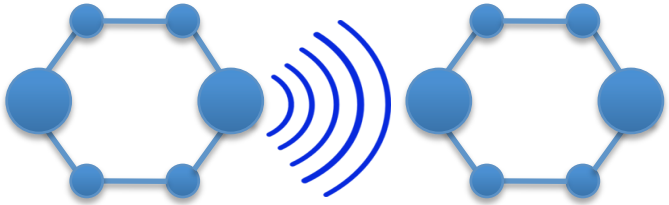


NanoWSN Tutorial for WPMC 2014

Nano-scale Wireless Sensor Networks:

Opportunities, Challenges, and Recent Advances

UNSW
THE UNIVERSITY OF NEW SOUTH WALES

Never Stand Still | Faculty of Engineering | Computer Science and Engineering

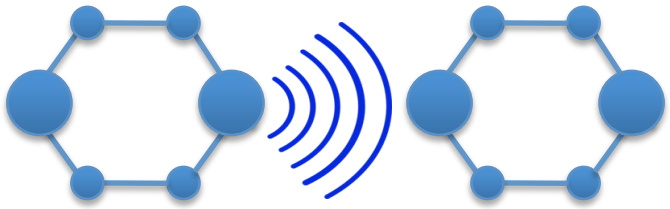
Mahbub Hassan

Professor, School of Computer Science and Engineering, UNSW

Distinguished Lecturer, IEEE Communications Society

Tutorial Modules

1. **Components** of a nanomote
2. **Applications** of NanoWSN
3. **Fundamentals** of nano communication
4. **Tools** for NanoWSN research
5. **Survey** of NanoWSN research
6. **Future** directions and research opportunities

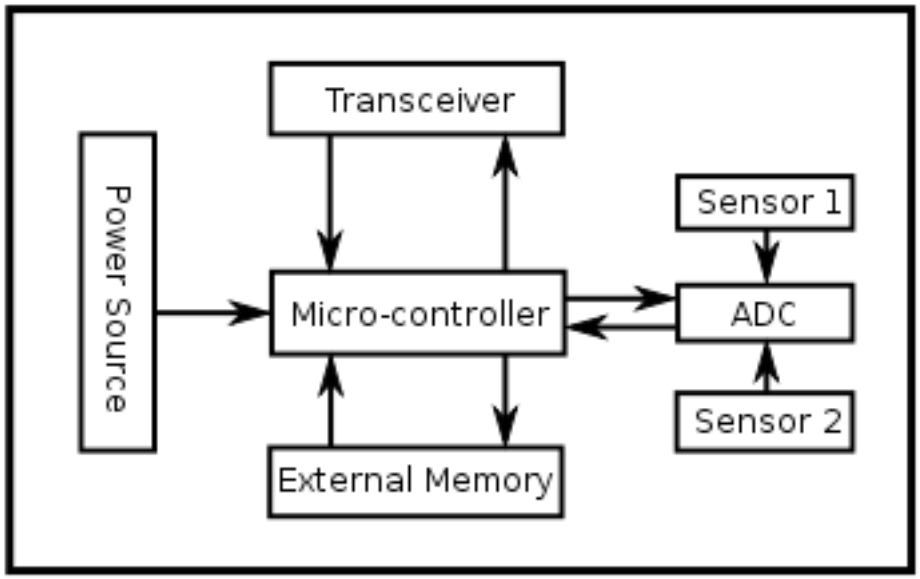


Module 1

Components of a Nanomote

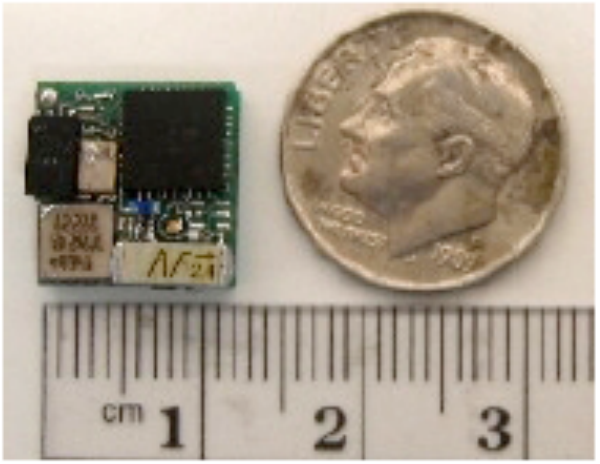
Architecture of a sensor node (mote)

MicaZ from Crossbow



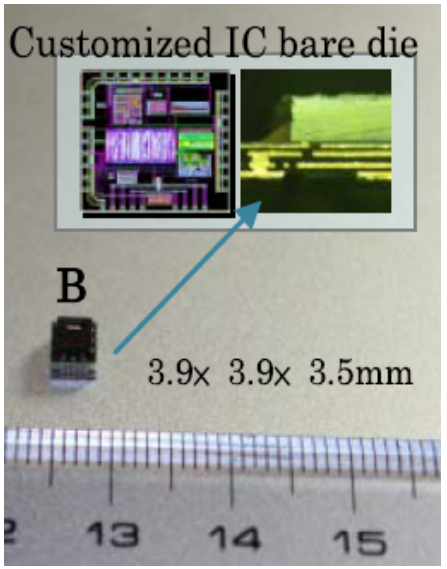
Source: wikipedia

The quest for the smallest mote



[Park2005]

12 mm to 4 mm in 9 years



[Lu2014]

[Park2005] Eco: an Ultra-Compact Low-Power Wireless Sensor Node for Real-Time Motion Monitoring, IPSN 2005
[Lu2014] Toward the World Smallest Wireless Sensor Nodes With Ultralow Power Consumption, IEEE Sensors Journal, 14(6), June 2014

The Reality of a Nanomote

- Technically, nanomote form factor < micrometer
- Nanomotes DO NOT exist today
- We may not ever achieve this dream with *conventional* material and component technology
- Initial breakthroughs have to come from *materials* and *components*

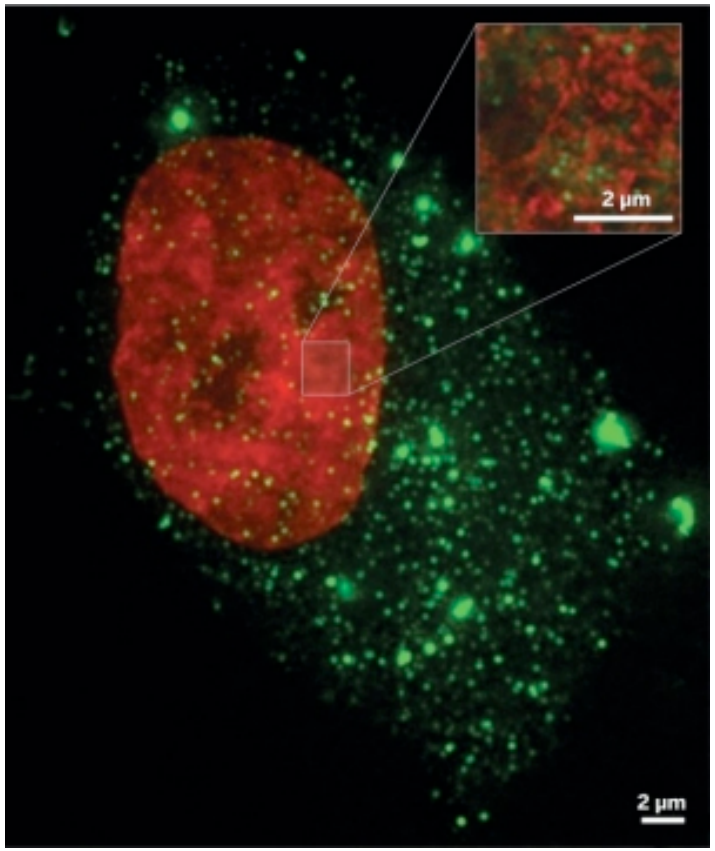
Nanomaterials

- A breakthrough in material technology
- We can now manufacture material at nano-scale
- At nano-scale, materials exhibit strange properties
- Nanomaterials are paving the way for nano components

Examples of nano materials
Gold nanoparticles

- 5-400 nm
- Drug delivery
- Food sensors
- Scatter lights – biological imaging
- Catalysis

Source: ACS Nano

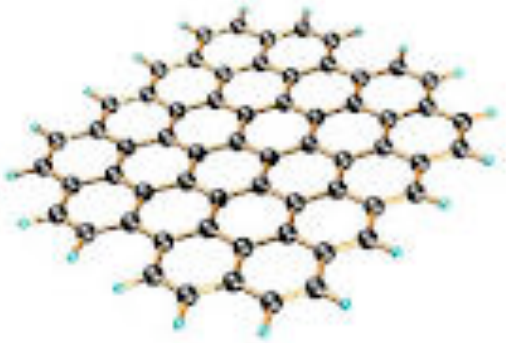


Examples of nano materials
Graphene (a true 2D material!)

- Thinnest (one atom thick)
- Lightest (0.77 mg for 1 sqm)
- Strongest (100-300x than steel)
- Best electricity conductor (could build antenna for nanomote)

Source: wikipedia

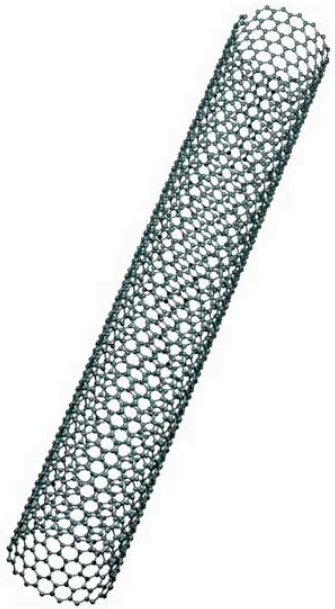
Graphene on substrate



Graphene molecule bonds

Examples of nano materials
Carbon Nano Tube (CNT)

Source: wikipedia

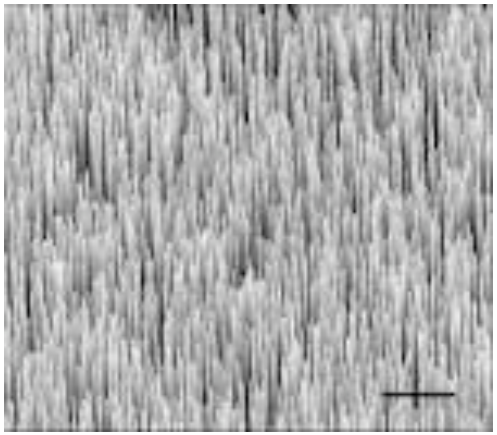


- Cube shaped material (diameter in nanometer scale)
- Batteries with improved lifetime
- Biosensors
- Flat-panel displays

Examples of nano materials nanowire

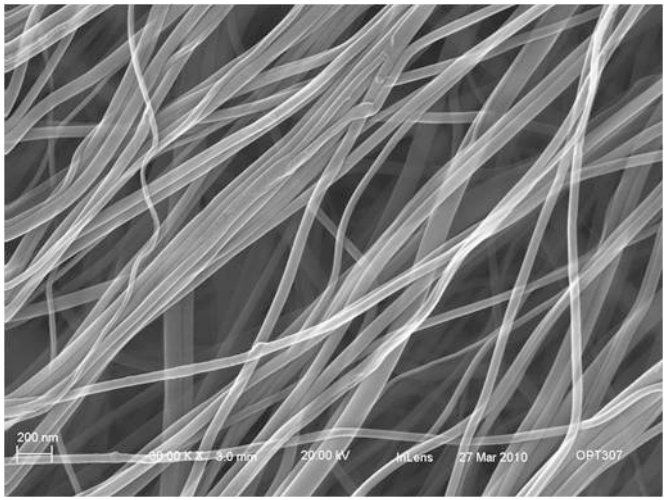
Source: wikipedia

ZnO nanowire



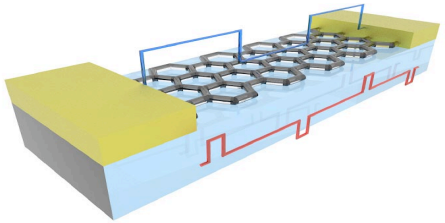
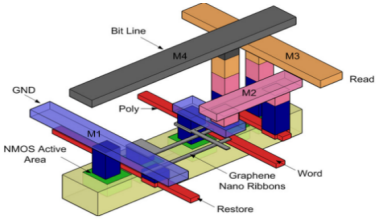
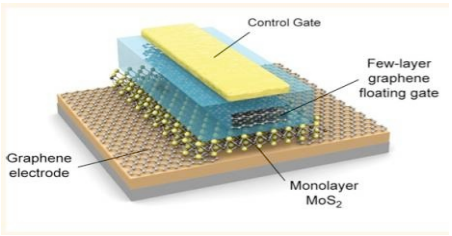
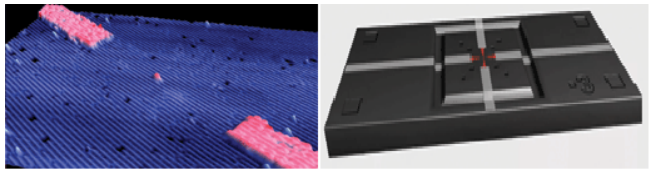
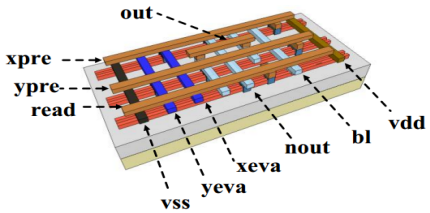
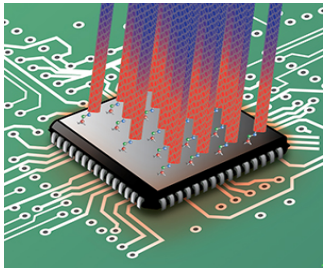
- Length is in microns
- Diameter in tens of nm
- Naowires can be used to build many components:
  - Nanobattery
  - nanoEH

Pt-Fe nanowire

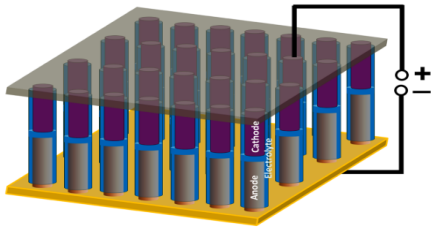


More examples of nanomaterials

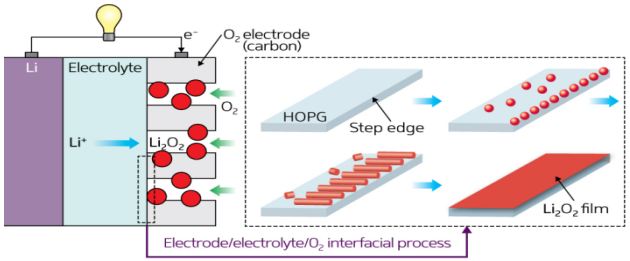
- Nanodiamond (bone growth around joint implants)
- Iron nanoparticles (clean up pollution in ground water)
- Palladium nanoparticles (hydrogen sensor)
- Copper nanoparticles (lead-free solder for space mission)
- Many more …

Nano-scale Memory	Nano-scale CMOS/Processor
 Graphene nanoribbon memory cell	 Graphen-based CMOS
 Nano-scale flash memory using graphene	 single-atom transistor developed at UNSW
 8T-Nanowire RAM Array	 A carbon nanotube CPU

