Finding Common Ground: Channel Analysis and Receiver Models for Diffusive Molecular Communication

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July 27, 2016

What?

Molecular Communication

Image: US Centers for Disease Control and Prevention http://www.cdc.gov/tb/education/corecurr/pdf/chapter2.pdf

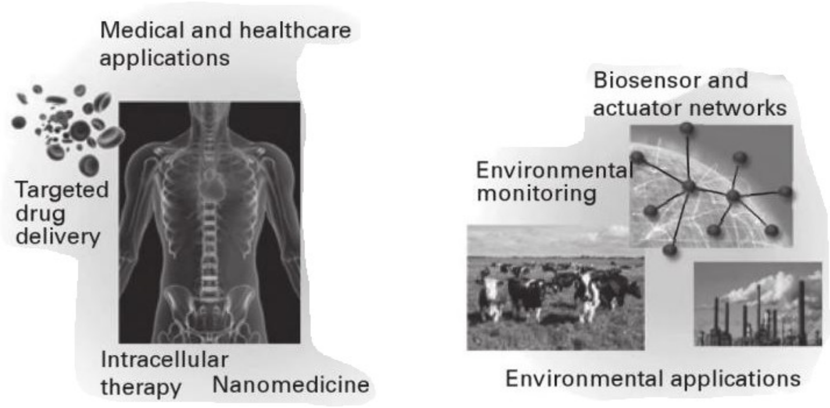
What?

Molecular Communication

- How do biological systems share information?
- Can synthetic networks use natural communication systems?
- What are the practical communication limits?

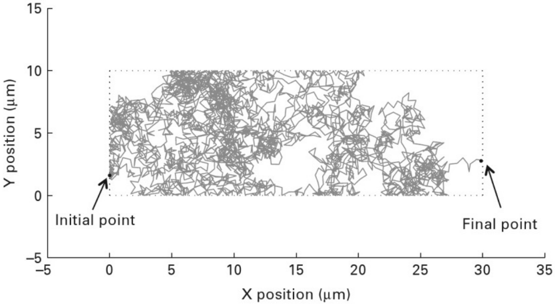
Image: US Centers for Disease Control and Prevention http://www.cdc.gov/tb/education/corecurr/pdf/chapter2.pdf

Why?



Edited Image From: Nakano, Eckford, Haraguchi, *Molecular Communication*. Cambridge University Press, 2013.

How?



Diffusion is motion of a molecule colliding with other molecules

Image: Nakano, Eckford, Haraguchi, *Molecular Communication*. Cambridge University Press, 2013.

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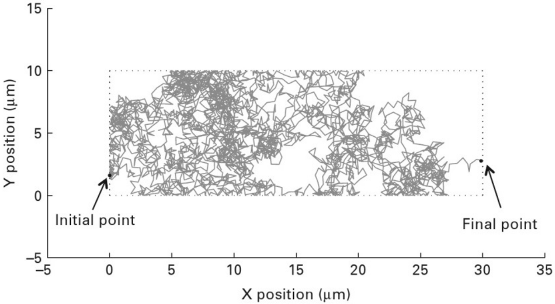
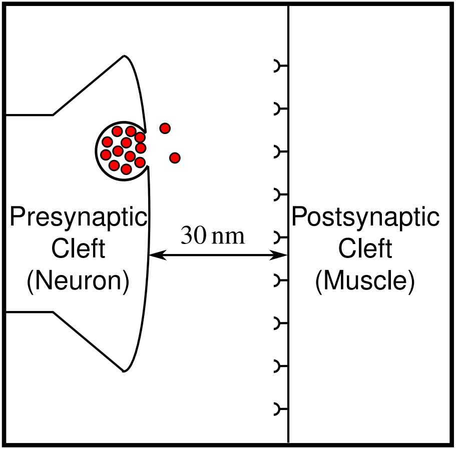


Diffusion is motion of a molecule colliding with other molecules

- No external energy or infrastructure required
- Very fast over “short” distances ($\leq 1\mu$m)
- Used by many cellular processes

Image: Nakano, Eckford, Haraguchi, *Molecular Communication*. Cambridge University Press, 2013.

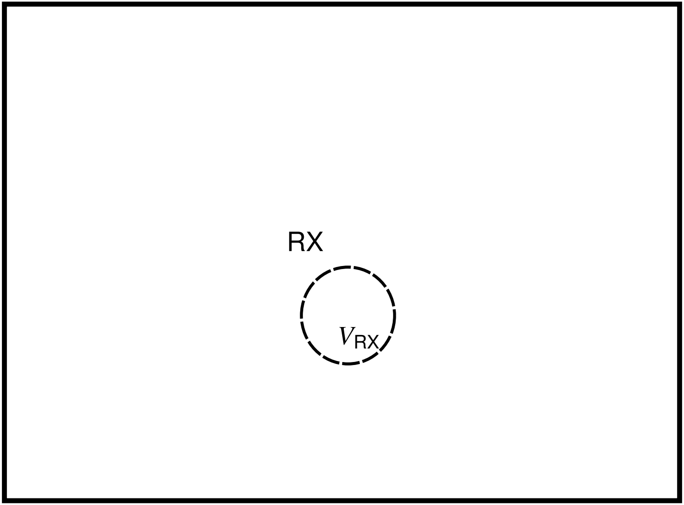


- Connect motor neuron to muscle fiber
- Molecules released ($\sim 10^4$)
- Reception leads to muscle contraction
- Up to $\sim$ 50 times per second

