Theoretical Foundations for ad hoc Wireless Networks

WINLAB Research Review
Nov 14, 2006

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WIRELESS INFORMATION NETWORK LABORATORY

Radio Resource Management

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Trends in Wireless Foundations I

- Scaling Laws
  - n nodes on a unit disk
  - each node communicates to a random destination at rate $R(n)$
  - Total rate $T(n)=nR(n)$
  - How does $T(n)$ grow as $n \to \infty$?

Trends in Wireless Foundations II

- Cooperation
  - $M \geq 2$ nodes cooperate as a MIMO antenna and/or receiver
  - Nodes with partial information act as relays

Scaling: Discouraging Results

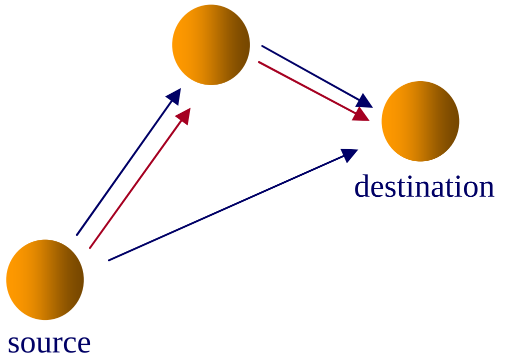
- Gupta and Kumar [2000]
  - Conventional single-user decoding
  - Interfering signals act as noise

- **Total Rate $T(n) = O(n^{1/2})$**

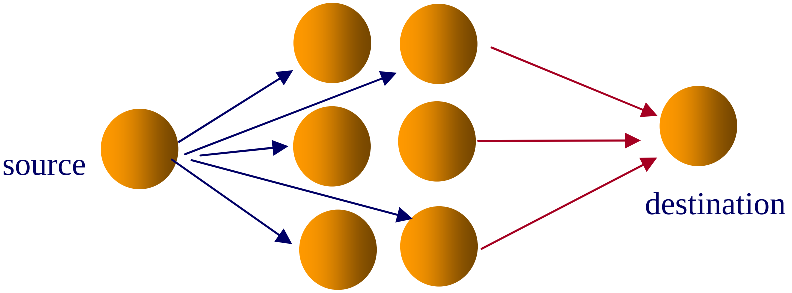
- **User Rate $R(n) = O(n^{-1/2})$** $\rightarrow 0$

Cooperation: Discouraging Results

- Small M=3 Relay Networks
  - Diversity gains in fading channels
  - Capacity unsolved



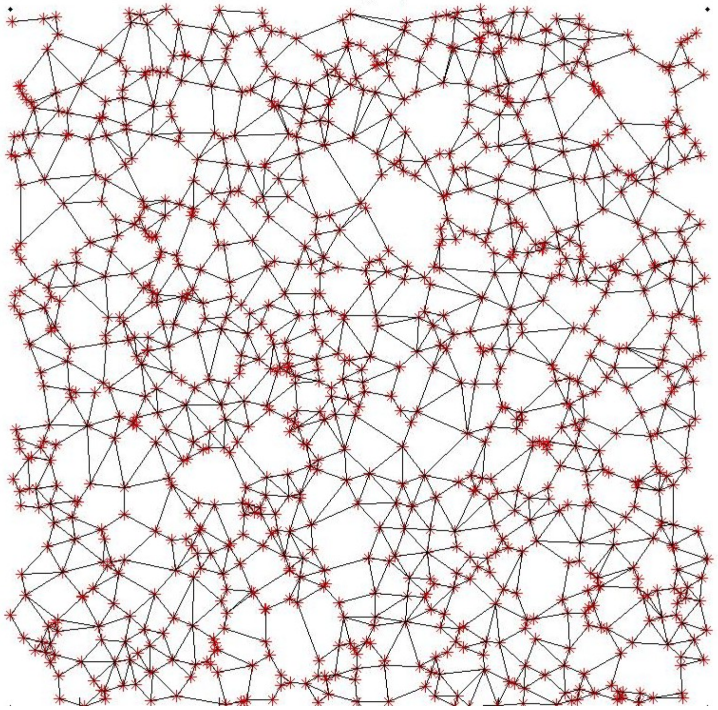
- M node transmit antenna clusters
  - Rate =O(log M)
  - Good perf needed coherent signaling



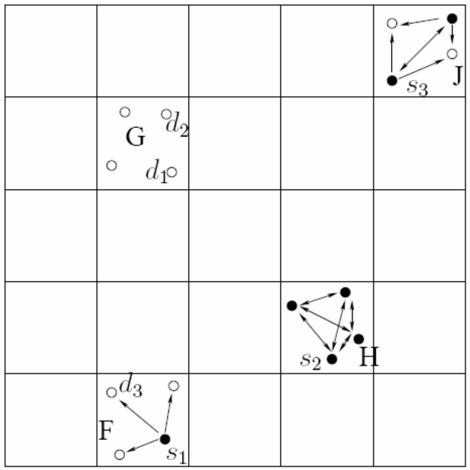
Nearest Neighbor Multihop

- Gupta-Kumar Strategy
  - Multihop forwarding
  - nearest neighbor transmission
- wired APs
  $\Rightarrow$ scalable networks
  - [Liu,Liu, Towsley 03]

