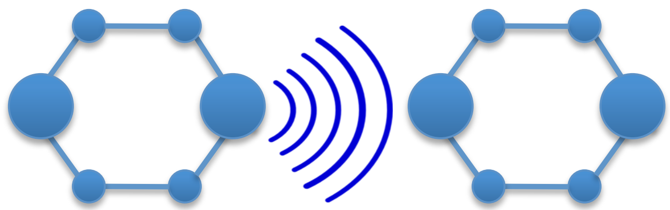


UNSW
THE UNIVERSITY OF NEW SOUTH WALES

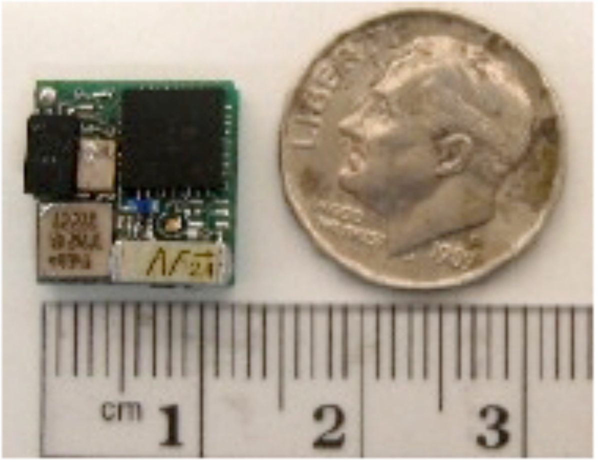
Recent Advances in Nano-scale Communication Networks

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

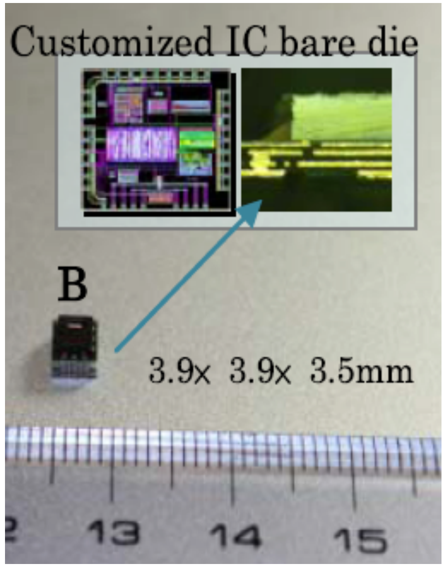
Mahbub Hassan

Professor, School of Computer Science and Engineering, UNSW

The quest for the smallest sensor node



12 mm to 4 mm in 9 years



[Park2005]

[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

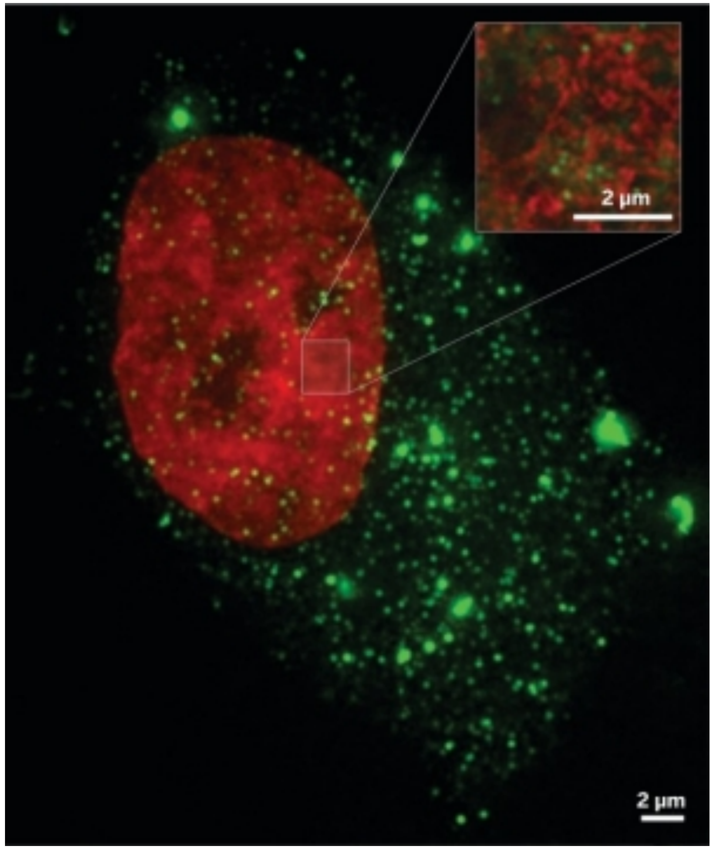
The wonder of nanotechnology

- A breakthrough in material and device technology
- We can now manufacture material at nano-scale
- At nano-scale, materials exhibit strange properties, which can be harnessed to achieve nano-scale wireless communication

Examples of nano materials
Gold nanoparticles

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

Source: ACS Nano

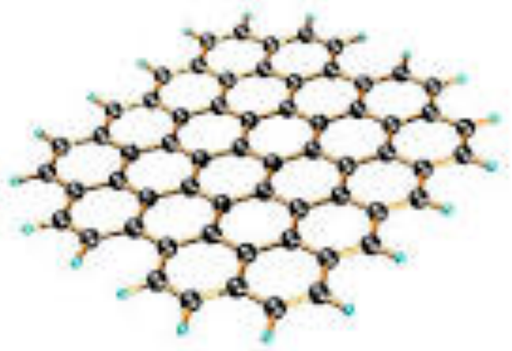


Examples of nano materials
Graphene (a true 2D material!)

- 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

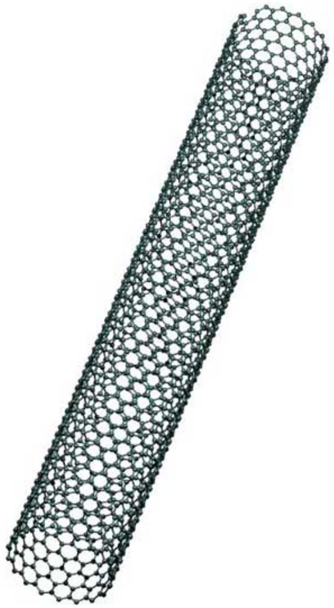
Graphene on substrate



Graphene molecule bonds

Examples of nano materials
Carbon Nano Tube (CNT)

Source: wikipedia

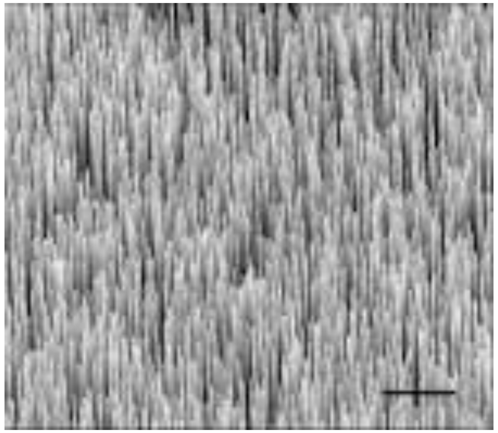


- Cube shaped material (diameter in nanometer scale)
- Batteries with improved lifetime
- Biosensors
- Flat-panel displays

Examples of nano materials
nanowire

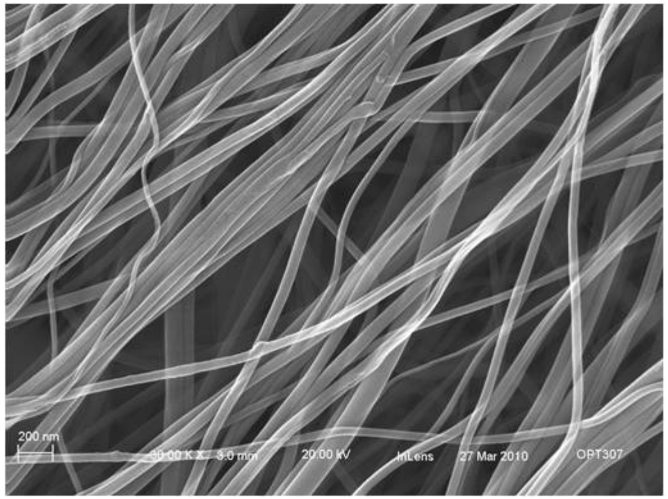
Source: wikipedia

ZnO nanowire



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

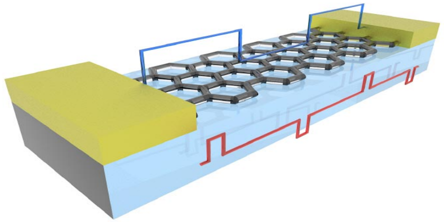
Pt-Fe nanowire



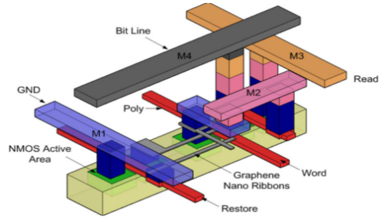
More examples of nanomaterials

- 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 …
- These can be used to build memory, cpu, battery, etc. in nano form factor

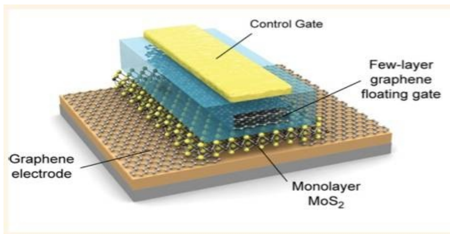
<table>
<tr><th>Nano-scale Memory</th><th>Nano-scale CMOS/Processor</th></tr>
<tr><td>



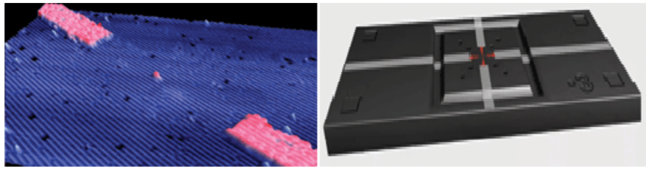
Graphene nanoribbon memory cell
</td><td>



