5G Networks & Nanonetworking Research @ Boğaziçi

Seminar @ ITU

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Outline

- About Boğaziçi University
- About me
- Our 5G Research
- Our Nanonetworking/Molecular Communications Research

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- Where I come from: Boğaziçi University
  - Besides her intellectual responsibility for the democracy in Turkey, Boğaziçi University is also known as a good international university
    - Top ranking Turkish university in the “Best Global Universities 2018” list of US News & World Report (rank: 234^{th})
    - Ranking 401-500 in Times Higher Education
    - Ranking 491-500 in QS Ranking (ranking 301-350 in Computer Science)
  - We owe our success to our students, crème-de-la-crème
    - One must rank in the **top 430 among 2.5 million candidates** to become a student in our department

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- Where I come from: Boğaziçi University
  - Member of:
    - IAU - The International Association of Universities
    - Magna Charta Universitatum
    - EUA - European University Association
    - UNIMED - Mediterranean Universities Union
    - Black Sea Universities Network
    - SEFI - European Society for Engineering Education
    - The Utrecht Network
  - Exchange/Erasmus programs with many European (231), North American (28), Asian (23), and Australian (5) universities
  - So, we welcome all students and professors to spend a semester or two at Boğaziçi University

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- Originally, a wireless networks researcher
  - Previously worked on:
    - 3G, 4G, Next Generation Wireless Networks
    - IEEE 802.16 (WiMAX)
    - Mesh networks
    - **Cognitive Radio**
      - Collaborative spectrum sensing
      - *Radio Environment Map (REM)* construction for geolocation database
    - ICN (Information Centric Networking)
  - Currently working on:
    - **5G**
      - **CloudRAN (C-RAN)**
      - **Network Slicing**
    - **Internet of Things & LoRaWAN**
  - In this respect, the term “cellular” means “related to a base station” for me

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- Also, a nanonetworking researcher
  - Member of the IEEE 1906.1 Nanoscale and Molecular Communications Working Group
  - Focused on Molecular Communications to enable Nanonetworking
    - How to enable communications among nanomachines by utilizing molecules as message carriers
    - A living cell constitutes a perfect model for a nanomachine that transmits and receives molecules
  - I do not have a biology or chemistry background
  - In this new respect, “cellular” means “related to a living cell”

  - I am a member of the Computer Networks Research Lab (NETLAB)
  - I also lead Nanonetworking Research Group at Boğaziçi University together with Prof. Ali Emre Pusane & Prof. Birkan Yılmaz

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- Besides regular academic responsibilities
  - Served on the Internet Council of Turkey for 5 years (reporting to Minister of Transportation and Telecommunications)
  - Served on the Audit Committee of Turk Telekom for 2 years (representing the Treasury of Turkish Republic)
  - Served as the advisor for the Telecom Group in Electrical and Electronic Technology Platform for 3 years (recommendation committee to the Prime Minister)
  - Served as the Vice Rector (2014-2016)
  - Served as the Director of the Computer Center (2014-2016)
  - Founder of TTO at Boğaziçi University
  - Consultant for several companies including Huawei-TR
  - A voluntary advocate and public educator for Internet rights in Turkey
  - Currently, chairperson in Computer Engineering

Our CloudRAN Research

Contents

- Why CloudRAN?
- Work done by our research group on 5G/CloudRAN
- Work plan in the proposed project

Why CloudRAN?

- Current status:
  - Operators plan the infrastructure for the worst-case
  - This approach results in overprovisioning (by all means)
    - Worst-case does not occur at all locations (cells) simultaneously
    - The population size in the city does not fluctuate daily; it is the same group of subscribers moving in herds according to the rush hour
    - See our animation at:
      - https://www.cmpe.boun.edu.tr/~tugcu/CloudRAN-animation

Why CloudRAN?

- What will happen in 5G?
  - The situation will worsen since the number of cells will explode (due to smallcells)
  - Higher number of cells implies:
    - More base station equipment *(BBU + RRU/RRH, cooling system, UPS, power generator, network connection)* to maintain
    - Unmanageable body of technicians to maintain the network
    - High CAPEX and OPEX
    - More power consumption
    - Difficulties in OSS

Why CloudRAN?

