Advanced Topics in Wireless Networking

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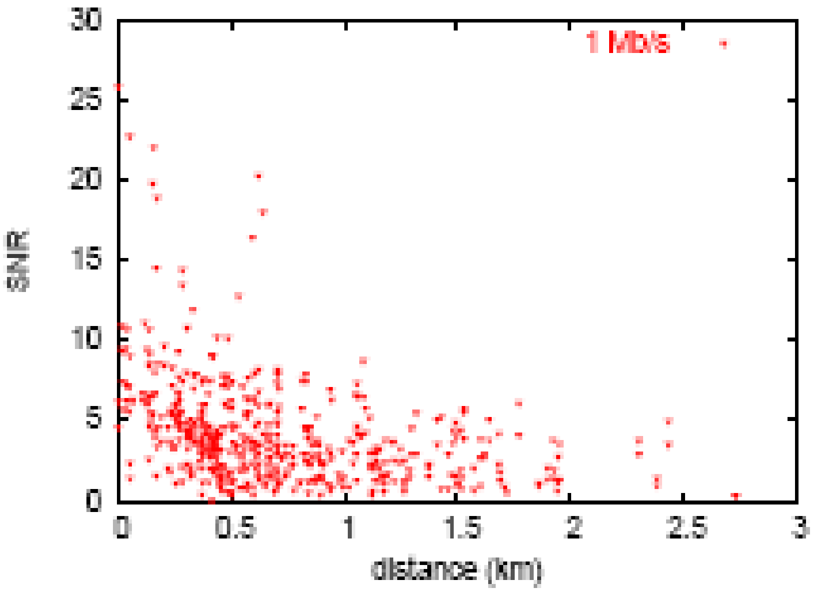
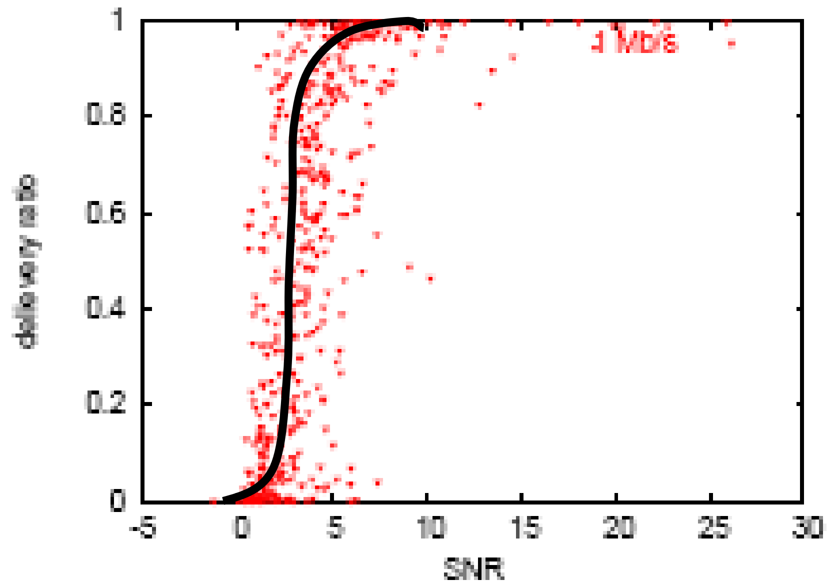
Problems and Challenges

- Initial success has been reported in wireless networks (the most notable of which is the success of WLANs).
- However, several performance-related and deployment problems have been identified in multi-hop wireless networks.
  - Unpredictable channel behaviors
  - Inability to locate stable and high-throughput paths due to the shortest path algorithm
  - Throughput degradation because of intra-flow and inter-flow interference
  - Lack of incentives (and a pricing mechanism) to forward transit packets
  - Security holes and lack of privacy protection mechanisms

