Computational Communication Theory:

A Modern Tool for Engineering Future Wireless Networks

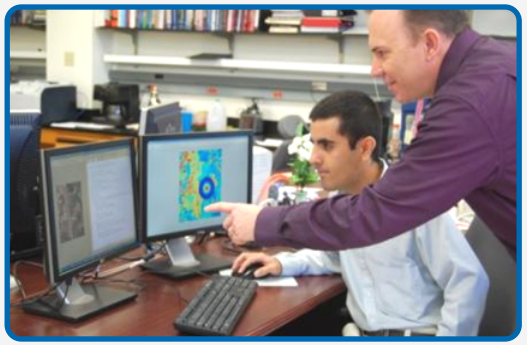
Matthew C. Valenti

April 7, 2014

Wireless Communications Research Lab

Personnel

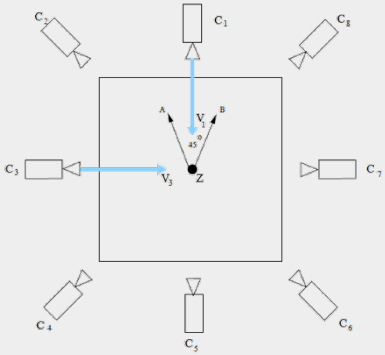
- Faculty
  - Matthew C. Valenti, Founder and Director
  - Daryl Reynolds, Associate Professor
  - Natalia Schmid, Associate Professor
  - Brian Woerner, Dept. Chair.
  - Vinod Kulathumani, Assistant Professor



- Approximately 20 graduate students

Research Topics

- Cooperative communications.
- Wireless and cellular networks.
- Wireless sensor networks.
- Radio astronomy.
- Cloud computing.
- Biometric and human activity detection.



Wireless Camera Network (ONR)

Funding Sources

- NSF: CRI program; CITeR I/UCRC.
- DoD: ONR, ARL.
- Industry: DoD STTR/SBIR programs; Cisco URP.
- NASA.

Tools and Facilities

- Camera network testbed.
- 400-core cluster computer.
- Open source simulation software: CML.
- Web portal for researchers: WebCML.

Outline

- Motivation: What's on the Wireless Horizon?
- Approach to Research
- Sampling of Results
- Broader Impacts
- Future Research Directions

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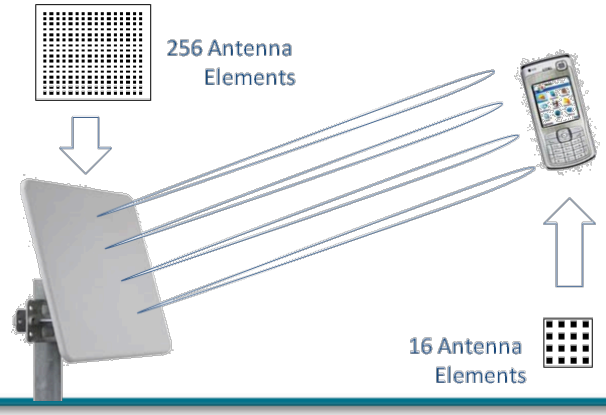
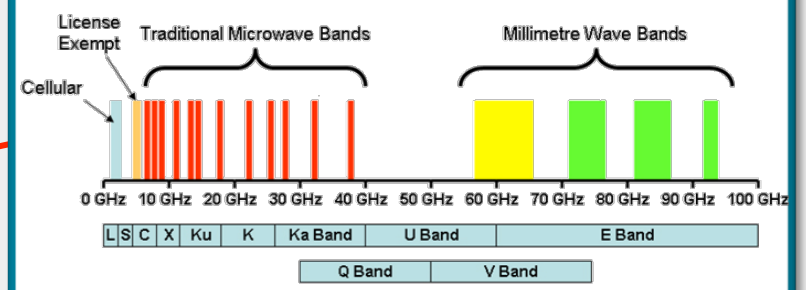
Greeting the Mobile Data Onslaught

Massive MIMO

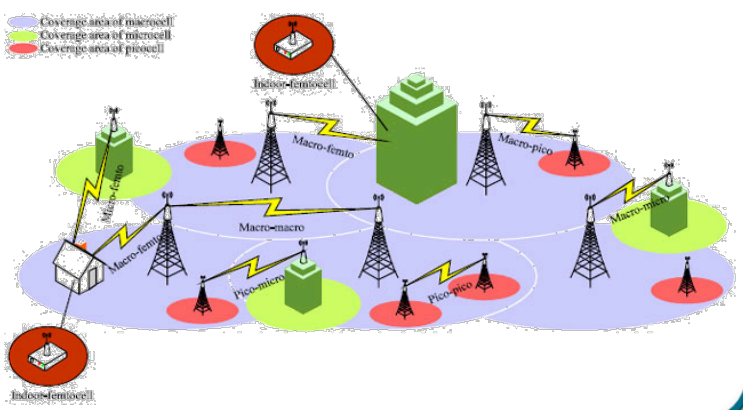


mmWave



$$C = m\left(\frac{W}{n}\right)\log\left(1+\text{SINR}\right)$$

Densification

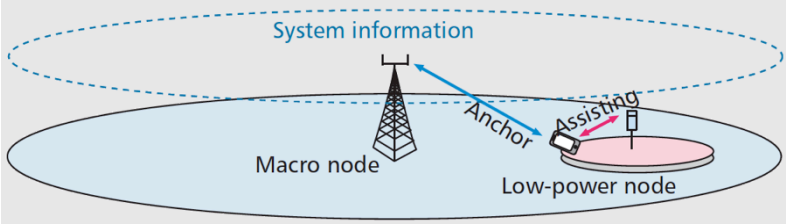


Interference Coordination

The Device-Centric Architecture

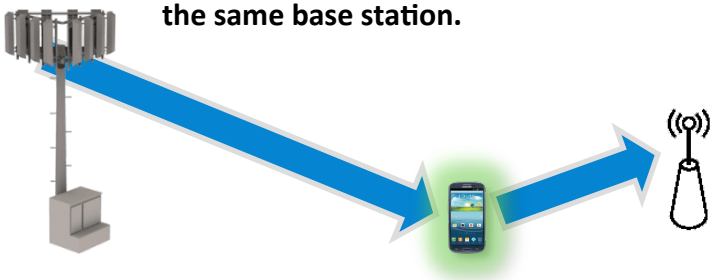
Control/Data Separation

Use microwave large cells for control (anchor node). and mmwave small cells for data (assisting node).



Uplink/Downlink Separation

Uplink and downlink need not be serviced by the same base station.



The end of cells as we know it?

Device to Device

Devices communicate directly.
Possibly under the control of the anchor node.

Smart Caching

Popular content downloaded from hotspots.
Made available to others via D2D.

Outline

- Motivation
- **Approach to Research**
- Sampling of Results
- Broader Impacts
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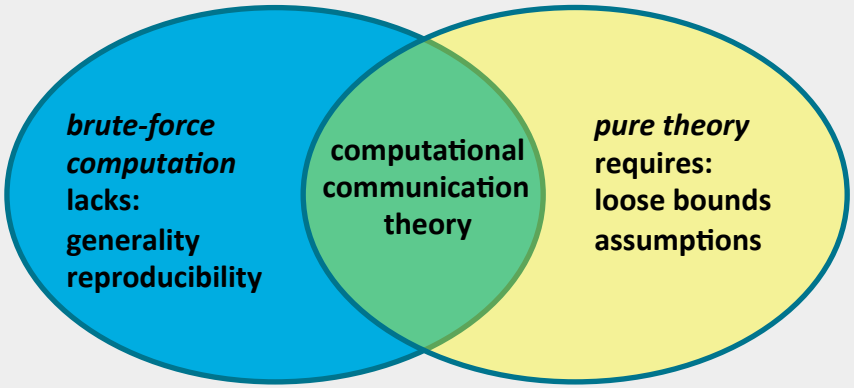
Computational Communication Theory

Research Approach

- Cheap utility computing allows for a *computationally intensive* approach to solving problems.
- While computing is cheap, it is not free.
  - Sound principles from communication theory guides smarter use of the available resources.
- Goal is to find "sweet spot" between theory and simulation.



- Much of the day-to-day work is writing code that makes utility computing easy to use.
  - Should not have to be a cloud-computing expert to use our resources.

