Electromagnetic communication in nanonetworks

Eugen Dedu

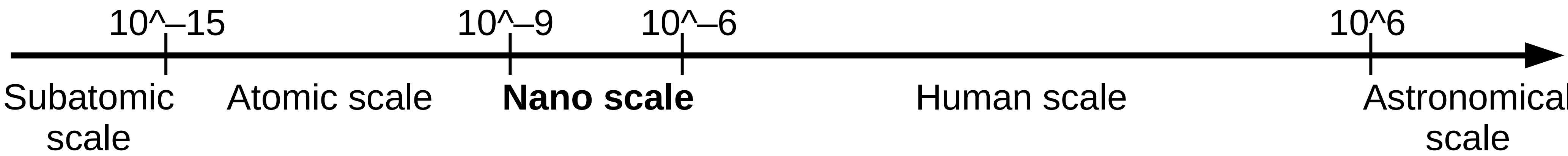
Maître de conférences HDR
UBFC, Univ. of Franche-Comté / Institut FEMTO-ST
Montbéliard, France
eugen.dedu@univ-fcomte.fr

Groupe de travail ARC, GdR MACS
Paris, 16 June 2016
http://eugen.dedu.free.fr/nanonet.pdf

Outline

- Positioning and motivations: nano, nanonetwork, electromagnetic communication, THz band
- Channel model, protocols of physical, MAC, routing and transport layers
- Simulators
- Applications
- Journals, conferences, project calls, key people

Positioning – nano



- Nanothing: whose size is 1..1000 nm (< 1 µm)
  - not to be confounded with "nanocomputer" (whose name comes from smaller than minicomputer, whose fundamental parts are smaller than a few nm), whose size is comparable to a credit card (Arduino, Raspberry Pi etc.)
- Nanothings: (from w nanotechnology)
  - molecular applications: typical carbon-carbon bond lengths (spacing between these atoms in a molecule) 0.12–0.15 nm
  - biological applications: DNA double helix 2 nm, smallest cellular life-form 200 nm in length
  - electrical circuit applications: 22 nm technology currently for µP

Positioning – nanoscience, nanotechnology

- Nanoscience : study of phenomena at nanoscale, where materials can show different properties compared to macroscale (from w nanotechnology):
  - opaque substances can become transparent (copper)
  - stable materials can turn combustible (aluminium)
  - insoluble materials may become soluble (gold)
  - in this context, nano means between 0.2 (atomic level) and 100 nm (in this range materials exhibit different properties)
  - National Nanotechnology Initiative, USA (government program for nanoscale projects) considers as nano manipulation of matter that has at least one dimension in 1..100 nm range (w nanotechnology)
- Nanotechnology: how to exploit these new phenomena to create nanothings
  - often, nanotechnology word includes also nanoscience

Nanotechnology fields

- IEEE Transactions on Nanotechnology (1st number in 2002): electronics, circuits, nanomagnetism, nanorobotics, nanosensors, nanofabrication
- NanoTech conference (1st edition in 2015 in USA, 1–3 June 2016 in Paris):
  - nanomaterials (carbon nanostructures and devices, graphene, polymer etc.)
  - nanoscale electronics (memory and logic devices, circuits, spin electronics, quantum electronics etc.)
  - nanotech in life sciences and medicine (biosensors, drug and gene delivery, cancer nanotechnology etc.)
  - nanotechnology safety (health, regulation etc.)
  - nanoapplications (food, textiles etc.)
  - etc.
- Project calls
  - CHIST-ERA 2015 call on *Terahertz Band for Next-Generation Mobile Communication Systems*: THz device and/or system fabrication and integration, THz power generation

Definition of a nanonetwork

- A nanonode alone is of little interest => let's network them
- S. Bush, Nanoscale Communication Networks, 2010 (book):
  - "nanonetworks are communication networks that exist mostly or entirely at the nanometer scale"
  - "node size is measured in nanometers and channels are physically separated by up to hundreds or thousands of nanometers"
- For us, following Jornet, nanonetwork means network of nanodevices

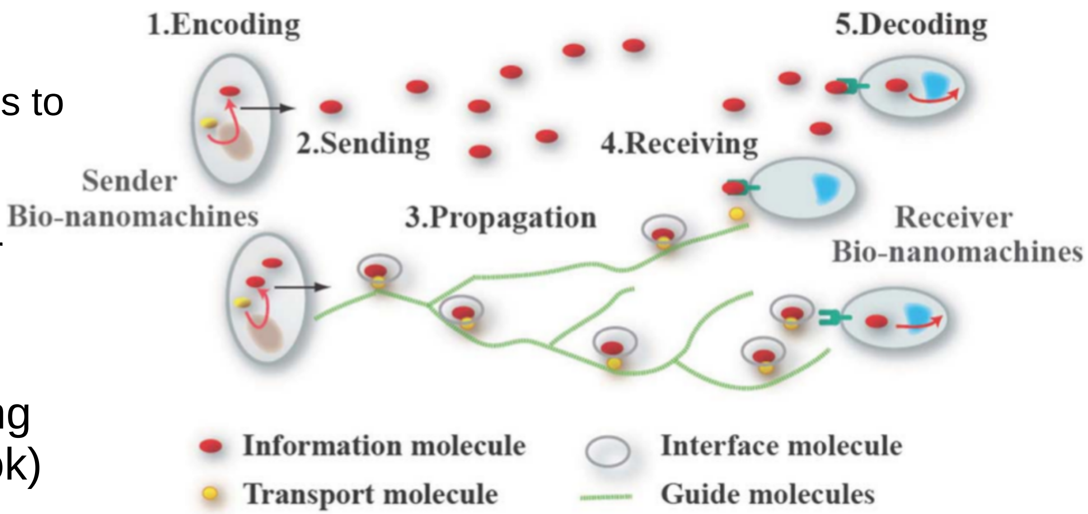
Positioning – communication, networking technologies

- Wired communication: uses a physical wire: electrical cable (e.g. Ethernet), fibre optic etc.
- Wireless: **electromagnetic** (radio waves), molecular (molecules as data carriers in the human body) etc.