Unpredictable Channel Behavior

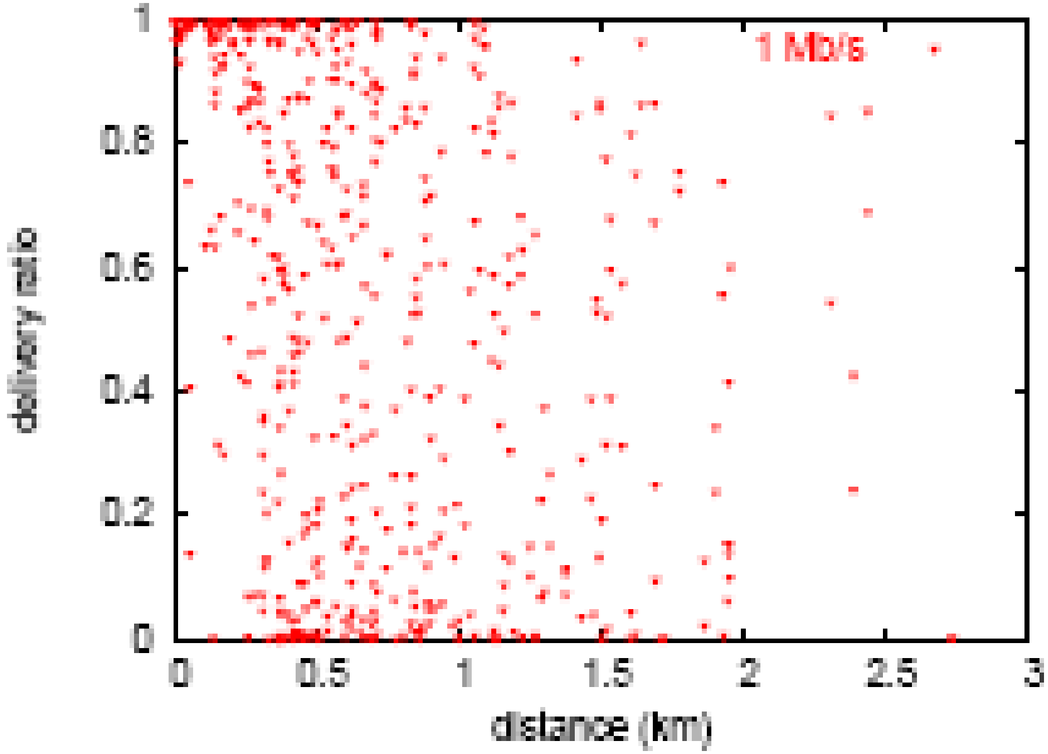




SNR versus distance

Delivery ratio versus distance

Unpredictable Channel Behavior



- Most links have *intermittent* loss rates
- The SNR and the distance are not good predictors of delivery probability

The Notion of a Link No Longer Exists

- A link is usually characterized by its bandwidth, latency, packet loss ratio and patterns.
- In wireless environments, most links have *intermittant* loss rates, and the delivery ratio has *little correlation* with the SNR or the distance.
- This is rooted in the fact that the wireless medium is a shared medium, and the sharing range is determined by
  - Each station's transmit power and carrier sense threshold
  - Intra-flow and inter-flow interference (determined in turn by the node distribution and the traffic distribution)
  - Multi-path fading, small-scale fading, shadowing
  - Temperature and humidity variation
  - Existence of objects or obstacles

The Notion of a Link No Longer Exists

- All the definitive metrics that characterize a link are no longer well defined for a wireless link.
- How does this affect higher-layer protocols?
  - A shortest-hop route consisting of long links give poor throughput.
  - A legacy routing protocol running on top of such wireless links may never converge, as re-route may constantly be triggered by false link breakage.

Course Topics

- We aim to take a *bottom-up* approach and tackle issues that work toward a better *characterization* of wireless links and its implication for higher-layer protocol design and optimization.
  - (1) Identify control knobs in MAC/PHY layers with which the network capacity can be optimized.
  - (2) Learn modeling methodologies for characterizing data transmission activities.
  - (3) Design and implement modular transparent device driver that exposes PHY/MAC attributes for cross layer optimization.
  - (4) Use of wireless mesh networks and vehicular ad-hoc networks as case studies.

