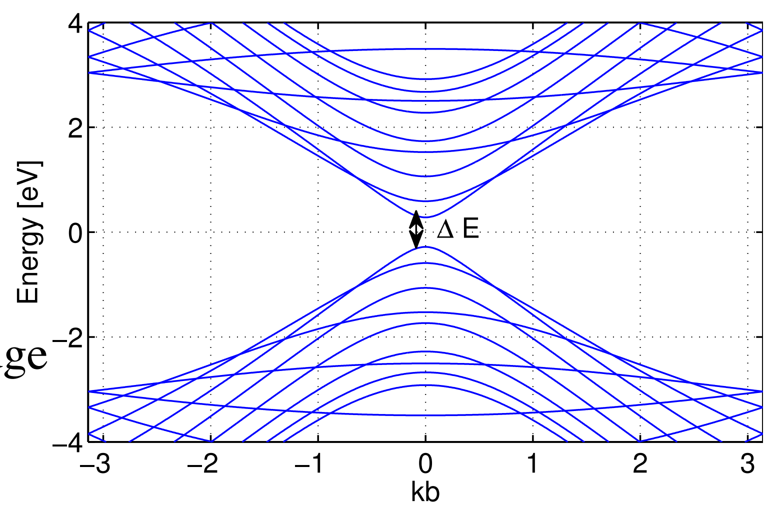
$\gamma_0 \sim 3\ eV$ = nearest-neighbor atom interaction

k = wave vector parallel to edge

$\theta_n = \frac{n\pi}{N+1}, n \in 1,2,..N =$ wave vector perpendicular to edge

$W = \sqrt{3}/2a_0(N-1)$

$b = 3a_0$, with $a_0 = 0.142nm$



# Conductivity of Graphene Nanoribbons

- The dynamical complex conductivity σ of GNRs depends on the polarization of the incident electromagnetic field (α = x, y):

$$\sigma_{\alpha\alpha}(f) = \mathrm{i}\frac{\hbar e^2}{S}\sum_{s,s'}\sum_{n,m}\sum_{k}\frac{\left(n_F(\varepsilon_m^{s'}) - n_F\left(\varepsilon_n^{s}\right)\right)}{\left(\varepsilon_n^{s} - \varepsilon_m^{s'}\right)}\frac{\left|\langle\phi_m^{s'}\mid v_\alpha \mid\phi_n^{s}\rangle\right|^2}{\left(\varepsilon_n^{s} - \varepsilon_m^{s'} + hf - \mathrm{i}\nu\right)}$$

where

$f =$ frequency

$\hbar =$ reduced Planck constant

$e =$ electron charge

$S =$ GNR size

$s, s' \in \{-1, 1\}$ = band indexes

$n, m \in \{1, 2, \ldots N\}$ = sub-band indexes

$\gamma_0 \sim 3\ eV$ = nearest-neighbor atom interaction

k = wave vector parallel to the GNR edge

$n_F(\varepsilon) = \dfrac{1}{1 + e^{\frac{\varepsilon - \mu}{k_B T}}}$ = Fermi-Dirac Distribution

