INTERNET OF NANOTHINGS & BIO-NANOTHINGS

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WAY OF COMMUNICATION

- Smartphones, tablets and personal computers
- Wearable devices (smart watch, smart ring, smart belt, …)
- Virtual assistants (Amazon Echo/Alexa, Apple HomePod/Siri, Google Home, …)

RESULTS

- **Not practical:**
  - Bulky devices, usually battery powered, not compatible among them
- **Not natural:**
  - Limited voice control, require more than one step to complete action
- **Limited functionality:**
  - Restricted to few home control actions, limited email/conversation, few fitness/medical data

FUTURE VISION

- **Pervasive and non-invasive devices**
  - Everywhere:
    - Indoors & Outdoors + Outside & Inside the Persons
  - Not perceptible to the user naked eye
- **User-friendly**
  - Can interact with humans in a natural way → Voice
- **Smarter**
  - Take advantage of distributed processing power / intelligence
- **Self-powered**
  - No more charging batteries → Energy harvesting

How????

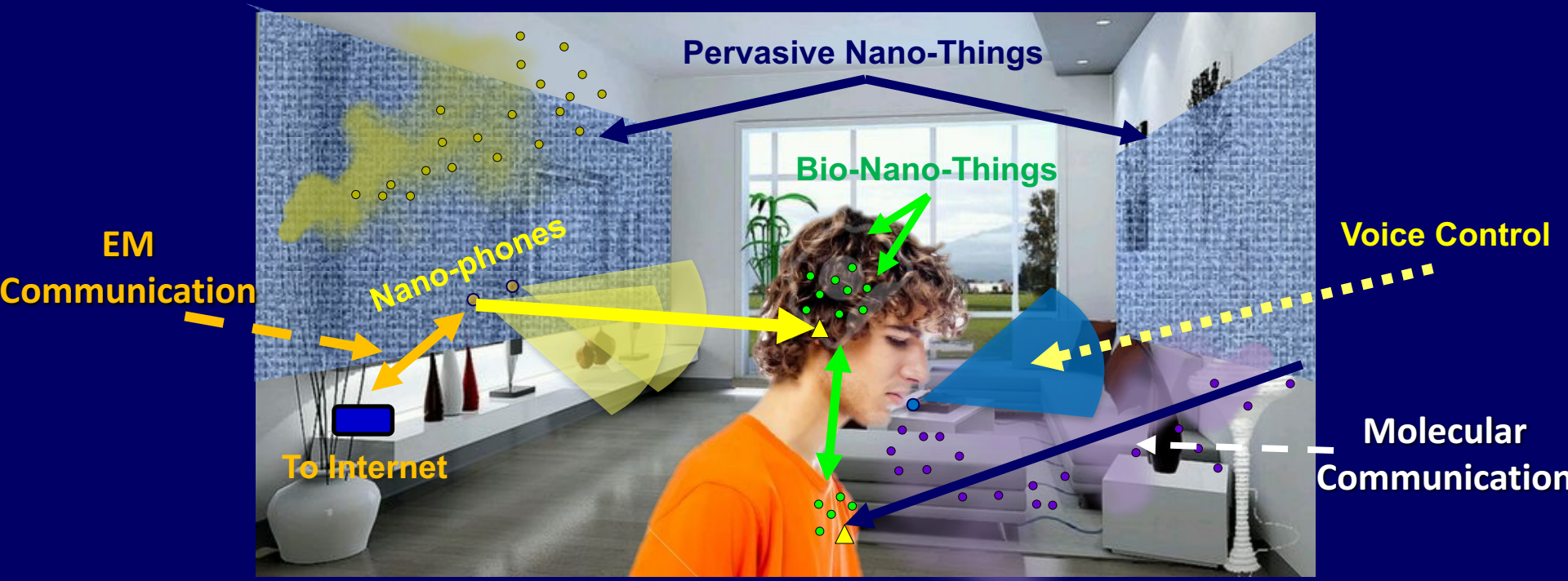
SCIENTIFIC AMERICA:
TOP 10 EMERGING TECHNOLOGIES OF 2016

- Internet of Things goes NANO

https://www.scientificamerican.com/report/the-top-10-emerging-technologies-of-2016/

INTERNET OF NANO-THINGS

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



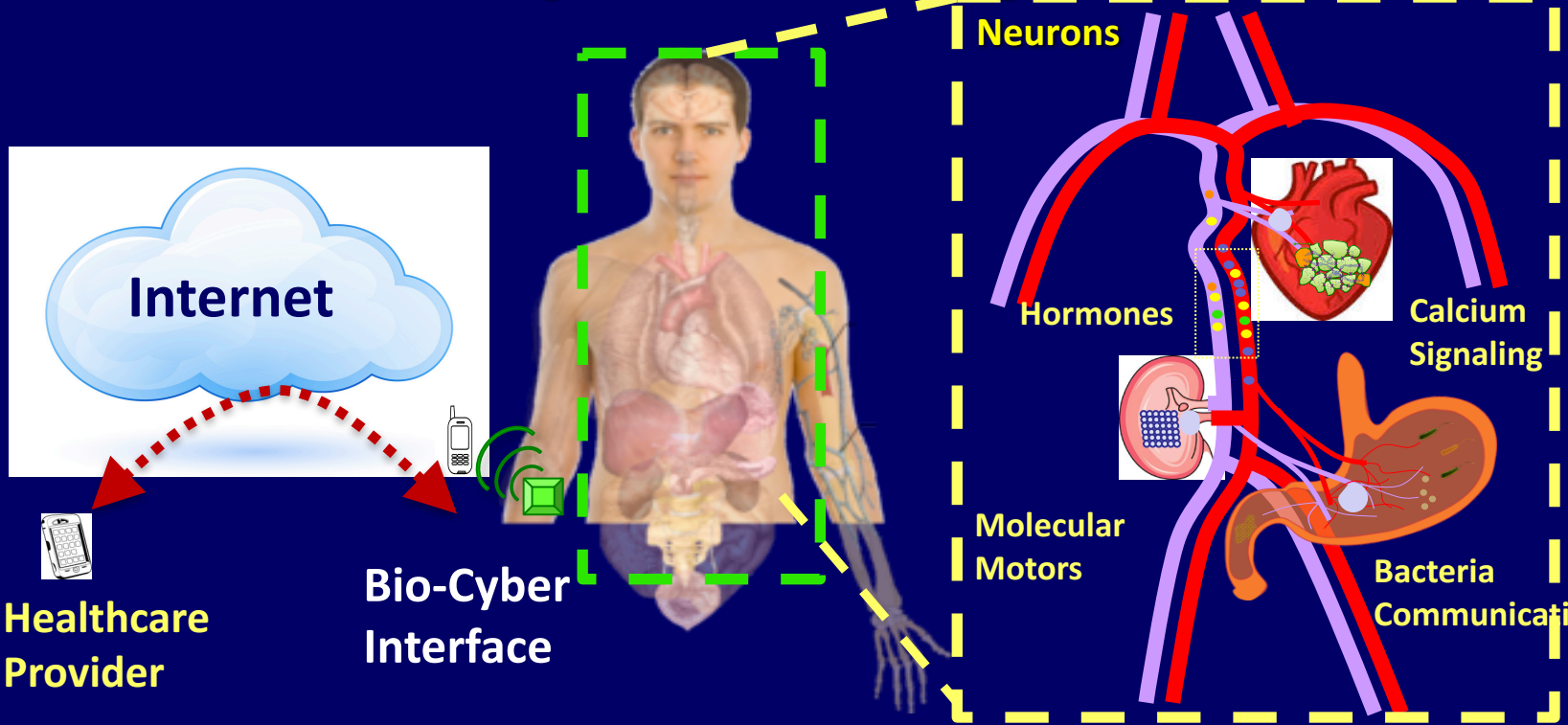
NANO-THINGS EVERYWHERE

INTERNET OF BIO-NANOTHINGS:

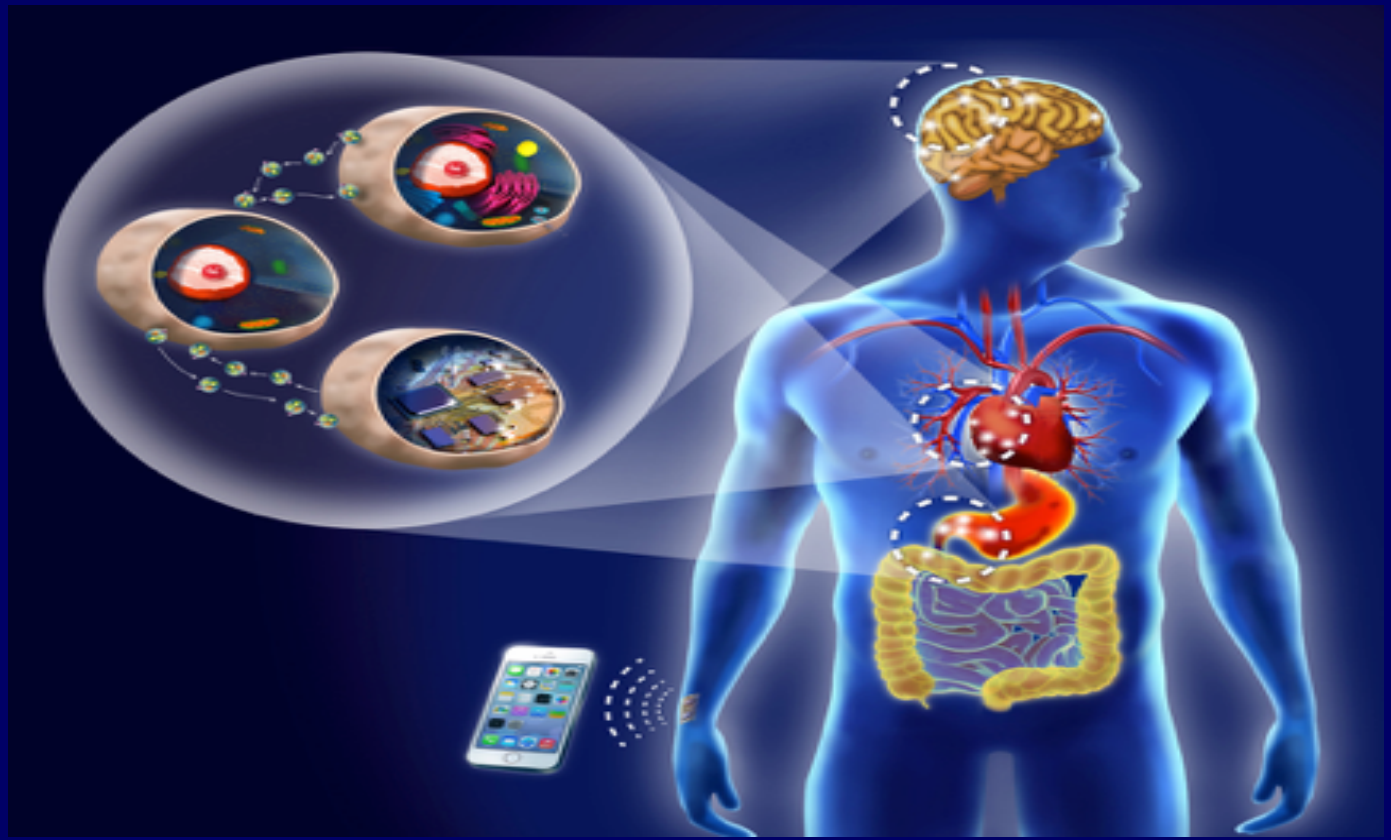
I.F. AKYILDIZ, M. PIEROBON, S. BALASUBRAMANIAM, Y. KOUCHERYAVY,
"THE INTERNET OF BIO-NANOTHINGS",
IEEE COMMUNICATIONS MAGAZINE, MARCH 2015