Tuning PHY/MAC Control Knobs for Capacity Optimization

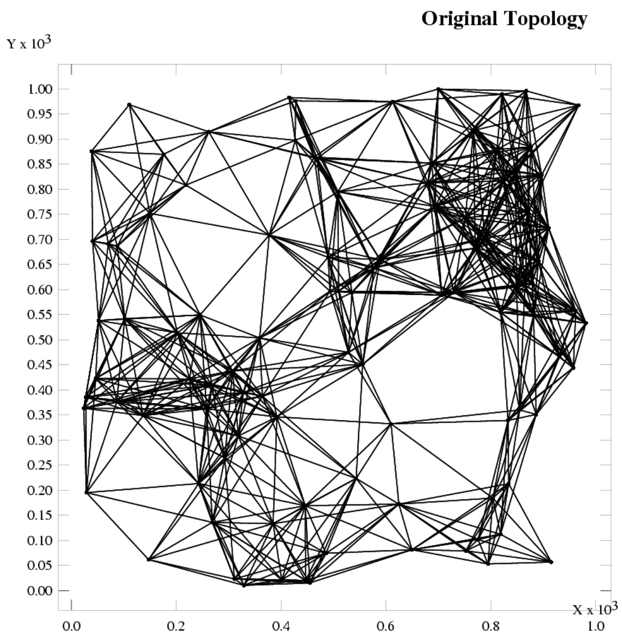
Control Knobs in PHY/MAC Layers

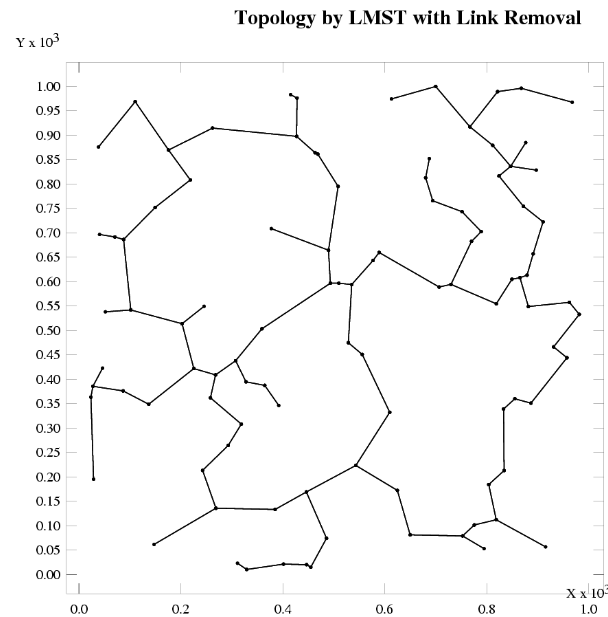
- To *mitigate interference, increase spatial reuse,* and *maximize the network capacity*, there are several control knobs:
  - Transmit power → power control
  - Carrier sense threshold → CS threshold tuning
  - Spatial and temporal domain in which a node transmits → scheduling
  - Channel diversity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

We seek a fundamental understanding of how, and to what extent, controlling these attributes impacts the capacity performance.

