Preface: Focus on Research in Wireless

- How Engineers Do Research:
  - Problem/applications “pull”
  - Theory/methodology “push”
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- **In Wireless:**
  - The APP is the “pull”
  - The PHY is the “push”
  - Also, we find bridges to other fields by virtue of this dichotomy
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• **My Talk:**
  - Illustrate these ideas by example
  - Hopefully, this will illuminate the future somewhat

The APP & the PHY in Wireless Nets
Wireless Networks: Layers

Application (APP) → Web Browsing, Voice, etc.

Network (NET) → Routing, Flow Control, etc.

Medium Access Control (MAC) → Scheduling, Access Control, etc.

Physical (PHY) → Data Transmission

The APP & the PHY in Wireless Nets
Research Trends in Wireless Nets

• The Past 25 Years: Key Developments at the PHY
  - CDMA
  - OFDM
  - UWB
  - MUD
  - MIMO
  - Turbo
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• Today: Focus on Interactions Among Nodes & Across Layers
  – Among Nodes:
    • Competition
    • Collaboration
    • Cooperation
  – Across Layers:
    • MAC-PHY
    • NET-PHY
    • APP-PHY ←
So, Four Examples (Very Briefly)

Pull: Security in Wireless Networks

- Push: Information Theoretic Security

Pull: Multimedia Communications

- Push: Finite-Blocklength Capacity

Pull: Inference in Sensor Networks

- Push: Distributed Learning

Pull: Social Networking

- Push: Small-World Networks

The APP & the PHY in Wireless Nets
SECURITY IN WIRELESS NETWORKS
Information Theoretic Security

[Joint work with Yingbin Liang, Shlomo Shamai, et al.]
Exploiting the Wireless PHY

- Key Techniques for Improving **Capacity & Reliability**:
  - MIMO, Cooperation & Relaying
  - Cognitive Radio

*Information Theoretic Security*
Exploiting the Wireless PHY

• **Key Techniques for Improving Capacity & Reliability**:  
  - MIMO, Cooperation & Relaying  
  - Cognitive Radio

• **What About Security?**  
  - Traditionally a higher-layer issue  
  - Encryption can be complex and difficult without infrastructure  
  - *Information theoretic security* examines the fundamental ability of the PHY to provide security  
  - *Origins*: Shannon (1949) & Wyner (1975) provided the tools  
  - *Today*: Application to wireless networking models

*Information Theoretic Security*
Physical Layer Security
Joint Encoding for Security and Reliability

Information Theoretic Security
Building Blocks
Secrecy Capacity Regions

Broadcast Channel:

Interference Channel:

Multiple-access Channel

Information Theoretic Security
A Rich Area for Bridging

Coding Theory

Cryptography

code design

key management

cross-layer design

adversarial model

Networking

Game Theory

Information Theoretic Security

(feedback, side info, etc.)
MULTIMEDIA COMMUNICATIONS
Finite-Blocklength Capacity

[Joint work with Yury Polyanskiy & Sergio Verdú]
A Fundamental Problem

- \((n,M,\varepsilon)\) code: \(P(W \neq \hat{W}) \leq \varepsilon\)
- **Fundamental limit:** \(M^*(n,\varepsilon) = \max\{M: \exists \text{ an } (n,M,\varepsilon) \text{ code}\}\)
- **Shannon:** As \(n \to \infty, \varepsilon \to 0\)
  \[
  \frac{\log M^*(n,\varepsilon)}{n} \to C \quad \text{(capacity)}
  \]
- In many apps (e.g., multimedia) \(n\) and \(\varepsilon\) are noticeably finite.

Finite-Blocklength Capacity
Finite $n$ and $\epsilon$

- **Bounds:**
  - Shannon-Feinstein (1954/57); Gallager (1965)
  - Random coding union (2008); dependence testing (2008)

- **Approximation:**
  - Strassen (1962) – discrete memoryless channels
  - New bounds yield (2008/09) – sharper for DMCs; Gaussian; fading

\[
\log M^*(n,\epsilon) = n C - \sqrt{nV} Q^{-1}(\epsilon) + O(\log n)
\]

\[
V = \text{Var}[i(X^*,Y^*)] \quad \text{("dispersion")}
\]

Finite-Blocklength Capacity
Ex: AWGN \((SNR = 0 \, dB; \, \varepsilon = 10^{-3})\)

Finite-Blocklength Capacity
Bridges
(Not Very Long Ones)

Analysis of Codes
(normalized to the approx.; $\epsilon = 10^{-4}$)

ARQ: Optimal $\epsilon$ vs. $n$
(AWGN; SNR = 0 dB)

More generally: information theory for finite $n$?