Molecular communication

2010 Nakano et al., Molecular communication and networking: Opportunities and challenges

- What it is
  - engineered nanomachines communicate with biological systems
  - new communication paradigm: uses molecules to convey information
  - sender encodes information in molecules and release them in the environment, and receiver decodes the information upon reception
- A single CNT (1 nm diameter) is small enough to penetrate a cell without triggering the cell's defensive responses (Bush's book)
- Application envisioned:
  - health monitoring, drug delivery
  - environment monitoring (toxic molecules)
  - create novel patterns of molecules



Communication	Telecommunication	Molecular Communication
Devices	Electronic devices	Bio-nanomachines
Signal types	Optical/electrical	Chemical
Propagation speed	Speed of light	Extremely slow
Propagation range	m - km	nm - μm
Media	Air/cables	Aqueous

Electromagnetic communication

- Uses classical EM waves to transmit data
- Pioneer: J. Jornet, who proposed:
  - channel modelling
  - physical layer protocol
  - MAC (collision avoidance) protocol
- Is the focus of this presentation

Nanomachine

- Our goal is to build nanomachines
  - the most difficult part to build seems to be nanoantenna

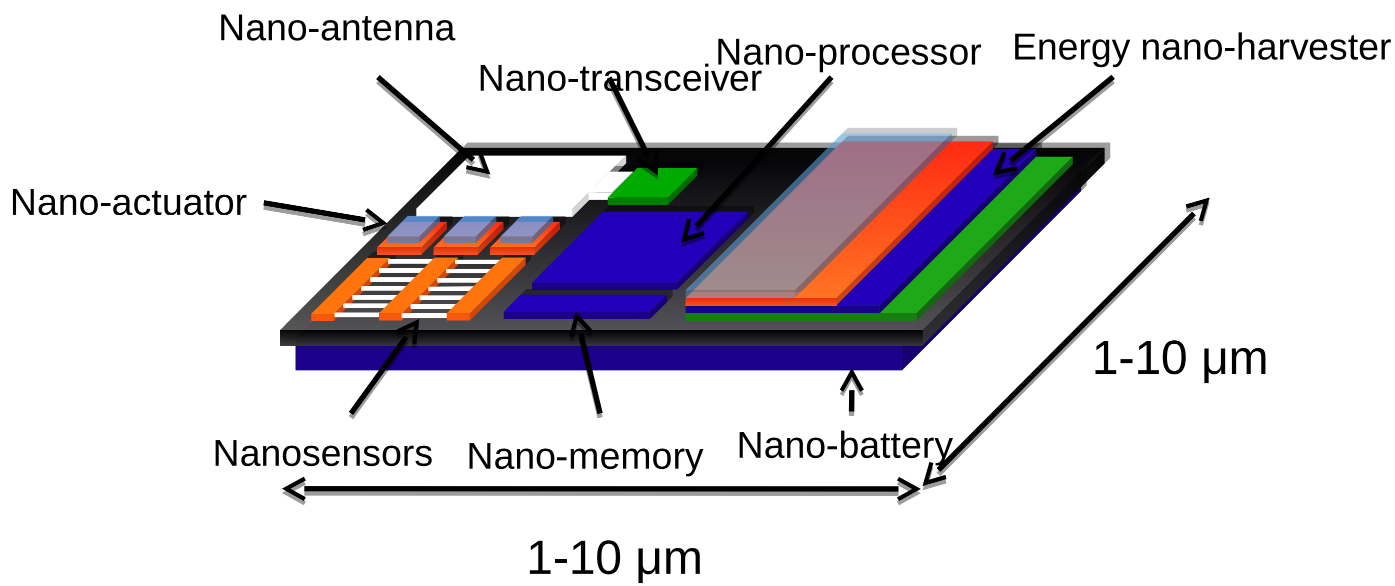
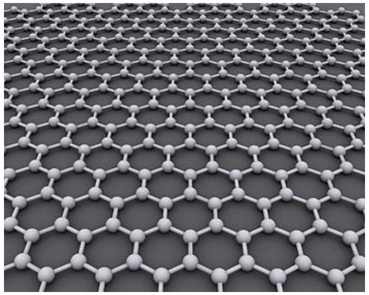


Image from Jornet



Nanoantenna

2014 Jornet et al, Graphene-based plasmonic nano-transceiver for terahertz band...

- Classical nanoantenna => very high frequencies (hundreds of THz)
  - following classical antenna theory, the size of a conventional (metallic) antenna resonating at wavelength λ should be at least λ/2
  - an antenna of 1 µm (max size for a nanoantenna) can process signals of max 2 µm wavelength

$$f = c/\lambda = \frac{3 \times 10^8 m/s}{2 \times 10^{-6} m} = 1.5 \times 10^{14} \text{ Hz} = 150 \text{ THz}$$

  - frequency is more than 150 THz => big propagation loss, even classical antenna theory needs to be revised
- Jornet proposed to use graphene, a one atom-thick layer of carbon, for nanoantennas and specific waves (SPP), which would allow 100 times smaller frequencies for the same size => irradiating in the THz band (0.1–10 THz)
  - graphene, isolated in 2004 by Geim and Novoselov (Nobel prize in 2010) has remarkable characteristics, such as 100 times stronger than steel and conducts very efficiently electricity

Spectrum background

Optical wireless comm.
- UV
- visible light comm.: Li-Fi
- IR

THz (0.1–10 THz, far&thermal IR)
- nano EM comm.