Objective:

To interconnect the heterogeneous Bio-NanoThings Networks to the Internet



Internet of Bio-NanoThings

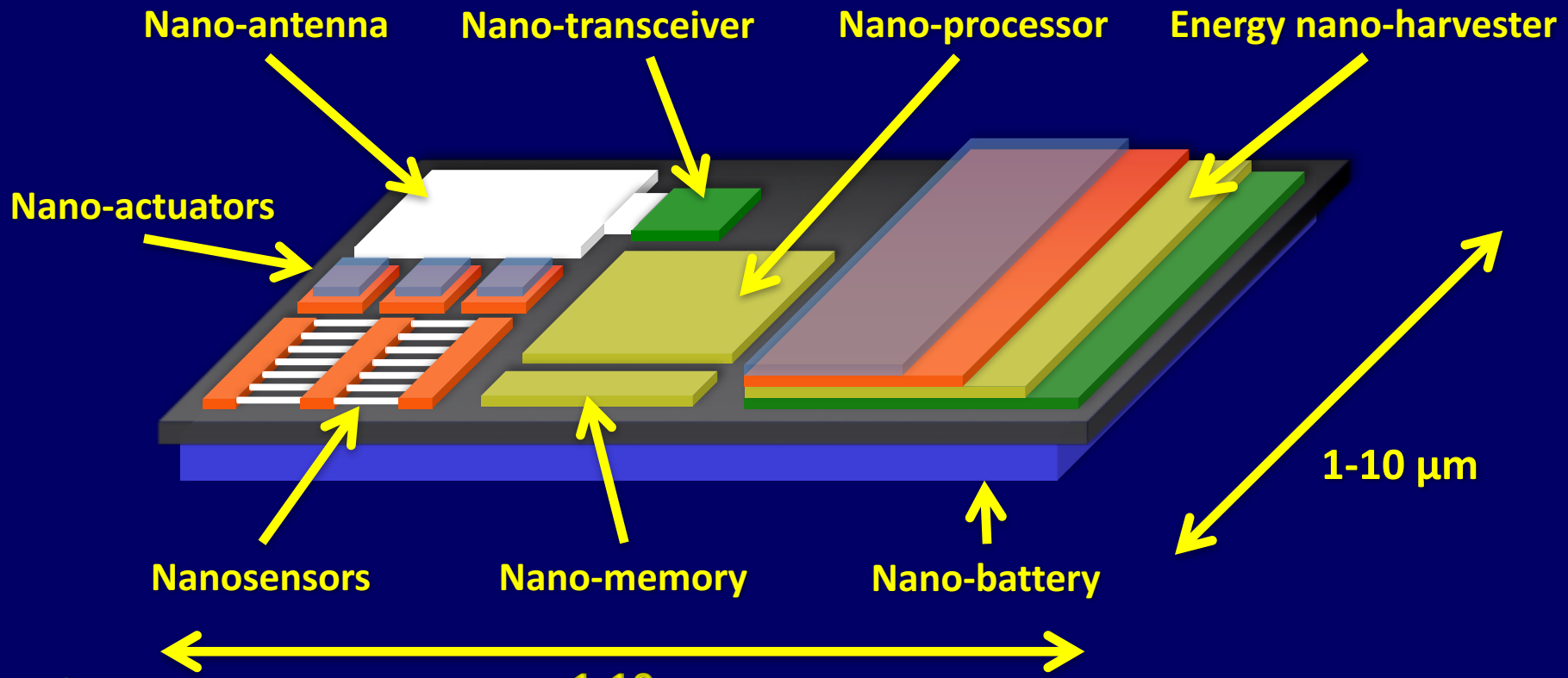


DESIGN OF NANO-THINGS

I. F. Akyildiz and J. M. Jornet,

"Electromagnetic Wireless Nanosensor Networks,"

Nano Communication Networks (Elsevier) Journal, March 2010.



TERANETS (FORMERLY GRANET; 2008-2013):

GRAPHENE BASED NANO SCALE COMMUNICATION NETWORKS IN THZ BAND

NSF; 2013-2016 & 2016-2019

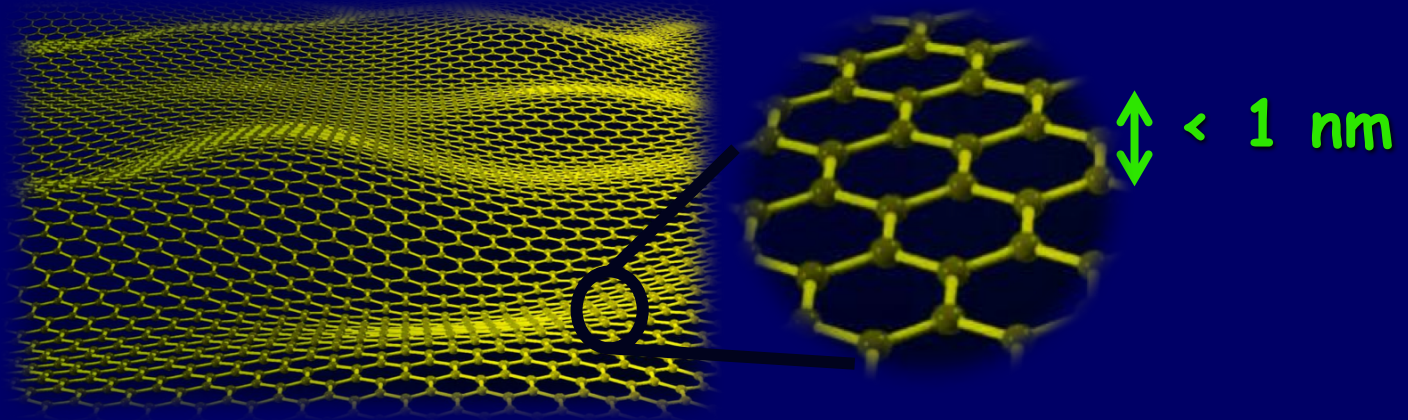
- **Objectives:**
  - To demonstrate the feasibility of graphene-enabled EM communication
  - To establish the theoretical foundations for EM nanonetwork
  - To establish the theoretical and experimental foundations of ultra-broadband com nets in the (0.1-10) THz band

NANO Materials & Devices	THz Channel	Nano-Scale (THz) Communications	Nano Networks
• Nano-Transceivers ✓	• Line-of-Sight ✓	• Pulse-based Modulation ✓	• Error Control ✓
• Nano-Antennas and Arrays ✓	• Multi-path ✓	• Multi-band Modulation ✓	• Medium Access Control ✓
• Fabrication	• 3D End-to-End ✓	• Equalization	• Addressing
• Experimental Measurement	• Ultra-massive MIMO	• Synchronization ✓	• Neighbor Discovery
	• Noise Modeling ✓	• Ultra-Massive MIMO ✓	• Relaying
	• Capacity Analysis ✓		• Routing
	• Experimental Measurement		• Transport Layer
			• Cross-layer

Experimental and Simulation Testbeds

NANOMATERIAL: GRAPHENE

- A one-atom-thick planar sheet of bonded carbon atoms in a honeycomb crystal lattice:



GRAPHENE INVENTORS

- 2010 Nobel Prize in Physics
  - Andre Geim and Konstantin Novoselov
  - Distinguished for "groundbreaking experiments regarding the two-dimensional material graphene"

Laureates of the Nobel Prize in Physics (2010)

GRAPHENE

- First 2D crystal ever known (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
- Conducts electricity much better than fiber and copper
- Transparent material
- Very good sensing capabilities

→Enable a plethora of new applications for device technology at the nanoscale and also at larger scales:

  - e.g., processors, memories, batteries, antennas,tx, sensors, etc

GRAPHENE-BASED PLASMONIC NANO-ANTENNAS

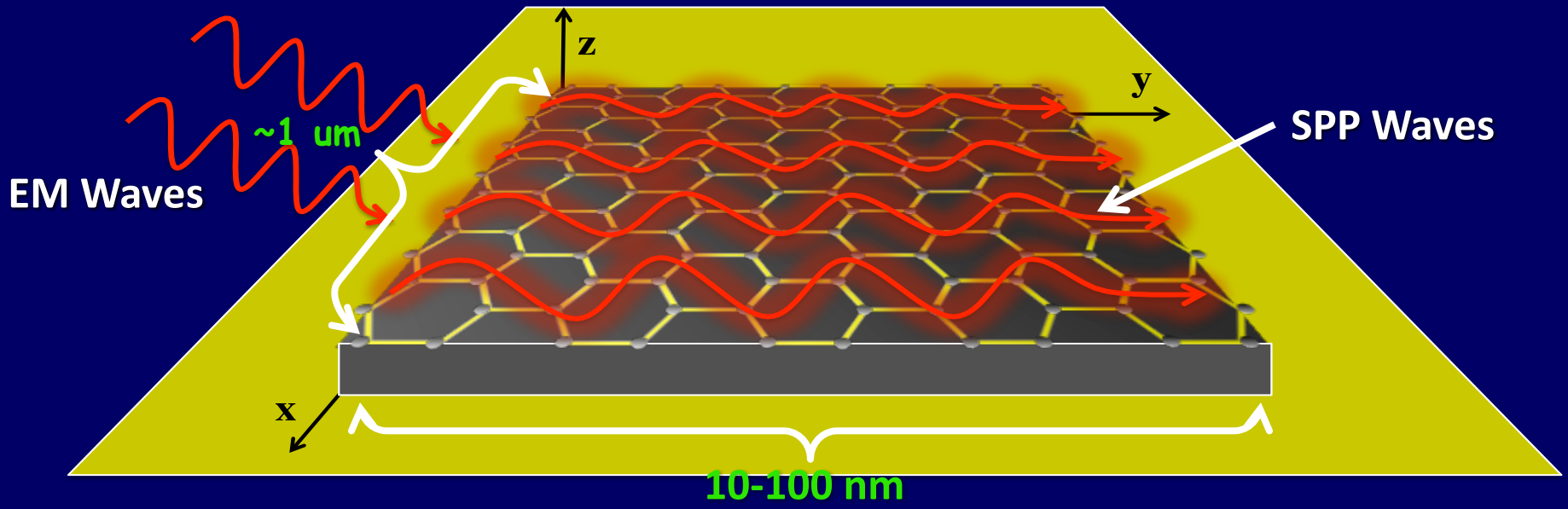
J. M. Jornet and I. F. Akyildiz,

"Graphene-based Plasmonic Nano-antennas for THz Band Communication in Nanonetworks,"

IEEE Journal of Selected Areas in Communications, Vol. 12, pp. 685-694, Dec. 2013.