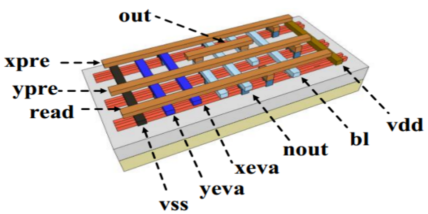
Graphen-based CMOS
</td></tr>
<tr><td>



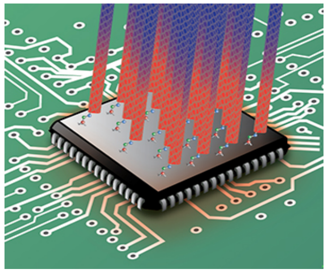
Nano-scale flash memory using graphene
</td><td>



single-atom transistor developed at UNSW
</td></tr>
<tr><td>

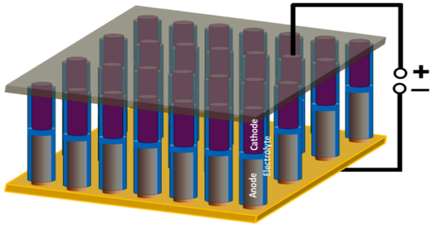


8T-Nanowire RAM Array
</td><td>

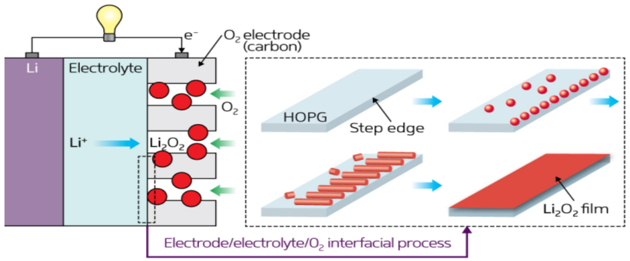


A carbon nanotube CPU
</td></tr>
</table>

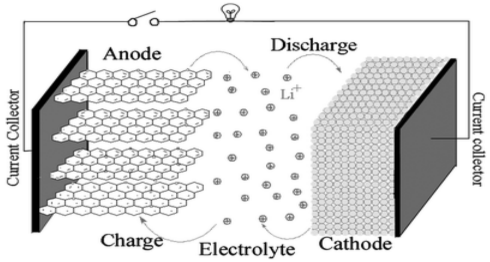
Nano-scale Battery



Nanoscale battery/supercapacitor devices

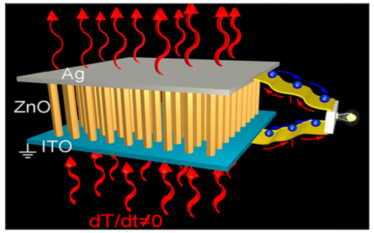


A nanoscale battery

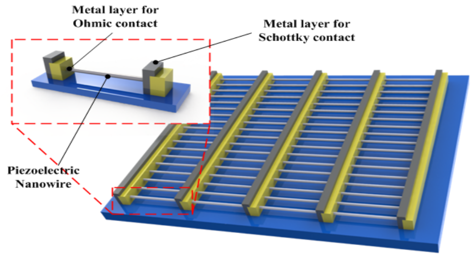


Schematic illustration of a rechargeable lithium battery

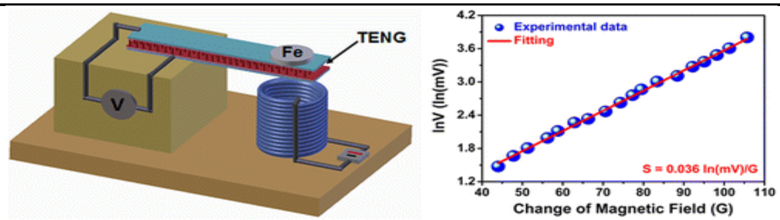
Nano-scale Energy harvesting devices



Pyroelectric Nanogenerators for Harvesting Thermoelectric Energy

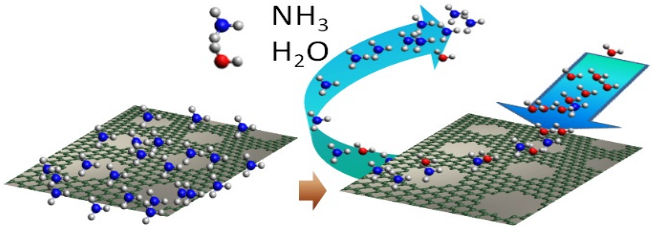


Schematic view of typical Lateral nanowire Integrated Nanogenerato

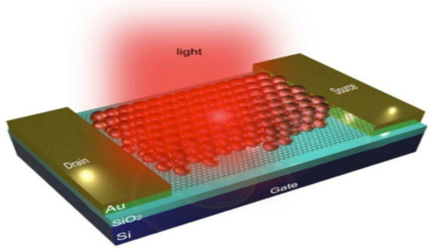


Triboelectric Nanogenerator **for harvesting** Magnetic Field

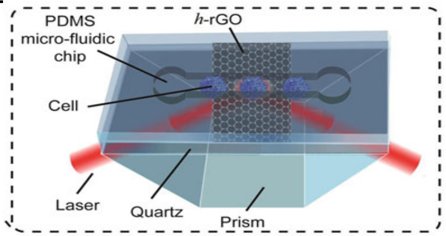
Nano-Sensors



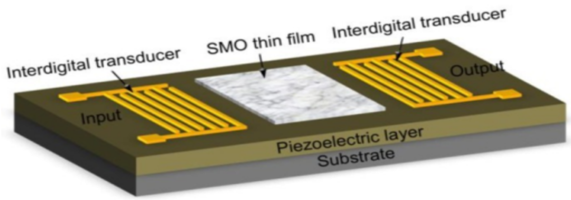
Nanoscale toxic gases Detector (Developed at CSIRO)



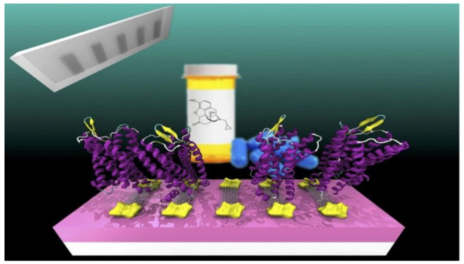
A graphene-based light detecter



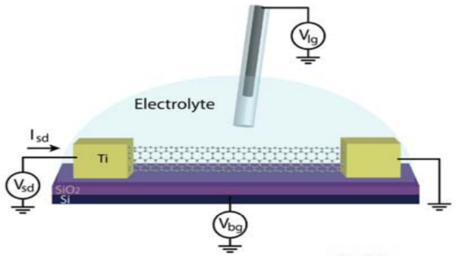
Graphene-based optical sensor detects single cancer cells



A Nano-scale hydrogen sensor

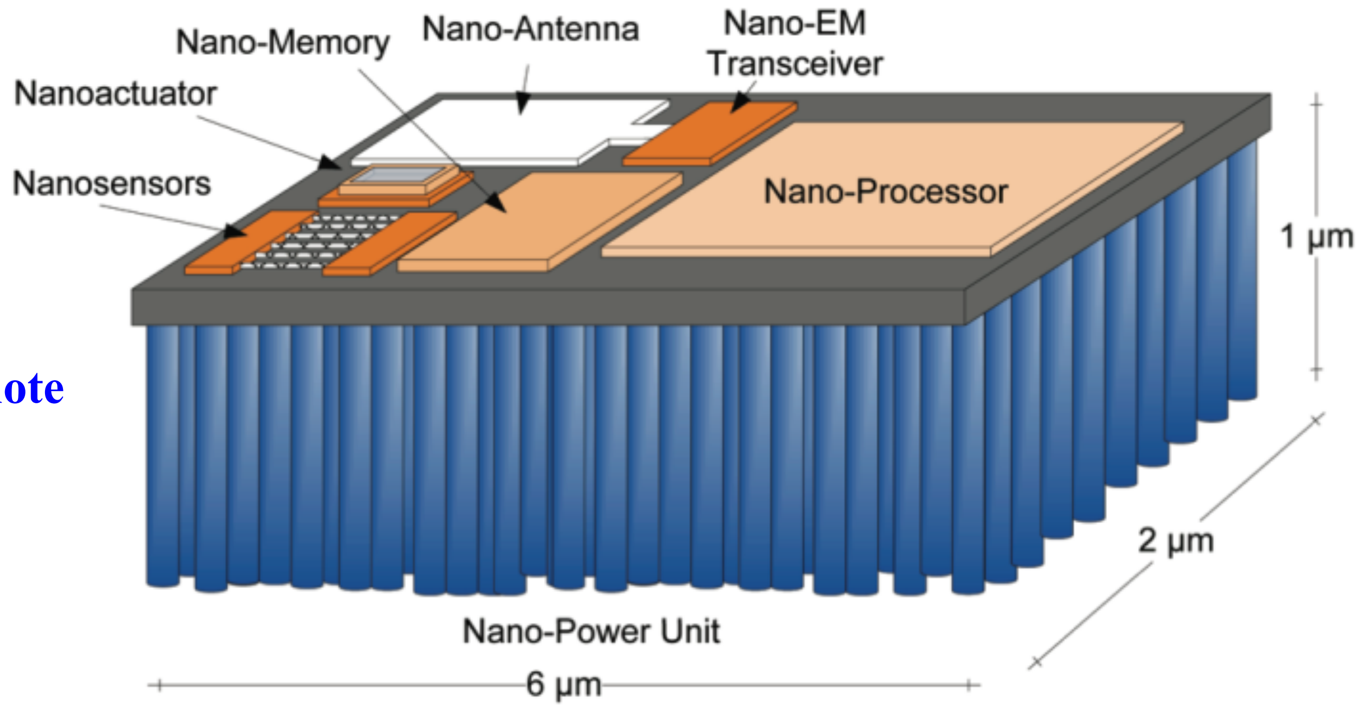


A Bio-Chemical Nanosensors



A Single-Molecule Detector

If we could put it altogether …we have nanomotes!