Channel Modeling

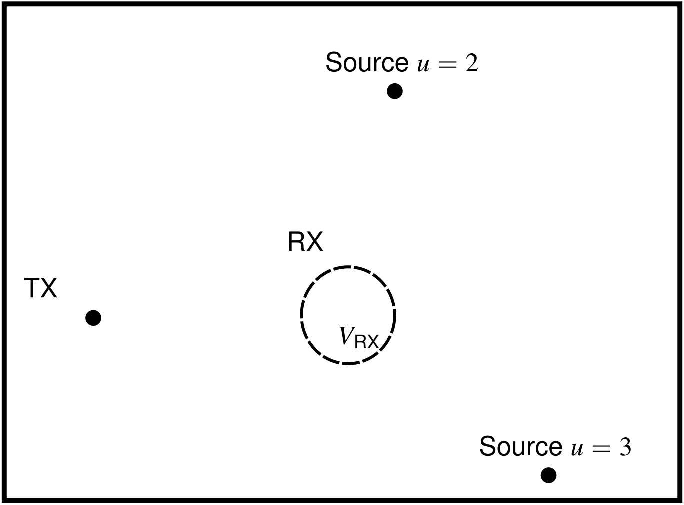
- Fluid

Channel Modeling



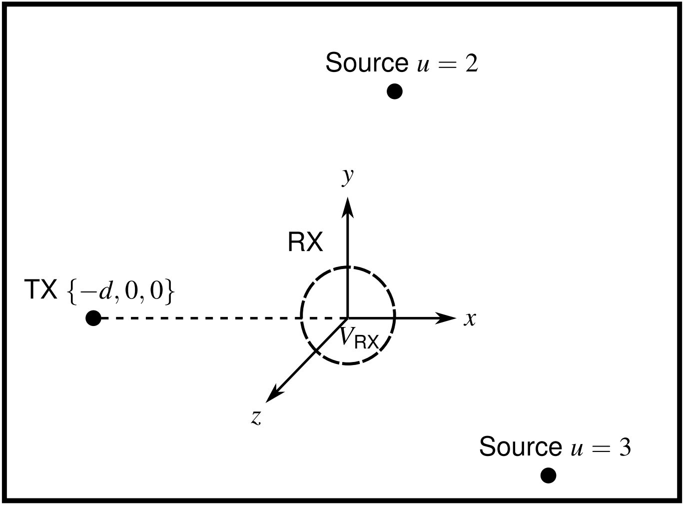
- Fluid
- Receiver (RX)

Channel Modeling



- Fluid
- Receiver (RX)
- Transmitter (TX)
- U sources

Channel Modeling



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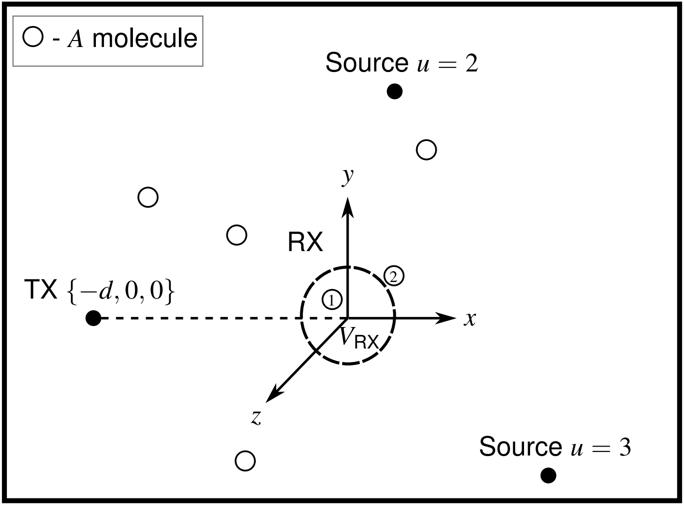
Channel Modeling



- Fluid
- Receiver (RX)
- Transmitter (TX)
- U sources
- A molecules
- Diffusion D

Channel Modeling
Simplified Receiver (Uniform Concentration)

3D Point Receiver Observation (Point TX)

$$\overline{N}_{\mathsf{RX}}(t) = \frac{NV_{\mathsf{RX}}}{(4\pi D t)^{3/2}} \exp\left(-\frac{d^2}{4Dt}\right)$$

Noel, Cheung, Schober, *Proc. IEEE ICC MoNaCom*, Jun. 2013.

Channel Modeling

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$$\overline{N}_{\mathsf{RX}}(t) = \frac{NV_{\mathsf{RX}}}{(4\pi Dt)^{3/2}} \exp\left(-\frac{d^2}{4Dt}\right)$$

3D Spherical Receiver Observation (Point TX)

$$\overline{N}_{\mathsf{RX}}(t) = \frac{N}{2}\left[\operatorname{erf}\left(\frac{r_{\mathsf{RX}} - d}{2\sqrt{Dt}}\right) + \operatorname{erf}\left(\frac{r_{\mathsf{RX}} + d}{2\sqrt{Dt}}\right)\right] + \frac{N}{d}\sqrt{\frac{Dt}{\pi}}\left[\exp\left(-\frac{(d + r_{\mathsf{RX}})^2}{4Dt}\right) - \exp\left(-\frac{(d - r_{\mathsf{RX}})^2}{4Dt}\right)\right]$$

Noel, Cheung, Schober, *Proc. IEEE ICC MoNaCom*, Jun. 2013.