- CloudRAN provides centralization of BS management
  - Key BS functionalities moved from the field to the center
    - Selection of the functionalities
  - Benefit from scale-up benefit of the cloud:
    - As the subscribers populate in different cells, the resources dedicated to the corresponding virtual BBUs can be re-arranged
    - Scale the network according to the total number of the subscribers, not the nightmare/worst-case
    - Additional benefits from previously infeasible tricks, such as signal combining
  - Hybrid approach:
    - CloudRAN is more effective for urban areas; rural areas may utilize the traditional devices as before
    - Traditional BSs will work in harmony with CloudRAN BSs
    - Smooth transition from traditional structure to CloudRAN-based network

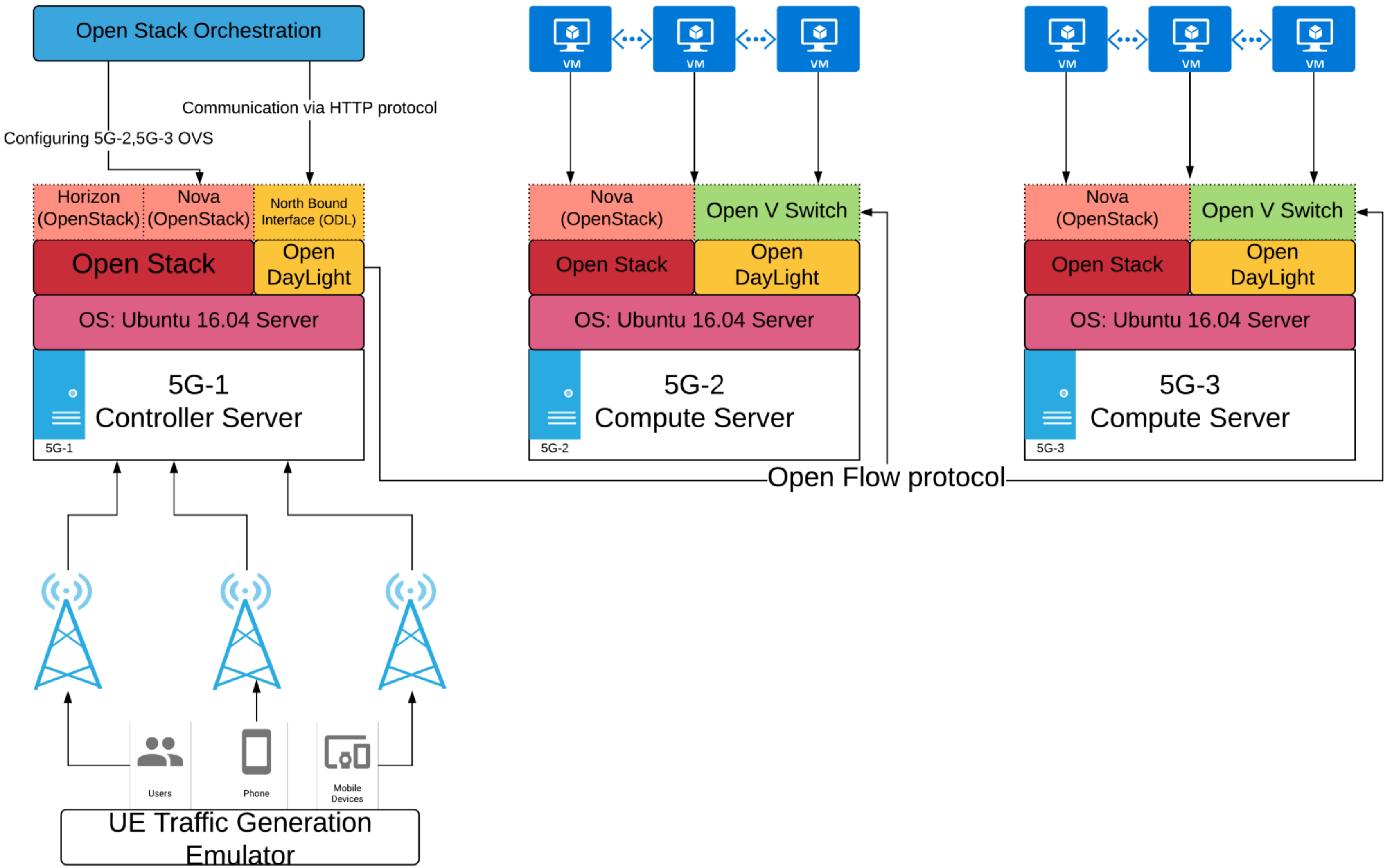
What we have done so far
Terminology

- BBU (Baseband Unit): Base station controller functionality
- RRH (Remote Radio Head, a.k.a. Remote Radio Unit-RRU): Base transceiver station functionality, i.e., antenna
- Compute node: Physical computer in the cloud (typically augmented with powerful signal processing hardware)
- vBBU (virtual BBU): Virtualized BBU functionality running on compute nodes
- SDN, NFV, and others are well-known acronyms in telecom