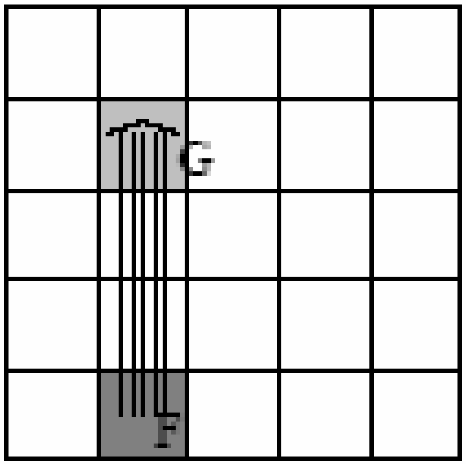
1000 nodes in a 10m X 10m region; Path Loss Exponent = 2



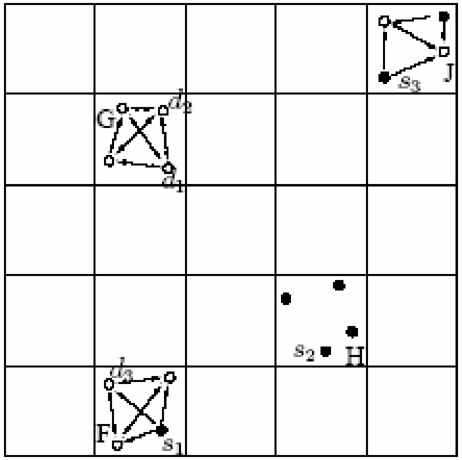
Three Stage "MIMO" [Ozgur, Leveque, Tse 2006]



Bit distribution in each M node cluster



Cluster to Cluster MIMO
M Tx to M Rx
M bits sent
(n TD stages)



Bit collection in each M node cluster

Network Throughput Boost

[Ozgur, Leveque, Tse 2006]

M node
cluster rate
$T(M) = O(M^b)$
$M = n^{g(b)}$

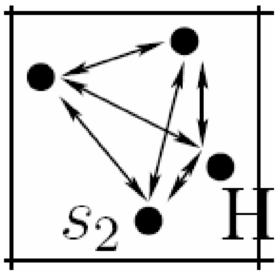
$\Rightarrow$

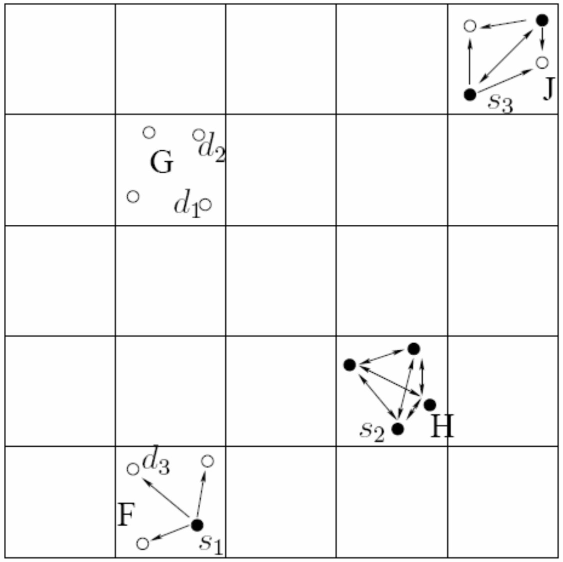
n node
network rate
$T(n) = O(n^{g(b)})$

$$g(b) = \frac{1}{2-b} \geq b$$

Network Throughput Boost

[Ozgur, Leveque, Tse 2006]





b=0
T(n)=O(1)

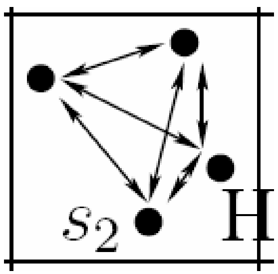
b_1=1/2
T(n) = O($n^{1/2}$)

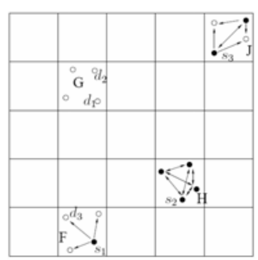
Recursive Network Construction!

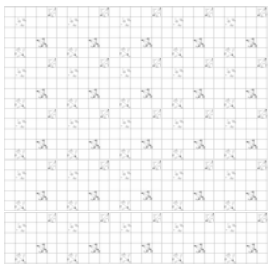
[Ozgur, Leveque, Tse 2006]

Throughput T(n)=n^b

$$b_{n+1} = g(b_n) = \frac{1}{2 - b_n}$$







b_0=0 O(1)

b_1=1/2 O($n^{1/2}$)

b_2=2/3 O($n^{2/3}$)

b_3=3/4 O($n^{3/4}$)

Questions/Issues

- How does the recursive network construction really work?
  - Routing, addressing?
- Mobility?
- Security?

