NanoWSN Tutorial for WPMC 2014
Nano-scale Wireless Sensor Networks: Opportunities, Challenges, and Recent Advances

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

IEEE WPMC 2014 NanoWSN Tutorial, Sydney, 07 September 2014
The quest for the smallest mote

12 mm to 4 mm in 9 years

[Park2005]

[Lu2014]

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)

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

Source: wikipedia
Examples of nano materials

- 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><strong>Nano-scale Memory</strong></th>
<th><strong>Nano-scale CMOS/Processor</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Graphene nanoribbon memory cell" /></td>
<td><img src="image2" alt="Graphen-based CMOS" /></td>
</tr>
<tr>
<td><strong>Graphene nanoribbon memory cell</strong></td>
<td><strong>Graphen-based CMOS</strong></td>
</tr>
<tr>
<td><img src="image3" alt="Nano-scale flash memory using graphene" /></td>
<td><img src="image4" alt="Single-atom transistor developed at UNSW" /></td>
</tr>
<tr>
<td><strong>Nano-scale flash memory using graphene</strong></td>
<td><strong>Single-atom transistor developed at UNSW</strong></td>
</tr>
<tr>
<td><img src="image5" alt="8T-Nanowire RAM Array" /></td>
<td><img src="image6" alt="A carbon nanotube CPU" /></td>
</tr>
<tr>
<td><strong>8T-Nanowire RAM Array</strong></td>
<td><strong>A carbon nanotube CPU</strong></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>A nanoscale battery</td>
<td>Schematic view of typical Lateral nanowire Integrated Nanogenerator</td>
</tr>
<tr>
<td><img src="image3" alt="Schematic illustration of a rechargeable lithium battery" /></td>
<td>Triboelectric Nanogenerator for harvesting Magnetic Field</td>
</tr>
</tbody>
</table>

**Notes:**
- **Nano-scale Battery:**
  - Schematic view of a rechargeable lithium battery
  - Charge and discharge processes

- **Nano-scale Energy harvesting devices:**
  - Pyroelectric Nanogenerators for harvesting Thermoelectric Energy
  - Schematic view of typical Lateral nanowire Integrated Nanogenerator

---

**Author:** Mahbub Hassan

**Conference:** IEEE WPMC 2014 NanoWSN Tutorial, Sydney, 07 September 2014
Energy Harvesting for NWSNs (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

Mahbub Hassan

IEEE WPMC 2014 NanoWSN Tutorial, Sydney, 07 September 2014
Energy Harvesting for NWSNs (2)

- "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 for NWSNs (3)


Mahbub Hassan

IEEE WPMC 2014 NanoWSN Tutorial, Sydney, 07 September 2014
Energy Harvesting for NWSNs (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, T. Chien Hou and Zhong Lin Wang, Energy&Environmental Science, 2013, Online


Mahbub Hassan
• “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

<table>
<thead>
<tr>
<th><strong>Nano-Sensors 1</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="NH₃, H₂O" /></td>
<td><strong>Nanoscale toxic gases Detector (Developed at CSIRO)</strong></td>
</tr>
<tr>
<td><img src="image" alt="Graphene-based optical sensor" /></td>
<td><strong>Graphene-based optical sensor detects single cancer cells</strong></td>
</tr>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td><strong>A Nano-scale hydrogen sensor</strong></td>
</tr>
<tr>
<td><img src="image" alt="Bio-Chemical Nanosensors" /></td>
<td><strong>A Bio-Chemical Nanosensors</strong></td>
</tr>
<tr>
<td><img src="image" alt="Single-Molecule Detector" /></td>
<td><strong>A Single-Molecule Detector</strong></td>
</tr>
</tbody>
</table>
# Nano-Sensors 2

<table>
<thead>
<tr>
<th><img src="image1.png" alt="Image" /></th>
<th><img src="image2.png" alt="Image" /></th>
</tr>
</thead>
</table>

A Nanoscale Temperature Sensor

A Nanoscale Temperature Sensor based on Seebeck effect

Nanoscale Mass Sensor
Nano-scale Transceivers (NTs)

Silicon-Germanium (SiGe) based 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 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

- **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.