$\mu$ = chemical potential

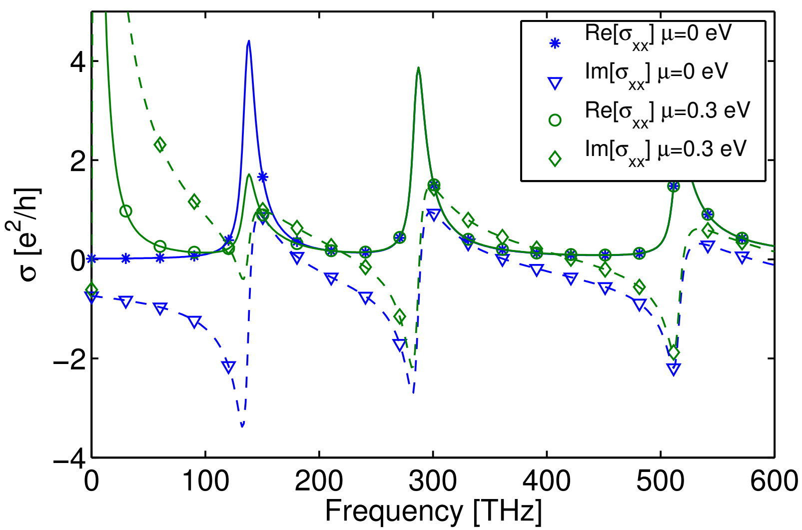
$k_B =$ Boltzmann constant

$T$ = temperature

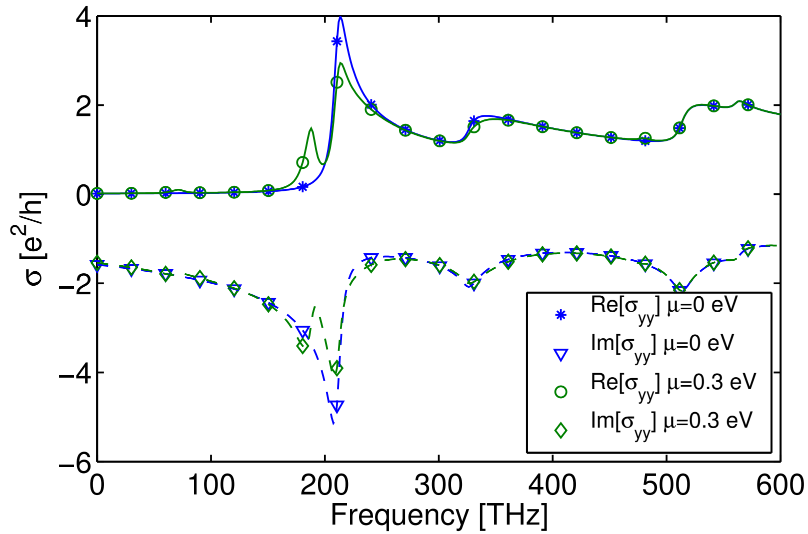
$\langle\phi_m^{s'}\mid v_\alpha \mid\phi_n^{s}\rangle =$ velocity operator for the transition from $(s, n)$ to $(s', m)$

K.I. Sasaki, K. Kato, Y. Tokura, K. Oguri, and T. Sogawa, "Theory of optical transitions in graphene nanoribbons," Physical Review B, vol. 84, p. 085458, Aug. 2011.

# Conductivity of Graphene Nanoribbons




$\sigma_{xx}$, W = 2.1 nm




$\sigma_{yy}$, W = 2.1 nm

- For μ=0 eV, the conductivity along the long edge (x) is dominated by inter-band transitions at specific frequencies (s≠s').
- For μ=0.3 eV, the conductivity along the long edge (x) is dominated by intra-band transitions at low frequencies (s≠s').

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# SPP waves in GNRs

- Surface Plasmon Polariton waves are confined EM waves coupled to surface electric charges at the interface between a metal and a dielectric
- The dynamic complex wave vector $k_{spp}$ of SPP waves in graphene determines the propagation properties of SPP waves:

$$\mathrm{Re}\{k_{spp}\} = \frac{2\pi}{\lambda_{spp}} = \text{ determines the SPP confiment factor}$$

$$\mathrm{Im}\{k_{spp}\} = \text{ determines the SPP decay}$$

- Two types of SPP modes can be supported by the GNR depending on its conductivity:
  - **Transverse Magnetic (TM):** there is no magnetic field in the direction of propagation
  - **Transverse Electric (TE):** there is no electric field in the direction of propagation

# TM SPP Waves

- Starting from the Maxwell's equations and applying the boundary conditions at the interfaces between air, graphene and the dielectric material, the dispersion equation for TM SPP waves is found as:

$$\frac{\epsilon_1^r}{\sqrt{k_{spp}^2 - \frac{\epsilon_1^r \omega^2}{c_0^2}}} + \frac{\epsilon_2^r}{\sqrt{k_{spp}^2 - \frac{\epsilon_2^r \omega^2}{c_0^2}}} = -i\frac{\sigma_{\alpha\alpha}}{\omega\epsilon_0}$$