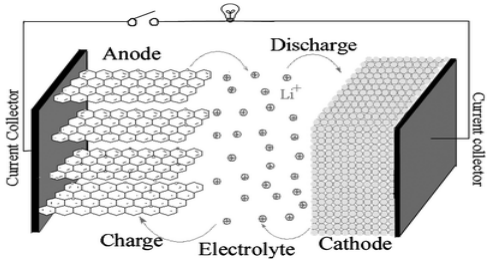
Nano-scale Battery



Nanoscale battery/supercapacitor devices

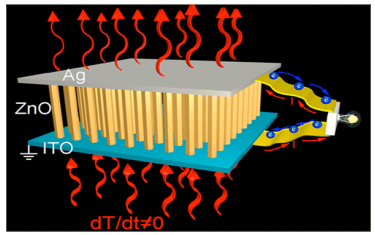


A nanoscale battery

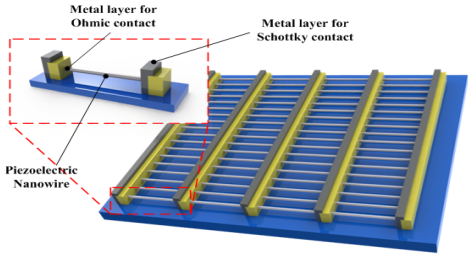


Schematic illustration of a rechargeable lithium battery

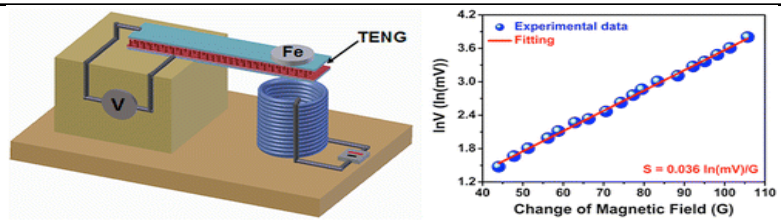
Nano-scale Energy harvesting devices



Pyroelectric Nanogenerators for Harvesting Thermoelectric Energy



Schematic view of typical Lateral nanowire Integrated Nanogenerato



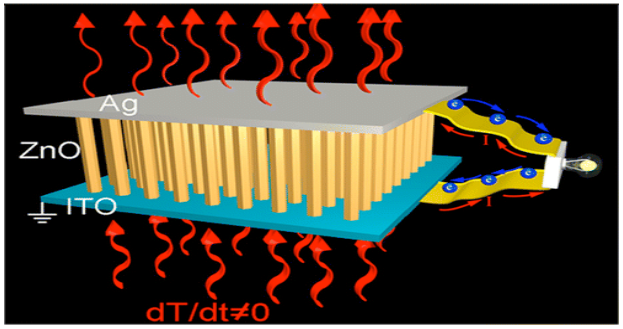
Triboelectric Nanogenerator **for harvesting** Magnetic Field

Energy Harvesting for NWSNs (1)

From thermal and motion

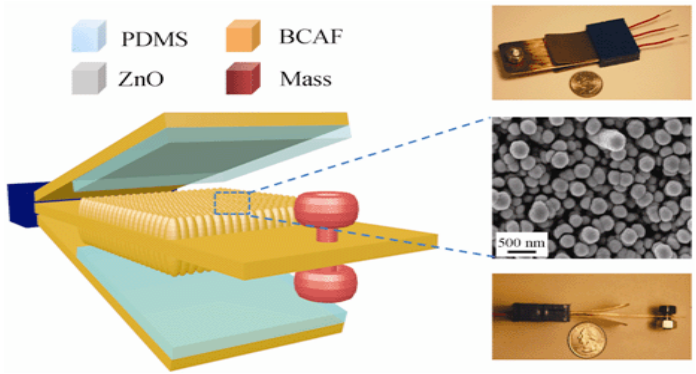
- "

  Pyroelectric Nanogenerators for Harvesting Thermoelectric Energy"Ya Yang, Wenxi Guo, Ken C. Pradel, Guang Zhu, Yusheng Zhou, Yan Zhang, Youfan Hu, Long Lin, and Zhong Lin Wang, Nano Letters, 2012, 12 (6), 2833–2838



- "

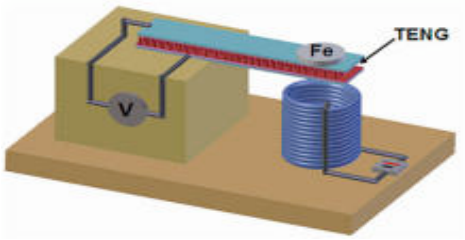
  Harvesting vibration energy by a triple-cantilever based triboelectric nanogenerator"Weiqing Yang, Jun Chen, Guang Zhu, Xiaonan Wen, Peng Bai, Yuanjie Su, Yuan Lin, and Zhonglin Wang, Nano Research, Online

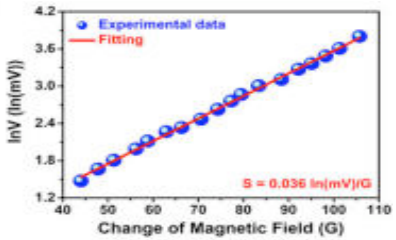


Energy Harvesting for NWSNs (2)

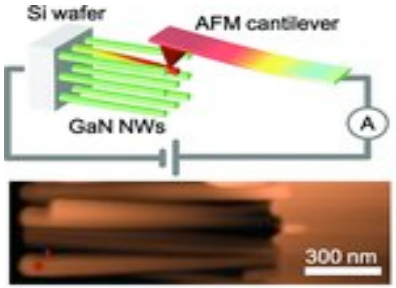
From magnetic field and gravity

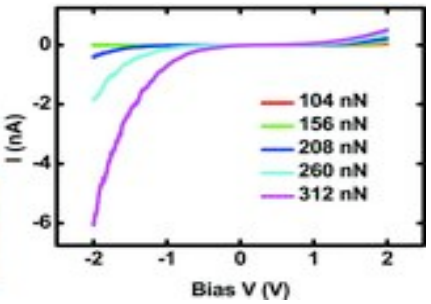
- “[Self-Powered Magnetic Sensor Based on a Triboelectric Nanogenerator]"Ya Yang, Long Lin, Yue Zhang, Qingshen Jing, Te-Chien Hou, and Zhong Lin Wang,ACS NANO, 2012, Online





- “[Nano-Newton Transverse Force Sensor Using a Vertical GaN Nanowire based on the Piezotronic Effect]"Yu Sheng Zhou, Ronan Hinchet, Ya Yang, Gustavo Ardila, Rudeesun Songmuang, Fang Zhang, Yan Zhang, Weihua Han, Ken Pradel, Laurent Montès, Mireille Mouis, and Zhong Lin Wang, Advanced Materials, 2012, Online

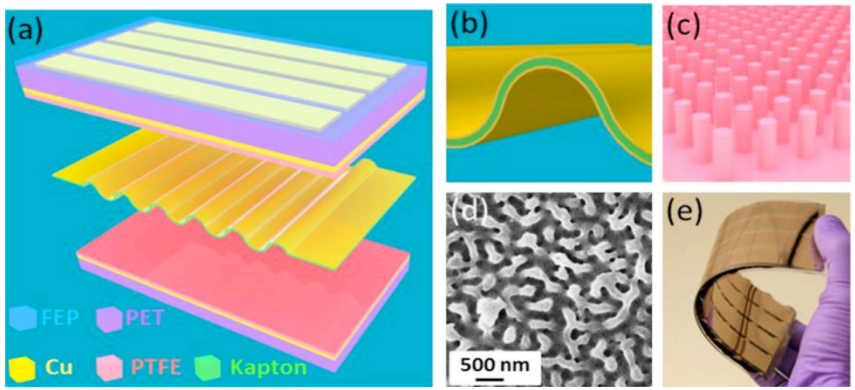




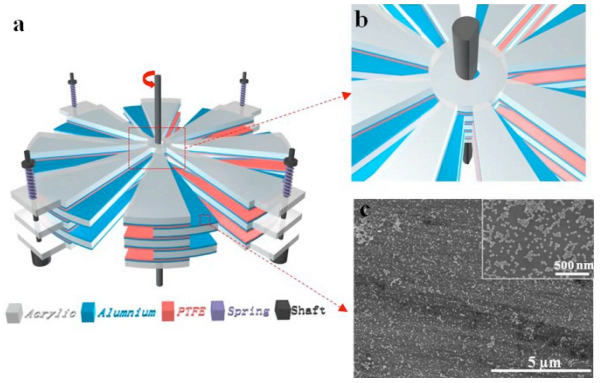
Energy Harvesting for NWSNs (3)

From water wave and hydropower

- “ [Hybrid triboelectric nanogenerator for harvesting water wave energy and as a self-powered distress signal emitter]“ Yuanjie Su, Xiaonan Wen, Guang Zhu, Jin Yang, Jun Chen, Peng Bai, Zhiming Wu, Yadong Jiang, Zhong Lin Wang, Nano Energy, 2014, Online



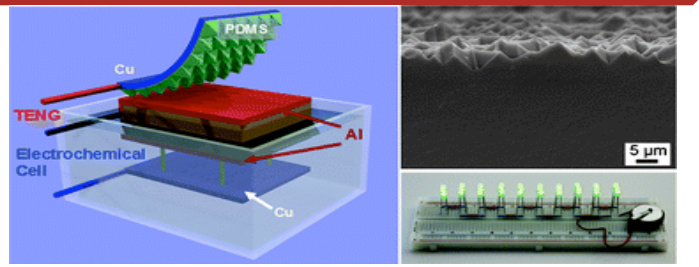
- ” [Multi-layered disk triboelectric nanogenerator for harvesting hydropower]"Yannan Xie, Sihong Wang, Simiao Niu, Long Lin, Qingshen Jing, Yuanjie Su, Zhengyun Wu, Zhong Lin Wang, Nano Energy, 2014, 6, 129–136



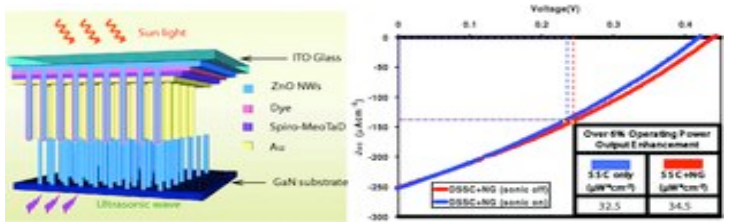
Energy Harvesting for NWSNs (4)

Hybrid schemas (1)

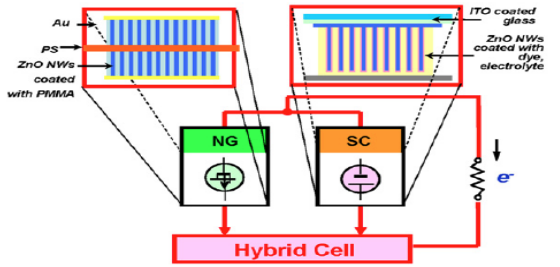
- “[Simultaneously harvesting mechanical and chemical energies by a hybrid cell for self-powered biosensors and personal electronics]"Ya Yang, Hulin Zhang, Jun Chen, Sangmin Lee, Te-Chien Hou and Zhong Lin Wang, Energy&Environmental Science, 2013, Online



- "[Compact Hybrid Cell Based on a Convoluted Nanowire Structure for Harvesting Solar and Mechanical Energy]" Chen Xu and Zhong Lin Wang, *Adv. Mater.*, 23(7), 873–877.



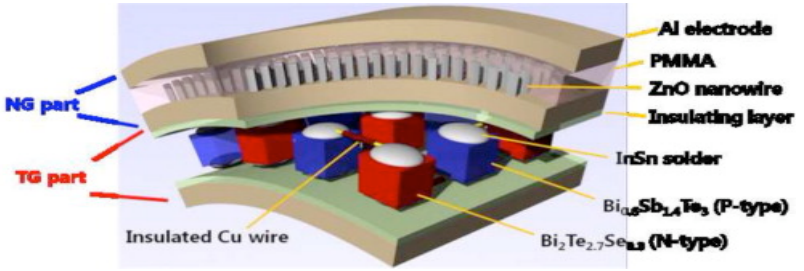
- “[Hybrid cells for simultaneously harvesting multi-type energies for self-powered micro/nanosystems]”Chen Xu,Caofeng Pan,Ying Liu,Z.L. Wang, Nano Energy, 2012, 1, 259-272



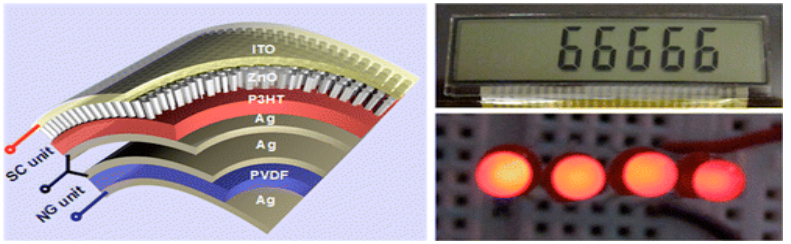
Energy Harvesting for NWSNs (5)

Hybrid schemas (2)

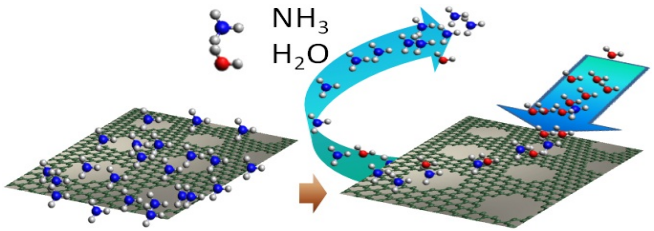
- “[Flexible hybrid cell for simultaneously harvesting thermal and mechanical energies]"Sangmin Lee, Sung-Hwan Bae, Long Lin, Seunghyun Ahn, Chan Park, Sang-Woo Kim, Seung Nam Cha, Young Jun Park, Zhong Lin Wang, Nano Energy, 2013, 2, 817-825



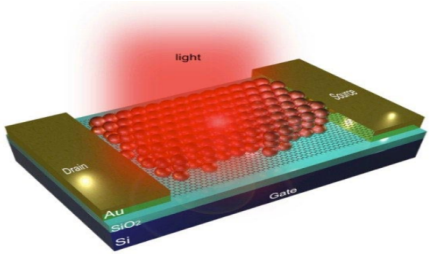
- “[Flexible Hybrid Energy Cell for Simultaneously Harvesting Thermal, Mechanical, and Solar Energies]"Ya Yang, Hulin Zhang, Guang Zhu, Sangmin Lee, Zong-Hong Lin, and Zhong Lin Wang, ACS NANO, 2012, Online



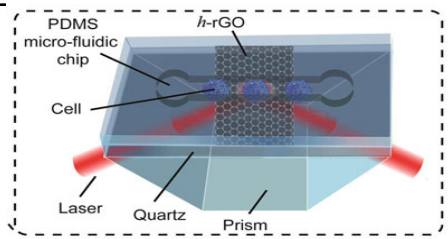
Nano-Sensors 1



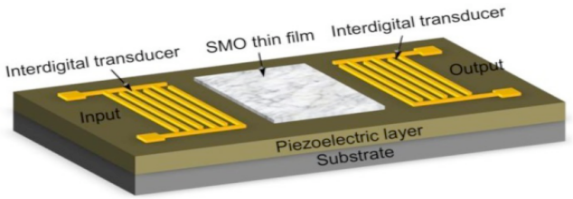
Nanoscale toxic gases Detector (Developed at CSIRO)



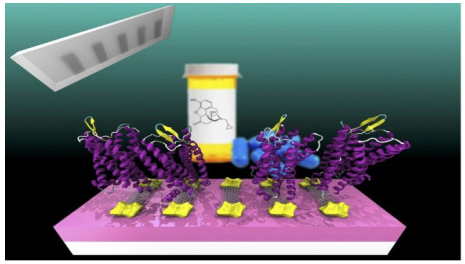
A graphene-based light detecter



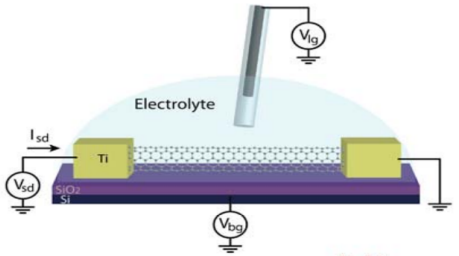
Graphene-based optical sensor detects single cancer cells