Mahbub Hassan

IEEE WPMC 2014 NanoWSN Tutorial, Sydney, 07 September 2014
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

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

HTP (hydrogen to parffin) reaction

$$C_4H_9 + H = C_4H_{10}$$
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 [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
References for Applications of NSNs:


[4]


Module 3

Fundamentals of Nano Communications
The problem with antenna miniaturization
Nano-scale communication seemed an impossible dream …

<table>
<thead>
<tr>
<th>Antenna Length (λ/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

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

Extreme path loss! Very high transmission power needed!!
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]
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 Coefficient at 296 Kelvin
Molecular Absorption

Impact of Molecular Composition

Molecular Absorption Coefficient at $T=550 \text{ K}$ $P=40 \text{ atm.}$
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 \( f \)
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

A 100-fs Gaussian pulse

The equation for a Gaussian pulse is given by:

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

The full width at half maximum (FWHM) is approximately:

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

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

\[ E_G = \int_{-\infty}^{+\infty} |p(t)|^2 dt = \frac{a_0^2 \times erf\left(\frac{t}{\sigma}\right)}{4 \times \sqrt{\pi} \times \sigma} = \frac{a_0^2}{2\sigma \sqrt{\pi}} \]
Two key issues in nano communication 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** *(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)*
  - A tool to extract absorption coefficient from HITRAN database
### Parameters for spectrum simulation

<table>
<thead>
<tr>
<th>Input selection</th>
<th>Required data</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas mixture</td>
<td>USA model, mean latitude, summer, H=0</td>
<td>Separate molecules</td>
</tr>
<tr>
<td>Simulation type</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>General parameters:</strong></td>
<td>Stick spectrum</td>
<td></td>
</tr>
<tr>
<td>$WN_{\text{min}}, \text{cm}^{-1}$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$WN_{\text{max}}, \text{cm}^{-1}$</td>
<td>58000</td>
<td></td>
</tr>
<tr>
<td>T, K</td>
<td>296</td>
<td></td>
</tr>
<tr>
<td>P, atm</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Contour parameters:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shape</td>
<td>Voigt</td>
<td></td>
</tr>
<tr>
<td>$WN_{\text{step}}, \text{cm}^{-1}$</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wing, HW 50</td>
</tr>
<tr>
<td>Function parameters:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opt. path, m</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>App. Function (AF)</td>
<td>Dirac</td>
<td></td>
</tr>
<tr>
<td>App. Resolution, cm$^{-1}$</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>AF wing, AR</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

### Parameters for spectrum simulation

<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>Absorption coeff</td>
</tr>
<tr>
<td><strong>General parameters:</strong></td>
<td>Room pressure/temperature</td>
</tr>
<tr>
<td>$WN_{\text{min}}, \text{cm}^{-1}$</td>
<td>33</td>
</tr>
<tr>
<td>$WN_{\text{max}}, \text{cm}^{-1}$</td>
<td>330</td>
</tr>
<tr>
<td>T, K</td>
<td>296</td>
</tr>
<tr>
<td>P, atm</td>
<td>1</td>
</tr>
<tr>
<td>$n_{\text{cut}}, \text{cm/mol}$</td>
<td>1E-28</td>
</tr>
<tr>
<td>Contour parameters:</td>
<td></td>
</tr>
<tr>
<td>Shape</td>
<td>Lorentz</td>
</tr>
<tr>
<td>$WN_{\text{step}}, \text{cm}^{-1}$</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Function parameters:</td>
<td></td>
</tr>
<tr>
<td>Opt. path, m</td>
<td>1</td>
</tr>
<tr>
<td>App. Function (AF)</td>
<td>Dirac</td>
</tr>
<tr>
<td>App. Resolution, cm$^{-1}$</td>
<td>0.1</td>
</tr>
<tr>
<td>AF wing, AR</td>
<td>50</td>
</tr>
</tbody>
</table>
Press **simulate** button (or download text data)

You can download the results

---

**Input selection**

<table>
<thead>
<tr>
<th>Gas mixture</th>
<th>Pure H2O</th>
</tr>
</thead>
</table>

**General parameters:**

| WNmin, cm⁻¹ | 3.3 |
| WNmax, cm⁻¹ | 330 |
| T, K | 296 |
| P, atm | 1 |
| Ical, cm/mol | 1E-28 |

**Contour parameters:**

| Shape | Lorentz |
| WNstep, 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

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 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


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


Channel modeling and capacity analysis

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


MAC for NanoWSN


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 (BODYPETS), September 2012
Internet of nano things


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


Nano Networking Research at UNSW
Optimisations for Composition Varying Channels
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


• 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

![Graph showing optimal allocated power via MDP and ratio of HTP reaction over reactor timeline]

\[ \bar{\rho}(t) = 0.1817 \times e^{(0.0017/438.6)^2} \]

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).

\[ \tilde{n}_s(t) = 2.73e^{-15} \cdot e^{0.003913 \cdot t} \]

R-square: 0.9806
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 devices=1000 nm.

• There are m equally spaced power levels in the range $\left[\frac{P_{\text{nominal}}}{100}, 100P_{\text{nominal}}\right]$.

• 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 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


- 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

Achievable SNR via different policies versus number of sub-channels.

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


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
- 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
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

Mohbub Hassan

IEEE WPMC 2014 NanoWSN Tutorial, Sydney, 07 September 2014
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?