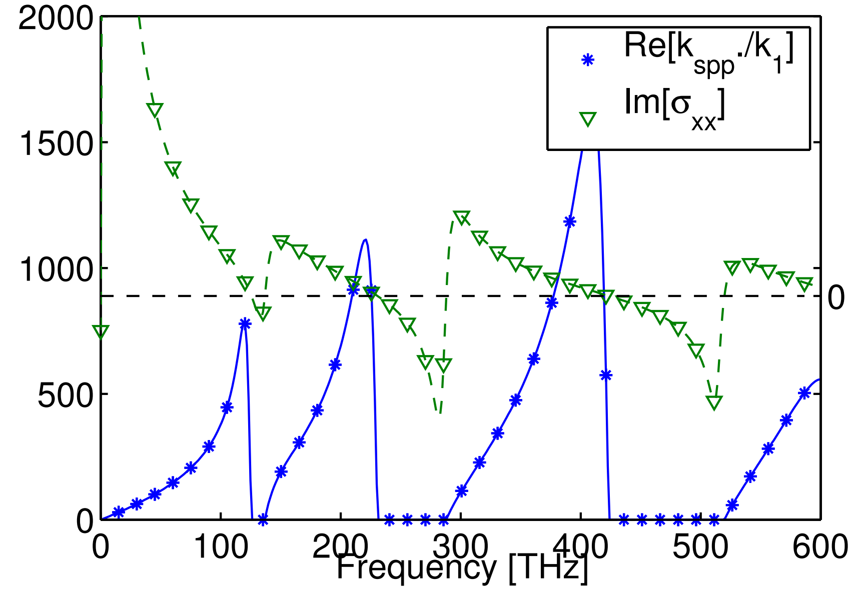
$\epsilon_n^r =$ relative permittivity of medium $n$

$\epsilon_0 =$ permittivity of the vacuum

$\omega = 2\pi f =$ angular frequency

$c_0 =$ speed of light in vacuum

$\sigma_{\alpha\alpha} =$ conductivity in the $\alpha$ direction




- TM modes along the α-axis only exist if the imaginary part of the conductivity, $\sigma_{\alpha\alpha}$, is positive. → Only along x, only when μ>0

# TE SPP Waves

- By following a similar procedure as in the previous case, the dispersion equation for TE SPP waves can be written as:

$$\sqrt{k_{spp}^2 - \frac{\omega^2}{c_0^2}\epsilon_1} + \sqrt{k_{spp}^2 - \frac{\omega^2}{c_0^2}\epsilon_2} + \mathrm{i}\omega\mu_0\sigma_{\alpha'\alpha'} = 0$$

A closed-form expression for $k_{spp}$ can be found

$$k_{spp} = \frac{\omega}{c_0}\sqrt{\epsilon_1^r - \left(\frac{\left(\epsilon_1^r - \epsilon_2^r\right) + \sigma_{\alpha'\alpha'}^2\eta_0^2}{2\sigma_{\alpha'\alpha'}\eta_0}\right)^2}$$

where

$\omega = 2\pi f =$ angular frequency

$c_0 =$ speed of light in vacuum

$\epsilon_n^r =$ relative permittivity of medium $n$

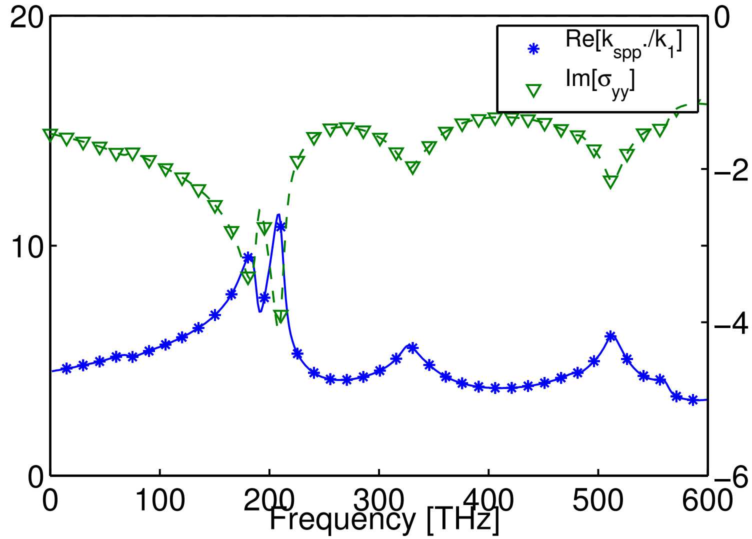
$\mu_0 =$ permeability of the vacuum

$\sigma_{\alpha'\alpha'} =$ conductivity in the $\alpha'$ direction

$\eta_0 = \mu_0 / \epsilon_0$

# TE SPP Waves

- TE SPP wave modes only exist when the imaginary part of the conductivity $\sigma_{\alpha'\alpha'}$ is negative.
  - However, there is only meaningful confinement for TE SPP modes that propagate along the x, only when μ>0.