Example Results

- Application of genetic algorithms.
  - Design of space-time codes.
  - Design of coded-modulation.
- Analysis of networks with random interferers.
  - Cognitive radio.
  - (Cooperative) cellular technologies.
  - Frequency-hopping ad hoc networks.
  - Cooperative relaying.
- Wireless sensing and (indoor) localization.

Broader Impacts

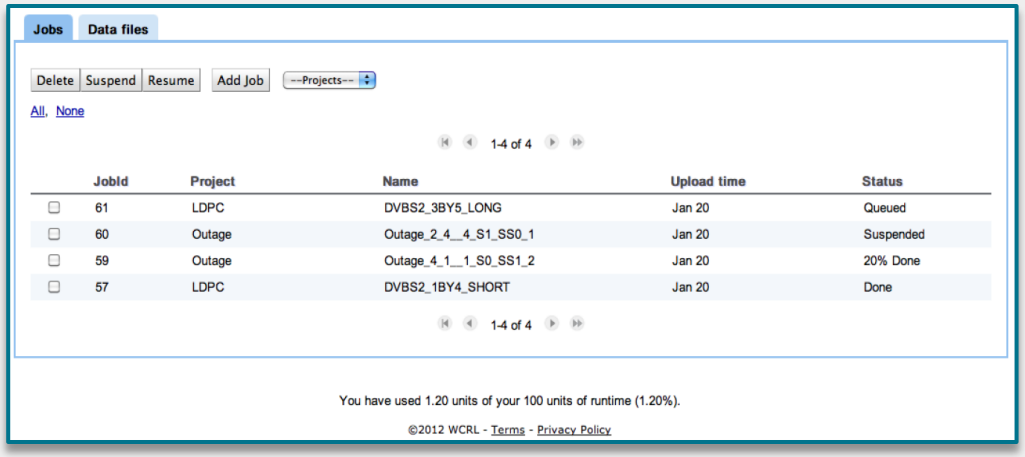
- Cloud-empowered course projects
  - Wireless networking
  - Coding theory
  - Communication theory
- Technology transfer
  - Creating custom cloud-empowered web applications.
  - Software for commercial products.

Cyber-Infrastructure

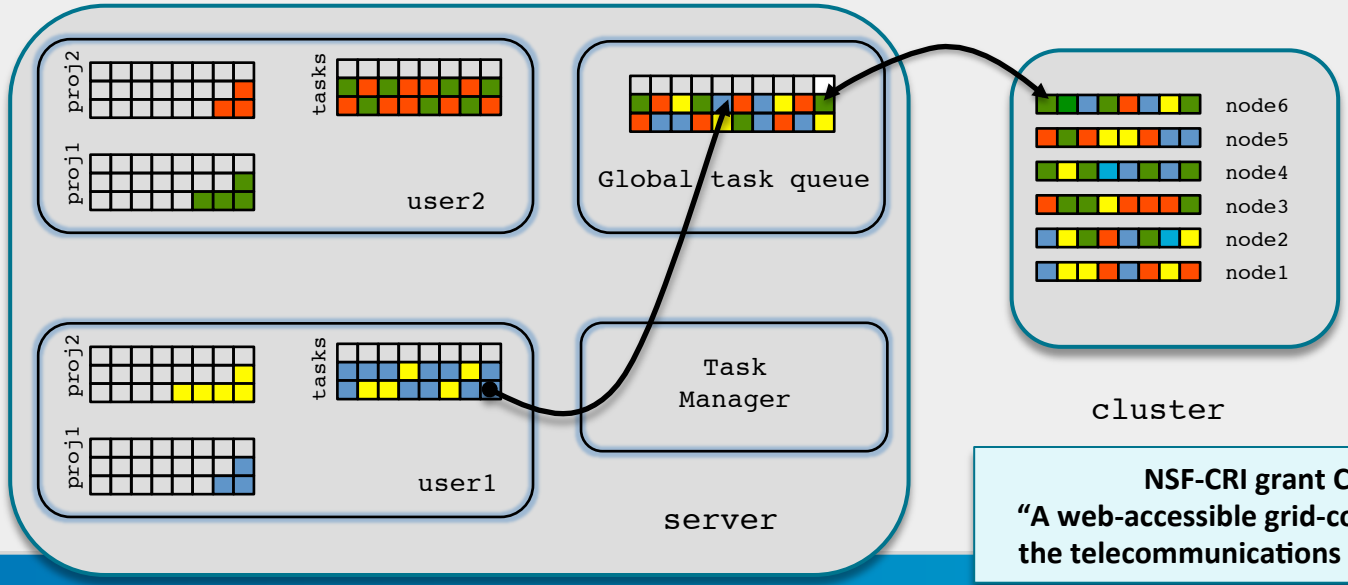
Open Source Software

- **Developed open source software for designing, simulating, and analyzing wireless systems.**
  - CML = Coded Modulation Library.
  - Google code project: code.google.com/p/iscml/
- **Runs in Matlab, but much of the low-level code is written in C.**

Web Portal



Parallel Computing Server



- **Job uploaded to user's project directory.**
- **Job manager breaks it into *tasks*.**
- **Task manager puts into queue.**
- **Workers autonomously service tasks.**

NSF-CRI grant CNS-0750821
"A web-accessible grid-computing resource for the telecommunications research community"

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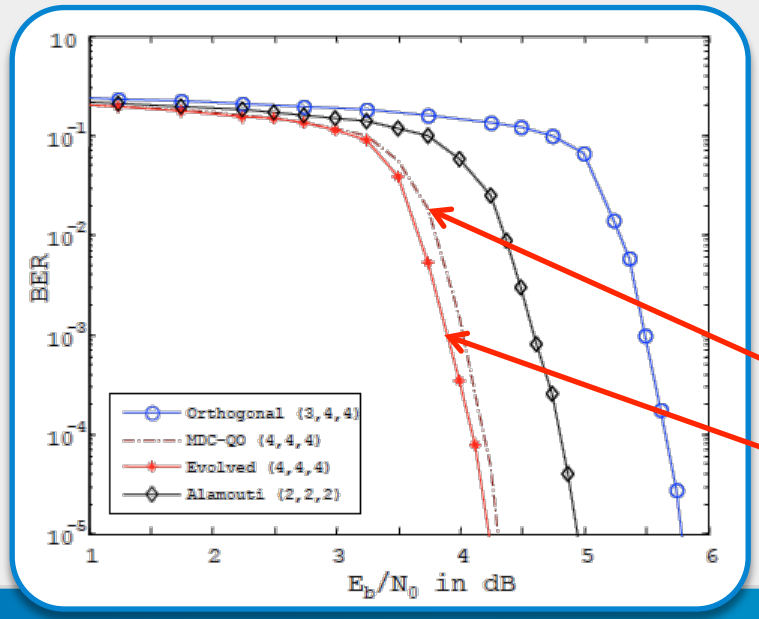
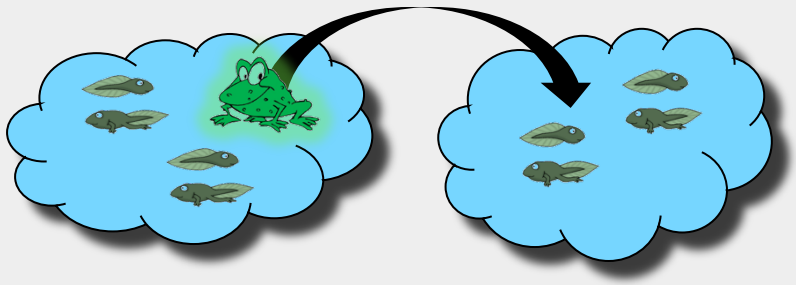
Genetic Algorithms and Space-Time Codes

Space-Time Codes

- Space-time codes use multiple transmit antennas to provide diversity.
- Constraints to reduce decoder complexity:
  - Orthogonal codes allow decoupled decoding, but are not full rate for more than two transmit antennas.
  - Quasi-orthogonal codes can be full rate but pairs of symbols must be jointly decoded.
- Our design criteria achieves full rate by trading ISI for true decoupled decoding.



Parallel Genetic Algorithms



- Each node in the cloud evolves its own pool.
- Periodically, the best individual among the pools is cloned and *immigrates* to other pools.