A Nano-scale hydrogen sensor

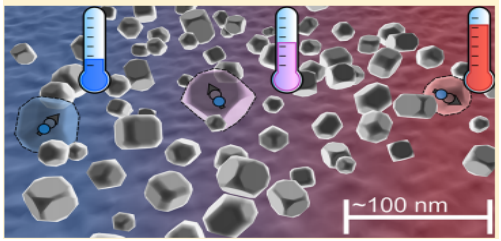


A Bio-Chemical Nanosensors

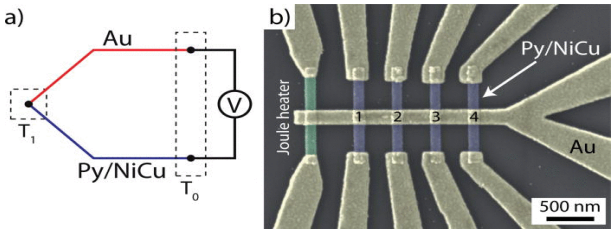


A Single-Molecule Detector

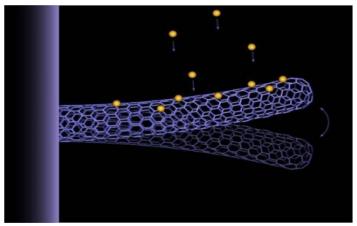
Nano-Sensors 2



A Nanoscale Temperature Sensor



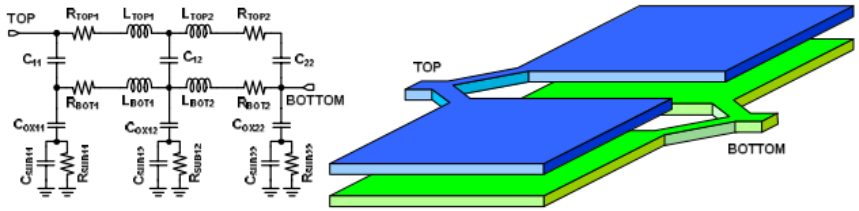
A Nanoscale Temperature Sensor based on Seebeck effect



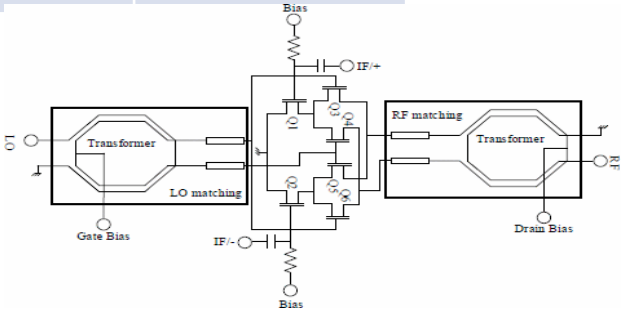
Nanoscale Mass Sensor

Exampls of SiGe CMOS based NTs

	Working Frequency (GHz)	Size (nm)	Technology	Reference
1	40	65-90	SiGe CMOS	1
2	170	110	SiGe CMOS	2
3	434	130	SiGe BICMOS (Bipolar CMOS)	3
4	130	28	SiGe CMOS	4
5	220		SiGe CMOS	5



A schematic of the SiGe NT [2]



A schematic of the SiGe NT [4]

Nano-scale Transceivers (NTs) — GaN diode based

- **Gunn diodes** are also known as transferred electron devices, TED, are widely used in microwave RF applications for frequencies between 1 and 100 GHz [6].
- **Gallium nitride** (GaN) based Gunn diodes has been widely used for terahertz oscillators.

Examples of GaN diode based NTs

	Working Frequency (GHz)	Size (nm)	Technology	Reference
1	450	20	GaN HEMTs	7
2	1600 (1.6 THz)	100	Gan Diode	8

Nano-scale Transceivers (NTs)

Graphene
and Carbon Nano Tubes (CNT) based

Graphene has a plasmonic resonant frequency in the THz band (0.1 - 10 THz) making it well suited for use as a plasmonic nano-antenna.

	Working Frequency (GHz)	Size (nm)	Technology	Reference	Year
1	100-30000 (0.1-30THz)	200	Graphene	9	2013
2	1500-6000 (1.5-6 THz)		Graphene	10	2013
3	100-10000 (0.1-10THz)	1000-2000	Graphene	11,13	2010-2014
4	100-5000 (0.1-5THz)	200	Graphene	12	2012
5	100THz	400	CNT	12	2012

References for Nano-scale Transceivers (NT)

[1] Chalvatzis, T., & Yau, K. (2007). Low-voltage topologies for 40-Gb/s circuits in nanoscale CMOS. IEEE Journal of Solid-State Circuits, 42(7), 1564–1573.

[2] Laskin, E., & Tang, K. (2008). 170-GHz transceiver with on-chip antennas in SiGe technology. In *IEEE Radio Frequency Integrated Circuits Symposium* (pp. 637–640). Atlanta, GA, USA.

[3] Hu, S., Wang, L., Xiong, Y. Z., Zhang, B., & Lim, T. G. (2011). A 434GHz SiGe BiCMOS transmitter with an on-chip SIW slot antenna. *IEEE Asian Solid-State Circuits Conference 2011*, 269–272.

[4] Parveg, D., & Varonen, M. (2013). Design of mixers for a 130-GHz transceiver in 28-nm CMOS. In *2013 9th Conference on Ph.D. Research in Microelectronics and Electronics (PRIME)* (pp. 77–80). Villach, Austria

[5] Gu, Q., Xu, Z., Jian, H., & Pan, B. (2012). CMOS THz generator with frequency selective negative resistance tank. *IEEE TRANSACTIONS ON TERAHERTZ SCIENCE AND TECHNOLOGY*, *2*(2), 193–202.

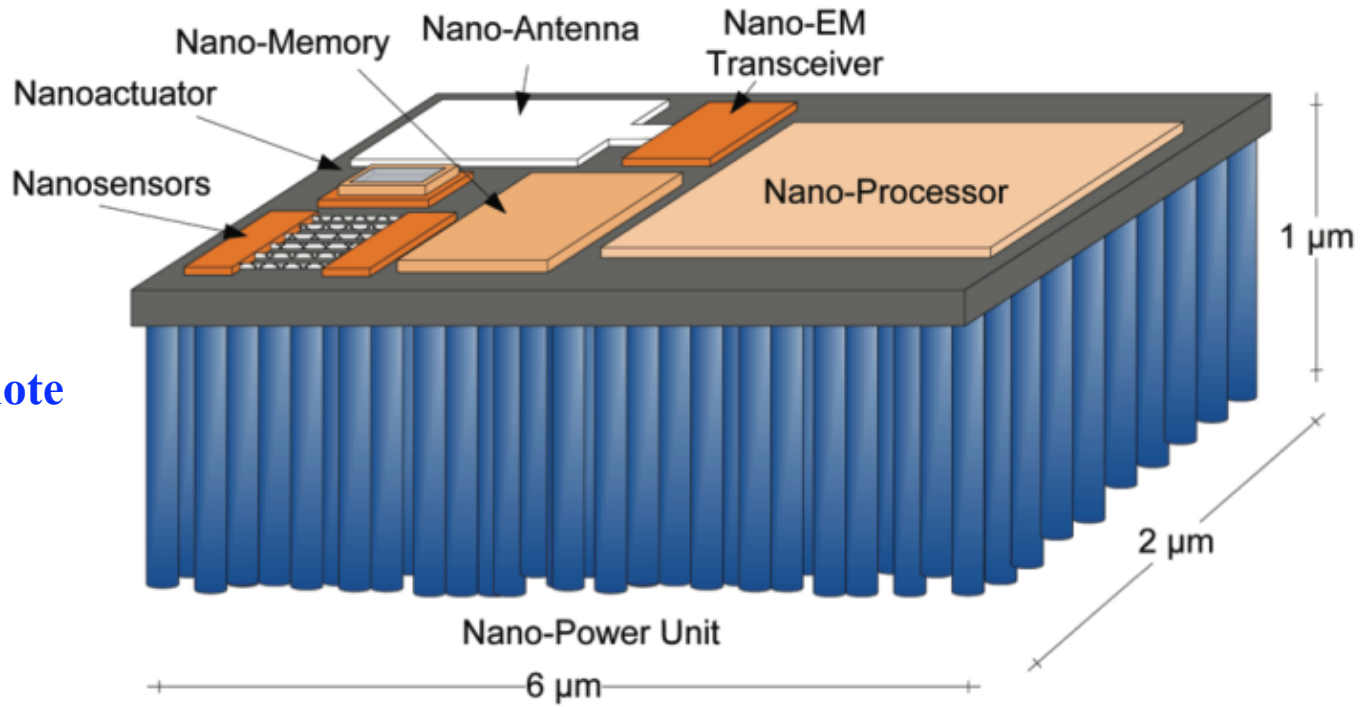
[6] http://www.radio-electronics.com/info/data/semicond/gunndiode/gunndiode.php

[7] Shinohara, K., Regan, D., & Tang, Y. (2013). Scaling of GaN HEMTs and Schottky diodes for submillimeter-wave MMIC applications. *IEEE TRANSACTIONS ON ELECTRON DEVICES*, *60*(10), 2982–2996.

[8] Sokolov, V. N., Kim, K. W., Kochelap, V. a., & Woolard, D. L. (2005). Terahertz generation in submicron GaN diodes within the limited space-charge accumulation regime. *Journal of Applied Physics*, *98*(6), 064507. doi:10.1063/1.206095

If we could put it altogether …

A Concept Nanomote [Akyildiz2010]



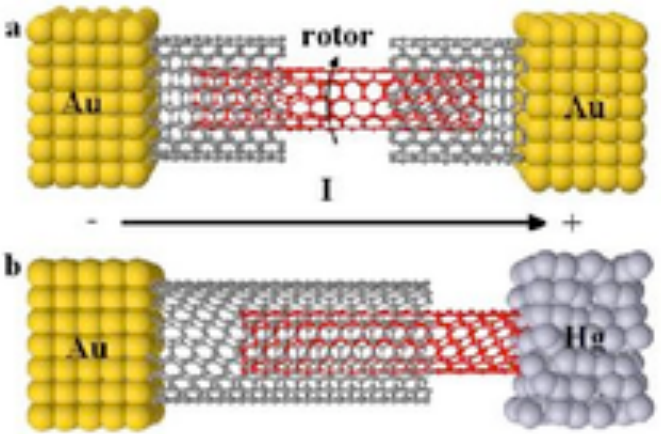
[Akyildiz2010] I.F. Akyildiz and J.M. Jornet, Electromagnetic wireless nanosensor networks, Nano Communication Networks, 1 (2010) 3-19

Nanoactuators

- Convert external stimuli into mechanical motion
- Today, this can be done at nano scale!
- Foundation for nanorobotics, artificial muscles, smart systems
- Nanosensors and nanoactuators could work as a connected system with nano communications

Examples of Nanoactuators

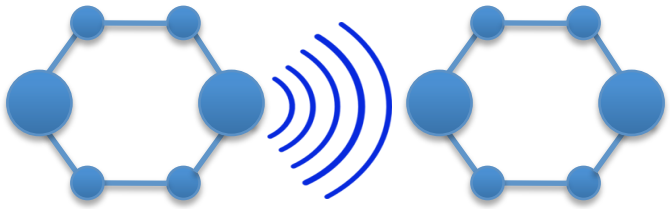
CNT-based nanomotors and nanodrill



nanomotor

nanodrill

Source: wikipedia



Module 2

Applications of NanoWSN

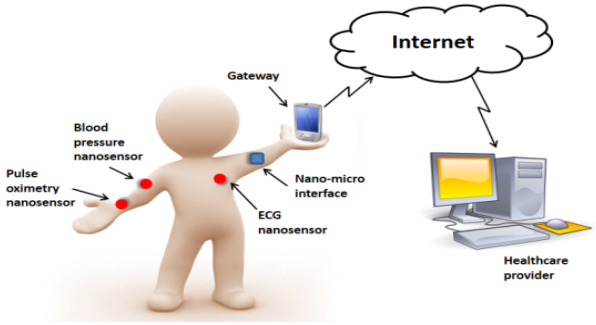
What can we do with nanomotes and nanoWSNs?

- Science fictions could become a reality
  - ‘Swallow the surgeon’ Feynman 1959
- Nanoparticles or nanorobots could collaborate
  - Highly successful cancer treatments without any side effects
- We could collect data at *atomic* level
  - Observe and control the nature from the very bottom
- We still do not know very well what we could do with NanoWSNs

Application of NSNs

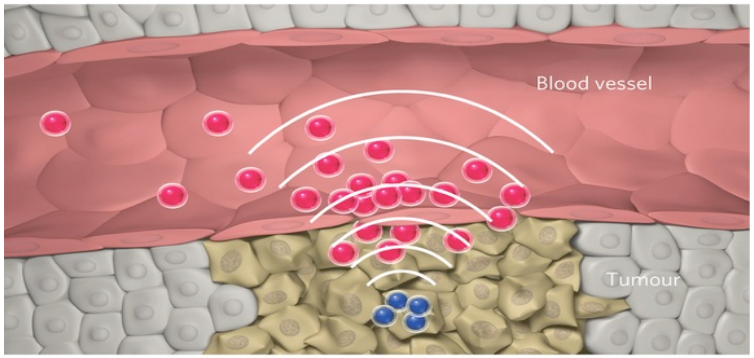
Biomedical 1

- **Health monitoring systems, for example:**
  - Monitoring of the sodium, glucose, cholesterol and other ions within the blood [1]



- **Tumour detection via cancer biomarkers:**

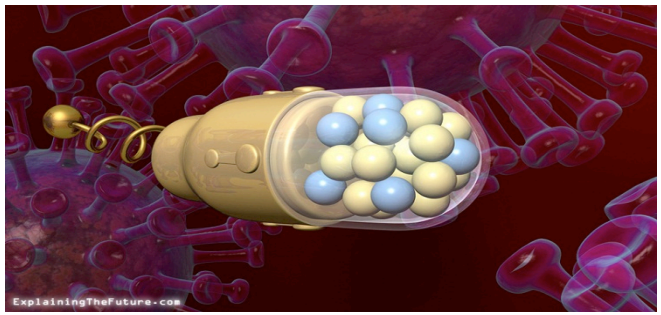
MIT researchers has shown that a communication-enabled tumour targeting system can target over **40 times more efficient** than non-communicating schema [2].



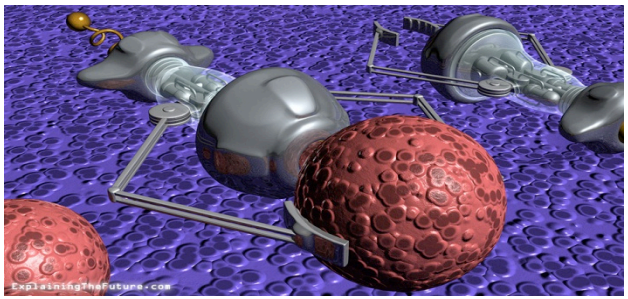
Application of NSNs

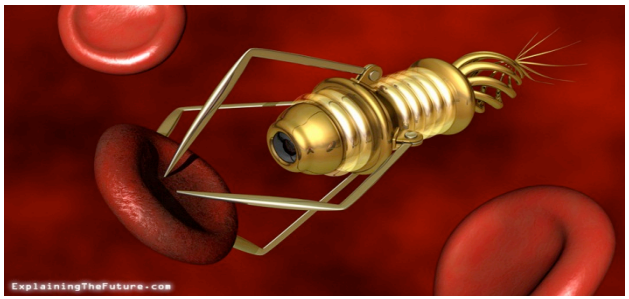
Biomedical 2

- Targeted drug delivery [1]



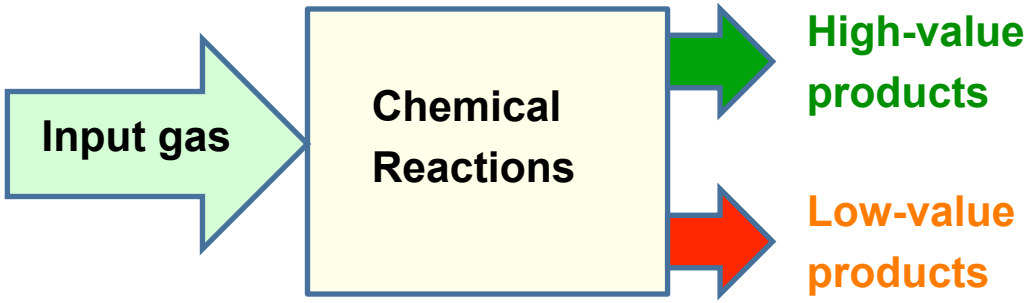
- Connecting bio-nano robots for different purposes, for example [3]:
  - Transmigration of the white blood cells (WBC) and other inflammatory cells to the inflamed tissues.
  - Nanorobots can help in the control and monitoring of glucose levels in diabetic patients.
  - Surgical nanorobots for nanomanipulation in the target site with programming and guidance from a surgeon.