Channel Modeling

Simplified Transmitter (Point Source)

1D Receiver Observation (Point TX)

$$\overline{N}_{\mathsf{RX}}(t) = \frac{N}{2}\left(\operatorname{erf}\left(\frac{r_{\mathsf{RX}} + d}{2\sqrt{Dt}}\right) - \operatorname{erf}\left(\frac{d - r_{\mathsf{RX}}}{2\sqrt{Dt}}\right)\right)$$

Noel, Makrakis, Hafid, *Proc. CSIT BSC*, Jun. 2016.

1D Receiver Observation (Point TX)

$$\overline{N}_{\mathrm{RX}}(t) = \frac{N}{2}\left(\mathrm{erf}\left(\frac{r_{\mathrm{RX}}+d}{2\sqrt{Dt}}\right) - \mathrm{erf}\left(\frac{d-r_{\mathrm{RX}}}{2\sqrt{Dt}}\right)\right)$$

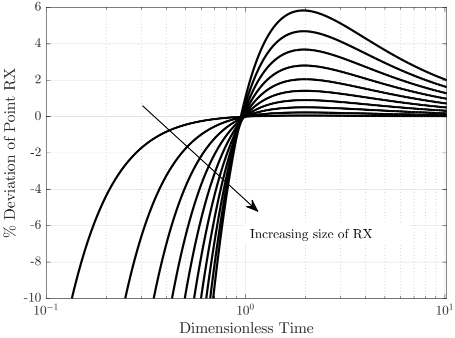
1D Receiver Observation (Volume TX)

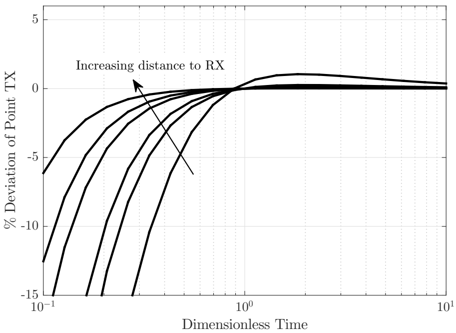
$$\overline{N}_{\mathrm{RX}}(t) = \frac{N}{2r_{\mathrm{TX}}}\left\{\sqrt{\frac{Dt}{\pi}}\left[\exp\left(-\frac{(x_{\mathrm{f}}+r_{\mathrm{RX}})^2}{4Dt}\right) - \exp\left(-\frac{(x_{\mathrm{f}}-r_{\mathrm{RX}})^2}{4Dt}\right) - \exp\left(-\frac{(x_{\mathrm{i}}+r_{\mathrm{RX}})^2}{4Dt}\right)\right.\right.$$
$$\left. + \exp\left(-\frac{(x_{\mathrm{i}}-r_{\mathrm{RX}})^2}{4Dt}\right)\right] + \frac{1}{2}\left[(x_{\mathrm{f}}+r_{\mathrm{RX}})\,\mathrm{erf}\left(\frac{x_{\mathrm{f}}+r_{\mathrm{RX}}}{2\sqrt{Dt}}\right)\right.$$
$$\left.\left. - (x_{\mathrm{i}}+r_{\mathrm{RX}})\,\mathrm{erf}\left(\frac{x_{\mathrm{i}}+r_{\mathrm{RX}}}{2\sqrt{Dt}}\right) - (x_{\mathrm{f}}-r_{\mathrm{RX}})\,\mathrm{erf}\left(\frac{x_{\mathrm{f}}-r_{\mathrm{RX}}}{2\sqrt{Dt}}\right) + (x_{\mathrm{i}}-r_{\mathrm{RX}})\,\mathrm{erf}\left(\frac{x_{\mathrm{i}}-r_{\mathrm{RX}}}{2\sqrt{Dt}}\right)\right]\right\}$$

Noel, Makrakis, Hafid, *Proc. CSIT BSC*, Jun. 2016.

Channel Modeling

Accuracy of Point-to-Point Model





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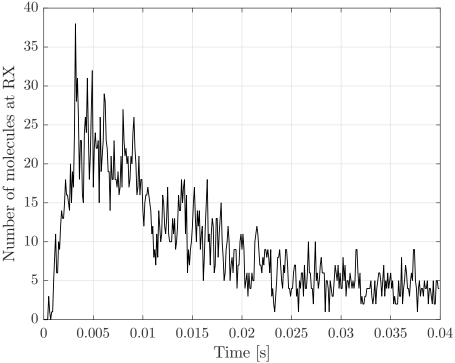
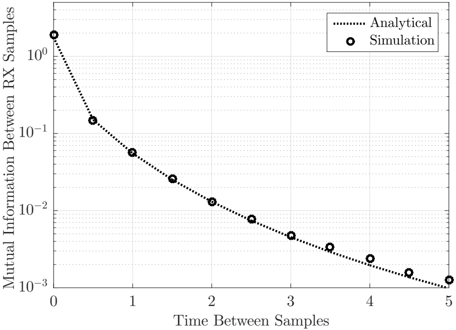
Channel Modeling

Observation Independence

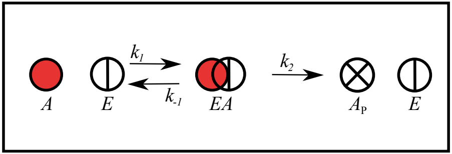




Noel, Cheung, Schober, *IEEE Trans. NanoBiosci.*, Sept. 2014.