RF (radio frequency), 3 kHz–300 GHz:
- wi-fi, ISM (2.4 GHz)
- cellular network 3G (UMTS, ...), 1.9 GHz
- zigbee, ISM (2.4 GHz)
- bluetooth, ISM

(ISM = industrial, scientific and medical bands)

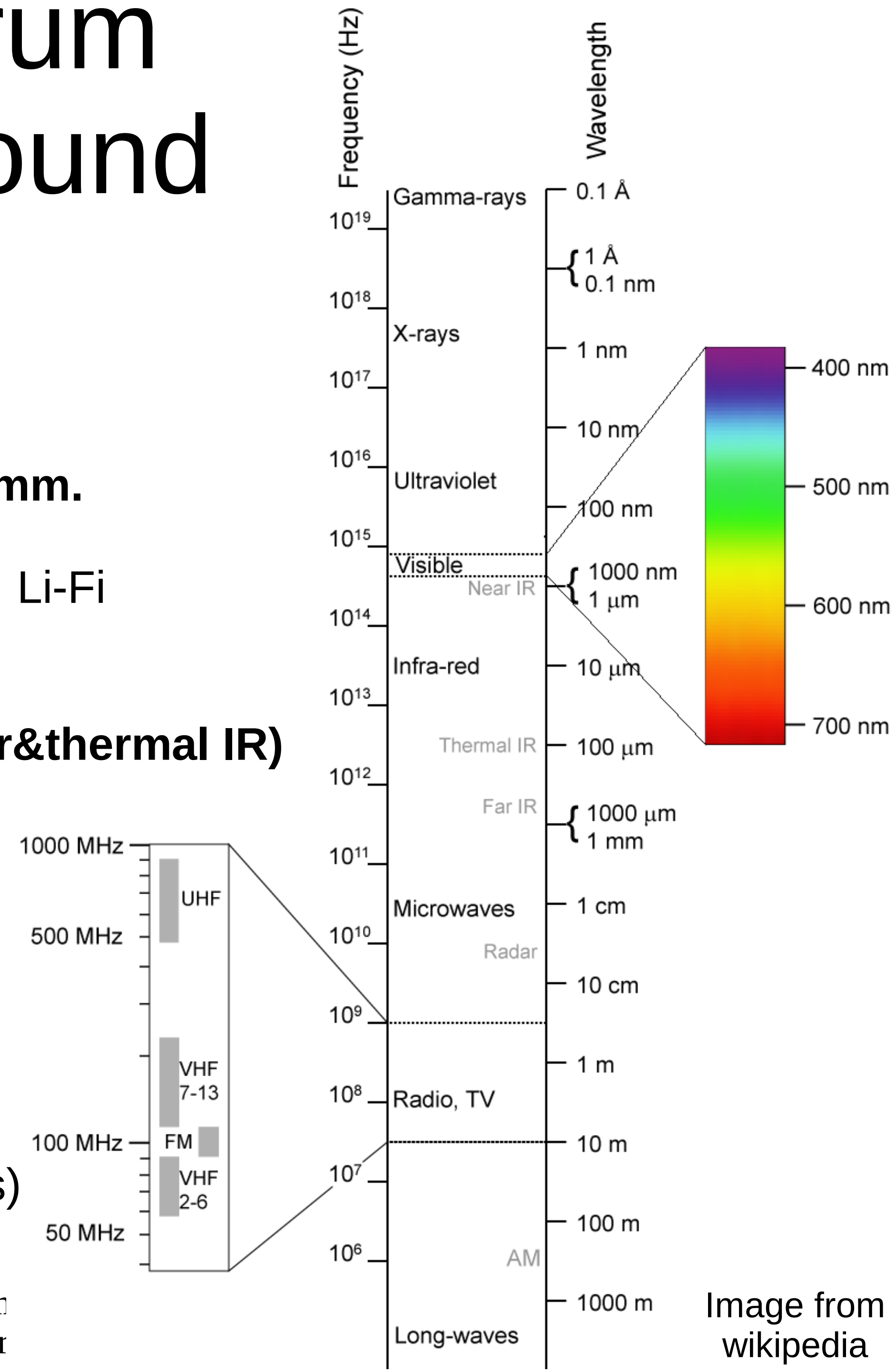


Image from wikipedia

Nanonetwork general specificities

- Comparison with Internet (S. Bush's book):
  - as we move from Internet computers to sensor networks, more nodes tend to be concentrated in a small area; node density increases more than linearly with the reduction of node size
  - in Internet all nodes have roughly equal capacity and each node can communication with any other node; a nanonetwork is asymmetric (sensors -> collection point)
  - Internet topology has clusters and important nodes (a few nodes highly connected, and many more have much fewer connections); a nanonetwork looks like a star (all paths lead to one or a few data collector nodes)
  - in nanonetworks, energy is very scarce
  - in nanonetworks, transmission distance has an optimum with regard to energy: a greater distance means more power to transmit, a smaller distance means intervening more nodes and thus more energy

THz band channel model – path loss and noise

Information and figures from 2011 Jornet et al., Channel modeling and capacity analysis...