Images from Explainingthefuture.com

NanoWSN in **Chemical Reactors**



Selectivity **= percentage of high-value products in the output**

Commercial reactors

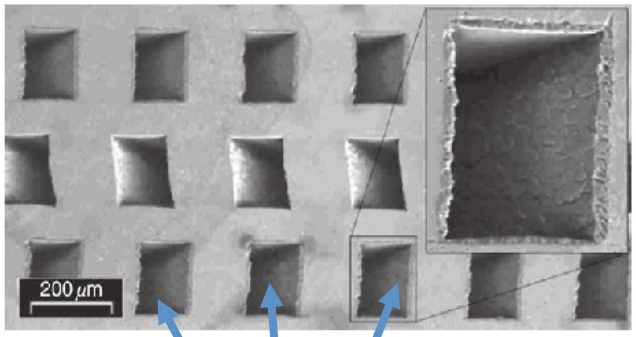
Source: wikipedia

E. Zarepour, A. A. Adesina, M. Hassan, and C. T. Chou, "*An innovative approach to improving gas-to-liquid fuels catalysis via nano-sensor network modulation*," **Industrial and Engineering Chemistry Research**, 53 (14), pp 5728-5736, 2014.

Catalyst Inside a Reactor

- Speeds up the reaction process
- Millions of tiny *sites* on the surface
- Molecules adsorb at empty *sites*
- Two molecules at two close-by *sites* may react and form a new composite molecule in one of the *sites*

Magnified View of Catalyst Surface



Source: [Renken2010]

Sites

[Renken2010] Renken and Kiwi-minsker, ”Microstructured Catalytic Reactors", Advances in catalysis, Vol. 53, pp. 47-122, 2010

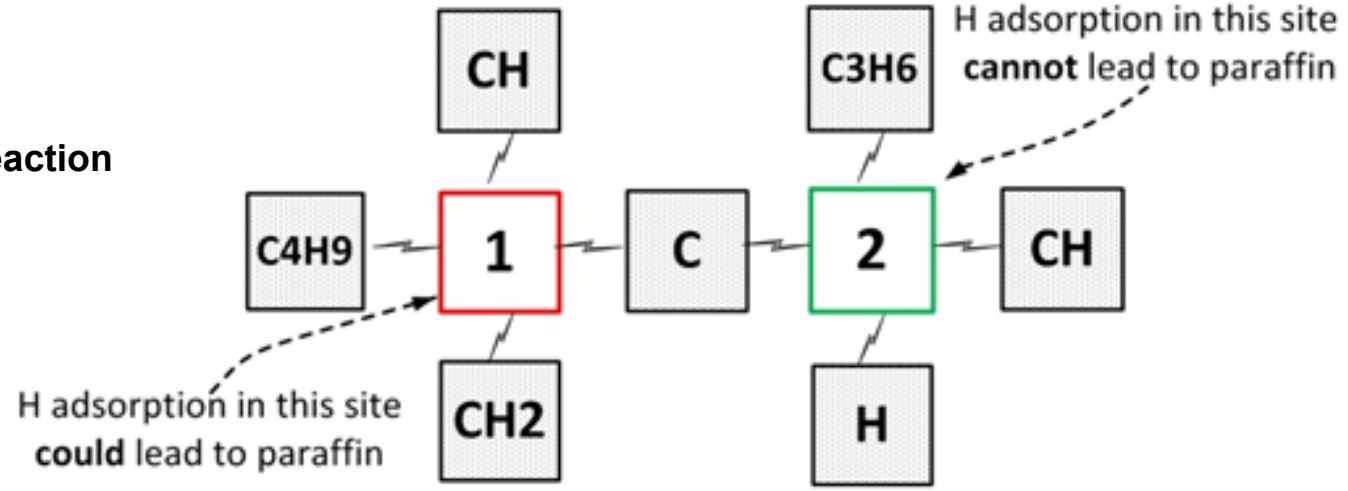
Selectivity in Fischer-Tropsch Reactor (Gas→Liquid)

- Input gas: C and H
- High-grade output products (Olefins): C_nH_{2n}
- Low-grade output products (Paraffins): C_nH_{2n+2}
- Paraffin production could be reduced (selectivity increased) if we could selectively control H adsorption

HTP (hydrogen to parffin) reaction

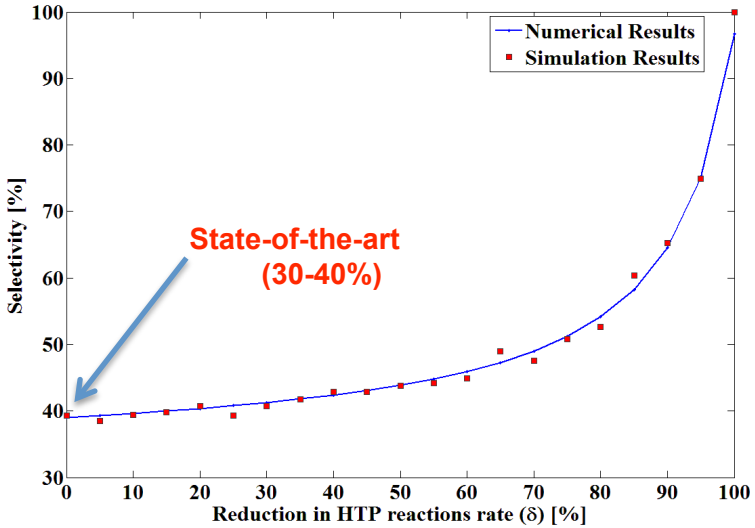
$C_4H_9 + H = C_4H_{10}$

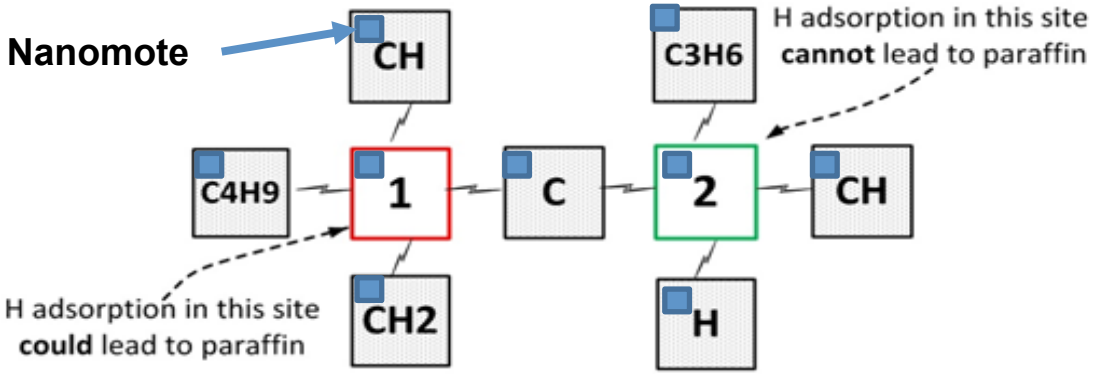
paraffin



How Can NanoWSN Help?
Nanomachine-to-nanomachine communication

- Place a nano device in each site
- Run the following simple algorithm in each nanomote
  - Search neighbourhood for C_nH_{2n+1} when an H attempts to adsorb in an empty site
  - If C_nH_{2n+1} is found in the neighbourhood, repel the H (prevent its adsorption)





Application of NSNs

Other applications

- Environmental monitoring, protection and control [6]
- Plants monitoring systems [1]
- Plagues defeating systems [1]
- Structure Health Monitoring as Enabler for Safer, Greener Aircrafts [7]
- Industrial and consumer goods applications [1]
- Ultrahigh sensitivity touch surfaces:
- Haptic interfaces:
- Future interconnected office
- Military and defense applications [1]
- Nuclear, biological and chemical (NBC) defenses
- Damage detection systems
- Application of Wireless Nano Sensor Networks for Wild Lives [8]

References for Applications of NSNs:

[1] Akyildiz, I. F., & Jornet, J. M. (2010). Electromagnetic wireless nanosensor networks. *Nano Communication Networks*, *1*(1), 3–19.

[2] Von Maltzahn, G., Park, J.-H., Lin, K. Y., Singh, N., Schwöppe, C., Mesters, R., … Bhatia, S. N. (2011). Nanoparticles that communicate in vivo to amplify tumour targeting. *Nature Materials*, *10*(7), 545–52.

[3] http://indiafuturesociety.org/an-essay-on-nanorobotics-the-future-of-medical-sciences/

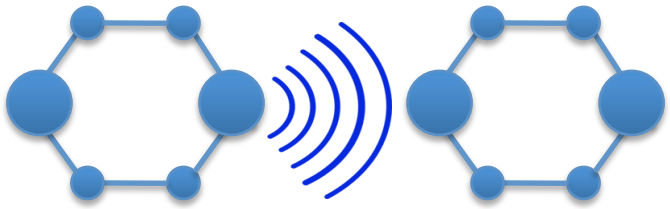
[4]

[5] Zarepour, E., Hassan, M., Chou, C. T., & Adesina, A. A. (2013). Nano-scale Sensor Networks for Chemical Catalysis. In *Proceedings of the 13th IEEE International Conference on Nanotechnology* (pp. 61–66). Beijing, China, August 5-8.

[6] Upal Mahfuz, M., & Ahmed, K. M. (2005). A review of micro-nano-scale wireless sensor networks for environmental protection: Prospects and challenges. *Science and Technology of Advanced Materials*, *6*(3-4), 302–306.

[7] Dragomirescu, D., Kraemer, M., Jatlaoui, M. M., Pons, P., Roche, C., & Toulouse, F.-. (2010). 60GHz Wireless Nano-Sensors Network for Structure Health Monitoring as Enabler for Safer , Greener Aircrafts. In *SPIE- Advanced Topics in Optoelectronics Microelectronics and Nanotechnologies*. Constanta, Romania.

[8] Upadhayay, V., & Agarwal, S. (2012). Application of Wireless Nano Sensor Networks for Wild Lives. *International Journal of Distributed and Parallel Systems (IJDPS)*, *3*(4), 173–181.



Module 3

Fundamentals of Nano Communications

The problem with antenna miniaturization

Nano-scale communication seemed an impossible dream …

Antenna Length (λ/2)	Frequency
33.33 cm / 2 = 16 cm	900 MHz
12.5 cm / 2 = 6 cm	2.4 GHz
5 mm / 2 = 2.5 mm	60 GHz
4 µm / 2 = 2 µm	**150 THz**

Speed of Light

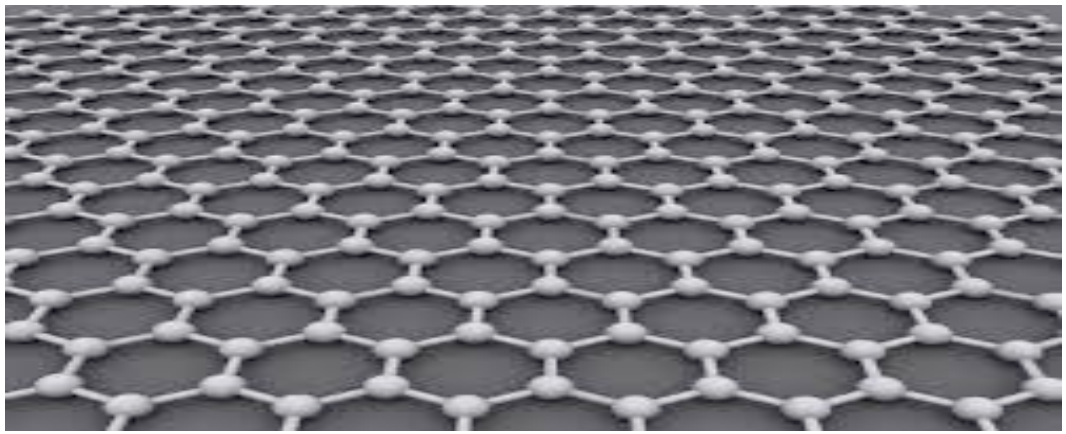
$f = 3 \times 10^8 / \lambda$

On a metallic surface, Electrons travel nearly at speed of light

Extreme path loss! Very high transmission power needed!!

Discovery of graphene, the *wonder material*

2011 Nobel Prize in Physics



Source: wikipedia

One atom thick 2D honeycomb structure

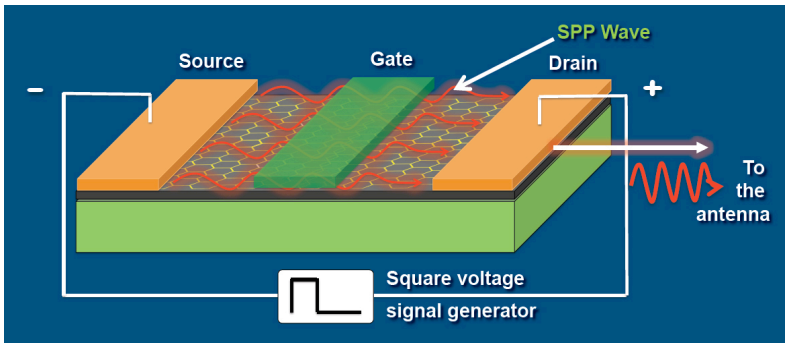
Honeycombs slow down electrons 300 times!

Larger wavelengths (lower frequencies) can be used with small antennas

[Neto2007] A.H. Castro Neto, Graphene: Phonons behave badly, Nature Materials 6, 176-177, 2007

The frequency band for nano communications
0.1-10 THz

- A graphene-based nano-scale antenna has resonance frequencies in 0.1-10 THz band
- Extremely wide band
  - A nano BS could allocate non-interfering channels to millions of nano devices
- Largely unused at the moment
  - Nano can easily co-exist with existing micro /macro deployments

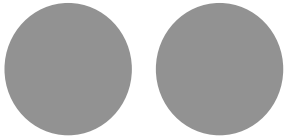


Source: [Akyildiz2013]

[Akyildiz2013] A. Wright, "Tuning in to Graphene," Communications of the ACM, 56(10), pp. 15-17, December 2013 [*the picture was courtesy of Akyildiz*]