A Concept Nanomote [Akyildiz2010]

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

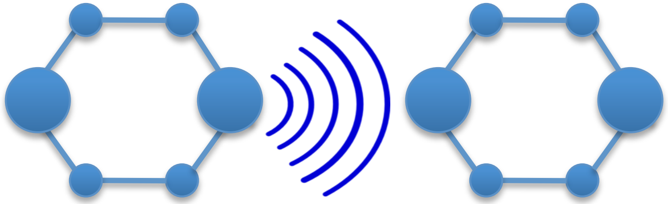
What can we do with nano communication networks?

- Science fiction becomes reality
  - ‘Swallow the surgeon’ Feynman 1959
- Nanoparticles or nanorobots can collaborate
  - Highly successful cancer treatments without any side effects
- Collect data at atomic level
  - Observe and control the nature from the very bottom

Today's Presentation

- Recent advances in nano communications (electro magnetic based)
  - Antenna and the frequency band
  - Propagation model
  - Modulation and coding (carrier-less, pulse-based)
  - Simulation tools

- Nano networking research at UNSW



Recent Advances in Nano Communications

Mahbub Hassan

IEEE Distinguished Lecture, University of Hawaii at Manoa, Honolulu, 11 September 2014

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

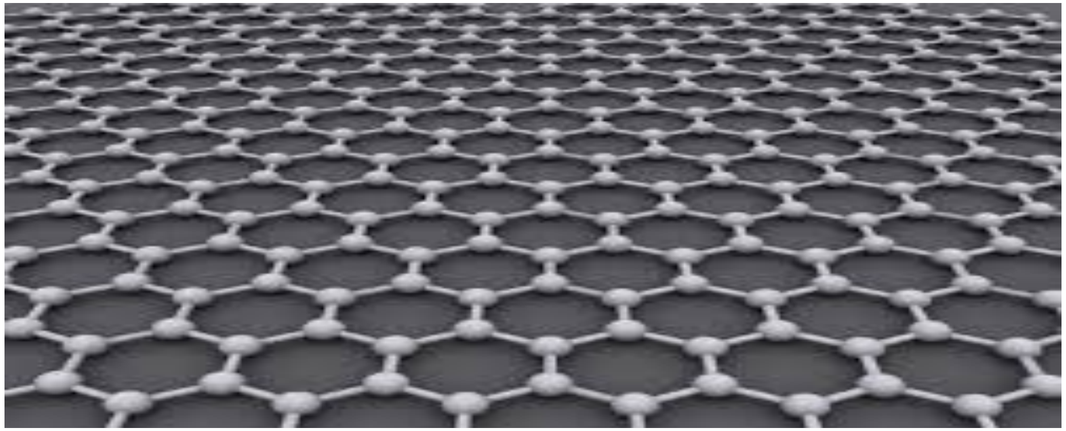
$$f = 3x10^8/\lambda$$

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

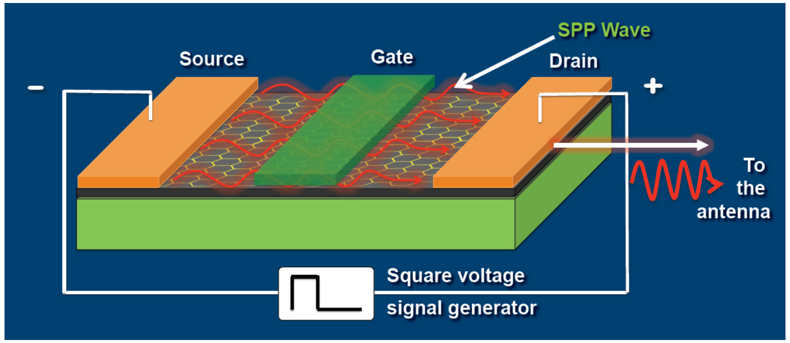
Honeycombs slow down electrons 300 times!

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

Path loss formula for nano-communication

free-space path loss → $\left(\frac{\lambda}{4\pi d}\right)^2$

Path loss due to molecular absorption → $e^{-K(f)d}$

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

K*(*f*): channel absorption coefficient for frequency *f

Molecular absorption of the channel (gas mixture)

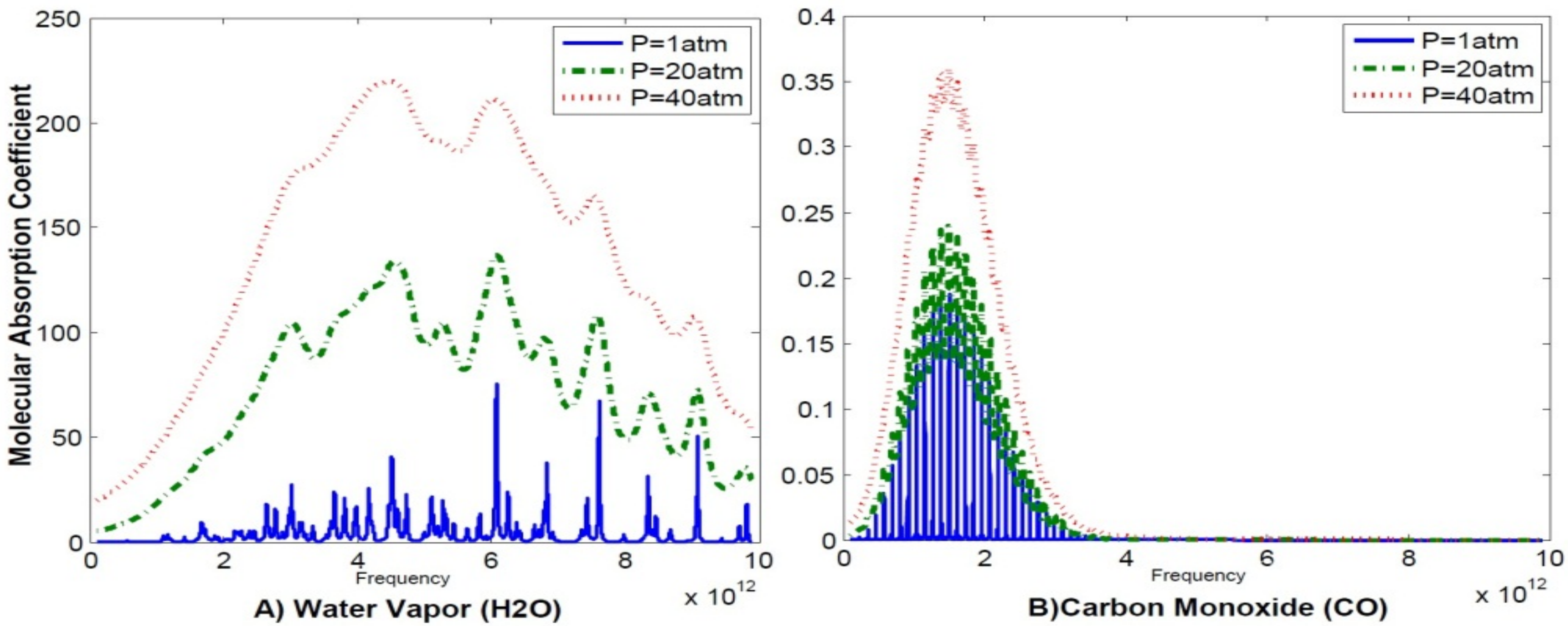
- Communication channel is typically a mixture of different types of molecules
- Need to know the molecular composition of the channel