U.S. PATENT NO. 9,643,841, ISSUED ON MAY 9, 2017.

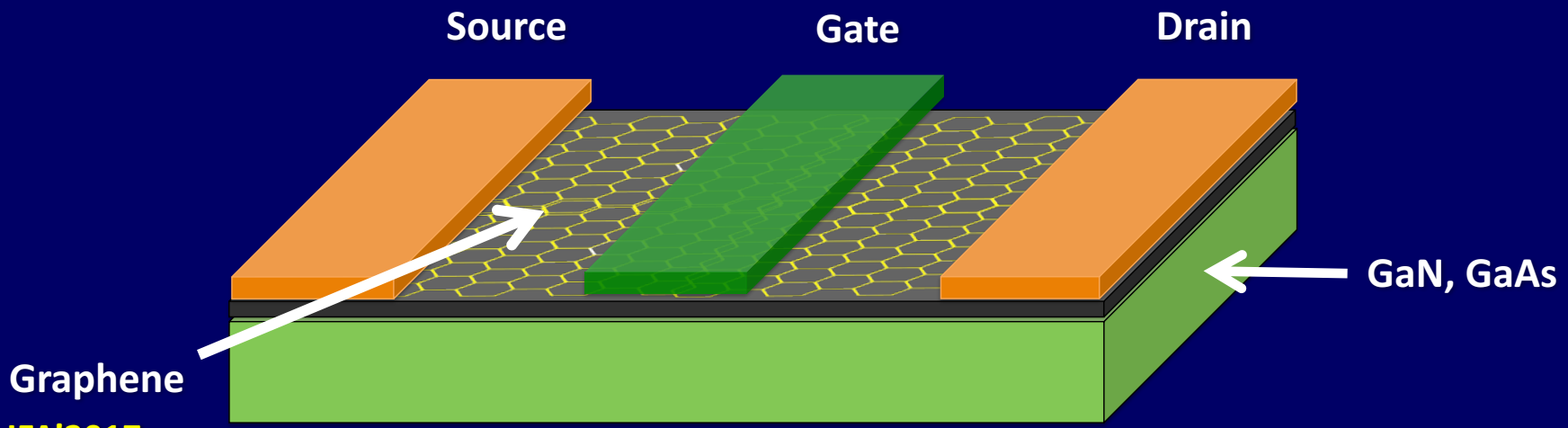
- Propagation of Surface Plasmon Polariton (SPP) waves at (0.1-10 THz) Band



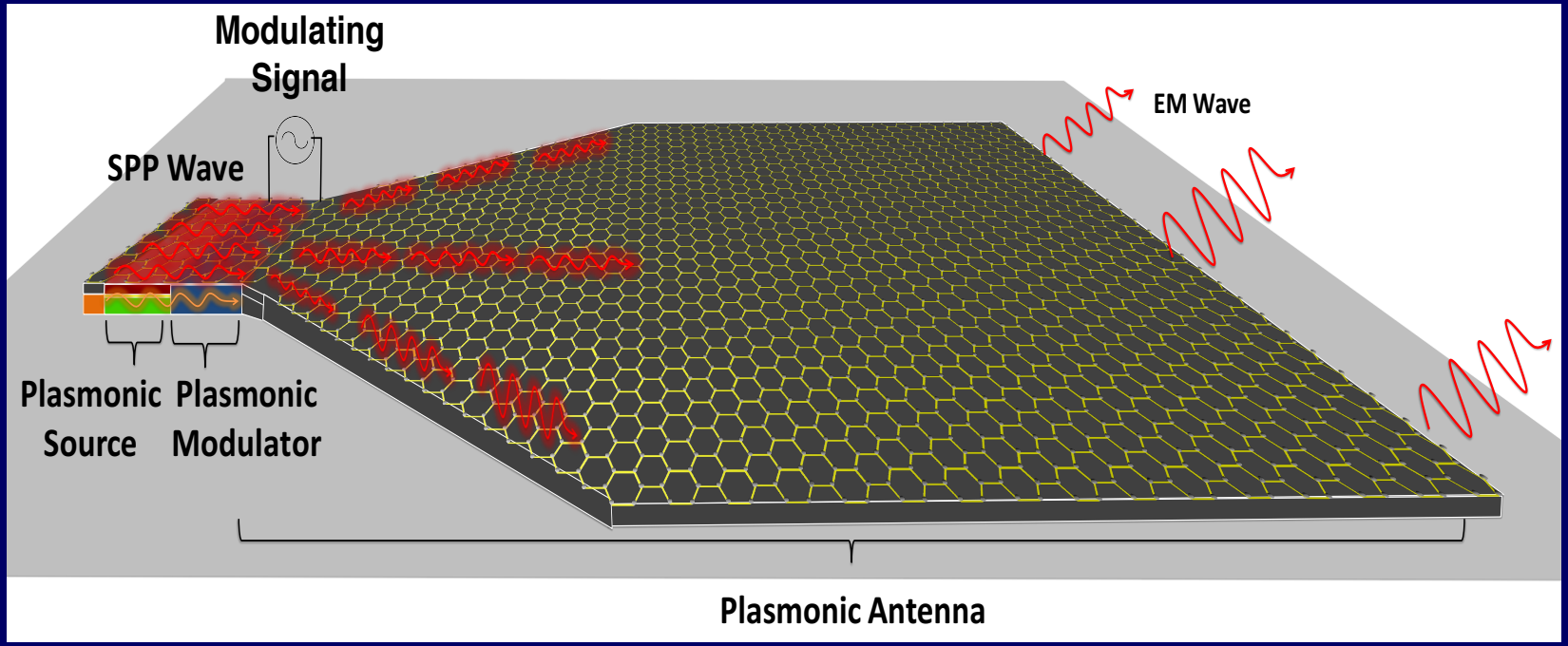
TERAHERTZ BAND PLASMONIC NANO-TRANSCEIVER

I. F. Akyildiz and J. M. Jornet,
"Graphene Plasmonic Nano-transceiver for Wireless Communication in the THz Band,"
U.S. PATENT NO. 9,397,758 ISSUED ON JULY 19, 2016.

- Generates/detects the signals radiated/received by the nano-antenna
- Built with Graphene (NOVELTY), GaN & GaAs
- Based on a High Electron Mobility Transistor (HEMT)



TERAHERTZ BAND PLASMONIC FRONT-END (TRANSCEIVER+ANTENNA)



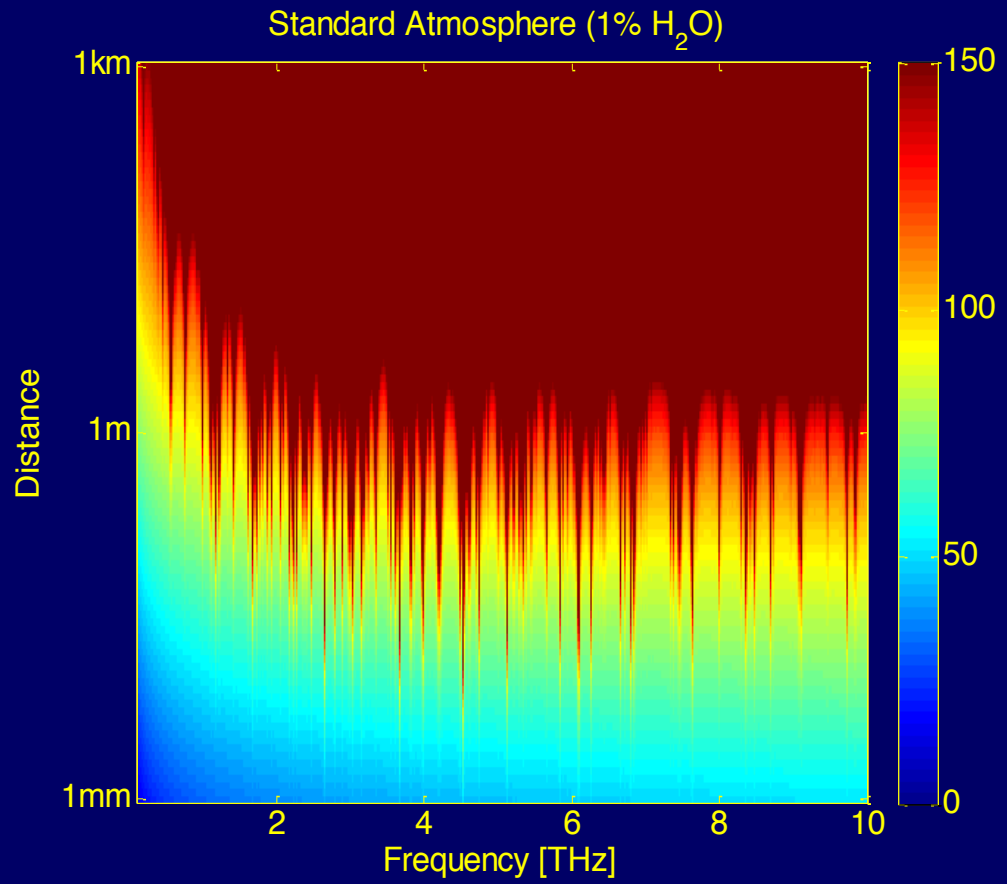
TERAHERTZ CHANNEL CHARACTERISTICS

J.M. Jornet and I.F. Akyildiz,
"Channel Modeling and Capacity Analysis of EM Wireless Nanonetworks in the THz Band",
IEEE Transactions on Wireless Communications, Oct. 2011.
Shorter version in Proc. of IEEE ICC, Cape Town, South Africa, May 2010.

- Developed path loss and noise models for EM communications in the Terahertz band (0.1-10 THz) by means of radiative transfer theory

- Proposed different power allocation schemes and computed the channel capacity as a function of distance and channel composition

TOTAL PATH LOSS



WHAT DID WE LEARN?