Channel Modeling

Changing the Channel



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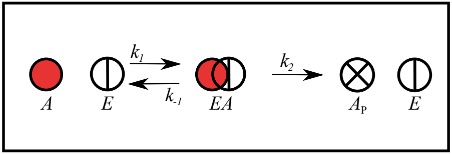
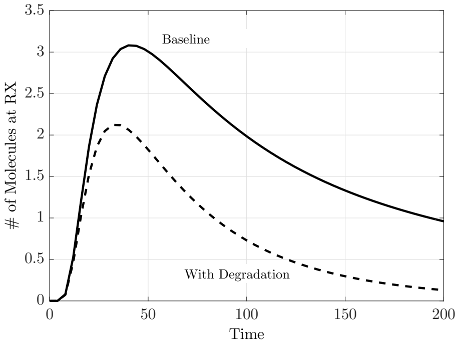


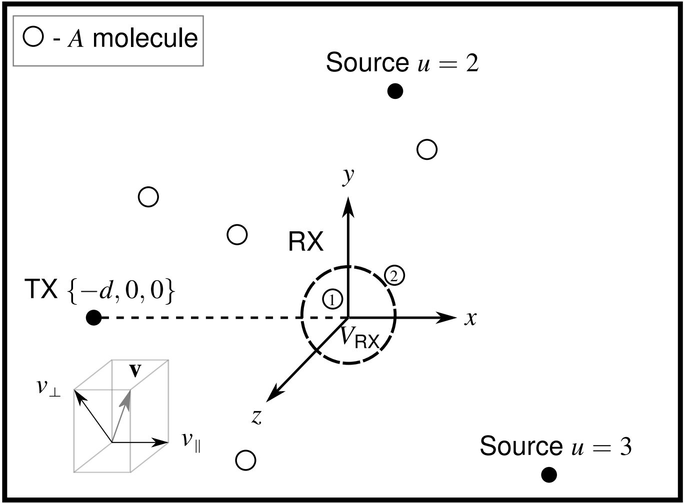


Impulse Response with Degradation

$$\overline{N}_{\mathrm{RX}}(t) = \frac{N V_{\mathrm{RX}}}{(4\pi D t)^{3/2}} \exp\left(-kt - \frac{d^2}{4Dt}\right)$$

Noel, Cheung, Schober, *IEEE Trans. NanoBiosci.*, Mar. 2014.

Channel Modeling
Uniform Flow in Any Direction



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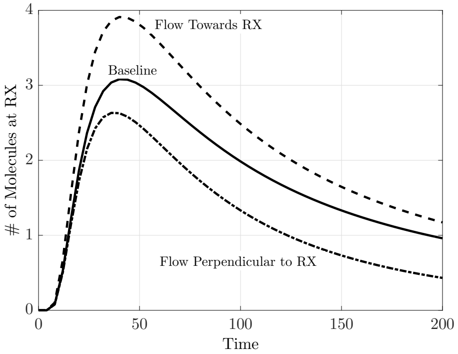

Impulse Response with Flow

$$\overline{N}_{\mathrm{RX}}(t) = \frac{NV_{\mathrm{RX}}}{(4\pi D t)^{3/2}} \exp\left(-kt - \frac{(d - v_{\parallel} t)^2 + (v_{\perp} t)^2}{4Dt}\right)$$

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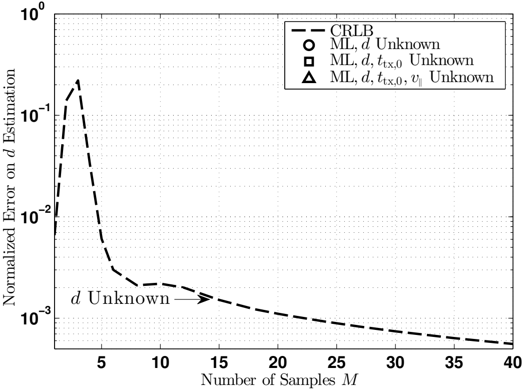
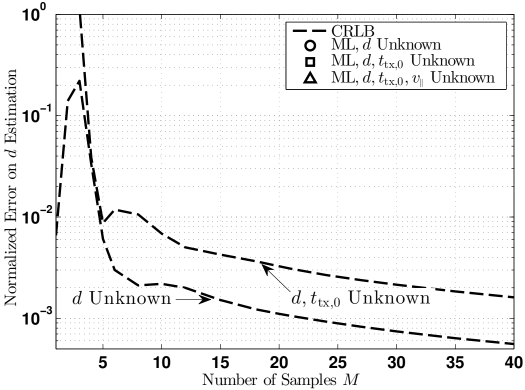
Channel Modeling
Parameter Estimation



Can we estimate underlying parameters? (e.g., d)

- Take M samples of impulse response
- Cramer Rao Lower Bound vs. Maximum Likelihood
- Bound increases as fewer parameters known
- ML is asymptotically efficient

Noel, Cheung, Schober, *IEEE Trans. Mol. Biol. Multi-Scale Commun.*, Mar. 2015.