Power/Topology Control

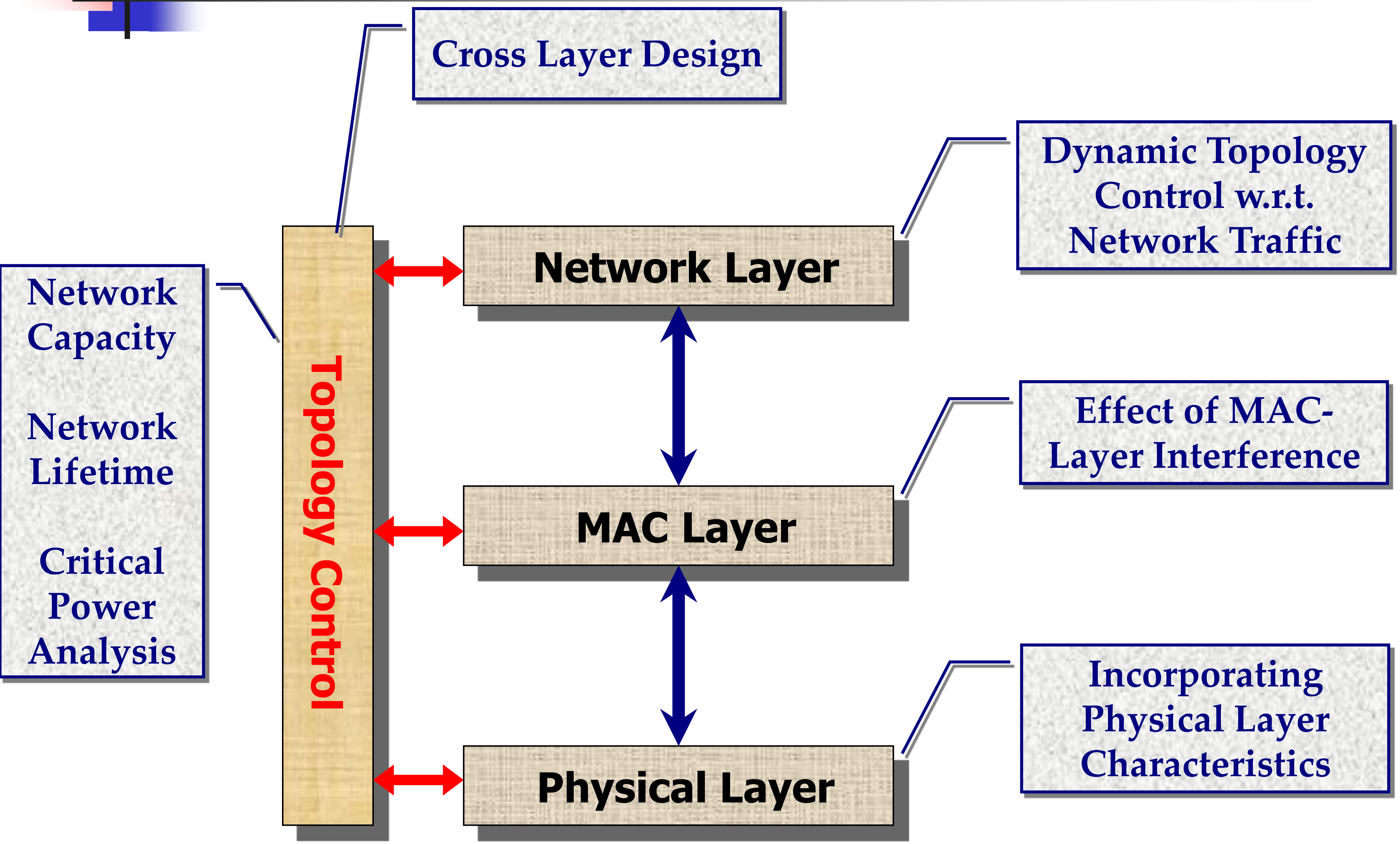
- **Power/Topology Control**: Instead of transmitting with the maximal power, each node collaboratively reduces its transmission power to defines the network topology





- Ning Li, Jennifer C. Hou and Lui Sha, "Design and analysis of a MST-based distributed topology control algorithm for wireless ad-hoc networks," *IEEE Trans. on Wireless Communications*, Vol. 4, No. 3, pp. 1195--1207, May 2005.
- Ning Li and Jennifer C. Hou, "Localized topology control algorithms for heterogeneous wireless networks" *IEEE/ACM Trans. on Networking,* Vol. 13, No. 6, pp. 1313--1324, December 2005.