- The confinement of TE SPP modes is much lower than that of TM SPP modes → We prefer higher compression modes for miniature antennas.

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# Plasmonic Nano-antenna Theory

- Plasmonic nano-antennas differ largely from classical metallic antennas:
  - **Finite complex conductivity:**
    - In classical antenna theory, it is common to assume Perfect Electrical Conductor (PEC) behavior of the antenna building components.
    - A PEC material has a conductivity that tends to infinity, which is not the case of graphene (as well as any real metal).
  - **Plasmonic current wave:**
    - In classical antenna theory, the electrical current wave traveling along a PEC antenna propagates at the speed of light in vacuum $c_0$ with wave vector $k_0$.
    - On the contrary, the electrical current wave traveling along a plasmonic antenna propagates at the much lower SPP wave propagation speed with wave vector $k_{spp}$.
    - Moreover, it can be analytically proven that a plasmonic nano-antenna cannot support an additional current which propagates with $k_0$.

# Antenna Frequency Response

- By modeling the graphene-based nano-antenna as a resonant plasmonic cavity, a condition on the antenna length (which so far has been just assumed much larger than the antenna width) is imposed:
  - For a TM SPP resonant mode along the x-axis:

$$L = m\frac{\lambda_{spp}}{2} = m\frac{\pi}{\mathrm{Re}\{k_{spp}\}}$$

  - For a TE SPP resonant mode along the x-axis:

$$L = \frac{2q-1}{\sqrt{\left(\frac{2p-1}{W}\right)^2 - \left(\frac{2}{\lambda_{spp}}\right)^2}} = \frac{(2q-1)\pi}{\sqrt{\left(\frac{(2p-1)\pi}{W}\right)^2 - \mathrm{Re}\{k_{spp}\}^2}}$$

where

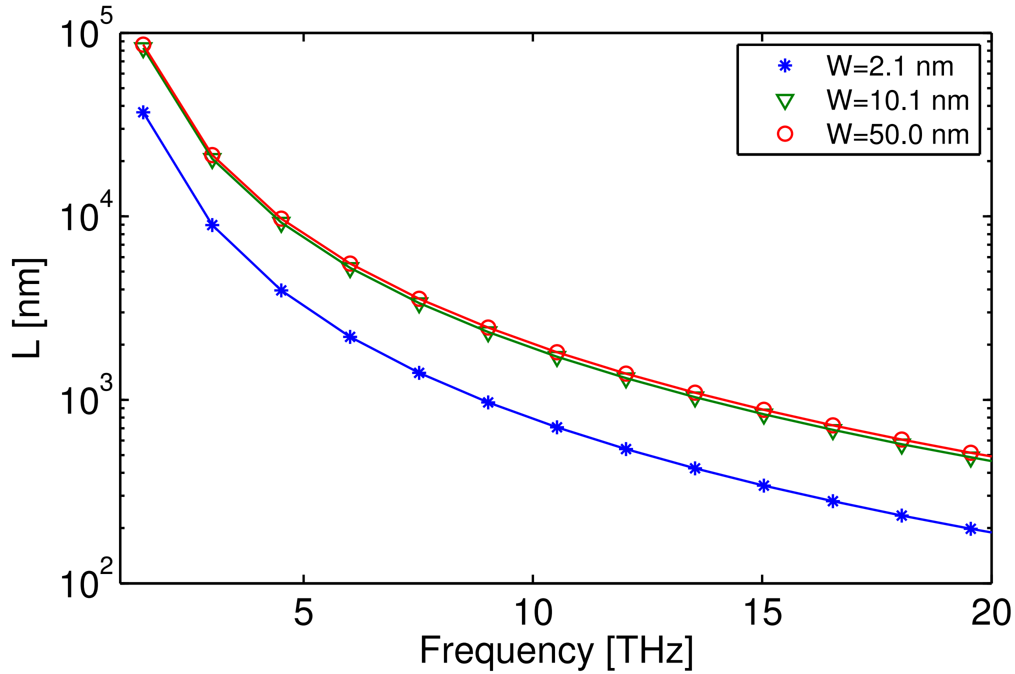
$k_{spp} = \frac{2\pi}{\lambda_{spp}} =$ SPP mode wave vector

L= nano-antenna length $m =$ TM resonant mode index, $m = 1$ for fundamental TM mode

W= nano-antenna width p,q $=$ TE resonant mode indexes, $p = q = 1$ for fundamental TE mode

# Antenna Frequency Response

- The most significant mode for radiative plasmonic cavities corresponds to the TM fundamental mode (m=1).




