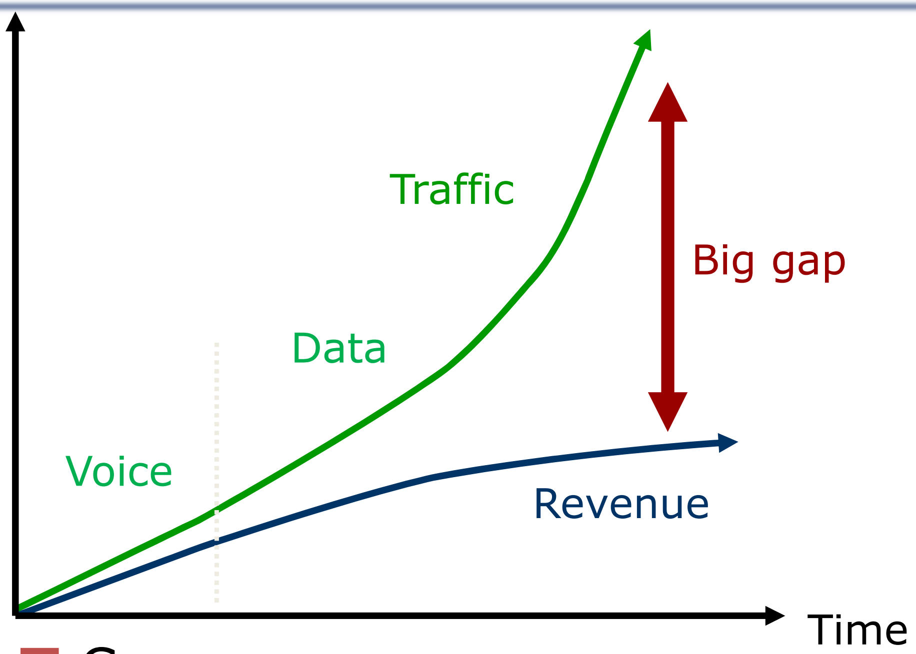
NSF JUNO: Energy-Efficient Hyper-Dense Wireless Networks with Trillions of Devices

Abolfazl Mehbodniya, Fumiyuki Adachi, Tohoku University
Ismail Guvenc, ECE Department, Florida International University
Walid Saad, ECE Department, Virginia Tech

Outline

1. Introduction
   - Trends and perspectives
   - Roadmap
   - Key research challenges
2. Overall Project Description
   - Research thrusts
   - Overall project Timeline
   - USA-Japan collaboration
3. Detailed Project Description
   - Thrust I: Mobility and Energy Efficiency for HDHNs
   - Thrust II: Self-Organization for HDHNs
   - Thrust III: Testbed and Experimentation for HDHNs
4. Conclusions

Trends and Perspectives for Future Mobile Networks



- Trends
  - Exponential growth in data traffic
  - Number of base stations / area increasing for higher capacity
  - Revenue growth constrained and dependent on new services
  - Carriers under pressure to dramatically reduce TCO and energy bill

- Consequences
  - Energy use cannot follow traffic growth without significant increase in energy consumption
    → **MUST REDUCE** Energy Per Bit
  - Number of base stations increasing
    → **MUST REDUCE** Operating Power Per Cell to save TCO

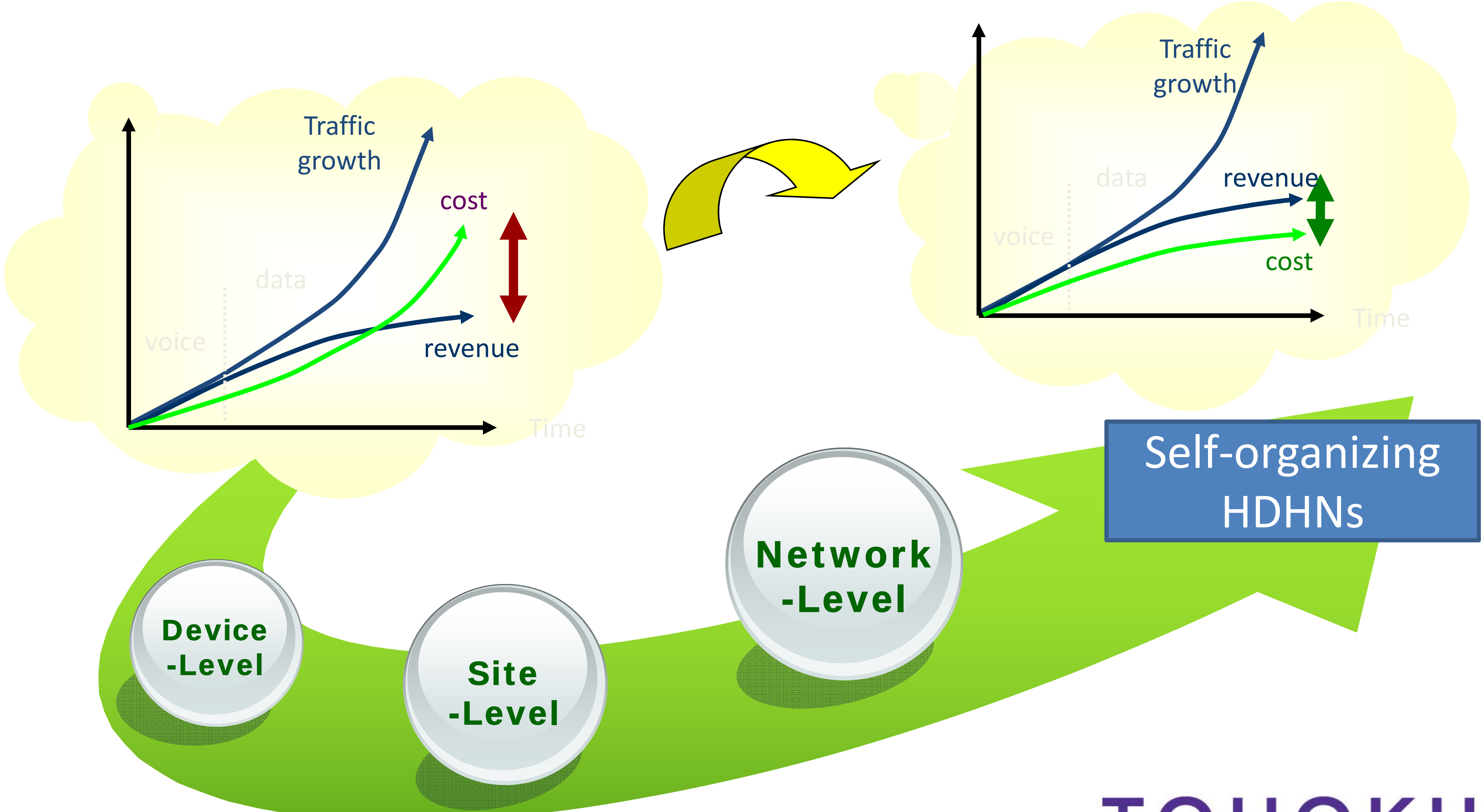
Two Perspectives:

1) Bandwidth Efficiency
2) Energy Efficiency

Self-organizing, heterogeneous, and hyper-dense networks are the keys to achieving both

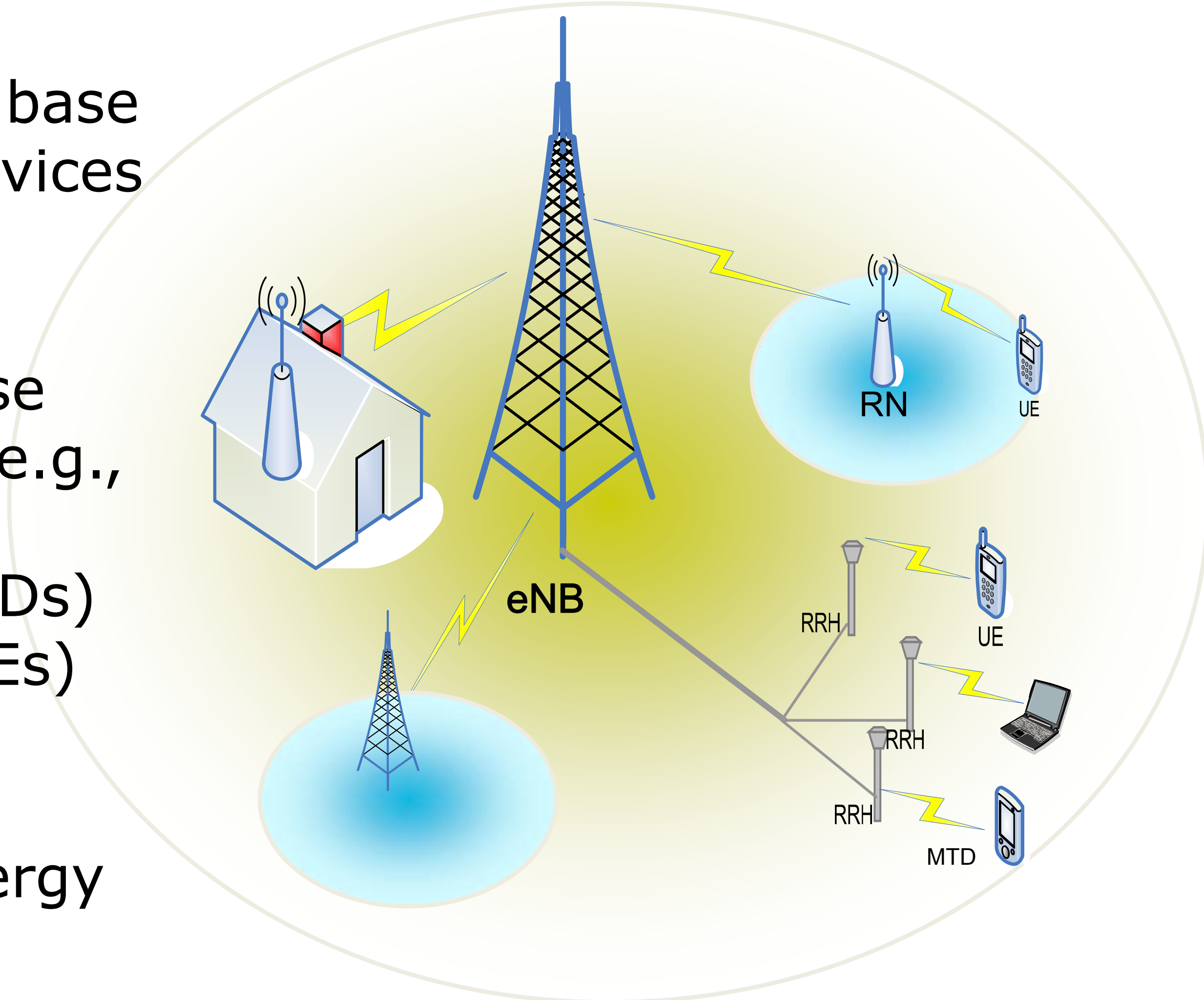
FLORIDA INTERNATIONAL UNIVERSITY · Virginia Tech · TOHOKU UNIVERSITY