Molecular absorption in terahertz band

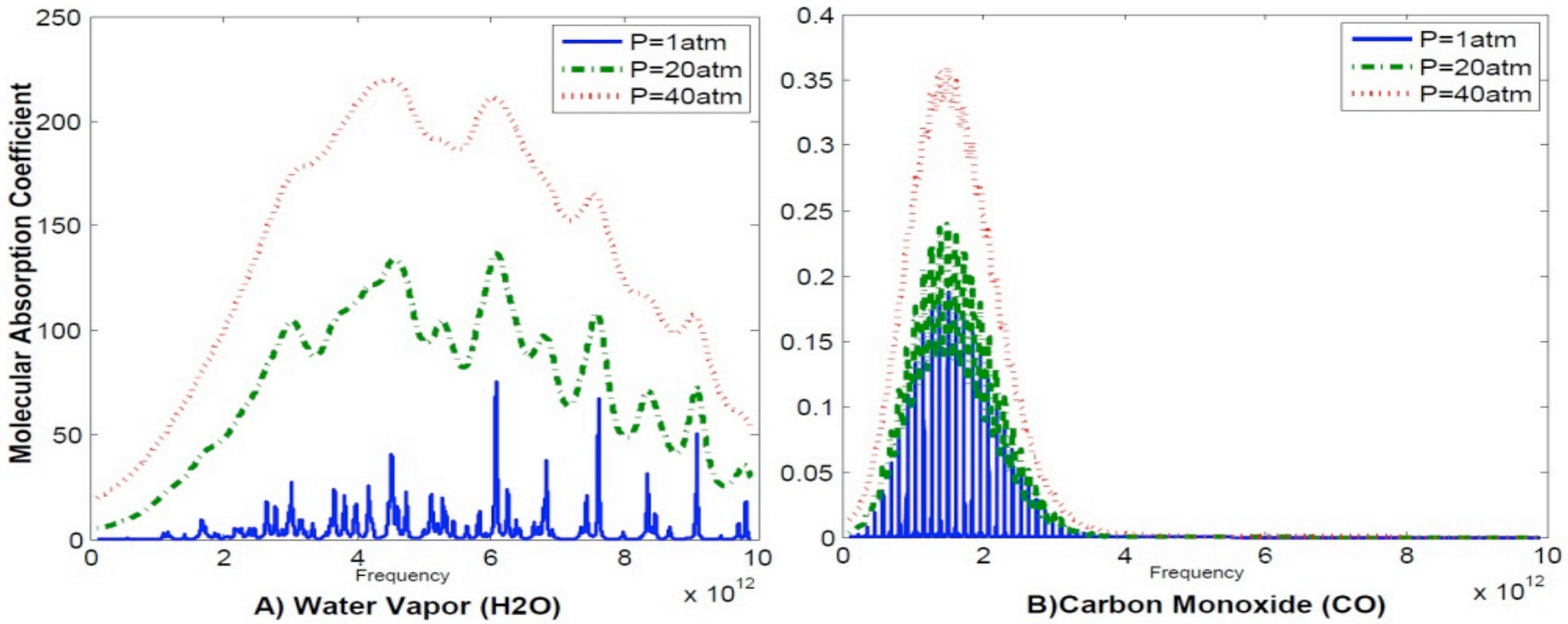
The curse of terahertz communication



- Many molecules resonate in terahertz frequencies
- A resonating molecule absorb energy from the signal
- Different molecules have different resonating frequency
- Different molecules absorb energy by different amounts (*absorption coefficient*)
- Molecular absorption also depends on pressure and temperature

Molecular Absorption

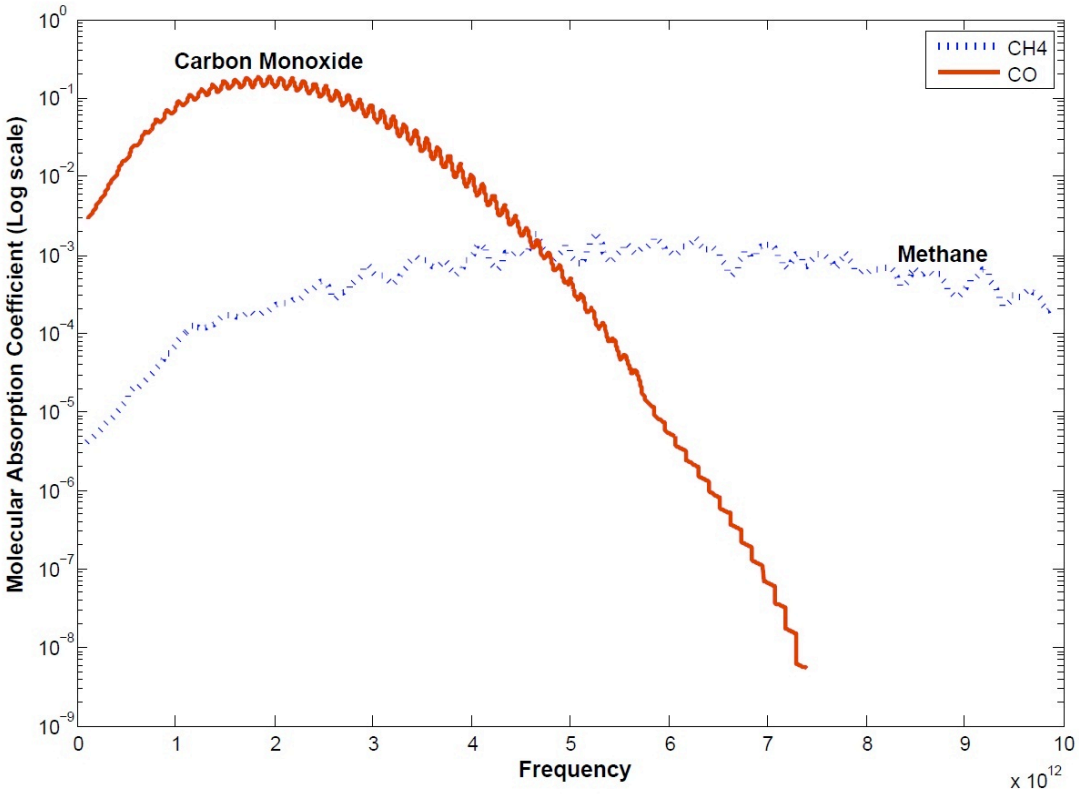
Impact of Pressure



Molecular Absorption Coefficient at 296 Kelvin

Molecular Absorption

Impact of Molecular Composition



Molecular Absorption Coefficient at T=550 K P=40 atm.

Molecular absorption of the channel

- Communication channel is typically a mixture of different types of molecules
- Need to know the molecular composition of the channel

$$k_{ch} = \sum_{i \in M} z_i k_i$$

Where $\mathcal{M}$ is the set of elements of the channel, z_i is the mole fraction and k_i is the absorption coefficient of element *i*

Path loss formula for nano-communication

free-space path loss

Path loss due to molecular absorption

$$P_r = P_t \times \left(\frac{\lambda}{4\pi d} \right)^2 \times e^{-k_{ch}(f)d}$$

$k_{ch}(f)$: channel absorption coefficient for frequency f

Modulation and coding for nano communication

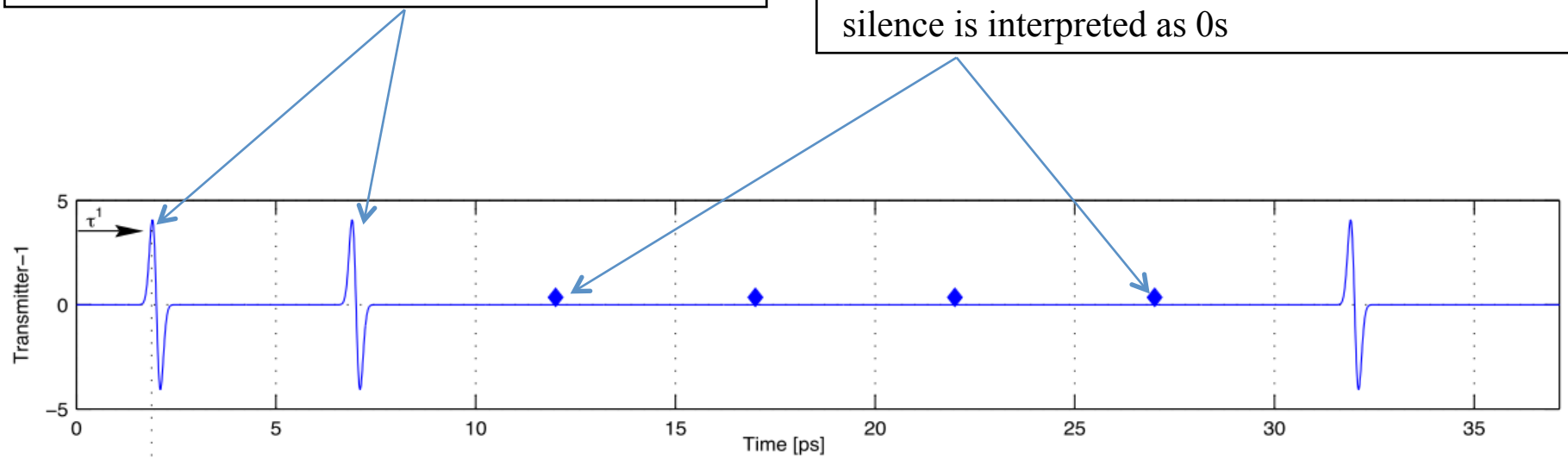
Going for *pulse-based* communication

- Carrier-based communication too energy demanding
- Carrier-less pulse-based communication is proposed for nano communication
- In particular, ON-OFF KEYING is proposed
  - Send a pulse for '1', but no pulse for '0'
- Time-spread ON-OFF KEYING (TS-OOK) is considered a more optimized OOK for nano communication

TIME SPREAD ON-OFF KEYING

A logical "1" is encoded with a pulse:
* Pulse length: Tp= 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



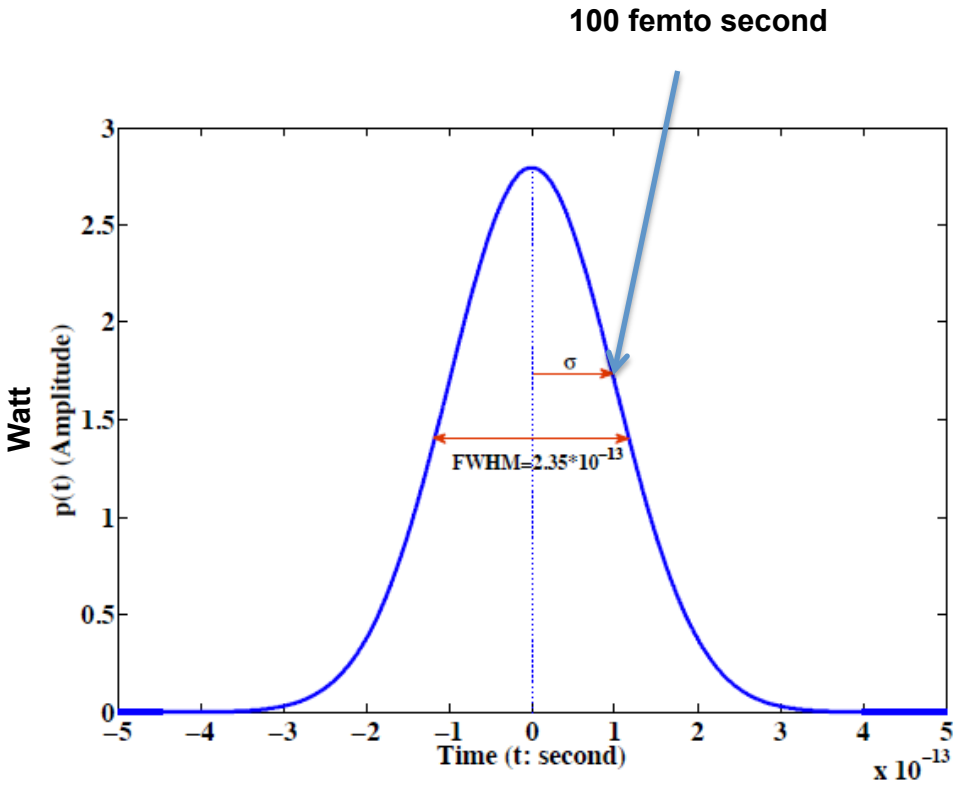
Source: [Jornet2011]

A Nano-sensor is transmitting the sequence "1100001"

Pulses are *spread in time* to simplify the transceiver architecture…

[Jornet2011] J.M. Jornet and I.F. Akyildiz, "Information capacity of pulse-based wireless nanosensor networks", IEEE SECON 2011

Gaussian Pulse



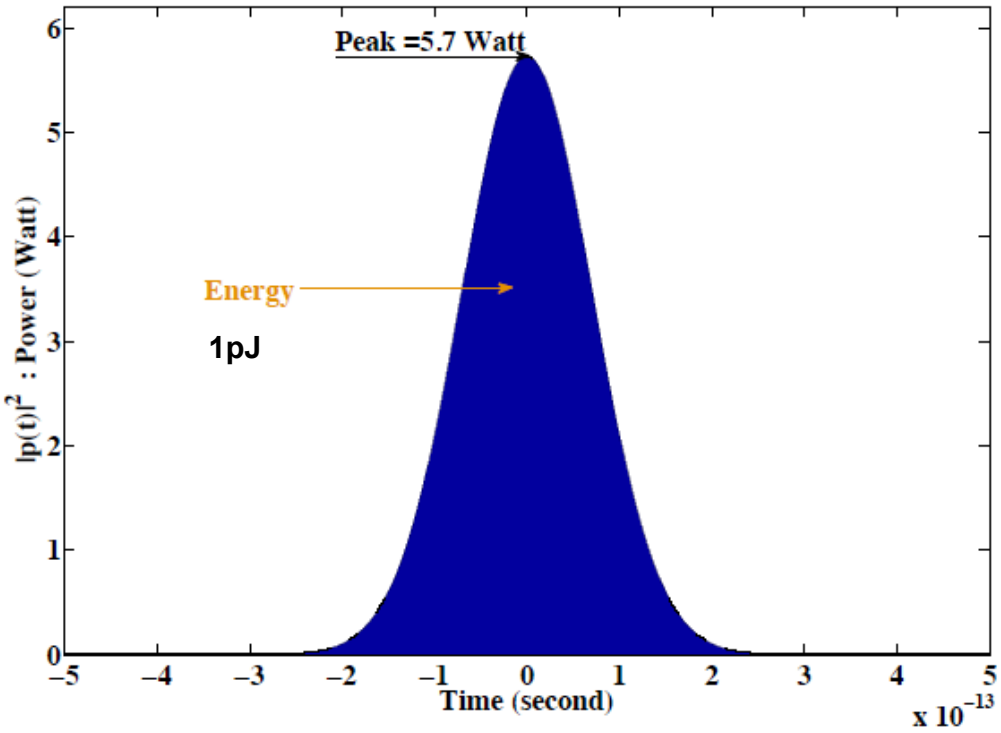
A 100-fs Gaussian pulse

$$p(t) = \frac{a_0}{\sqrt{2\pi}\sigma} e^{-(t-\mu)^2/(2\sigma^2)}$$

$$\text{FWHM} = 2\sqrt{2ln(2)}\sigma \simeq 2.35\sigma.$$

Small energy, high power

$$E_G = \int_{-\infty}^{+\infty} |p(t)|^2 dt = \frac{a_0^2 \times erf(\frac{t}{\sigma})}{4 \times \sqrt{\pi} \times \sigma} = \frac{a_0^2}{2\sigma\sqrt{\pi}}$$

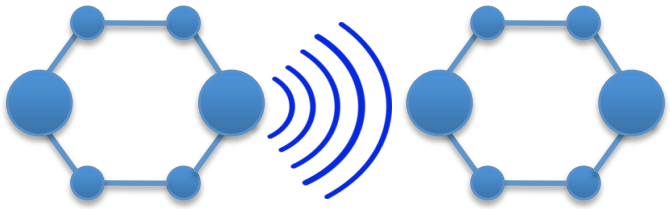


To generate a 100 fs Gaussian pulse with peak power of 2.55 W, we need only 1pJ

Two key issues in nano communicaton networks

- Extreme path loss due to molecular absorption
  - Chemical composition of channel becomes relevant
  - Communication protocols need to be 'chemo-smart'

- Extremely restricted power supply
  - Needs more intelligent use of power (application driven intelligence)
  - Intelligent use of energy harvesting



