INTERNET OF μTHINGS, NANOTHINGS & BIO-NANOTHINGS

I. F. AKYILDIZ

Ken Byers Chair Professor in Telecommunications
Georgia Institute of Technology
School of Electrical and Computer Engineering
BWN (Broadband Wireless Networking) Lab
Atlanta, GA 30332, USA
http://bwn.ece.gatech.edu

INTERNET OF THINGS

Kevin Ashton, "The Internet of Things",
Procter & Gamble, 1999.

L. Atzori, A. Iera, G. Morabito,"The Internet of Things: A Survey",
Computer Networks (Elsevier) Journal, Oct. 2010.

- Interconnection of Things or Objects or Machines,

  e.g., sensors, actuators, mobile phones, electronic devices, home appliances, any existing items

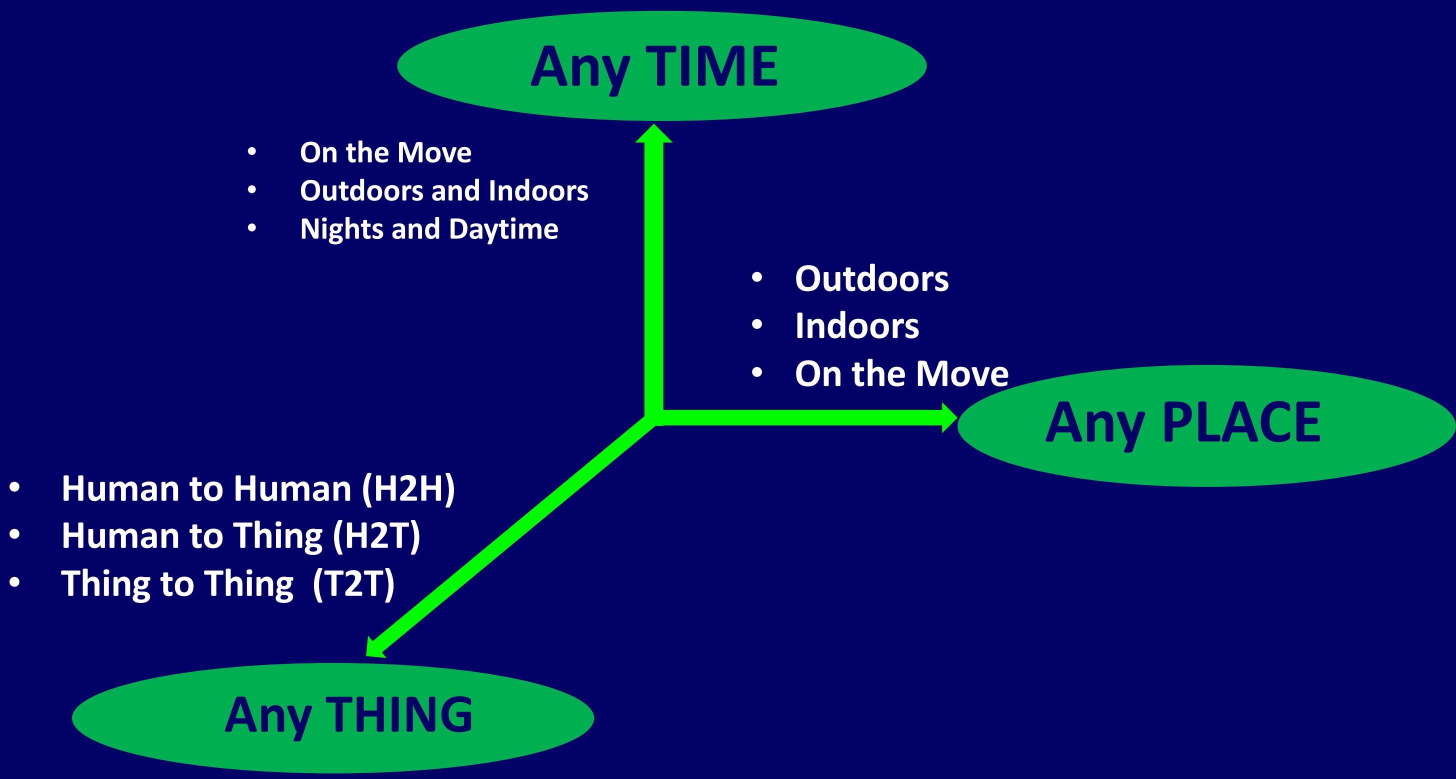
  and interact with each other via Internet

THINGS CONNECTED: COMMUNICATED BETWEEN PHYSICAL WORLD AND INFORMATION WORLD

ROUGH MARKET SIZE

- **Current Internet**
  - 700 Million hosts
  - 1.4 Billion users
- **Internet of Things has the potential for a size in Trillions**
- **5G Systems: Billions of People/Trillions of Things**

INTERNET OF THINGS: PERSPECTIVE

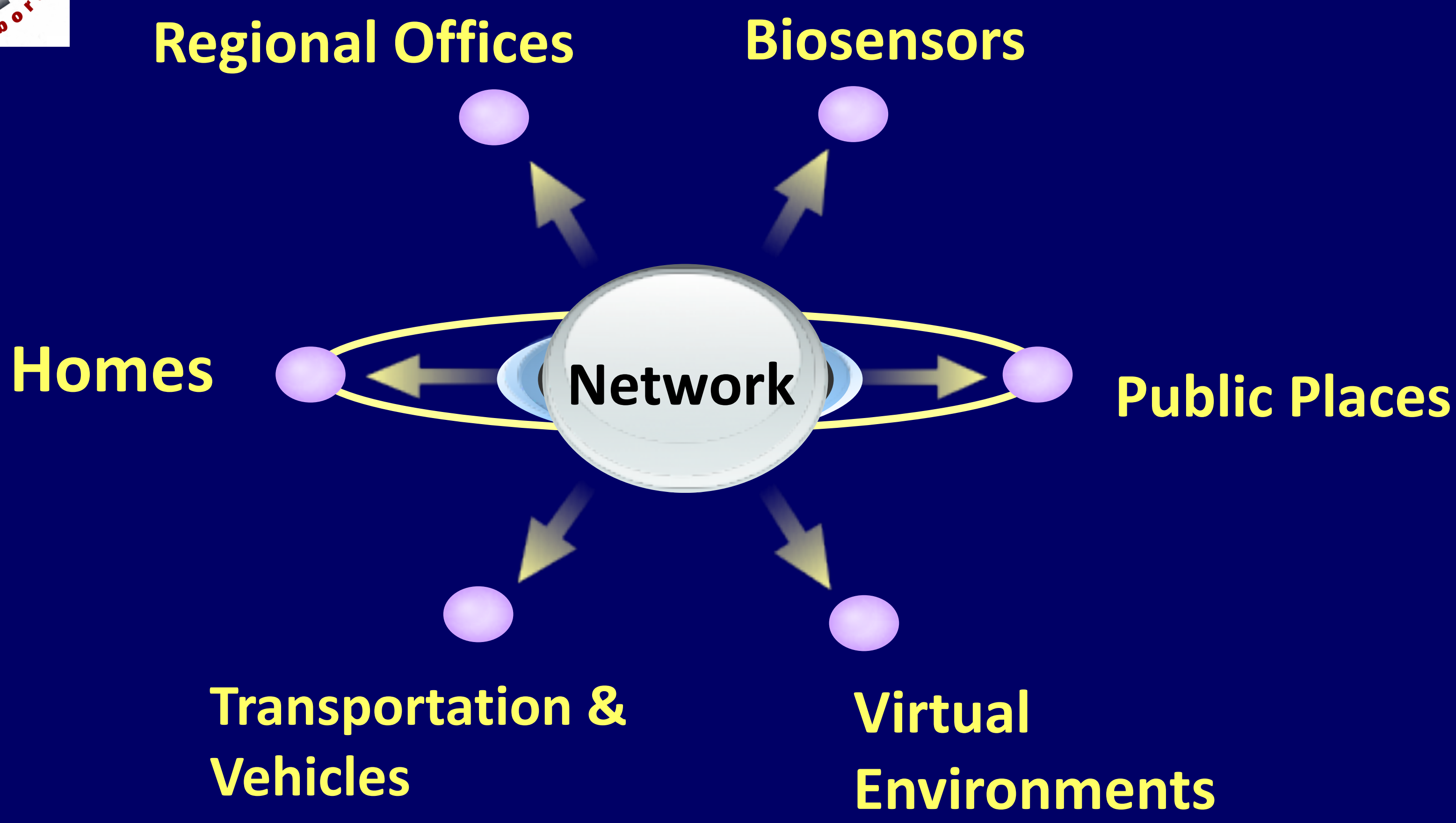


MAJOR CHARACTERISTICS

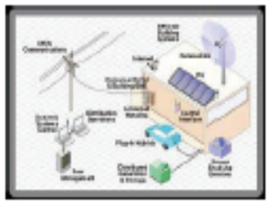
- Very Large Scale
- Heterogeneity
- Pervasivity

  Computing and communication technologies will be embedded in our environments

APPLICATIONS OF IOT



IoT APPLICATIONS



Smart Grid

Smart Health

Smart Home

Smart Cities

Smart Industries

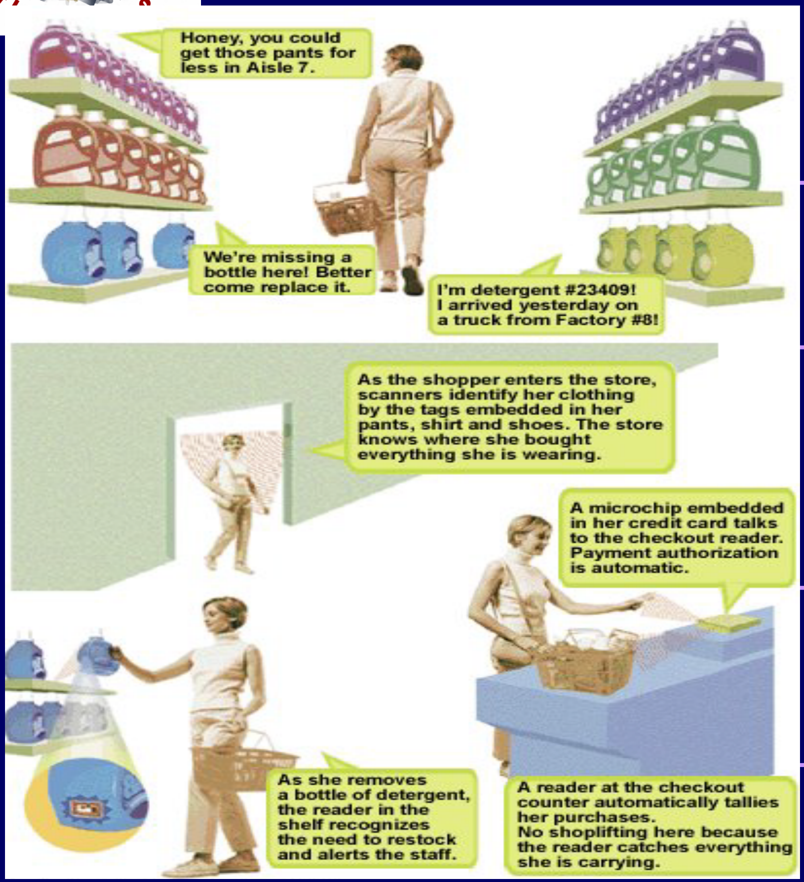
Smart TV

Smart Watch

Smart Car

Smart Kegs

APPLICATION OF IoT: SHOPPING



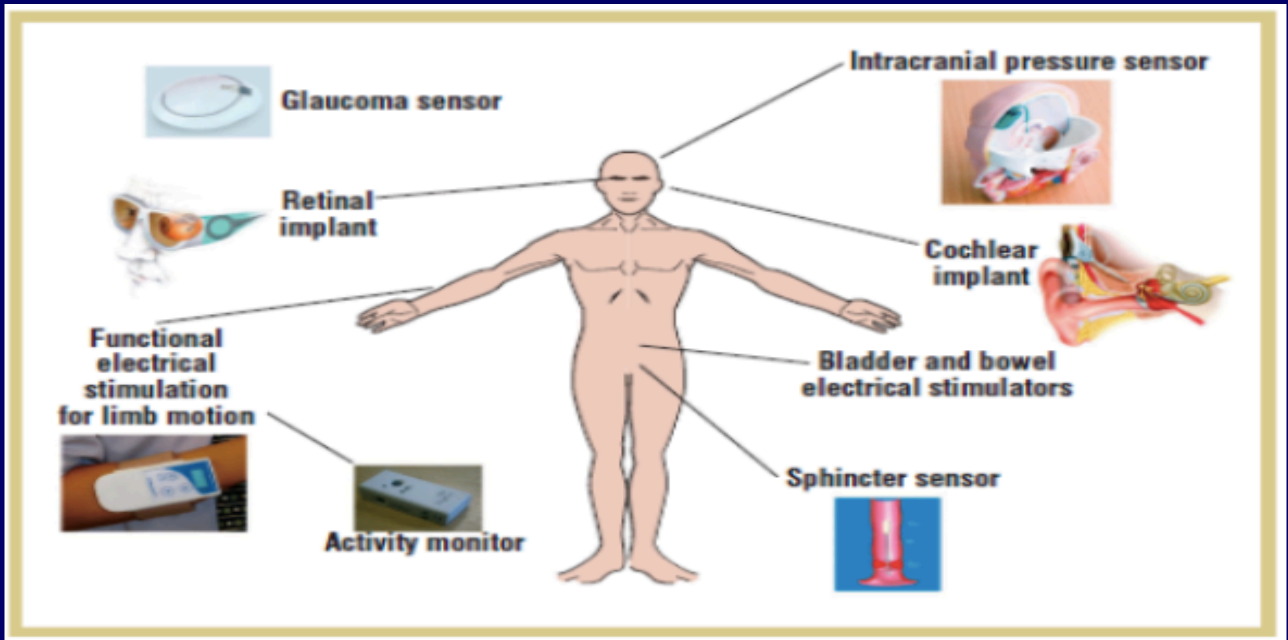
When shopping in the market, the goods will introduce themselves.

When entering the doors, scanners will identify the tags on her clothing.

When paying for the goods, the microchip of the credit card will communicate with checkout reader.

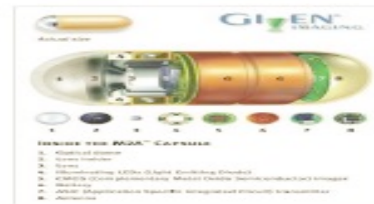
When moving the goods, the reader will tell the staff to put a new one.

APPLICATION OF IoT: HEALTHCARE



APPLICATION OF IoT: HEALTHCARE

- National Health Information Network
- Electronic Patient Record
- Home Care: Monitoring and Control
- Operating Room of the Future
- Progress in Bioinformatics
- Tracking for Healthcare (tracking patients)
- Patient and Staff Identification and Authentication
- Medical Data Collection



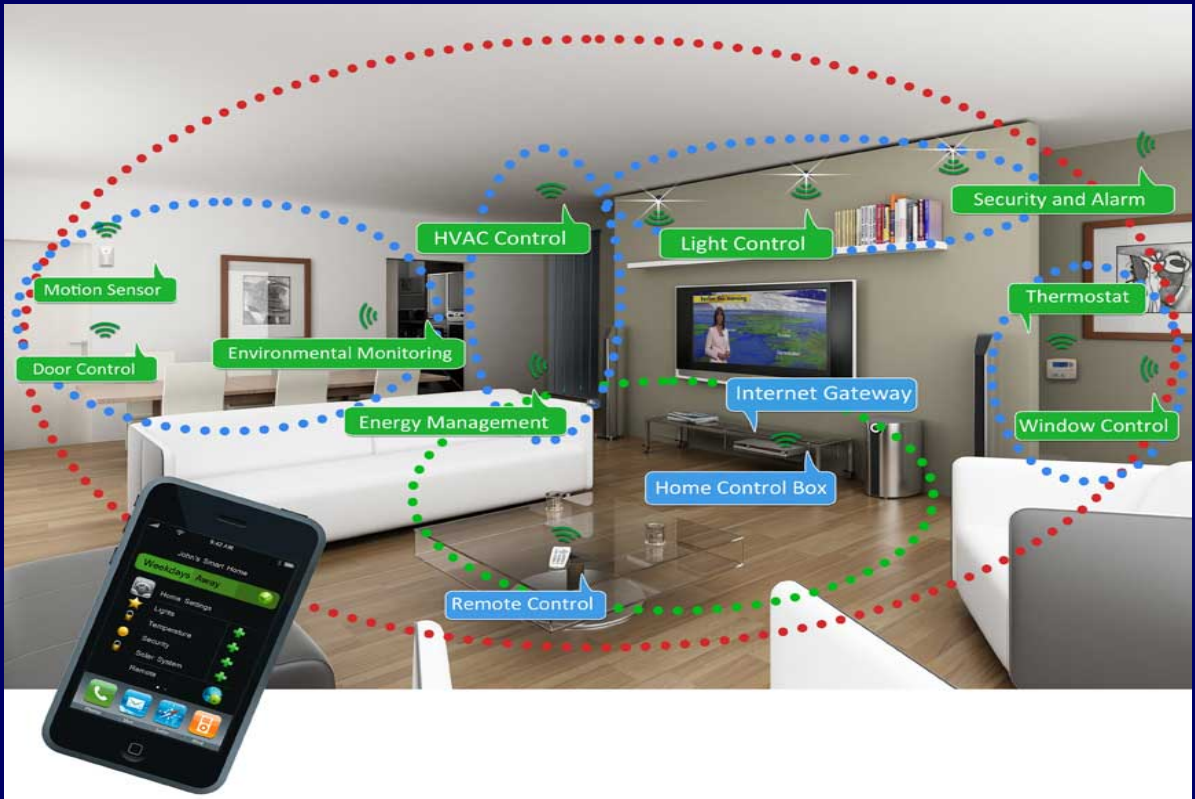
APPLICATION OF IoT: SMART ENVIRONMENT DOMAIN

* Comfortable Homes and Offices
  (IoT is a green technology!)
- Smart Industrial Plants
- Smart Entertainment Environments (gym)
- Smart Schools