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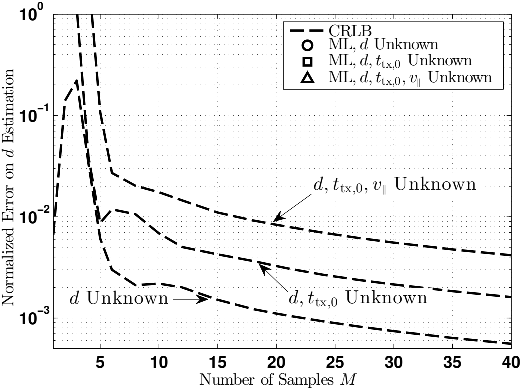

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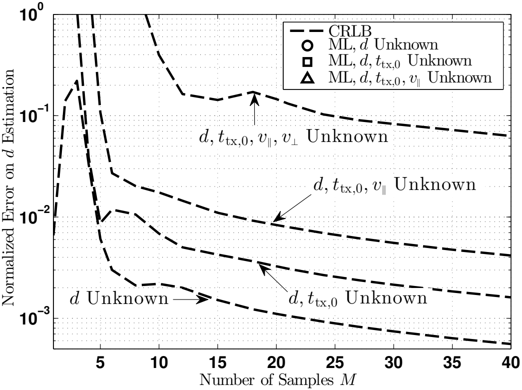

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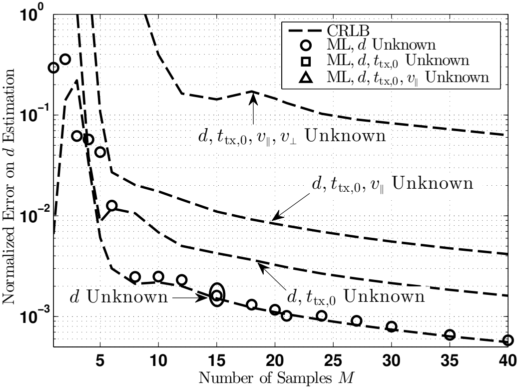

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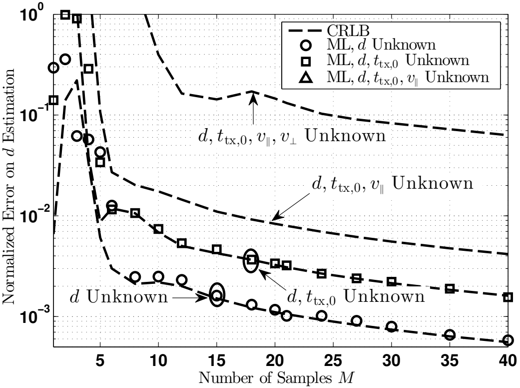

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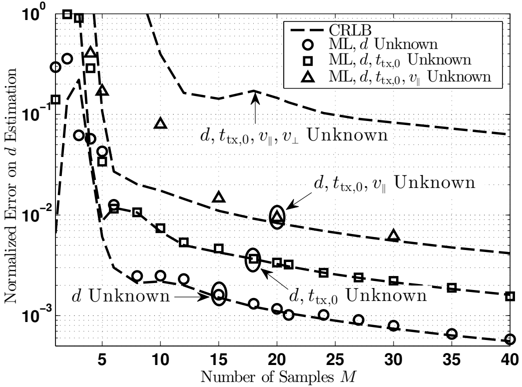

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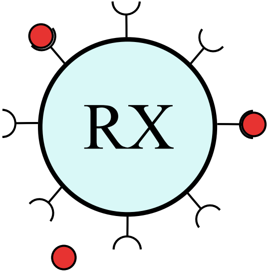
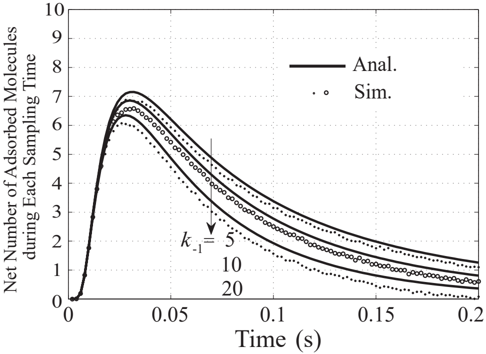
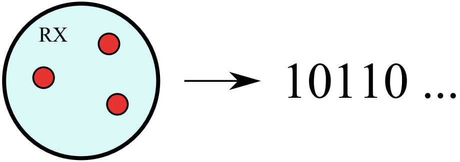
Molecules adhere to RX surface and can detach





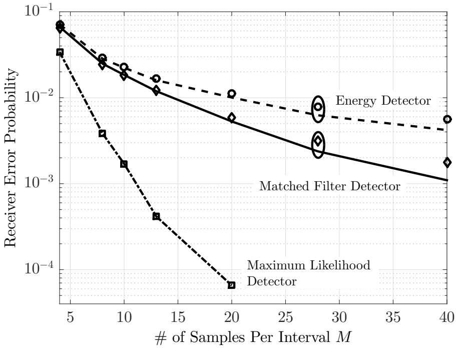
Deng, **Noel**, Elkashlan, Nallanathan, Cheung, to appear in *IEEE Trans. Mol. Biol. Multi-Scale Commun.*, 2016.