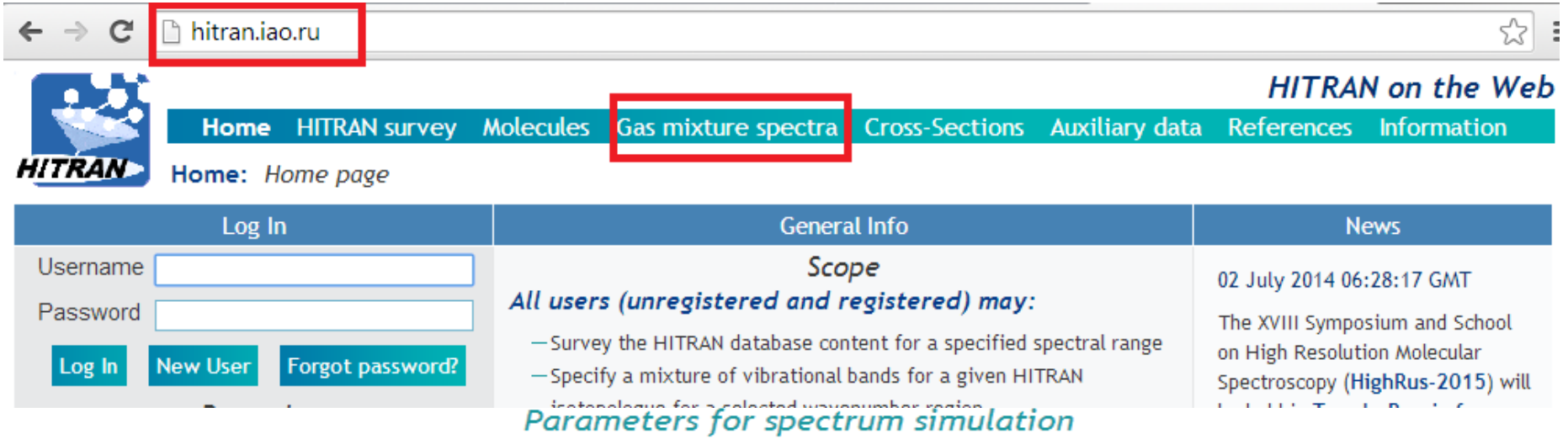
Module 4

Some Useful Tools for NanoWSN Research

Calculating molecular absorption coefficient

The HITRAN database

- Absorption depends on many parameters of a molecule and it is a complex process to measure those parameters
- HTRAN (**hi**gh-resolution **tran**smission molecular absorption database) is an international database holding important spectroscopic parameters of many common molecules
- Currently 42 different molecules are covered
- This database can be used to compute molecular absorption of a specific nano communication channel of interest
- HITRAN on the Web (e.g., http://hitran.iao.ru)
  - A tool to extract absorption coefficient from HITRAN database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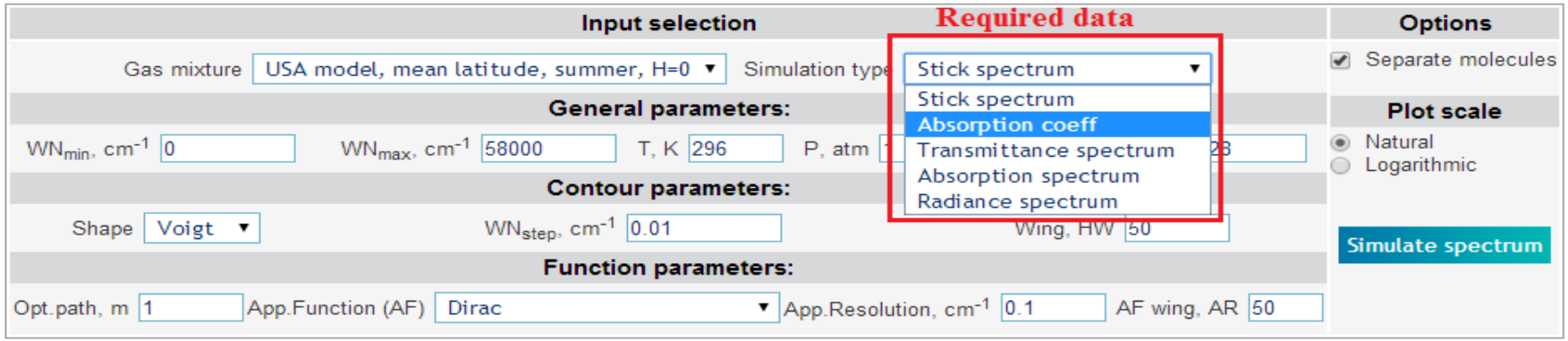
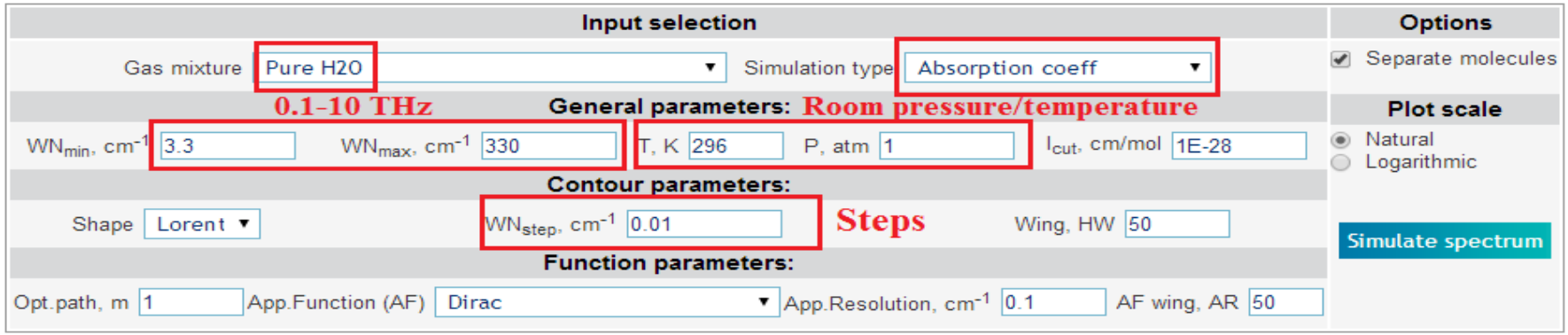
General Info
Scope
All users (unregistered and registered) may:
—Survey the HITRAN database content for a specified spectral range
—Specify a mixture of vibrational bands for a given HITRAN
News
02 July 2014 06:28:17 GMT
The XVIII Symposium and School on High Resolution Molecular Spectroscopy (HighRus-2015) will
Parameters for spectrum simulation
Composition
Input selection
Options
Gas mixture
USA model, mean latitude, summer, H=0
Simulation type
Stick spectrum
Separate molecules
IAO model, mean latitude, winter, H=0
IAO model, high latitude, summer, H=0
IAO model, high latitude, winter, H=0
IAO model, tropics, H=0
Pure H2O
Pure CO2
Pure O3
Pure N2O
Pure CO
Pure CH4
Plot scale
Natural
Logarithmic
WNmin, cm-1
0
P, atm
1
Icut, cm/mol
1E-28
Shape
Voigt
Wing, HW
50
Simulate spectrum
Opt.path, m
1
App.Resolution, cm-1
0.1
AF wing, AR
50

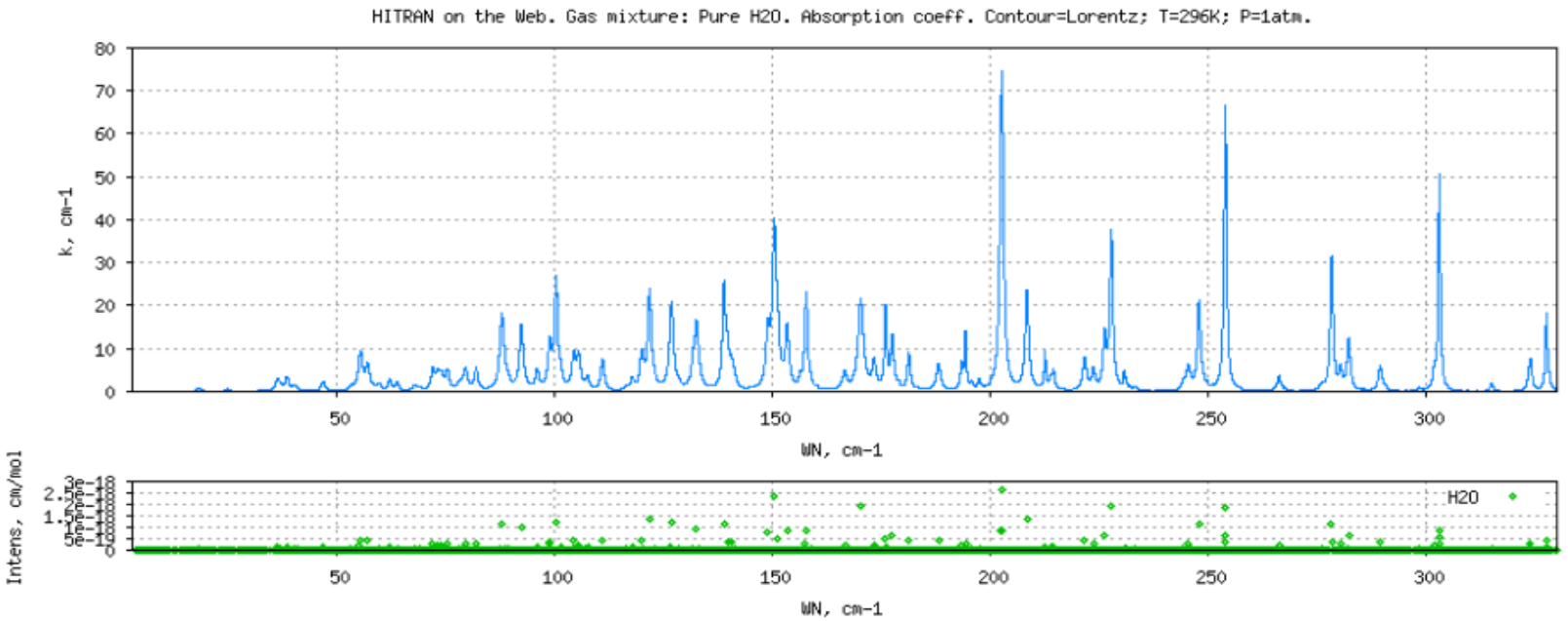
Parameters for spectrum simulation



Parameters for spectrum simulation



Press **simulate** button (or download text data)



You can download the results Download gzipped data

Input selection								Options
Gas mixture: Pure H2O			Simulation type: Absorption coeff					Separate molecules
General parameters:								**Plot scale**
WN_{min}, cm^{-1}: 3.3		WN_{max}, cm^{-1}: 330		T, K: 296		P, atm: 1	I_{cut}, cm/mol: 1E-28	Natural / Logarithmic
Contour parameters:								
Shape: Lorent		WN_{step}, cm^{-1}: 0.01				Wing, HW: 50		

NANO-SIM

- An open source tool for simulating NanoWSN
- Implemented within NS3
- Nanonodes, nanorouters, nanointerfaces
- Message generation application: CBR (constant bit rate)
- TS-OOK at the PHY layer
- Transparant MAC – packet directly delivered to PHY destination
- Simulate performance of NanoWSN applications, such as health monitoring at nanoscale with nanonodes and nano routers inside human body

G. Piro, et al., ``*Nano-Sim: simulating electromagnetic-based nanonetworks in the network simulator 3*,'' International ICST Conference on Simulation Tools and Techniques, 2013

COMSOL

- Multi physics
- Model and simulate any physics-based systems
- Accurate simulation of signal propagation under molecular absorption, radiative transfer and diffusion theory
- Impact of antenna on transmission

Recent use of COMSOL in nano communications research:

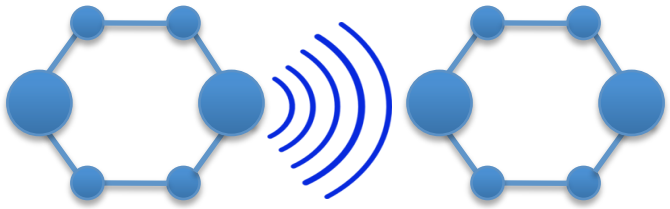
Jornet and Akyildiz "Femtosecond-Long Pulse-Based Modulation for Terahertz Band Communication in Nanonetworks," IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 62, NO. 5, MAY 2014

SSA (Stochastic Simulation Algorithm)

- Simulate chemical kinetic systems with disparate reactions rates
- Useful for nano communication channel simulation in a chemical reactor
- Markov processes used to determine transitions to next chemical state of the channel

Recent use of SSA in NanoWSN research

1. Zarepour, E., Adesina, A. A., Hassan, M., & Chou, C. T., "**An innovative approach to improving gas-to-liquid fuels catalysis via nano-sensor network modulation**," *ACS Industrial & Engineering Chemistry Research*, vol. 53, no. 14, pp. 5728–5736, Mar. 2014
2. Zarepour, E., Hassan, M., Chou, C. T., & Adesina, A. A. (2014). **Power Optimization in Nano Sensor Networks for Chemical Reactors**. In *1st ACM International Conference on Nanoscale Computing and Communication (ACM NANOCOM)*. 13-14 May 2014, Atlanta, Georgia, USA.
3. Zarepour, E., Hassan, M., Chou, C. T., & Adesina, A. A. (2014). **Frequency Hopping Strategies for Improving Terahertz Sensor Network Performance over Composition Varying Channels**. *IEEE WoWMoM* 2014.



Module 5

A Survey of NanoWSN Research

Taxonomy of NanoWSN Research

http://nanocom.web.cse.unsw.edu.au/Taxonomy01.html

- Nanoantenna design
- Channel modeling and capacity analysis
- MAC
- Energy harvesting
- Internet of nano things
- Optimisations for composition varying channels

Nanoantenna design

- Designing small antennas is a challenging problem
- Recent research favours
  - graphene-based nanoantenas
  - CNT-based nanoantenas

1. J. M. Jornet and I. F. Akyildiz, "Graphene-based Nano-antennas for Electromagnetic Nanocommunications in the Terahertz Band," in Proc. of EUCAP 2010, Fourth European Conference on Antennas and Propagation, Barcelona, Spain, April 2010.
2. Llatser, Ignacio - Graphene-enabled Wireless Communication Networks at the Nanoscale, Science pp. 1--9,2011
3. Jornet, J. M. and Akyildiz, I. F., "Graphene-based Plasmonic Nano-antennas for Terahertz Band Communication in Nanonetworks," to appear in IEEE Journal on Selected Areas in Communications (JSAC), Special Issue on Emerging Technologies in Communications, 2013
4. Hanson, G. W. , Fundamental transmitting properties of carbon nanotube antennas, IEEE Transactions on Antennas and Propagation 53(11):3426--3435,2005
5. Atakan, Baris, Akan, Ozgur B , Carbon Nanotube Sensor Networks, Proc. IEEE NanoCom pp. 1--6,2009,
6. Emre Koksal, C., Ekici, E., & Rajan, S. (2010). Design and analysis of systems based on RF receivers with multiple carbon nanotube antennas. Nano Communication Networks, 1(3), 160–172.

Channel modeling and capacity analysis

- Real experiments with nanomotes still not possible
- Researchers employ physics-based theories to model nano communication channels

Akyildiz, I.F., Jornet, J.M., Pierobon, Massimiliano , Propagation Models for Nanocommunication Networks, Antennas and Propagation (EuCAP), 2010 Proceedings of the Fourth European Conference on pp. 1--5,2010

Jornet, Josep Miquel, Member, Student, Akyildiz, Ian F , Channel Modeling and Capacity Analysis for Electromagnetic Wireless Nanonetworks in the Terahertz Band, October 10(10):3211--3221,2011

Jornet, J. M., & Akyildiz, I. F. (2011). Information capacity of pulse-based Wireless Nanosensor Networks. 2011 8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, 80–88.

MAC for NanoWSN

Wang, P., Jornet, J. M., Malik, M. G. A., Akkari, N., and Akyildiz, I. F., "Energy and Spectrum-aware MAC Protocol for Perpetual Wireless Nanosensor Networks in the Terahertz Band," to appear in Ad Hoc Networks (Elsevier) Journal, 2013.

Jornet, J. M., Capdevila Pujol, J., & Solé Pareta, J. (2012). PHLAME: A Physical Layer Aware MAC protocol for Electromagnetic nanonetworks in the Terahertz Band. Nano Communication Networks, 3(1), 74–81.

Energy harvesting NanoWSN

Jornet, J. M. and Akyildiz, I. F., "Joint Energy Harvesting and Communication Analysis for Perpetual Wireless NanoSensor Networks in the Terahertz Band," IEEE Transactions on Nanotechnology, Vol. 11, No. 3, pp. 570-580, May 2012.

R. G. Cid-Fuentes, A. Cabellos-Aparicio and E. Alarcón, "Energy harvesting enabled wireless sensor networks: Energy model and battery dimensioning", in proc. of the 7th International Conference on Body Area Networks (BODYNETS), September 2012

Internet of nano things

1 F. Akyildiz, and J. M. Jornet, "The Internet of Nano-Things," IEEE Wireless Communications Magazine, Vol. 17, n. 6, pp. 58-63, December 2010.