Discovered Space-Time Code

- 4 TX antennas
- Turbo-Coded 8PSK
- Worse-than-Rayleigh fading (Nakagami m=1/2)

Best known QO STBC designed using algebraic principles and a rotated constellation

Linear dispersion STBC discovered through genetic algorithm

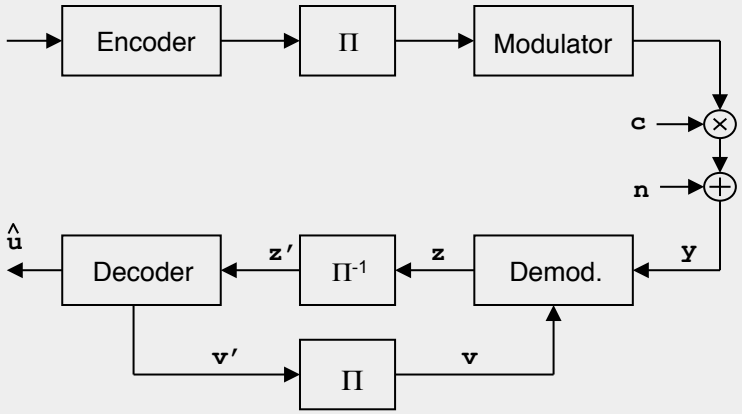
0.1 dB gain with reduced complexity

Torrieri & Valenti, "Efficiently decoded full-rate space-time block codes," *IEEE T-Comm*, 2010.

Genetic Algorithms and Signal Constellations

Iterative Detection

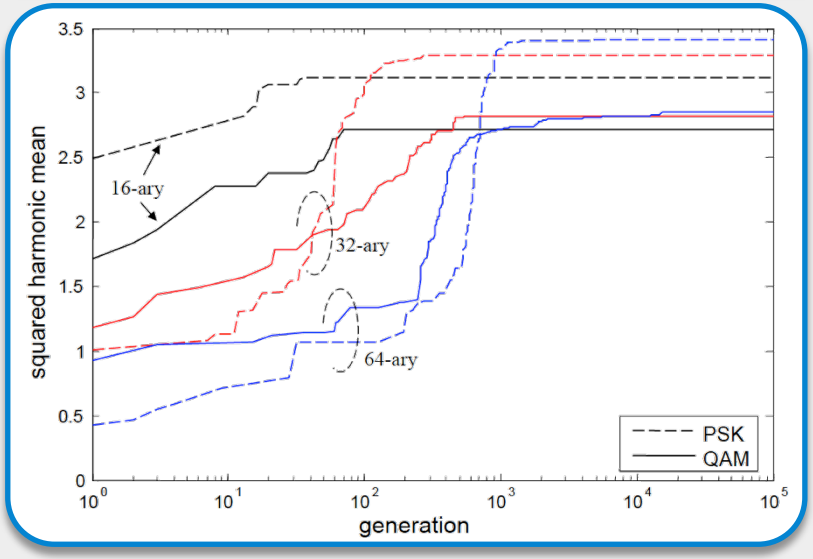
- **Coded modulation is iteratively detected**



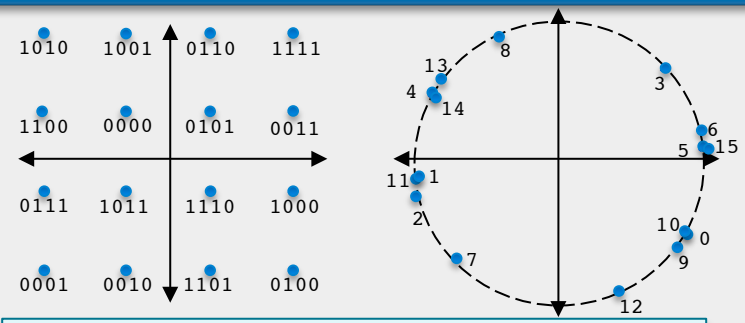
Lowering the Error Floor

- **The error floor depends on the *harmonic mean* "d_h" of the squared-Euclidian distances between signal pairs whose labels differ in just one bit position.**
- **A genetic algorithm can find the symbol labeling map that maximizes d_h.**
- **We can further use a genetic algorithm to design a constellation with high d_h.**

Genetic Algorithm



Discovered Constellations

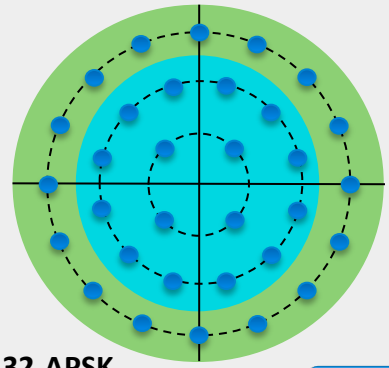


Valenti, Doppalapudi & Torrieri, "A genetic algorithm for designing constellations with low error floors," *CISS*-2008.

Design of Satellite Links

LDPC-Coded APSK

- **The DVB-S2 system uses:**
  - Amplitude phase-shift keying (APSK)
  - Low-density parity check codes (LDPC)
- **APSK performance depends on ring radii.**
- **LDPC performance depends on degree distributions.**



32-APSK

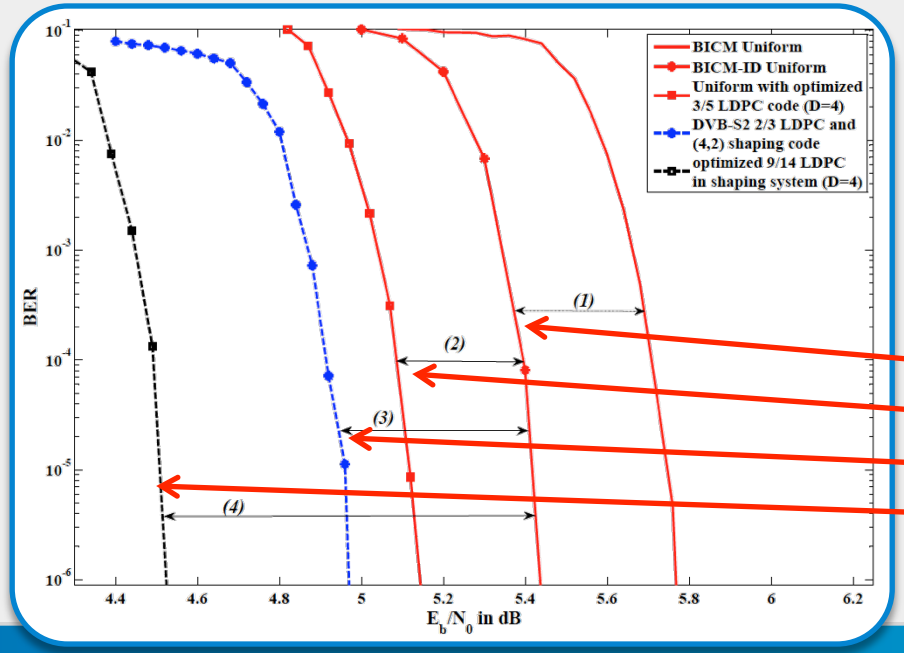
Constellation Shaping

- **Energy efficiency can be improved by sending low-energy signals more often than high-energy signals.**
- **We use the MSB to select from the outer or inner rings.**
  - Requires a non-linear shaping code

Joint Optimization

- **We jointly optimize:**
  - Nonlinear shaping code
  - APSK ring radii
  - LDPC degree distributions
- **Procedure combines EXIT charts & simulations to obtain the following gains:**

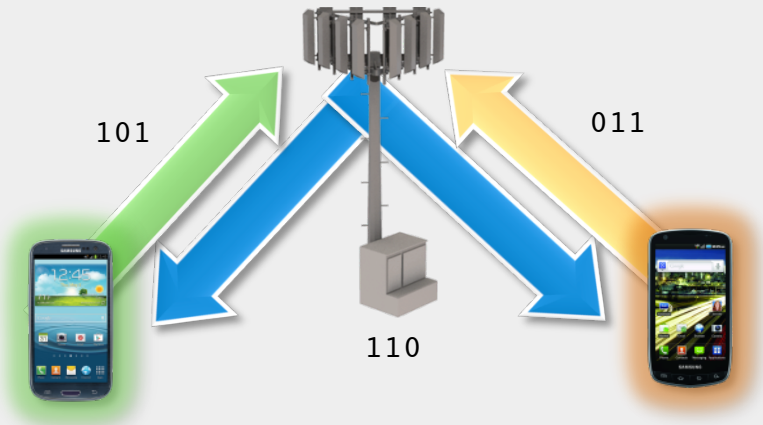
1. Iterative decoder: 0.3 dB
2. Optimized LDPC code: 0.3 dB
3. Constellation shaping: 0.5 dB
4. Both shaping and LDPC optimization: 0.9 dB



Valenti & Xiang, "Constellation shaping for bit-interleaved LDPC coded APSK," *IEEE T-Comm*, 2012.