$$K = \sum_{i \in M} z_i k_i$$

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*

Molecular Absorption

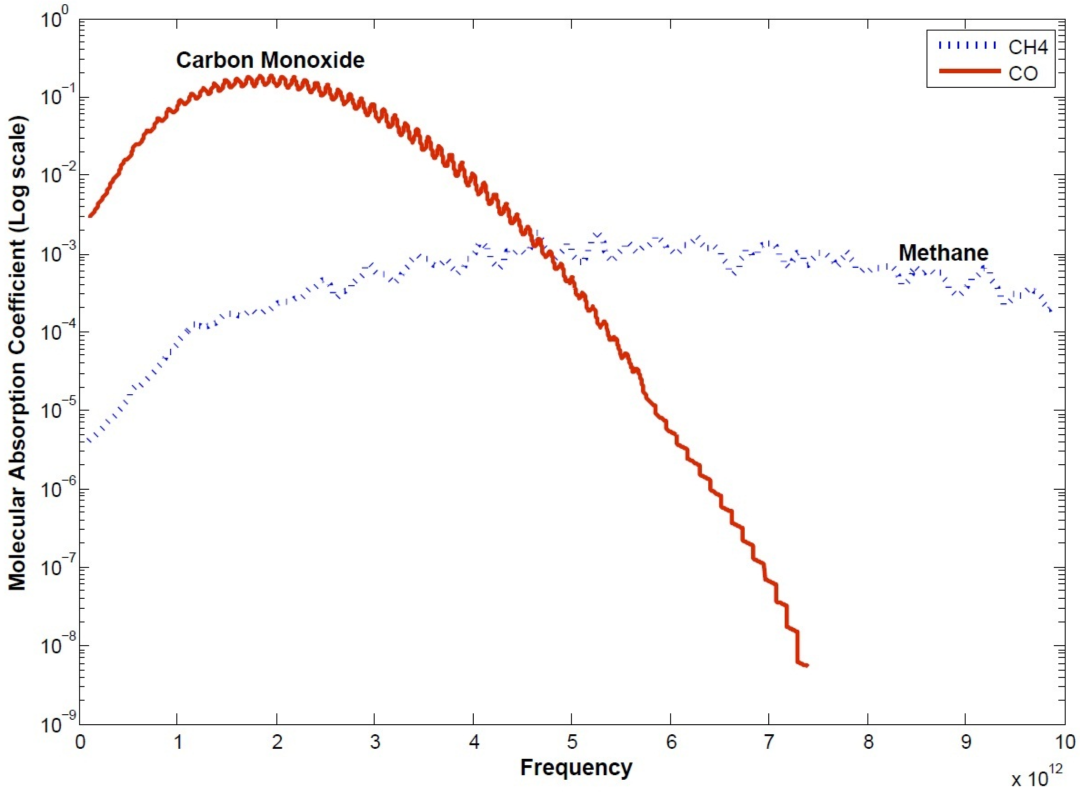
Impact of Pressure



Molecular Absorption Coefficient at 296 Kelvin

Molecular Absorption

Impact of Molecular Composition



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

Modulation and coding for nano communication

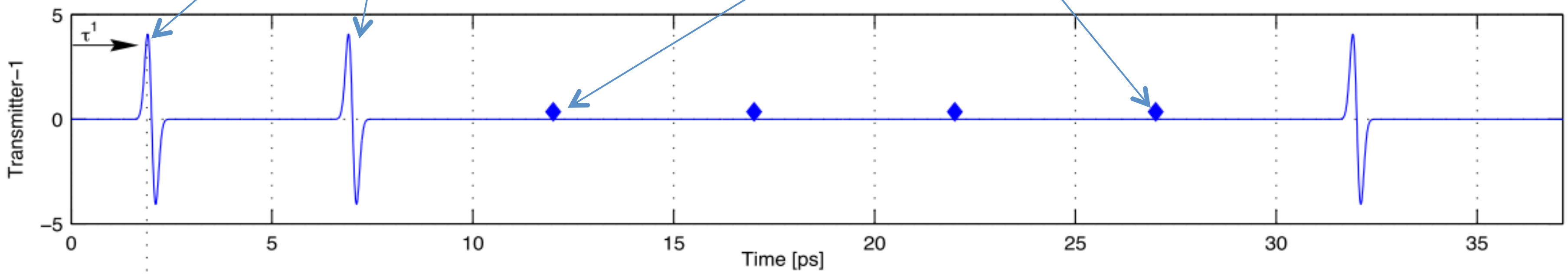
Going for *pulse-based* communication

- 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]

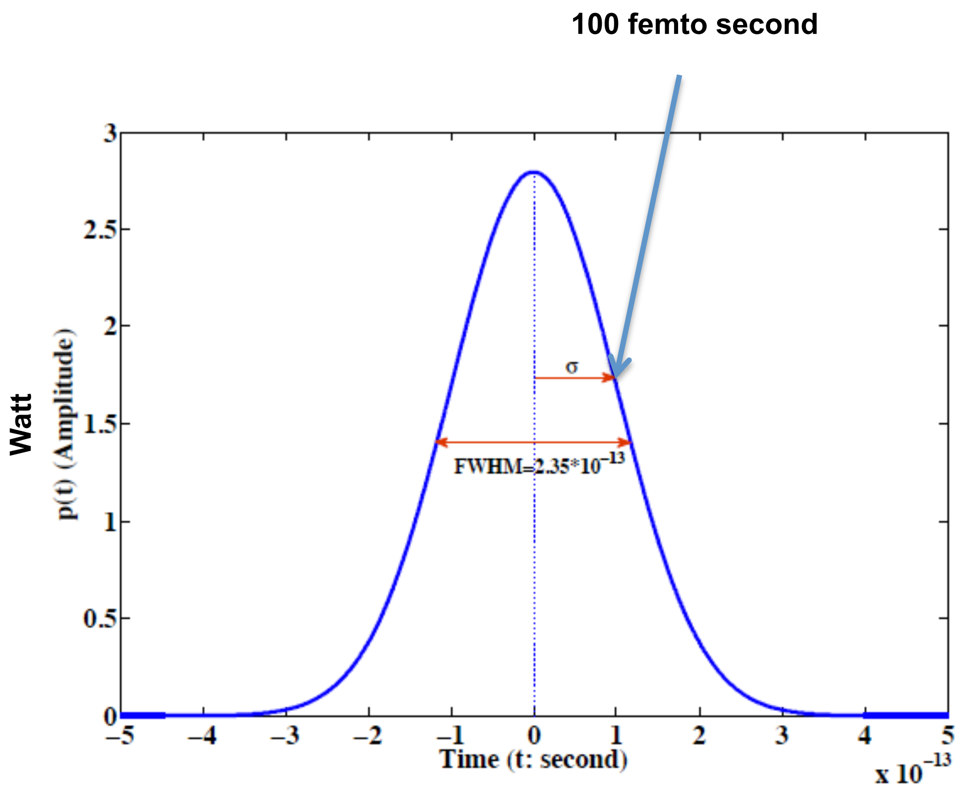
A Nano-sensor is transmitting the sequence "1100001"

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

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

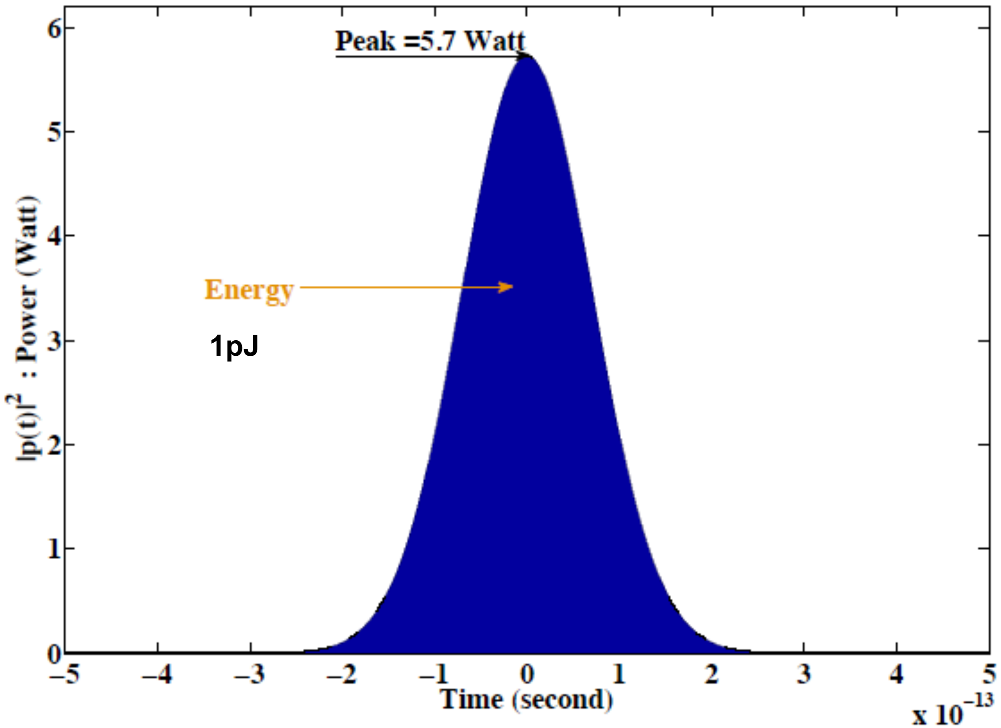


A 100-fs Gaussian pulse

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

Small energy, high power

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



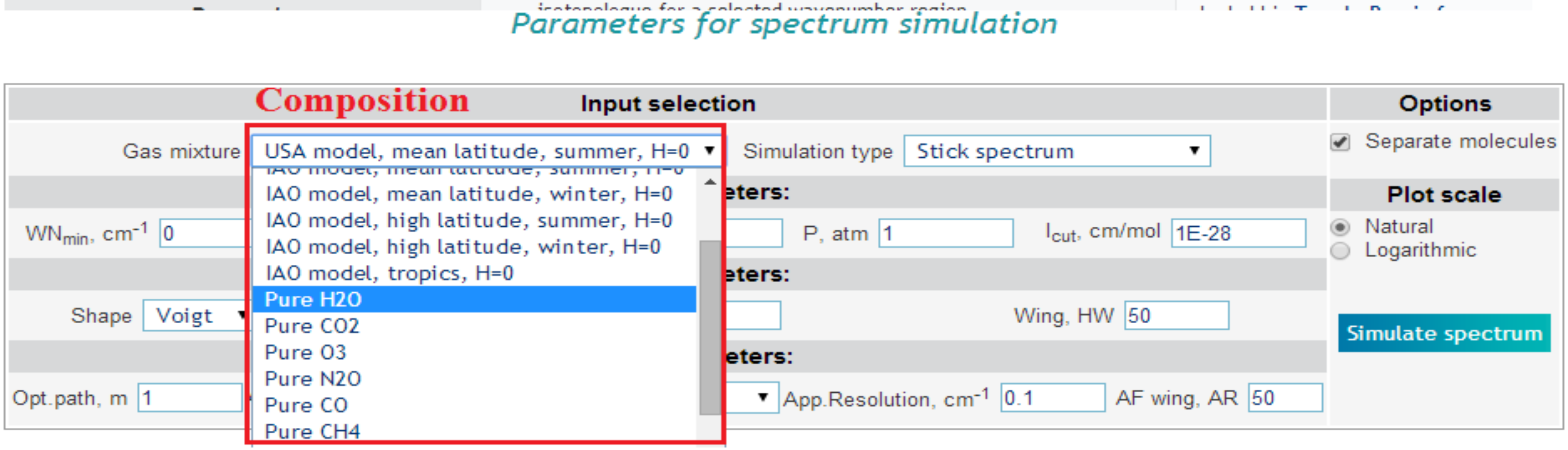
To generate a 100 fs Gaussian pulse with peak power of 2.55 W, we need only 1pJ

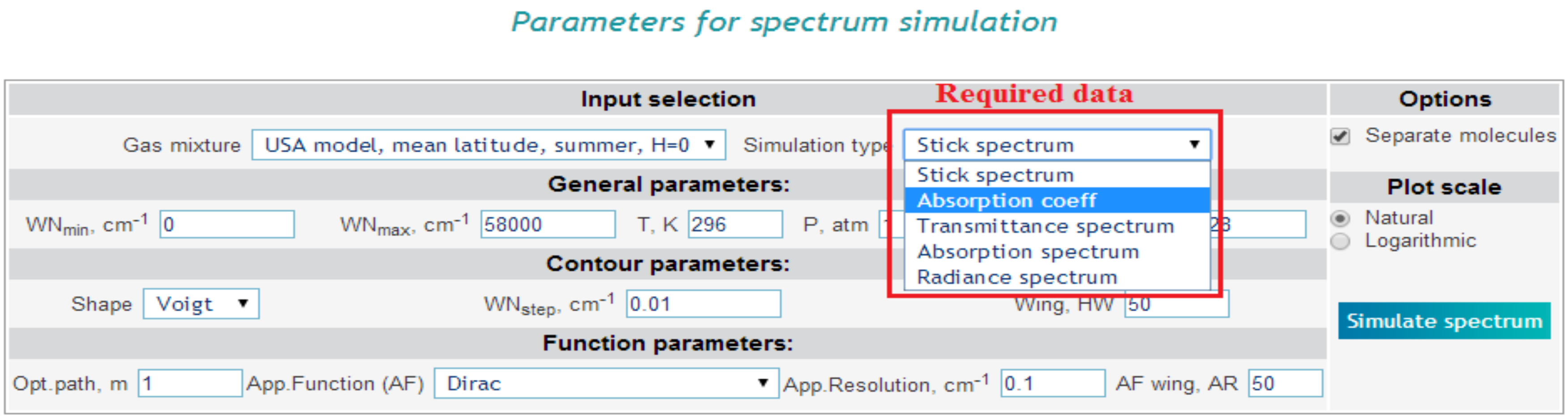
Calculating molecular absorption coefficient