Path loss (spreading loss + absorption loss) and noise greatly affect transmission quality

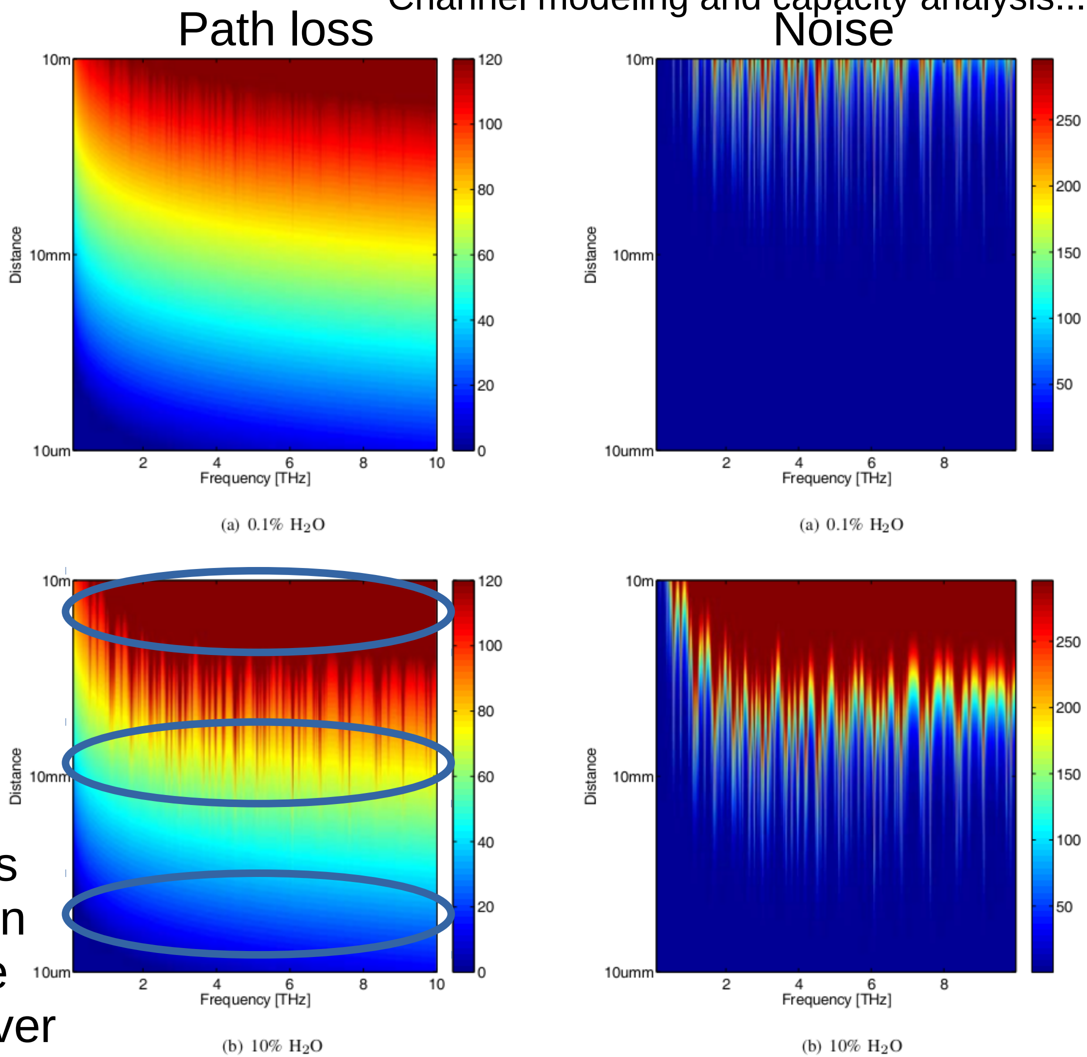
Results are got using HITRAN (HIgh resolution TRANsmission molecular absorption database)

Path loss depends heavily on medium, distance and frequency

- limited transmission above 10 m; we will need very directional antennas!
- several windows which are tens of GHz wide each for distances between 1 to 10 meters
- almost 10 THz wide transmission window for distances much below 1 m

Noise depends on temperature and waves

- noise only around the picks of absorption
- almost negligible in the ultra-short range
- adds to the electronic noise at the receiver



(a) 0.1% H_2O (b) 10% H_2O

First **experiments** seem to confirm the model, will be presented in NanoCom conf. (Sept. 2016)

Physical layer protocol – TS-OOK

Information from 2014 Jornet et al.,
Femtosecond-Long Pulse-Based Modulation...

- Because of tiny size, energy is very scarce in nanonodes => cannot use carriers to transmit data => pulses
- Technology limitation in SPP wave generation => pulses cannot be sent in burst, need relaxation time
- Proposition : TS-OOK, Time Spread On-Off Keying modulation, i.e. pulse or silence at big intervals
- Characteristics:
  - Tp = 100 fs-long pulses
  - Ts time between two symbols, proposed β = Ts/Tp = 1000
  - if β = 10, then **rate = 1 Tb/s**
  - pulse energy = a few aJ, peak power = a few µW
  - need extremely high synchronisation between src and dest nodes
- Model validated using COMSOL Multiphysics

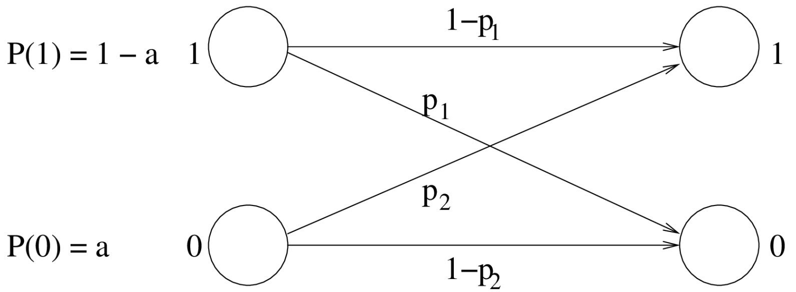
On sender:

```
Signal:   /\____/\____.____/\____
Bit sent: 1     1     0    1
```

Signal on receiver:

```
Expected:  /\____/\____.____/\____
```

Nanonetworks use BAC channel model:



Physical layer – low-weight coding

Information and figures from 2016 Zainuddin et al.,
Low-Weight Code Comparison...