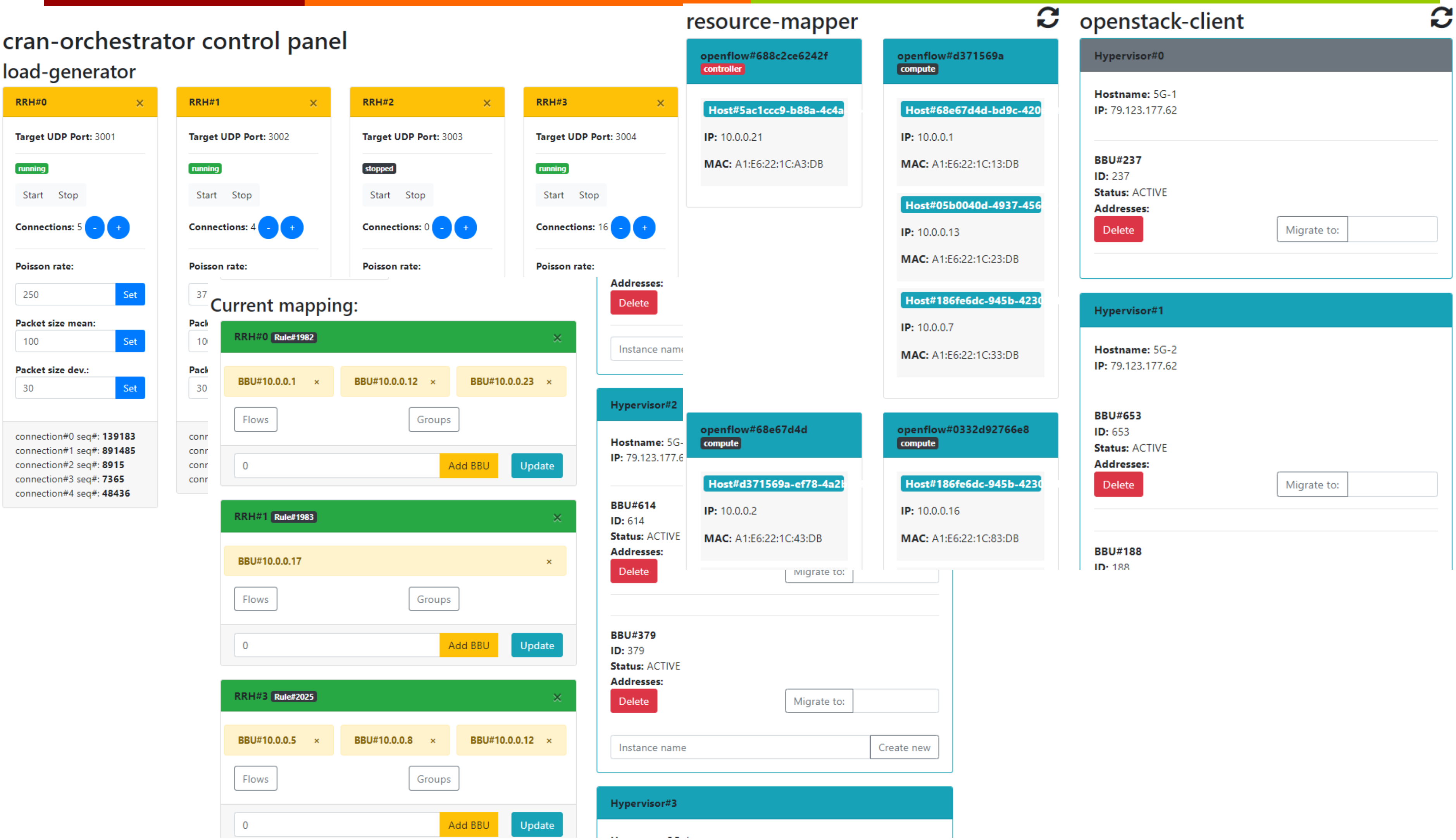
What we have done so far
Overview

- We have **implemented** two separate testbeds (one in Kuzey Campus and the other in Kandilli) for CloudRAN where:
  - We have 3 physical servers that act as compute nodes in a cloud system
  - On each compute node, several vBBUs are hosted
  - Since we do not have real RRH devices, we simulate them
    - RRH is not a part of CloudRAN; simulation of RRH does not constitute loss of generality