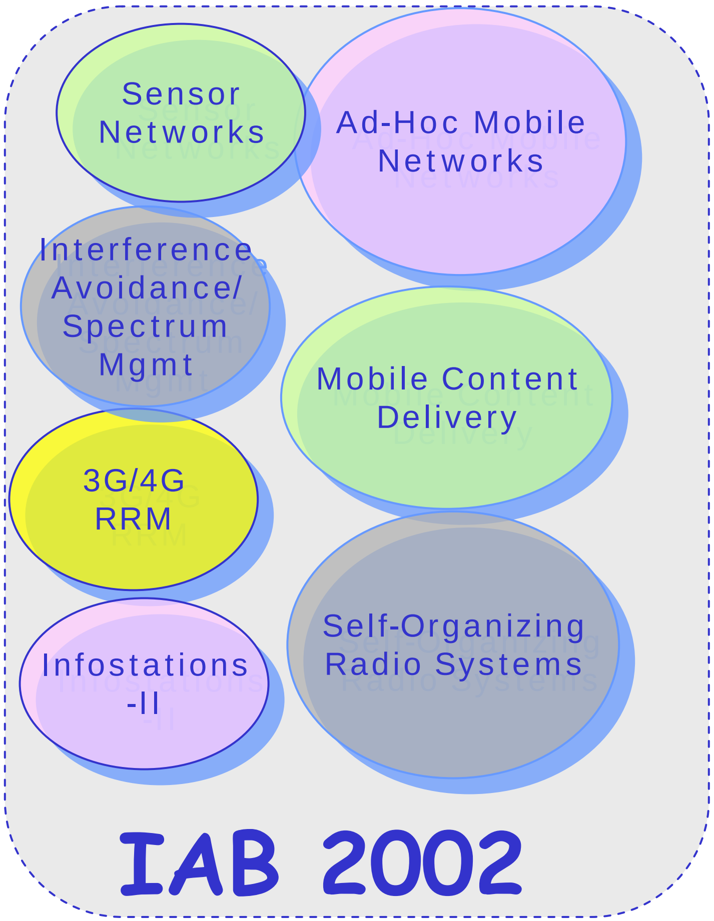
RRM Research at WINLAB

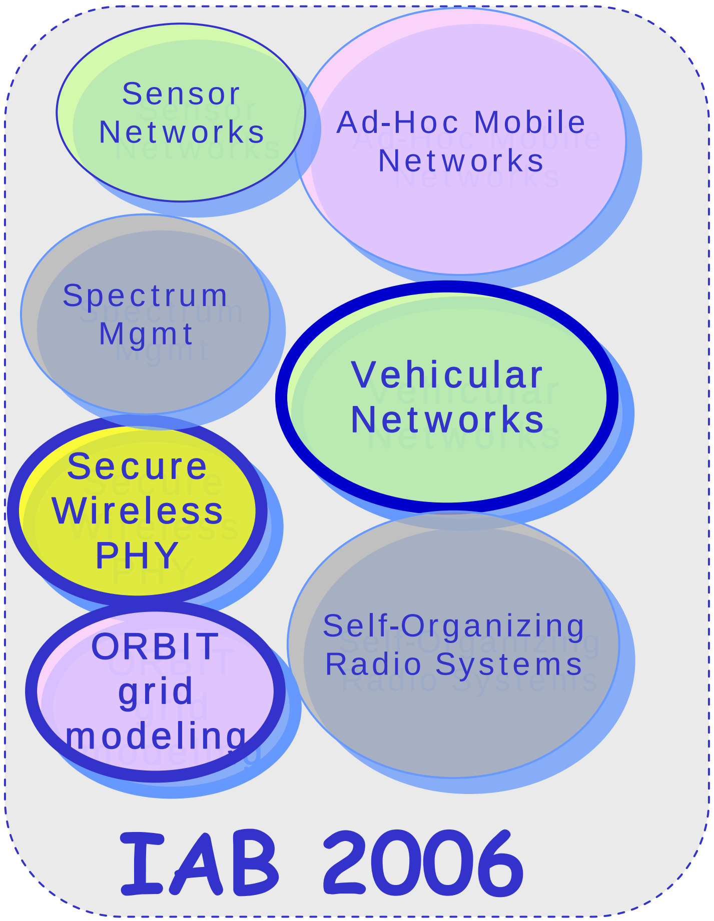
- All Investigators
  - Frenkiel, Gajic, Greenstein, Gruteser, Mandayam, Paul, Raychaudhuri, Rose, Spasojevic, Trappe, Yates, Zhang
- All networks
  - cellular, infostations, (hierarchical) sensors, multihop ad hoc, vehicular networks
- 33 Student Projects