APPLICATION OF IoT: SMART HOME

APPLICATION OF IoT: SMART HOME

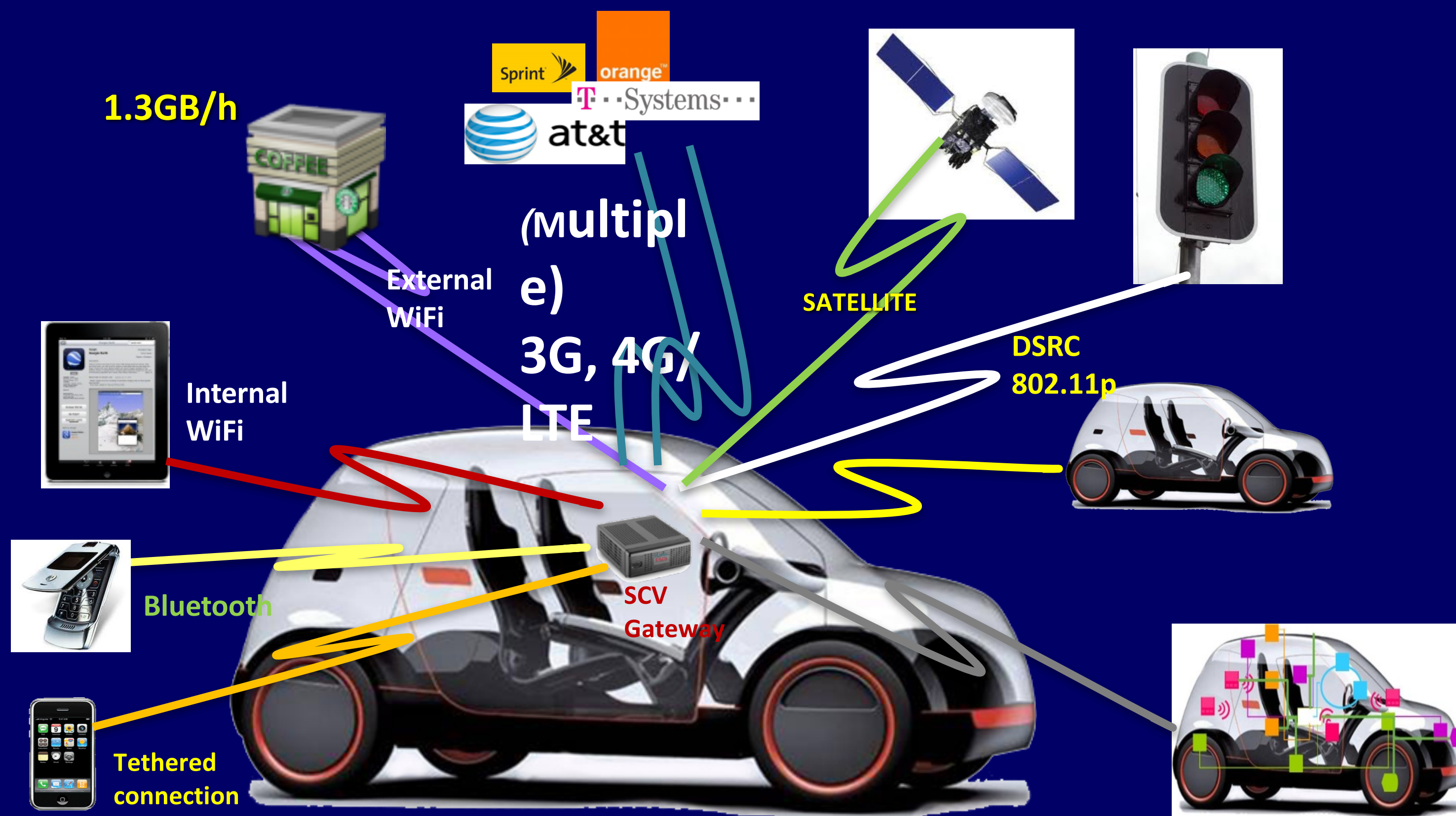
- **Energy Management**
- **In-house entertainment Control**



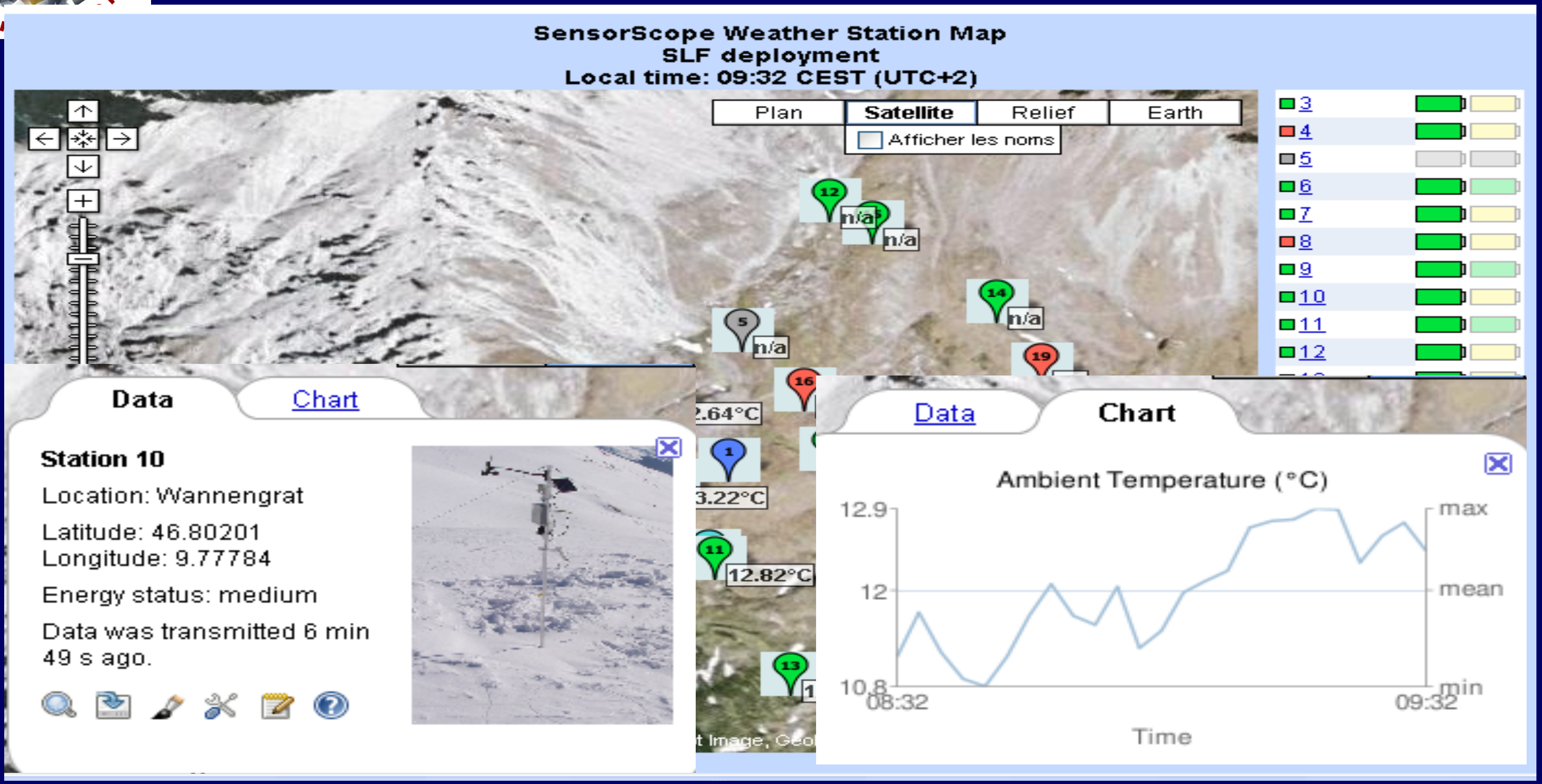
Application of IoT: Transportation

- Save lives and property
- Reduce emissions and
- Cut commuting time and effort

Application of IoT: Transportation



Application of IoT: Monitoring the Environment



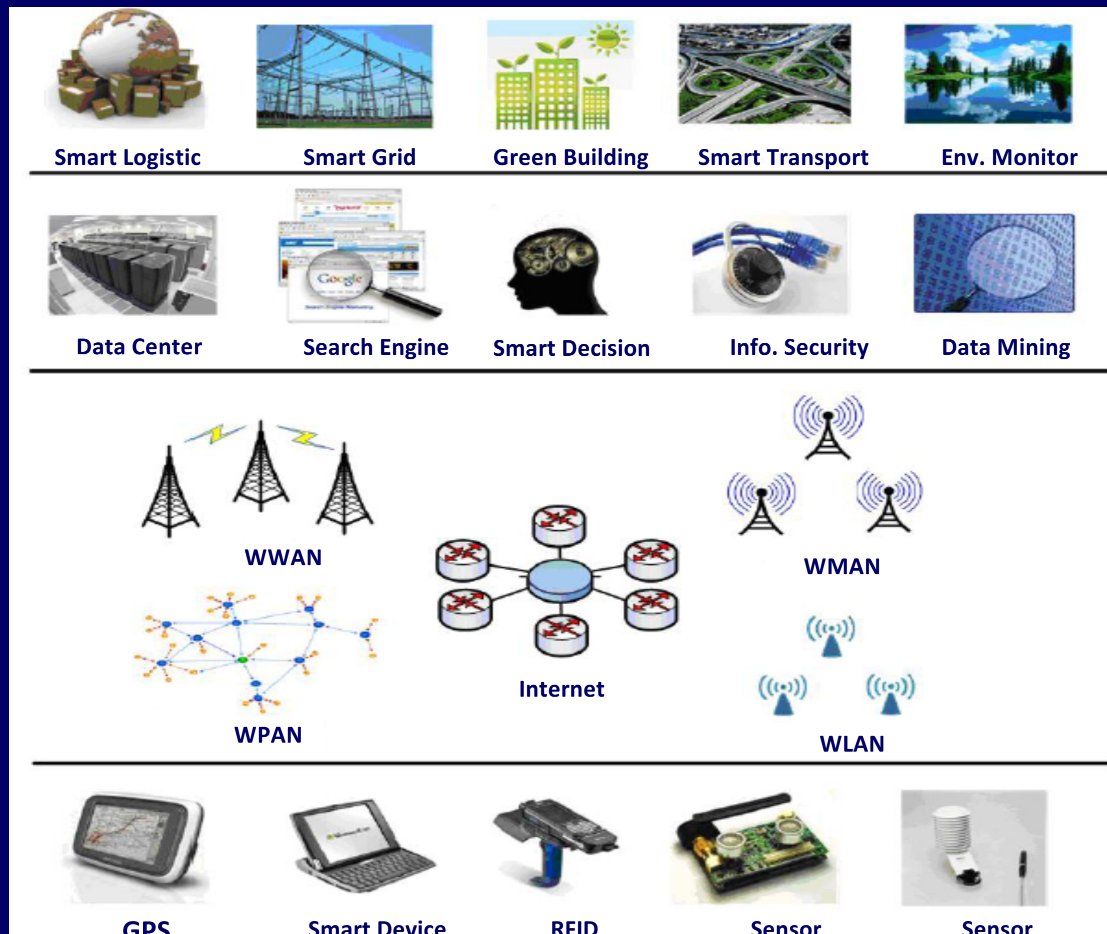
4 LAYERS MODEL OF IoT

Integrated Application

Information Processing

Network Construction

Sensing and Identification



RECENT IoT PRODUCTS

IoT PLATFORMS ON THE MARKET

- GE Predix
- Cisco IoT Cloud
- IBM Watson IoT
- PTC ThingWorx

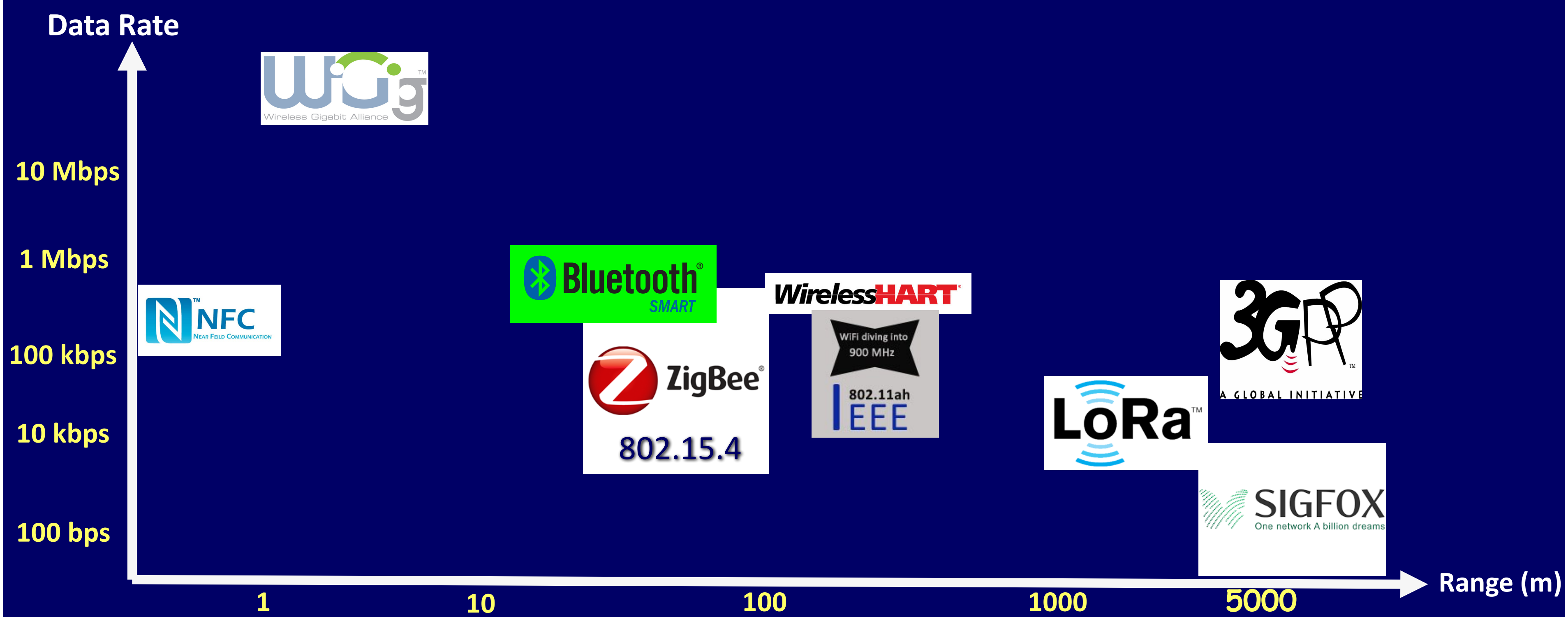
IoT TRENDS TO WATCH IN THE FUTURE

- IT services (business consulting) → Major Driver
- IoT drives demand for DATA ANALYTICS:
  Data must be managed, integrated and analyzed
- IoT drives demand for CLOUD COMPUTING
- IoT data → DATA BROKER
  IoT generated data is bought, analyzed and sold
  e.g., IBM buys The Weather Company data
- Interoperability Problems
- Security

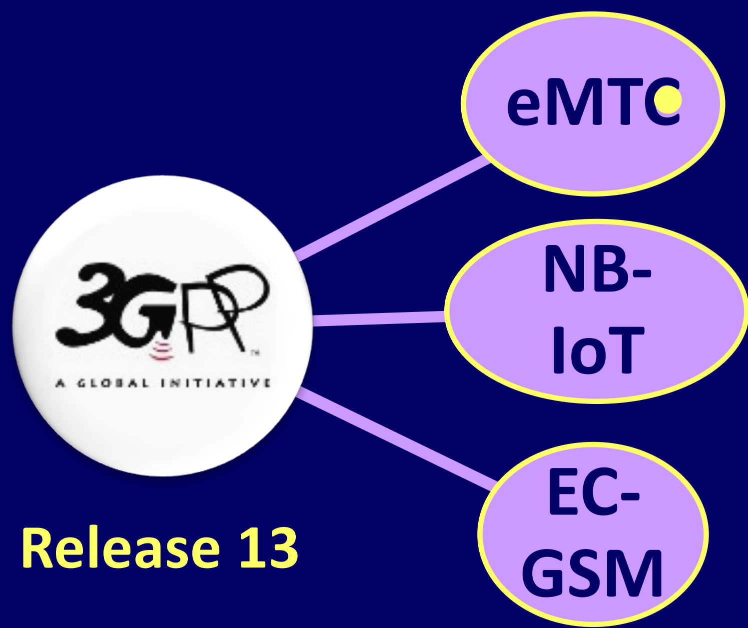
RESEARCH CHALLENGES

- Scalability
- Handle data generated by 50 billion devices
- Move cloud services to edge of the network (Fog Computing)
- Reduce data to be stored (Processing and Storage)
- Standardization
- Interoperability
- Interfaces to CLOUD servers must be standardized
- Power Consumption Problem (Energy Harvesting)
- SDN/NFV Based IoT

IoT CONNECTIVITY COMPETITIVE LANDSCAPE



Current 3GPP Standardization for IoT



- Category M device for LTE
- Narrowband IoT
- Extended Coverage GSM

SCALING TO CONNECT THE INTERNET OF THINGS

← Scaling up in performance and mobility

Scaling down in complexity and power →

LTE Advanced	LTE Cat-1	eMTC (Cat-M1)	NB-IoT (Cat-M2)
> 10 Mbps	Up to 10 Mbps	Up to 1 Mbps	10s of kbps to 100s of kbps
n x 20 MHz	20 MHz	1.4 MHz narrowband	180 kHz narrowband

LTE Advanced (Today+)

LTE IoT (Release 13+)

- Connected Healthcare
- Mobile
- Object Tracking
- Video Security
- Environment Monitoring

Significantly widening the range of enterprise and consumer use cases

- Wearables
- Smart Buildings
- Connected Car
- Utility Metering
- City Infrastructure

5G IoT: EXPECTED DESIGN TARGETS

10-100x more devices	10 year battery life	>20 dB coverage extension	Up to 10 Gbps	Under 1ms latency	$<10^{-7}$ packet error rate
Massive Number of devices	Extended Battery Life	Extended Coverage	High Data Rate	Ultra-low latency	Very-high reliability

Release 13 3GPP IoT

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; Meta-materials; Devices and Communications

3. A Virus Shield for the Internet of Things

(The High Assurance Cyber Military Systems program, or HACMS)

4. Rapid Threat Assessment

ENABLING TECHNOLOGIES OF IOT

RFID → Sensor → Smart Tech → Nano Tech

Tagging Things:

To identify and track the data of things

Sensing Things:

To collect and process the data to detect the changes in the physical status of things

Thinking Things:

Build intelligence at the NW border

Shrinking Things:

To make the smaller things with the ability to connect and interact.

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

CURRENT IoT ENABLING TECHNOLOGIES AND THEIR LIMITATIONS

- **RFID Tags:**
  - Small size, do not have a battery, but…
  - No processing, data storing or sensing capabilities.

- **Micro-Sensor-Actuator Networks:**
  - Some processing and data storage capabilities, but…
  - Large Sizes; High Energy Limitations; Limited Sensing Capabilities;
  - Operation and Maintenance Cumbersome

CAN WE DO BETTER???