What we have done so far
Architecture



What we have done so far
Orchestrator & Resource Mapper GUI



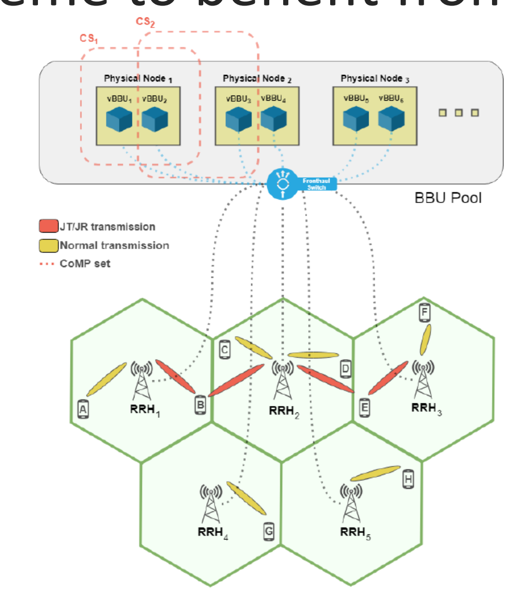
What we have done so far
Status

- **Currently, we are capable of migrating a vBBU (base station) with all of its active connections to the RRHs while it is alive**
  - vBBU-RRH connections are **not** lost and data transmission resumes after migration
  - Migration operation **takes 10-20 sec at the moment**
    - We have achieved this migration performance without any modifications in the code
    - We can take it down to **less than 1 msec** by making modifications in the code
      - We need financial support for this study, thus the reason for this project proposal
      - The current results have been obtained with no financial support from any organization (TÜBİTAK, Boğaziçi University or any other financial supporter), so we do not have any IPR conflicts

What we plan to do

- We have used open source projects such as OpenStack, Neutron, etc. to achieve this outcome (~10-20 sec migration delay)
- We will modify the source code to take the delay below 1 msec
- We will also develop signal combining scheme to benefit from CloudRAN to improve signal quality

Signal combining is a method that utilizes interfering signal at the nearby BS rather than trying to erase it as noise



What we plan to do

- In most wireless communications applications, the receiver has access to multiple copies of the transmitted signal, which results in diversity.
- Diversity can be achieved in
  - **space** *(multiple antennas that are placed sufficiently apart)*
  - **time** *(transmission of the same signal at different times)*
  - **frequency** *(transmission of the same signal at different frequencies)*
  - **polarization** *(not very popular)*
  - **multipath** *(signal copies arrive at different times, angles, etc.)*
- CRAN can take advantage of the inherent space diversity that results from having multiple RRUs listening to the same user's signal.

What we plan to do

- Popular mechanisms to take advantage of diversity are
  - selection diversity (select and use the best signal, ignore the others)
  - equal gain combining (add up the signals coherently after equalizing delays)
  - maximum ratio combining (add up the signals coherently after equalizing delays and weighing them)
- CRAN implementations usually assume selection diversity and treat the unwanted copies as interference, whereas maximum ratio combining has the potential to significantly increase the overall SNR.
- As a rough rule, the bit error rate (BER) is inversely proportional to Ω^L, where Ω is the average SNR and L is the diversity order.

Our Nanonetworking Research

Nanomachines: Overview

- A nanomachine is a device composed of nanoscale components that perform a useful function
  - Nanobots, nanoids, nanites, or nanomites are other names used in the literature
- From our perspective, the important features are:
  - At least one dimension should be in the nanoscale
  - Must be human controlled
  - Must be able to process data
  - Must be capable of communicating by utilizing carriers of information in the nanometer range

Nanomachines: Design Approaches

Approaches for Nanomachine Construction

- **Top-Down:** Bigger machines building smaller machines
  - Similar to well-known lithography techniques
- **Bottom-Up:** Molecules and/or atoms form together and build machines
- **Bio-Mimicking:** Machines based on cells, organelles
  - Bio-engineered cells

Nanomachines: Design Approaches

Capabilities:

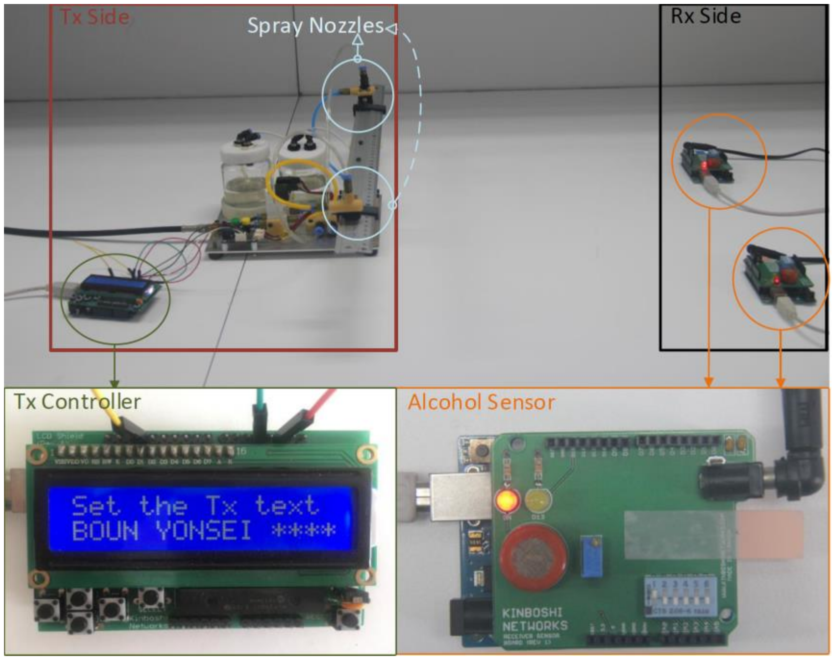
- Self-assembly and/or Self-replication
- Self-repairing
- Self-sustainable