33 WINLAB Projects

- The Truth About Spectrum Servers: Greedy Users and Resource Allocation Advisory Services
- *Christopher Rose and Jasvinder Singh*
- Network Formation Among Selfish Wireless Devices
- *Narayan Mandayam, Roy Yates and Hithesh Nama*
- Dynamic Spectrum Access Models for Bridging the Divide between Open Access and Property Rights
- *Narayan Mandayam and Omer Ileri*
- Capacity Theorems and Cooperative Strategies for a Multiaccess Relay Channel
- *Narayan Mandayam and Lalitha Sankaranarayanan*
- Distributed Scheduling Algorithms for Dynamic Spectrum Access
- *Narayan Mandayam, Roy Yates, Chandrasekharan Raman and Jasvinder Singh*
- Fingerprints in the Ether: Using the Physical Layer for Wireless Authentication
- *Larry Greenstein, Narayan Mandayam, Wade Trappe and Liang Xiao*
- A Framework for Dynamic Spectrum Sharing between Cognitive Radios
- *Roy Yates and Joydeep Acharya*
- A Cache-and-Forward Architecture for the Future Internet
- *Roy Yates and Umut Akyol*
- Pathloss Interpolation for ORBIT Testbed Calibration
- *Roy Yates, Larry Greenstein and Jing Lei*
- BeSpoken Protocol for Data Dissemination in Wireless Sensor Networks
- *Roy Yates, Predrag Spasojevic and Silvija Kokalj-Filipovic*
- Information Security for Multi-Terminal Networks
- *Predrag Spasojevic, Roy Yates, Ruoheng Liu and Ivana Maric (Stanford University)*
- Characterization of the ORBIT Indoor Testbed Radio Environment
- *Ivan Seskar, Larry Greenstein, Predrag Spasojevic and Haris Kremo*
- Cognitive Radio: Spectrum Sensing and Signal Identification
- *Predrag Spasojevic, Ivan Seskar and Goran Ivkovic*
- System Performance and Scalability of Hierarchical Hybrid Wireless Networks
- *Dipankar Raychaudhuri and Suli Zhao*
- CLAP: A Cross Layer Aware Transport Protocol for Time-Varying Wireless Links
- *Sanjoy Paul, Dipankar Raychaudhuri and Sumathi Gopal*
- A Distributed Naming and Addressing Scheme for Cognitive Radio Networks
- *Dipankar Raychaudhuri and Xiangpeng Jing*
- IRMA: Integrated Routing and MAC Scheduling in Multi-hop Wireless Mesh Networks
- *Dipankar Raychaudhuri and Zhibin Wu*
- DCMA: Interface Contained Forwarding for Efficient Data Transfers in Multi-hop Wireless Networks
- *Dipankar Raychaudhuri, Arup Acharya, Archan Misra and Sachin Ganu*
- Modeling and Interference Evaluation of Overhead Medium-Voltage Broadband
- Power Line (BPL) Systems
- *Dipankar Raychaudhuri, Larry Greenstein and Song Liu*
- Is User-Cooperation in Wireless Networks Always Beneficial?
- *Narayan Mandayam, Suhas Mathur and Lalitha Sankaranarayanan*
- A QoS Routing and Admission Control Scheme for 802.11 Ad Hoc Networks
- *Marco Gruteser, Dipankar Raychaudhuri and Lin Luo*
- Packet Probes for Available Bandwidth Estimation in Wireless Ad Hoc Networks
- *Marco Gruteser, Dipankar Raychaudhuri and Mesut Ali Ergin*
- Experimental Scalability Analysis of Rate Adaptation Techniques in Dense IEEE 802.11 Networks
- *Marco Gruteser, Predrag Spasojevic, Ivan Seskar, Kishore Ramachandran and Haris Kremo*
- Enhancing Security and Privacy in GPS-Based Traffic Monitoring Systems
- *Marco Gruteser and Baik Hoh*
- Creating Multi-hop Topologies Through Noise Generation on ORBIT
- *Marco Gruteser and Sanjit Krishnan Kaul*
- Precise Channel Modeling in Vehicle to Vehicle Communication
- *Marco Gruteser and Sangho Oh*
- An Efficient Secure Ad Hoc on Demand Routing Algorithm for Wireless Networks
- *Wade Trappe and Qing Li*
- Channel Surfing: Defending Wireless Sensor Networks from Jamming and Interference
- *Wade Trappe, Yanyong Zhang and Wenyuan Xu*
- An Identity-Based Security Framework for Vehicular Networks
- *Wade Trappe, Pandurang Kamat and Arati Baliga*
- Secrecy Capacity of Independent Parallel Channels
- *Wade Trappe, Roy Yates and Zang Li*
- Power-Modulated Challenge-Response Schemes for Verifying Location Claims
- *Wade Trappe, Yu Zhang and Zang Li*
- Managing the Mobility of a Mobile Sensor Network
- *Yanyong Zhang, Wade Trappe and Ke Ma*
- DADA: A Two-Dimensional Adaptive Node Schedule to Provide Smooth Sensor
- Network Services against Random Failures
- *Yanyong Zhang, Shengchao Yu and Antony Yang*

WINLAB RRM Research





Common Themes
Methods for Efficient Systems

- Power Conservation
  - Conserve Battery, Reduce Interference
- Cooperation
  - Multihop Forwarding, Multi-antenna Signal Combining, Cooperative Detection
- Distributed Protocols/Algorithms
  - Local Measurements
- **Security**