Roadmap: Towards Energy Efficient HDHNS



Key Research Challenges

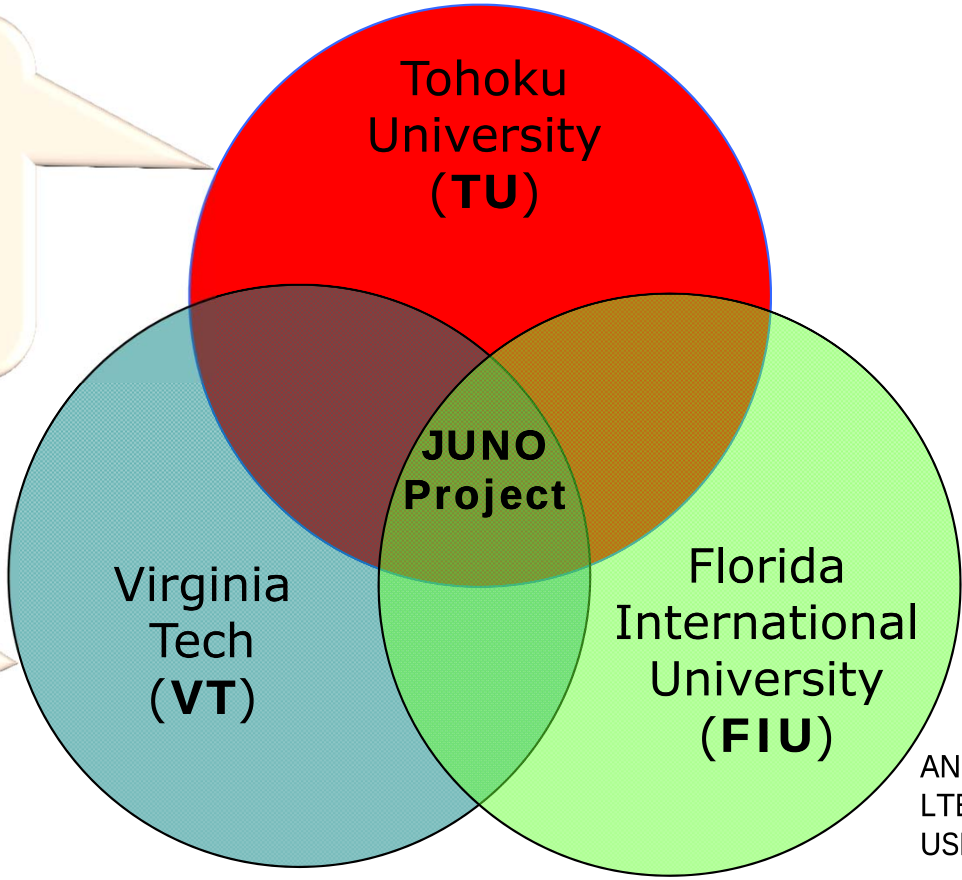
- Density, due to trillions of base stations and connected devices
- Network dynamics, due to mobility
- Heterogeneity, at both base station and device levels, e.g., concurrent existence of machine type devices (MTDs) and users equipment's (UEs) connections
- Inherent spectral-energy efficiency tradeoff and energy efficiency issue



US-Japan Collaboration

Expertise:
- ✓Physical Layer design
- ✓ Radio resource management
- ✓ Fuzzy Logic and ANN techniques
- …

Expertise:
- ✓Game Theory
- ✓Energy-efficient wireless designs
- ✓Energy-Harvesting
- …

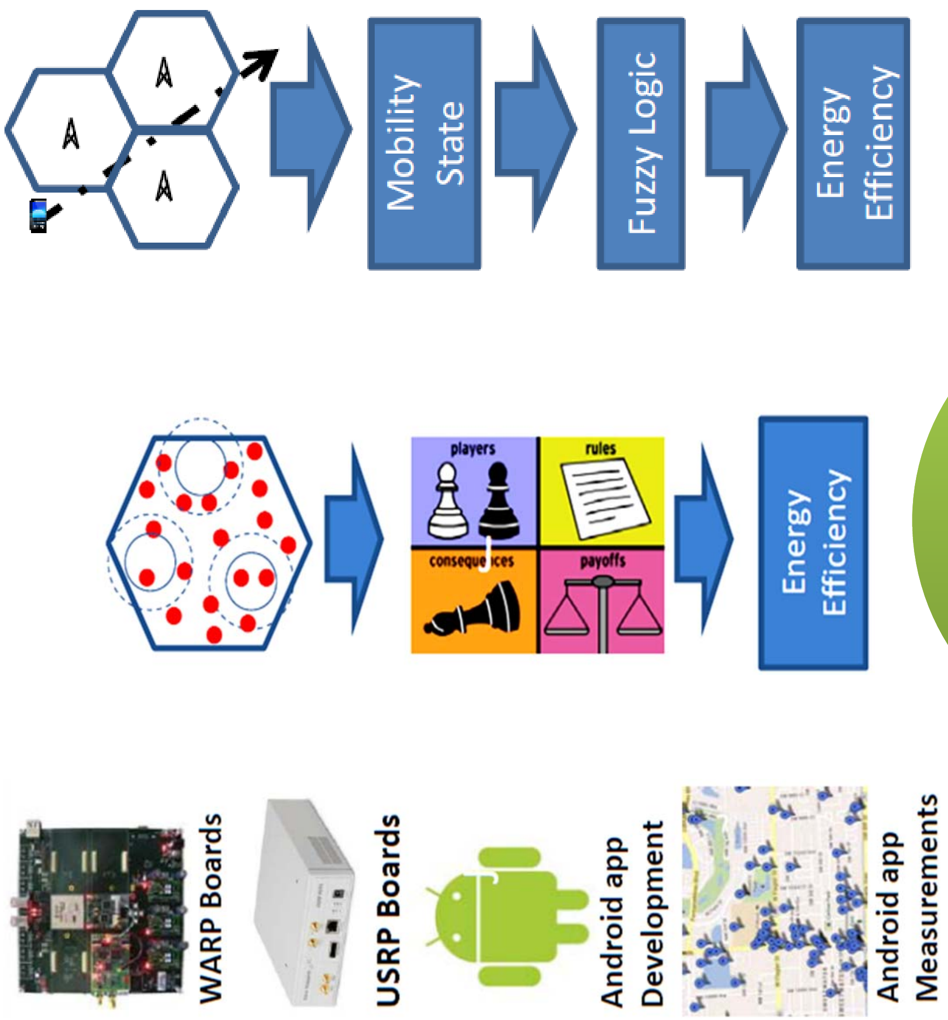


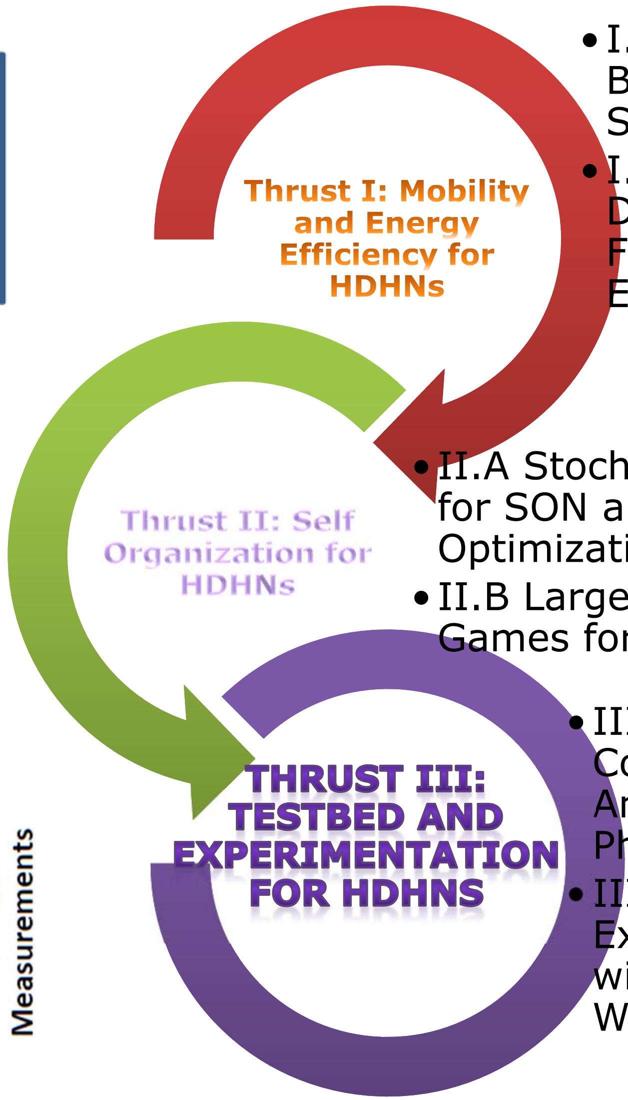
Expertise:
- ✓LTE
- ✓USRP testbed
- ✓ Mobility Management
- …

ANN: Artificial Neural Network
LTE: Long Term Evolution
USRP: Universal Software Radio Peripheral