- These results match our preliminary results based on the transmission line properties of GNRs.

# Graphene-based Nano-transceivers

- Graphene is also enabling the development of:
  - **Signal generators**

T. Otsuji, S. Boubanga Tombet, A. Satou, M. Ryzhii, and V. Ryzhii, “Terahertz-wave generation using graphene - toward new types of Terahertz lasers,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. PP, no. 99, p. 1, 2012.

  - **Signal modulators**

B. Sensale-Rodriguez, R. Yan, M. M. Kelly, T. Fang, K. Tahy, W. S. Hwang, D. Jena, L. Liu, and H. G. Xing, “Broadband graphene terahertz modulators enabled by intraband transitions,” *Nature Communications*, vol. 3, pp. 780+, Apr. 2012.

  - **Polarizers and filters**

H. Yan, X. Li, B. Chandra, G. Tulevski, Y. Wu, M. Freitag, W. Zhu, P. Avouris, and F. Xia, “Tunable infrared plasmonic devices using graphene/insulator stacks.” *Nature Nanotechnology*, vol. 7, no. 5, pp. 330–4, 2012.

  - **Signal detectors**

G. Deligeorgis, F. Coccetti, G. Konstantinidis, and R. Plana, “Radio frequency signal detection by ballistic transport in y-shaped graphene nanoribbons,” *Applied Physics Letters*, vol. 101, no. 1, p. 013502, 2012.

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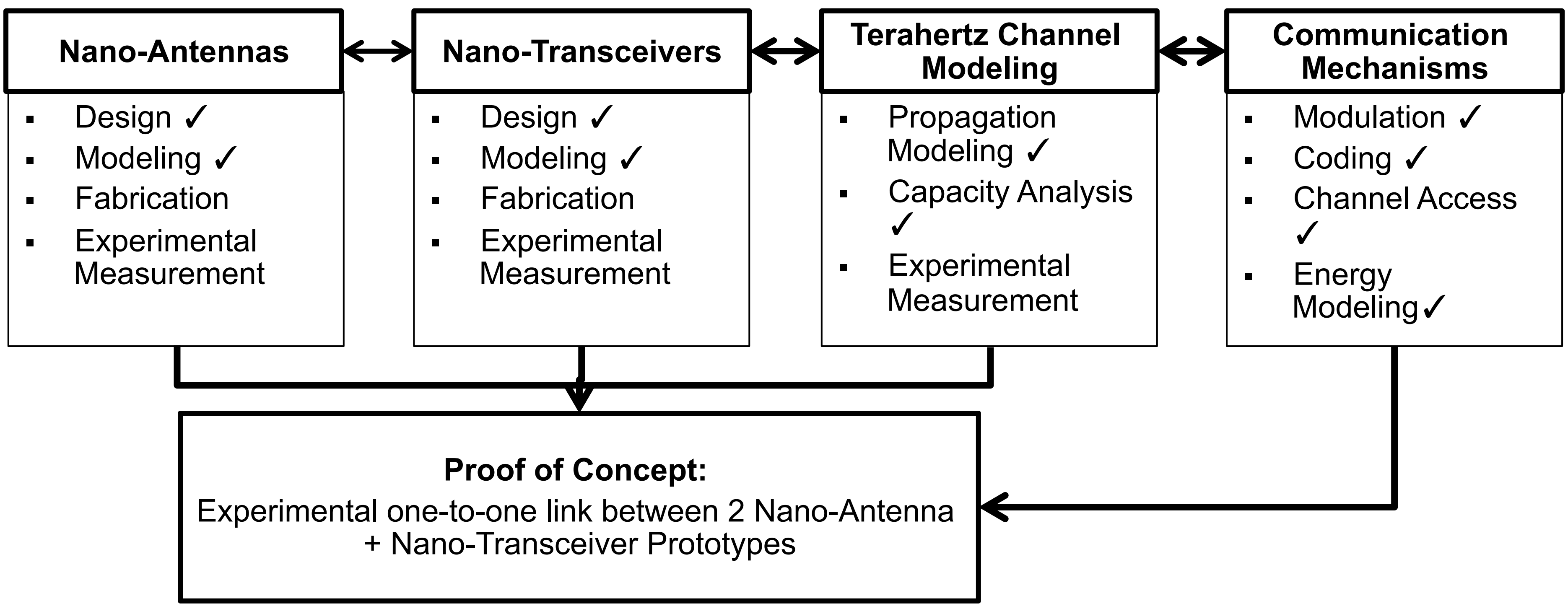
# Conclusions