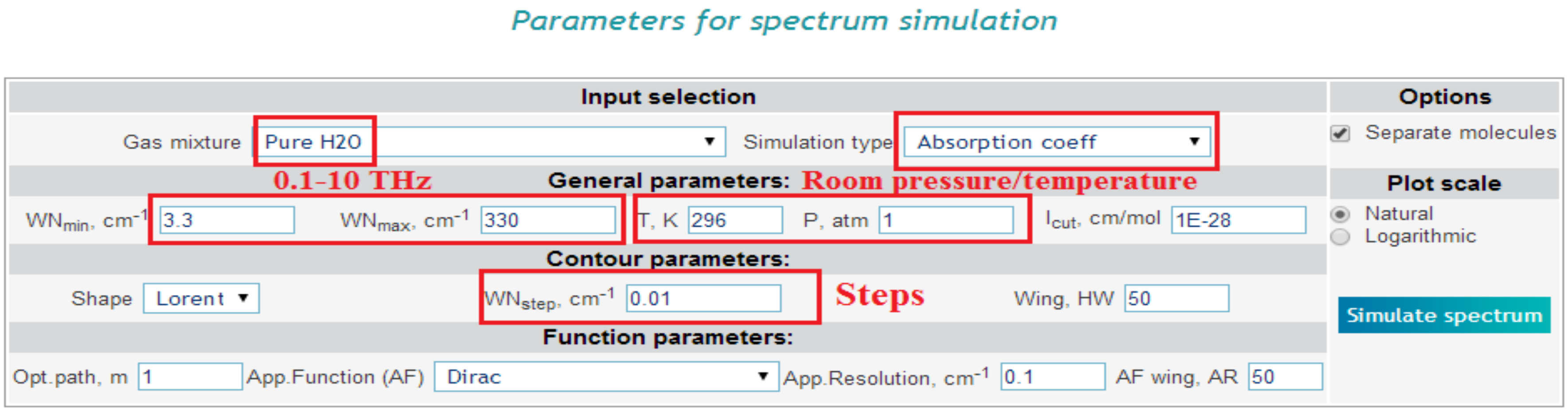
The HITRAN database

- 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

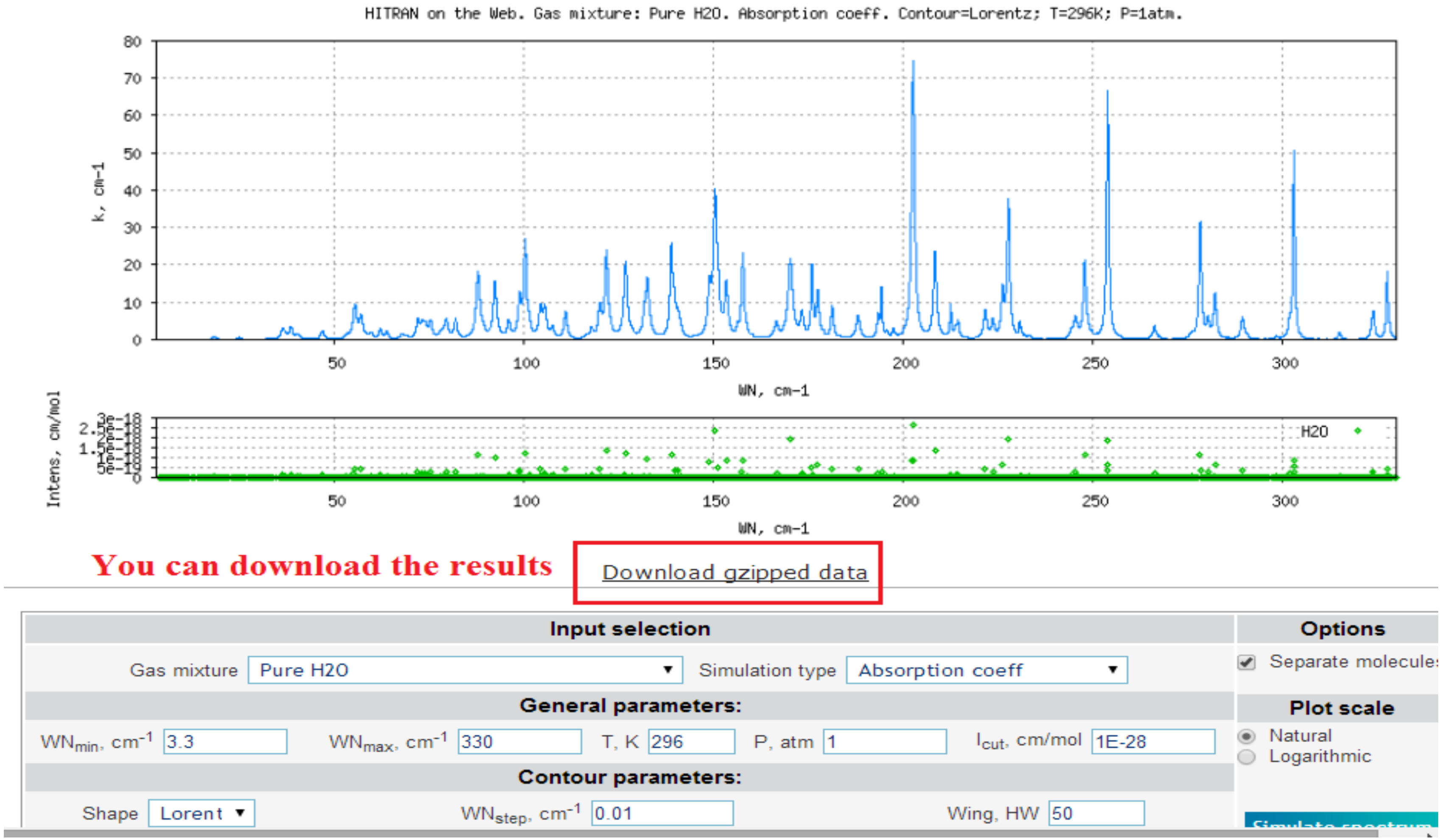

hitran.iao.ru
HITRAN on the Web
Home
HITRAN survey
Molecules
Gas mixture spectra
Cross-Sections
Auxiliary data
References
Information
HITRAN
Home: Home page
Log In
General Info
News
Username
Password
Log In
New User
Forgot password?
Scope
All users (unregistered and registered) may:
—Survey the HITRAN database content for a specified spectral range
—Specify a mixture of vibrational bands for a given HITRAN
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
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
Simulation type
Stick spectrum
Separate molecules
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
Input selection
Required data
Options
Gas mixture
USA model, mean latitude, summer, H=0
Simulation type
Stick spectrum
Stick spectrum
Absorption coeff
Transmittance spectrum
Absorption spectrum
Radiance spectrum
Separate molecules
General parameters:
WNmin, cm-1
0
WNmax, cm-1
58000
T, K
296
P, atm
Plot scale
Natural
Logarithmic
Contour parameters:
Shape
Voigt
WNstep, cm-1
0.01
Wing, HW
50
Simulate spectrum
Function parameters:
Opt.path, m
1
App.Function (AF)
Dirac
App.Resolution, cm-1
0.1
AF wing, AR
50


Parameters for spectrum simulation
Input selection
Options
Gas mixture
Pure H2O
Simulation type
Absorption coeff
Separate molecules
0.1-10 THz
General parameters:
Room pressure/temperature
Plot scale
WNmin, cm-1
3.3
WNmax, cm-1
330
T, K
296
P, atm
1
Icut, cm/mol
1E-28
Natural
Logarithmic
Contour parameters:
Shape
Lorent
WNstep, cm-1
0.01
Steps
Wing, HW
50
Simulate spectrum
Function parameters:
Opt.path, m
1
App.Function (AF)
Dirac
App.Resolution, cm-1
0.1
AF wing, AR
50

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



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:

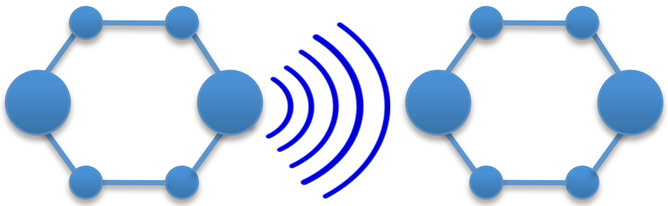
Jornet and Akyildiz "Femtosecond-Long Pulse-Based Modulation for Terahertz Band Communication in Nanonetworks," IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 62, NO. 5, MAY 2014

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.

