Nano-scale Wireless Networking: Opportunities, Challenges, and Recent Advances

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Tutorial Modules

1. Introduction – the promise of nanomotes
2. Applications
3. Energy
4. Antenna, propagation and noise
5. Communication protocols
6. Simulation tools
7. Future directions
Module 1

Introduction – The Promise of Nanomote
Architecture of a sensor node (mote)
The quest for the smallest mote

12 mm to 4 mm in 9 years

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
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
Examples of nano materials

**Carbon Nano Tube (CNT)**

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

Source: wikipedia
Examples of nano materials

Nanowire

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

Source: wikipedia

ZnO nanowire

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 …
<table>
<thead>
<tr>
<th>Nano-scale Memory</th>
<th>Nano-scale CMOS/Processor</th>
</tr>
</thead>
<tbody>
<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>
<tr>
<td>Nano-scale Battery</td>
<td>Nano-scale Energy harvesting devices</td>
</tr>
<tr>
<td>-------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td><strong>Nanoscale battery/supercapacitor devices</strong></td>
<td><strong>Pyroelectric Nanogenerators for Harvesting Thermoelectric Energy</strong></td>
</tr>
<tr>
<td><img src="image1" alt="Schematic view of typical Lateral nanowire Integrated Nanogenerator" /></td>
<td><img src="image2" alt="Schematic view of typical Lateral nanowire Integrated Nanogenerator" /></td>
</tr>
<tr>
<td><strong>A nanoscale battery</strong></td>
<td><strong>Schematic view of typical Lateral nanowire Integrated Nanogenerato</strong></td>
</tr>
<tr>
<td><img src="image3" alt="Schematic illustration of a rechargeable lithium battery" /></td>
<td><img src="image4" alt="Triboelectric Nanogenerator for harvesting Magnetic Field" /></td>
</tr>
</tbody>
</table>

**Triboelectric Nanogenerator** for harvesting Magnetic Field
Nano-Sensors

Nanoscale toxic gases Detector (Developed at CSIRO)

Graphene-based optical sensor detects single cancer cells

A Nano-scale hydrogen sensor

A Bio-Chemical Nanosensors

A Single-Molecule Detector
## Nano-Sensors 2

<table>
<thead>
<tr>
<th><img src="image1.png" alt="Image" /></th>
<th><img src="image2.png" alt="Image" /></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A Nanoscale Temperature Sensor</strong></td>
<td><strong>A Nanoscale Temperature Sensor based on Seebeck effect</strong></td>
</tr>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Nanoscale Mass Sensor</strong></td>
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</tbody>
</table>

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*Mahbub Hassan*  
*IEEE ICC 2016 Tutorial, Kuala Lumpur, 23 May 2016*
**Nano-scale Transceivers (NTs)**

Examples of SiGe CMOS based NTs

<table>
<thead>
<tr>
<th>Working Frequency (GHz)</th>
<th>Size (nm)</th>
<th>Technology</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>65-90</td>
<td>SiGe CMOS</td>
</tr>
<tr>
<td>2</td>
<td>170</td>
<td>110</td>
<td>SiGe CMOS</td>
</tr>
<tr>
<td>3</td>
<td>434</td>
<td>130</td>
<td>SiGe BICMOS (Bipolar CMOS)</td>
</tr>
<tr>
<td>4</td>
<td>130</td>
<td>28</td>
<td>SiGe CMOS</td>
</tr>
<tr>
<td>5</td>
<td>220</td>
<td></td>
<td>SiGe CMOS</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>Working Frequency (GHz)</th>
<th>Size (nm)</th>
<th>Technology</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>450</td>
<td>20</td>
<td>GaN HEMTs</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>1600 (1.6 THz)</td>
<td>100</td>
<td>Gan Diode</td>
<td>8</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th></th>
<th>Working Frequency (GHz)</th>
<th>Size (nm)</th>
<th>Technology</th>
<th>Reference</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100-30000 (0.1-30THz)</td>
<td>200</td>
<td>Graphene</td>
<td>9</td>
<td>2013</td>
</tr>
<tr>
<td>2</td>
<td>1500-6000 (1.5-6 THz)</td>
<td></td>
<td>Graphene</td>
<td>10</td>
<td>2013</td>
</tr>
<tr>
<td>3</td>
<td>100-10000 (0.1-10THz)</td>
<td>1000-2000</td>
<td>Graphene</td>
<td>11,13</td>
<td>2010-2014</td>
</tr>
<tr>
<td>4</td>
<td>100-5000 (0.1-5THz)</td>
<td>200</td>
<td>Graphene</td>
<td>12</td>
<td>2012</td>
</tr>
<tr>
<td>5</td>
<td>100THz</td>
<td>400</td>
<td>CNT</td>
<td>12</td>
<td>2012</td>
</tr>
</tbody>
</table>
References for Nano-scale Transceivers (NT)