FIU FLORIDA INTERNATIONAL UNIVERSITY VirginiaTech TOHOKU UNIVERSITY

NSF JUNO Research Thrusts

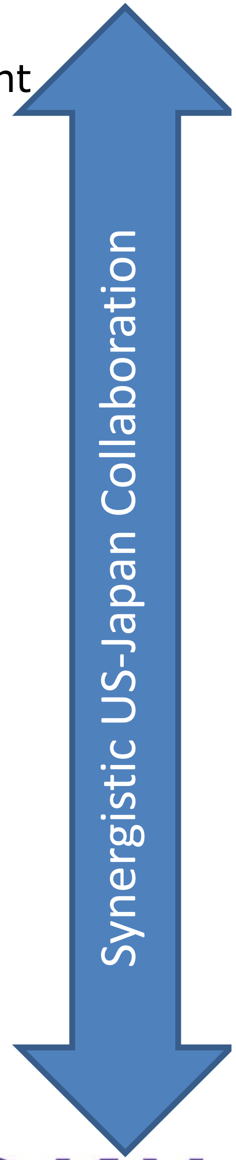




- I.A Handover Count Based Mobility State Estimation
- I.B Speed Dependent and Fuzzy Logic Based EE Enhancement

- II.A Stochastic Geometry for SON and EE Optimization
- II.B Large Population Games for SON in HDHNs

- III.A Data Collection through Android Smart Phones
- III.B Experimentation with USRPs and WARP Boards



FIU FLORIDA INTERNATIONAL UNIVERSITY

1872 VirginiaTech

TOHOKU UNIVERSITY

Project Timeline

FIU FLORIDA INTERNATIONAL UNIVERSITY

VirginiaTech 1872

TOHOKU UNIVERSITY

Collaborative Efforts

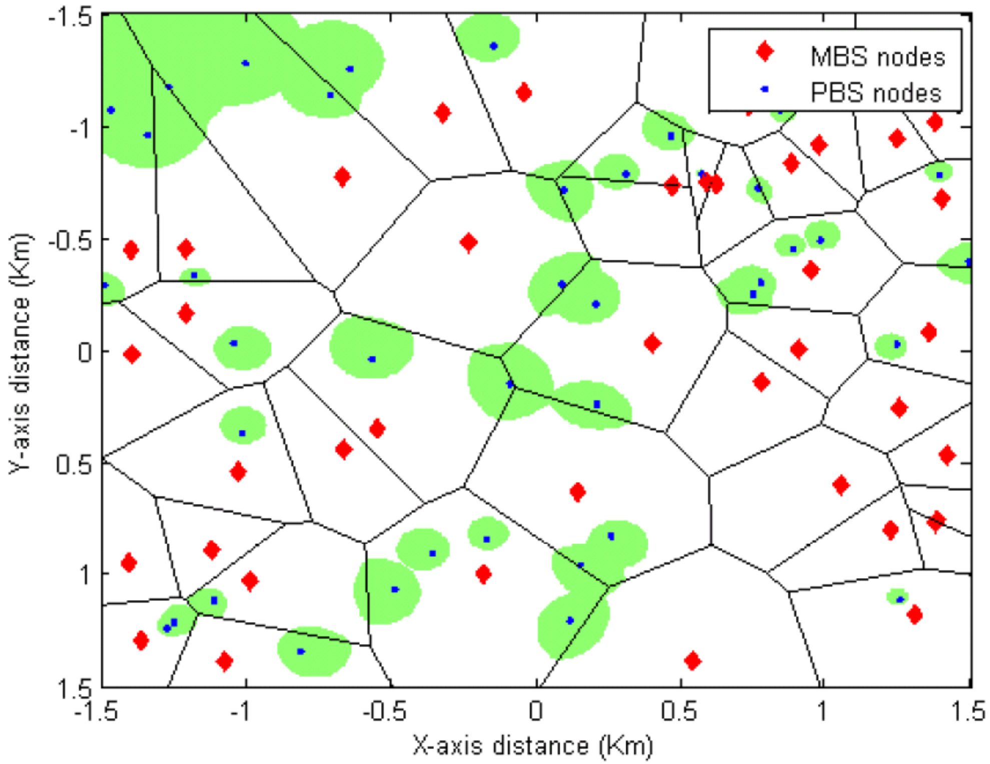
- Collaborative Research and Education
  - Dr. Guvenc students took Game Theory course with Dr. Saad in Spring 2014
  - MS students at TU working with the VT PI on game theory for sleep mode optimization
  - Continuous exchange of data, results, and research ideas
- Collaborative Tutorials and Talks
  - IEEE VTC-Fall, Vancouver, Canada, Sep. 14, 2014 (Tutorial Accepted)
  - IEEE MILCOM 2014, San Diego, CA, Oct. 2014 (under review)
  - ICTF 2014, Poznan, Poland 28th May 2014 (Invited talk)
  - IEICE RCS Workshop, Nagoya, Japan 18 April 2014 (JUNO Introduction)
  - CITS 2014, Jeju Island, Korea, 9th July 2014 (Tutorial Accepted)
  - EUSIPCO 2014, Lisbon, Portugal, 1-5 Sep., 2014 (Tutorial Accepted)
- Collaborative Papers
  - A. Merwaday, N. Rupasinghe, **I. Guvenc**, **W. Saad**, M. Yuksel, "USRP-Based Indoor Channel Estimation for D2D and Multi-Hop Communications", in Proc. IEEE Wireless and Microwave Conf. (WAMICON), Tampa, FL, June 2014. **[Thrust-III]**
- Collaborative Workshops
  - IEEE HetSNets Workshop, Globecom 2014, Austin, TX (Co-chair: **I. Guvenc**, Keynote speaker and panelist: **F. Adachi**)
  - IEEE WDPC Workshop, WCNC 2014, Istanbul, Turkey (Co-chairs: **I. Guvenc and W. Saad**)
  - IEEE WDPC Workshop, WCNC 2015, New Orleans, LA (Co-chairs: **I. Guvenc and W. Saad**, Publicity Chair: **A. Mehbodniya**) (in review)

Project Website for all updates: https://sites.google.com/site/nsfjuno/

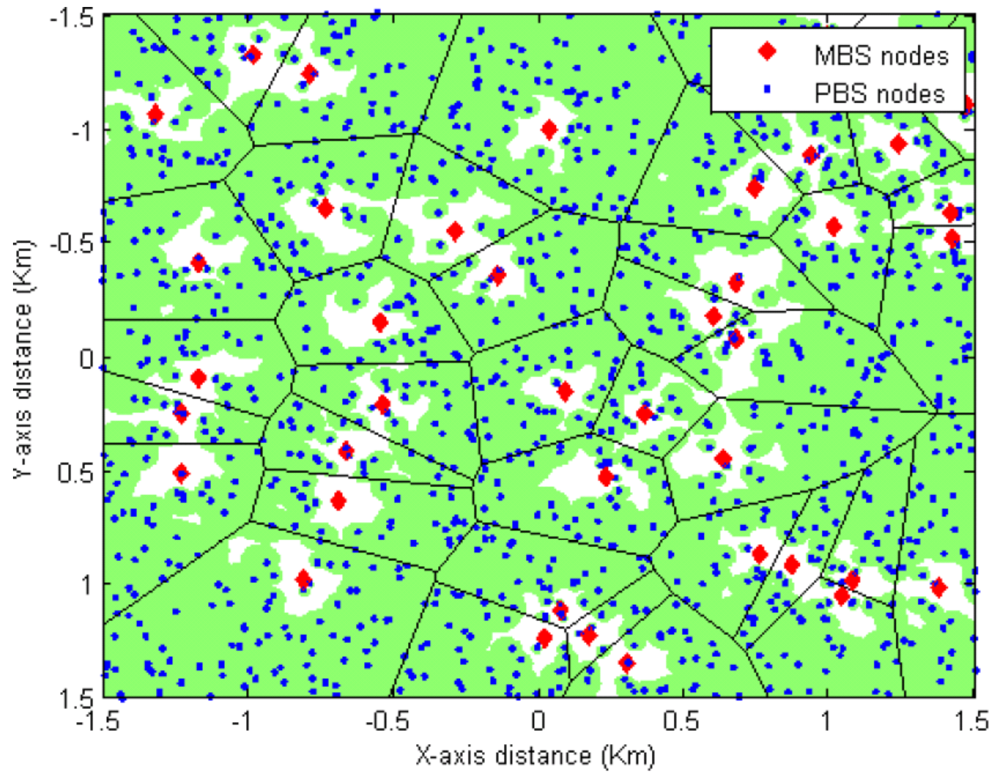
FIU FLORIDA INTERNATIONAL UNIVERSITY | 1872 VirginiaTech | TOHOKU UNIVERSITY