Noncoherent Two-Way Relaying

Physical-Layer Network Coding



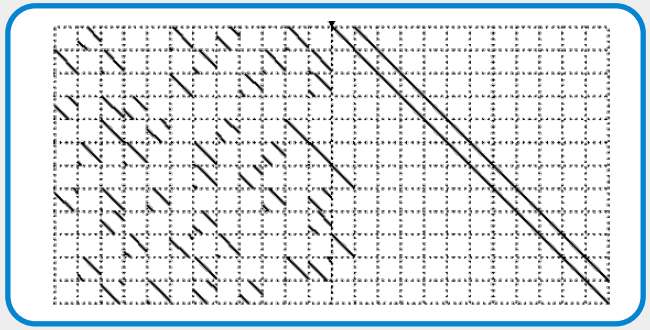
- **Two users wish to exchange information through a relay**
- **Can be done in two phases:**
  - MAC: Both users simultaneously transmit.
  - Broadcast: The relay sends the sum signal.
- **Since each UE knows what it transmitted, it can cancel its signal to reveal the other signal.**
- **A regenerative relay will try to detect the sum of the transmitted information prior to broadcasting.**
  - It is difficult to implement a coherent relay receiver.

Noncoherent PLNC

- **Developed a noncoherent solution.**
  - Relies on FSK signaling.
  - Can support nonbinary FSK and iterative reception.
  - Can work with or without fading gain estimates.
  - Data transmissions are further LDPC coded.

Optimization

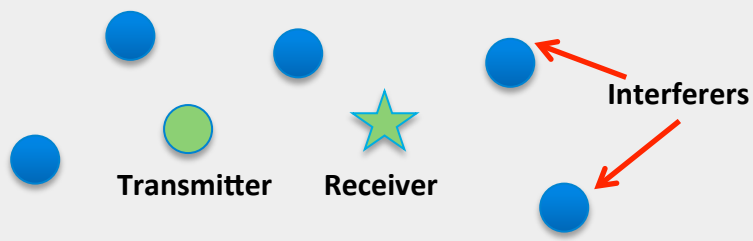
- **Performance depends on the degree distributions of the LDPC code.**
- **Can identify the best LDPC code through a combination of EXIT charts & simulation.**



Valenti, Torrieri & Ferrett, "Noncoherent physical-layer network coding with FSK modulation," *IEEE T-Comm*, 2011.

Outage Probability & Stochastic Geometry

Interference Networks



- Transmitter & receiver are arbitrarily placed.
- Interferers placed according to some point process.

SINR and Outage

- The signal-to-interference-and-noise ratio is:

$$\mathrm{SINR} = \frac{\mathrm{S}}{\mathrm{N} + \sum_k \mathrm{I}_k}$$

where S and I_k are subject to fading.

- An *outage* occurs when the SINR falls below a threshold β.

Outage Probability

- Classes of networks can be characterized by their spatially averaged outage probability:

$$\epsilon = \mathbb{E}_{\mathbf{g},\mathbf{x}}\left\{P\left[\mathrm{SINR} \leq \beta\right]\right\}$$

where *g* is the fading and *x* the topology.

- For simple networks, *stochastic geometry* can compute the above in one step.

Direct Approach

- Our approach is to first fix the network topology and theoretically derive the *conditional* outage probability.

theory →

$$\epsilon(\mathbf{x}) = \mathbb{E}_{\mathbf{g}}\left\{P\left[\mathrm{SINR} \leq \beta \middle| \mathbf{x}\right]\right\}$$

- Then the spatial average is taken:

simulation →

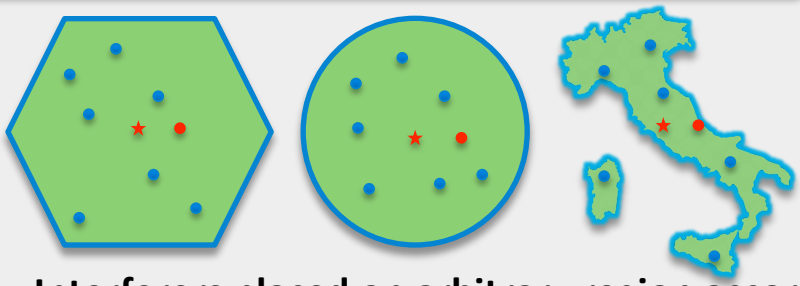
$$\epsilon = \mathbb{E}_{\mathbf{x}}\left\{\epsilon(\mathbf{x})\right\}$$

- For complicated networks, the latter average can be found through a simulation.
- Simulation can be done in computing cloud.

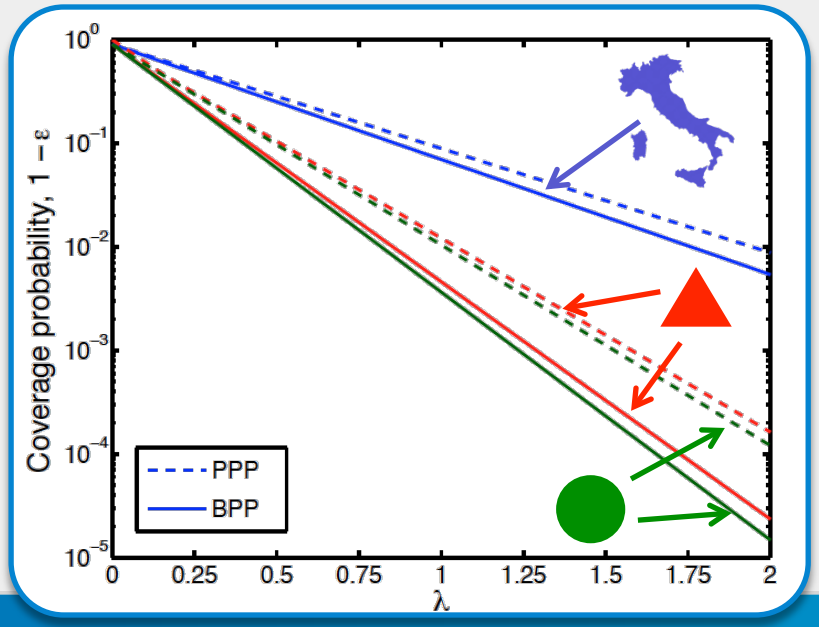
Torrieri & Valenti, "The outage probability of a finite ad hoc network in Nakagami fading," *IEEE T-Comm*, 2012.

Arbitrary Topologies & Cognitive Radio

Arbitrary Topologies

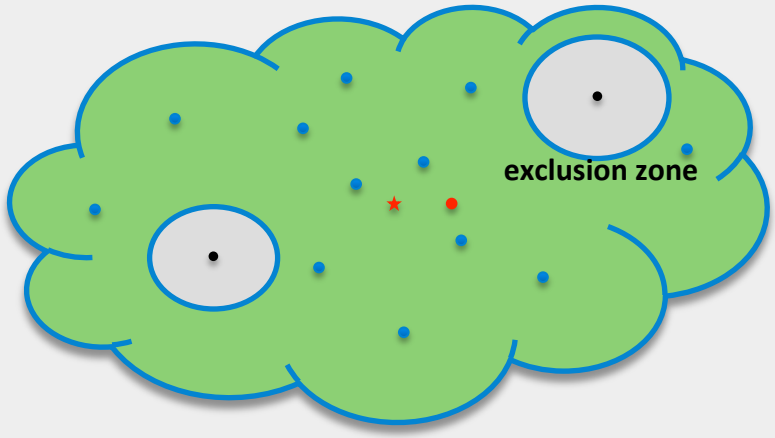


- Interferers placed on arbitrary region according to some point process.
- Can compute the spatially averaged outage probability numerically.