PHY Layer Projects I

- *Spectrum*
  - The Truth About Spectrum Servers: Greedy Users and Resource Allocation Advisory Services
    - *Christopher Rose and Jasvinder Singh*
  - Dynamic Spectrum Access Models for Bridging the Divide between Open Access and Property Rights
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PHY Layer Projects II

- *ORBIT Grid Characterization*
  - Pathloss Interpolation for ORBIT Testbed Calibration
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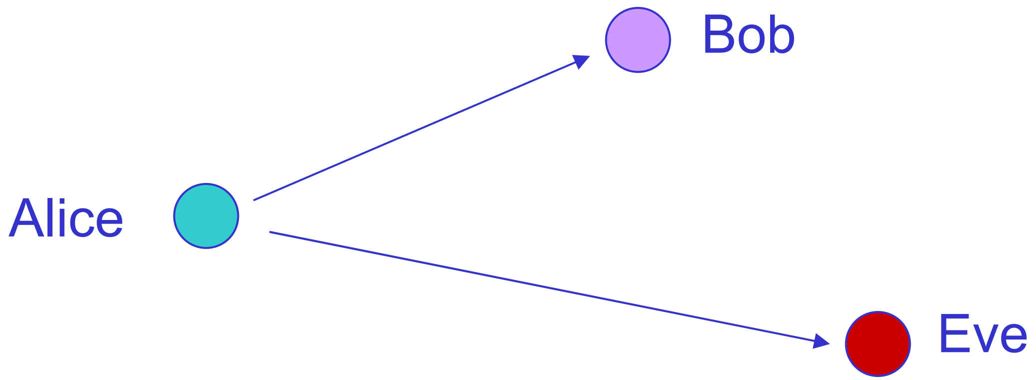
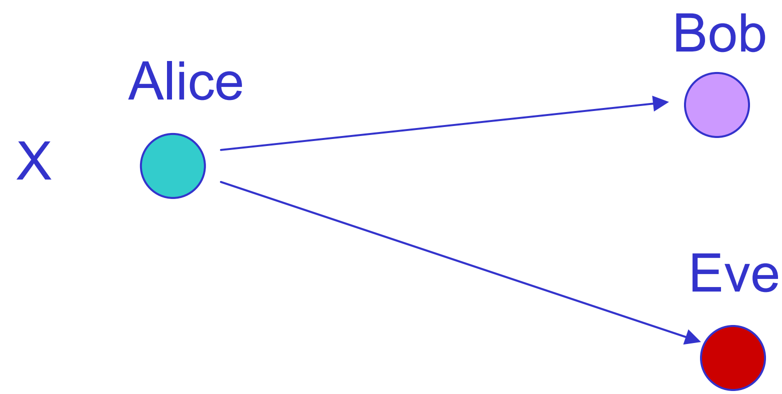
Secure Wireless PHY

- Information Theoretic Basis
  - The Wiretap Channel [Wyner 1975]
  - Broadcast channel [Csiszar & Korner 78]



- Wireless = easy eavesdropping & jamming
- Unique properties of wireless medium can be exploited

Gaussian Broadcast Channel



$$Y = \sqrt{b}X + W_1$$

$$Z = \sqrt{g}X + W_2$$

$W_1, W_2 \sim N(0,1)$

Secrecy capacity is

$$C_{AWGN} = \max_{P(x)} I(X;Y) - I(X;Z) = \frac{1}{2}\left(\log(1+bP) - \log(1+gP)\right)^+$$

(Leung-Yan-Cheong & Hellman 78, Van Dijk 97)

$C_{AWGN} = 0$ if Eve's channel is better

Fading Channels

- Secrecy Capacity of Independent Parallel Channels

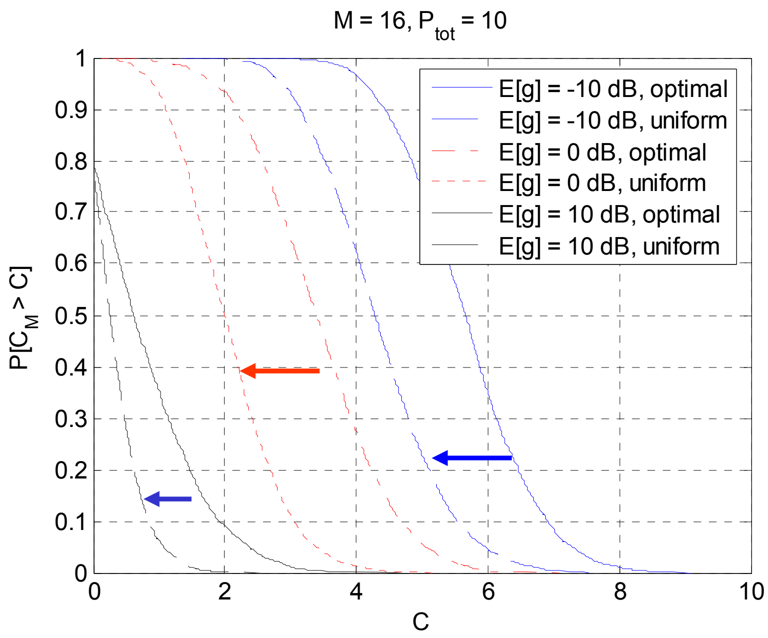
  [Z. Li, R. Yates, W. Trappe]