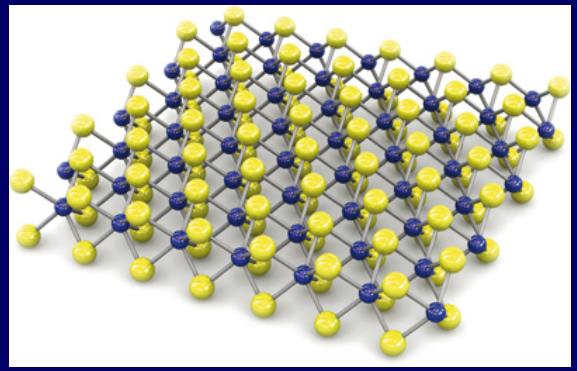
- Terahertz channel has a strong dependence on
  - Transmission distance
  - Medium molecular composition
- Main factor affecting the performance
  - Presence of water vapor molecules
- Incredibly huge BWs for short ranges (< 1m):
  - 100 Tbps rates are feasible

FURTHER CHALLENGES

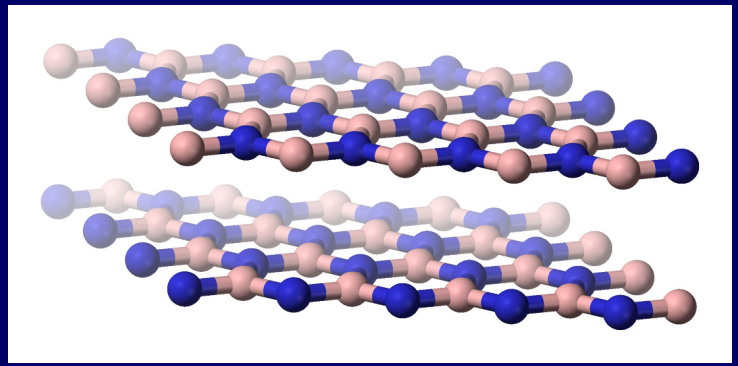
- HOW ABOUT LOWER FREQUENCIES ?
- HOW TO COMBAT DISTANCE PROBLEM ?

NEW OPPORTUNITIES:
OTHER 2D NANOMATERIALS

- Graphene is "the first of a kind" → But not the only one!



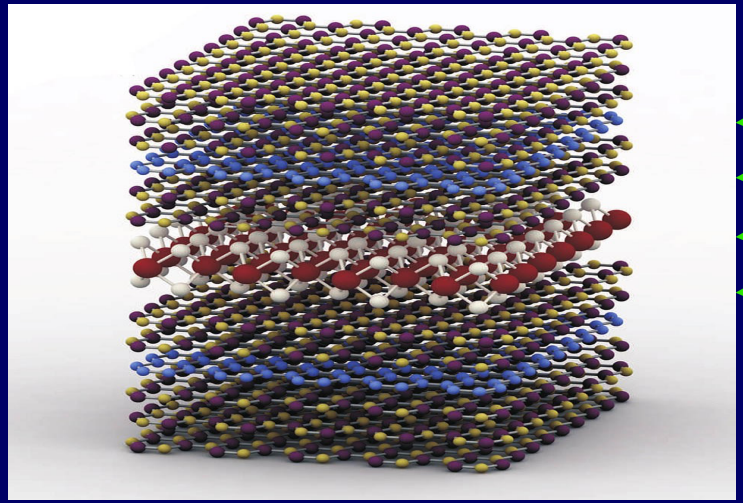
Molybdenum disulfide (MoS2):
Molybdenum + Sulfur
1-atom thick dielectric



Hexagonal Boron Nitride (h-BN):
Boron + Nitrogen
1-atom thick dielectric,
Combines very well with graphene

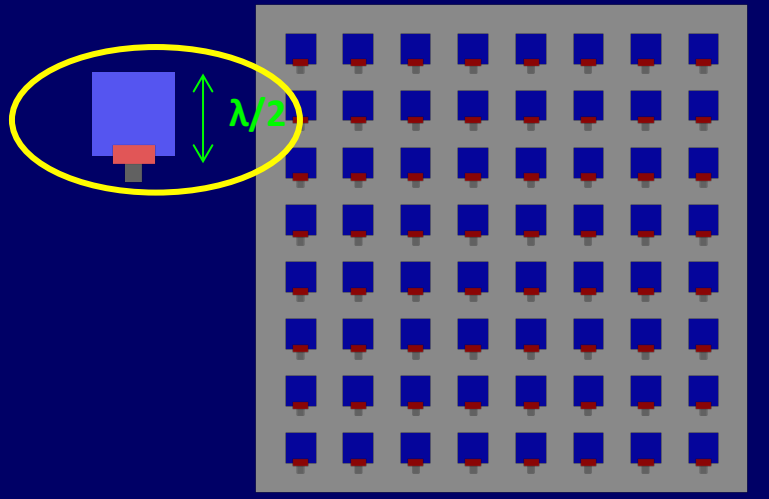
NEW OPPORTUNITY:
2D NANOMATERIAL STACKS

- New structures can be created by stacking different 2D nanomaterials
  - Unprecedented electrical & optical properties → This is just the beginning!

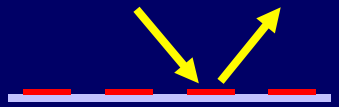


COMBATING THE DISTANCE PROBLEM

Reflectarray

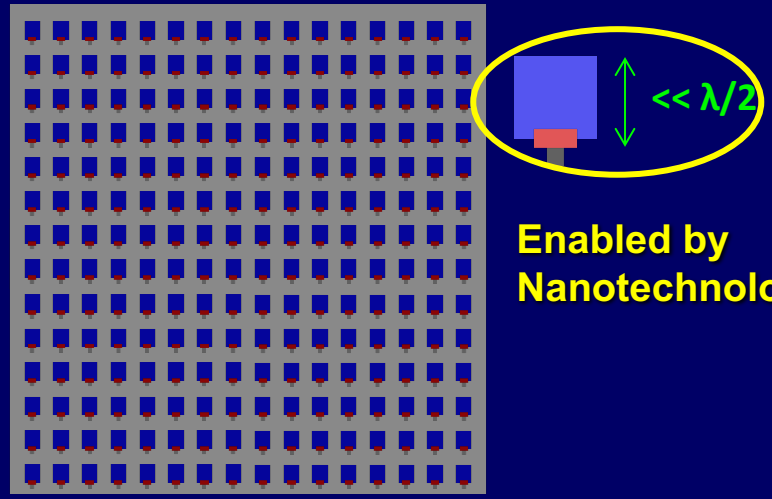


Supports only:



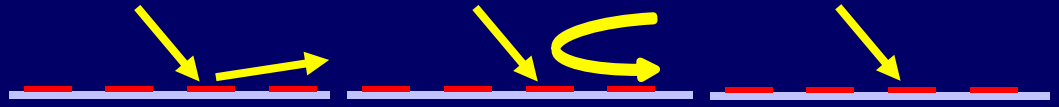
Normal reflection

Metasurfaces



Enabled by Nanotechnology

Additionally supports:



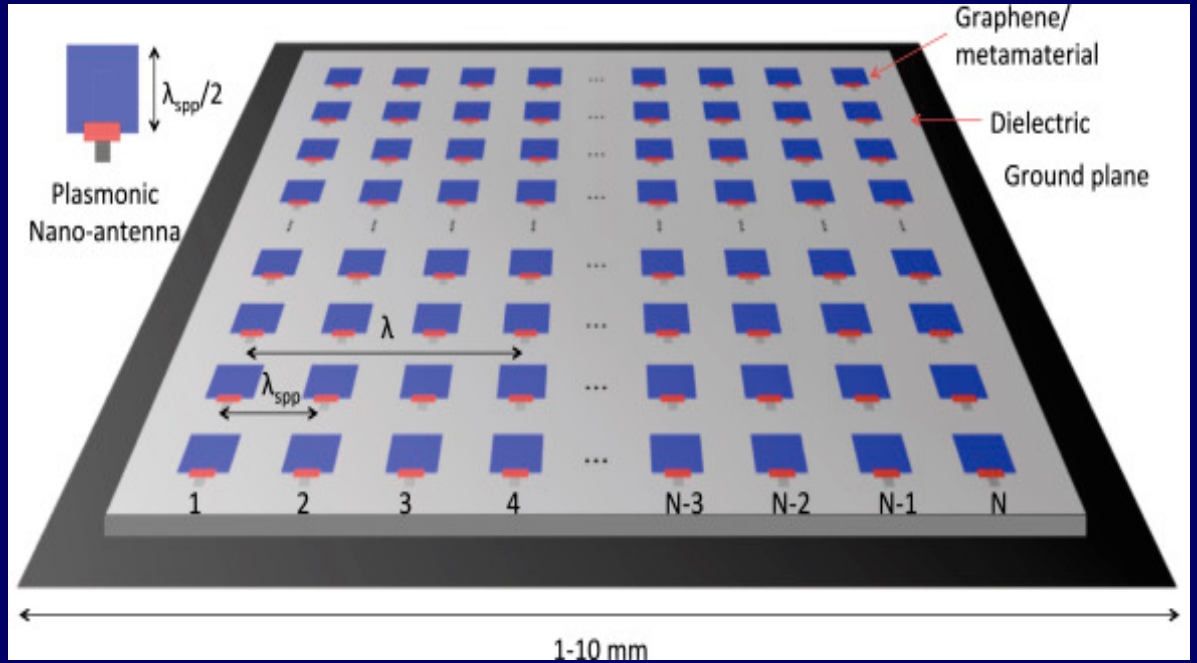
Controlled reflection | Polarized reflection | Absorption

COMBATIN DISTANCE PROBLEM: ULTRA-MASSIVE MIMO

I. F. Akyildiz and J. M. Jornet

"Realizing Ultra-Massive MIMO Communication in the (0.06–10) TeraHertz Band"
Nano Communication Networks, (Elsevier) Journal, available online March 2016;
U.S. Patent 15/211,503 awarded on Sept. 7, 2017.