Thrust-I: Mobility and Energy Efficiency for HDHNs

1 PBS per MBS



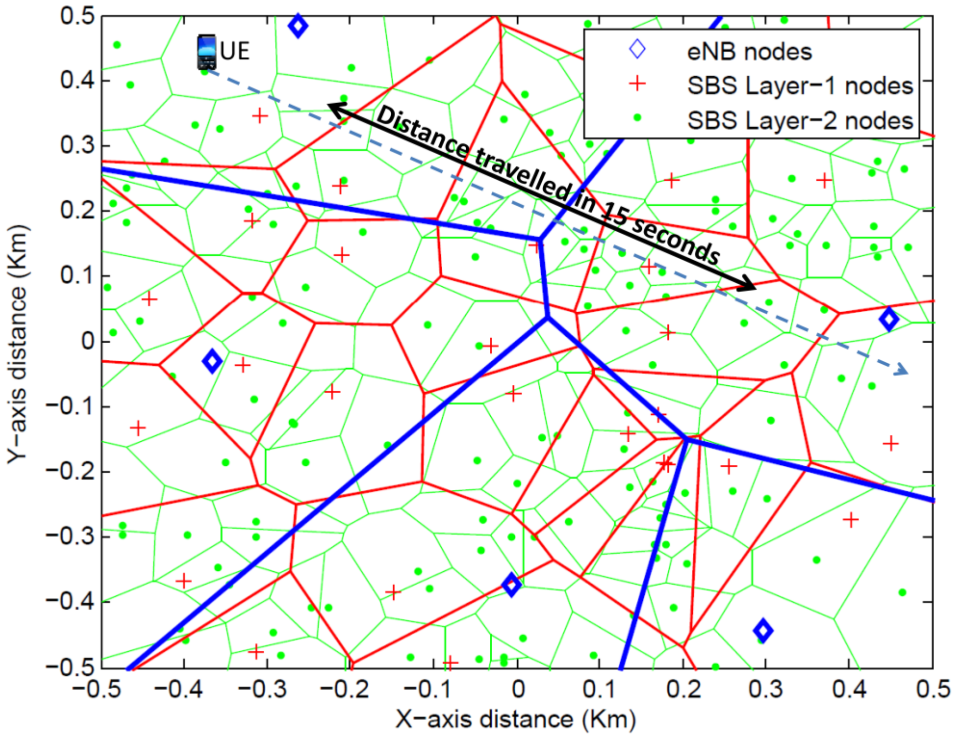
30 PBSs per MBS

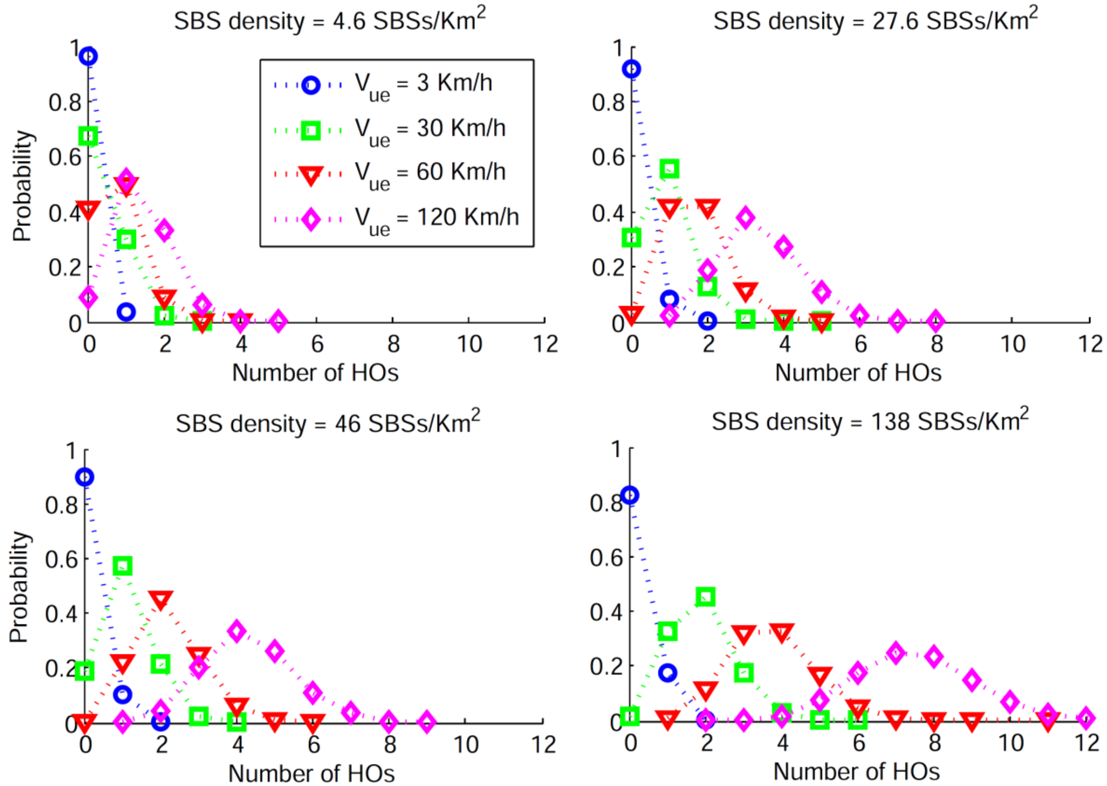


- Interference and mobility challenges will be more and more severe
- Self organization/optimization is the key for good performance

FIU FLORIDA INTERNATIONAL UNIVERSITY 1872 VirginiaTech TOHOKU UNIVERSITY

Mobility State Estimation

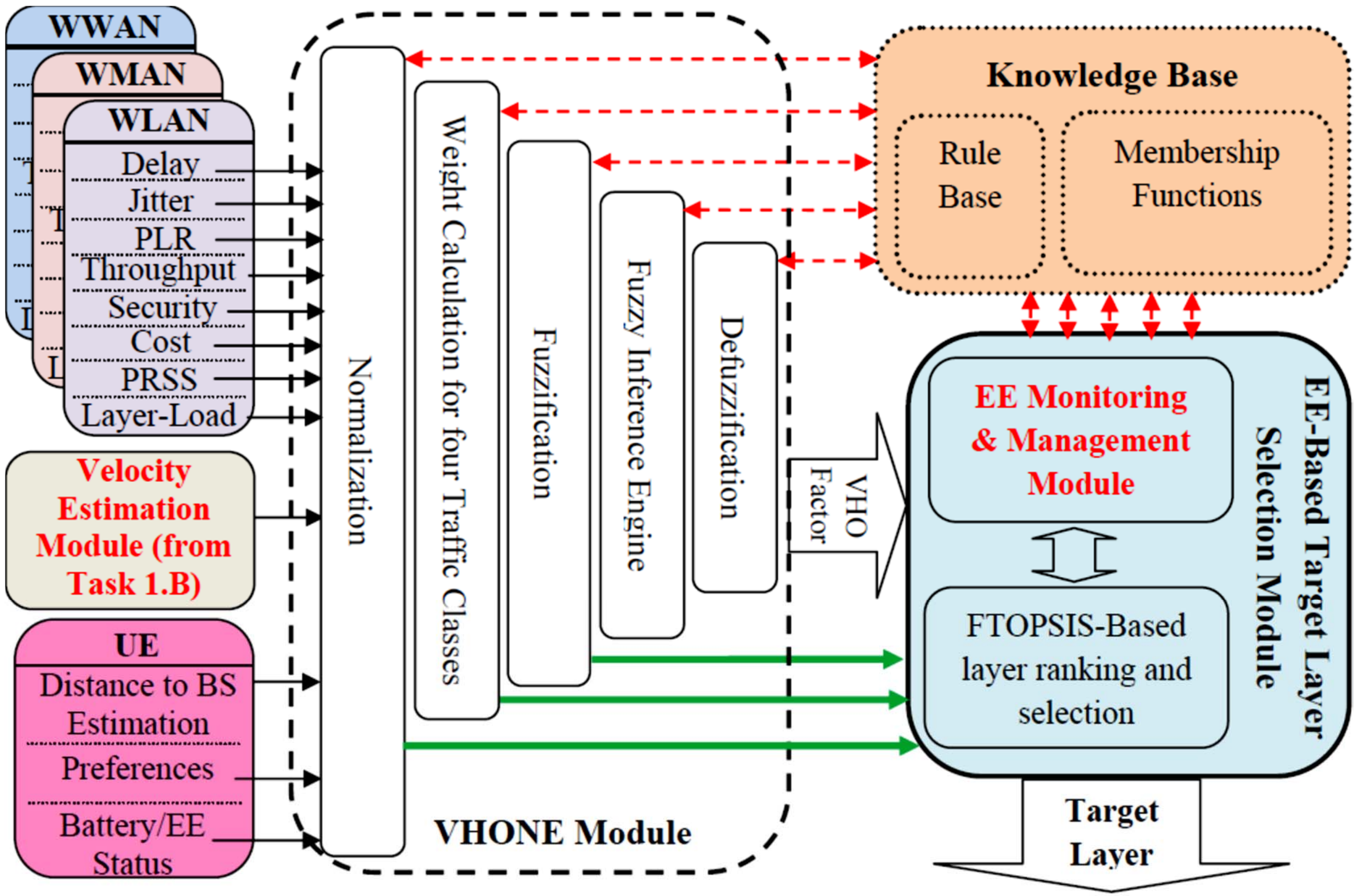




- Estimating the mobility states of user equipment (UE) is instrumental for interference and mobility management
- Commonly handled through handover counts in existing standards
- HDHNs allow more accurate estimation for a UE's mobility state
- Goal: to derive fundamental bounds on mobility state estimation accuracy through stochastic geometry

FIU FLORIDA INTERNATIONAL UNIVERSITY VirginiaTech 1872 TOHOKU UNIVERSITY

Fuzzy Logic for Vertical Handover (1)

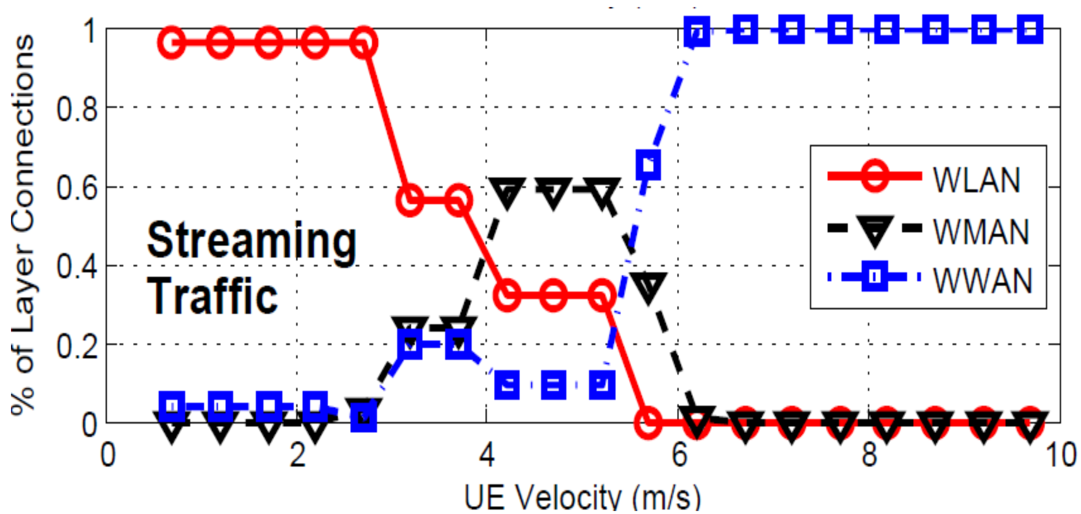


FIU FLORIDA INTERNATIONAL UNIVERSITY VirginiaTech TOHOKU UNIVERSITY

Fuzzy Logic for Vertical Handover (2)

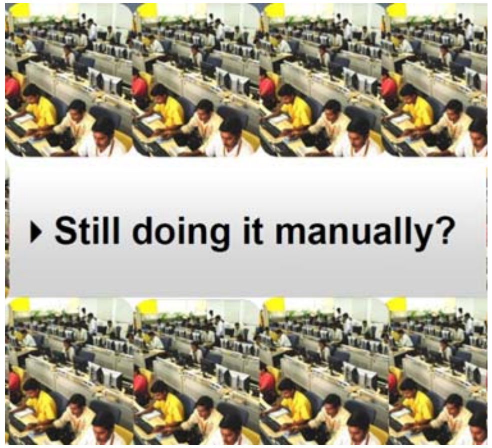
Mehbodniya, A.; Kaleem, F.; Yen, K.K.; Adachi, F., "Wireless network access selection scheme for heterogeneous multimedia traffic," *Networks, IET* , vol.2, no.4, pp.214,223, December 2013

- An intelligent, flexible, and scalable scheme to perform
  - Handoff necessity estimation
  - Handoff target network selection
- A Fuzzy Logic Based Handoff Necessity Estimation scheme
- A Fuzzy TOPSIS MADM scheme to select the best target network
- Network Types that are considered: WLAN, WMAN, WWAN
- Traffic Types that are considered: Conversational, Streaming, Background, Interactiv



Thrust II: Self-Organization for HDHNs

- Traditional ways of network optimization using base station controlled processes, staff monitoring, maps, trial and error, ...**is difficult in HDHNs!**
  - Self-organization is now a **necessity** not a privilege!