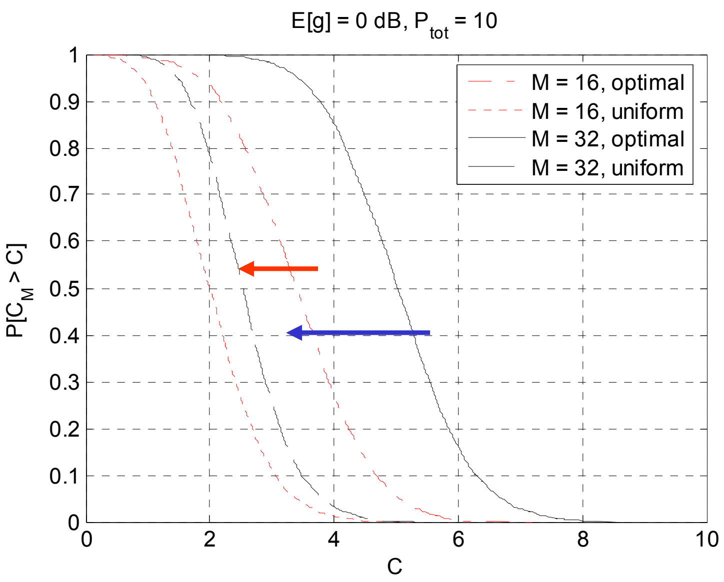
  - Fading channel state $\gamma = (b,g)$
  - Opportunistic transmission when Bob > Eve
    - Effective even if Eve > Bob on average

$$C_{\sec} = \max_{S(\gamma):E_\gamma[S(\gamma)]=\bar{S}} E_\gamma\left[C(\gamma, S(\gamma))\right]$$

$$S^*(\gamma) = \frac{W}{2}\left(\sqrt{\left(\frac{1}{b}+\frac{1}{g}\right)^2 + 4\left[\frac{1}{\lambda}\left(\frac{1}{g}-\frac{1}{b}\right)-\frac{1}{gb}\right]} - \left(\frac{1}{b}+\frac{1}{g}\right)\right)^+$$

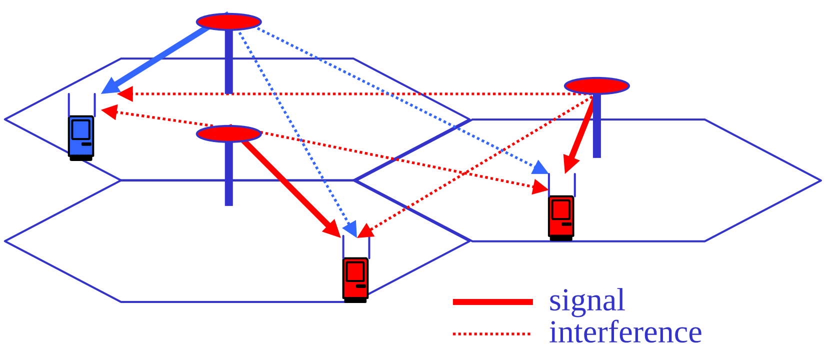
Uniform vs. Optimal Power Allocation

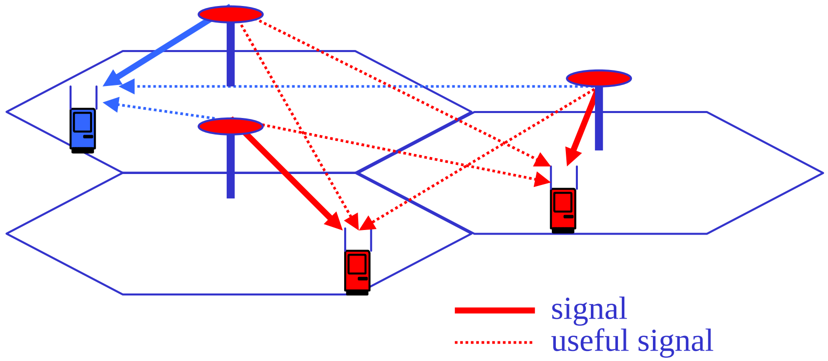




- Uniform power allocation results in significant secrecy capacity loss comparing to optimal power allocation, especially at large M
  - Loss of about 1~1.5 bits/channel use for M=16
  - Loss of about 2~3 bits/channel use for M=32