Depending on channel, bits to be sent are better to be replaced

Mapping table for various codes:

Input symbol	Symbol freq.	ME	NME	PG	NPG	MTE	MEC	LWC	Unary
111	80	000	000	1000000	0000000	1100	0…0011	10010	1
110	70	001	001	0100000	0000001	0110	0…1100	10001	01
101	60	010	010	0010000	0000010	0011	.	01100	001
100	50	100	100	0001000	0000100	1000	.	01010	0001
011	40	011	101	0000100	0001000	0100	.	01001	00001
010	30	101	011	0000010	0010000	0010	.	00110	000001
001	20	110	110	0000001	0100000	0001	0011…0	00101	0000001
000	10	111	111	0000000	1000000	0000	1100…0	00011	00000001

Performance of the analysed codes:

Code	Energy efficiency	Bandwidth expansion	Sequential bits 1	Multi-user interference	Robustness
ME, NME	++	++	−	−	++
PG, NPG	++	− −	++	++	+
MTE	++	−	−	+	+
MEC	+	− −	− −	++	+
LWC	+	−	−	+	+
Unary	++	+	+	+	− −

Conclusion: NPG and PG are better on all criteria except bw expansion

MAC layer protocol – PHLAME

2012 Jornet et al. PHLAME: A Physical Layer Aware MAC Protocol...

- Rate Division Time Spread On-Off Keying (RD TS-OOK)
  - same as TS-OOK, but βs are different for different nanonodes and for different types of packets => collisions are temporary
- PHysical Layer Aware MAC protocol for EM nanonetworks (PHLAME)
  - handshaking request, packet contains: sync, src, dest, packet id, β, CRC
  - handshaking acknowledgement, packet is similar: sync, src, dest, packet id, coding scheme (according to perceived quality of received pulse), CRC
  - data, packet contains: src, dest, data

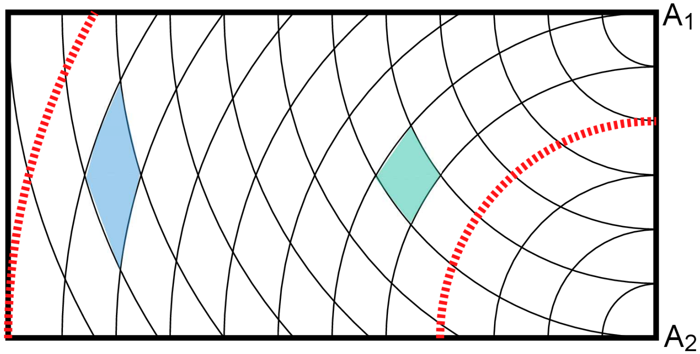
Example of routing protocol – Stateless Linear-path Routing

2016 A. Tsioliaridou et al. Stateless Linear-path Routing for 3D Nanonetworks

2D node addressing:

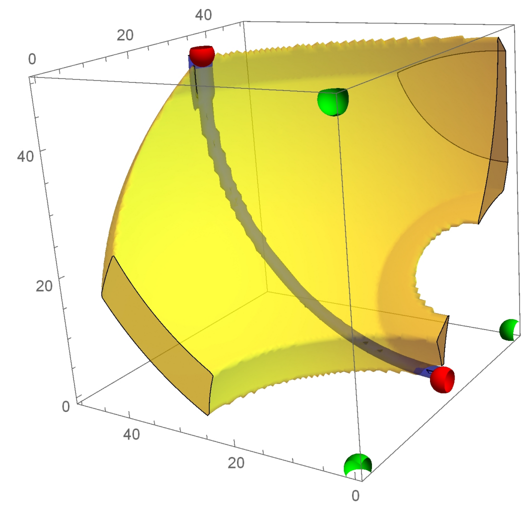
- curvilinear coordinate system
- the distance compared to 2 anchors

Initially, each anchor sends a beacon so that all nodes know their position compared to the 2 anchors



Routing:

Packet contains sender and destination
Nodes receiving a packet retransmit it iff:
(0<=diffs<n AND tj=sj+diffs)
 OR (diffs==n AND n<=diffr<=n+k AND tj=sj+diffr)
where diffs=ti-si, diffr=ti-ri
ri=si+n and rj=sj+n+k, with n,k>=0



Characteristics:

- 3D
- parametrisable path width for increased robustness

Transport protocol – none

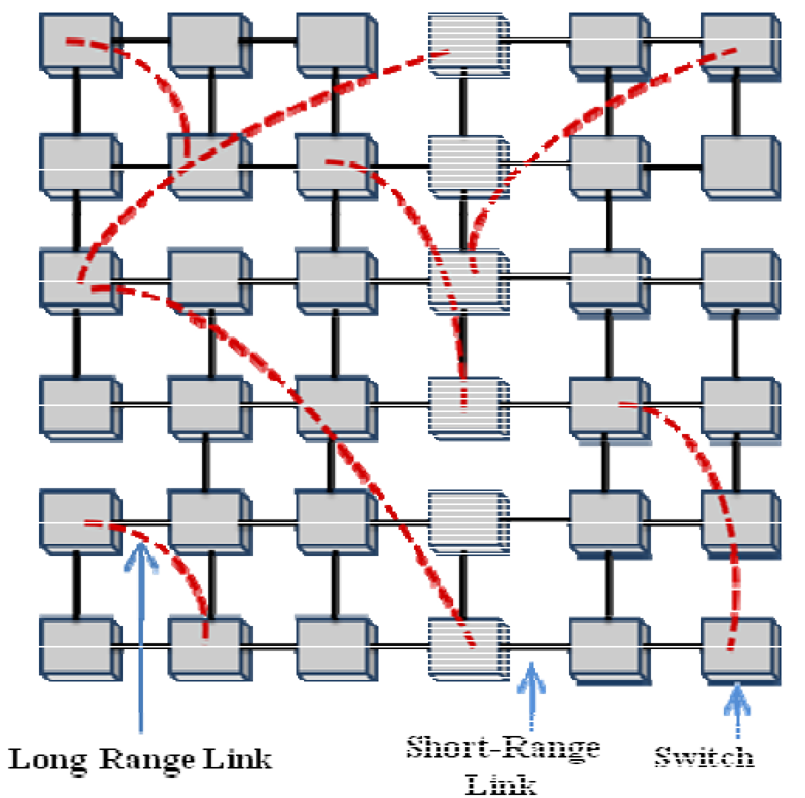
- We have a closed PhD position on this topic
- Specificities, challenges:
  - Tb/s throughput
  - specific physical environment to take into account (cross-layer?)
  - little energy => should be much simpler than TCP
  - little energy => different modulation
    - can receive numerous packets in Ts interval and send only one packet
    - better to send 0s than 1s
  - tiny size => need to harvest enough energy to send/receive a packet => the channel may be free, but node has no energy to send the packet
  - propagation time bigger than emission time => several packets in the same time on the channel => classical ARQ (wi-fi) inappropriate

Simulators

- No nanoantenna has ever been built, so we need simulators for nanonetworks
- 2013 Nano-Sim (Modena, Italy): NS3 module
  - simple propagation model (all or nothing)
  - 3 types of node: nanonode (sensor), nanorouter (collects data and forwards it), nanointerface (process data, gateway to external world)
  - 2 types of routing: flooding, random next hop
  - buggy
- 2016 Vouivre (Montbéliard, France): standalone library
  - realistic propagation and channel
  - scalable (1 million nodes)
  - see Julien's presentation for more

Applications: wireless network-on-chip (WNoC) in multi-core processors

From amazonaws

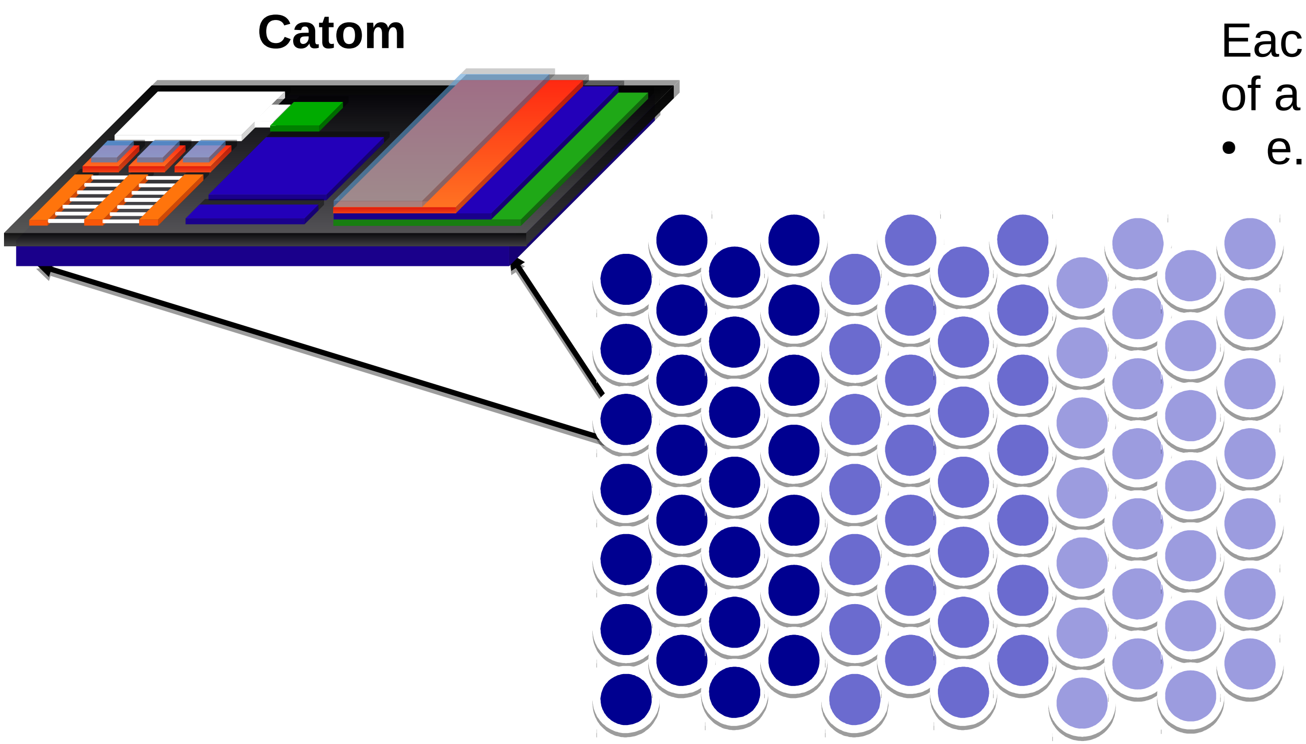


WNoC can be used for:

- long range links
- cache coherence

Applications: programmable matter

From Jornet

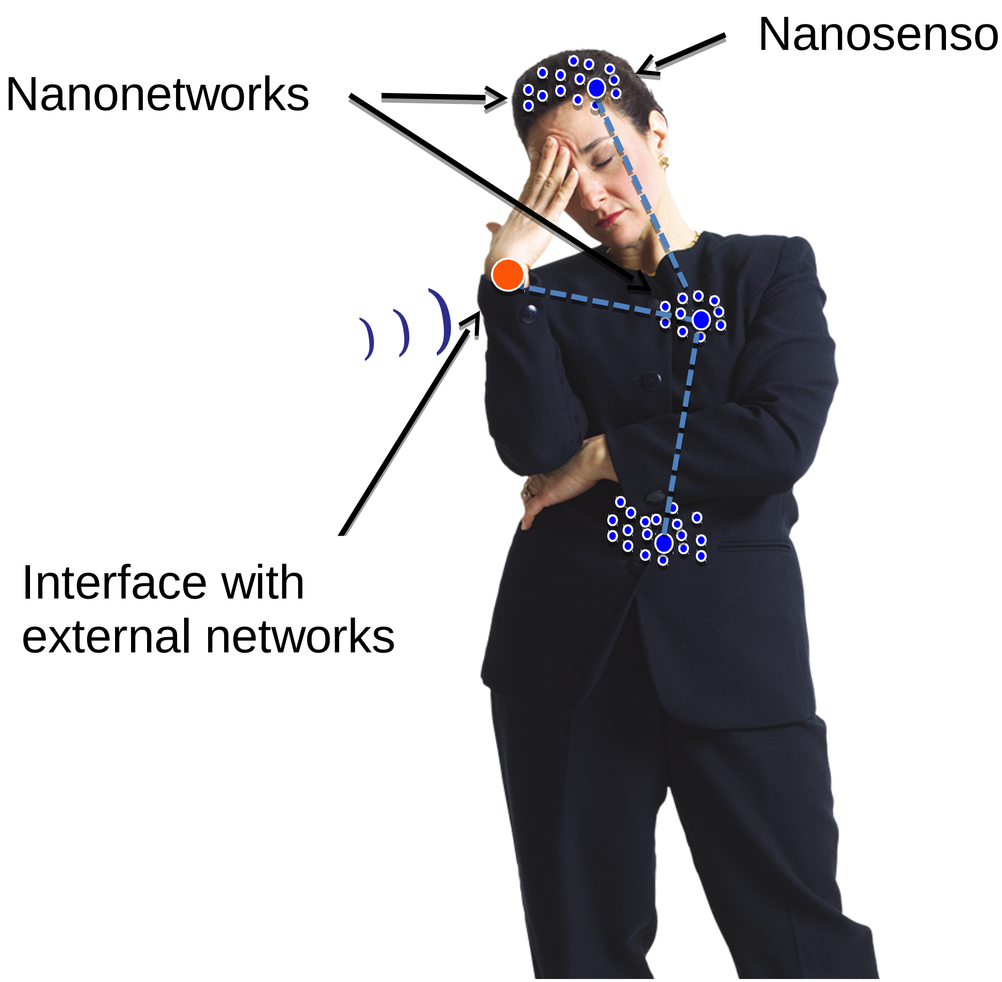


Each nanomachine can play the role of a fundamental unit

- e.g., a catom in claytronics

Applications: advanced health monitoring

From Jornet



Chemical and biological nanosensors can be used to:

- monitor glucose, sodium, cholesterol
- detect infectious agents
- localise cancerous cells
- etc.

Nanocameras with:

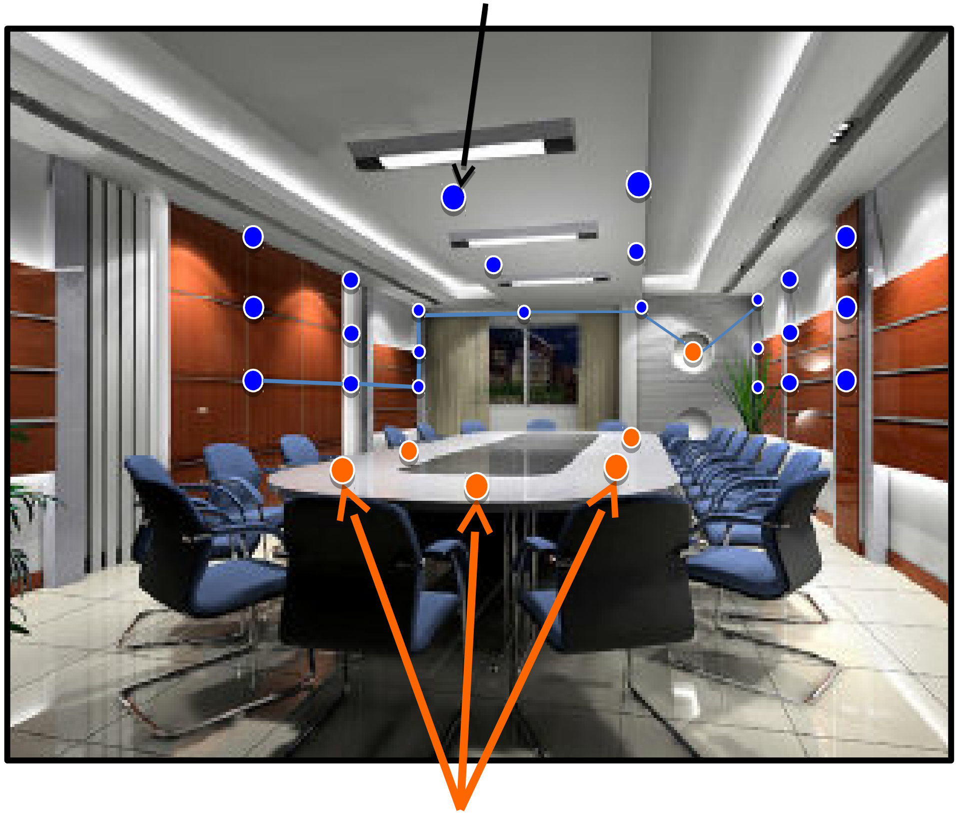
- high sensivity
- low power consumption