2 Han, C., Jornet, J. M., Fadel, E., and Akyildiz, I. F., "A cross-layer communication module for the Internet of Things,"Computer Networks (Elsevier) Journal, vol. 57, no. 3, pp. 622-633, February 2013.

3 Jornet, J. M. and Akyildiz, I. F., "The Internet of Multimedia Nano-Things," Nano Communication Networks (Elsevier) Journal, vol. 3, no. 4, pp. 242-251, December 2012.

Optimisations for composition varying channels

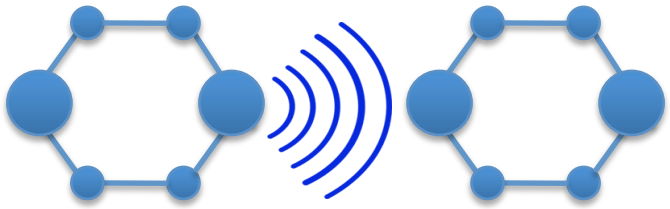
- Molecular composition of the NanoWSN channel is important
- Researchers are finding new applications of NanoWSN where channel composition varies due to different reasons
- Power, frequency, and other parameters must be selected based on the channel composition
- Three types of composition variations
  - Different locations in human body has different compositions
  - Moisture level variation causes channel composition variation in agriculture monitoring
  - Chemical reactions cause continuous composition variations within a chemical reactor (UNSW Research)

Frequency band selection

1 T. Javed and I. H. Naqvi, “Frequency band selection and channel modeling for WNSN applications using simplenano,” in Proceeding of the 2013 IEEE International Conference on Communications (ICC)., Jun. 2013, pp. 5732–573

2 Afsharinejad et al., “GA-based frequency selection strategies for graphene-based nano-communication networks” ICC 2014

3 Afsharinejad et al., “Frequency Selection Strategies under varying Moisture levels in Wireless Nano-Networks” NANOCOM 2014



Nano Networking Research at UNSW

Optimisations for Composition Varying Channels

Mahbub Hassan

IEEE WPMC 2014 NanoWSN Tutorial, Sydney, 07 September 2014

Our Recent Research

1. Intelligent use of power (application driven intelligence)
   - ACM NANOCOM 2014

2. 'Chemo-smart' communication to avoid molecular absorption as much as possible
   - IEEE WOWMOM 2014

Contribution of ACM NANOCOM 2014

Eisa Zarepour, Mahbub Hassan, Chun Tung Chou, Adesoji A. Adesina, "Power Optimization in Nano Sensor Networks for Chemical Reactors", 1st ACM International Conference on Nanoscale Computing and Communication (NANOCOM), Atlanta, USA, May 13-14, 2014.

- How to allocate transmission power so that we maximise *selectivity* with minimal power consumption?

- Note that transmission power affects the ability of the nano device to search the neighbourhood, which in turn affects the *selectivity*

Contribution Overview

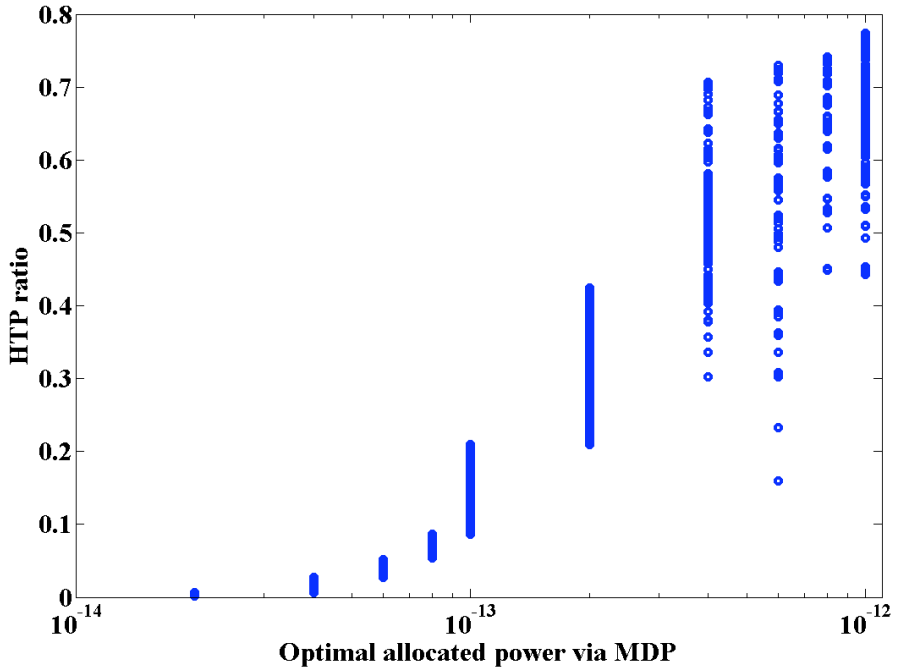
- Optimal power allocation modelled as Markov Decision Process (MDP)
  - Optimal but difficult to realize
- Three *local* power allocation policies
  - Not optimal, but easy to realize
- Performance evaluation and comparison of proposed local policies

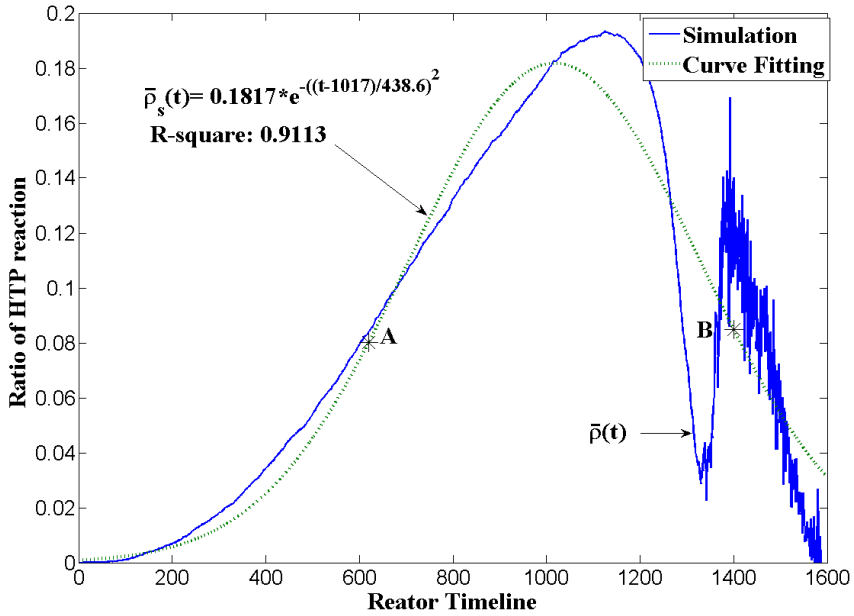
MDP for Nanosensor Power Allocation

- States: #of each type of molecules in the reactor at any given time
- Actions: after each reaction, choose a power level from a predefined set
- Transition probabilities between states depend on power level chosen
  - Power level affects probability of successful neighbourhood search, which also depends on the current state (molecular composition of the channel)
- Revenues
  - Smaller revenue for choosing higher power levels, and vice versa (we want to minimise power consumption)
  - Larger revenue for higher probability of successful neighbourhood search, and vice versa
- We cannot solve the MDP for large scale reactors (too many states), so we used an approximation method to obtain selectivity and power levels

Reaction Rate Based Local Policy (RRLP

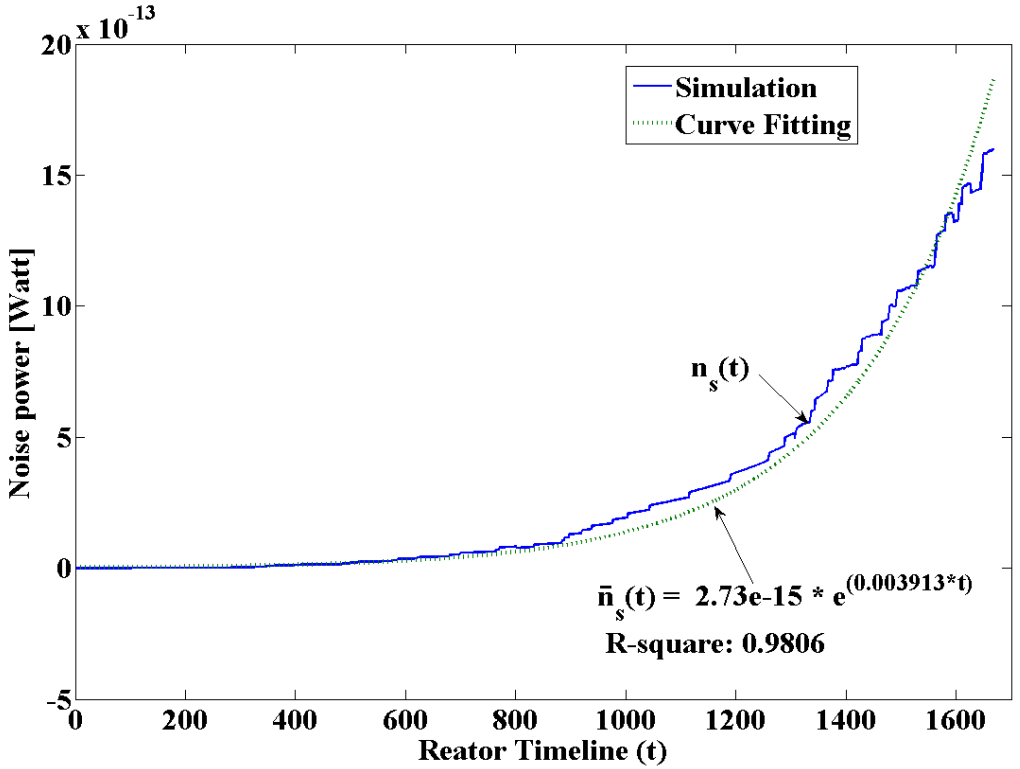
•Choose high transmission power when HTP reactions are more likely to occur, save power in other times





Noise Based Local Policy (NLP)

- RRLP does not take into account the channel variation due to varying composition in the reactor
- In NLP, higher power is allocated when higher level of molecular noise/absorption is expected(improves neighbourhood search)



Local Policy RRLP+NLP

- RRLP allocates higher transmission power when the HTP reaction rate is high while NLP allocates higher power when the noise is high.
- During the third quarter of the reaction cycle, reaction rate is high while noise is low, but during the last quarter, the reaction rate is low but noise is high.
- Therefore, RRLP may not perform well in the last quarter and NLP not performing well in the third quarter.
- To overcome this problem, we propose a local policy that uses both reaction rates and noise levels
- The rationale of this local policy is to use high transmission power when either reaction rate or noise is high.

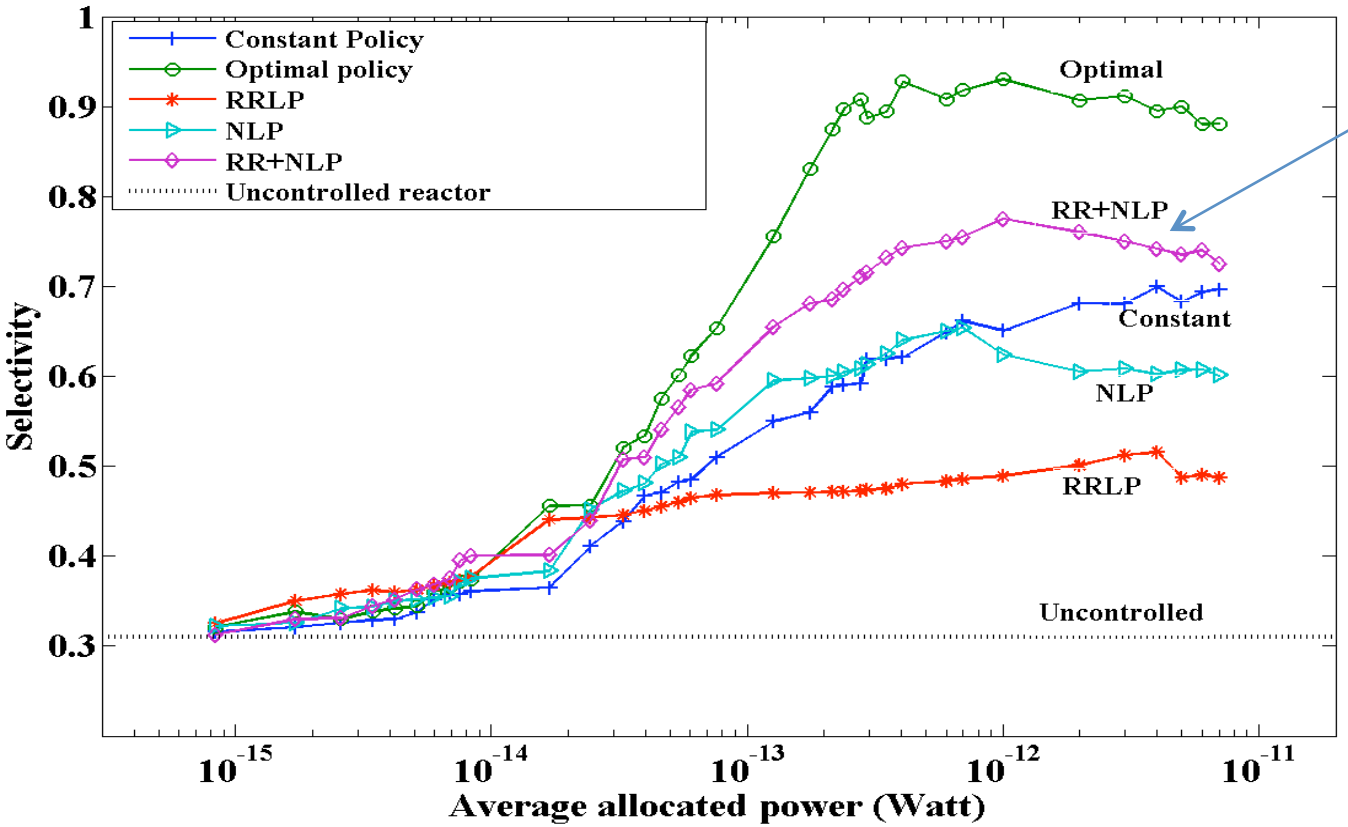
$$\hat{P}_{RR,n}(t) = P_m \max\left(\frac{\bar{\rho}_s(t)}{\max_t \bar{\rho}_s(t)}, \frac{\bar{n}_s(t)}{\max_t \bar{n}_s(t)}\right)$$

Simulation Experiments

- We use Stochastic Chemical Kinetics for simulation, which describes the time evolution of a well-stirred chemically reacting system)
- FT reactor starts with 500 carbon and 1200 hydrogen atoms and operates under 500K and 10 atm
- Nano devices use TS-OOK modulation; distance between two device=1000 nm
- There are m equally spaced power levels in the range $[\frac{P_{\text{nominal}}}{100}, 100P_{\text{nominal}}]$
- We conduct 30 sets of experiments, each with a deferent P_{nominal} from 10^{-16} to 10^{-11} W