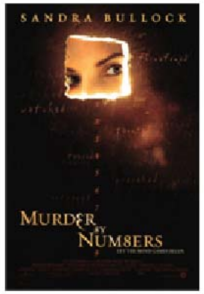


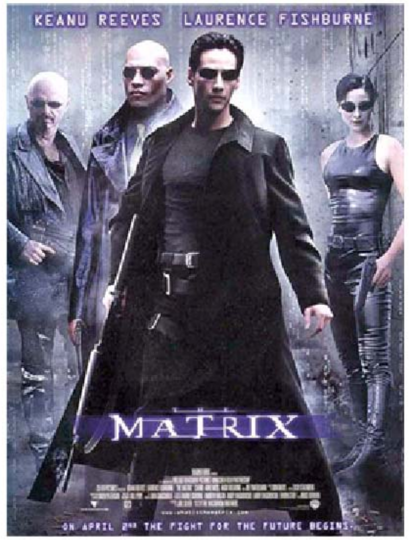
- Popular buzzword ☺ but…
  - …we view it as a distribution of intelligence throughout the network’s nodes, each depending on its capability and features
  - Simply: **smarter devices and smarter network**

- Most importantly, self-organizing resource management to exploit the HDHNs features with minimal overhead!
  - How to enable self-organization? **Game Theory!**

Game Theory: What? Why?

- What is Game Theory?
  - Has nothing to do with PS3 or Medal of Honor ☺
  - Distributed optimization of environments where **multiple players** interact and make coupled decisions
- Heard of it before?
  - In Movies
  - Childhood games
  - You have done at least one game-theoretic decision in your life without knowing!
- For HDHNs
  - Noncooperative vs. cooperative





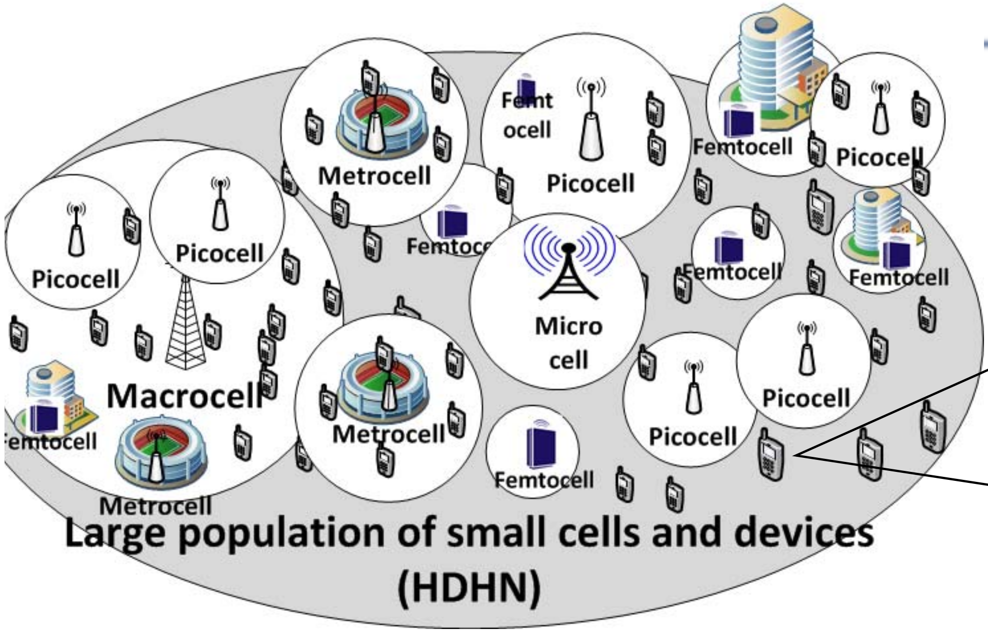
FIU FLORIDA INTERNATIONAL UNIVERSITY VirginiaTech TOHOKU UNIVERSITY

Game-Theoretic Framework for HDHNs

- **Step 1:** Basic noncooperative games as building blocks
  - Players: base stations (if downlink) or devices (if uplink)
  - Actions: sleep mode, resource allocation, mobility decisions, etc.
  - Utilities: emphasis on tradeoffs between network performance and energy-efficiency
- **Step 2:** Learning as a means to achieve equilibria or desirable operating points
  - Focus on learning with minimal information
  - **Preliminary work:** IEEE ICC (June 2014) and IEEE ISWCS (August 2014). Extension to IEEE Transactions ongoing.
- **Step 3:** Incorporate dynamics and build stochastic games
  - Game meets stochastic geometry
- **Step 4:** The "trillions" dimension
  - Large population games (e.g., mean-field and evolutionary games)

FIU FLORIDA INTERNATIONAL UNIVERSITY VirginiaTech TOHOKU UNIVERSITY

To Sleep or Not To Sleep?



- How to maintain energy efficiency?
  - **Put BS to sleep?**
  - **Wake BS up?**
  - **When to do what?**

- Each BS faces a tradeoff between increasing its rate/reducing load (in terms of fractional time needed to service users) and the associated increase in the power consumption
- We formulate a noncooperative game:
  - **Players:** BSs both MBSs and SBSs.
  - **Strategies:** State (sleep or active), power level, and cell bias
  - **Utilities:** tradeoff between energy and load (fractional time)

FIU FLORIDA INTERNATIONAL UNIVERSITY | VirginiaTech | TOHOKU UNIVERSITY

To Sleep or Not To Sleep?

- Power consumption includes:

$$P_b^{\text{Total}} = \begin{cases} P_b^{\text{Idle}} = \dfrac{P_{\text{RF}} + P_{\text{BB}}}{(1-\sigma_{\text{DC}})(1-\sigma_{\text{MS}})(1-\sigma_{\text{cool}})} = \dfrac{P_{\text{RF}} + P_{\text{BB}}}{\sigma} & \text{if } S_b = 0, \\ (P_b^{\text{Work}} + P_b^{\text{Idle}}) = \dfrac{P_b}{\eta\sigma(1-\sigma_{\text{feed}})} + P_b^{\text{BCK}} + P_b^{\text{Idle}} & \text{if } S_b = 1, \end{cases}$$