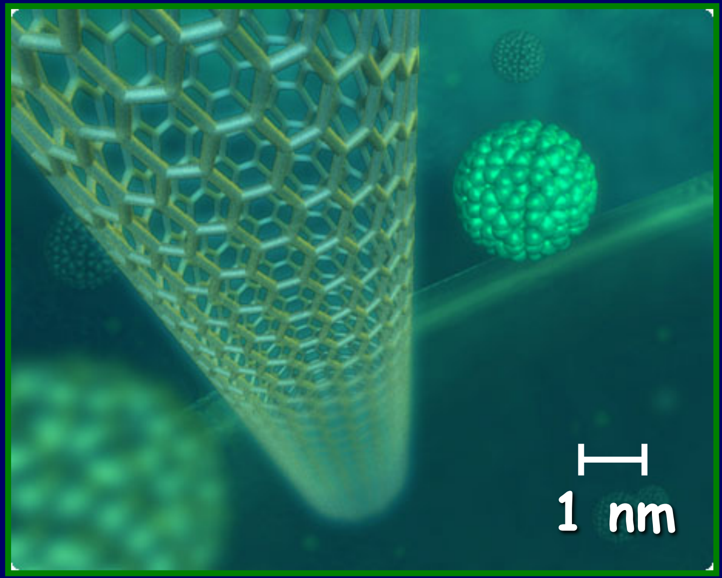
NANO-THINGS

- Much smaller
- Less power hungry + self-powered
- Able to do some processing + data storage
- More sensitive (enabling more applications)
- New nanosensing capabilities

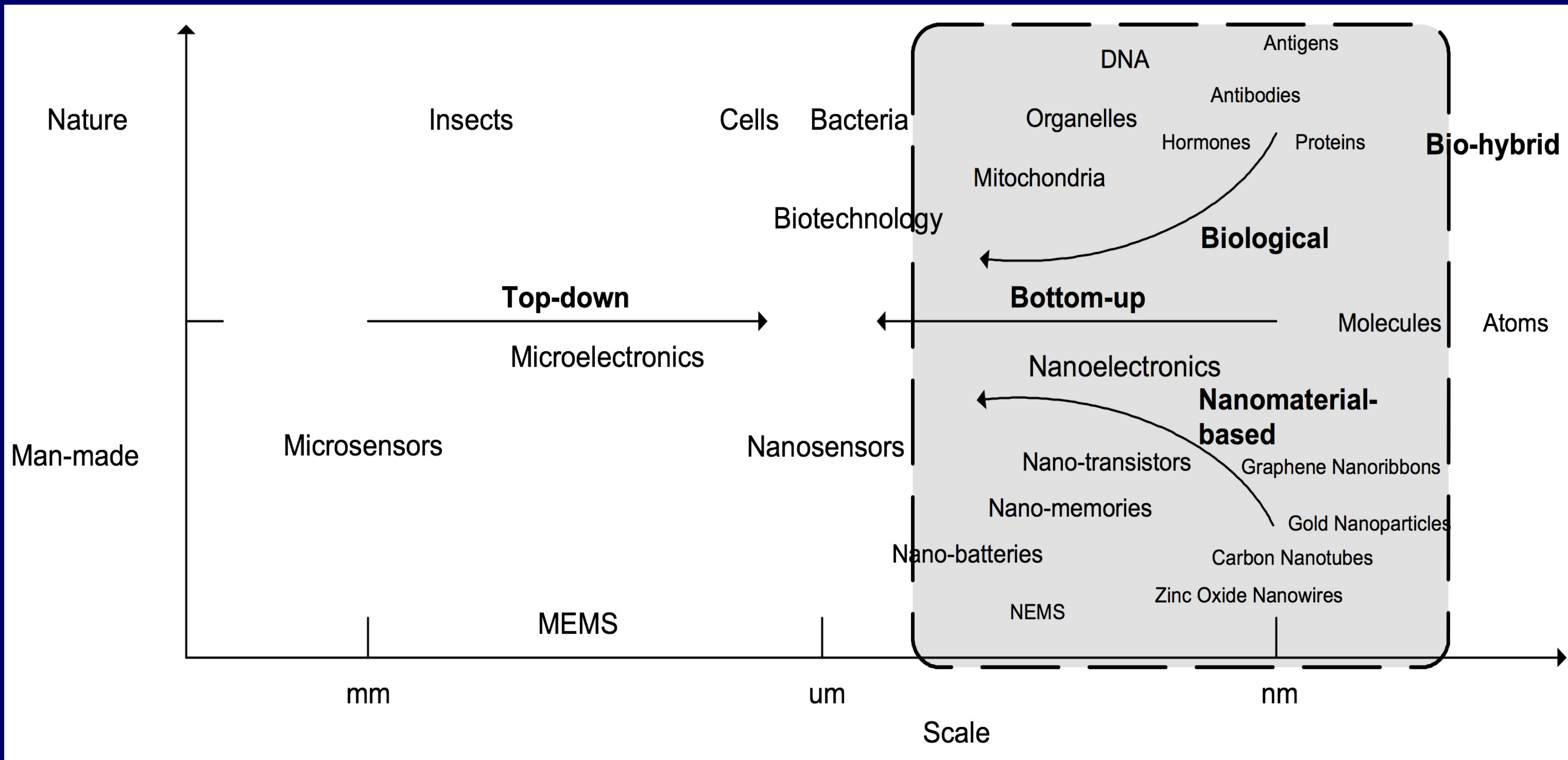
HOW CAN WE CREATE THESE NANO-THINGS???

NANOTECHNOLOGY

- Enables the control of matter at an atomic and molecular scale:
  - At this scale, nanomaterials show new properties not observed at the microscopic level
  - Objective:
    Exploit these properties & develop new devices and applications

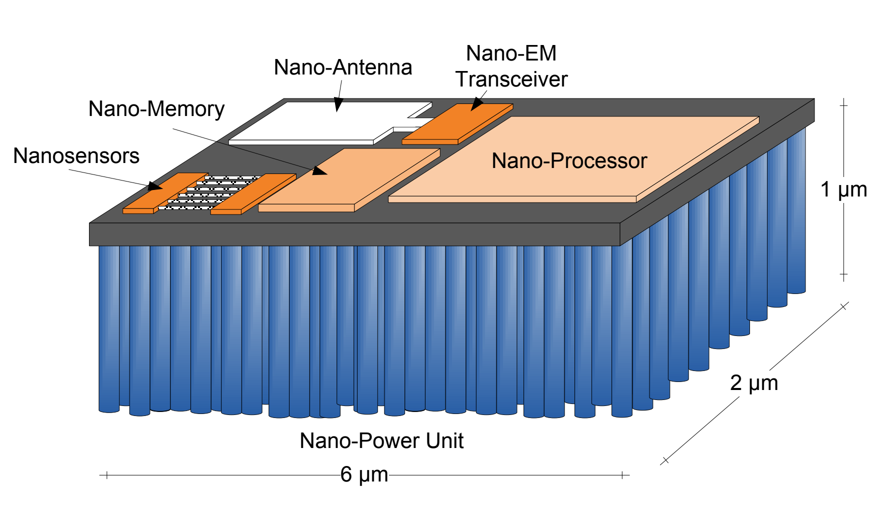


DESIGN OF NANO-THINGS

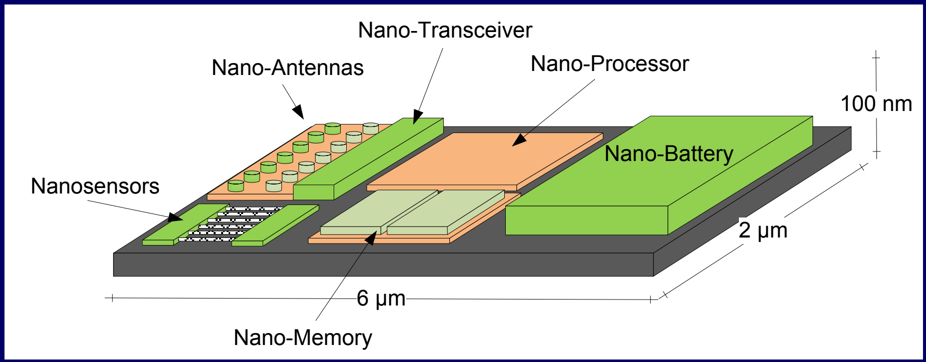


DESIGN OF NANO-THINGS

Nanomaterial Based Design

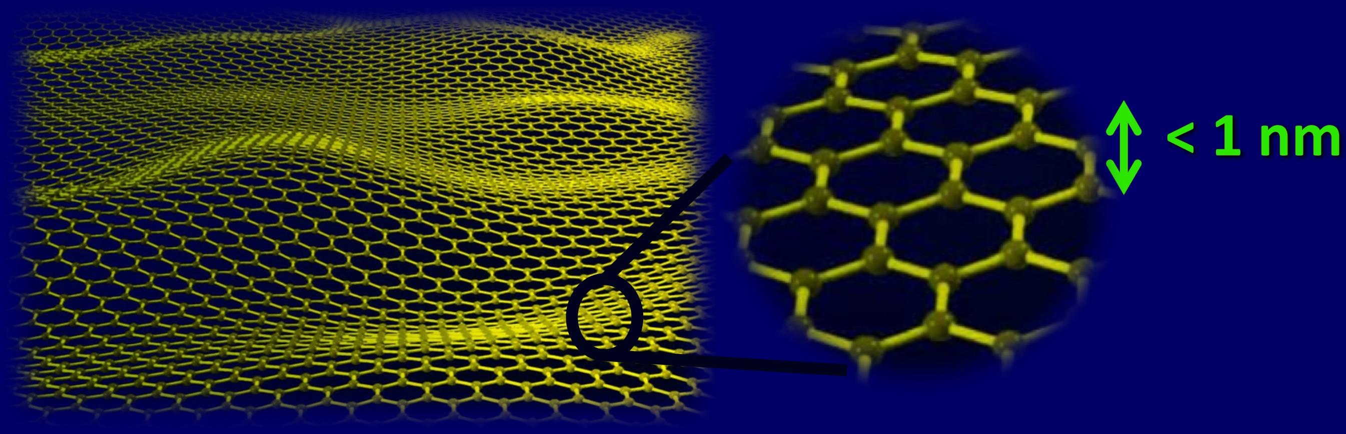


Bio-inspired Design



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"

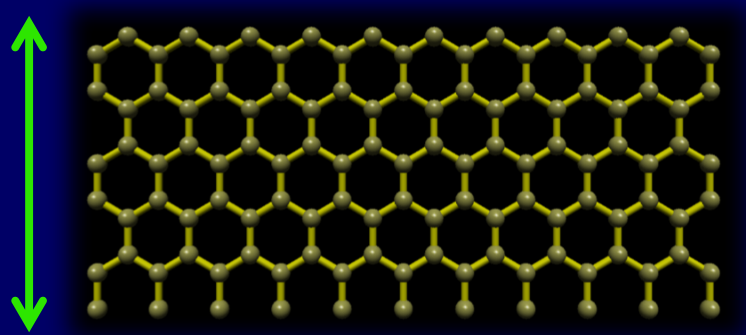
Laureates of the Nobel Prize in Physics (2010)

NANOMATERIALS:

CARBON NANOTUBES & GRAPHENE NANORIBBONS & FULLERENES

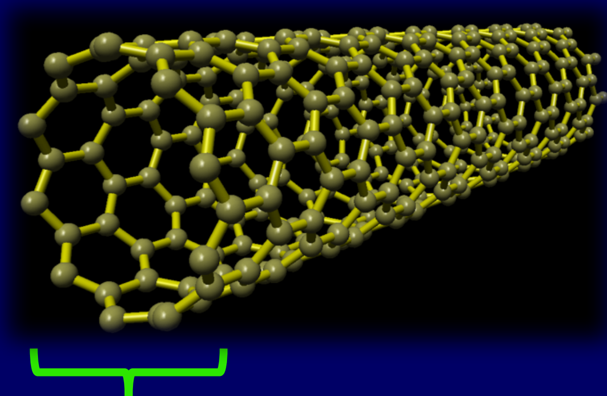
- **Graphene Nanoribbons (GNR):** a thin strip of graphene
- **Carbon Nanotubes (CNT):** rolled graphene
- **Bucky Balls:** a graphene sphere

GNR



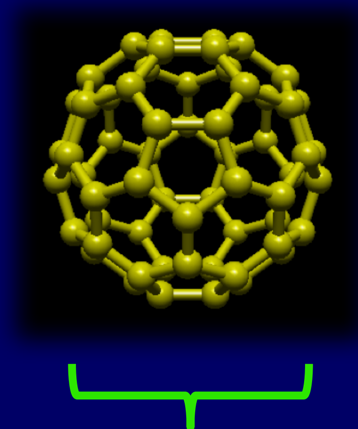
<50 nm

CNT



1-50 nm

Bucky Ball



>5 nm

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

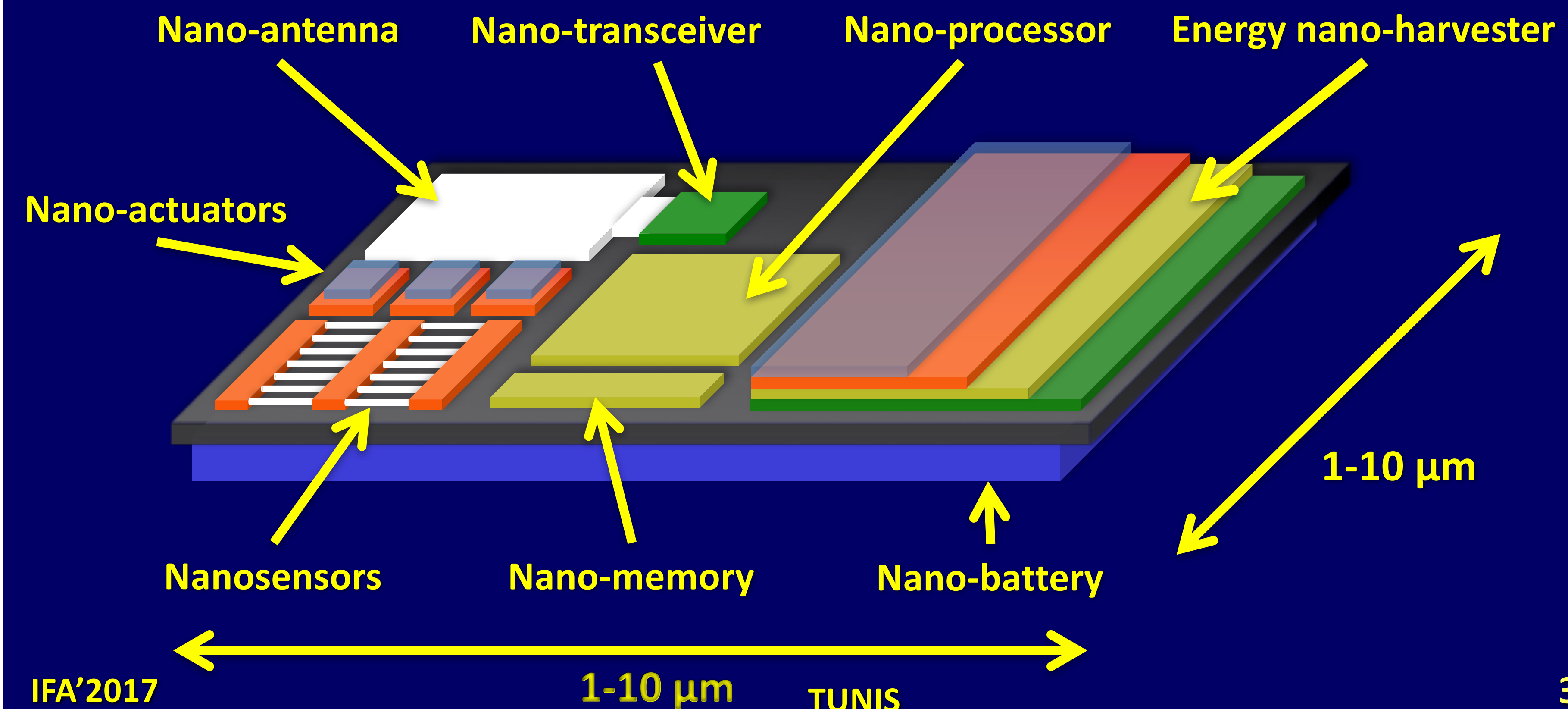
→Enable a plethora of new applications for device technology at the nanoscale and also at larger scales:
  - e.g., processors, memories, batteries, antennas,tx, sensors, etc

DESIGN OF NANO-THINGS

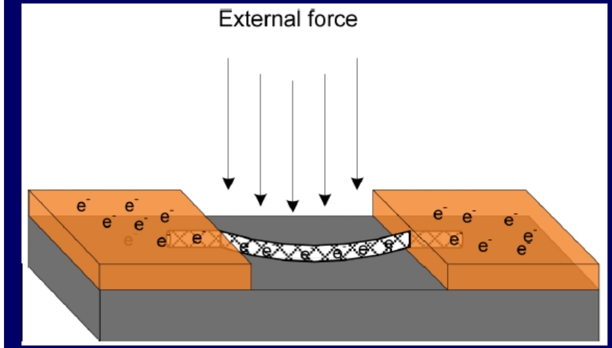
I. F. Akyildiz and J. M. Jornet,

"Electromagnetic Wireless Nanosensor Networks,"

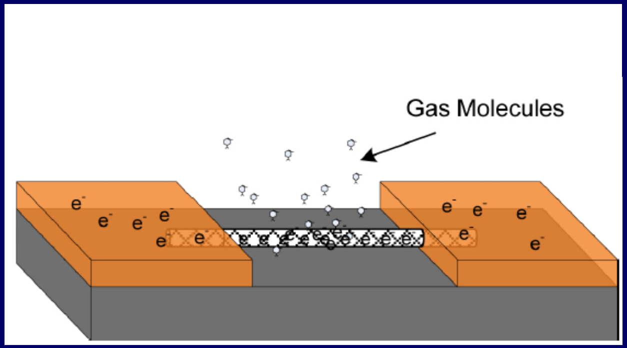
Nano Communication Networks (Elsevier) Journal, March 2010.



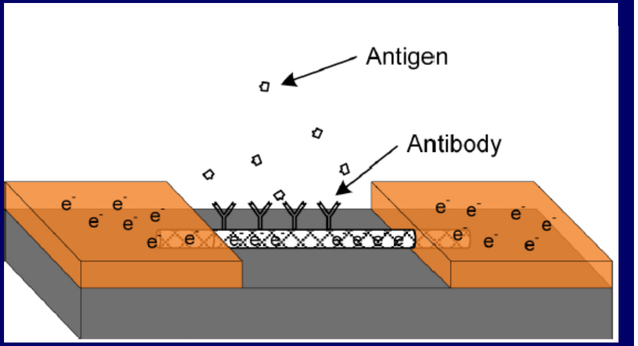
NANO-SENSING UNIT



Physical Nanosensor



Chemical Nanosensor

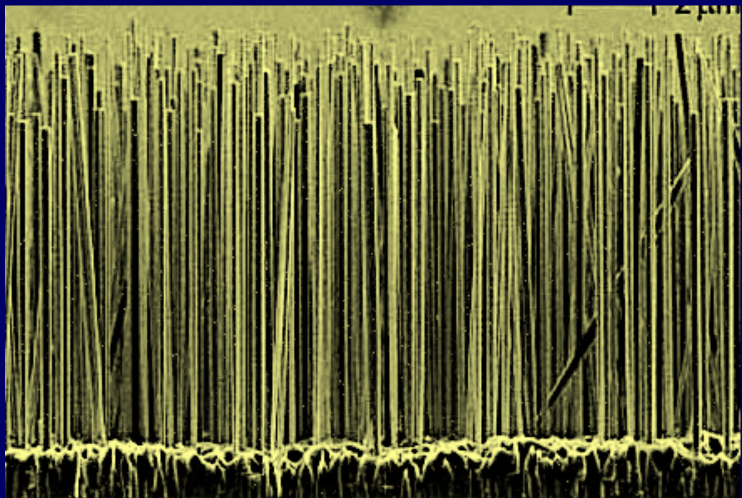


Biological Nanosensor

NANO-POWER GENERATOR

(OTHER NANO-MATERIALS?)