Are We Daydreaming?

Early Work on Nanomachines/Nanonetworks

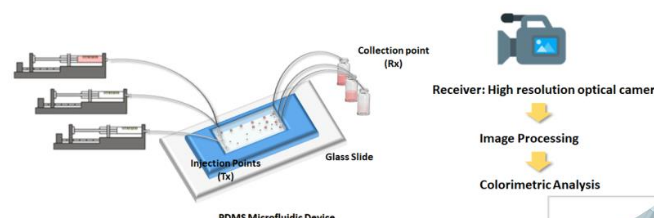
- **Looks futuristic?**
  - **Adder implementation:** Half-adder (Terzer *et al.*) and full adder (Remacle *et al.*) nanomachines have already been implemented as early as 2005
  - **Hypothetical Chemical Turing Machine:** It has been shown that using DNA strands and enzymes, a Turing Machine can be built (Benenson *et al.*)
  - **Cover story in IEEE Spectrum (March 2011):** "Biological Transistors"
  - **IEEE 1906.1 Standards Group** established and in action
    - Released the communication framework draft in 2015
    - Spawned *IEEE Transactions on Molecular, Biological and Multi-Scale Communications* journal

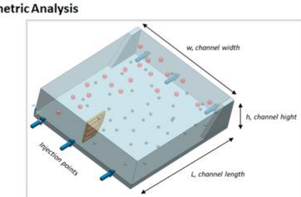
Our Macro-scale and Micro-scale PoC Nanonetworking Testbeds



MIMO macro-scale testbed based on:

N.-R. Kim, N. Farsad, C.-B. Chae, A.W. Eckford, “A Realistic Channel Model for Molecular Communication with Imperfect Receivers,” IEEE ICC, 2014.





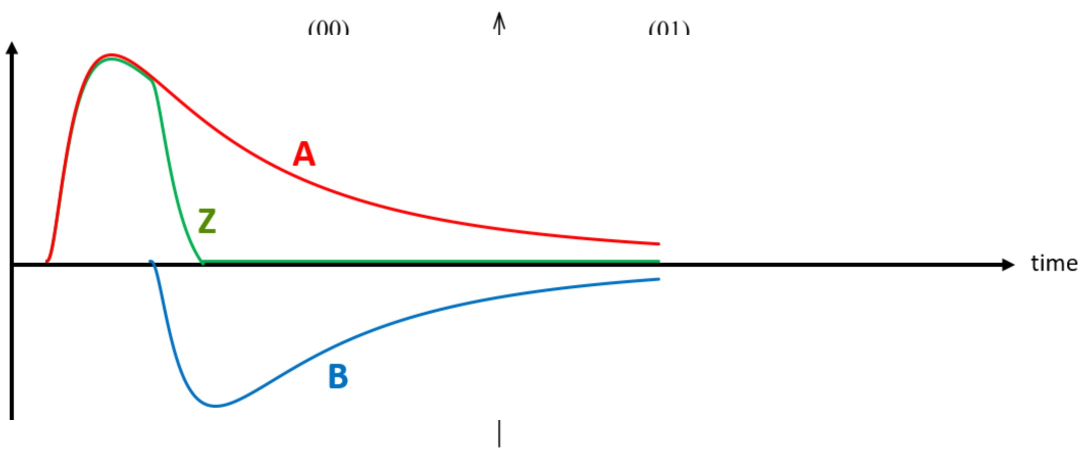
New micro-scale testbed we are working on:

http://nrg.boun.edu.tr

What We Have Done Up To Now

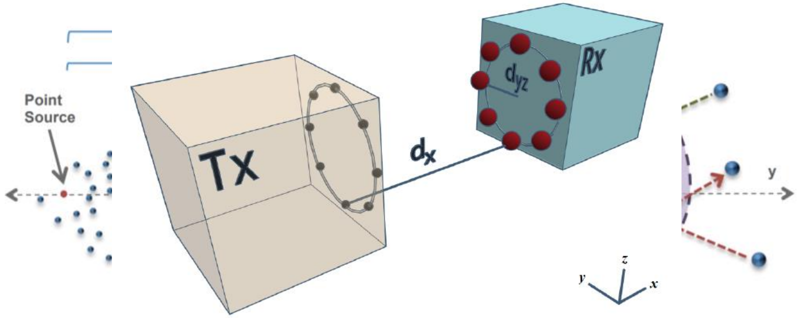
What We Have Done Up To Now

- Defined the energy model for MCvD
- Defined several modulation techniques for MCvD
- Molecule-as-a-frame
- Studied Calcium Signaling
- Pre-equalization and ISI mitigation



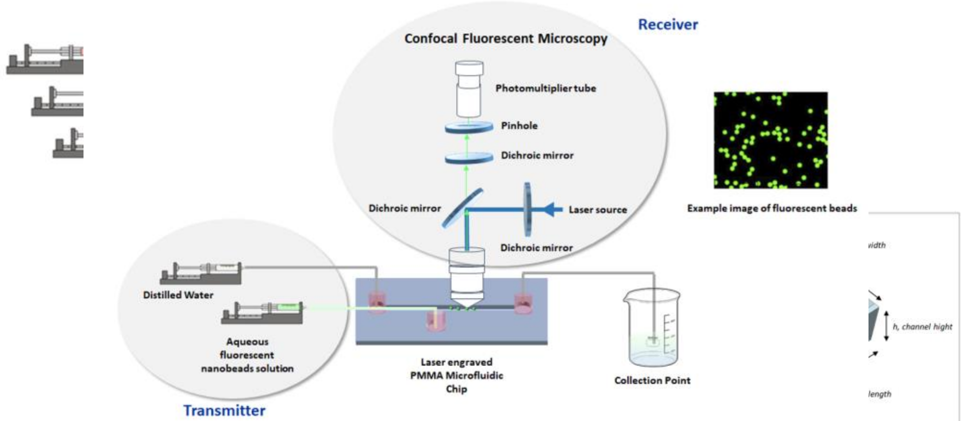
What We Have Done Up To Now

- Analytical formulation of 3D channel characteristics with absorbing receiver & Achievable rate analysis of MCvD
- Network Coding for MCvD & Position-based modulation
- Partially receiving counting absorbing receiver & Optimal reception delay
- Several simulation methods (incl. HLA, GPU programming)
- Index modulation in molecular communications



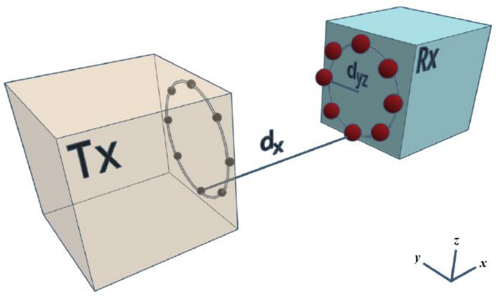
What We Are Doing Right Now

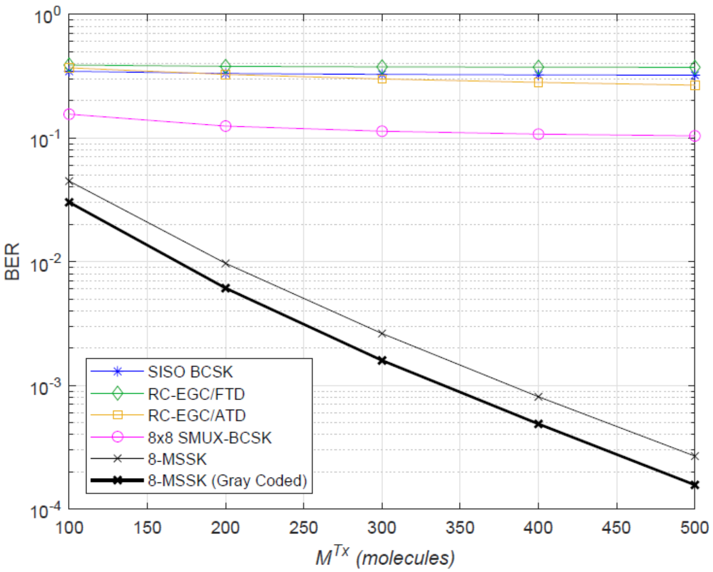
- Our new project on colorimetric analysis project just received funding
- Working on a joint project with S.Korea on MCvD in vessel-like environment
- Working on a EU-funded Project (including transceiver design, circulatory system, and in-body antennas)