Backhaul power consumption

Transmit power

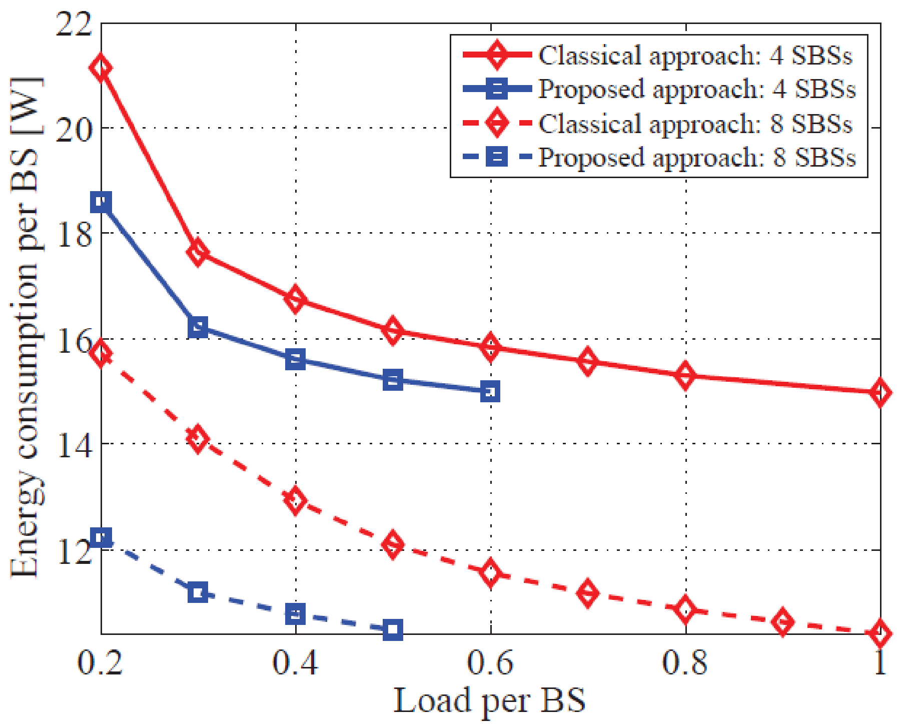
Power of RF and baseband components

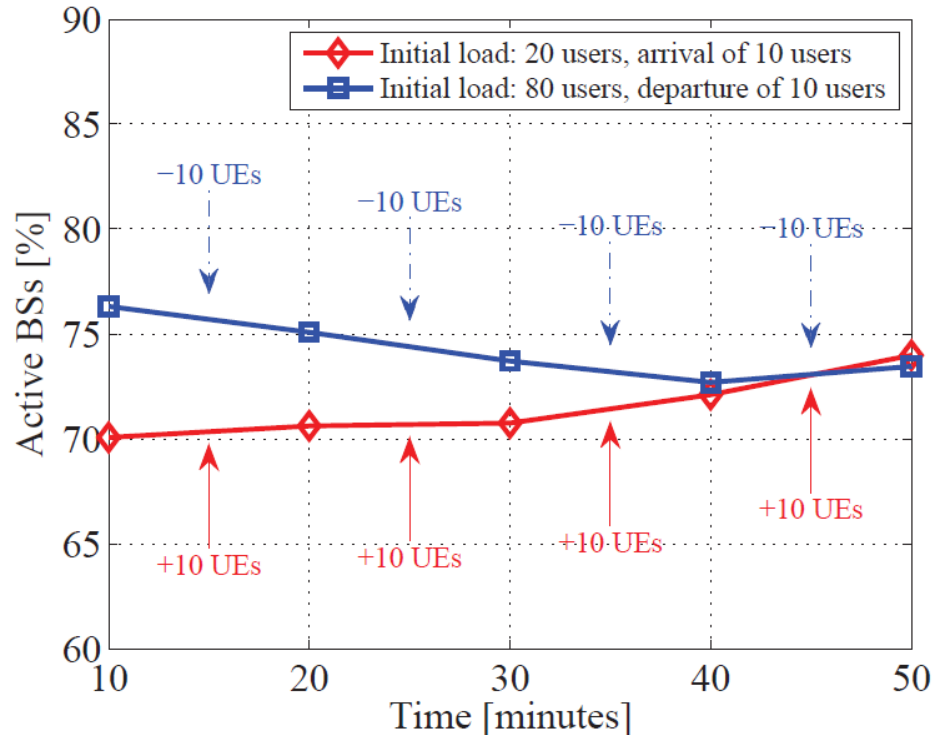
σ terms are loss fractions in feeders, DC-DC conversion, etc.

- We look at games in **mixed** strategies where players choose an action probabilistically (a certain frequency)
- The goal is to find an equilibrium solution that can be reached in a self-organizing manner
  – Epsilon-equilibrium, where no BS can improve by unilaterally changing its strategy (within ϵ)

To Sleep or Not To Sleep?

- Fully distributed learning algorithm based on the Boltzman-Gibbs process reaches an equilibrium (IEEE ICC 2014)
  – Update utility and actions jointly with no information exchange
  – Small overhead, only measurements of the current utility

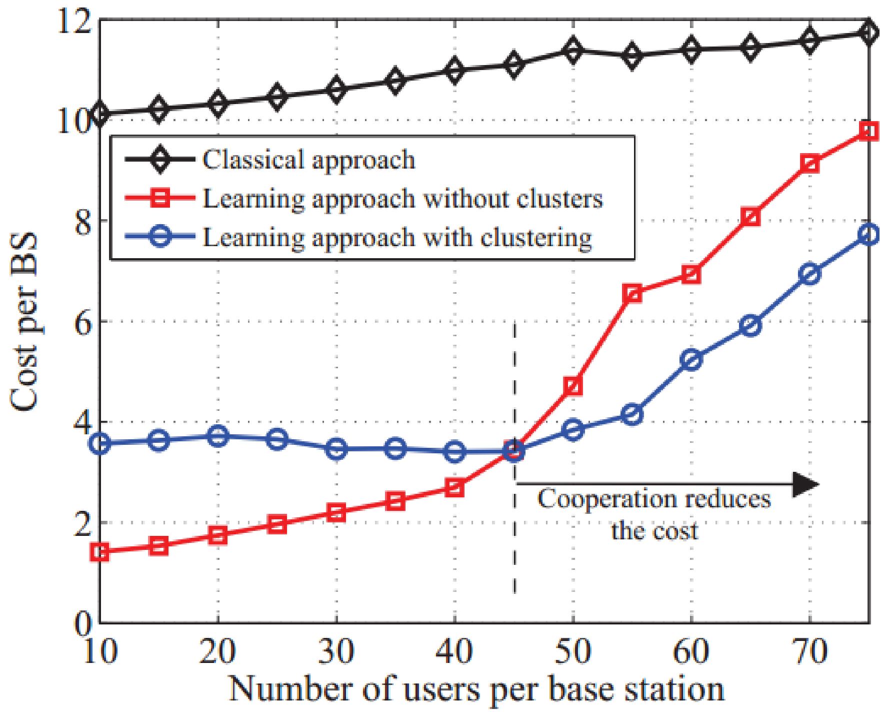


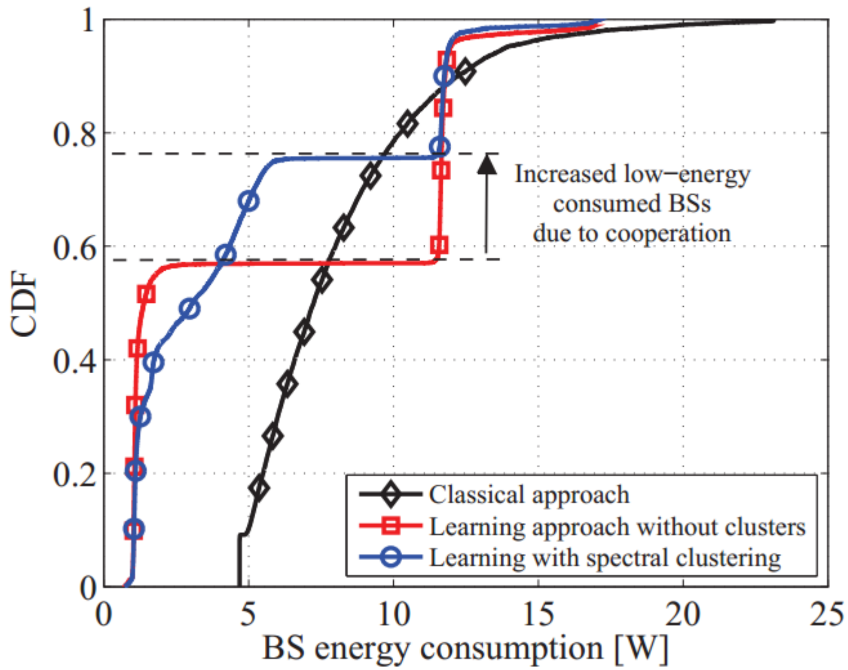


FIU | FLORIDA INTERNATIONAL UNIVERSITY   VirginiaTech 1872   TOHOKU UNIVERSITY

Clustering and Sleep Mode Optimization

- What if small cells can also cooperate and form clusters before learning? (IEEE ISWCS, appeared June 2014)
  - Location and load-aware clustering (graph theoretic)
  - Clustering meets game theory and learning
  - Extensions: stochastic geometry, dynamics, large population