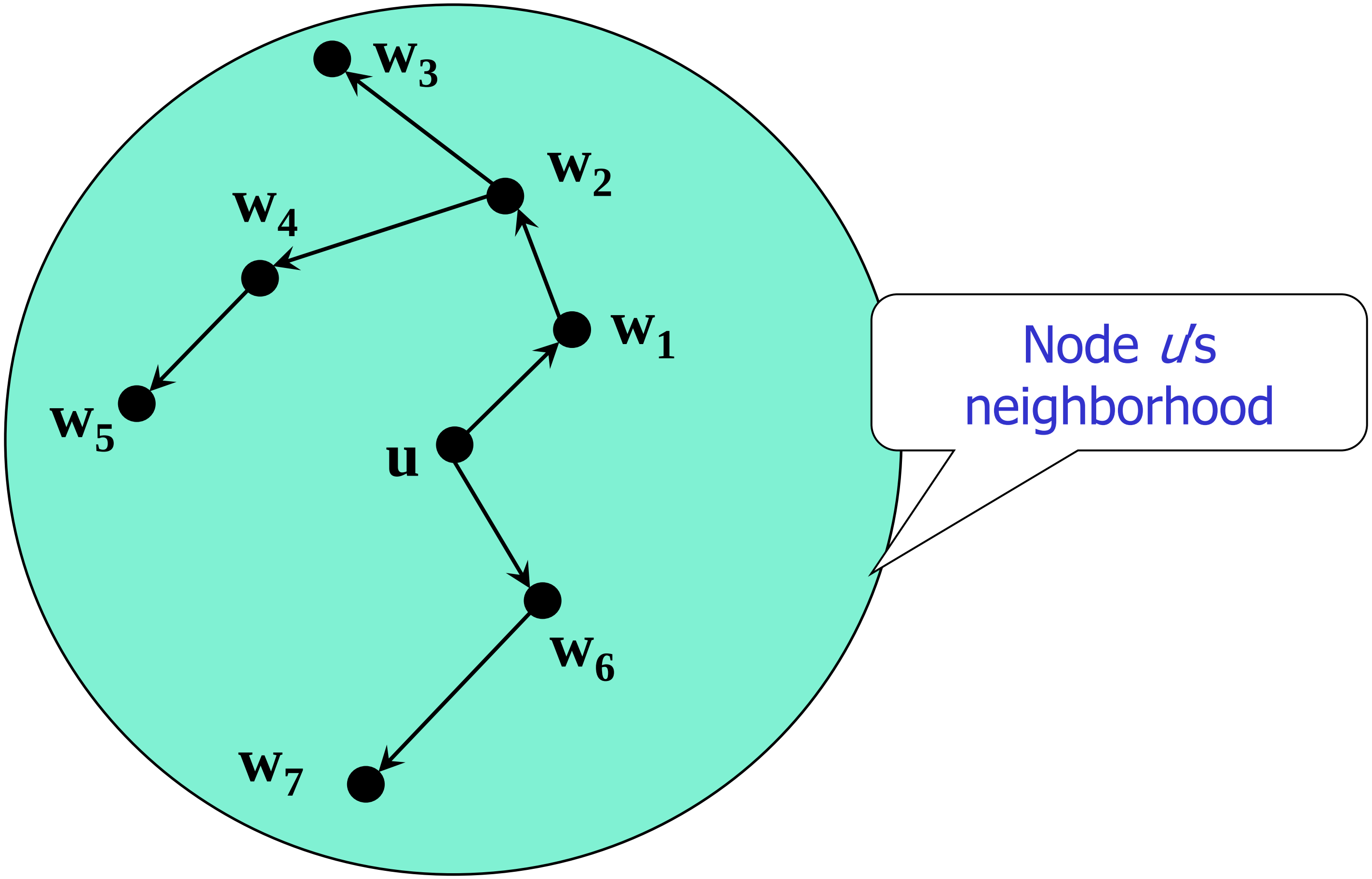
Topology Control – Cross Layer Design View



Problem Formulation

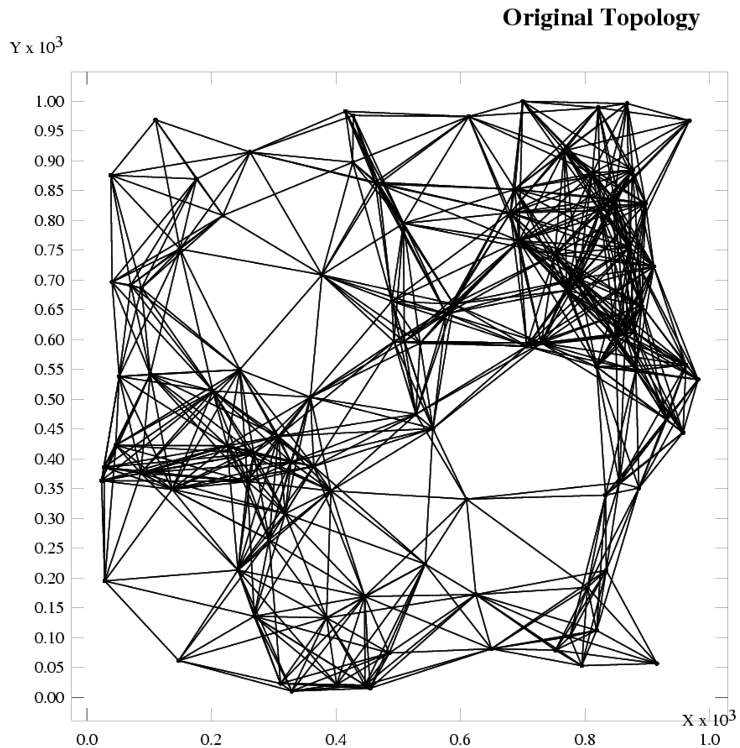
- **Objective**: To reduce power consumption, mitigate MAC interference, increase spatial reuse, while preserving network connectivity
- **Requirement:** The algorithm/protocol should rely only on local information
- **Input**: A set of wireless nodes *in the view of a node* in the 2/3-D plane
- **Output**: The transmission power (range) for each node to form the appropriate neighbor relation