- The unique conductivity of semi-finite-size GNRs allows the propagation of tightly confined SPP waves in graphene.
- Graphene-based nano-structures can be modeled as radiative plasmonic cavities, which support different resonant modes.
- Due to the very tight confinement of the SPP waves, compact antennas can be developed.
  - The resonant frequency for a one-micrometer-long few-nanometer-wide antenna lies in the Terahertz Band.
- Next steps:
  - What is the efficiency of these antennas?
  - How can it be improved?

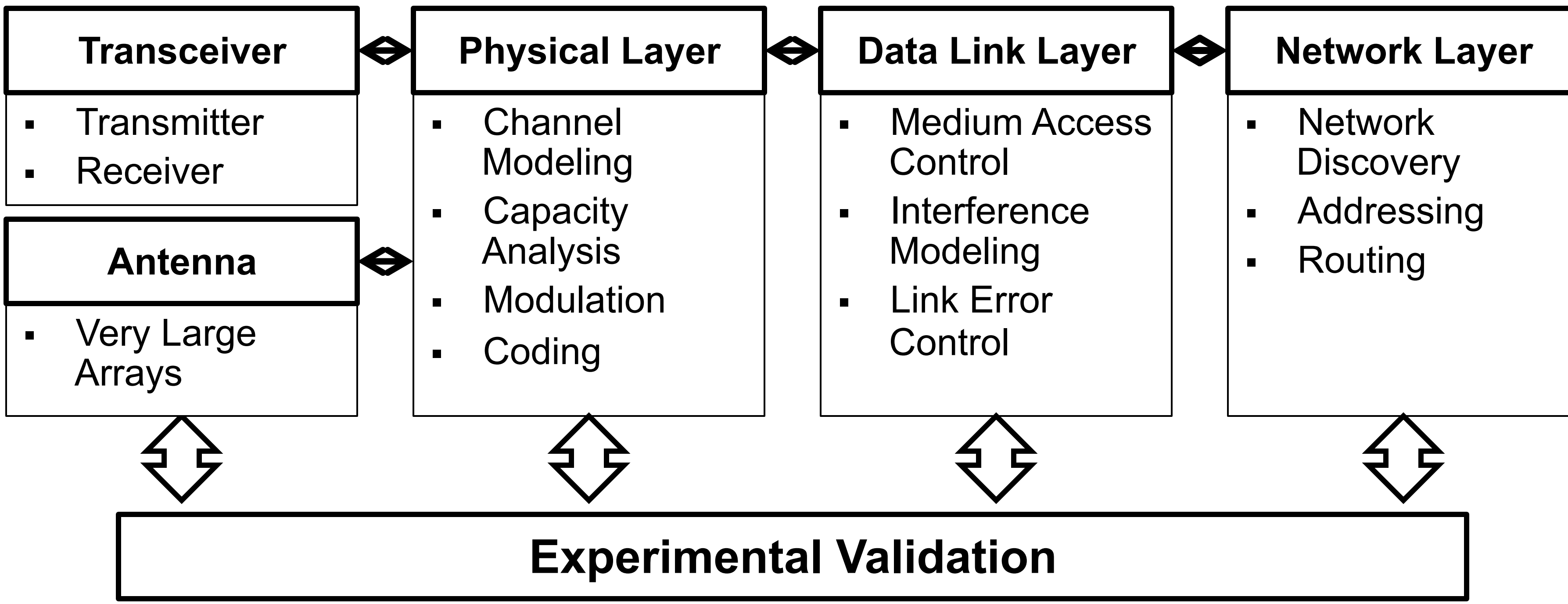
# GRANET: Graphene-enabled Nanocommunication Networks

- **Objectives:**
  - To prove the feasibility of graphene-enabled EM NANOCOMMUNICATION
  - To establish the theoretical foundations for EM NANONETWORKS



# TERANETS: Terahertz Band Communication Networks

- **Objectives:**
  – To establish the theoretical and experimental foundations of Terahertz Band communication networks (not NANOSCALE, not just GRAPHENE)



# Thank You!

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