How to design communication system?

- Different ways to modulate (time of release, # of molecules, type of molecules)
- Choose impulsive binary ON/OFF keying
- Detect using multiple RX samples per symbol interval

- Energy detector and matched filter with constant decision thresholds
- Maximum Likelihood detector based on Viterbi algorithm
- We can approach ML performance with molecule degradation and/or strong flow (not shown)



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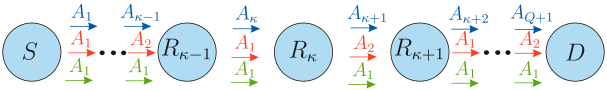
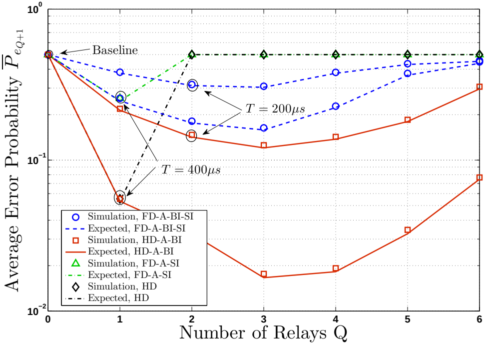


- Motivation: Reach further destinations faster
- Decode-and-forward, amplify-and-forward
- Various schemes for re-using molecule types in different hops
- Identified self-interference (SI) and backward ISI (BI)

Ahmadzadeh, **Noel**, Schober, *IEEE Trans. Mol. Biol. Multi-Scale Commun.*, Jun. 2015.

Ahmadzadeh, **Noel**, Burkovski, Schober, *Proc. IEEE GLOBECOM*, Dec. 2015.

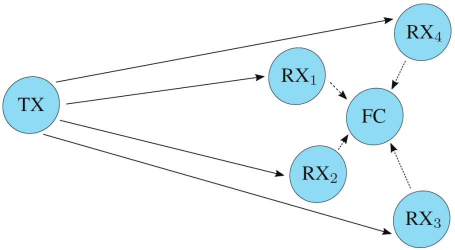
- Optimized decision threshold or number of molecules
- Adaptive relay adjusts decision threshold
- There is an optimal number of relays

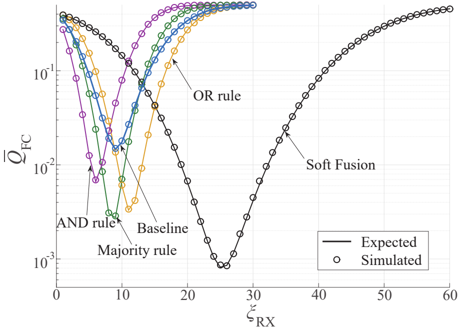


Ahmadzadeh, **Noel**, Schober, *IEEE Trans. Mol. Biol. Multi-Scale Commun.*, Jun. 2015.

Multiuser Communication

Cooperative Communication





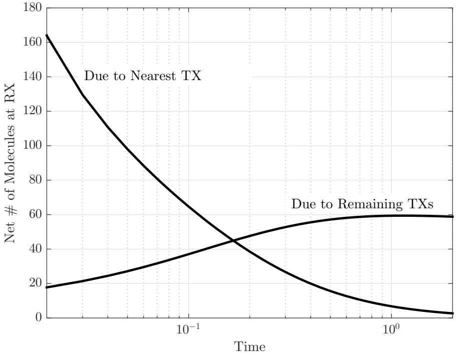
- Limited work about MC devices actually “cooperating”
- Derived performance in symmetric and asymmetric networks
- Convex optimization of thresholds (in preparation)

Fang, **Noel**, Yang, Eckford, Kennedy, to be presented at *IEEE GLOBECOM*, Dec. 2016.

Multiuser Communication

Large-Scale Systems

- Consider “large” number of TXs defined by density
- What is capability to communicate with closest TX?
- Derived channel response of closest vs remaining TXs



Deng, **Noel**, Guo, Nallanathan, Elkashlan, to be presented at *IEEE GLOBECOM*, Dec. 2016.

Simulator Development

Motivate Sandbox

- Reaction-diffusion solvers
  - Physical-chemistry community
  - Generic “sandbox” tools with flexible accuracy
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  - Constrained environmental design options

Simulator Development

Motivate Sandbox

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  - Generic “sandbox” tools with flexible accuracy
  - Not designed for communications (channel statistics, data modulation)
- Molecular communication simulators
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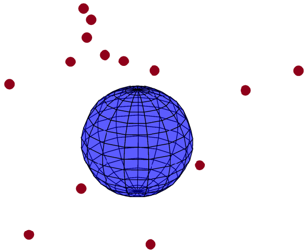
  - Designed for communications research
  - Constrained environmental design options
- Need: A “sandbox” simulator for communications research in reaction-diffusion systems



AcCoRD (**Ac**tor-based **Co**mmunication via **R**eaction-**D**iffusion)

- Flexible environmental design (accuracy vs efficiency)
- Generate “many” independent realizations
- Release molecules based on modulated data
- Output local molecule counts or specific locations

Noel, Cheung, Schober, Makrakis, Hafid, in preparation, 2016.