- **1024x1024 Antenna Element Array**



A square uniform plasmonic nano-antenna array

CHALLENGES FOR UM MIMO

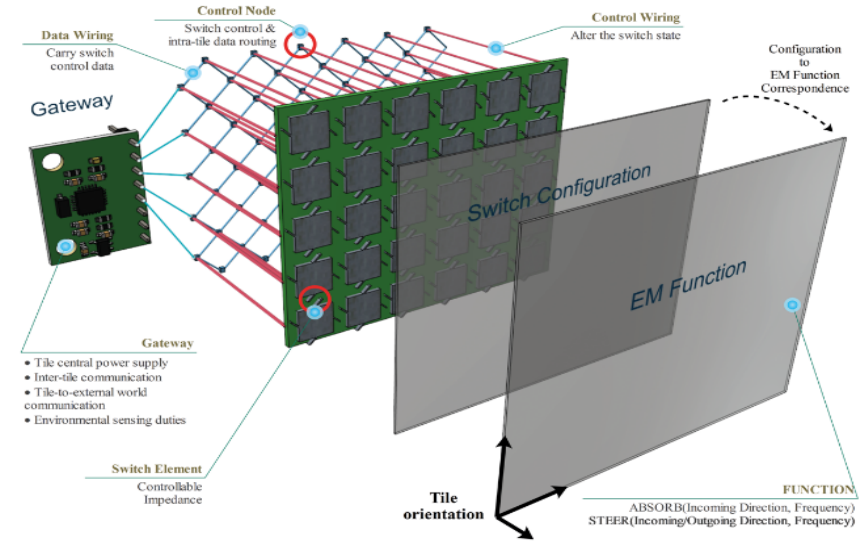
- Fabrication of plasmonic nano-antenna arrays
- 3D Channel modeling
- Optimal control of each antenna array element, codebook design, beamforming beamsteering,
- Link layer and above
  - New network protocols that leverage (multiple) ultra-narrow beams, and support Tbps links
- Study of the maximum achievable distance in real-world indoor and outdoor scenarios
  - Preliminary results show distance increased from 5 m to 40 m at 300 GHz and 30 m at 1 THz with satisfying SNR (10 dB)

EU-FET PROJECT: HyperSurfaces (2017-2021)

METASURFACE HYPERVISOR

Visor SURF

A Hardware Platform for Software-Driven Functional Metasurfaces



"To control electro-magnetic interaction via software"

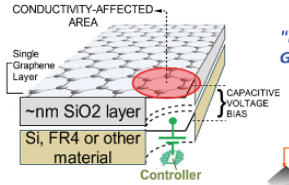
Objectives

VisorSurf's main objective is the development of a hardware platform the HyperSurface to achieve adaptive and reusable metasurfaces HyperSurface merges existing metasurfaces with nanonetworks, acting as a reconfigurable metasurface, whose properties can changed via software interface.

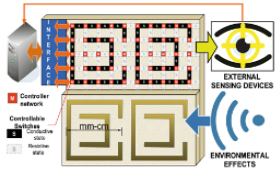
Implementation

Two experimental prototypes will be implemented:

- a switch-based fabric array as the control medium;
- a Graphene based, making use of its exquisite properties to provide finer control.



"Exploration of the Graphene properties"



"Incorporating the Electro-magnetic behavior of mater into smart control loops"

Embedded Systems
Electromagnetism
Metasurfaces
Nano-networks
Softwarization

Horizon 2020
FETOPEN – RIA
Project ID: 736876

Duration:
2017 – 2020

Total cost:
EUR 5.748.000

Coordinated by FORTH

Get more info
www.visorsurf.eu

Stay Tuned
VisorSurf
@VisorSurf

This project has received funding from the European Union's Horizon 2020 research and innovation programme-Future Emerging Topics (FETOPEN) under grant agreement No 736876

FORTH · University of Cyprus · Fraunhofer Gesellschaft · SignalGeneriX · Universitat Politècnica de Catalunya BarcelonaTech · Aalto University

NANO-CAMERAS

- Nano-photodetectors and nano-lenses will help
  - Very high pixel resolution
  - Very high spatial resolution
  - Very high color resolution (hyper spectral cameras).

NANO-PHONES

- Enable novel acoustic transducers with:
  - Higher directional resolution (surround effects)
  - Higher frequency resolution (higher quality audio)

FURTHER RESEARCH CHALLENGES

- Addressing
- Routing
- Reliability
- Congestion Control
- Energy Consumption
- Security and Privacy
- Mobility

LESSON: DARPA NEWS (2014):

4 DARPA PROJECTS BIGGER THAN THE INTERNET

1. ATOMIC GPS
   (C-SCAN → Chip-Scale Atomic Navigation
   QuASAR → Quantum Assisted Sensing)

2. Terahertz Frequency Electronics, Devices, Meta-materials and Communication

3. A Virus Shield for the Internet of Things
   (The High Assurance Cyber Military Systems program, or HACMS)

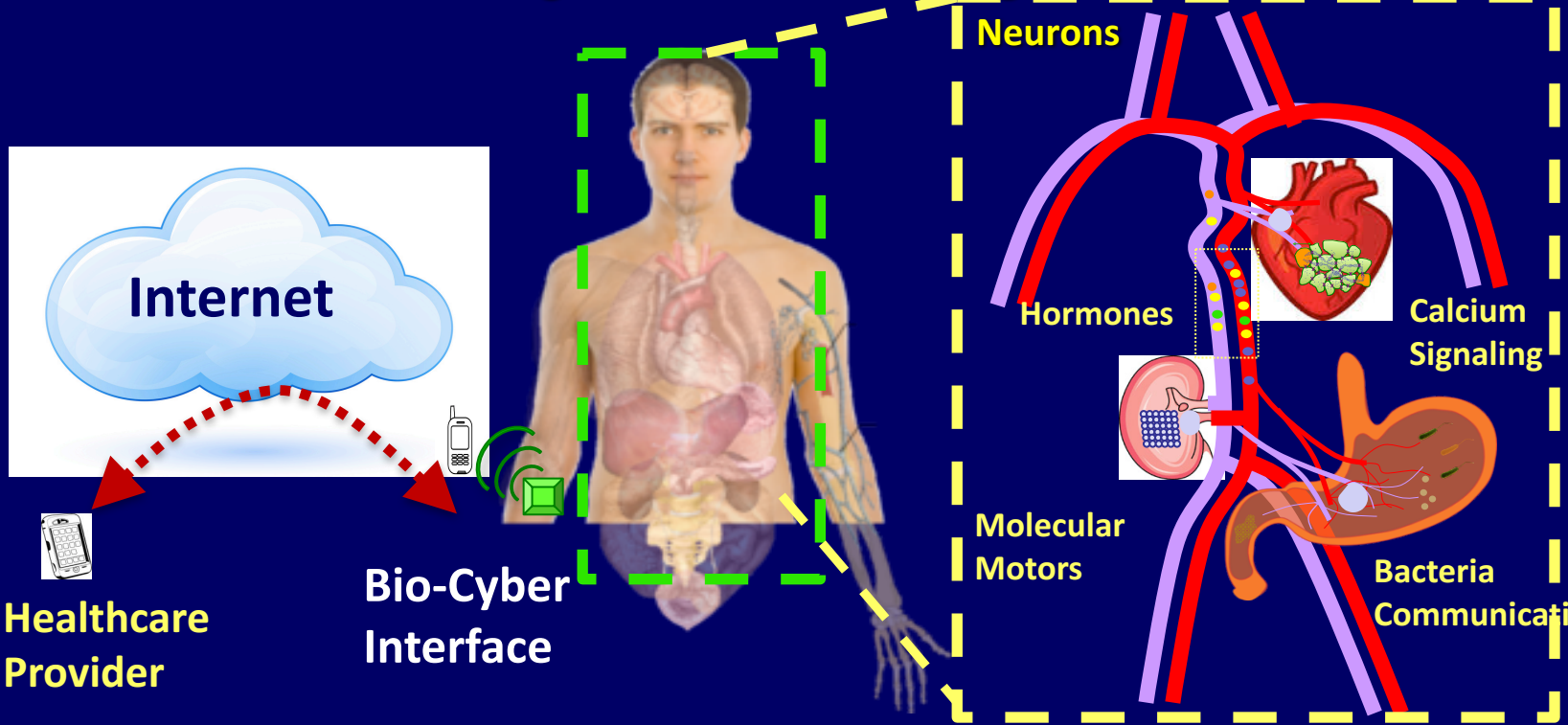
4. Rapid Threat Assessment

INTERNET OF BIO-NANOTHINGS:

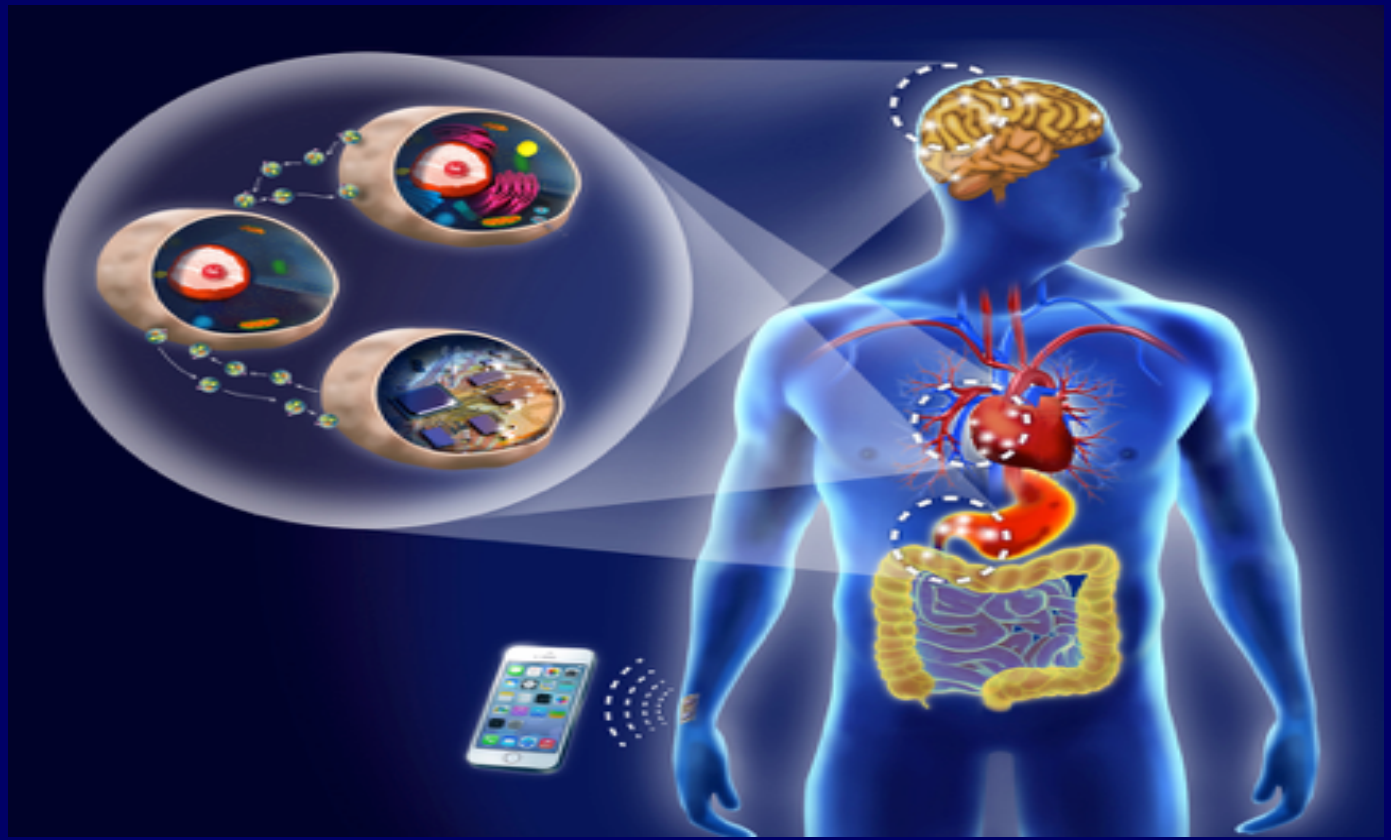
I.F. AKYILDIZ, M. PIEROBON, S. BALASUBRAMANIAM, Y. KOUCHERYAVY,
"THE INTERNET OF BIO-NANOTHINGS",
IEEE COMMUNICATIONS MAGAZINE, MARCH 2015