Application: Cognitive Radio

- Primary transmitters are placed in fixed location.
- *Exclusion zone* surrounds each primary.
- Secondary transmitters are randomly placed outside of the exclusion zones.



- Guard zones can also be used to model a CSMA protocol.

Torrieri & Valenti, "Exclusion and guard zones in DS-CDMA ad hoc networks," *IEEE T-Comm*, 2013.

Valenti, Torrieri, Talarico, "A direct approach to computing spatially averaged outage probability," to appear in *IEEE Comm Letters*, 2014.

WVU Whitespace Initiative

TV Whitespace Project

- **By using unused television bands, can extend the reach of the WVU network.**
- **Collaborative effort between:**
  - WVU Office of Information Technology
  - Air.U Consortium
  - Declaration Networks
  - Adaptrum
- **Technical details:**
  - Radios FCC certified for 470-698 MHz operation.
  - 1 W transmit power (4 W EIRP)
  - TDD OFDMA up to 16 Mbps over 6 MHz channel.
  - Uses Google TV white space geolocation database.

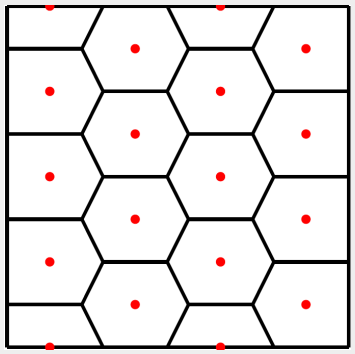
Connecting the PRT

- **Personal Rapid Transit.**
- **Base station at top of engineering.**
- **73 PRT cars randomly in constrained region.**

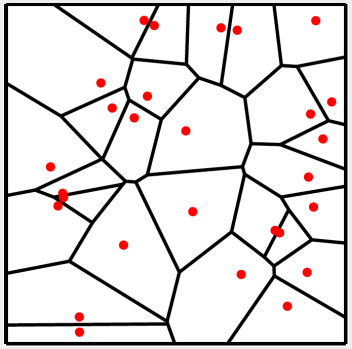
Modeling Cellular Networks

Modeling Base Stations

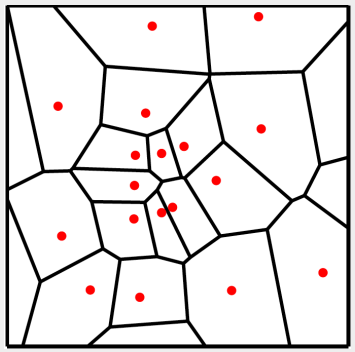
- In collaboration with AT&T Mobility, developed a stochastic model for base station placements.



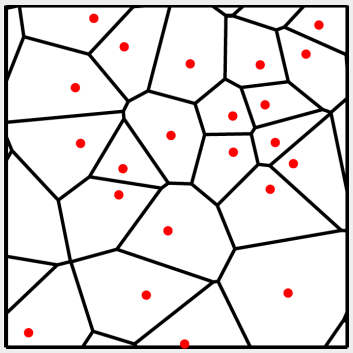
hexagonal grid



Poisson point process



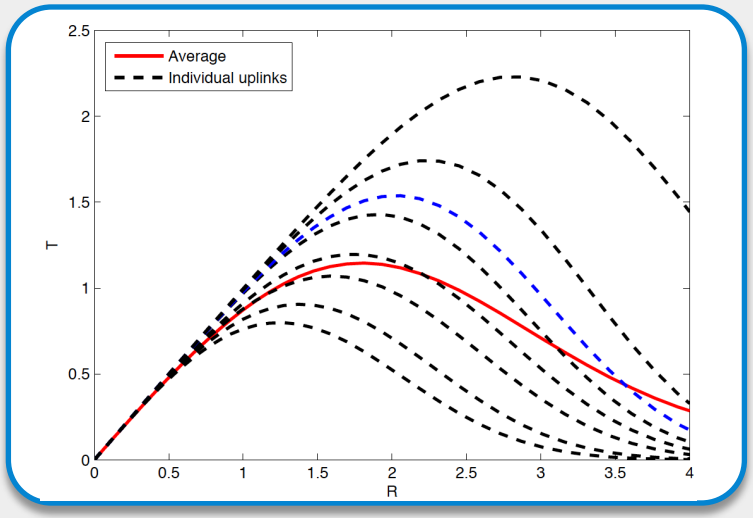
actual data (AT&T)



stochastic model

- Using this model, we can synthesize *realistic* cellular networks with simulated BS locations.

Rate Allocation Problem



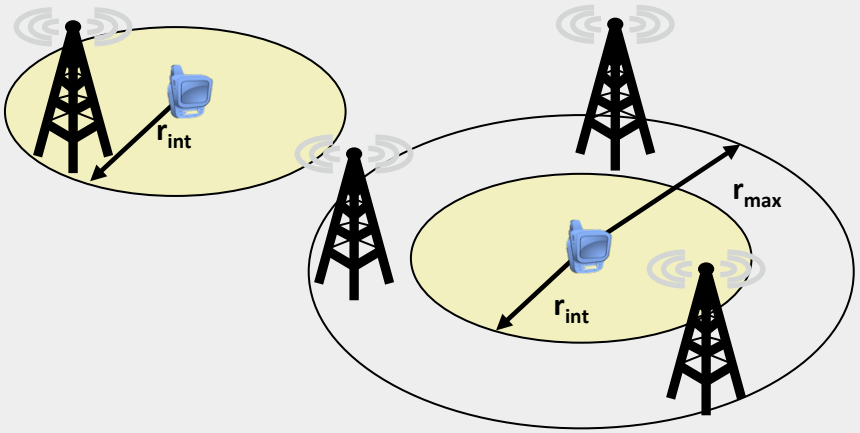
- Approaches that rely on stochastic geometry can only optimize the *average* rate under an outage constraint.
- Our approach allows the rate to be optimized for each user, and allows the fairness to be analyzed.

Valenti, Torrieri & Talarico, "A new analysis of the DS-CDMA cellular downlink under spatial constraints," *ICNC*-2013.

Torrieri, Valenti & Talarico, "An analysis of DS-CDMA cellular uplink for arbitrary and constrained topologies," *IEEE T-Comm*, 2013.

Cooperative Cellular Technologies

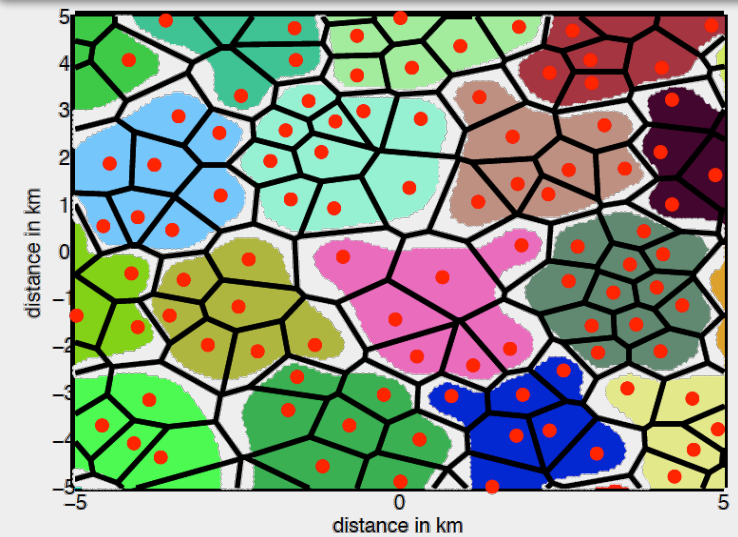
CoMP



- **Coordinated Multipoint (CoMP).**
  - Cell-edge users served by multiple base station.
  - Signals from multiple base stations get diversity combined at the mobile as if they were multipath.
- **We model CoMP using two distances:**
  - r_{int}: Cell interior. Mobile connected to 1 base station.
  - r_{max}: Maximum distance. Mobile connected to all base stations within distance r_{max}.
- **Question is how to optimize the distances.**

Talarico, Valenti & Torrieri, "Analysis of multi-cell downlink cooperation with a constrained spatial model" *Globecom*-2013.