Zinc Oxide nanowires can be used for vibrational energy harvesting systems in nano-devices

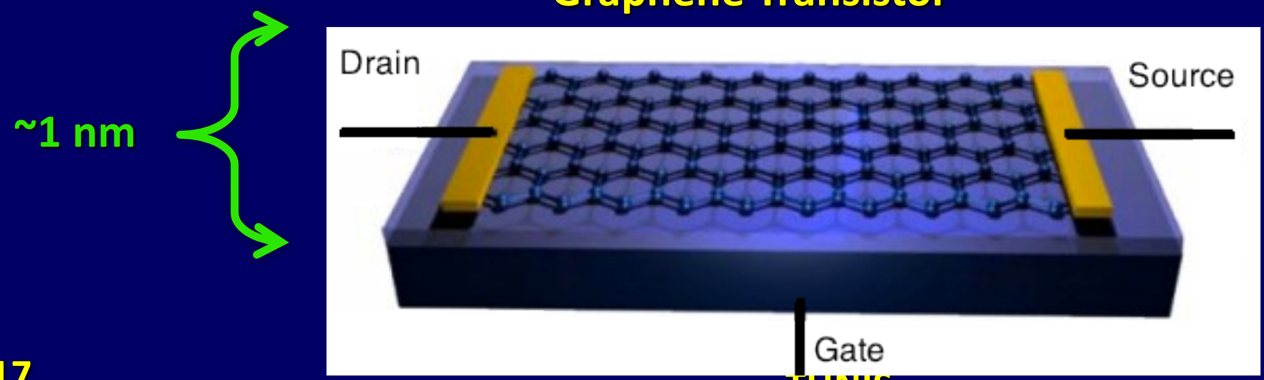


High density array of nanowires used in piezoelectric nano-generators

NANO-PROCESSOR

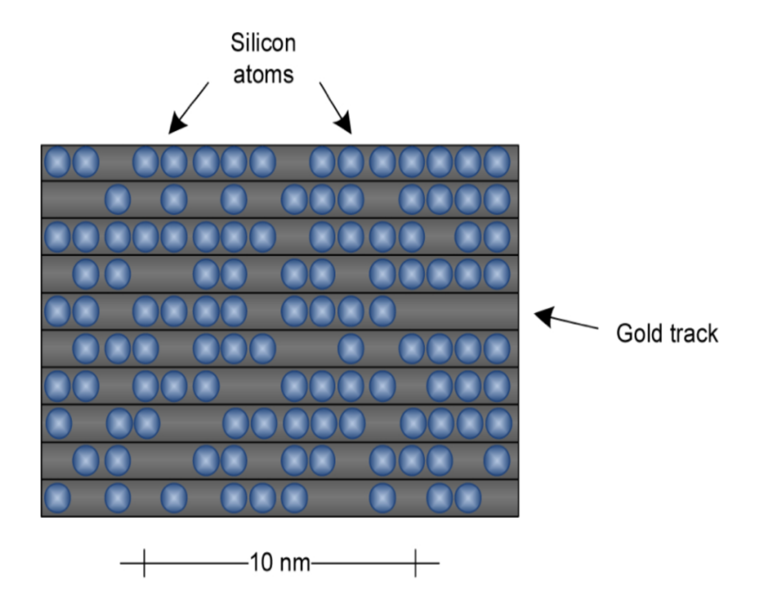
- 32 nm or 20 nm transistor technology existing already !
  (e.g., IBM, Qualcomm, Samsung)…
  - World's smallest transistor (2008) is based on a graphene nanoribbon just 1 atom x 10 atoms (1 nm transistor)
  - Operating frequency close to 1 THz
    (compare to few GHz in current silicon transistors)

Graphene Transistor



NANO-MEMORY

- Single atom memories: Store a bit in a single atom
  - Richard Feynman defined them back in 1959!
    - In his example, 5x5x5 atoms were used to store a bit and to avoid inter-atom interference
      - 125 atoms per bit
      - DNA uses 32 atoms per bit
  - Example:
    - Gold nano-memories



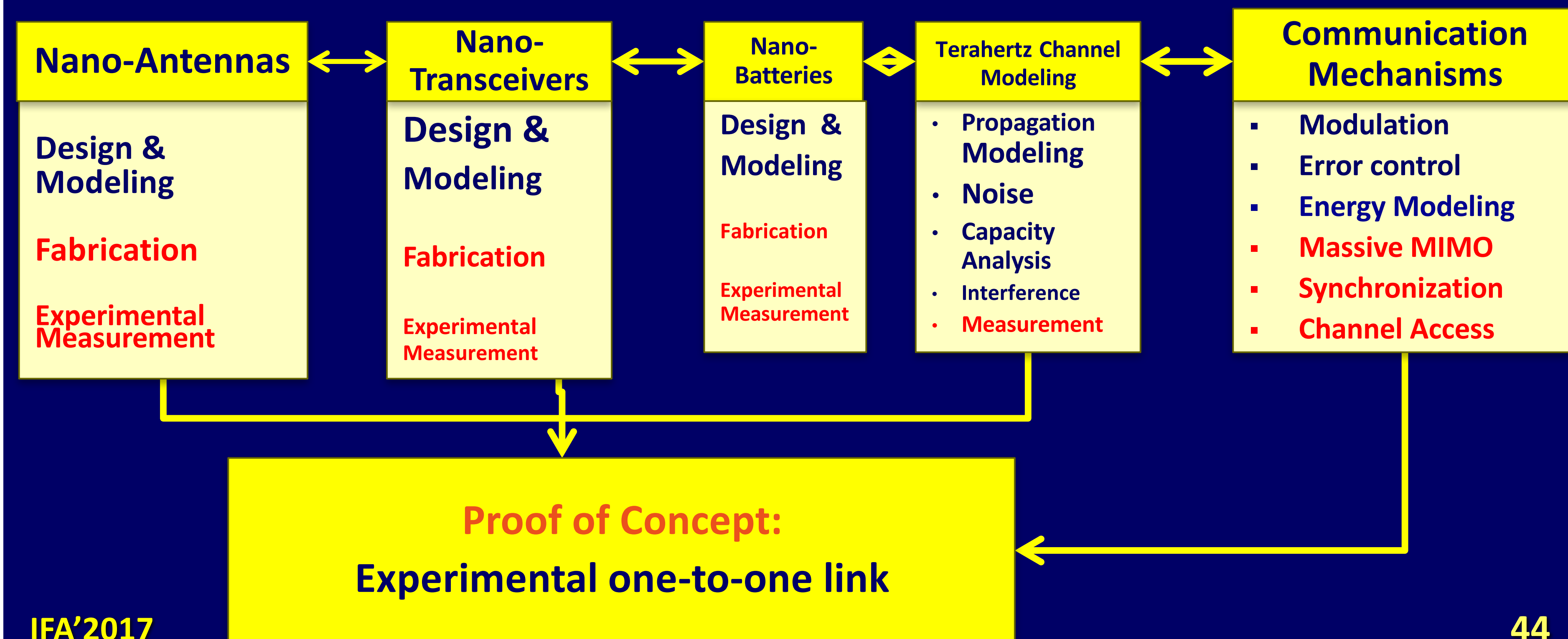
TERANETS (FORMERLY GRANET; 2009-2013):

GRAPHENE BASED NANO SCALE COMMUNICATION NETWORKS IN THZ BAND

NSF; 2013-2016; 2016-2019

Objectives:

* To prove the feasibility of graphene-enabled EM communication
* To establish the theoretical foundations for EM nanonetworks

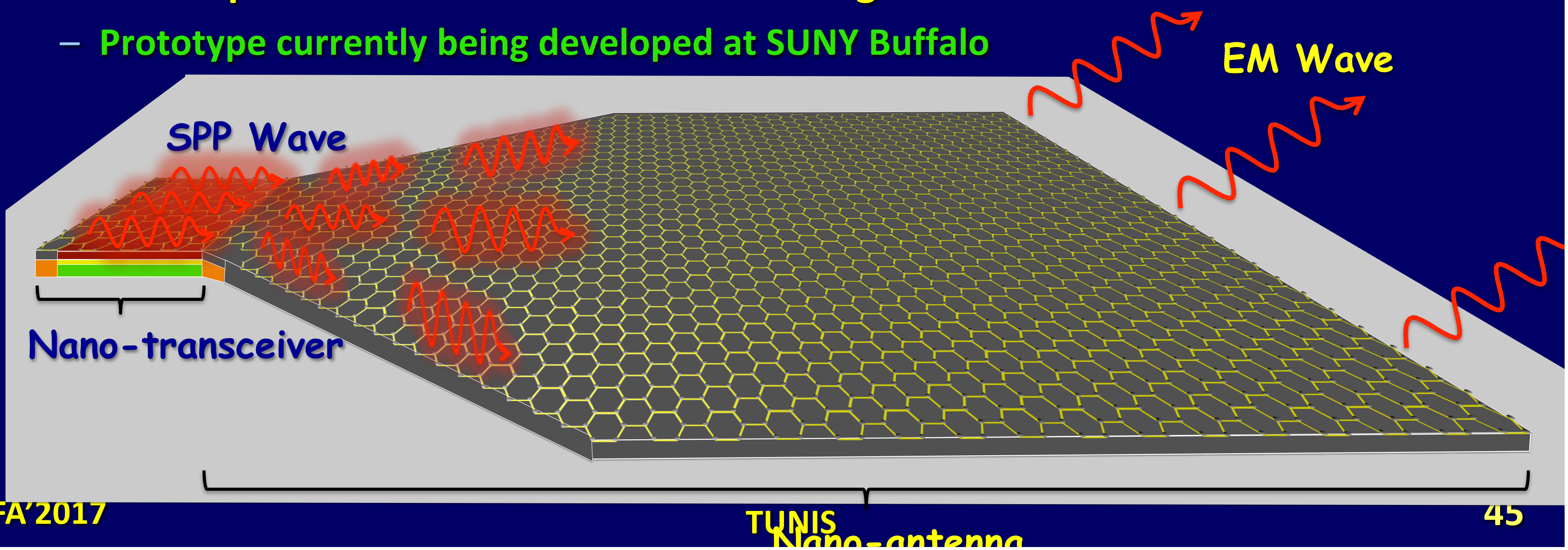


TERAHERTZ BAND PLASMONIC FRONT-END

J. M. Jornet and I. F. Akyildiz,
"Graphene-based Plasmonic Nano-antennas for THz Band Communication in Nanonetworks,"
IEEE JSAC, Dec. 2013. Patent, March 2013 applied; March 2017 granted.

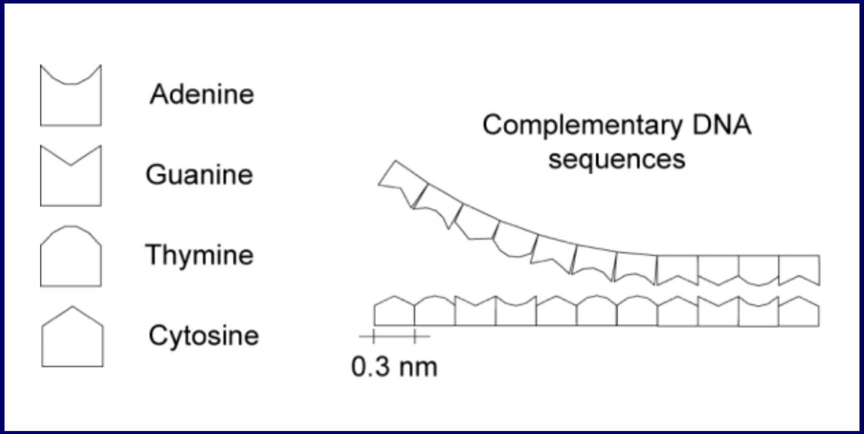
I. F. Akyildiz and J. M. Jornet,
"Graphene-based Plasmonic Nano-transceiver for Wireless Communication in the THz Band,"
Patent, Dec. 2013 applied; July 2016 granted

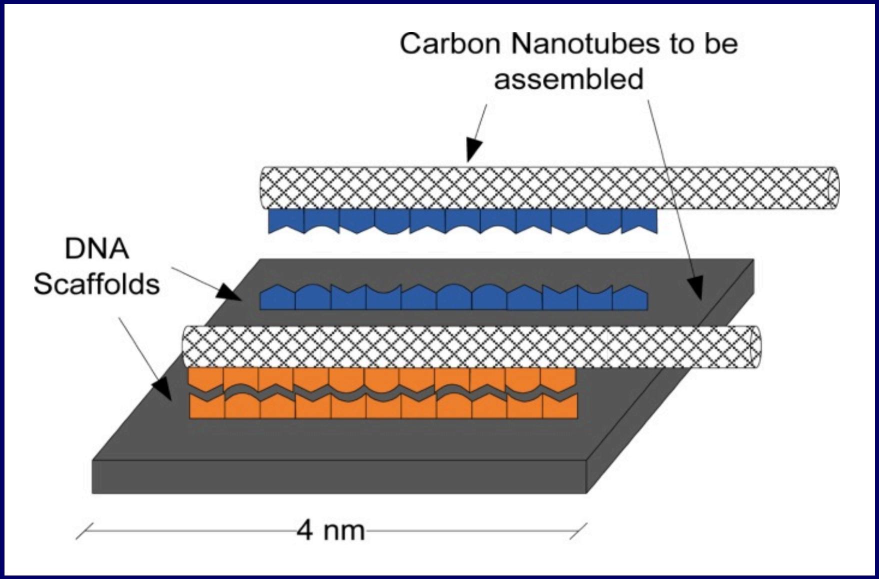
- First fully-integrated THz Band front-end
- Most compact transceiver + antenna existing to date!!!
  - Prototype currently being developed at SUNY Buffalo



INTEGRATION OF NANO-COMPONENTS

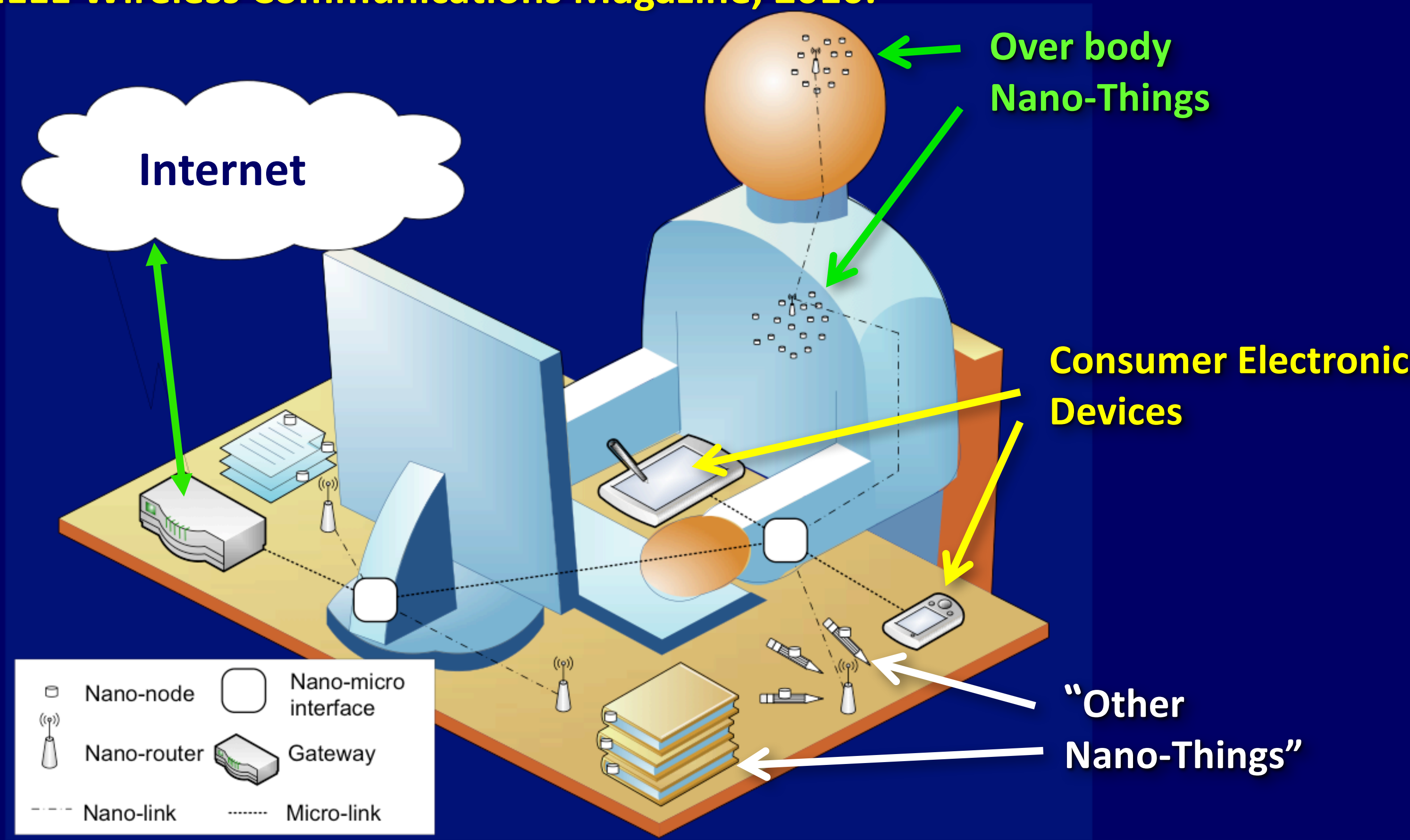
Research Challenge!!! → DNA Scaffolding





INTERNET OF NANOTHINGS

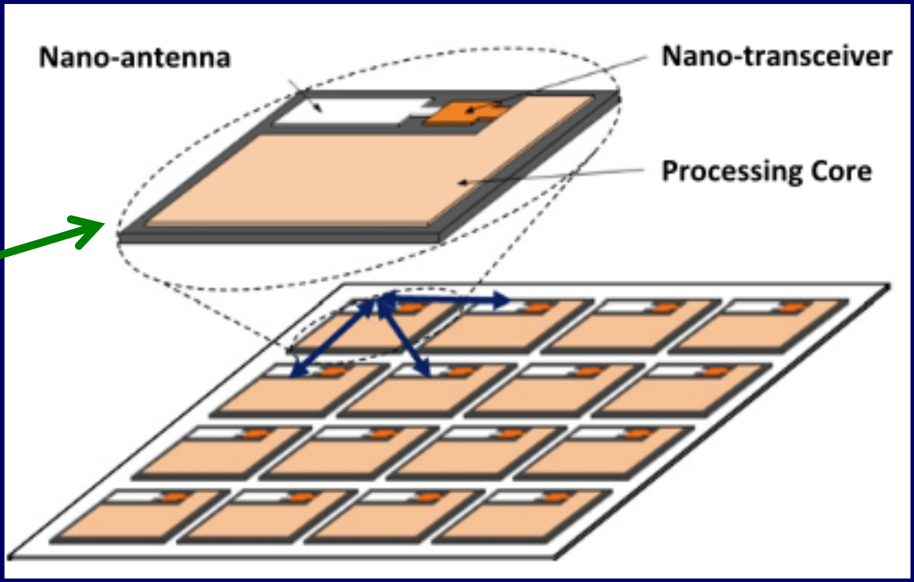
I. F. Akyildiz and J. M. Jornet, "The Internet of Nano-Things," IEEE Wireless Communications Magazine, 2010.