Finding Common Ground
Active vs Passive

Passive RX - No affect on molecule propagation

- Easier to simulate
- Easier to analyze
- Some biological justification

Finding Common Ground

Active vs Passive

Passive RX - No affect on molecule propagation

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Active RX - Model chemical detection of molecules

- More realistic
- Harder to simulate
- Less convenient analysis

Passive RX (Sampling)

$$\overline{N}_{\mathsf{RX}}\left(t\right)\big|^{\mathsf{PA}} = \frac{N V_{\mathsf{RX}}}{(4\pi D t)^{3/2}} \exp\left(-\frac{d^2}{4Dt}\right)$$

Finding Common Ground

Compare 3D Impulse Responses

Passive RX (Sampling)

$$\overline{N}_{\mathsf{RX}}(t)\,|^{\mathsf{PA}} = \frac{NV_{\mathsf{RX}}}{(4\pi Dt)^{3/2}} \exp\left(-\frac{d^2}{4Dt}\right)$$

Absorbing RX (Accumulating)

$$\overline{N}_{\mathsf{RX}}(t)\,|^{\mathsf{AB}} = \frac{Nr_{\mathsf{RX}}}{d} \mathrm{erfc}\left(\frac{d - r_{\mathsf{RX}}}{\sqrt{4Dt}}\right)$$

Fundamentally different RX models ... can we unify them?

Finding Common Ground

Compare 3D Impulse Responses

Fundamentally different RX models ... can we unify them?

$$\text{Absorbing Signal} \stackrel{?}{=} \mathcal{S}(\text{Passive Signal})$$

Finding Common Ground

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Idea to Unify Models

Compare RX models such that they are either both accumulating or both sampling instantaneous behavior

Fundamentally different RX models ... can we unify them?

$$\text{Absorbing Signal} \stackrel{?}{=} \mathcal{S}(\text{Passive Signal})$$

Idea to Unify Models

Compare RX models such that they are either both accumulating or both sampling instantaneous behavior

Why should we bother?

- Unify literature that has chosen one RX over the other
- Selection of RX model is less critical

Finding Common Ground

Sample Transform

Integrate passive RX signal to get energy detector

$$\overline{\mathsf{ED}}\left(t\right)\Big|^{\mathsf{PA}} = \frac{NV_{\mathsf{RX}}}{4\pi Dd}\mathrm{erfc}\left(\frac{d}{\sqrt{4Dt}}\right)$$

Finding Common Ground

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Use approximation of error function to separate terms inside erfc

$$\mathrm{erfc}\left(x\right) \approx \exp\left(-\frac{16}{23}x^2 - \frac{2}{\sqrt{\pi}}x\right)$$

Integrate passive RX signal to get energy detector

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Use approximation of error function to separate terms inside erfc

$$\mathrm{erfc}\left(x\right) \approx \exp\left(-\frac{16}{23}x^2 - \frac{2}{\sqrt{\pi}}x\right)$$

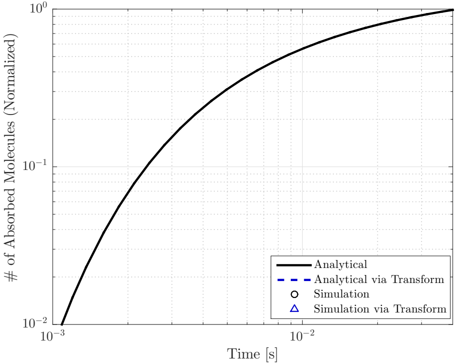
Write absorbing signal as function of passive energy detector

$$\overline{N}_{\mathsf{RX}}\left(t\right)\big|^{\mathsf{AB}} \approx \frac{3DA(t)}{r_{\mathsf{RX}}^2}\overline{\mathsf{ED}}\left(t\right)\big|^{\mathsf{PA}}$$

where

$$A(t) = \exp\left(\frac{r_{\mathsf{RX}}}{\sqrt{Dt}}\left(\frac{8(2d - r_{\mathsf{RX}})}{23\sqrt{4Dt}} + \frac{1}{\sqrt{\pi}}\right)\right)$$

Consider signal of 3D absorbing RX



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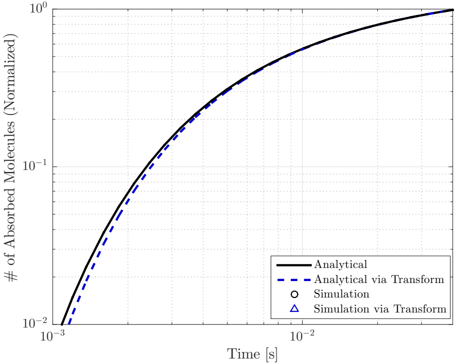
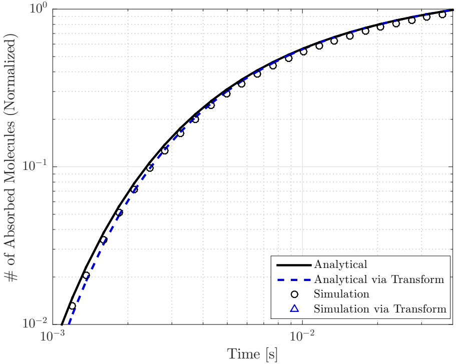


Noel, Deng, Makrakis, Hafid, to be presented at *IEEE GLOBECOM*, Dec. 2016.