MBSFN

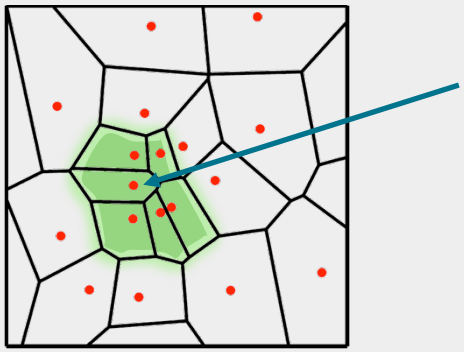


- **MBSFN**
  - Multicast-Broadcast Single-Frequency Network.
  - Broadcast content (e.g., TV programming, data feed) sent during special reserved subframes.
  - All base stations in an MBSFN group send the same signal.
  - The signal is diversity received by the mobile.
- **Question is how large to make an MBSFN group and how to find its optimal rate.**

Talarico & Valenti, "An accurate and efficient analysis of an MBSFN network," *ICASSP*-2014. *to appear.*

Cloud Radio Access Networks

Radio Access Clouds



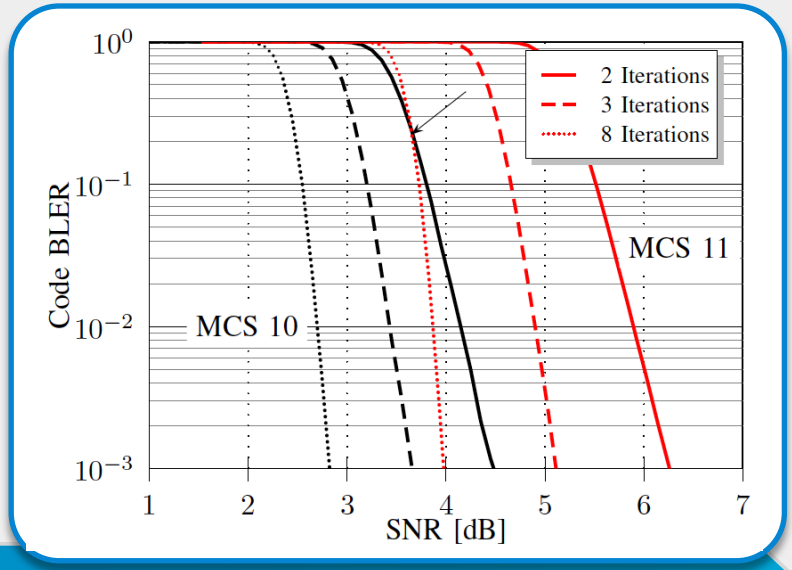
Cloud group:
The signals for these 6 base stations are jointly processed in the cloud.

- **Cloud Radio Access Network**
  - The signals from multiple base stations are jointly processed by a computing cloud.
  - Allows for simpler processing at each base station.
  - Enables cooperative processing schemes.
  - Clouds could service multiple tenants (providers).
  - Also *called centralized baseband*.
- **Technical issues:**
  - Backhaul needs to be fast and have low latency.
  - Transport blocks need to be processed in real time.
  - The computational load cannot exceed available resources.
- **For such architectures, responsiveness may be more limiting that interference or fading.**

Collaboration with NEC Laboratories, Europe.

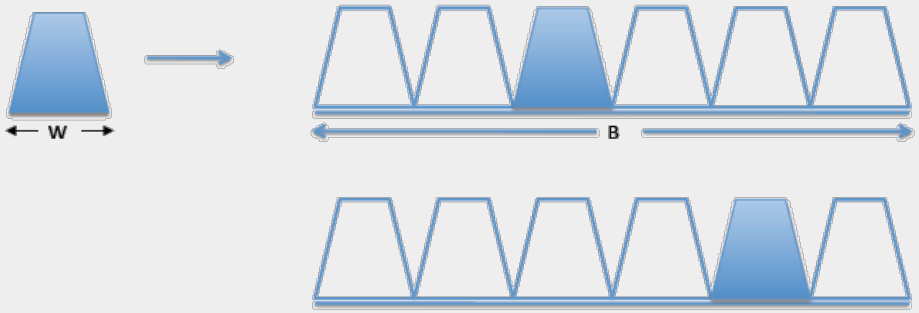
Computational Outage

- **A *computational outage* occurs if there is not enough computing resources to process all of the transport blocks in a 1 msec subframe**
- **Challenges:**
  - Characterize the probability of computational outage.
  - Develop computation-aware scheduling policies.
- **Opportunities:**
  - Turbo decoding is the most computationally demanding task and depends on the number of iterations.
  - By increasing the SINR margin, can get by with fewer iterations.



Frequency-Hopping Ad Hoc Networks

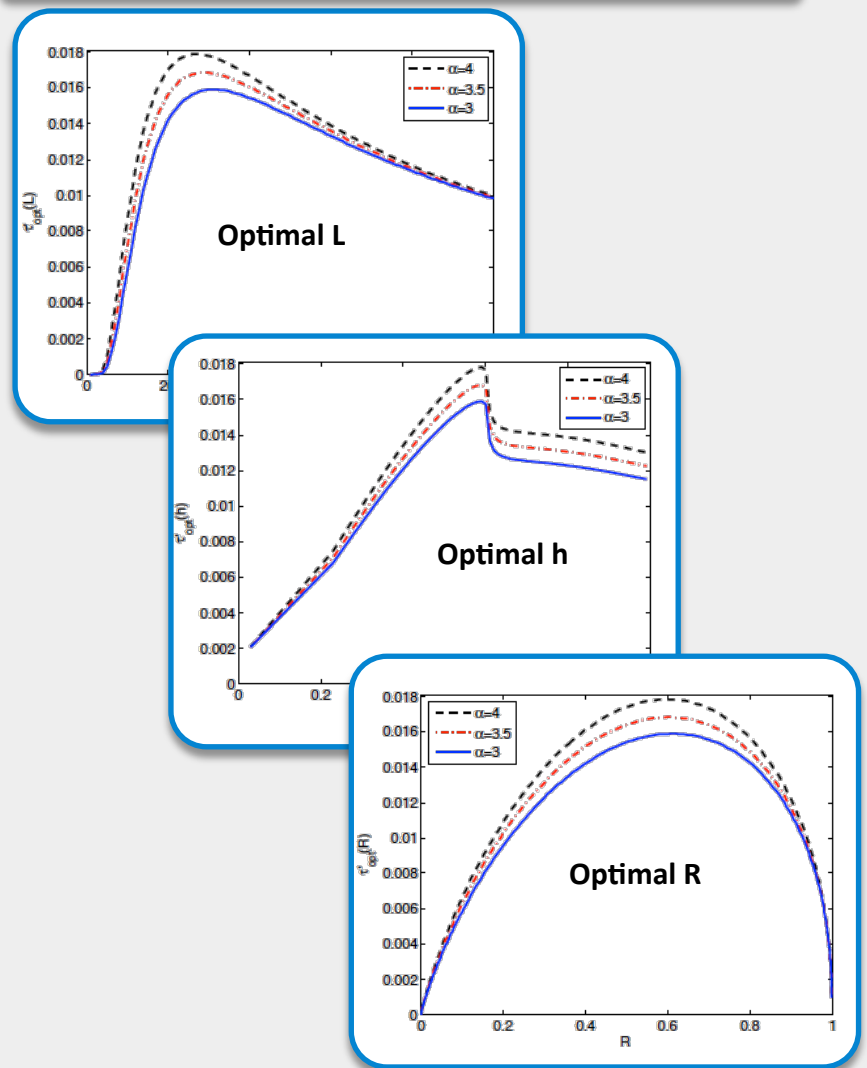
Frequency Hopping



- **Transmitter randomly picks from among L frequency subchannels.**
- **Typically, coded CPFSK modulation used.**
- **Issue is how to jointly select:**
  - Number of hopping channels L = B/W.
  - Modulation index h of the CPFSK modulation.
  - Rate R of the code (assumed to be capacity approaching).
- **Goal of optimization is to maximize the *transmission capacity*.**
  - Area spectral efficiency: bps/Hz/m^2.
- **Interferers are randomly located.**

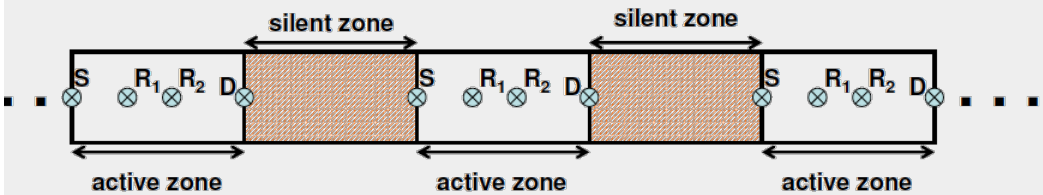
Valenti, Torrieri & Talarico, "Optimization of a finite frequency-hopping ad hoc network in Nakagami fading,"*MILCOM*-2012.