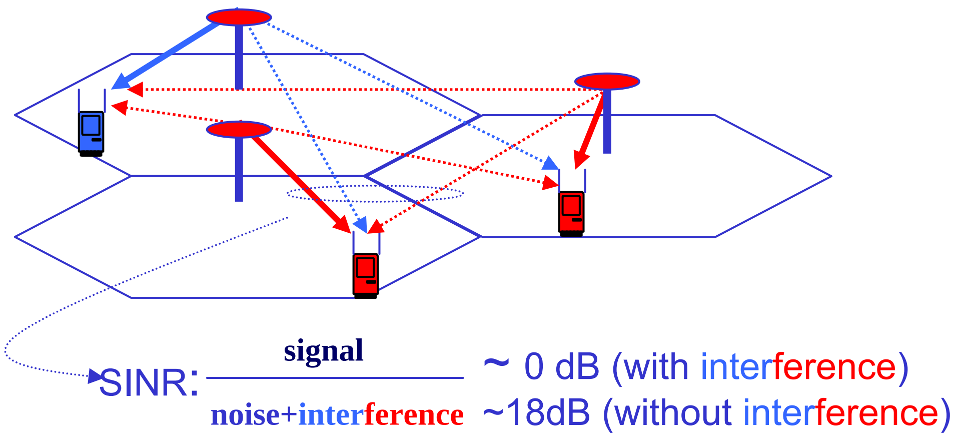
Coordinated Cellular Networks
[Karakayali, Foschini, Valenzuela, Yates]

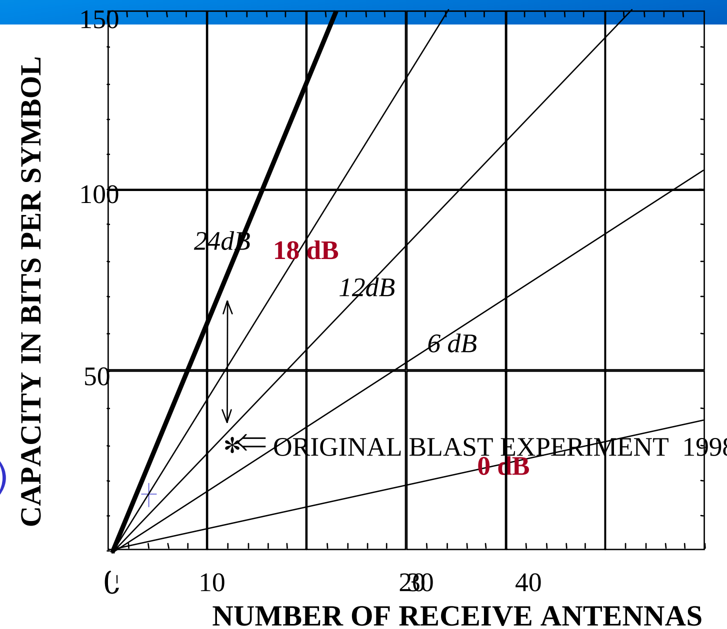




- **Conventional Networks:**
  - Each mobile served by a unique BS. Mobiles suffer interference.
- **Inter-base Coordinated Networks:**
  - Base stations act together, all users are served by all BSs.
  - Coordinated BS transmissions mitigate interference
- **Problem: How to coordinate?**
  - What is the value of BS coordination? Multiple antennas?
    Goal: Achieve maximum spectral efficiency

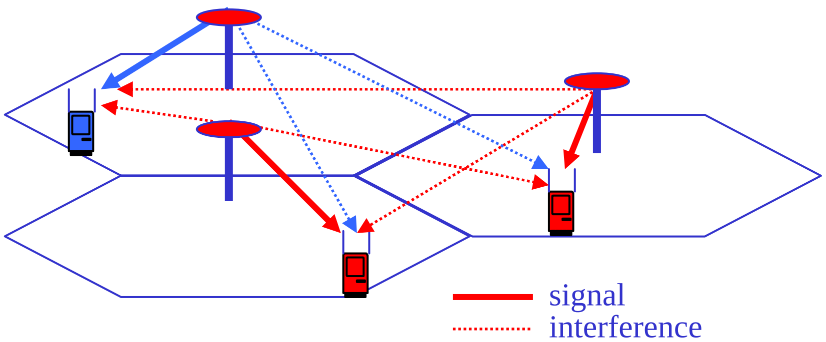
Mitigation of Out-of-cell Interference





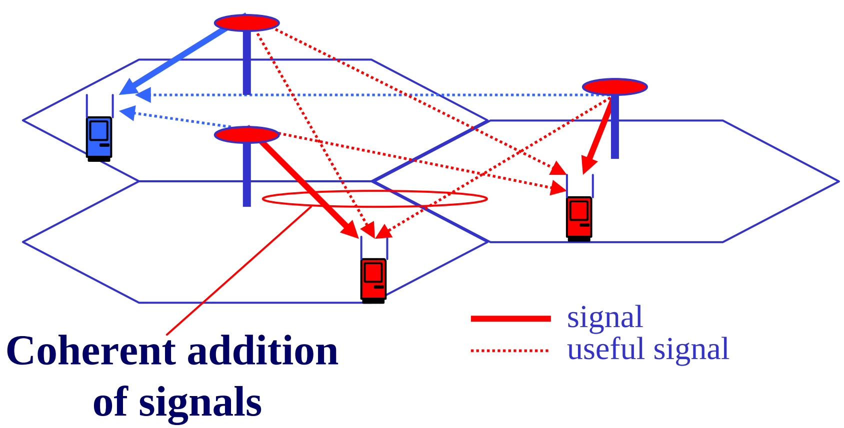
- Objective: Mute inter-cell interference to enhance **per antenna** spectral efficiency:
  1. Networks with just single antenna bases and mobiles
  2. Multiple antennas at both bases and mobiles.
- Context: Cellular Downlink
  - Equal rate (ER), to emphasize fairness to users.