Index Modulation in MCvD

- MIMO in MC already implemented and tested on a macro-scale testbed
- Index modulation is an alternative
  - 8x8 MIMO setup considered
  - Uniform circular array
  - Corresponding TX & RX antennas are alignec
  - Inter-link interference is a problem
    - Use only a single antenna at a time
  - Yields lower BER than MIMO





- M. C. Gursoy, E. Basar, A. E. Pusane, T. Tugcu, "Index modulation for molecular communication via diffusion systems," IEEE Transactions on Communications, vol. 67, no. 5, pp. 1558-0857, May 2019
- A. Celik, M. C. Gursoy, E. Basar, A. E. Pusane, T. Tugcu, "A low-complexity solution to angular misalignments in molecular index modulation," PIMRC September 2019

Pulse Position Modulation in MCvD

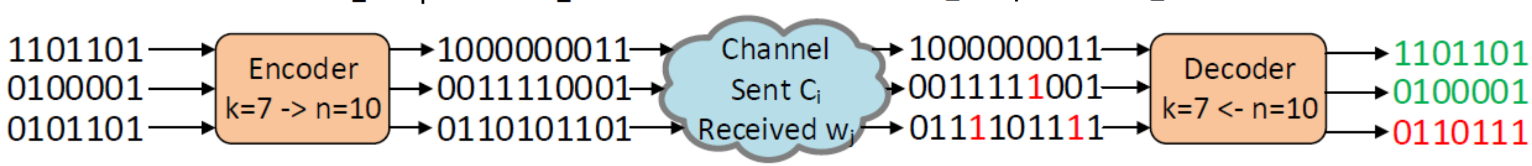
- Employ K-PPM for different K values by only releasing molecules at i^{th} time slot where $i < 2^K$
- Decoder aims to identify the slots that involve maximum number of molecules → No threshold requirement → Good for MC
  - Its sparsity reduces ISI

B.C. Akdeniz, A.E. Pusane, T. Tugcu, "Position-based Modulation in Molecular Communications," Elsevier Nano Communication Networks, vol. 16, pp. 60-68, June 2018

Error Control Coding for MCvD

- The classical coding techniques are mainly based on Hamming distance
  - They are not tailored for molecular communications
- An ISI-minimizing code is designed recursively:

$$\mathbf{CW}_{n+1} = \left[\begin{array}{c:c} 0 & \mathbf{CW}_n \\ \hdashline 0 & \mathbf{W}_n \end{array}\right] \qquad \mathbf{W}_{n+1} = \left[\begin{array}{c:c} 1 & 0 \\ \hdashline 1 & \mathbf{CW}_n \end{array}\right]$$



A. O. Kislal, H. B. Yilmaz, A. E. Pusane, T. Tugcu, “ISI-aware channel code design for molecular communication via diffusion,” IEEE Transactions on NanoBioscience, vol. 18, no. 2, pp. 205-213, April 2019

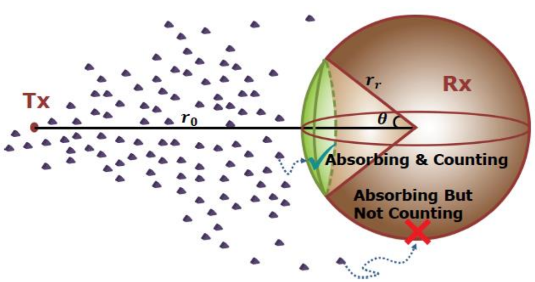
Optimal Reception Delay in MCvD

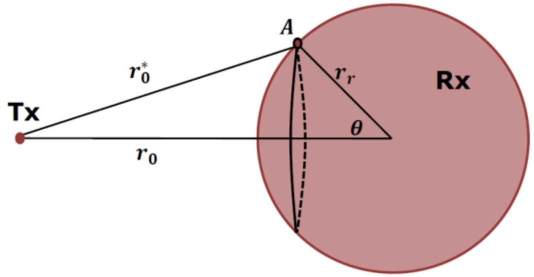
- A receiver-based approach that finds optimal delay for decoding to reduce ISI
- I Requires no additional complexity other than conventional CSK.
- Finding τ that increases the power of the signal and reduces ISI optimally
  - Use Signal to Interference Difference (SID):
    - $SID = h_1 - \sum_{k=2}^{K} h_k$
    - Maximize signal and minimize ISI as in SIR
    - Tractable to find optimum and avoid excessive decrement of h_1