Optimal Parameters



Barrage Relay Networks

Barrage Networks

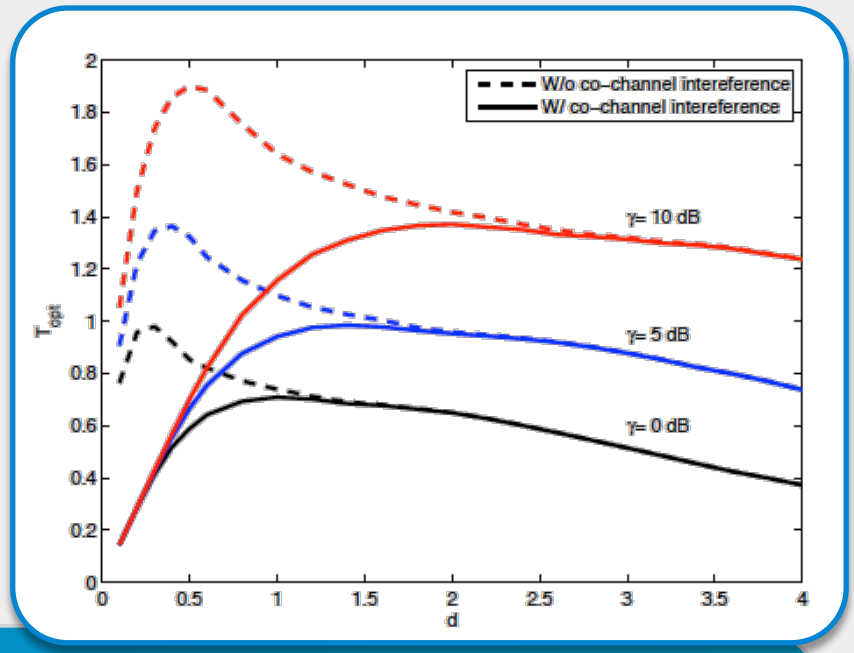


- **An ad hoc network comprised of alternating active zones and silent zones.**
  - **Routing within each zone is *cooperative*.**
    - Every relay receives each transmission.
    - Relays can transmit simultaneously, creating a cooperative diversity effect.
    - Each transmitter in a zone fires at most once until the destination successfully decodes the message.

Collaboration with TrellisWare Technologies, Inc.

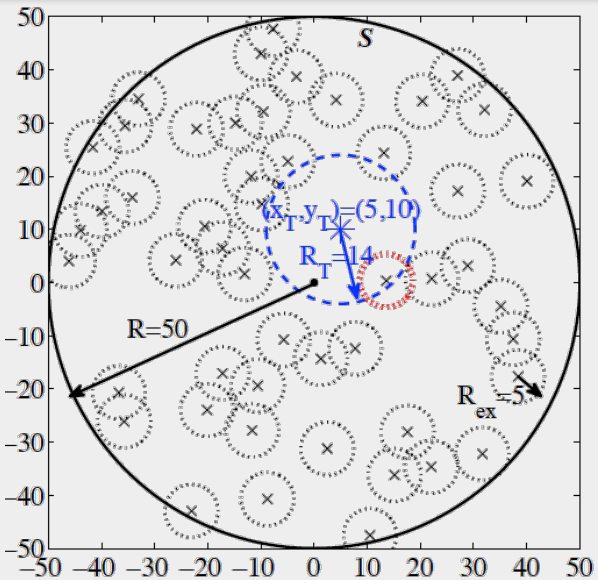
Optimization Issues

- **Issues:**
  - Number relays per barrage zone.
  - Placement of relays within the zone.
  - Size of the zone (distance from S to D)
  - Optimal transmission rate.
- **Optimization with respect to Transport Capacity (bps/m).**



Indoor Localization

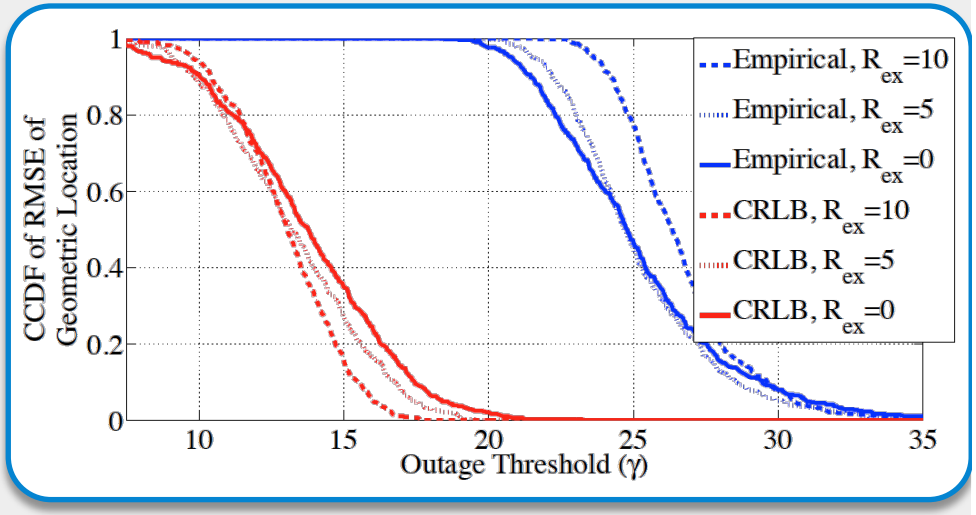
Localization w/ Random Sensors



- **A single point source is to be located using a network of randomly placed sensors.**
- **Issue is how the randomness of the placement effects the quality of the location estimate.**
- **Leverages our approach to stochastic geometry.**

Localization Outage

- **Localization outage:**
  - How many network realizations fail to achieve a target root mean square error (RMSE) in the location estimate?
- **Found numerically**
  - Draw a synthetic network realization, where each sensor surrounded by radius-R_{ex} exclusion zone.
  - Determine bound on the location RMSE.



Fanaei, Valenti & Schmid, "Effect of spatial randomness on locating a point source with distributed sensors,"
***ICC*-2014 *ANLN Workshop*. *to appear.* (invited paper).**

Outline

- Motivation
- Approach to Research
- Sampling of Results
- **Broader Impacts**
- Future Research Directions

Course Projects

Cloud Enabled Projects

Add Auction | Add Users | Auctions | Jobs | Users | Admin Users

Delete

All, None

1-6 of 6

	JobId	Username	Name	Upload time	Status	Technology	Channels	% Coverage	Users	Cost
☐	33	arawat	SquintMGW	12/10/2013	Done	4G	24	99.7	18269	$12.400M
☐	32	sandryzc	Swift Arrow File Submission	12/10/2013	Done	4G	17	98.0	16063	$9.800M
☐	31	dkirby3	KHND Wireless Network	12/10/2013	Done	4G	32	99.6	24078	$10.680M
☐	30	jlucas9	Wanna GA - Group 3 - Lucas	12/09/2013	Done	4G	17	97.0	24368	$14.040M
☐	29	mtdoyle	Underscore/Michael Doyle	12/08/2013	Done	4G	22	95.7	23191	$11.280M
☐	28	cpeyatt1	TECO_Final	12/04/2013	Done	4G	24	95.0	25160	$11.920M

1-6 of 6

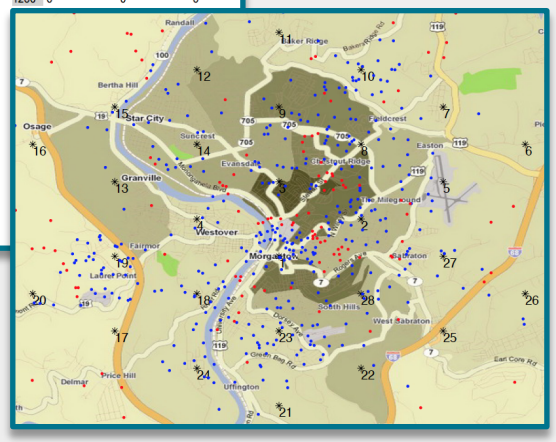
- The same computing infrastructure used for research is used to empower course projects.
- Students submit jobs though web interface.
- Rapid simulation promotes exploration.