Results

Performance of different policies

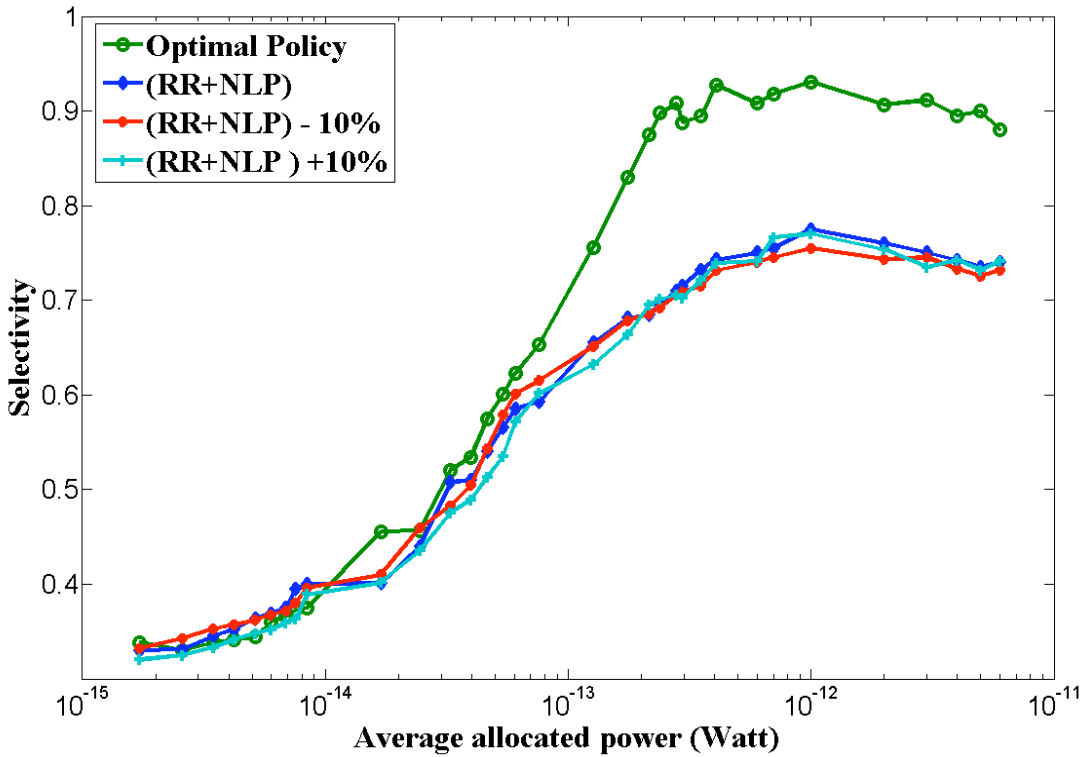


- **93% improvement in selectivity compared to uncontrolled reactor**
- **61% improvement in power consumption**

Results

Robustness

- It may not be possible to precisely control the initial composition of the reactor
- How robust are these local policies under perturbed initial conditions?
- We consider two perturbed initial compositions: 450 carbon and 1080 hydrogen atoms (-10% deviation) and 550/1320 (+10% deviation)



Conclusion of NANOCOM 2014

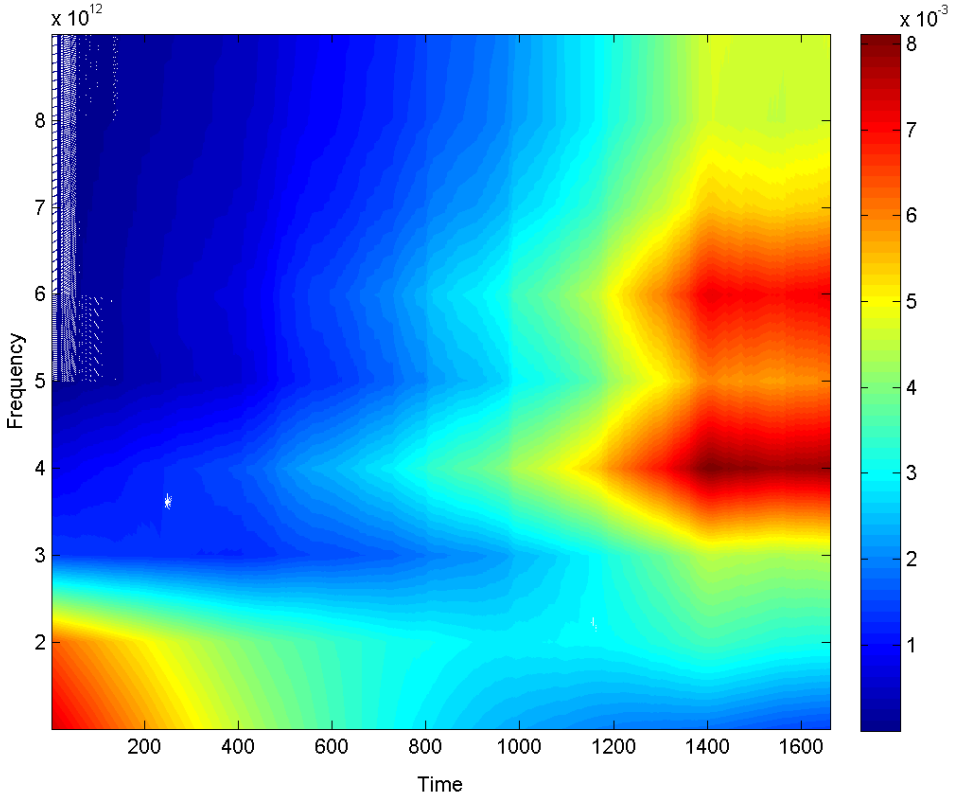
- This work has shown that dynamic power allocation significantly reduces power consumption of nano sensor networks used in chemical reactors
- Simple time-based local policies can provide substantial benefits over constant power allocation schemes
- Local policies proposed in this paper could not realise the full potential of dynamic power allocation (as predicted by MDP-based allocation)
- There is room for improving the local policies (future work)

Contribution of IEEE WOWMOM 2014

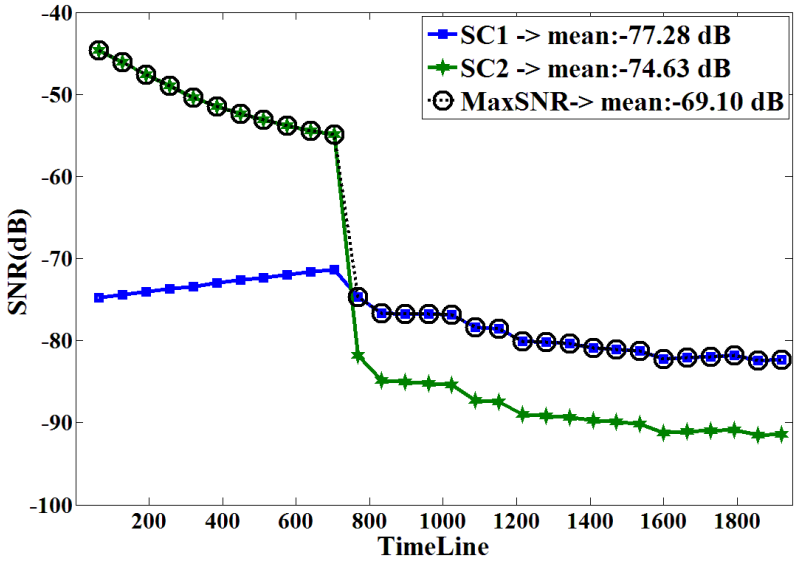
E. Zarepour, M. Hassan, C. T. Chou, A. A. Adesina, "Frequency Hopping Strategies for Improving Terahertz Sensor Network Performance over Composition Varying Channels", IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, 16-19 June, 2014

- How to dynamically choose a frequency to minimize molecular absorption at any given time?
- Policies
  - MDP (optimal): reward for SNR, but penalty for frequency switch
  - Best channel: no frequency hopping
  - Offline 1: based on most probable composition at time t (using simulation)
  - Offline 2: based on average composition at time t (using simulation)

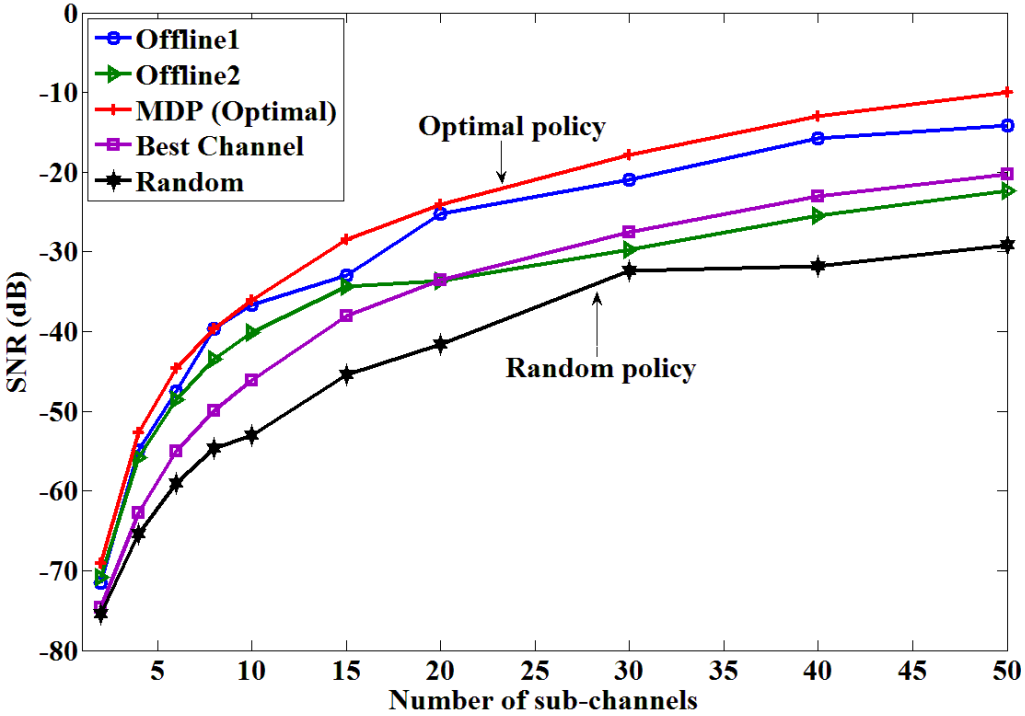
Absorption Spectrogram of F-T Reactor



Results of WOWMOM 2014 -



SNR over time for using two different sub-channels; SC1 (1-5.5 THz), SC2 (5.5-10 THz) and MaxSNR (Optimal).



Achievable SNR via different policies versus number of sub-channels

Key outcomes of NANOCOM 2014 and WOWMOM 2014

1. Molecular absorption is highly dynamic within a chemical reactor (there may be other applications as well)
2. Communication protocols must be *adaptive* to optimize power and performance
3. Can be formulated as an MDP problem, but it requires *observation of chemical composition of the channel*, which is prohibitive for nano-scale devices
4. Close to optimal may be possible with offline simulation (no state observation is required)

Our publications so far

1. Zarepour, E., Adesina, A. A., Hassan, M., & Chou, C. T., "**An innovative approach to improving gas-to-liquid fuels catalysis via nano-sensor network modulation**," *ACS Industrial & Engineering Chemistry Research*, vol. 53, no. 14, pp. 5728–5736, Mar. 2014
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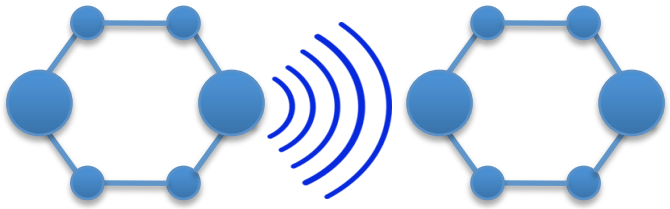
4. Zarepour, E., Adesina, A. A., Hassan, M., & Chou, C. T. (2013). **Nano Sensor Networks for Tailored Operation of Highly Efficient Gas-To-Liquid Fuels Catalysts**. In *Chemeca 2013*. Brisbane, Australia.
5. Zarepour, E., Hassan, M., Chou, C. T., & Adesina, A. A. (2013). **Nano-scale Sensor Networks for Chemical Catalysis**. In *Proceedings of the 13th IEEE International Conference on Nanotechnology (IEEE NANO)* (pp. 61–66). Beijing, China, August 5-8.



Module 6

Future Directions and Research Opportunities

Five important areas

- Applications
- Simulation and experimental methodology
- Modulation and coding
- Energy harvesting

Applications

- Few applications have been investigated in detail, probably because nanomotes are not available yet
- Nanocommunicatios models, albeit theoretical at the moment, are adequately developed to enable application design
- Research in application design may uncover new communication challenges for NanoWSN
- Communication researchers must work with domain experts --- opportunities for true multidisciplinary research

Experiment Methodology

- Nanomotes not available yet --- can't do the real experiments
- Experimental opportunity in NanoWSN is non-existent at the moment
- Can we develop methodologies that will enable us to test some aspects of nanoscale communication using available hardware?

Simulation

- At the moment, different simulators exist for different layers
  - COMSOL for physics
  - SSA for ‘chemical evolution’ of the communication channel
  - NS-3 for wireless propagation
- A simulation framework is needed to integrate these simulators to allow real-time interactions between them
  - Similar to simulations in vehicular communications, e.g., SUMO-NS3 (SUMO simulates cars on the roads and ns3 simulates the wireless communication for the cars)

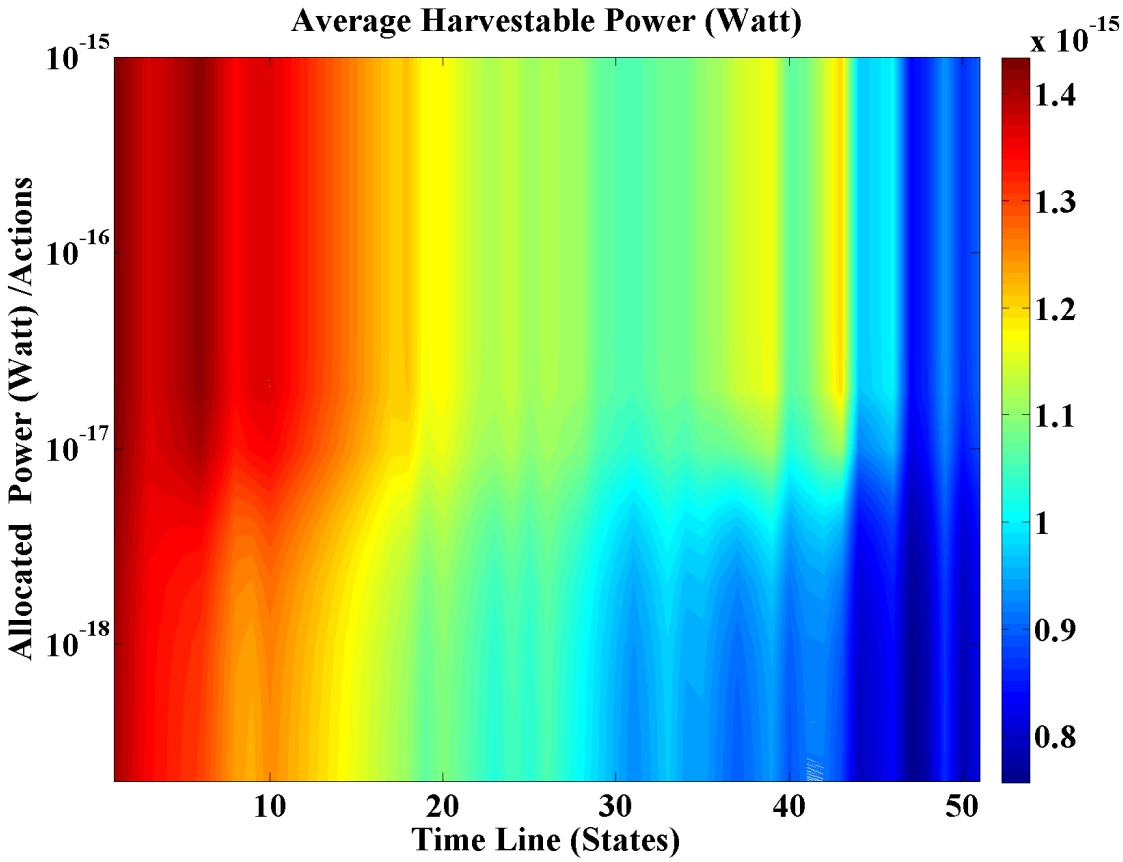
Modulation and Coding

- OOK is the only modulation discussed so far for NanoWSN
- As new applications, new communication environments, and new energy harvestings opportunities emerge, it may be useful to investigate new modulation and coding for the best trade offs

Energy Harvesting

- Energy harvesting in NanoWSN applications can be a complex system
- New communication models may be required to best utilize energy harvesting properties at nano scale

Interaction between transmission power and harvestable power inside a F-T chemical reactor



Acknowledgement

- Eisa Zarepour helped preparing some of the figures

- The speaker acknowledges useful discussions and communications with Chun Tung Chou and Adesina Adesoji

Thanks for your Attention

Any Question ?