The Next Wave in Wireless Technology: Challenges and Solutions

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Winlab’s 20th Anniversary Celebration Event
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Me and Winlab

1989-1990

Since then...
- Seminars
- DIMACs
- Ph.D Defense
- Postdoc Recruiting
- Great Friends
Future Wireless Networks

Ubiquitous Communication Among People and Devices

Next-generation Cellular
Wireless Internet Access
Wireless Multimedia
Sensor Networks
Smart Homes/Spaces
Automated Highways
In-Body Networks
All this and more ...
Future Cell Phones

Burden for this performance is on the backbone network

San Francisco

BS

Nth-Gen Cellular

Phone System

Internet

Nth-Gen Cellular

New York

BS

Much better performance and reliability than today

- Gbps rates, low latency, 99% coverage indoors and out
Future Wifi:
*Performance burden also on the (mesh) network*

- Streaming video
- Gbps data rates
- High reliability
- Coverage in *every* room
Multichip radios today are large, consume a lot of power, and have problems with interference and coexistence.

SDRs: Wideband antennas and A/Ds span BW of desired signals
- DSP programmed to process desired signal: no specialized HW

Today, this is not cost, size, or power efficient.

Compressed sensing may solve the front-end and processing burdens.
System Challenges

- Managing interference
- Reliability
- High-bandwidth applications
- Scarce spectrum
- Real-time constraints
- Ubiquitous coverage indoors and out
System Solutions

- Better link layer design
  - Low-complexity OFDM and MIMO (1990 PHY wars over)
  - High-performance modulation and coding
  - Adaptive techniques (in time, space, and frequency)
- Better access and networking techniques
- More efficient use of wireless spectrum
  - Relaying
  - Picocells and Femtocells
  - Cooperation and Cognition
- Cross-Layer Design

Much room for improvement and innovation
Coverage Indoors and Out:  
*Cellular (Wimax) versus Mesh*

- **Outdoors**
  - Cellular has good coverage outdoors
  - Relaying increases reliability and range
  - Wifi mesh has a *niche* market outdoors
  - Hotspots/picocells enhance coverage, reliability, and data rates.
  - Multiple frequencies can be leveraged to avoid interference

- **Indoors**
  - Cellular cannot provide reliable indoor coverage
  - Wifi networks already ubiquitous in the home
  - Alternative is a consumer-installed Femtocell
  - Winning solution will depend on many factors

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Diagram:
- Outdoors: Cellular towers with connections, Femtocell, and Hotspots/picocells.
- Indoors: Femtocell with connections to a home, Wifi mesh network.
MIMO in Wireless Networks

Space: The Final Frontier

- How should MIMO be *fully* exploited?
- At a base station or Wifi access point
  - MIMO Broadcasting and Multiple Access
- Network MIMO: Form virtual antenna arrays
  - Downlink is a MIMO BC, uplink is a MIMO MAC
  - Can treat “interference” as a known signal or noise
  - Can cluster cells and cooperate between clusters
Multiplexing/diversity/interference cancellation tradeoffs in MIMO networks

- Spatial multiplexing provides for multiple data streams
- TX beamforming and RX diversity provide robustness to fading
- TX beamforming and RX nulling cancel interference

*Optimal use of antennas in wireless networks unknown*
Scarce Wireless Spectrum

and Expensive
Spectral Reuse

Due to its scarcity, spectrum is *reused*

In licensed bands

Cellular, Wimax

and unlicensed bands

Wifi, BT, UWB,...

Reuse introduces interference
Interference: *Friend or Foe?*

- If treated as noise: Foe

  \[
  SNR = \frac{P}{N + I}
  \]

  *Increases BER, reduces capacity*

- If decodable: *Neither friend nor foe*

  *Multiuser detection can completely remove interference*
Ideal Multiuser Detection

Signal 1

Signal 2

Signal 1 - Signal 2

Why Not Ubiquitous Today? Power and A/D Precision
Interference: *Friend or Foe?*

If exploited via cooperation and cognition

Friend

*Especially in a network setting*
Cooperation in Wireless Networks

Many possible cooperation strategies:
- Virtual MIMO, generalized relaying, interference forwarding, and one-shot/iterative conferencing

Many theoretical and practice issues:
- Overhead, forming groups, dynamics, synch, ...
General Relay Strategies

- Can forward message and/or interference
  - Relay can forward all or part of the messages
    - Much room for innovation
  - Relay can forward interference
    - To help subtract it out

\[
Y_3 = X_1 + X_2 + Z_3 \\
Y_4 = X_1 + X_2 + X_3 + Z_4 \\
Y_5 = X_1 + X_2 + X_3 + Z_5
\]
Beneficial to forward both interference and message
Multiple Antennas in Multihop Networks

- Antennas can be used for multiplexing, diversity, or interference cancellation
  - Cancel M-1 interferers with M antennas
  - Errors occur due to fading, interference, and delay
- What metric should be optimized?

**Cross-Layer Design**
Intelligence beyond Cooperation: Cognition

- Cognitive radios can support new wireless users in existing crowded spectrum
  - Without degrading performance of existing users

- Utilize advanced communication and signal processing techniques
  - Coupled with novel spectrum allocation policies

- Technology could
  - Revolutionize the way spectrum is allocated worldwide
  - Provide sufficient bandwidth to support higher quality and higher data rate products and services
Cognitive Radio Paradigms

- **Underlay**
  - Cognitive radios constrained to cause minimal interference to noncognitive radios

- **Interweave**
  - Cognitive radios find and exploit spectral holes to avoid interfering with noncognitive radios

- **Overlay**
  - Cognitive radios overhear and enhance noncognitive radio transmissions
Overlay Cognitive Systems

- Cognitive user has knowledge of other user’s message and/or encoding strategy
  - Used to help noncognitive transmission
  - Used to presubtract noncognitive interference

![Diagram showing the interaction between CR, RX1, RX2, NCR]
Performance Gains from Cognitive Encoding

Achievable rate region and outer bound

Only the CR transmits

outer bound

our scheme

prior schemes

\[ P_1 = P_2 = 6 \]
\[ a^2 = 0.3 \]
\[ b^2 = 2 \]
Wireless Sensor and “Green” Networks

- Energy (transmit and processing) is the driving constraint
- Data flows to centralized location (joint compression)
- Low per-node rates but tens to thousands of nodes
- Intelligence is in the network rather than in the devices
- Similar ideas can be used to re-architect systems and networks to be green

- Smart homes/buildings
- Smart structures
- Search and rescue
- Homeland security
- Event detection
- Battlefield surveillance
Distributed Control over Wireless

Interdisciplinary design approach

- Control requires fast, accurate, and reliable feedback.
- Wireless networks introduce delay and loss
- Need reliable networks and robust controllers
- Mostly open problems: Many design challenges

Automated Vehicles
- Cars
- Airplanes/UAVs
- Insect flyers
Apps in Health, Biomedicine and Neuroscience

Neuro/Bioscience applications
- EKG signal reception/modeling
- Information science
- Nerve network (re)configuration
- Implants to monitor/generate signals
- In-body sensor networks

Doctor-on-a-chip
- Cell phone as repository of medical information
- Monitoring, remote intervention and services

Recovery from Nerve Damage
Summary

- The next wave in wireless technology is upon us

- This technology will enable new applications that will change people’s lives worldwide

- Design innovation will be needed to meet the requirements of these next-generation systems

- A systems view and interdisciplinary design approach holds the key to these innovations