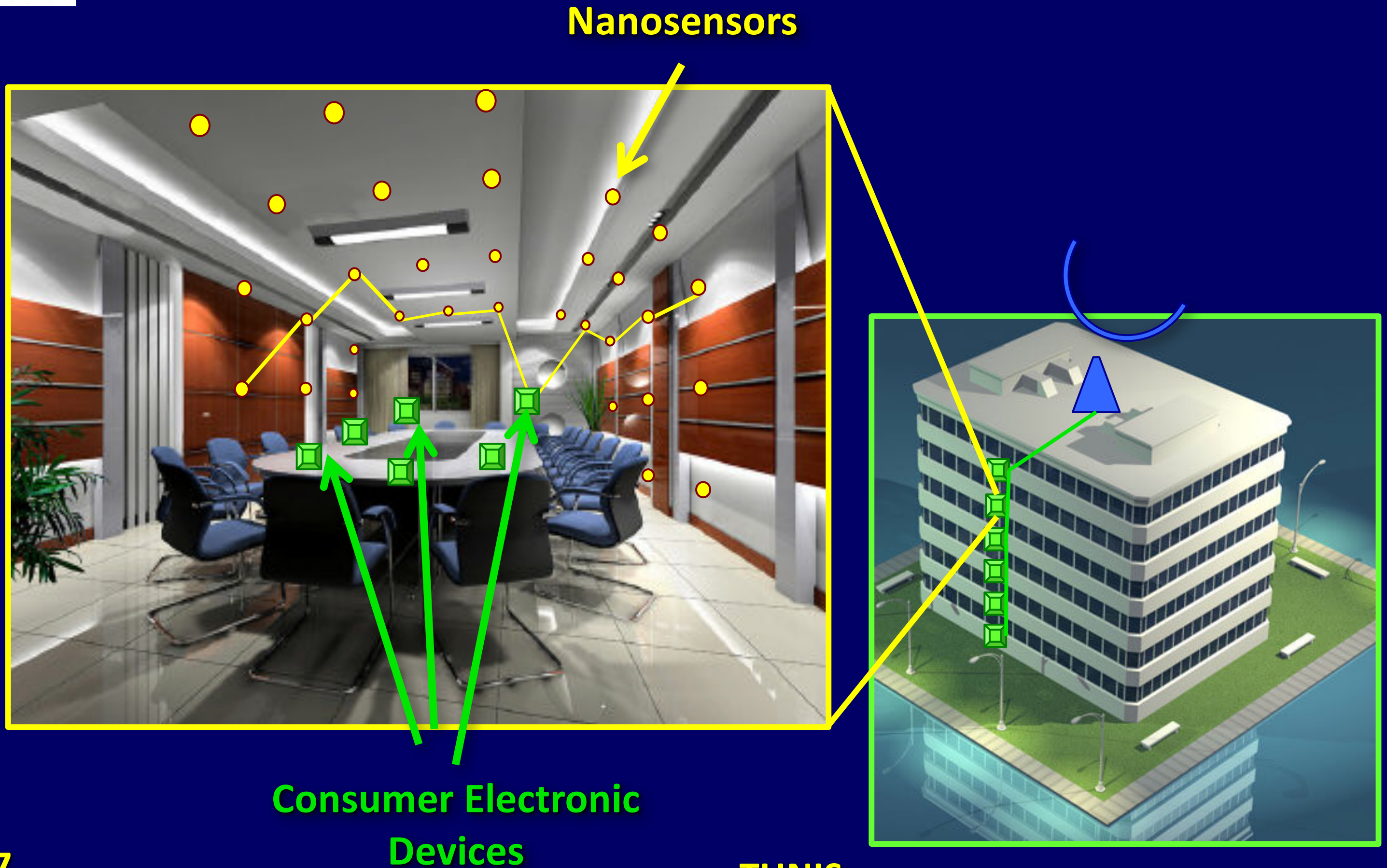
APPLICATION: WIRELESS ON-CHIP COMMUNICATION

S. Abadal, E. Alarcon, A. Cabellos-Aparicio, M. C. Lemme, M. Nemirovsky, "Graphene-Enabled Wireless Communication for Massive Multicore Architectures", IEEE Communications Magazine, 2013

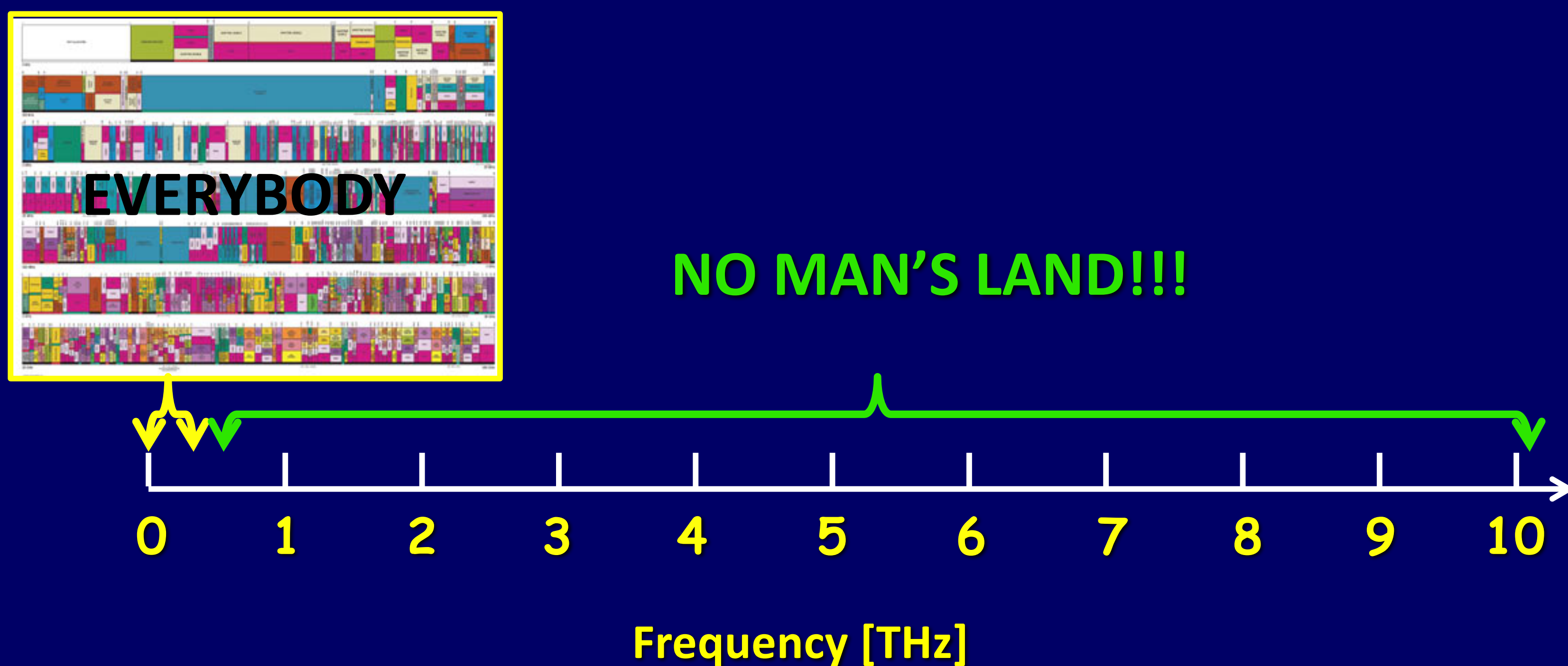
Wireless on-chip networks by using planar nano-antennas to create ultra-high-speed links



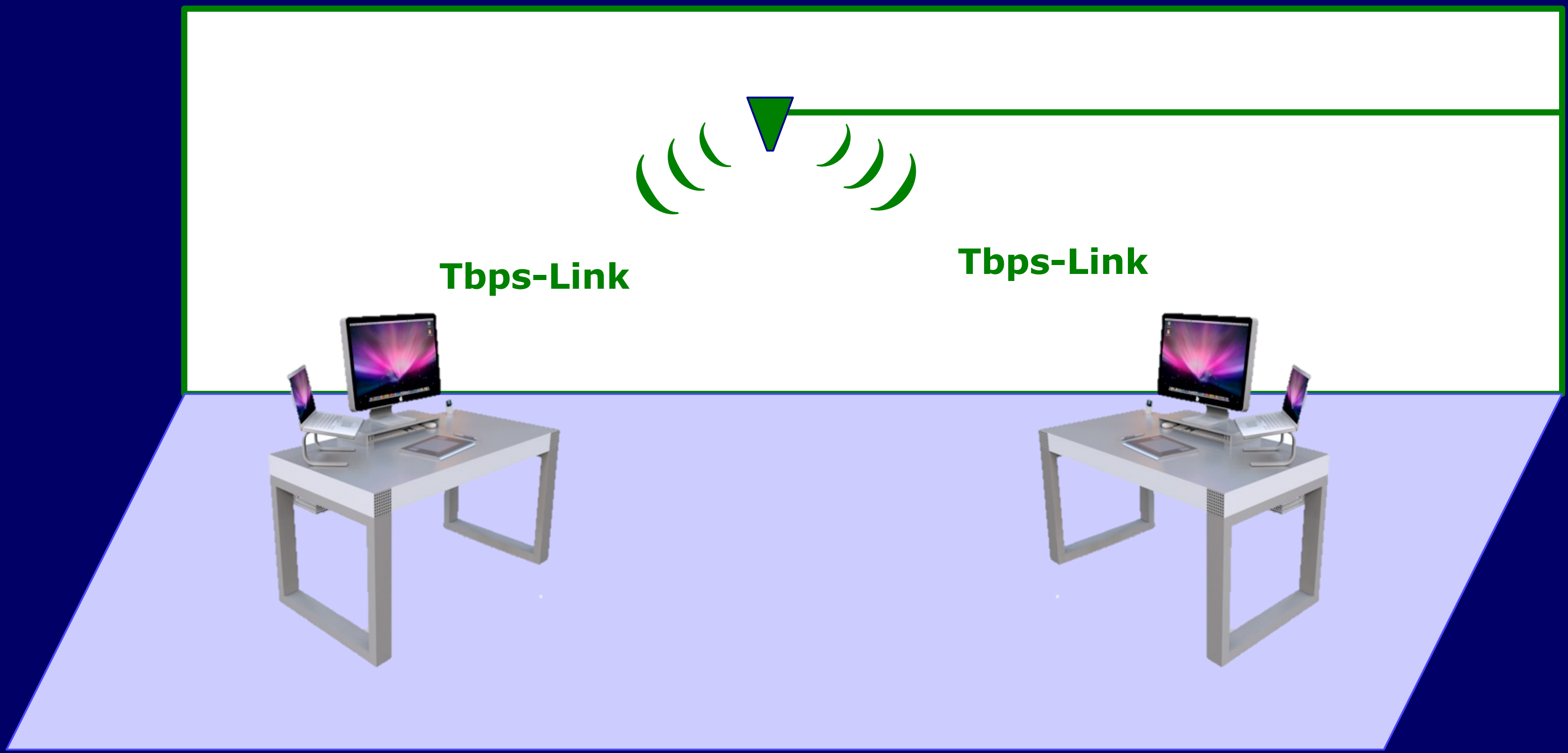
APPLICATION:
CHEMICAL/BIOLOGICAL ATTACK PREVENTION



TERAHERTZ BAND



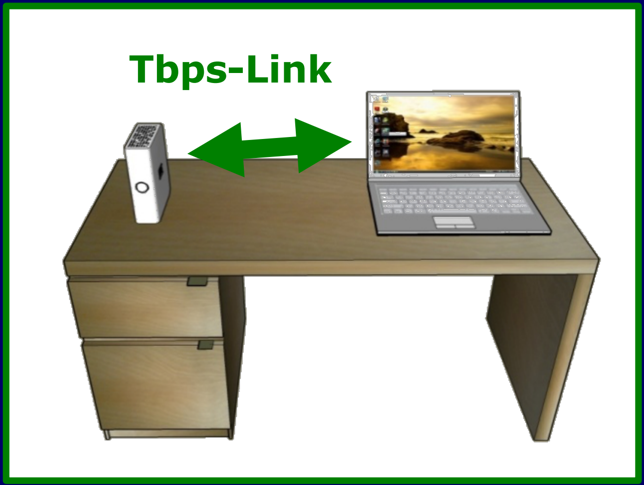
APPLICATION:
WIRELESS ULTRA HIGH SPEED INDOOR NETWORKS



APPLICATION:
WIRELESS HIGH-VOLUME STORAGE TRANSFERS

– Instantaneous transfer of high-volume storage data between consumer devices

– Multimedia kiosks



TERANETS (FORMERLY GRANET; 2009-2013):

GRAPHENE BASED NANO SCALE COMMUNICATION NETWORKS IN THZ BAND

NSF; 2013-2016; 2016-2019

Objectives:

* To prove the feasibility of graphene-enabled EM communication
* To establish the theoretical foundations for EM nanonetworks

Nano-Antennas

Design & Modeling

Fabrication

Experimental Measurement

Nano-Transceivers

Design & Modeling

Fabrication

Experimental Measurement

Nano-Batteries

Design & Modeling

Fabrication

Experimental Measurement

Terahertz Channel Modeling

- Propagation Modeling
- Noise
- Capacity Analysis
- Interference
- Measurement

Communication Mechanisms

- Modulation
- Error control
- Energy Modeling
- Massive MIMO
- Synchronization
- Channel Access

Proof of Concept:

Experimental one-to-one link

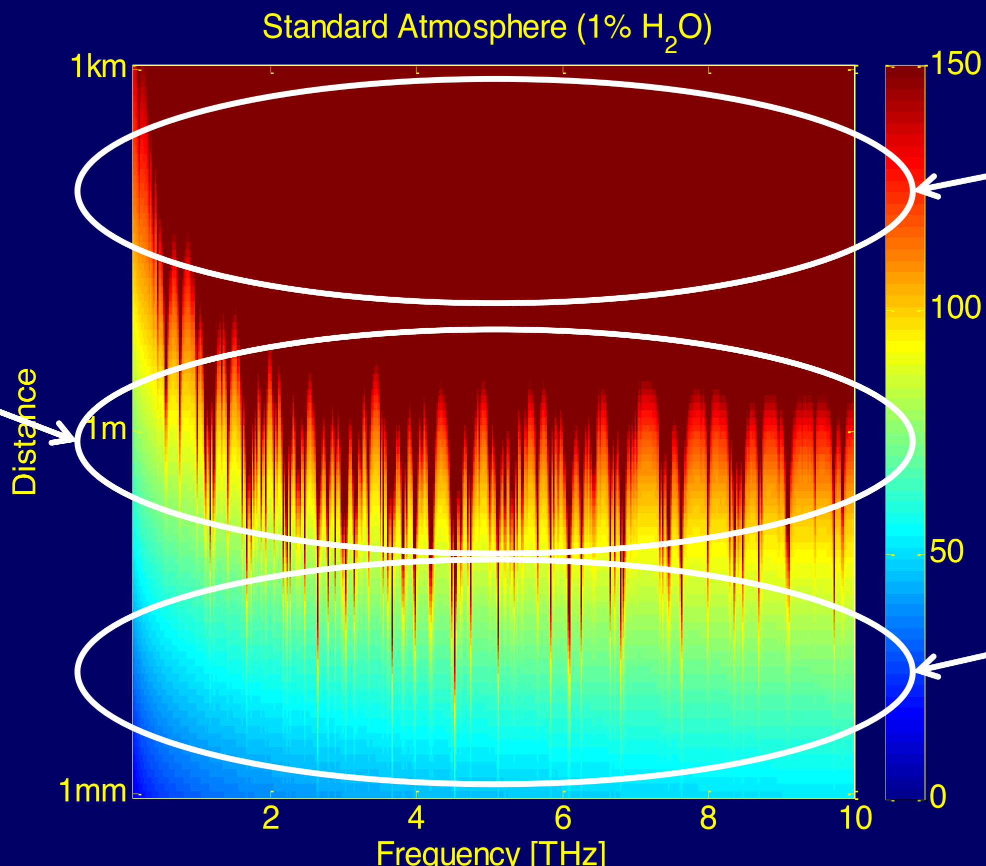
TERAHERTZ CHANNEL

J.M. Jornet and I.F. Akyildiz,
"Channel Modeling and Capacity Analysis of EM Wireless Nanonetworks in the THz Band",
IEEE Trans. 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 (0.1-10 THz) band 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



For the middle range, there are several windows TENS OF GIGAHERTZS WIDE.
Can we exploit this?

We can certainly not go further

The almost absence of molecules in short distances does simplify everything in the short range

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

NEW MODULATION TECHNIQUE & CAPACITY ANALYSIS

J.M. Jornet and I.F. Akyildiz,
"Femtosecond-long Pulse-based Modulation for THz Band Communication in Nanonetworks"
IEEE Tr. on Communications, May 2014.
Shorter form in Proc.of IEEE SECON, June 2011.

- A new modulation scheme based on the exchange of femtosecond-long pulses spread in time:

TS-OOK (Time Spread On/Off Keying Mechanism)

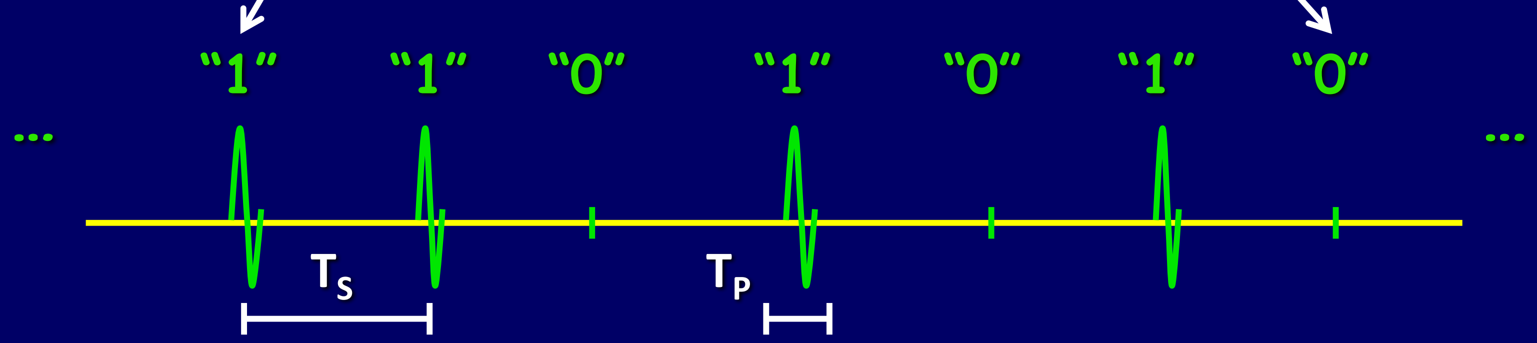
TIME SPREAD ON-OFF KEYING

A logical “1” is encoded with a pulse:

* Pulse length: T_p= 100 fs
* Pulse energy: < 1 pJ !!!

A logical “0” is encoded with silence:

* Ideally no energy is consumed!!!
* After an initialization preamble, silence is interpreted as 0s



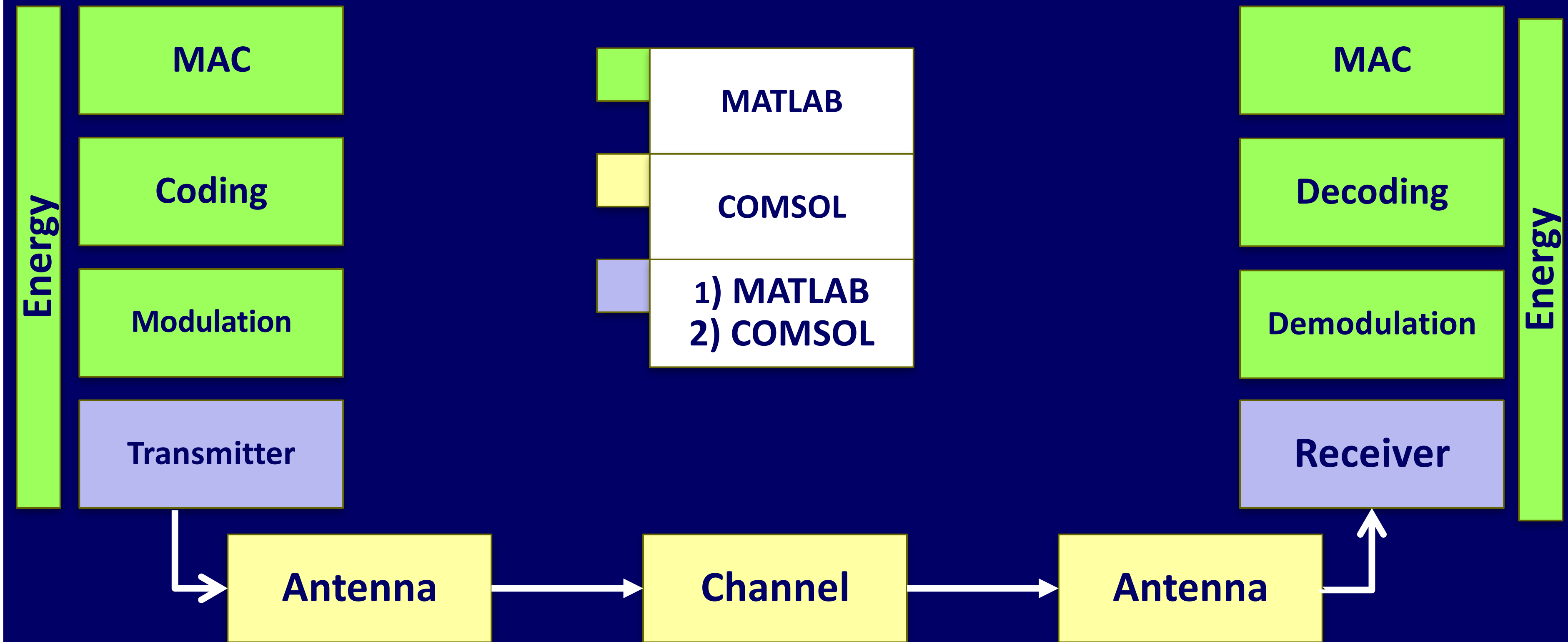
Pulses are spread in time to simplify the transceiver architecture…

WHAT DID WE LEARN?

