Nano-scale Communication Networks

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

Nanotechnology changes the game from *visible* to *microscopic* networks

- Nano-meter components
- Micro-meter communicating sensor nodes

Concept Device [Akyildiz2010]

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

- Fundamentals of nano communications (electro magnetic based)
  - The frequency (the encounter with THz)
  - The propagation model (the curse of molecular absorption)
  - The modulation and coding (carrier-less, pulse-based)

- Key issues in nano communications

- Nano networking research at UNSW
Fundamentals of Electromagnetic Nano Communications
The problem with antenna miniaturization
Nano-scale communication seemed an impossible dream …

<table>
<thead>
<tr>
<th>Antenna Length ($\lambda/2$)</th>
<th>Frequency</th>
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</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>

Extreme path loss! Very high transmission power needed!!

\[ f = \frac{3 \times 10^8}{\lambda} \]

On a metallic surface, Electrons travel nearly at speed of light
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 Coefficient at $T=550 \text{ K}$ $P=40 \text{ atm.}$
Calculating molecular absorption coefficient
The HITRAN database (e.g., http://hitran.iao.ru)

- 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

**Home**

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

### General Info

**Scope**

- All users (unregistered and registered) may:
  - Survey the HITRAN database content for a specified spectral range
  - Specify a mixture of vibrational bands for a given HITRAN
    isotope for a selected geographical region

**Parameters for spectrum simulation**

### Composition

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

- Separate molecules

### Plot scale

- Natural
- Logarithmic

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

<table>
<thead>
<tr>
<th>Input selection</th>
<th>Required data</th>
<th>Options</th>
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#### General parameters:

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#### Contour parameters:

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### Parameters for spectrum simulation

<table>
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<tr>
<td>T, K</td>
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<tr>
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<td>Lorent</td>
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**Steps**
Press **simulate** button (or download text data)

You can download the results **Download gzipped data**

<table>
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<td>Gas mixture</td>
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<table>
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<td>WN_{max}, cm^{-1}</td>
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<td>T, K</td>
<td>296</td>
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<td>l_{cut}, cm/mol</td>
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Path loss formula for nano-communication

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

- \( P_r \): received power
- \( P_t \): transmitted power
- \( \lambda \): wavelength
- \( d \): distance
- \( k(f) \): absorption coefficient for frequency \( f \)

free-space path loss
Path loss due to molecular absorption

\( k(f) \): absorption coefficient for frequency \( f \)
Modulation and coding for nano 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 logical “1” is encoded with a pulse:
* Pulse length: $T_p = 100$ 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

A Nano-sensor is transmitting the sequence “1100001”

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

Source: [Jornet2011]

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)
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

Selectivity in Fischer-Tropsch Reactor (Gas → Liquid)

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

**HTP (hydrogen to paraffin) reaction**

$$\text{C}_4\text{H}_9 + \text{H} = \text{C}_4\text{H}_{10}$$
How Can Nano Sensor Networks Help?


- 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


- 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**
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).

\[
\bar{n}_x(t) = 2.73 \times 10^{-15} \cdot e^{0.003913 \cdot t}
\]

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)
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)


Future works

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

- Eisa Zarepour helped preparing some of the figures

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