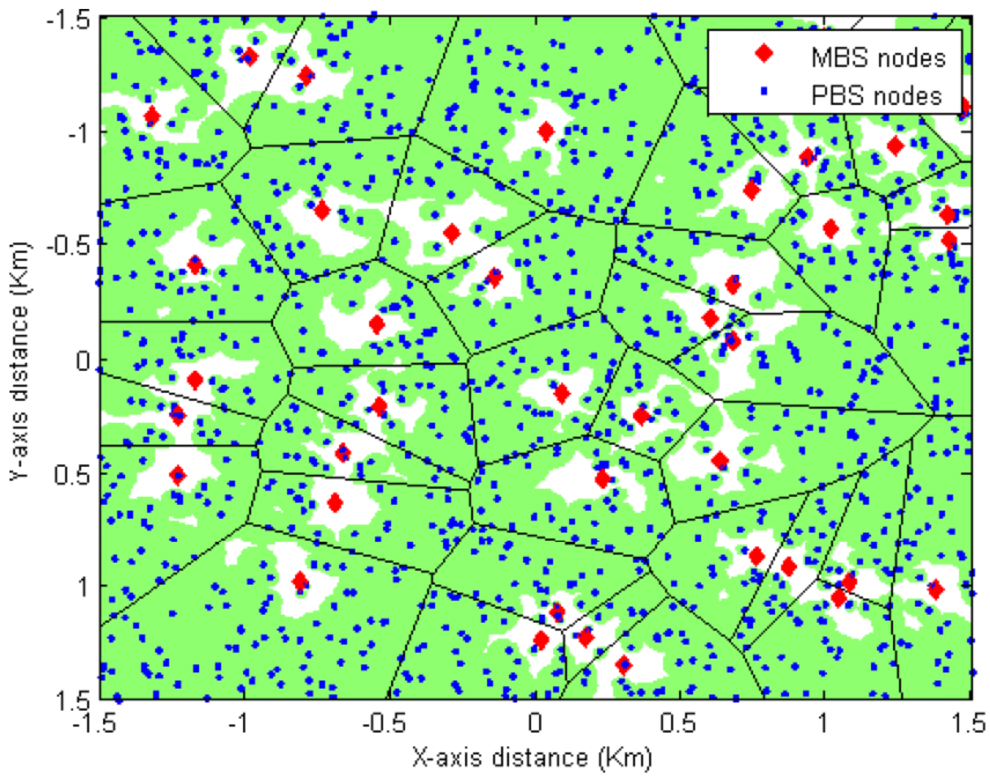




FIU FLORIDA INTERNATIONAL UNIVERSITY   VirginiaTech 1872   TOHOKU UNIVERSITY

SON Analysis through Stochastic Geometry

30 PBSs per MBS

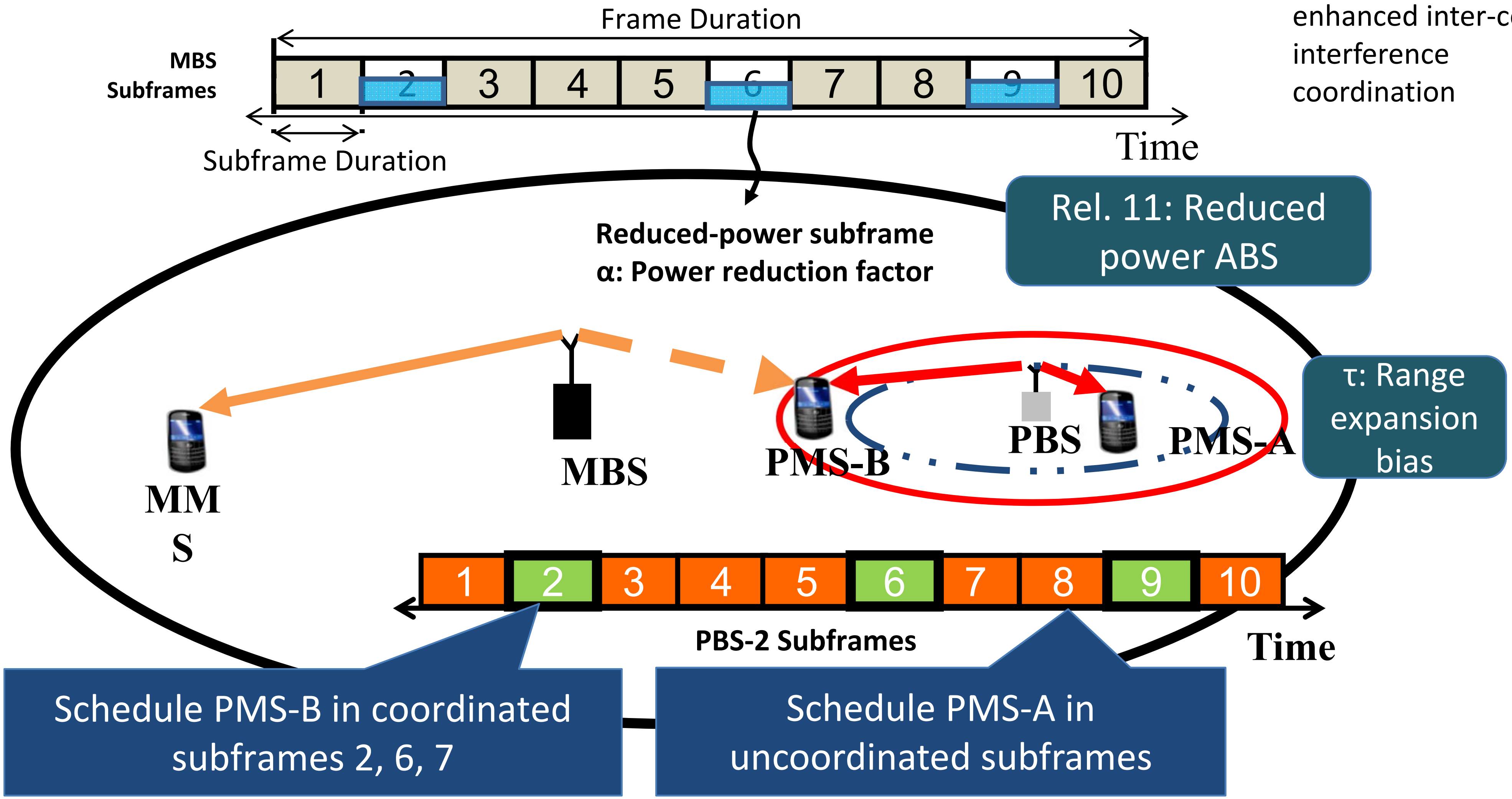


- Stochastic geometry: a popular tool to capture statistics of the interference in HDHNs
- Can analyze key network metrics (outage, capacity) in closed form under some assumptions
- We will use it to design and optimize interference coordination for HDHN deployments

FIU FLORIDA INTERNATIONAL UNIVERSITY   1872 VirginiaTech   TOHOKU UNIVERSITY

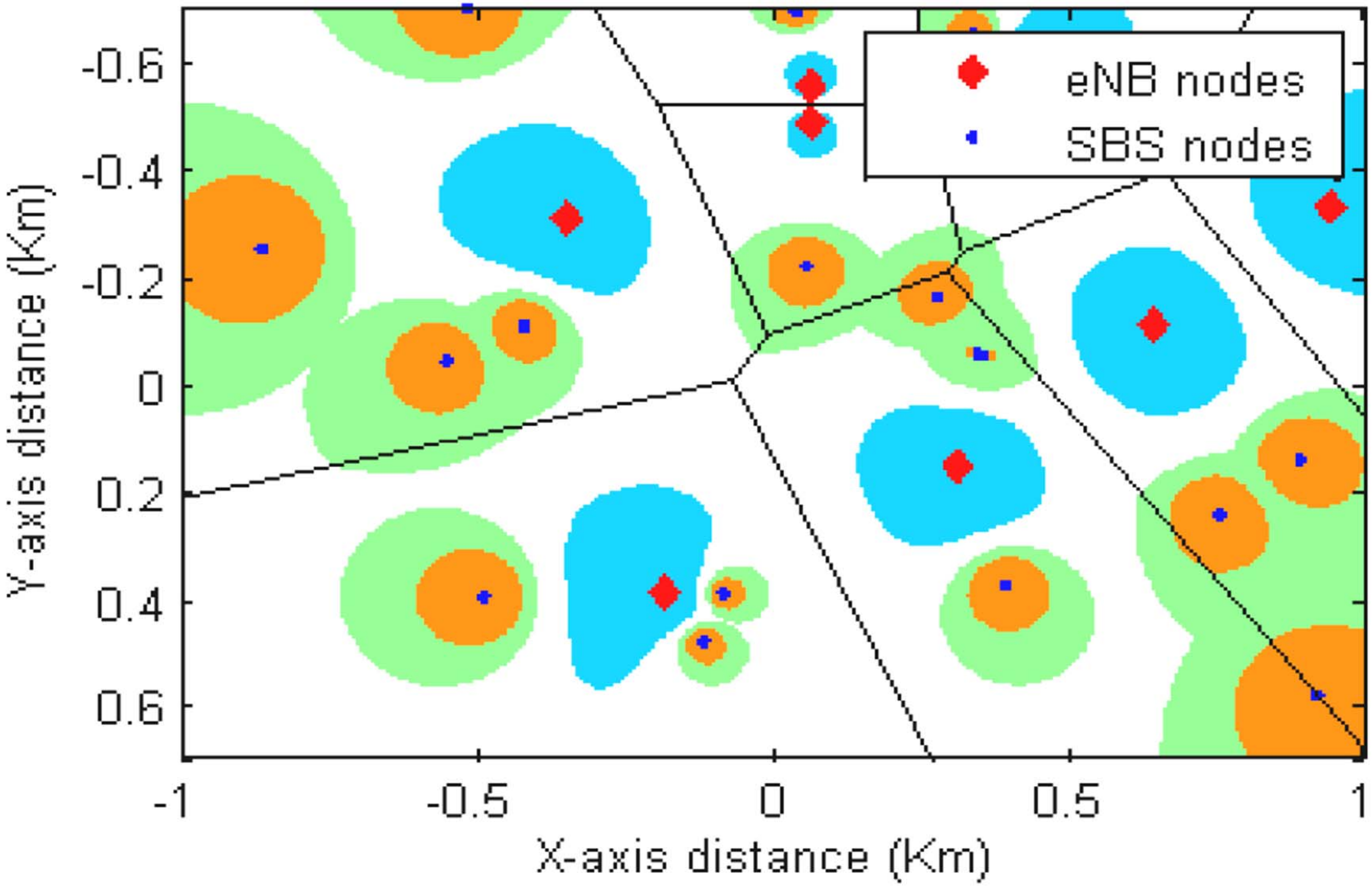
Interference Coordination with LTE Release-11 (FeICIC)

FeICIC: Further-enhanced inter-cell interference coordination



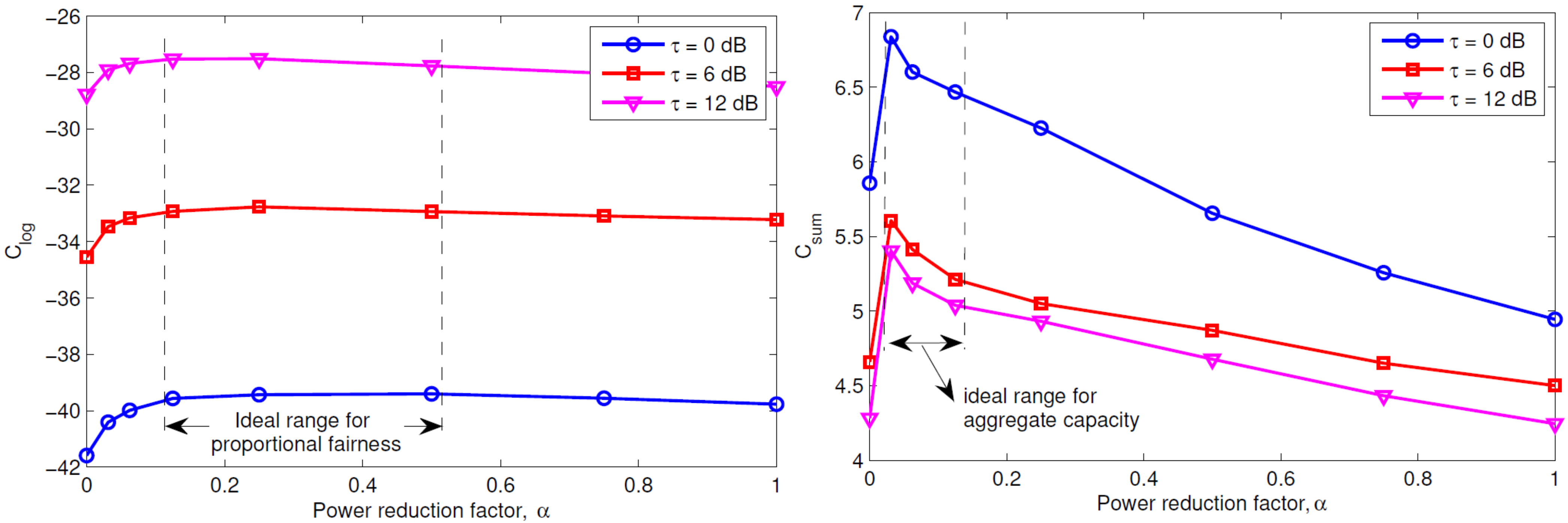
FIU FLORIDA INTERNATIONAL UNIVERSITY VirginiaTech 1872 TOHOKU UNIVERSITY