- **Capacity is maximized when "more 0s than 1s" are transmitted:**
  - **By being silent, absorption noise and interference are reduced**
  - **New coding schemes that exploit this result should be developed!**

VALIDATION:
ONE-TO-ONE LINK EMULATION

- Emulation platform to validate the proposed solutions:



ULTRA MASSIVE MIMO ENABLED BY PLASMONIC ANTENNA ARRAYS

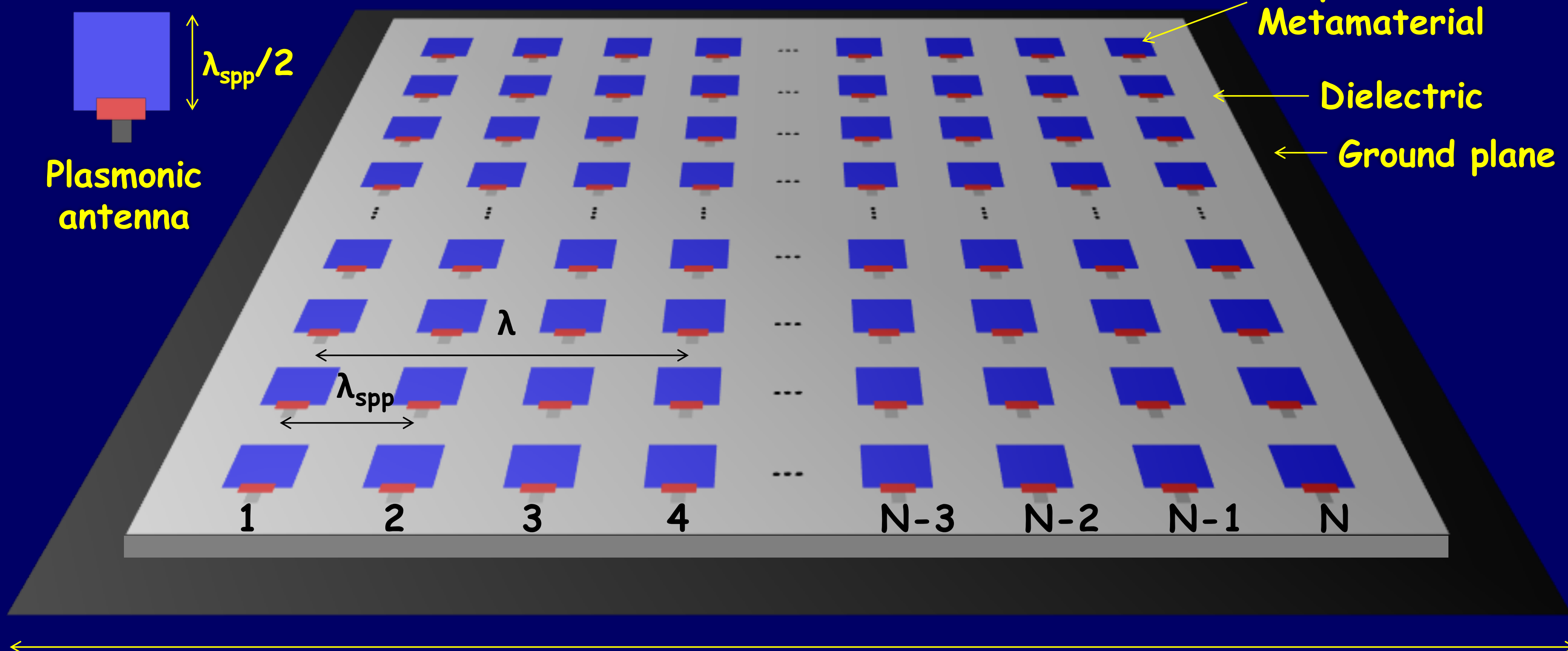
I. F. Akyildiz and J. M. Jornet,
"Realizing Ultra-Massive MIMO (1024 by 1024) Communication in the Terahertz Band (0.06-10 THz),"
Nano Communication Networks (Elsevier) Journal, March 2016.
Patent applied in March 2016.

Combatting the transmission distance problem:

Very large antenna arrays with thousands of elements (1024) in a very small foot print (a few millimeters)!!!

- Metamaterials for 0.05-1 THz
- Graphene for 1-10 THz (and above)

PLASMONIC ANTENNA ARRAY



FURTHER RESEARCH CHALLENGES

- Addressing Problem
- Multihop MAC Protocol
- Synchronization
- Equalization
- New routing metrics
- Reliable transport protocol (end-to-end QoS requirements)
- Network Association and Service Discovery
- Security
- Authentication
- Data Integrity

STANDARDIZATON

– **THz band is still not regulated**
  IEEE 802.15 (WPAN) Terahertz Interest Group (IG-thz)
  (300 GHz to 3THz)
  http://www.ieee802.org/15/pub/IGthz.html

- **A New IEEE Standardization Group created for 100Gbps in 2014.**

Internet of Bio-NanoThings

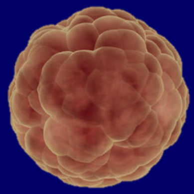
I.F. AKYILDIZ, M. PIEROBON, S. BALASUBRAMANIAM, Y. KOUCHERYAVY,

"THE INTERNET OF BIO-NANOTHINGS",

IEEE COMMUNICATIONS MAGAZINE, MARCH 2015.

INTERNET OF BIO-NANOTHINGS

- Cells are nanoscale-precise biological machines

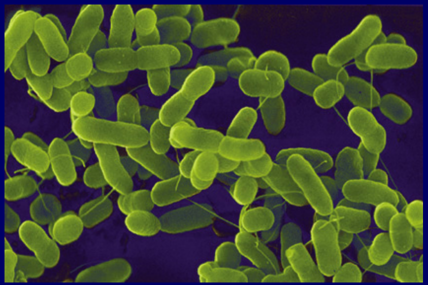


Eukaryotic Cell

Prokaryotic Cell

- They communicate and interact/cooperate

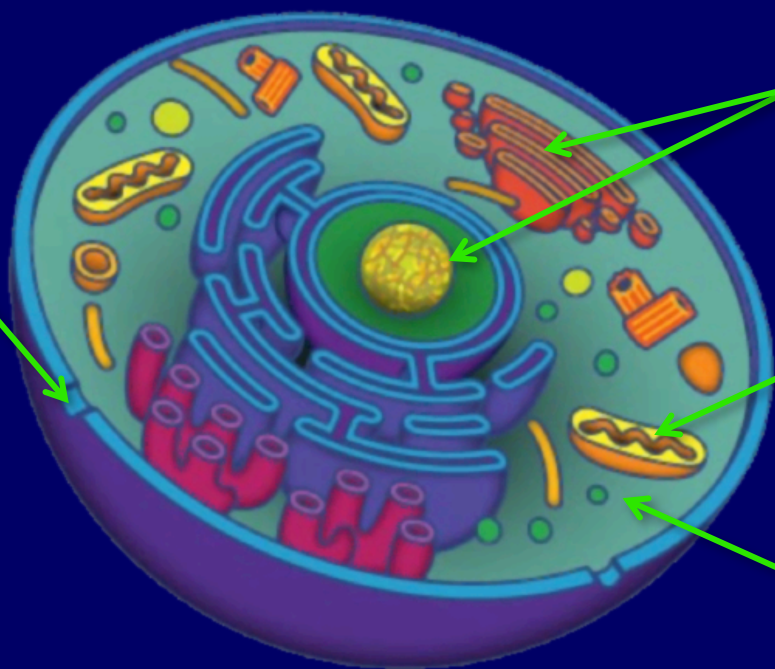
Eukaryotic Cell Tissue



Bacteria Population

CELLS AS BIOLOGICAL NANOMACHINES

Gap Junctions
= Molecular
Transmitters

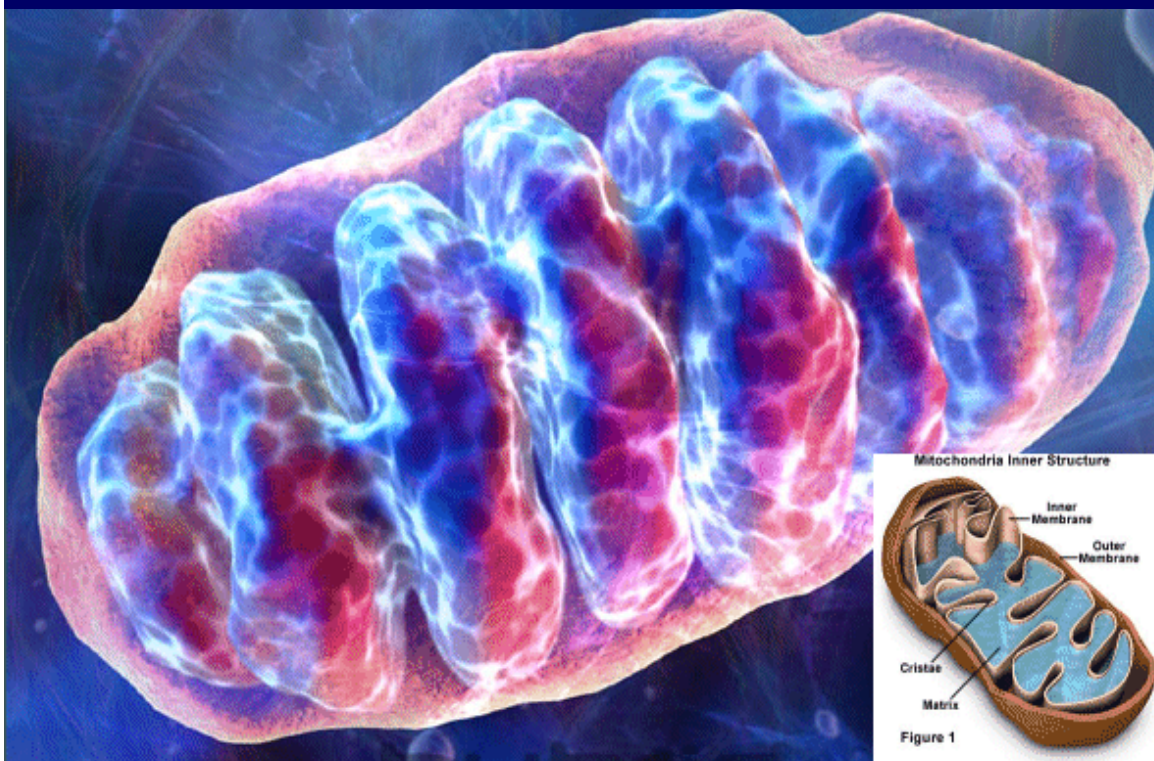


Nucleus and Ribosomes
= Biological Memory
and Processor

Mitochondria
= Biological Battery

Chemical receptors
= Biological
Sensors/
Molecular Rx

BIOLOGICAL NANOMACHINES:
BIOLOGICAL BATTERY



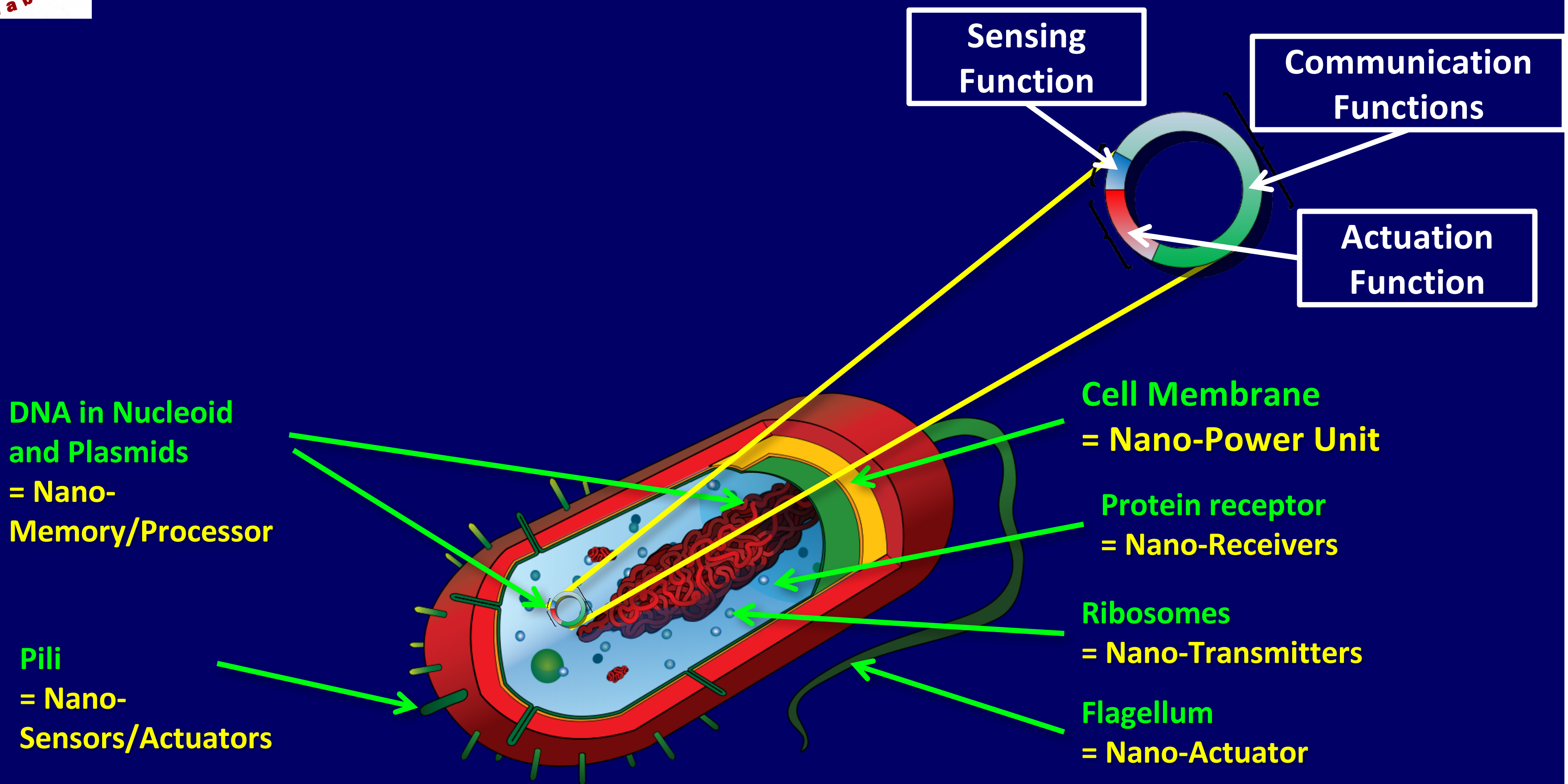
Mitochondria obtain energy by combining:

- Glucose
- Amino Acids
- Fatty Acids
- Oxygen

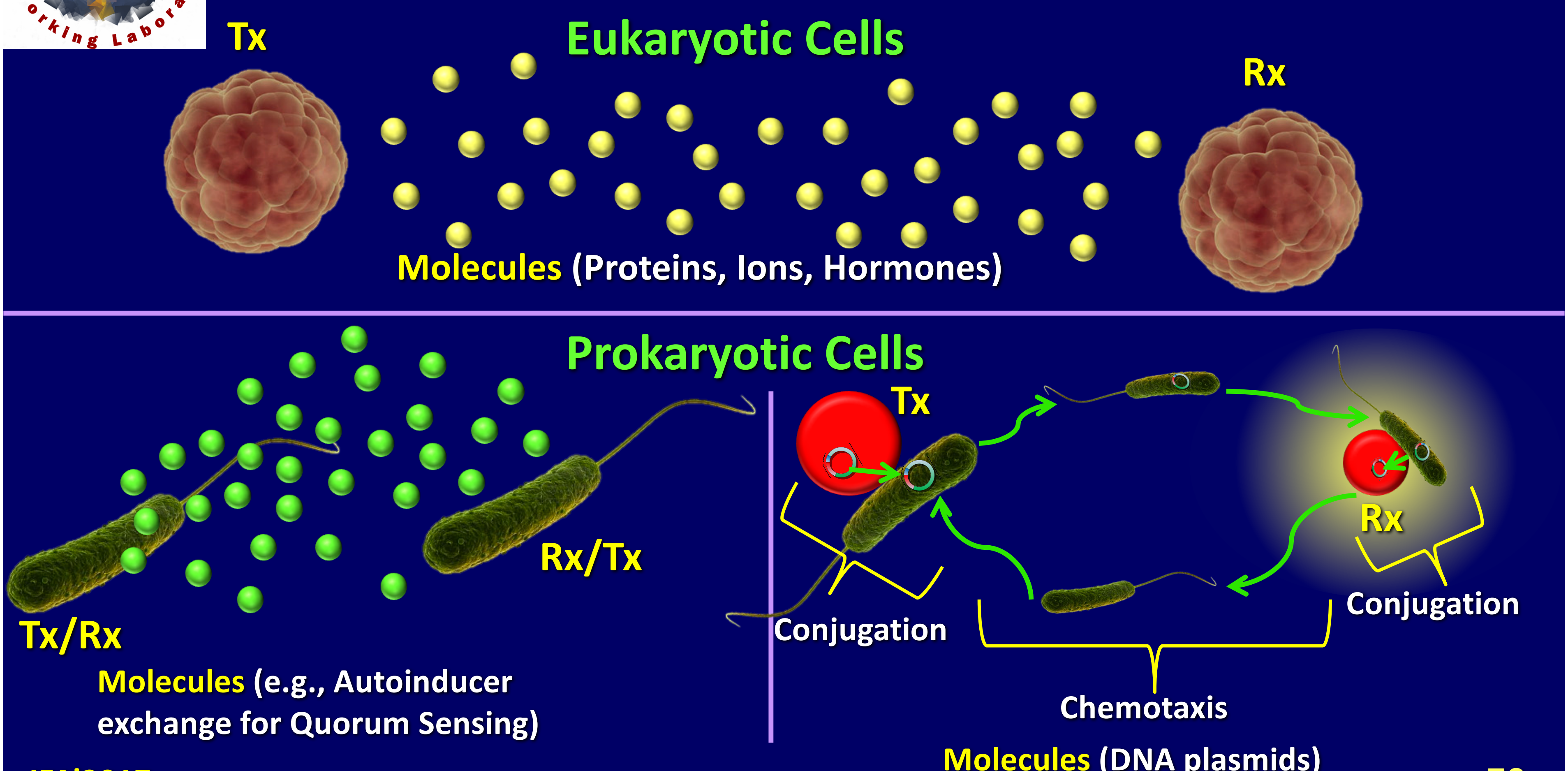
and synthesizing:

→ Adenosine TriPhosphate or ATP

BACTERIA-BASED NANOMACHINES



BIOLOGICAL NANOMACHINES:
COMMUNICATION THROUGH MOLECULES



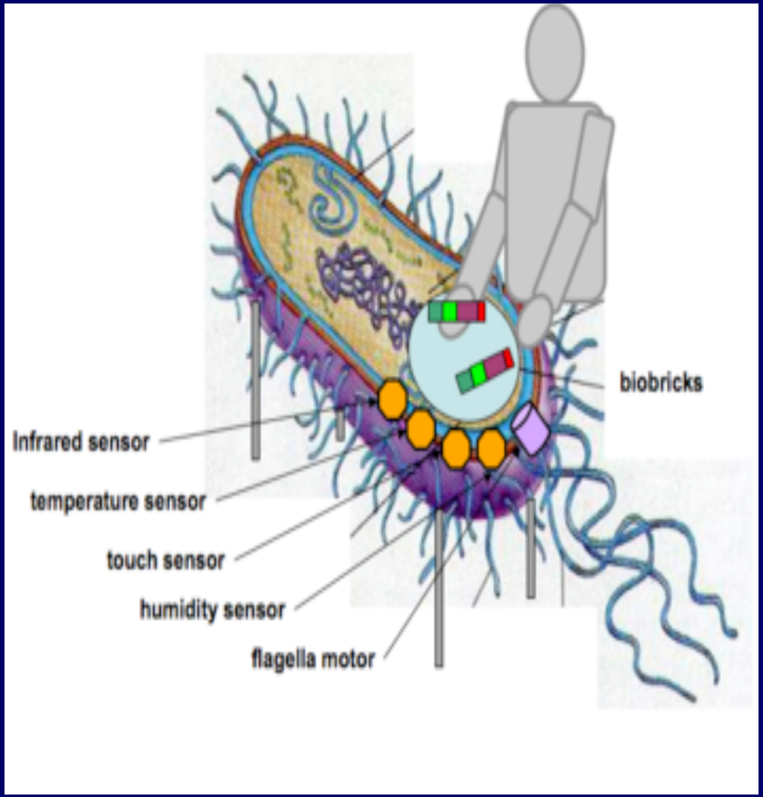
BIOLOGICAL NANOMACHINES

- **Can we create man-made biological nanomachines**
  (Bio-NanoThings)?