If we could put it altogether …

A Concept Nanomote

[Akyildiz2010]

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

Source: wikipedia
Module 2

Applications
What can we do with nanomotes?

- 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
- Many applications will emerge
Application of NSNs

• 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

- 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](http://Explainingthefuture.com)
NanoWSN in Chemical Reactors

Input gas → Chemical Reactions → High-value products → Low-value products

Selectivity = percentage of high-value products in the output

Source: wikipedia


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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

Source: [Renken2010]

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

\[
C_4H_9 + H = C_4H_{10}
\]
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

- Environmental monitoring, protection and control [6]
- Plants monitoring systems [1]
- Plagues defeating systems [1]
- Structure Health Monitoring as Enabler for Safer, Greener Aircrafts [6]
- 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
References for Applications of NSNs:


Module 3

Energy
Energy for nanomotes

- Energy consumption
- Energy storage
- Energy harvesting
## Energy consumption by sensors

<table>
<thead>
<tr>
<th>Category</th>
<th>Nano sensors</th>
<th>MEMs or macro sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type</td>
<td>Power consumption</td>
</tr>
<tr>
<td></td>
<td>NO2 sensor</td>
<td>10 uW [38]</td>
</tr>
<tr>
<td></td>
<td>Methane sensor</td>
<td>4 nW - 4 uW [5]</td>
</tr>
<tr>
<td>Biomedical sensor</td>
<td>Glucose biosensor</td>
<td>0.1 uW [25]</td>
</tr>
<tr>
<td>Pressure &amp; Temperature Sensors</td>
<td>Pressure sensor</td>
<td>1 nW [20] - 1 uW [55]</td>
</tr>
<tr>
<td></td>
<td>Temperature sensor</td>
<td>1 nW [30]</td>
</tr>
</tbody>
</table>
Transmission energy consumption

- Use short pulses
- 1 pJ per pulse (per bit ‘1’) for 10mm distance and zero power for transmitting bit ‘0’ [Jornet 2012]

Energy storage

- Ultra-nanocapacitor: about 800pJ
- Nanoscale batteries: 2 billion batteries per sq cm (image next slide) with density 147 mAh/g
Nano batteries

“An all-in-one nanopore battery array”, Nature nanotechnology, 10 Nov 2014
Energy Harvesting (1)


- "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 (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

Energy Harvesting (3)


Energy Harvesting (4)

- "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


Module 4

Antenna, Propagation, Noise
The problem with antenna miniaturization

Nano-scale communication seemed an impossible dream …

<table>
<thead>
<tr>
<th>Antenna Length ($\lambda/2$)</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>33.33 cm / 2 = 16 cm</td>
<td>900 MHz</td>
</tr>
<tr>
<td>12.5 cm / 2 = 6 cm</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>5 mm / 2 = 2.5 mm</td>
<td>60 GHz</td>
</tr>
<tr>
<td>4 µm / 2 = 2 µm</td>
<td>150 THz</td>
</tr>
</tbody>
</table>

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

Extreme path loss (high transmission power needed) and very challenging to operate at this frequency
Nanoantenna design

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


2. Llatser, Ignacio - Graphene-enabled Wireless Communication Networks at the Nanoscale, Science pp. 1--9, 2011


Discovery of graphene, the *wonder material*
2011 Nobel Prize in Physics

One atom thick 2D honeycomb structure

Honeycombs slow down electrons 300 times!