HDHN Coverage with Rel-11 FeICIC



SBS: Small base station
eNB: Macrocell base station

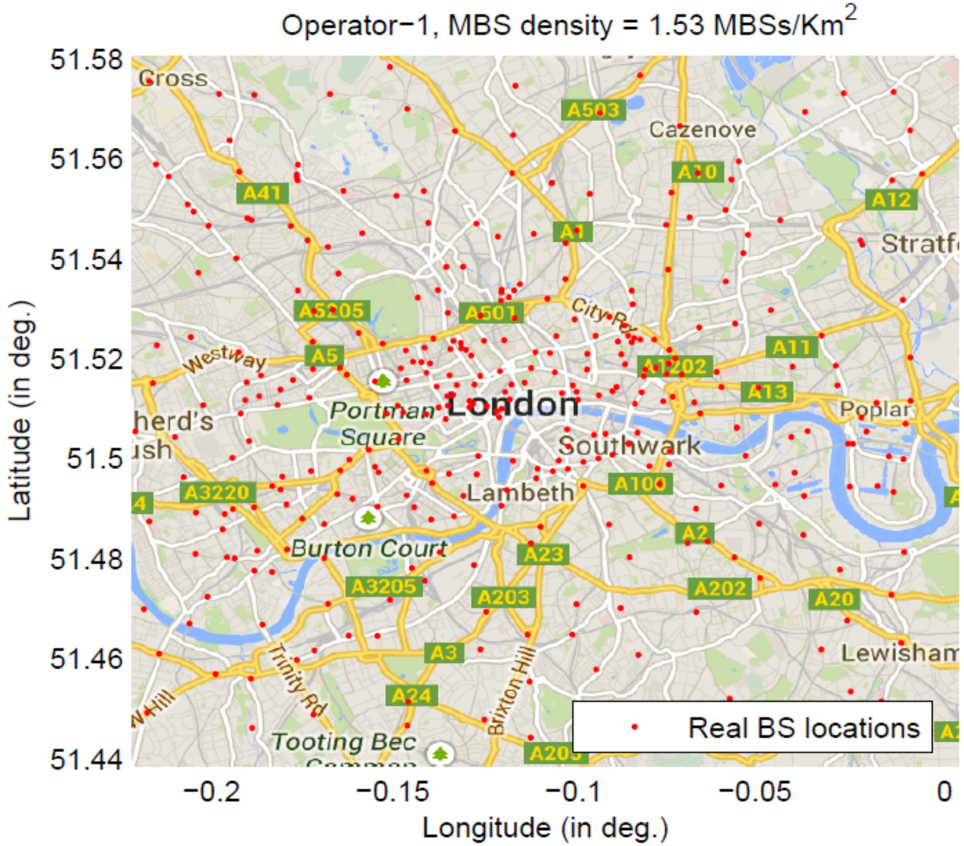
FeICIC Optimization -- Preliminary Results

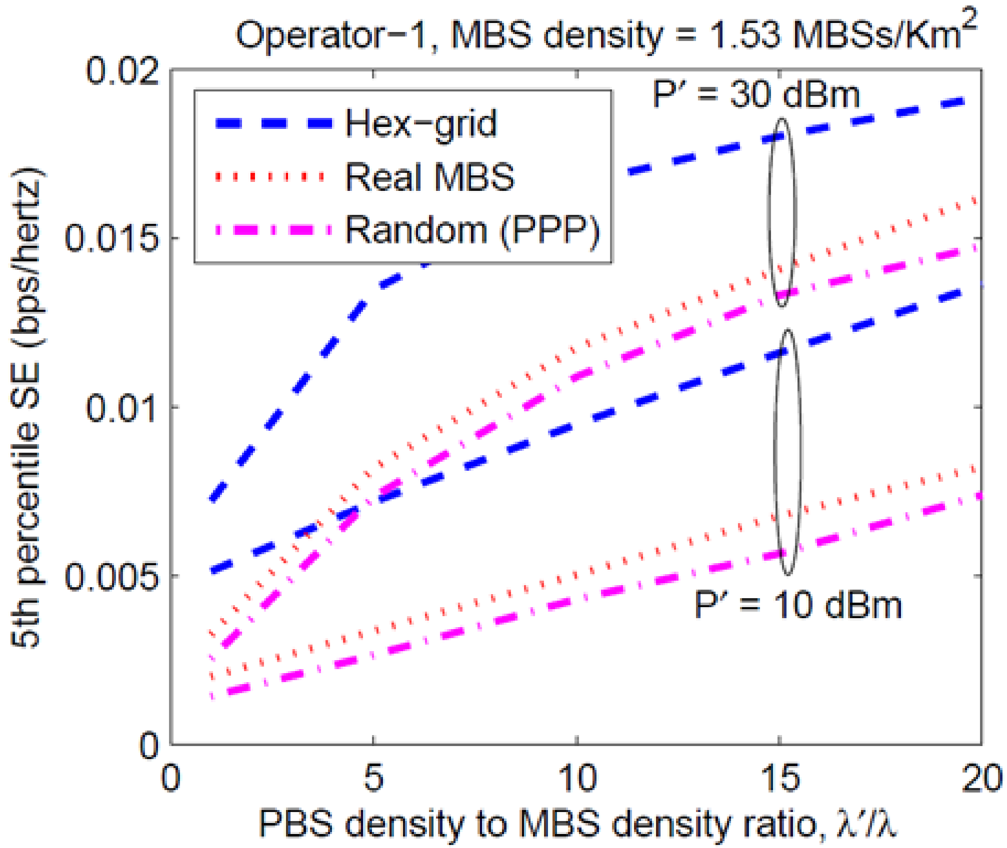


- Preliminary work: optimize ICIC for spectral efficiency (WCNC-2014)
- Reasonable range of power reduction in blank subframes is between 0.1-0.4
- Larger range expansion bias improves fairness, but hurts aggregate capacity
- Future work: design and optimize FeICIC by jointly considering energy and spectral efficiency

FIU FLORIDA INTERNATIONAL UNIVERSITY | VirginiaTech 1872 | TOHOKU UNIVERSITY

How does Stochastic Geometry Analysis Compare to Real Deployments?



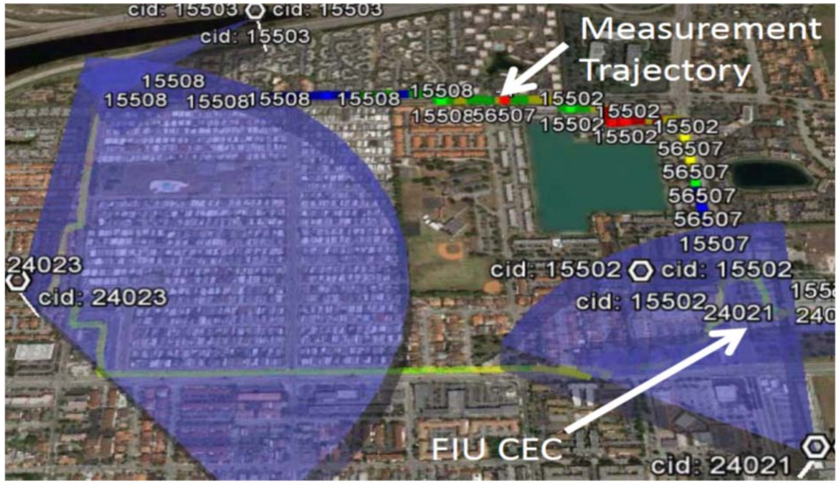


- Compared performance with stochastic geometry, hex. grid, and real BS locations
- Stochastic geometry (PPP) gives much closer 5th percentile results to real BS deployments when compared with hex-grid

Considers Rel-11 FeICIC with the following parameters: τ = 6 dB, α = 0.5, β = 0.5, ρ = 4 dB, ρ' = 12 dB, and P_{tx} = 46 dBm

FIU FLORIDA INTERNATIONAL UNIVERSITY VirginiaTech TOHOKU UNIVERSITY

Thrust III – Testbed and Experimentation for HDHNs



- Experimentation with USRPs, WARP boards, CORENET testbed, and software simulations
  - To verify the feasibility of our proposed RRM algorithms
  - To emulate our massive deployment scenarios
  - To help students develop a practical insight into their simulation works
  - Optimizing the algorithms designed in Thrusts I and II with conjunction to physical layer parameters and designing experiments to verify them on our USRP testbed
  - NSF REU Supplement awarded at FIU to support two undergraduate students between Aug. 2014 – July 2015
- Data collection via Android smartphones
  - To verify the developed algorithms for mobility management through a massive data collection campaign

FIU FLORIDA INTERNATIONAL UNIVERSITY   1872 VirginiaTech   TOHOKU UNIVERSITY

Collaboration Plan

Thrusts	Subtasks	TU	FIU	VT
Thrust I: Mobility and Energy Efficiency for HDHNs	**I.A:** Handover Count Based Mobility State Estimation	✓	✓ LEAD	
	I.B: Speed Dependent and Fuzzy Logic Based EE Enhancement	✓ LEAD	✓	✓
Thrust II: Self-Organization for HDHNs	**II.A:** Stochastic Geometry for SON and EE Optimization	✓	✓ LEAD	✓
	II.B: Large Population Games for SON in HDHNs	✓		✓ LEAD
Thrust III: Testbed and Experimentation for HDHNs	**III.A:** Data Collection through Android Smart Phones	✓ LEAD	✓	✓
	III.B: Experimentation with USRPs and WARP Boards	✓	✓	✓ LEAD

FIU FLORIDA INTERNATIONAL UNIVERSITY VirginiaTech TOHOKU UNIVERSITY

Conclusions

- **Project's key outcome:** new foundational science for analyzing, optimizing, and building energy-efficient 5G wireless systems
  - Investigating fundamentals of **mobility** in HDHNs and developing analytical and simulation tools to estimate it
  - Designing **self-organizing resource management mechanisms** using innovative techniques such as game theory, i.e., large population games, etc, for HDHNs.
  - **Physical layer** enhancement and its cross-layer optimization with our proposed modules and algorithms.
  - Developing a multi-institutional, intercontinental **hardware/software testbed** based on Android, WARP, and USRP technologies and then, validating, evaluating, and enhancing the proposed algorithms.
  - Creating a new, long-term US-Japan collaborative network

FIU FLORIDA INTERNATIONAL UNIVERSITY | 1872 VirginiaTech | TOHOKU UNIVERSITY

FIU FLORIDA INTERNATIONAL UNIVERSITY

VirginiaTech

TOHOKU UNIVERSITY