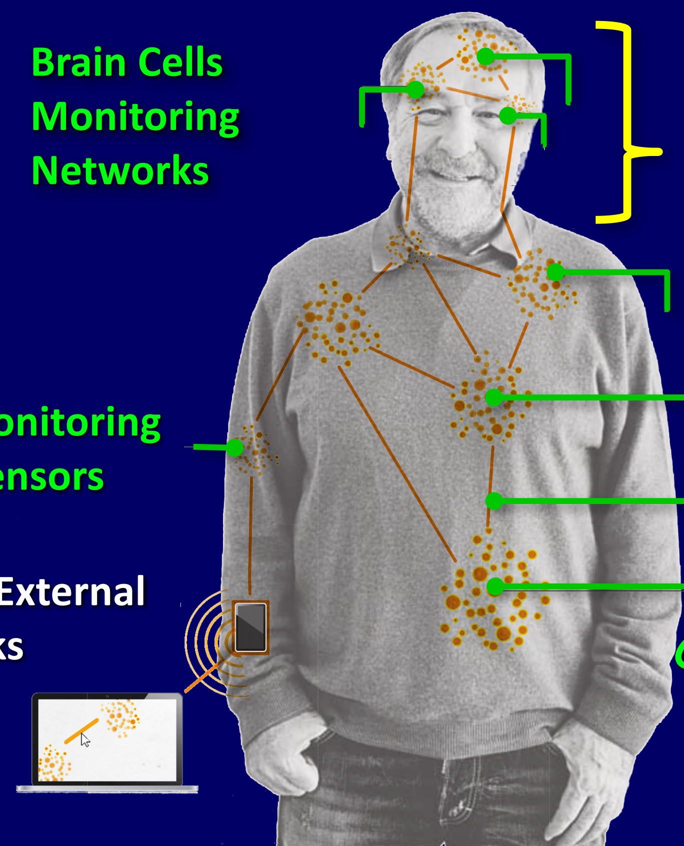
→ YES!!!

Cells can be "reprogrammed" via DNA manipulation

(genetic engineering)

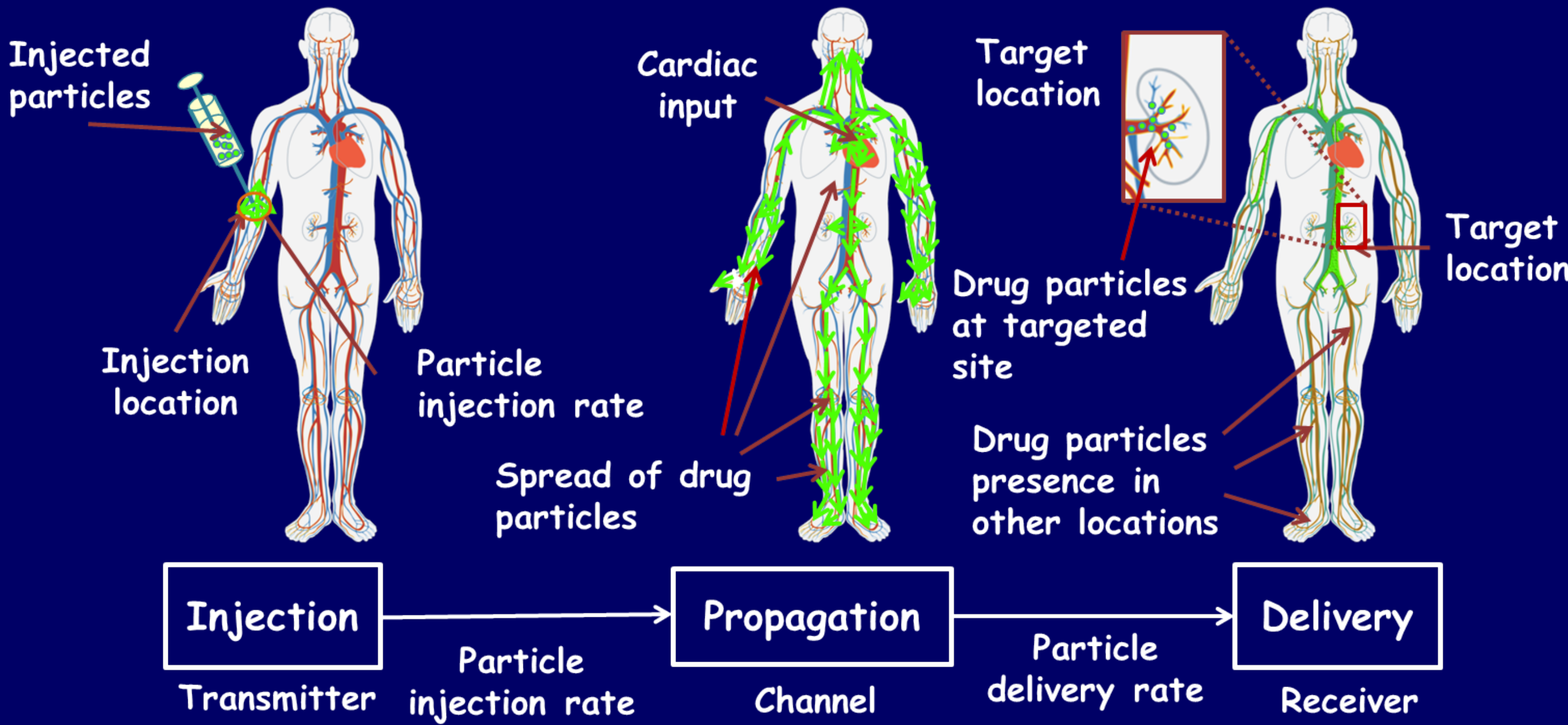


BIO-NANOTHINGS APPLICATIONS:
ADVANCED HEALTH SYSTEMS



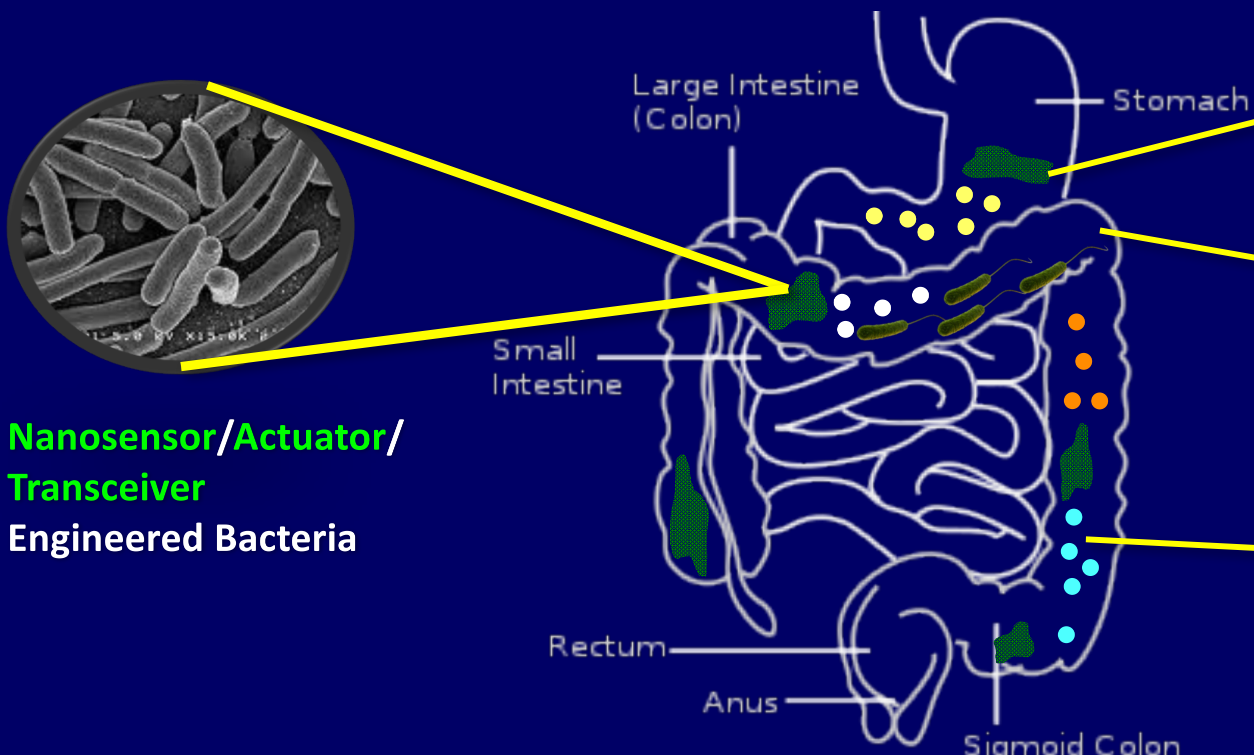
TARGETED DRUG DELIVERY

Y. Chahibi, M. Pierobon, S. O. Song, and I. F. Akyildiz
"Molecular Communication Modeling of a Particulate Drug Delivery System"
IEEE Tr. on Biomedical Engineering, 2013.



BIO-NANOTHINGS:
LONG-TERM APPLICATION

- **Bacteria-based Sensor Network in the Gastrointestinal Tract**



Nanosensor/Actuator/ Transceiver
Engineered Bacteria

Bacteria Population

Bacteria Motion by Chemotaxis

Propagation of Molecular Signal

MOLECULAR COMMUNICATION

- **Very Short Range (nm)** → Calcium Ions
- **Short Range (nm to µm)** → Molecular Motors
- **Medium Range (µm to mm)** → Bacteria (Chemotaxis)
- **Long Range (mm to m)** → Pheremones and Hormones

NOBEL PRIZE IN CHEMISTRY 2016

Jean-Pierre Sauvage
University of Strasbourg
France

Sir J. Fraser Stoddart
Northwestern University
USA

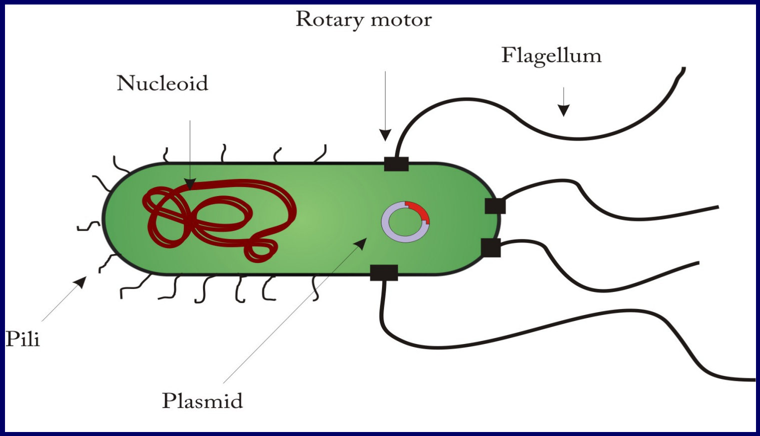
Bernard L. Feringa
University of Groningen
The Netherlands

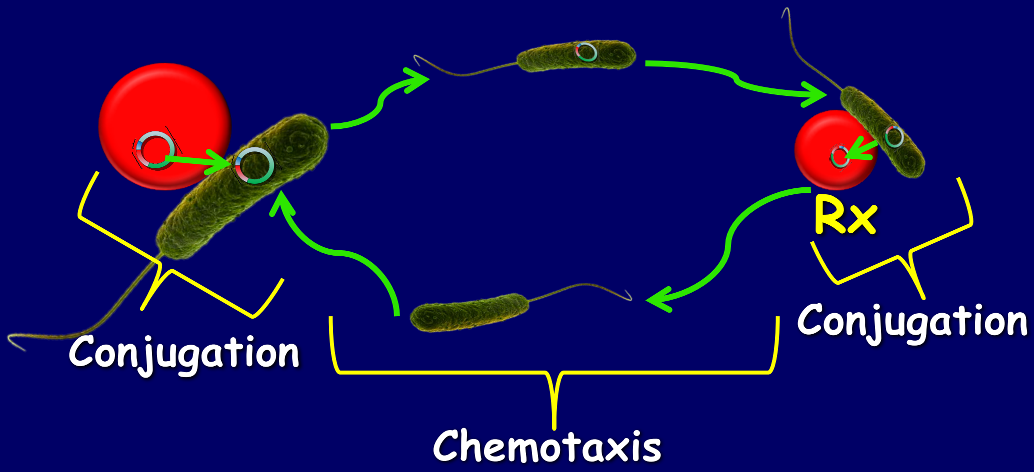
"for the design and synthesis of molecular motors"

MEDIUM RANGE MOLECULAR COMMUNICATION THROUGH BACTERIAL CHEMOTAXIS

M. Gregori and I. F. Akyildiz,

"A New NanoNetwork Architecture using Flagellated Bacteria and Catalytic Nanomotors",
IEEE JSAC (Journal of Selected Areas in Communications), May 2010.





- Bacteria are microorganisms composed only by one prokaryotic cell
- Flagellum allows them to convert chemical energy into motion
- 4 and 10 flagella (moved by rotary motors, fuelled by chemical compounds)
- Approximately 2 µm long and 1 µm in diameter.

MEDIUM RANGE MOLECULAR COMMUNICATION THROUGH BACTERIAL CHEMOTAXIS

TX inserts the information (plasmid) in the bacterium (conjugation)

Bacterium moves in a series of runs and tumbles

RX releases chemical attractant to "guide" the bacterium until it obtains the information

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

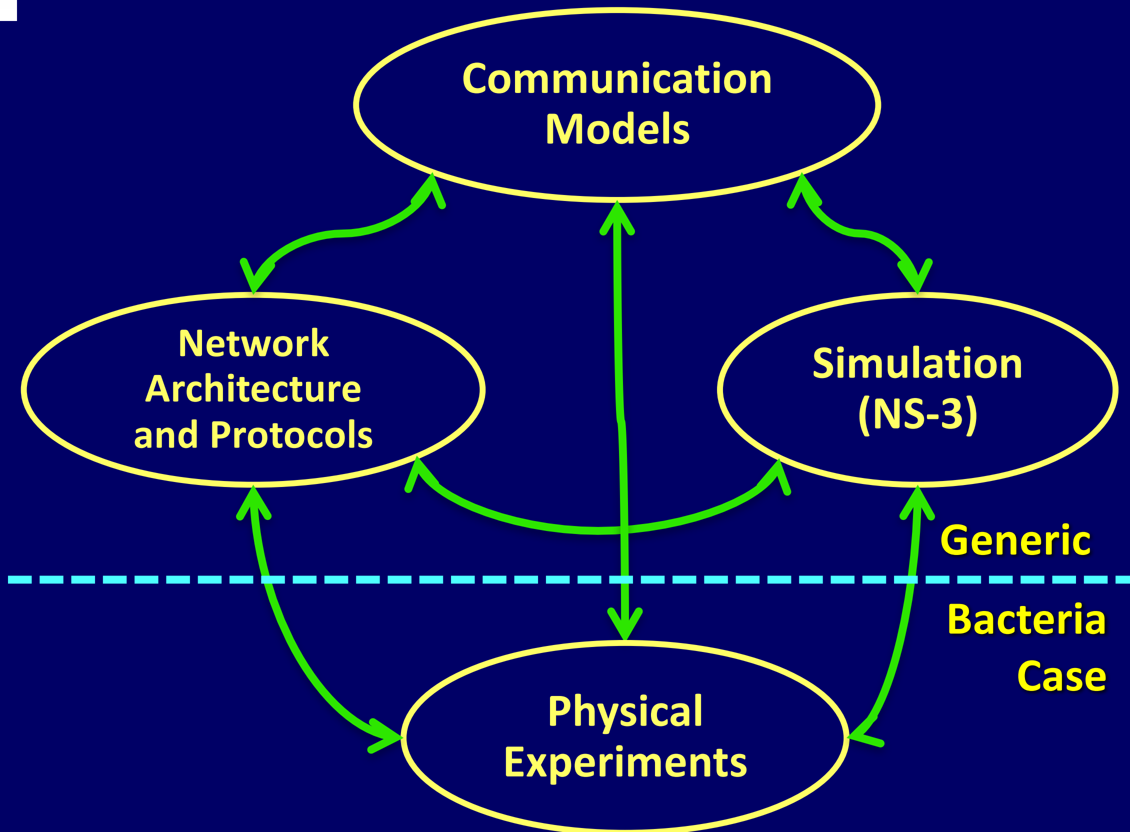
- **NSF Funding:**
  - $3M in 4 years (2012-2016)
  - 5 PIs in wireless communication and networks, biology and microfluidic engineering

- **Project webpage:**

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

MONACO TEAM (2012 AND 2016)

NSF MONACO PROJECT: SPECIFIC OUTCOMES

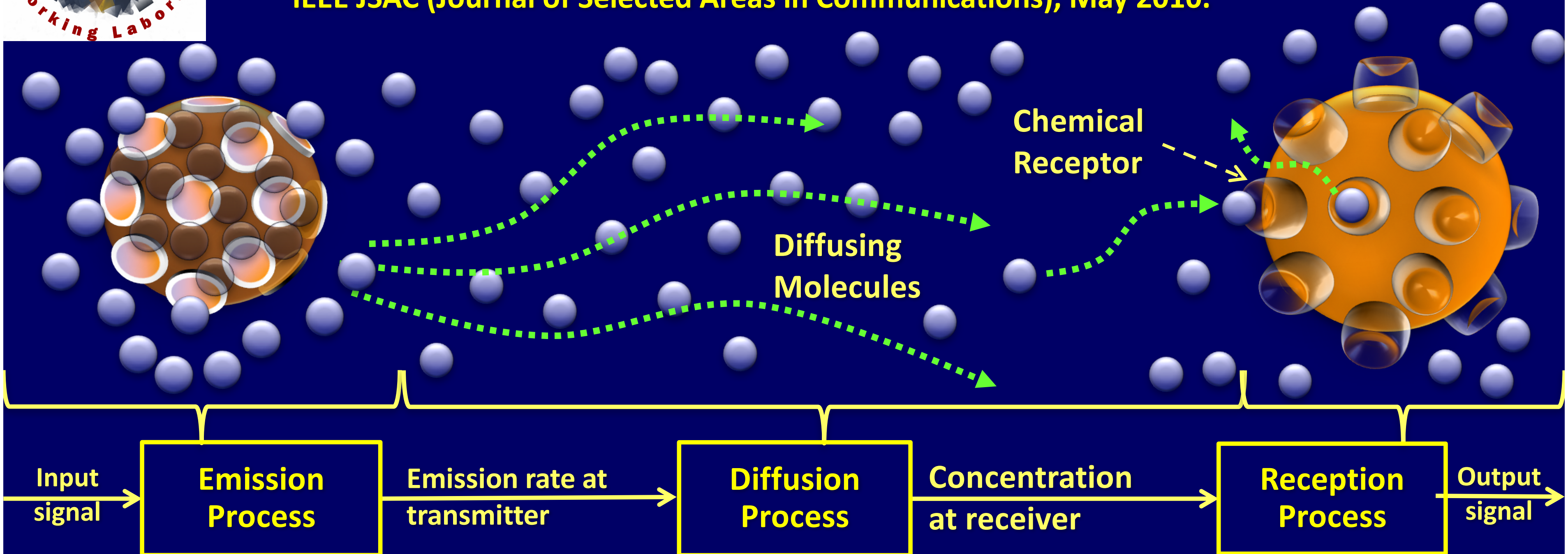


END TO END MODEL (2 NODES)

M. Pierobon, and I. F. Akyildiz,

"A Physical End to End Model for Molecular Communication in Nanonetworks,"

IEEE JSAC (Journal of Selected Areas in Communications), May 2010.