B.C. Akdeniz, A.E. Pusane, T. Tugcu, "Optimal Reception Delay in Diffusion-based Molecular Communication," IEEE Communications Letters, vol. 22, no. 1, pp. 57-60, Jan. 2018

Partially Receiving Absorbing Receiver

- Received molecules tend to accumulate on the parts of the receiver that are closer to the transmitter
- Significant part of ISI is due to the molecules received by other parts





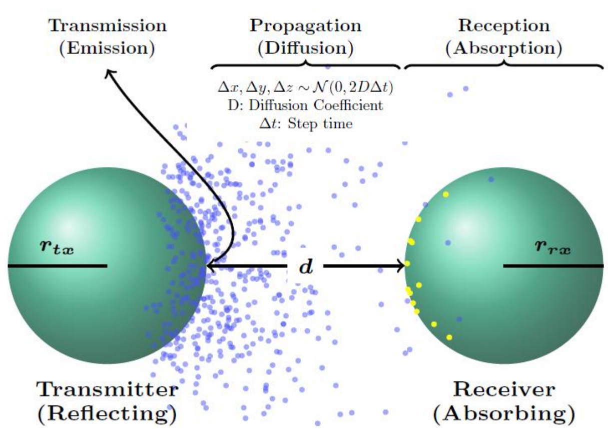
$$p(\theta, t) = \frac{\sin\theta \,\mathrm{erfc}\left(\frac{r_0^*}{\sqrt{4Dt}}\right) F_{\mathrm{hit}}(t, r_0, r_r)}{\left(1 - \frac{2r_r}{r_0}\cos\theta + \frac{r_r^2}{r_0^2}\right)^{\frac{3}{2}} \int_0^{\pi} \frac{\sin\theta' \,\mathrm{erfc}\left(\frac{r_0^*}{\sqrt{4Dt}}\right)}{\left(1 - \frac{2r_r}{r_0}\cos\theta' + \frac{r_r^2}{r_0^2}\right)^{\frac{3}{2}}} d\theta'}$$

B.C. Akdeniz, N.A. Turgut, H.B Yilmaz, C.B. Chae, T. Tugcu, A.E. Pusane, “Molecular signal modeling of a partially counting absorbing spherical receiver,” IEEE Transactions on Communications, vol. 66, no. 2, pp. 6237-6246, December 2018

Analytical formulation of 3D channel characteristics with absorbing receiver

- Distribution of the first passage time for sphere-to-sphere communication is analytically challenging
- Two new distributions and prove by Kolmogorov-Smirnov test that KBIGG can successfully model the first passage time

Visual constructed using real data from our particle based simulator



$$f_{KBIGG}(t;\alpha,\theta,\beta,a,b,c)=\frac{K\beta\,\Gamma\left(\alpha,(\theta/t)^{\beta}\right)^{a-1}(\theta/t)^{\alpha\beta+1}\,e^{-(\theta/t)^{\beta}-c\frac{\Gamma\left(\alpha,(\theta/t)^{\beta}\right)}{\Gamma(\alpha)}}}{\theta\,\Gamma(\alpha)^{a+b-1}\left(\Gamma(\alpha)-\Gamma\left(\alpha,(\theta/t)^{\beta}\right)\right)^{1-b}}$$

G. Genc, Y.E. Kara, T. Tugcu, and A.E. Pusane, "Reception modeling of sphere-to-sphere molecular communication via diffusion," Elsevier Nano Communication Networks, vol. 16, pp.69-80, June 2018

Achievable rate analysis of MCvD

- MCvD is a channel with memory – Shannon's channel capacity formula is not applicable
- MCvD channel can be represented as a finite state machine with $2^{\eta+1}$ states

Distance (μm)	Optimistic Achievable Rate (η =1) (bits/ch. use)	More Realistic Achievable Rate (η =14) (bits/ch. use)
4	1	1
8	0.9996	0.9972
12	0.9959	0.9831
16	0.9846	0.9557
20	0.9662	0.923

G. Genc, Y.E. Kara, H.B. Yilmaz, and T. Tugcu, "ISI-Aware Modeling and Achievable Rate Analysis of the Diffusion Channel," IEEE Communications Letters, Vol. 20, No 9, pp. 1729-1732, September 2016

Summary of Our 5G & Nanonetworking Research

- In 5G, we are at the phase of developing a CloudRAN system
  - Optimizing migration of BBUs between computer nodes in the cloud
  - Also looking into network slicing issues
  - In collaboration with vendors for mobile networks

- In nanonetworking/molecular communications:
  - One of the leading teams in the field
  - Beyond analytical modeling and simulations, we are now capable of implementing our testbed in nanoscale

- Contact info:

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