Consider signal of 3D absorbing RX

- Analytical transform no less accurate than simulation



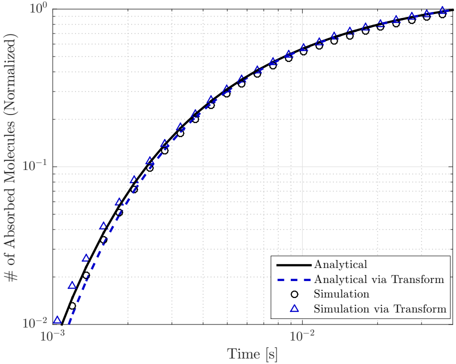
Noel, Deng, Makrakis, Hafid, to be presented at *IEEE GLOBECOM*, Dec. 2016.

Finding Common Ground

Results

Consider signal of 3D absorbing RX

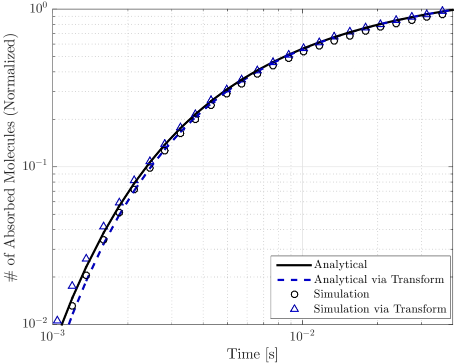
- Analytical transform no less accurate than simulation
- Can also transform passive simulations



Noel, Deng, Makrakis, Hafid, to be presented at *IEEE GLOBECOM*, Dec. 2016.

Consider signal of 3D absorbing RX

- Analytical transform no less accurate than simulation
- Can also transform passive simulations
- Similar results with passive RX and in 1D



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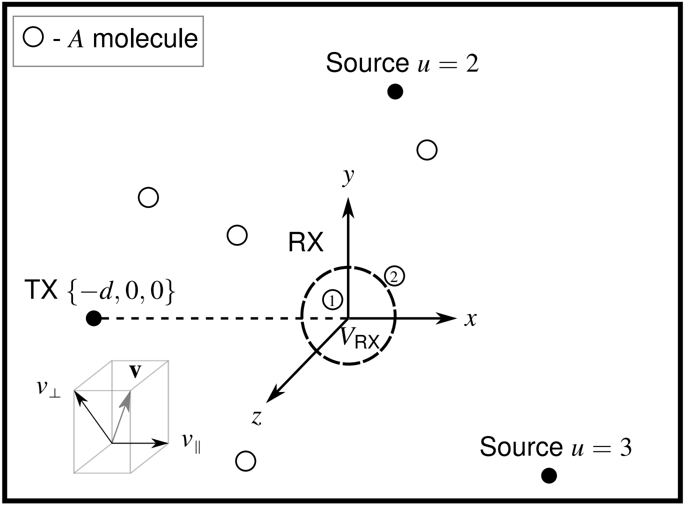
Where We're Going

General Directions of MC Research:

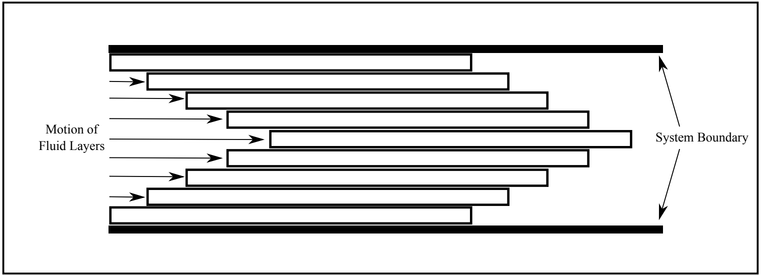
1. Improving physical and simulation models
2. Obtaining experimental data

AcCoRD simulator is in on-going development and publicly available

Expanding Physical Model



Oscillating Laminar Flow



Solvent in laminar flow moves as sliding layers with different velocities

- Small cross-sections lead to laminar flow
- E.g., small blood vessels
- Blood flow oscillates

Final Words

- Molecular communication is a promising interdisciplinary field

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- Interesting variations on “traditional” communications analysis techniques

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- Molecular communication is a promising interdisciplinary field
- Interesting variations on “traditional” communications analysis techniques
- Inspiration between biology and engineering is bidirectional

Acknowledgments

- Supervisors
  - Robert Schober, FAU Erlangen-Nuremberg
  - Karen C. Cheung, UBC
  - Dimitrios Makrakis, University of Ottawa
  - Abdelhakim Hafid, University of Montreal
- "Horizontal" Collaboration
  - Arman Ahmadzadeh, FAU Erlangen-Nuremberg
  - Yansha Deng, King's College London
  - Jonas Yang & Yuting Fang, Australian National University
- Funding
  - Natural Sciences and Engineering Research Council

The End

That's All, Folks

Thanks for your time!
Papers: adamnoel.ca
Simulator code: github.com/adamjgnoel/accord

Slide Backup