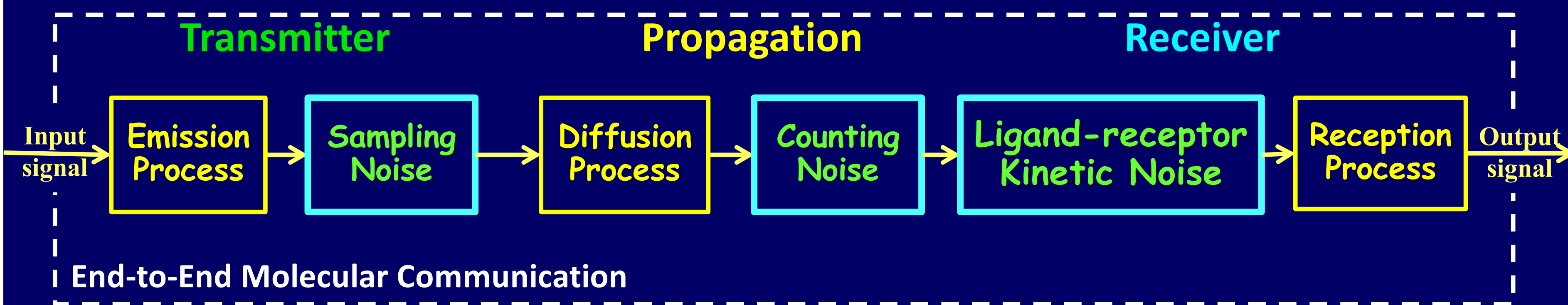


- **Attenuation**
  - As high as 150dB in 50µm distance
- **Delay**
  - In the range of seconds per 50µm

NOISE MODELS

* M. Pierobon, and I. F. Akyildiz,
"Diffusion-based Noise Analysis for Molecular Communication in Nanonetworks,"
IEEE Tr. on Signal Processing, June 2011.

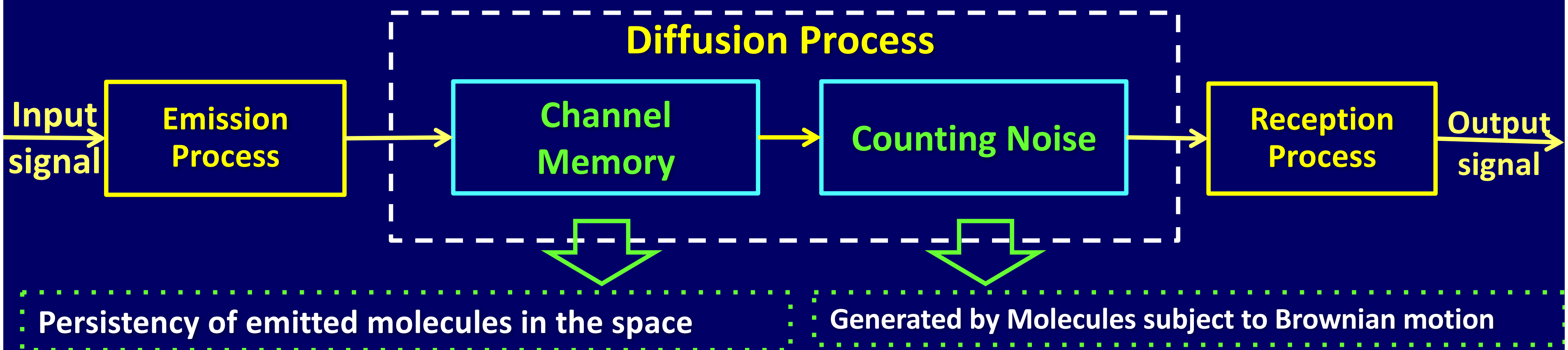
* M. Pierobon, and I. F. Akyildiz,
"Noise Analysis in Ligand-binding Reception for Molecular Communication in Nanonetworks,"
IEEE Tr. on Signal Processing, Sept. 2011.



INFORMATION CAPACITY

M. Pierobon and I. F. Akyildiz,
"Capacity of a Diffusion-based Molecular Communication System with Channel Memory and Molecular Noise,"
IEEE Tr. on Information Theory, Feb. 2013.
(Shorter version appeared in Proc. of IEEE INFOCOM 2011).

- Found analytical closed-form expression of the theoretical maximum achievable rate (capacity) in [bits/sec]
- Focus on the Diffusion Process propagation



INFORMATION CAPACITY

- Theoretical upper bound of the communication performance of a diffusion-based molecular communication

Fick's Diffusion

$$C = \overbrace{2W\left(1+\log_2\frac{2\bar{P}_{\mathcal{H}}}{3WK_bT}\right)-2\log_2(\pi Dd)-\frac{4d}{3\ln 2}\sqrt{\frac{\pi W}{D}}}^{\text{Fick's Diffusion}}+$$

$$\left.\begin{aligned}&-2W\frac{4\bar{P}_{\mathcal{H}}R_{V_R}}{9W^2dK_bT}+2W\ln\left(W\frac{R_{V_R}}{D}\right)+\\&-2W\ln\left(\Gamma\left(\frac{4\bar{P}_{\mathcal{H}}R_{V_R}}{9W^2dK_bT}\right)\right)+\\&-2W\left(1-\frac{4\bar{P}_{\mathcal{H}}R_{V_R}}{9W^2dK_bT}\right)\psi\left(\frac{4\bar{P}_{\mathcal{H}}R_{V_R}}{9W^2dK_bT}\right)\end{aligned}\right\}\text{Molecule Location Displacement}$$

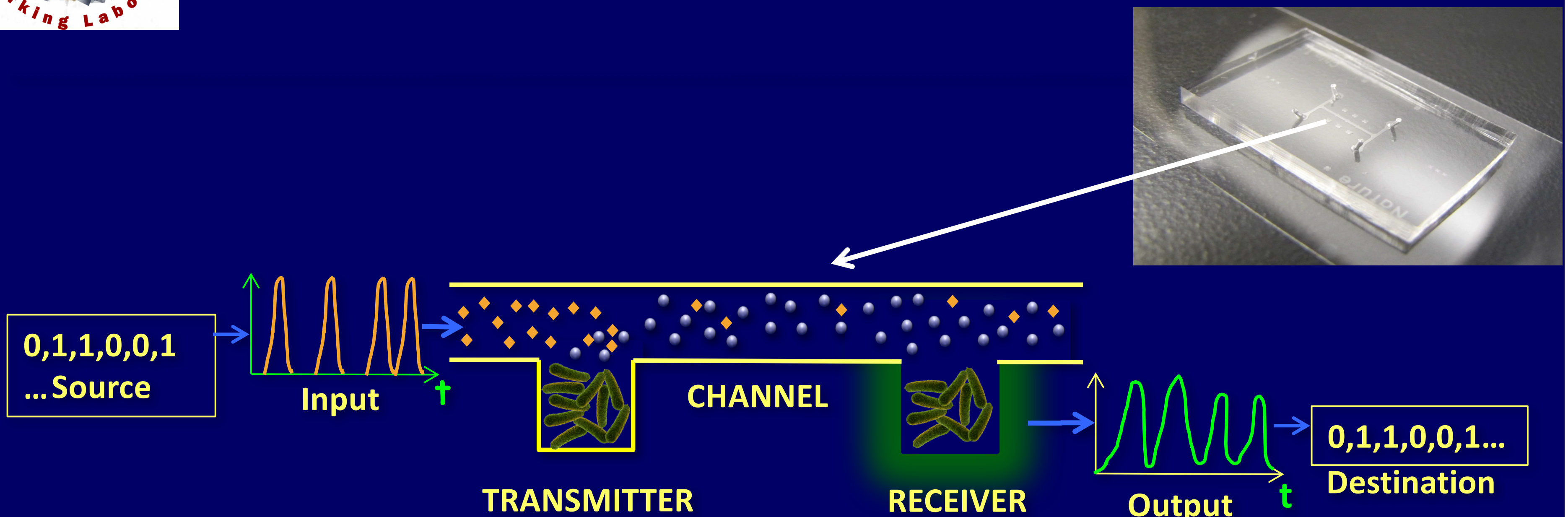
Variables

Diffusivity	D
Temperature	T
Transmission range	d
Bandwidth	W
Transmission power	$\bar{P}_{\mathcal{H}}$
Receiver radius	R_{V_R}

K_B = Boltzmann's constant

$\Gamma(.)$ = Gamma function

VALIDATION PLATFORM



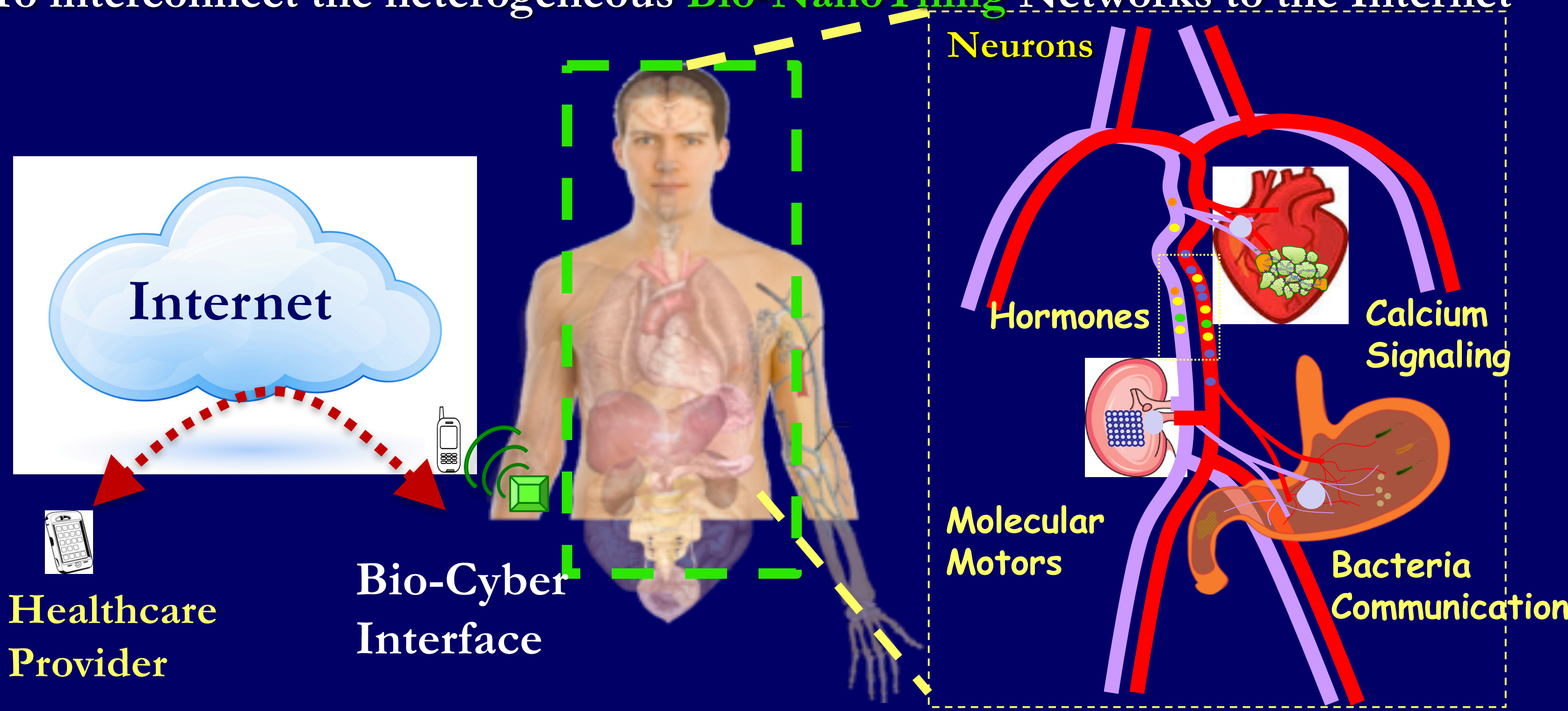
- Analyze the channel and information capacity
- Design information encoding/decoding techniques, and modulation schemes

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-NanoThing Networks to the Internet



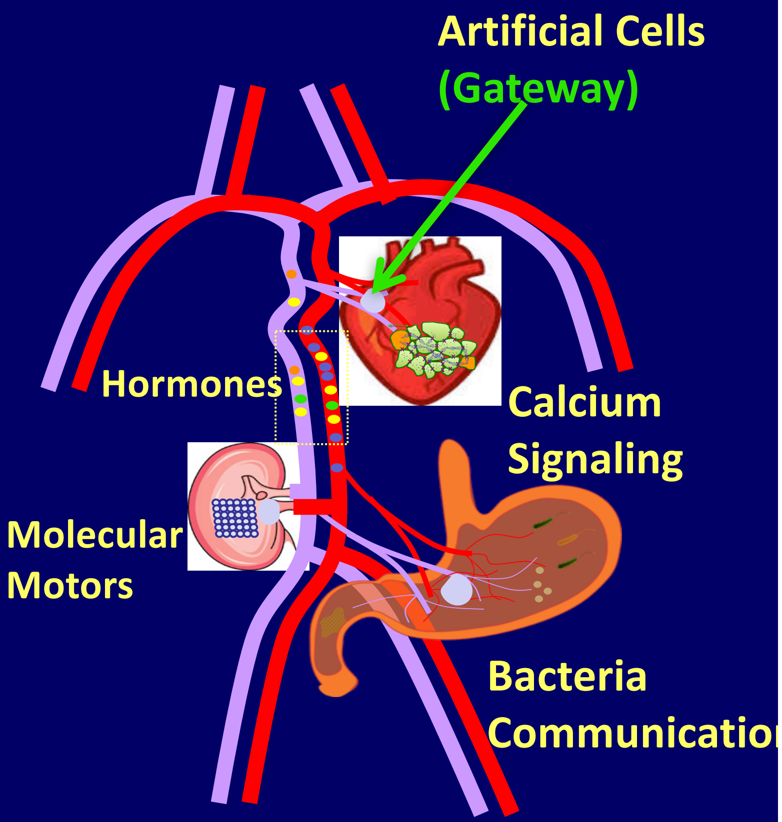
HETEROGENEOUS BIO-NANOTHINGS NETWORK

Challenge

- Translating information between the different Bio-NanoThings networks.

Approach

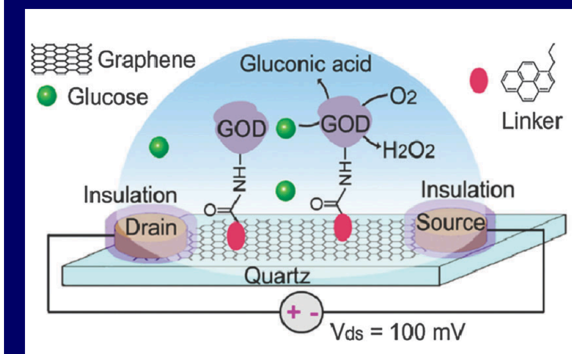
- Design Artificial cells for translating between different molecule types.

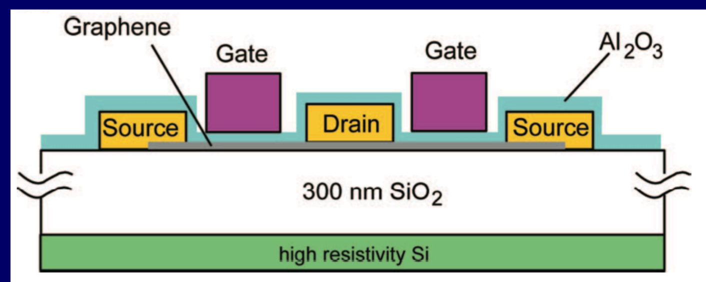


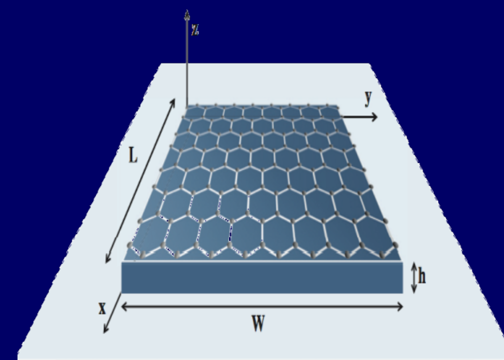
BIO-CYBER INTERFACE:

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





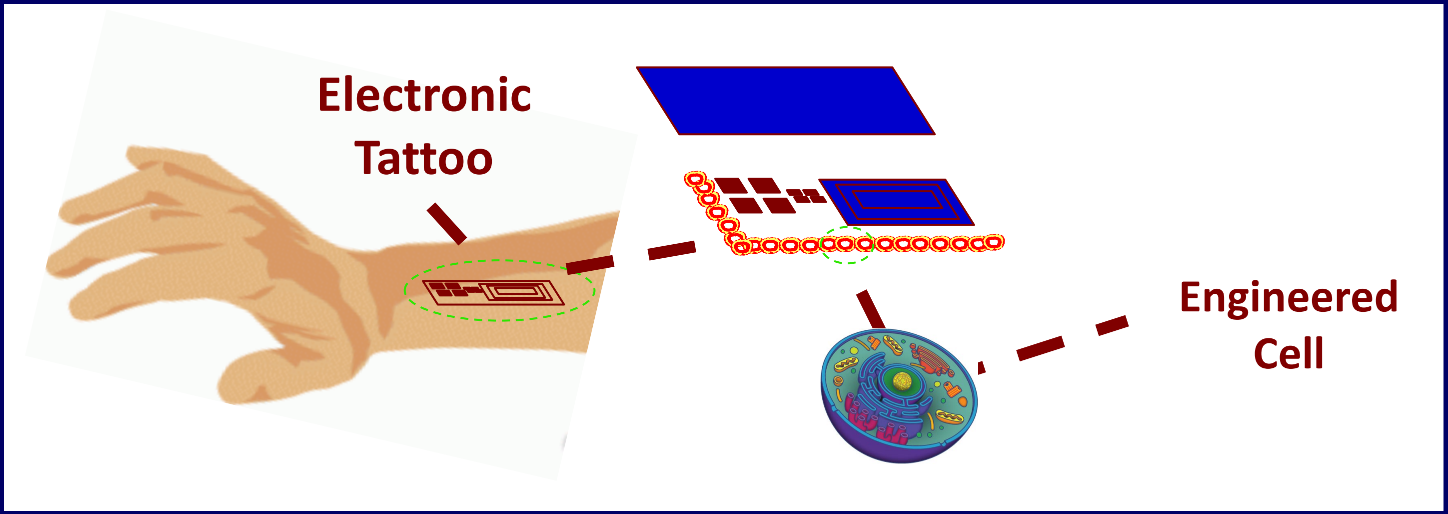


Hormones, calcium ions, etc. → MC Receiver → Processing Unit → EM Antenna → EM Waves

Battery

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 μIoT

*** 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.