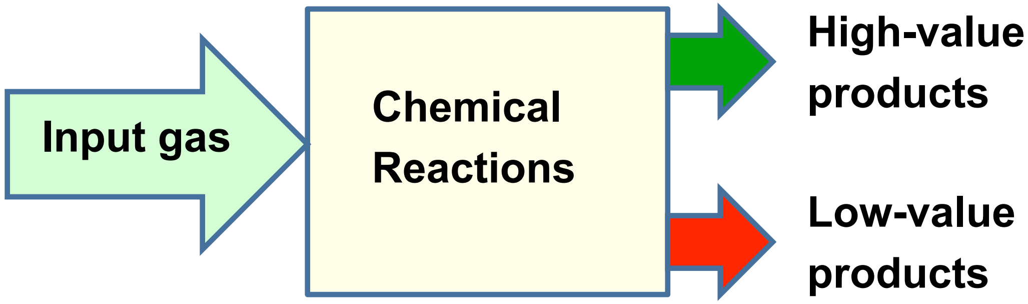


Nano Networking Research at UNSW

The application (initial goals)

1. Find an application that really needs networking between nano-scale devices
2. Should be conceptually feasible
3. If successful, should make dramatic difference compared to the state-of-the-art

Chemical Reactors



Selectivity = percentage of high-value products in the output

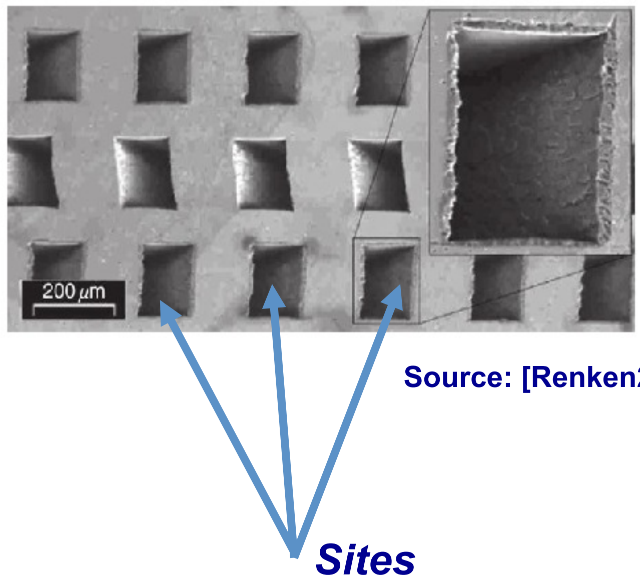
Commercial reactors

Source: wikipedia

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]

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

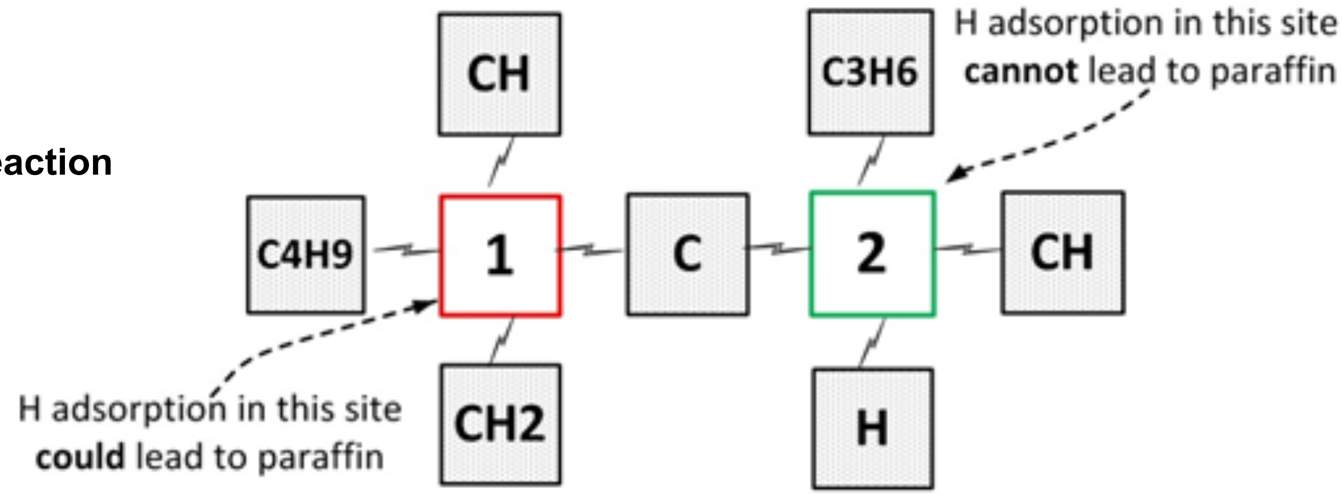
Selectivity in Fischer-Tropsch Reactor (Gas→Liquid)

- 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

$$C_4H_9 + H = C_4H_{10}$$

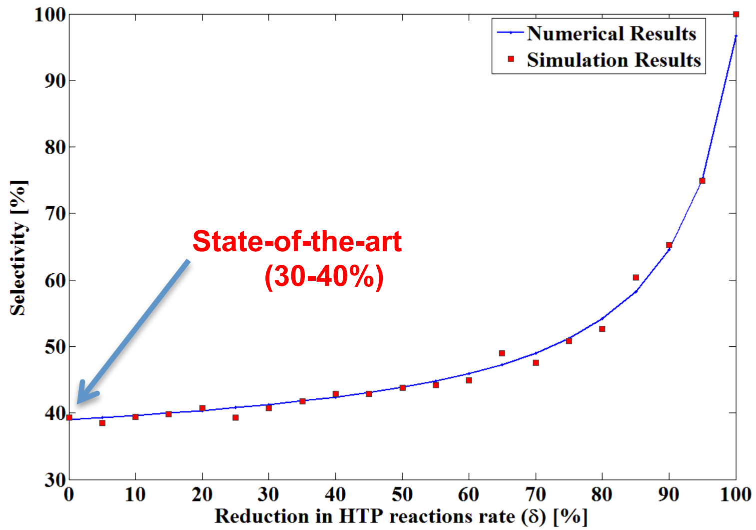
paraffin

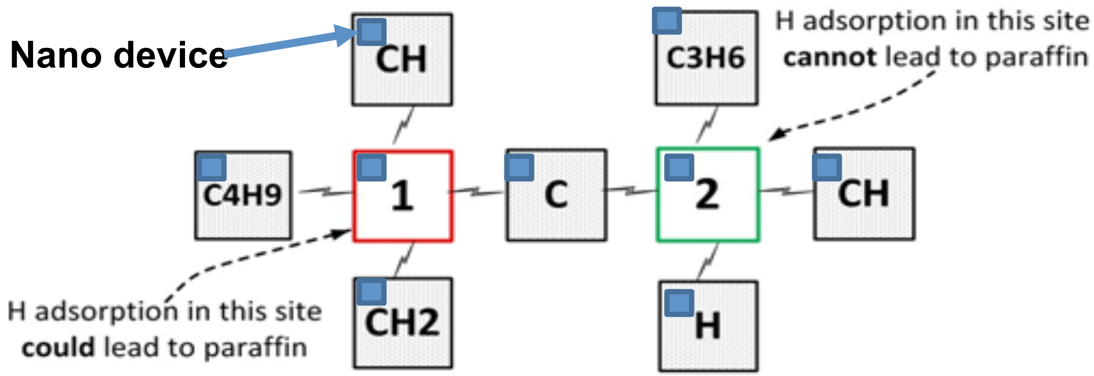


How Can Nano Sensor Networks Help?

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.

- Place a nano device in each site
- Run the following simple algorithm in each nano device
  - 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)





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

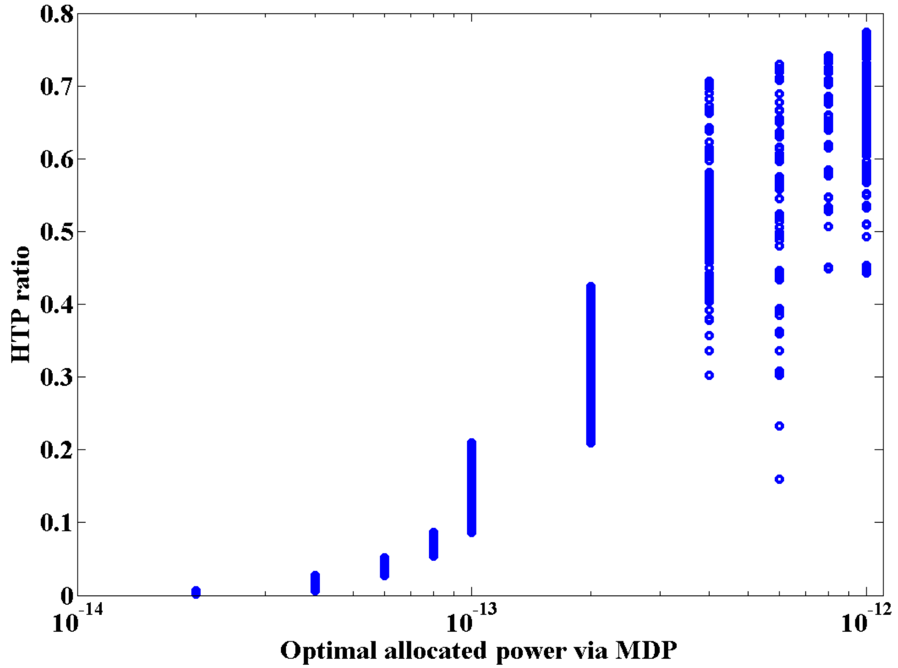
- Optimal power allocation modelled as Markov Decision Process (MDP)
  - Optimal but difficult to realize
- Three *local* power allocation policies
  - Not optimal, but easy to realize
- Performance evaluation and comparison of proposed local policies

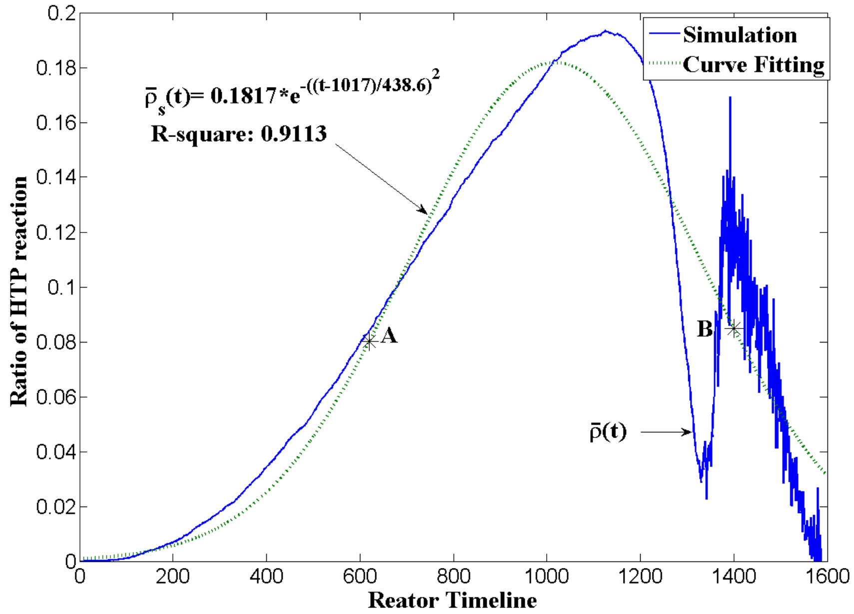
MDP for Nanosensor Power Allocation

- 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)

