Wireless Mesh Networks at Illinois

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WMN Research at UIUC

- Fundamental Laws of WMNs
  - Network capacity
  - Coverage and connectivity
  - Topology control
  - Critical power analysis
  - Cross-layer design and optimization

- Protocol/Algorithm Design and Evaluation
  - Topology control
  - Power management
  - Carrier sense threshold tuning
  - Channel assignment
  - Multi-radio, multi-channel routing
  - Wireless QoS
  - Security, privacy, and incentives

- System Prototyping, Implementation and validation
  - Champaign Urbana Wireless Mesh Network (CUWiN)
  - Testbed for wireless distributed control
  - NeX – multi-channel mesh
Theoretical Analysis

Theoretical foundation for wireless networks

- Network capacity analysis: how much traffic can be carried by wireless networks?
- Scaling laws for wireless networks with respect to coverage, connectivity, critical power, and lifetime.
- Gives performance bounds or limiting behaviors
- Sheds lights on how optimal protocol operations can be devised.
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Protocol Stack for Wireless Networks

- **Application Layer**
- **Transport Layer**
- **Network Layer**
- **MAC Layer**
- **Physical Layer**

**Group membership management**

- **UDP**
- **TCP**

**Multicast Routing**

**Routing**

**Mobility Management**

**Topology Control**

**Scheduling**

**Medium Access**

- **GPS Positioning & Synchronizing**
- **Channels Selection (frequency/code)**
- **Directional Beam-Forming**

**Power Mgmt**

**Power Adjustment**
UIUC Wireless Research in the Stack

- **Group membership management**
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  - **Routing**
  - **Mobility Management**
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  - **Scheduling**
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- **Power Mgmt**
- **Channels Selection** (frequency/code)
- **Directional Beam-Forming**
- **GPS Positioning & Synchronizing**

- Data management in mobile ad-hoc networks (Klara)
  - Organize, store data in mobile nodes
  - Disseminate data to all mobile nodes
  - Search data among mobile nodes

- **Power Adjustment**

- **Application Layer**
- **Transport Layer**
- **Network Layer**
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- Multi-radio, multi-channel routing (Vaidya)
- Optimization in MaxWeight routing (Meyn)
- Routing matrices for multi-hop wireless networks (Kravets)

Group membership management over wireless

UDP

TCP

Multicast Routing

Routing

Mobility Management

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How each node adjusts its transmission power so as to:
- maintain network connectivity
- increase spatial reuse
- increase network capacity
- mitigate MAC interference

COMPOW/CLUSTERPOW (Kumar)
LMST/FLSS (Hou)

Application Layer
Transport Layer
Network Layer
MAC Layer
Physical Layer

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Wireless devices may go to sleep in the absence of activities
• When a node switches to the low-power state
• When a node in the low-power state switches to the active state

Hou, Kravets, Kumar
1. Enhancement of IEEE 802.11 to
   • improve achievable throughput
   • mitigate the hidden/exposed
terminal problems
   • Provide QoS (IEEE 802.11e)
2. Contention resolution with the
   use of
   • temporal/spatial diversity
   • different frequencies/codes
   • different power levels

Hou, Luo, Vaidya
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Cross layer issues
1. Security and privacy (Hu, Borisov)
2. Dependability and trustworthiness (Sanders)
3. Extensibility and hybrid networks (Luo)
4. Cross-layer optimization (Kumar)

Group membership management over wireless

- Application Layer
- Transport Layer
- Network Layer
- MAC Layer
- Physical Layer

- UDP
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Control Knobs in PHY/MAC Layers

- To *mitigate interference, increase spatial reuse, and maximize the network capacity*, there are several control knobs:
  - Transmit power $\rightarrow$ power control
  - Carrier sense threshold $\rightarrow$ CS threshold tuning
  - Spatial and temporal domain in which a node transmits $\rightarrow$ scheduling
  - Channel diversity $\rightarrow$ use of non-overlapping channels
  - MAC parameter tuning (CW, backoff timer, inter-frame spacing) $\rightarrow$ QoS provisioning

*We seek a fundamental understanding of how, and to what extent, controlling these attributes impacts the capacity performance.*
Power/Topology Control: Instead of transmitting with the maximal power, each node collaboratively reduces its transmission power to define the network topology.
Topology Control – Cross Layer Design View

- Network Layer
- MAC Layer
- Physical Layer

Cross Layer Design

- Dynamic Topology Control w.r.t. Network Traffic
- Effect of MAC-Layer Interference
- Incorporating Physical Layer Characteristics

Topology Control

Network Capacity
Network Lifetime
Critical Power Analysis
Pulsar: Energy Conservation in Multi-hop Wireless Networks

- **Pulsar**
  - Comprehensive energy modeling
    - Communication-time, control, idle-time and transition energy consumption
  - Integration of communication-time and idle-time energy conservation
    - Heuristic solutions to energy-efficient network design
  - Energy conservation in dual radio sensor nodes
    - Multi-hop wake up using low power radio
    - Bulk data transmission using high power radio
Multi-Radio, Multi-Channel Assignment

Net-X

Multi-Channel Mesh
Theory to Practice

Capacity bounds
Insights on protocol design
OS improvements
Software architecture