Finite-Blocklength Capacity
INFERENCExE IN SENSOR
NETWORKS
Distributed Learning

[Joint work with Joel Predd, Sanjeev Kulkarni, et al.]
Sensor Field

Distributed Learning
A Model for Dist’d Learning in WSNs

“A distributed sampling device with a wireless interface”

- Each sensor measures a **subset** of a large data set
- Each sensor can access all **neighboring** sensors’ measured data.

*Distributed Learning*
A General Model

- $m$ learning agents (i.e., sensors)
- $n$ training examples $S = \{(x_i, y_i)\}_{i=1}^{n}

Distributed Learning
Example:
Spatio-Temporal Field Estimation

Distributed Learning
“Local” Learning: A Natural Approach

- Each learns the field with its locally available data.
- This is generally locally incoherent – e.g., $\hat{f}_1(x_1) \neq \hat{f}_m(x_1)$
A Collaborative Algorithm

- Message passing is used to update the database.
- Nice properties & combines coherence with locality.

Distributed Learning
• 50 sensors uniform in [-1, 1]
• Sensor $i$ observes $y_i = f(x_i) + n_i$
  - $\{n_i\}$ is i.i.d. $N(0,1)$
  - regression function $f$ is linear
  - $i$ and $j$ are neighbors: $|x_i - x_j| < r$
• Sensors employ linear kernel

**Experiment**

![Graph showing Connectivity vs. Error rate for Distributed Learning]
Related Results/Bridging

- **Consistency w/o Cooperation**
  
  [w/ Predd et al. *IT’06*]

- **Psychology: Judgment Aggregation**
  
  [w/ Osherson et al. *Decision Analysis ’08*]

- **Dimensionally Distributed Data**
  
  [w/ Zheng et al., *FUSION’09*]
SOCIAL NETWORKING
Small-World Networks

[Joint work with Mung Chiang & Hazer Ilantekin]
Social Overlay/Communication Underlay

**virtual:**

Social Networking Layer

**physical:**

Interactions between two layers

Communication Networking Layer

Social overlay imposes new structure (e.g., trust).

Small-World Networks
Message Delivery in Small World Social Networks

• Milgram’s 1967 experiment:

  “\[ \mathbb{E}[\text{Path Length}] = 6. \]”

  – Two striking conclusions:
    • people are connected through short chains of acquaintances
    • these chains can be found via local information

• Analysis can help explain this
- Source and target nodes are placed at arbitrary positions.
- \( n \) other relay nodes are distributed uniformly over the domain.
- Each node has local communication range \( r \).
- Each node has one long-distance neighbor.
- Greedy geographic routing.

E.g.:

- **Social networks**: Granovetter, *Am. J. Sociology* 78
- **Ad hoc networks**: Reznik, Kulkarni, Verdú, *Comm. Inf. Syst.* 04

*Small-World Networks*
**Effects of Short-cuts on Packet Delay:**
- short distances: message delivery grows linearly
- long distances: message delivery time saturates to a constant
- agrees with experimental observations of Travers & Milgram \([\text{Sociometry}’69]\)
- similar results for other network topologies (circle, sphere, etc.)

**Average Message Delivery Time**

- Can get closed form in the continuum limit:

\[ R = 102 \cdot r \]

\[ R = 502 \cdot r \]
Bridging (It’s Pretty Broad Here)

**Sociology**

- Spread of HIV

**Politics**

- Foreign policy analysis

Small-World Networks
Summary

Basics of Wireless Research – Pull (APP)/Push (PHY):

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- Social Networking/Small-World Networks
Summary

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The Future?

- **Let’s wait and see!**

The APP & the PHY in Wireless Nets
Happy 20th WINLAB!