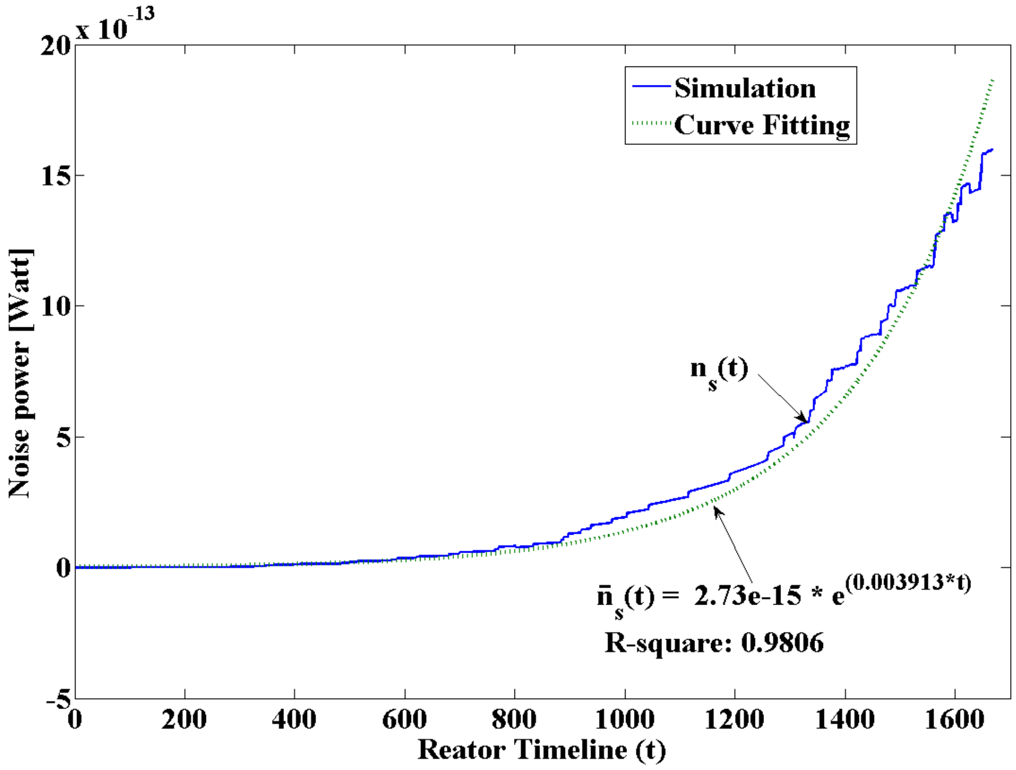
•Choose high transmission power when HTP reactions are more likely to occur, save power in other times





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.

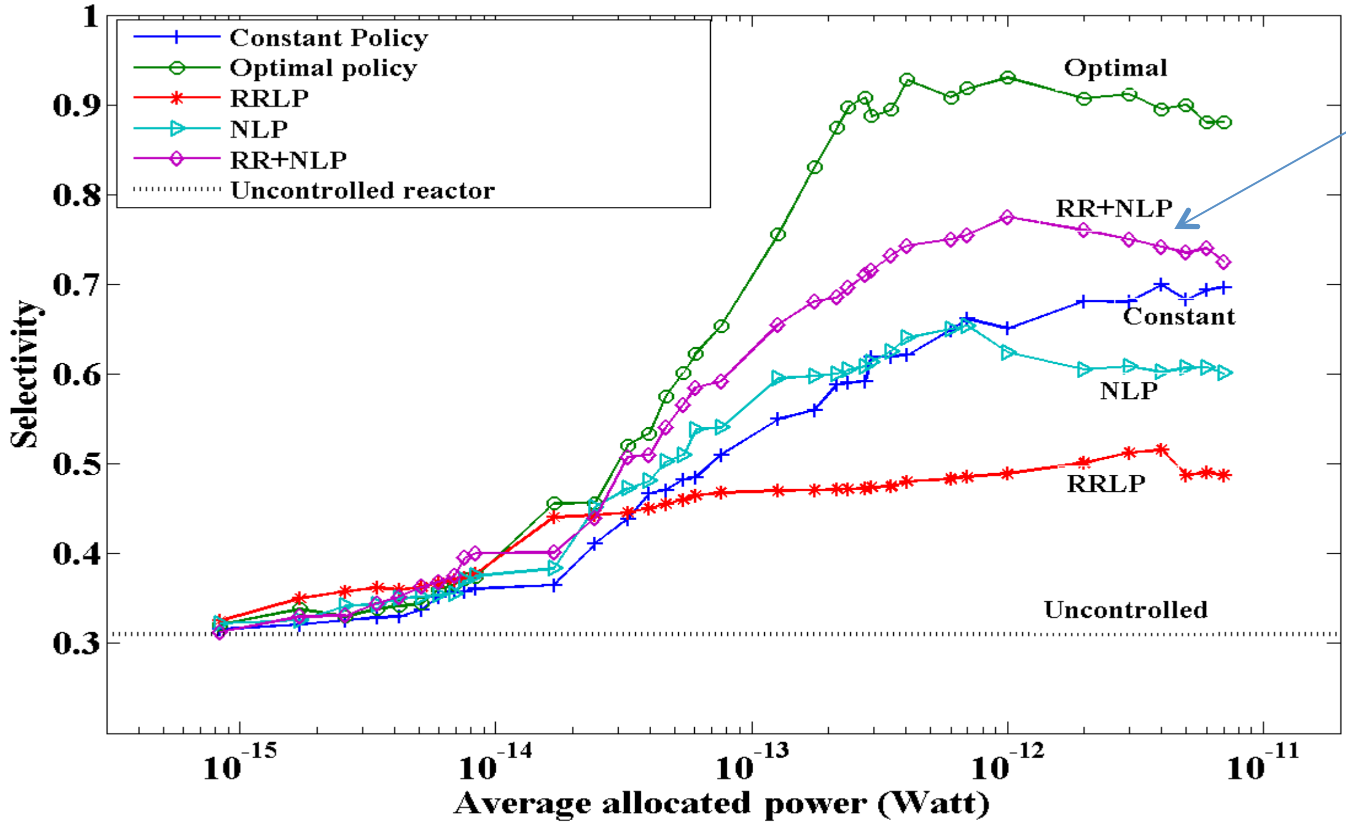
$$\hat{P}_{RR,n}(t) = P_m \max\left(\frac{\bar{\rho}_s(t)}{\max_t \bar{\rho}_s(t)}, \frac{\bar{n}_s(t)}{\max_t \bar{n}_s(t)}\right)$$

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

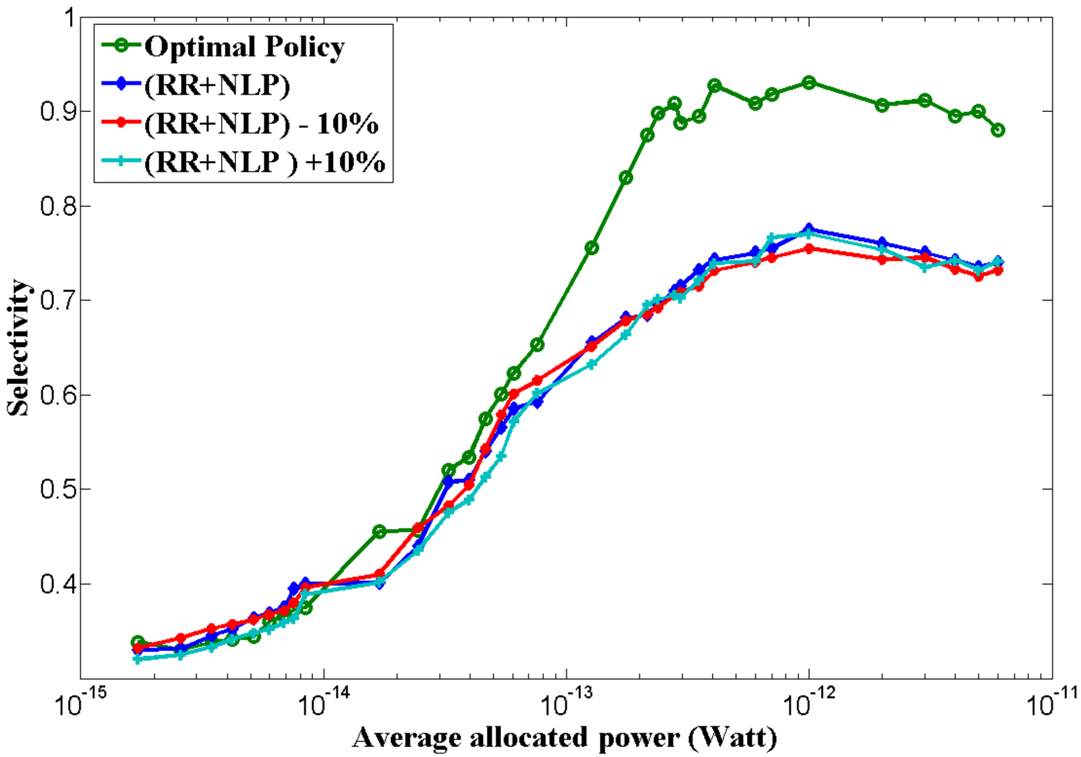


- **93% improvement in selectivity compared to uncontrolled reactor**
- **61% improvement in power consumption**