Objective:

To interconnect the heterogeneous Bio-NanoThings Networks to the Internet

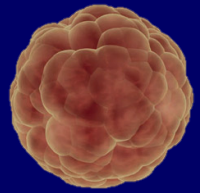


Internet of Bio-NanoThings:
Network Architecture



INTERNET OF BIO-NANOTHINGS

- Cells are nanoscale-precise biological machines

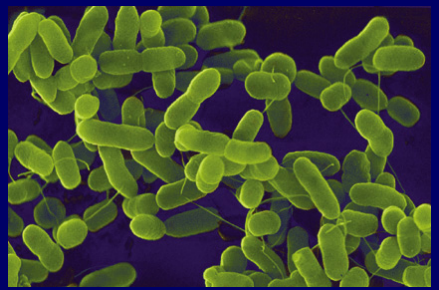


Eukaryotic Cell

Prokaryotic Cell

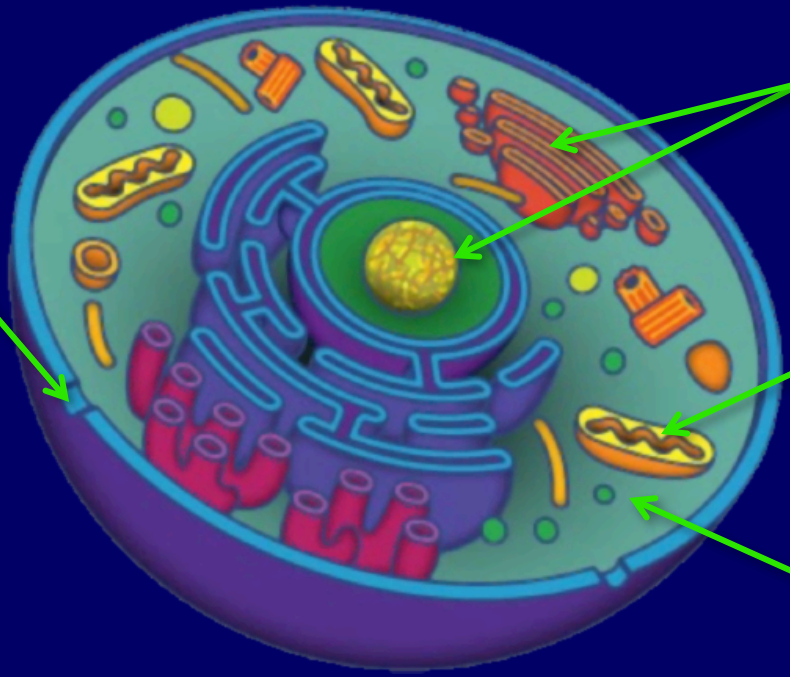
- They communicate and interact/cooperate

Eukaryotic Cell Tissue



Bacteria Population

CELLS AS BIOLOGICAL NANOMACHINES



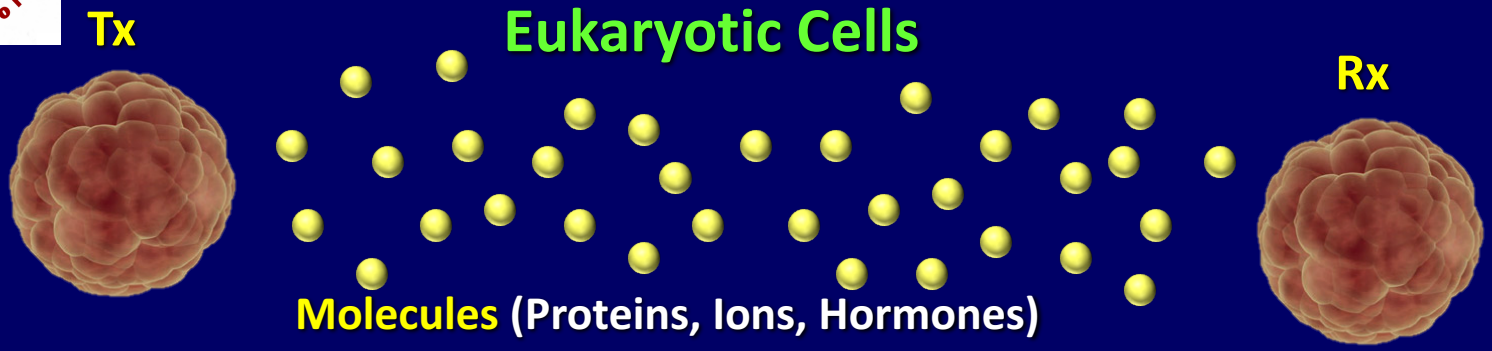
Gap Junctions
= Molecular Transmitters

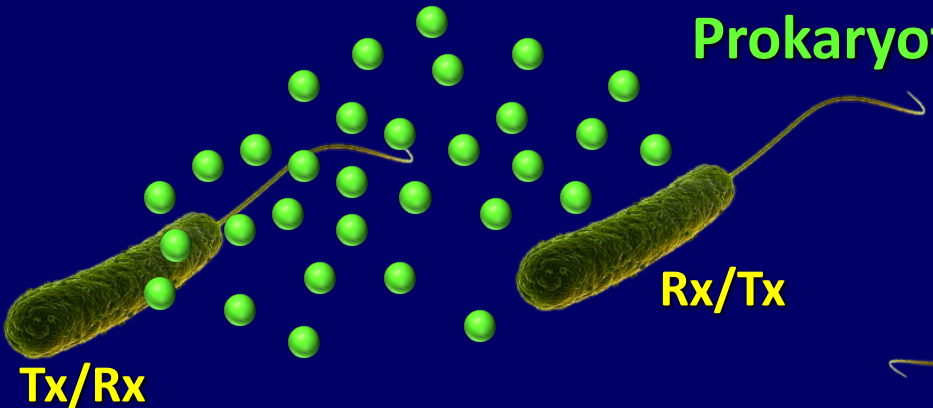
Nucleus and Ribosomes
= Biological Memory and Processor

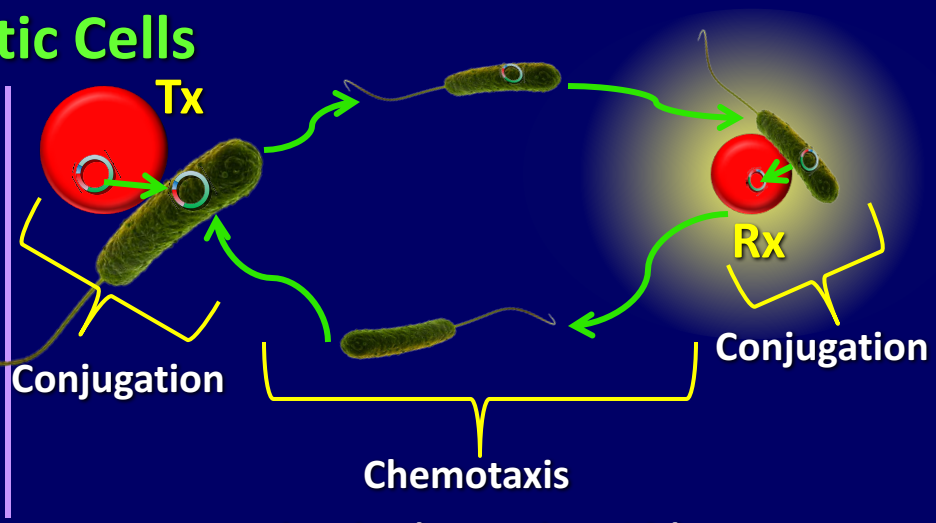
Mitochondria
= Biological Battery

Chemical receptors
= Biological Sensors/ Molecular Rx

BIOLOGICAL NANOMACHINES:
COMMUNICATION THROUGH MOLECULES







NSF MONACO PROJECT

I. F. Akyildiz, F. Fekri, C. R. Forest, B. K. Hammer, and R. Sivakumar,
"MONACO: Fundamentals of Molecular Nano-Communication Networks,"
IEEE Wireless Communications Magazine, October 2012.

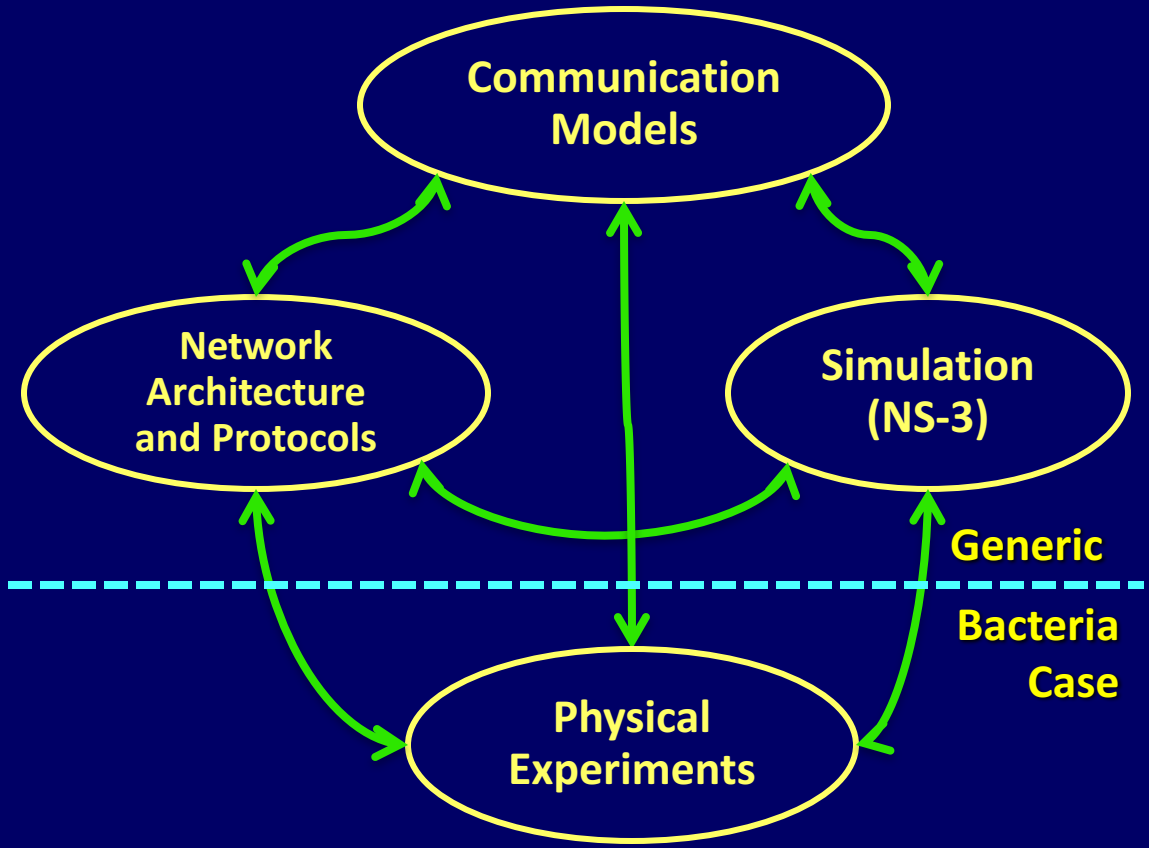
This material is based upon work supported by the National Science Foundation under Grant No. 1110947