can be used to transmit nanoscale images in a video transmission

Applications: biological and chemical attack prevention

From Jornet

Nanosensors



Consumer electronic devices

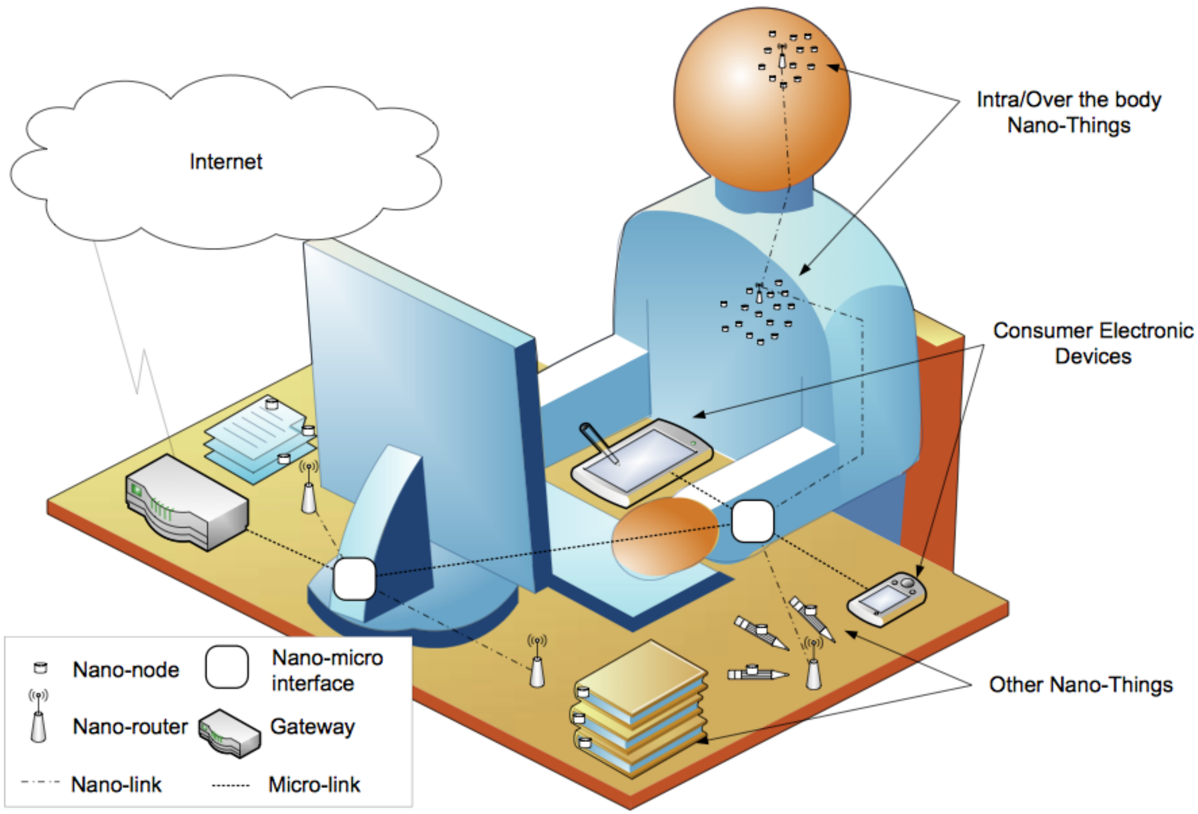
Nanosensors can detect biological and chemical hazards

- faster
- in lower concentrations

than existing microsensors

Applications: the Internet of nano-things

From Jornet



Journals, conferences, project calls

- Journals
  - Elsevier Nano Communication Networks (1st number in 2010, received SCIE/ISI status in 2016)
- Conferences
  - ACM NanoCom (1st edition in 2014)
- Appreciated topic: some "awards" in general conferences, ICT 2016 (23rd Int. Conf. on Telecommunications):
  - 1 of 3 best papers *N3: Addressing and Routing in 3D Nanonetworks* (Greece)
  - 1 of 3 keynotes: *Molecular communication for future nanonetworks* (Germany)

Key people and labs

- Field "creation":
  - nanonetworks envisioned ("created") by I. Akyildiz at GeorgiaTech (Internet of nano-things article)
  - EM communication "created" by J. Jornet supervised by I. Akyildiz
- Now:
  - I. Akyildiz, Georgia Tech, USA – EM and molecular ??
  - J. Jornet (Buffalo, NY, USA) – EM
  - N3Cat (NaNoNetworking Center in Catalunya), Barcelona, Spain – EM and molecular
- The only researchers active in this field in France are in our team

Conclusions

- Emerging topic (conferences younger than 5 years)
- Very different than classical networks
- Tb/s throughput
- Sometimes material has not yet been built, hence no experimentation possible, only simulation
- New collaborators are welcome :-)