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

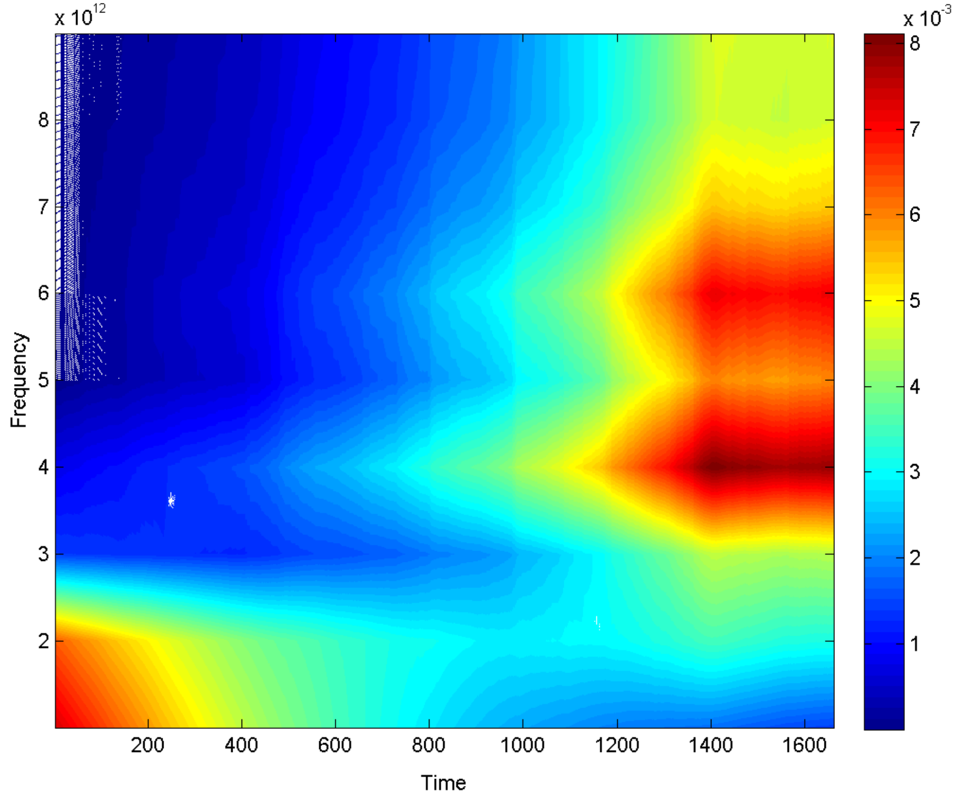
- This work has shown that dynamic power allocation significantly reduces power consumption of nano sensor networks used in chemical reactors
- Simple time-based local policies can provide substantial benefits over constant power allocation schemes
- Local policies proposed in this paper could not realise 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

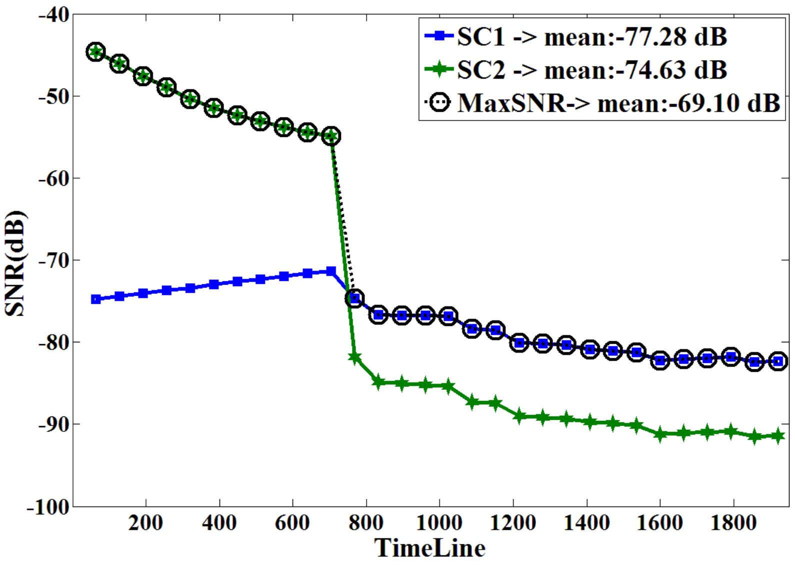
E. Zarepour, M. Hassan, C. T. Chou, A. A. Adesina, "Frequency Hopping Strategies for Improving Terahertz Sensor Network Performance over Composition Varying Channels", IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, 16-19 June, 2014

- 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)

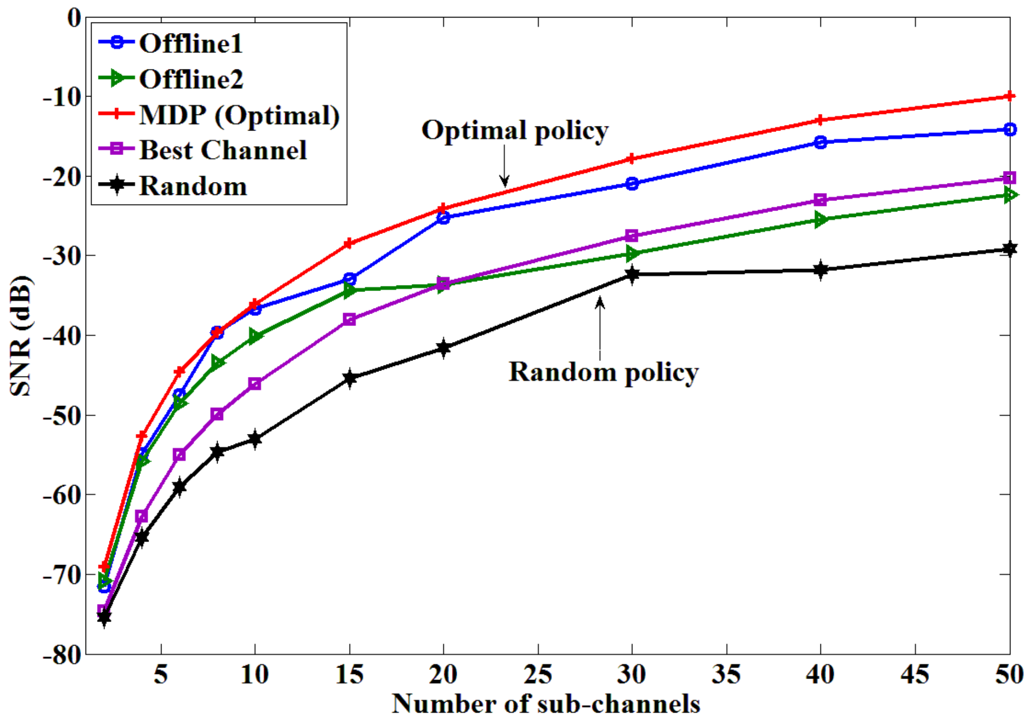
Absorption Spectrogram of F-T Reactor



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
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.
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.

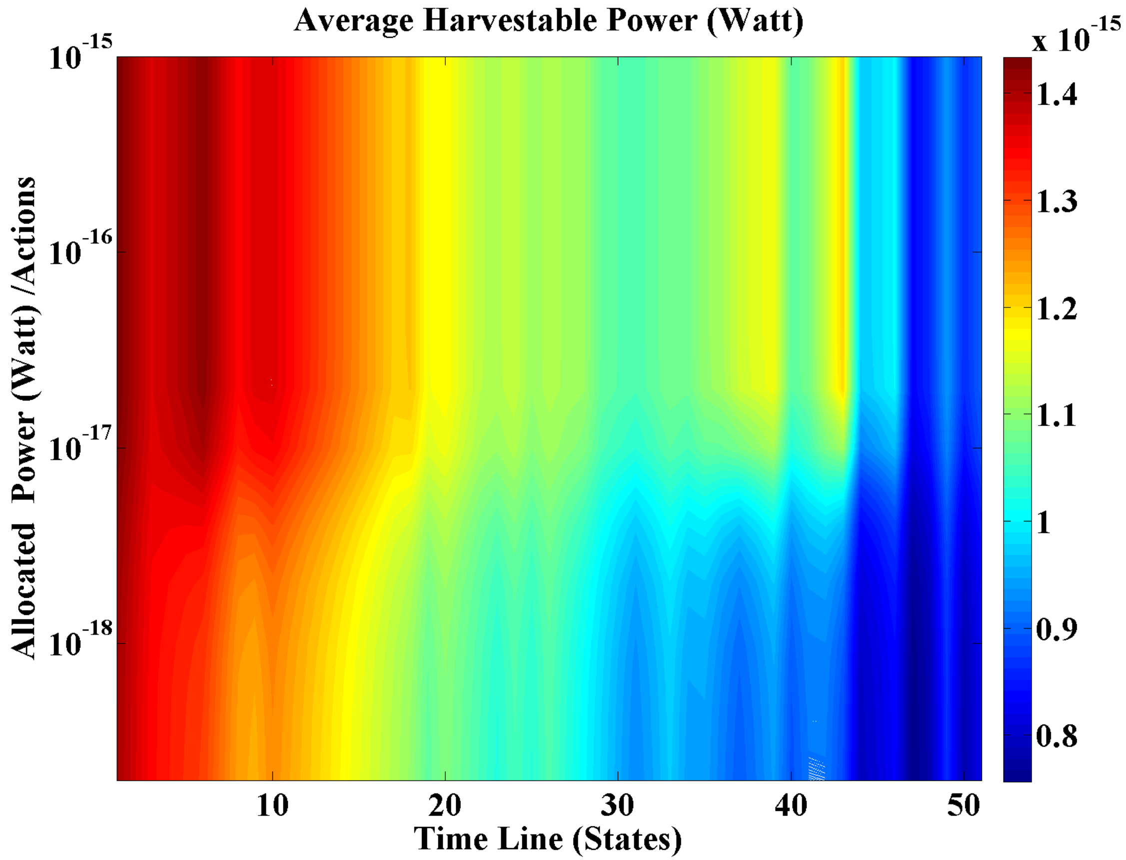
Future works

- Energy harvesting self-powered nano communication networks
- Data collection from nano-scale sensor networks
- Experimentation (?)

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

MAHALO

Any Question ?