- **NSF Funding:**
  - $4M in 4 years (2012-2016)
  - 5 PIs in wireless communication and networks, biology and microfluidic engineering
- **Project webpage:**

  http://www.ece.gatech.edu/research/labs/bwn/monaco/index.html

NSF MONACO PROJECT: SPECIFIC OUTCOMES

- Establish theoretical foundations of diffusion-based molecular nanonetworks
- Design network architectures, modulation schemes and protocols
- Develop a molecular communication network based on genetically modified/ engineered prokaryotic cells (bacteria) in a microfluidic device



HETEROGENEOUS BIO-NANOTHINGS NETWORK

Problem

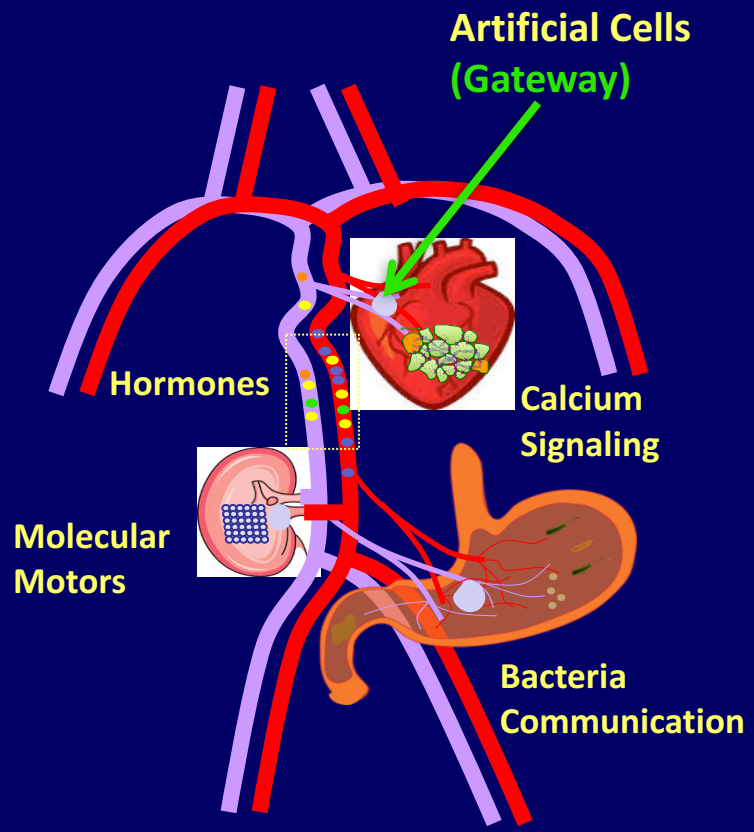
- Connecting different type of networks to each other.

Challenge

- Translating information between the different Bio-NanoThings networks.

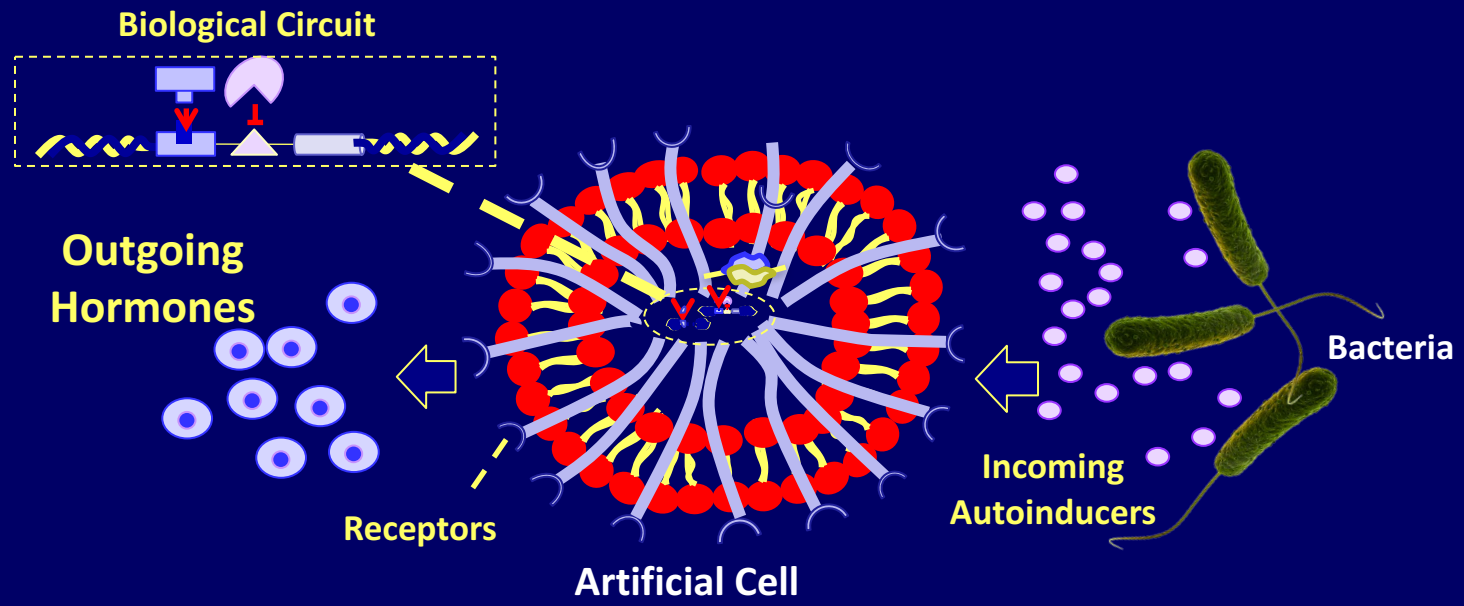
Approach

- Design Artificial cells for translating between different molecule types.



ARTIFICIAL CELLS AS GATEWAYS

- Receptors intercept the incoming molecules (e.g.,autoinducers from bacteria).
- Activates Biological Circuit to synthesize outgoing molecules (e.g., hormones)

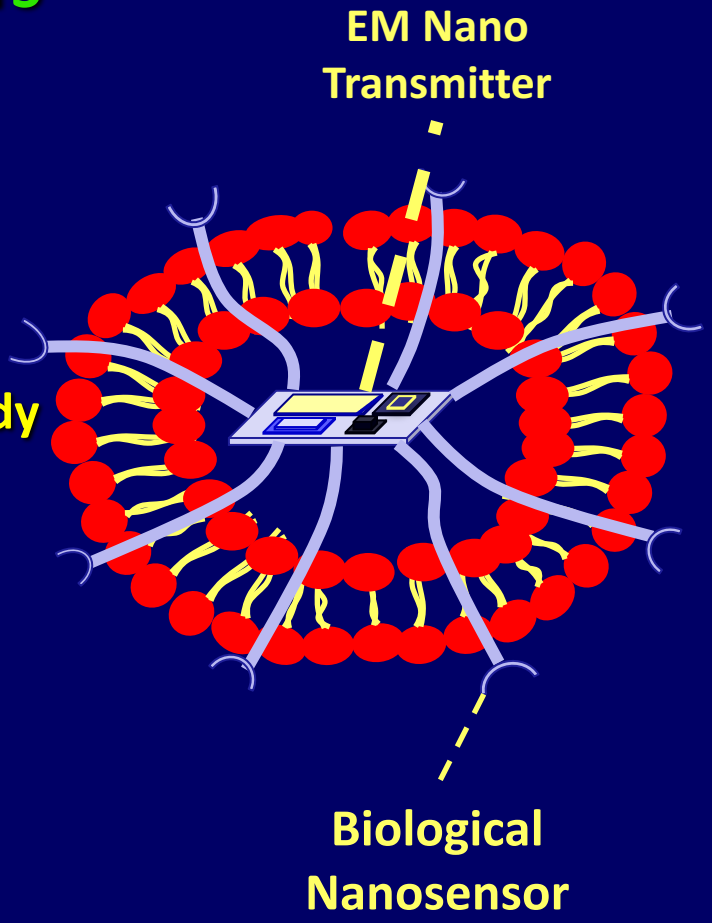


BIO-CYBER INTERFACE:
EM NANOMACHINE GATEWAYS

- Translates information from biochemical domain to electrical domain.
- EM waves emit information to outside the body

Challenge

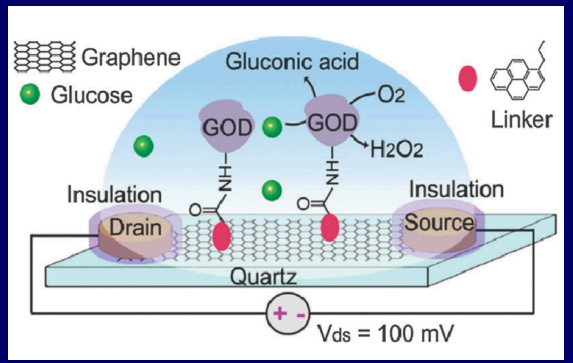
- Bio-compatibility

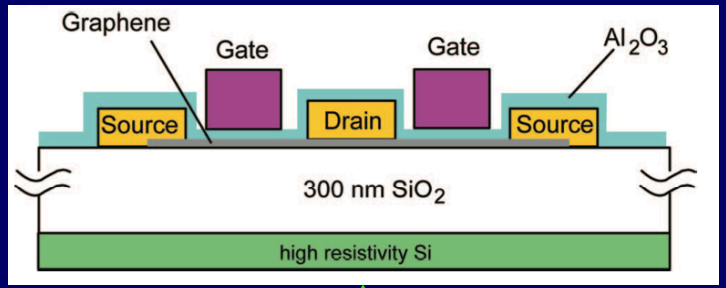


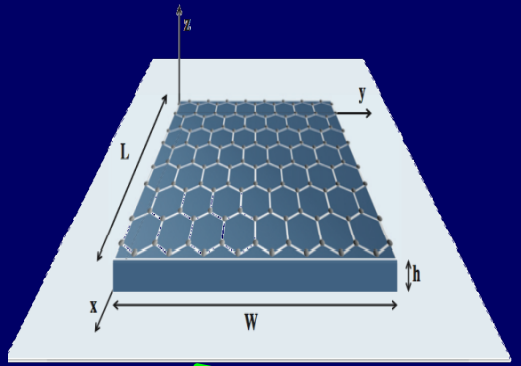
BIO-CYBER INTERFACE:

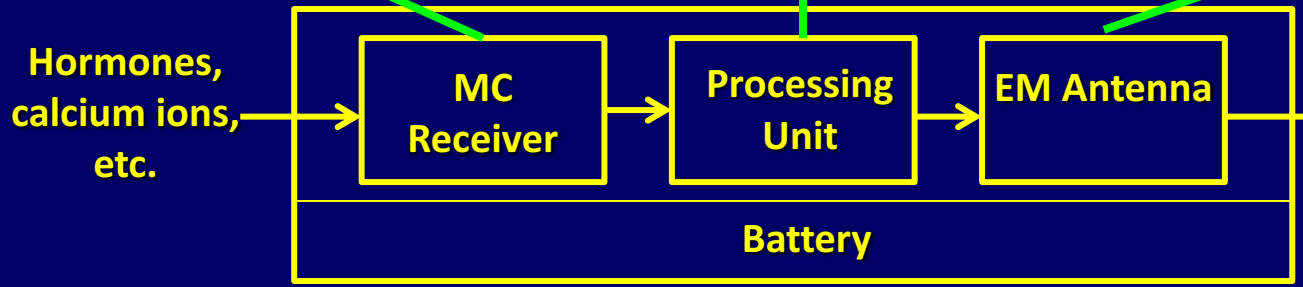
EM NANOMACHINE GATEWAYS WITH GRAPHENE

- Graphene-based sensors for biological detection of MC signals
- Graphene-based transistors for information processing
- Graphene–based plasmonic nano-antenna



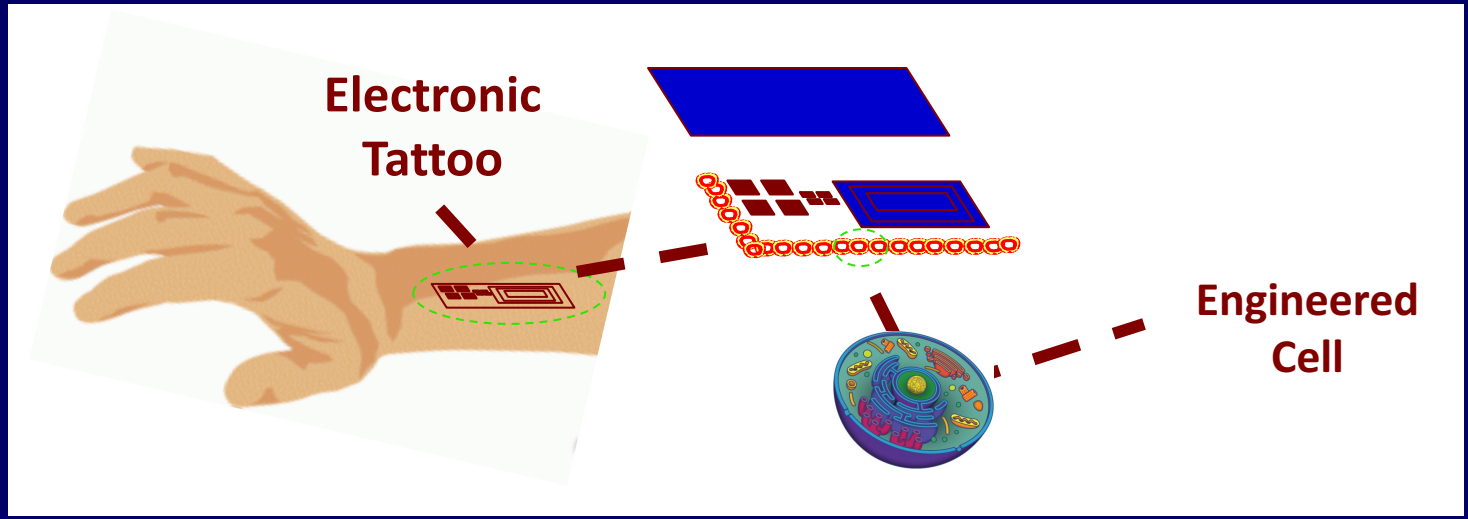






BIO-CYBER INTERFACE: ELECTRONIC TATTOO

- Integrated circuit with wireless interface tattooed on the skin
- Senses bio-chemical information from cells on the epidermis, sweat glands, or nervous terminations.



FURTHER CHALLENGES

Security

- Emergence of new forms of terrorism:

  Bio-cyber terrorism that utilize IoBNT

  - Interacts and hacks the biological environment
  - Steal personal health information
  - Create new disease to disrupt legitimate Bio-NanoThing networks

FURTHER CHALLENGES

Localization and Tracking

- Design of Bio-NanoThings to cooperatively:
  - Monitor disease locations
    (e.g., follow biomarkers from cancer cells)
  - Identification of toxic agents within the environment

FURTHER CHALLENGES

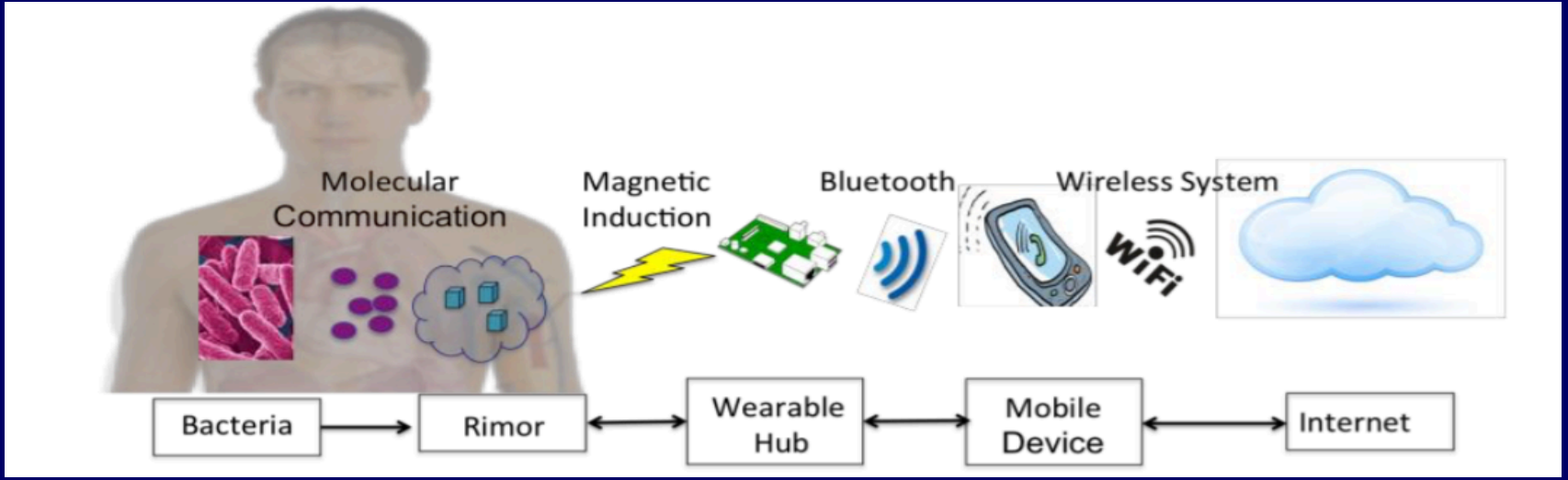
Interconnecting IoBNT to IoNT to IoT

* **Interconnection will:**
  - Escalate “Big Data” to a new level.
  - Require new services to semantically map data from IoBNT and IoNT to IoT.
  - Require new service discovery required to search deep into the biological environment to collect information.

EARLY DETECTION OF INFECTIONS: PANACEA (2017-2022)

Design a tiny implantable Bio-NanoThing, called RIMOR

to detect the communication among cells in the human body



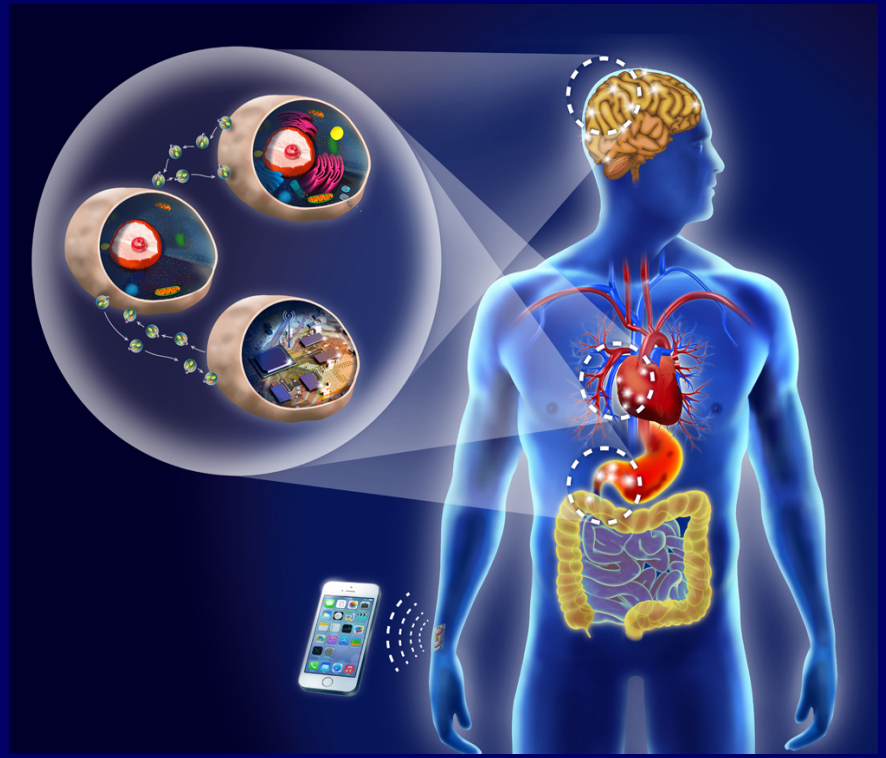
Continuous monitoring of P. aeruginosa infections (lungs) with IoBNT.

→ Reducing mortality and hospital costs

Center for Bio-NanoThings for Human Health

Directors: Dr. Ian Akyildiz and Dr. Ilangko Balasingham
PIs: Dr. Christopher Contag, Dr. Ulf Österberg, Dr. Snorre Aunet, and Dr. Jacob Bergsland

"Cells wirelessly connected to the Internet"



VISION:

"Create an internationally renowned center for bio-integral implantable communications technologies that sense and guide bio-molecular processes to monitor health and direct therapy "

APPLICATIONS:

1. ***Brain: Neuromodulation systems & regeneration*** of cells
2. ***Heart problems & cardiac function***
3. ***Crohn's Disease***

BOTTOMLINE

TRANSDISCIPLINARY RESEARCH