Net-X testbed

Linux
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DEPARTMENT OF COMPUTER SCIENCE
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Optimizing MaxWeight

**What is the state of the art and what are its limitations?**
Static routing: ignores dynamics
MW routing: inflexible with respect to performance improvement
Subramanian & Leigh 2007: MW can be irrational

**KEY NEW INSIGHTS:**
MW = \( h \)-myopic for a fluid model, with \( h \) quadratic

Fluid model: \( \frac{d}{dt} q(t) = \Delta_h(q(t)) \)
\( h \)-myopic policy: \( \arg \min \{ \nabla h(x), \Delta_h(x) \} \)

Key geometric property of quadratic is identified:
\( \frac{\partial}{\partial x_i} h(x) = 0 \) whenever \( x_i = 0 \)

Leads to broad new classes of policies

**HOW IT WORKS:**
Key analytical tool is Lyapunov theory for Markov processes: The function \( h \) satisfies Condition (V3) of Meyn & Tweedie 1992; An exponentiated version satisfies (V4)
For approximate optimality, workload relaxation Relaxation also provides tool for visualization of high dimensional dynamics. Optimal solutions evolve in region containing monotone region for the effective cost.

**MAIN RESULT:**
Perturbation technique to generate functions with appropriate geometry
Application to policy synthesis for approximately optimal performance (delay or backlog) in heavy traffic, with logarithmic regret

**APPLICATION TO:**
- Decentralized implementation: Policy can be designed to use available information.
- Adaptation - on-line policy improvement
- Full analysis of multiple bottlenecks
- Integration with Network Coding projects: Can we code around network hot-spots?

**ACHIEVEMENT DESCRIPTION**

**END-OF-PHASE GOAL**

**COMMUNITY CHALLENGE**

**NEW INSIGHTS**

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**DATA MANAGEMENT IN MOBILE AD HOC NETWORKS**

**Objectives**
- Organize, store data in mobile nodes
- Disseminate data to all mobile nodes
- Aggregate data to save bandwidth
- Search data among mobile nodes

**Scenario: Disaster/Recovery**

**System Architecture**

- **Disaster/Recovery Message Manager**
  - Operators (Add, Update, Delete, Rank)
  - Message Collections
  - Importance Score Calculator

- **Adaptive Estimator**
  - Broadcast Period Estimator
  - Time-to-Send Estimator

- **Mobility-assisted Data Disseminator**
  - Receiver
  - Neighbor Manager
  - Sender

- Periodically broadcasts top k Disaster/Recovery messages

**Current work**
- Data dissemination
- Data caching under different mobility models

**Ref: MILCOM 2007 paper**
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Urbana Champaign Wireless Community Network

- We are currently working with Champaign-Urbana Wireless Community Network to deploy an open, city-wide wireless community network in Urbana Champaign.

- Currently 40 wireless nodes are operational in downtown Urbana, and we expect to extend to 100 nodes providing full coverage of Champaign and Urbana.

- Both a research testbed and a production network.

*Supported by NSF Computing Research Infrastructure program.*
Hardware

- The CUWiN rooftop router
  - Contains a Soekris Engineering net4526 single-board computer in a weatherproof enclosure and an 802.11b/g radio with Atheros chipset.
  - Operates in 802.11b-standard IBSS mode, and uses 802.11b rates, 1, 2, 5.5, and 11 Mb/s.
  - Is equipped with a CUWiN software solution to defeat 802.11 IBSS network partitioning and powered by the power-over-Ethernet injector.
  - Can configure itself as either an Internet gateway or a client, depending on whether it detects a DHCP server on the Ethernet interface.
- Approximately $375 per node ($500 including installation)
CUWireless Software Architecture

Configuration database

- dhcpd
- dhcpselect
- dhclient

/etc

- routevizd
- zebra

Routing socket

nsbridge

mDNS responder

Kernel

- FIB

- Ethernet NIC
- Wireless NIC
Wireless NIC (Atheros Chipset)

Hardware abstraction layer

Channel behavior modeling

Measurement

Interference Detection & mitigation

Frame transport

Power assignment & Parameter turning

Frame scheduling

Channel utilization optimization

Zebra

New Quagga Clients

CUWireless Software Environment

Modified Madwifi
Desirable Features

- Controlled transparency: The TDD provides a transparent and generic interface for higher-layer protocol modules to access, through well-defined APIs, a rich set of PHY/MAC attributes and functionalities in the device driver.
  - (i) the transmit power level,
  - (ii) the carrier sense threshold,
  - (iii) the data rate,
  - (iv) the receive signal strength index (RSSI), and
  - (v) the channel used to transmit a frame/upon which a frame is received, and
  - (vi) the time instant at which a frame is scheduled for transmission/receive.

Through an event subscription mechanism, higher-layer protocol modules can also receive timely update of channel status, without directly inserting callback functions in various places of the device driver.
Desirable Features

- **Flexibility**: The event subscription mechanism is simple and elegant
  - allows multiple higher-layer protocol modules to (i) subscribe, and be alerted of, PHY/MAC events of interest; and (ii) register with the event subscription mechanism their callback functions, allowing adequate actions to be taken upon event occurrence.
  - allows the time granularity at which PHY/MAC properties are controlled to be on a per-packet or per-connection basis, or permanently (i.e., until the property is reset).
Questions and Comments?