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

Source: wikipedia

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]
More designs for Graphene antenna

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

A) Water Vapor (H2O)

B) Carbon Monoxide (CO)

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IEEE ICC 2016 Tutorial, Kuala Lumpur, 23 May 2016
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 \( M \) 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

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

\( k_{ch}(f) \): channel absorption coefficient for frequency \( f \)
Molecular Noise

\[ S_{N_{\text{abs}}}(t, f, d) = S_N^B(f, d) + S_N^X(t, f, d) \]

\[ S_N^B(f, d) = \lim_{d \to \infty} \left( k_B T_0 \left( 1 - e^{-K(f)d} \right) \left( \frac{c}{\sqrt{4\pi f_0}} \right)^2 \right) \]

\[ S_N^X(t, f, d) = P(f) \left( 1 - e^{-K(t,f)d} \right) \left( \frac{c}{4\pi df_0} \right)^2 \]

Module 5

Communication Protocols
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
A Nano-sensor is transmitting the sequence “1100001”

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

Gaussian Pulse

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

FWHM = \(2\sqrt{2\ln(2)\sigma} \approx 2.35\sigma\).
Small energy, high power

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

To generate a 100 fs Gaussian pulse with peak power of 5.7 W, we need only 1pJ
Adaptive power control and dynamic frequency selection

- THz channel is highly dependent on molecular composition
- If molecular composition is time-varying, we may need adaptive power control and dynamic frequency selection (not all frequencies are equally affected)
- Challenge: channel feedback could be impractical at nanoscale
- Solution: design open-loop power adaptation and frequency selection
Contribution of IEEE TMBC 2015 paper


• Application: Improve selectivity of chemical reactors by deploying a nanosensor network inside a reactor

• How to allocate transmission power so that we maximise reactor 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 (requires channel feedback)

• Three local (open-loop) power allocation policies
  – Not optimal, but easy to realize

• Performance evaluation and comparison of proposed open-loop 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
Choose high transmission power when HTP reactions are more likely to occur, save power in other times

\[
\bar{\rho}(t) = 0.1817 \cdot e^{-(0.1017/438.6)^2}
\]

R-square: 0.9113
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 different \(P_{\text{nominal}}\) 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 TMBC 2015

- 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).
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)
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).

Distance between Tx-Rx = 1m

Achievable SNR via different policies versus number of sub-channels
Key outcomes of TMBC 2015 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)
Module 6

Simulation Tools
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
- **HITRAN** (high-resolution transmission 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](http://hitran.iao.ru))
  - A tool to extract absorption coefficient from HITRAN database
### HITRAN on the Web

**Home** | **HITRAN survey** | **Molecules** | **Gas mixture spectra** | **Cross-Sections** | **Auxiliary data** | **References** | **Information**
---|---|---|---|---|---|---|---

#### Log In

<table>
<thead>
<tr>
<th>Username</th>
<th>Password</th>
<th>Log in</th>
<th>New User</th>
<th>Forgot password</th>
</tr>
</thead>
</table>

#### General Info

*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 wavelength range

#### Parameters for spectrum simulation

**Composition**

<table>
<thead>
<tr>
<th>Gas mixture</th>
<th>Input selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA model, mean latitude, summer, H=0</td>
<td></td>
</tr>
<tr>
<td>IAO model, mean latitude, summer, H=0</td>
<td></td>
</tr>
<tr>
<td>IAO model, mean latitude, winter, H=0</td>
<td></td>
</tr>
<tr>
<td>IAO model, high latitude, summer, H=0</td>
<td></td>
</tr>
<tr>
<td>IAO model, high latitude, winter, H=0</td>
<td></td>
</tr>
<tr>
<td>IAO model, tropics, H=0</td>
<td></td>
</tr>
<tr>
<td>Pure H2O</td>
<td></td>
</tr>
<tr>
<td>Pure CO2</td>
<td></td>
</tr>
<tr>
<td>Pure O3</td>
<td></td>
</tr>
<tr>
<td>Pure N2O</td>
<td></td>
</tr>
<tr>
<td>Pure CO</td>
<td></td>
</tr>
<tr>
<td>Pure CH4</td>
<td></td>
</tr>
</tbody>
</table>