Wireless Networking

- Student groups for virtual companies.
- Bid on spectrum using FCC/SMR auction rules.
- Design and analyze network for Morgantown.

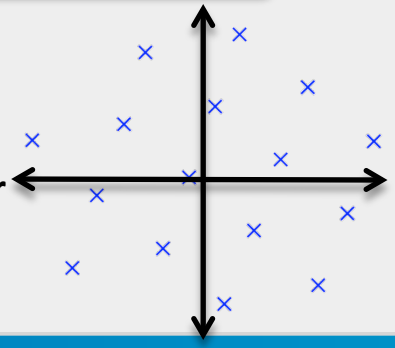
<< < 16 of 16

Block	Bandwidth	Previous Highest bid	TECO	KHND	LLW	Underscore	Swift Arrow	Squint
Cellular Block A	25 MHz	2500	0	2500	0	0	0	0
Cellular Block B	25 MHz	2500	0	2500	0	0	0	0
PCS Block A	30 MHz	4001	0	0	0	0	0	4001
PCS Block B	30 MHz	3400	0	0	0	0	0	3400
PCS Block C	30 MHz	4049	0	4049	6	0	0	0
PCS Block D	10 MHz	1200	0	0	0	1200	0	0
PCS Block E	10 MHz	1200	0	0	1200	0	0	0
PCS Block F	10 MHz	1200	0	0				
PCS Block G	10 MHz	3652	2000	0				
700 MHz Block A	12.5 MHz	2400	0	0				
700 MHz Block B	12.5 MHz	2500	0	0				
700 MHz Block C	22.5 MHz	3150	0	0				
700 MHz Block D	10 MHz	2051	0	0				
700 MHz Block E	12.5 MHz	2252	0	0				
AWS Block A	20 MHz	2700	2700	0				
AWS Block B	20 MHz	2700	2700	0				
AWS Block C	10 MHz	1797	0	0				
AWS Block D	10 MHz	1250	0	0				
AWS Block E	10 MHz	1250	0	0				
AWS Block F	20 MHz	2600	2600	0				



Communications Theory

- Design multidimensional constellation.
- Optimized with respect to symbol error rate, bit error rate, and mutual information.



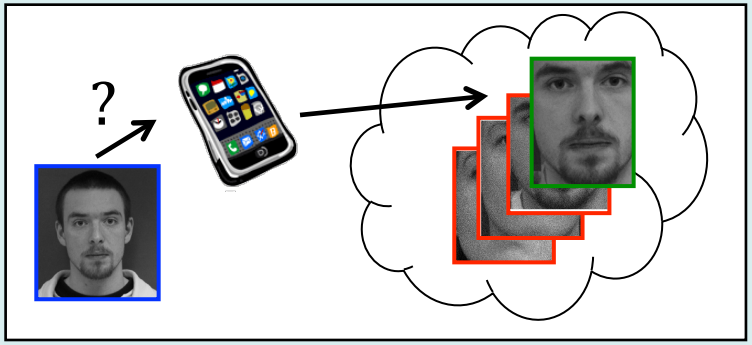
Coding Theory

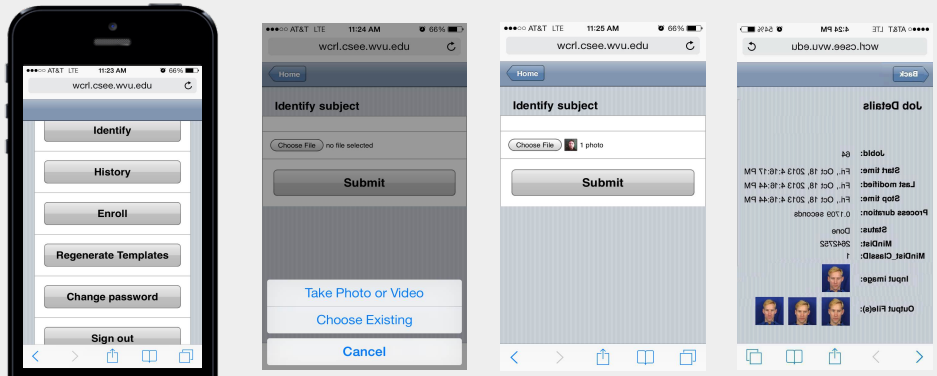
- Design and simulate an irregular LDPC code for the binary erasures channel.

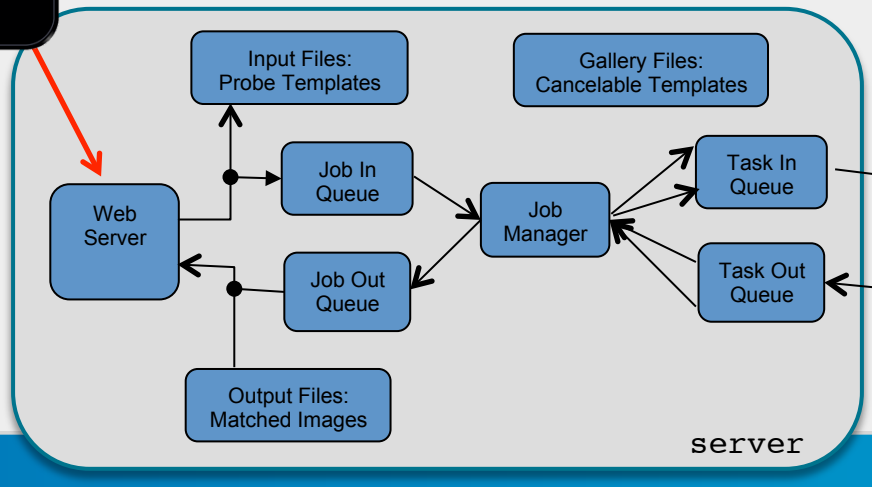
Rapid Prototyping of Custom Applications

Custom Applications

- **Computing environment implemented in a very generic way.**
  - Optimized for running Matlab applications in parallel.
- **Can quickly adapt it for other applications.**
  - Successfully applied it to biometric identification.

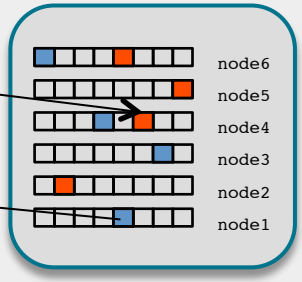






Secure Mobile Biometrics

- **Through funding by the CITeR NSF I/UCRC, quickly developed a facial recognition app.**
  - Accessible by mobile phone.
  - Empowered by the computing cluster.
  - Emphasis on keeping biometric data confidential.
  - Cyber-security applications.



NSF CITeR I/UCRC
"Cloud Empowered Mobile Biometrics"

"Enabling Biometric Research in the Cloud: Design and Demonstration"

Outline

- Motivation
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Future Research Directions

Questions

- **How do mmWave, small-cell, and massive-MIMO technologies effect the design of future wireless networks?**
  - Control signaling?
  - Channel access protocols?
  - Resource allocation policies?
- **What is the effect of having orders-of-magnitude more connected devices (M2M)?**
- **How to best leverage smarter devices?**
  - D2D?
  - Data caching?
  - Smart processing?
- **What is the impact of wireless network virtualization?**
  - How will base stations of the future be implemented?
  - How will carriers share equipment and spectrum?
- **What will replace the concept of a cell?**
  - Phantom cells?
  - Soft cells?
  - Liquid cells?

Tool & App Development

- **Custom software and cloud-empowered apps add value to an industrial affiliates program.**
- **Commercialization potential:**
  - Simulation-as-a-service?
  - Identification-as-a-service?
  - Software for SDR implementations.

Funding Options

- **Industry:**
  - Affiliates.
  - Small business via STTR/SBIR collaboration.
- **NSF:**
  - Enhancing Access to the Radio Spectrum (EARS).
  - Cyber-innovation for Sustained Engineering (CyberCEES).
- **DoD:**
  - Signal intelligence.
  - Military communications.
- **Grand challenges.**

Thank You

Questions?