Downlink Transmission Methods with Single Antenna Mobiles and Base Stations



SINGLE BASE TRANSMISSION (SBT)

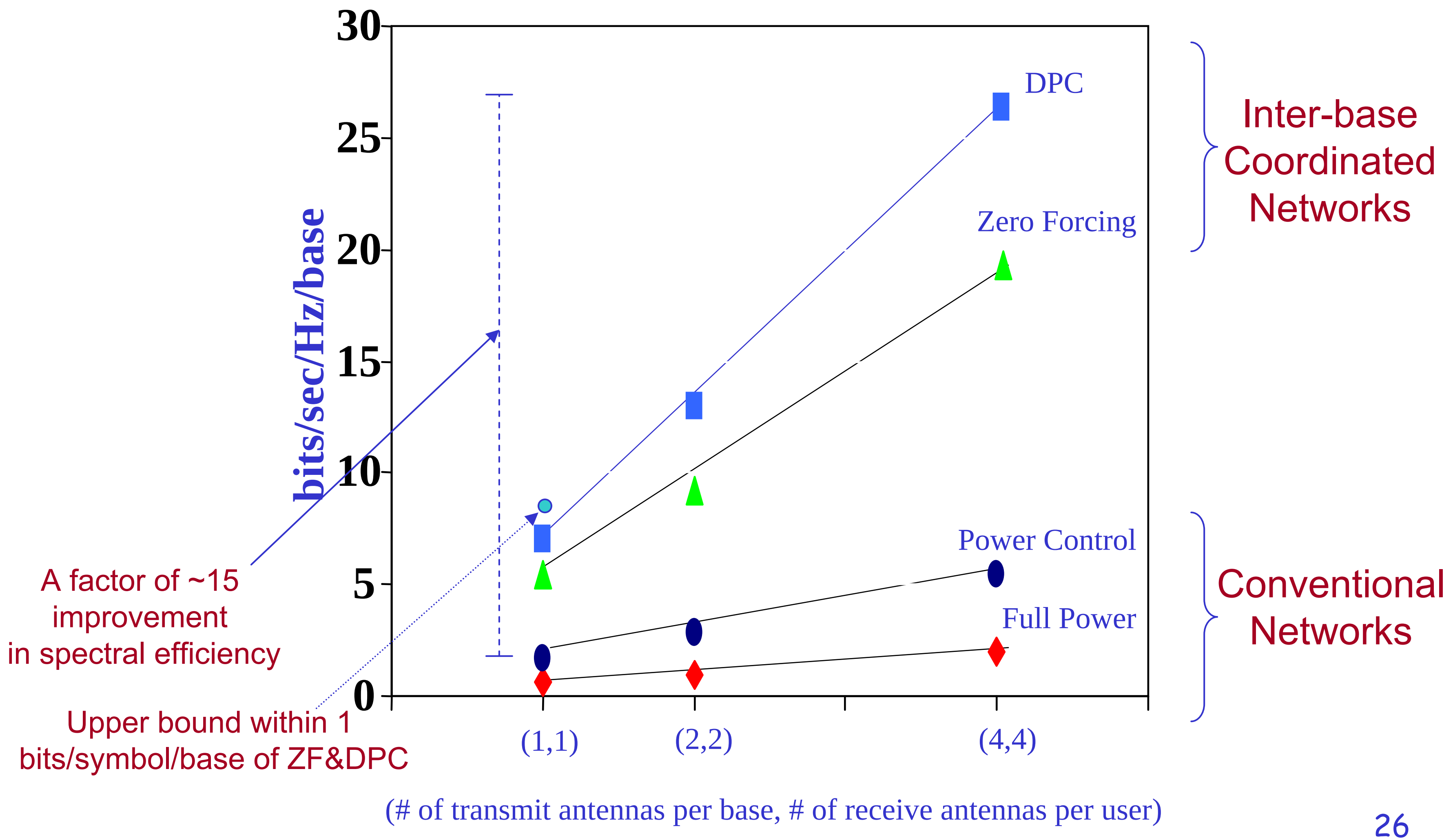
- Phase information not required.
- Neighboring base transmissions cause interference
- Means for mitigating interference:
  - Power Control ⇐ *BASELINE*
  - Transmit at Full Power (FP)



MULTIBASE COHERENTLY COORDINATED TRANSMISSION (CCT)

- Channel magnitude, phase information needed
- Signals coherently add at the receivers.
- Means for mitigating interference
  - Zero Forcing (ZF)
  - Dirty Paper Coding (DPC)

Network Coordination Gains with Multiple Antennas



Summary

- Promising recent results
- Lots of interesting problems