Computational Communication Theory:
A Modern Tool for Engineering Future Wireless Networks

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April 7, 2014
Wireless Communications Research Lab

Personnel

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Funding Sources

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

Research Topics

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

Tools and Facilities

• Camera network testbed.
• 400-core cluster computer.
• Open source simulation software: CML.
• Web portal for researchers: WebCML.
• Motivation: What’s on the Wireless Horizon?
• Approach to Research
• Sampling of Results
• Broader Impacts
• Future Research Directions
Outline

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Greeting the Mobile Data Onslaught

Massive MIMO
- 256 Antenna Elements
- 16 Antenna Elements

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

mmWave
- License Exempt
- Traditional Microwave Bands
- Millimetre Wave Bands

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.

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.

The end of cells as we know it?
Outline

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

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.

- 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.

brute-force computation lacks: generality reproducibility

pure theory requires: loose bounds assumptions

computational communication theory

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.

Cheap utility computing allows for a computationally intensive approach to solving problems.

Much of the day-to-day work is writing code that makes utility computing easy to use.

Brute-force computation lacks generality and reproducibility. Pure theory requires loose bounds assumptions in computational communication theory.
**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.

**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.

**Web Portal**

- 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

Iterative Detection

- Coded modulation is iteratively detected

Genetic Algorithm

- Iterative Detection

Gene(c Algorithm

Discovered Constellations

- 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 \( d_h \).

Lowering the Error Floor

Encoder \( \Pi \) Modulator

Decoder \( \Pi^{-1} \) Demod.

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.

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

Noncoherent Two-Way Relaying

Physical-Layer Network Coding

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.

• 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.

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:
  \[
  \text{SINR} = \frac{S}{N + \sum_{k} I_k}
  \]
  where S and I_k are subject to fading.
- An outage occurs when the SINR falls below a threshold \( \beta \).

Outage Probability

- Classes of networks can be characterized by their spatially averaged outage probability:
  \[
  \epsilon = \mathbb{E}_{g, x} \left\{ P [\text{SINR} \leq \beta] \right\}
  \]
  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.
  \[
  \epsilon(x) = \mathbb{E}_g \left\{ P [\text{SINR} \leq \beta | x] \right\}
  \]
- Then the spatial average is taken:
  \[
  \epsilon = \mathbb{E}_x \left\{ \epsilon(x) \right\}
  \]
- For complicated networks, the latter average can be found through a simulation.
- Simulation can be done in computing cloud.

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.

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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.

- 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.


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.**

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, Valentì & Torrieri, “Analysis of multi-cell downlink cooperation with a constrained spatial model” *Globecom-2013.*

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 than 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.

Challenges:

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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/m².
- Interferers are randomly located.

**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.

**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,”
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Course Projects

Cloud Enabled Projects

- The same computing infrastructure used for research is used to empower course projects.
- Students submit jobs through a 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.

Coding Theory

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

Communications Theory

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

Web Server

Job In Queue

Job Manager

Job Out Queue

Task In Queue

Task Out Queue

Input Files: Probe Templates

Gallery Files: Cancelable Templates

Output Files: Matched Images

node1

node2

node3

node4

node5

node6

cluster

NSF CITeR I/UCRC
“Cloud Empowered Mobile Biometrics”

“Enabling Biometric Research in the Cloud: Design and Demonstration”
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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?