#### Options

- Simulation type: Stick spectrum

#### Plot scale

- Natural
- Logarithmic

#### Simulate spectrum
### Parameters for spectrum simulation

**Input selection**
- Gas mixture: USA model, mean latitude, summer, H=0
- Simulation type: Stick spectrum

**General parameters**
- $W_{\text{min}}$, cm$^{-1}$: 0
- $W_{\text{max}}$, cm$^{-1}$: 58000
- $T$, K: 296
- $P$, atm: 1

**Contour parameters**
- Shape: Voigt
- $W_{\text{step}}$, cm$^{-1}$: 0.01

**Function parameters**
- Opt. path, m: 1
- App. Function (AF): Dirac
- Window, HW: 50

**Options**
- Separate molecules

**Plot scale**
- Natural

---

### Parameters for spectrum simulation

**Input selection**
- Gas mixture: Pure H2O

**General parameters**
- Simulation type: Absorption coeff
- Room pressure/temperature: 0.1-10 THz
- $W_{\text{min}}$, cm$^{-1}$: 3.3
- $W_{\text{max}}$, cm$^{-1}$: 330
- $T$, K: 296
- $P$, atm: 1

**Contour parameters**
- Shape: Lorentz
- $W_{\text{step}}$, cm$^{-1}$: 0.01

**Function parameters**
- Opt. path, m: 1
- App. Function (AF): Dirac
- Window, HW: 50

**Options**
- Separate molecules

**Plot scale**
- Natural
Press **simulate** button (or download text data)

![Graph of HITRAN on the Web. Gas mixture: Pure H2O. Absorption coeff. Contour= Lorentz; T=296K; P=1atm. Intensity, cm²/ mol.](image)

**You can download the results**

**Download gzipped data**

<table>
<thead>
<tr>
<th>Input selection</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas mixture</td>
<td>Pure H2O</td>
</tr>
<tr>
<td>Simulation type</td>
<td></td>
</tr>
<tr>
<td>Absorption coeff</td>
<td></td>
</tr>
</tbody>
</table>

**General parameters:**

- \( \text{WN}_{\text{min}}, \text{cm}^{-1} \): 3.3
- \( \text{WN}_{\text{max}}, \text{cm}^{-1} \): 330
- \( T, \text{K} \): 296
- \( P, \text{atm} \): 1
- \( I_{\text{cut}}, \text{cm}^{2}/\text{mol} \): 1E-28

**Contour parameters:**

- Shape: Lorentz
- \( \text{WN}_{\text{lap}}, \text{cm}^{-1} \): 0.01
- Wing, HW: 50

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Mahbub Hassan

IEEE ICC 2016 Tutorial, Kuala Lumpur, 23 May 2016
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
- Transparent 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

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:

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

Module 7

Future Directions
Six important areas

- Applications
- Simulation and experimental methodology
- Modulation and coding
- Propagation and noise models
- Higher layer protocols – MAC and Routing
- Energy harvesting
Applications

- Few applications have been investigated in detail, probably because nanomotes are not available yet.
- Nanocommunications 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.
Channel modeling and capacity analysis

- Real experiments with nanomotes still not possible
- Researchers employ physics-based theories to model nano communication channels
- Will need experimentally validated models


MAC

- Without MAC, we cannot deploy large scale nanomotes – one sink needs to coordinate communications with many nanomotes
- However, MAC requires significant computation overhead – nanomotes have extremely limited logic and memory

Some research on MAC for nanosensors


Routing

- Routing will eventually be required to communicate to a ‘distant’ sink (single hop range may be too long to achieve with low energy harvesting power at nanoscale)
- Routing, however, requires significant computations

Research on Routing for nanosensors very limited

SEMANTA RAJ NEUPANE, ROUTING IN RESOURCE CONSTRAINED SENSOR NANONET-WORKS, Master of Science Thesis, Tampere University of Technology, June 2014

Energy harvesting NanoWSN


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
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Any Question?