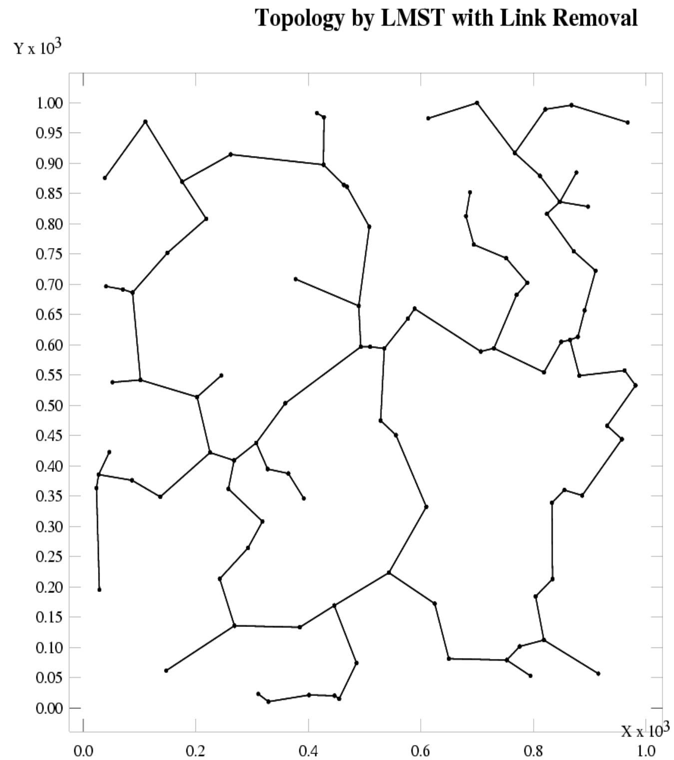
Local Minimum Spanning Tree Algorithm



- Node *u* only retains w_1 and w_6 as its neighbors in the final topology.

Properties of LMST

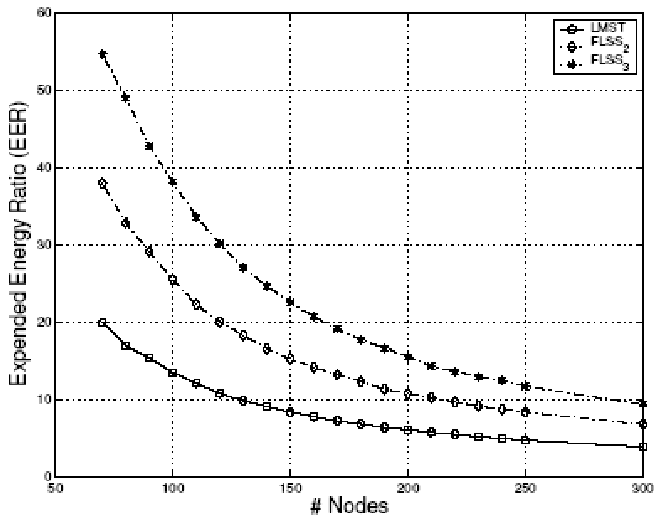




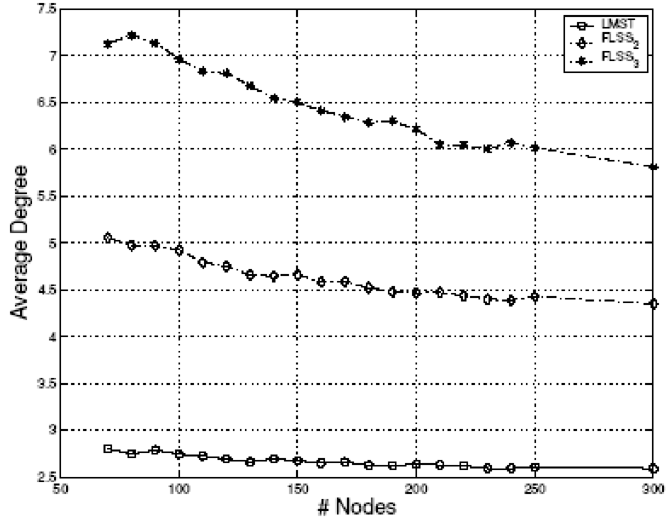
- First localized topology control algorithm!
- Preserves connectivity.
- After removal of asymmetric links, all links are bi-directional and the connectivity is still preserved.
- The (logical) degree of any node is bounded by 6.

Power Control for VANETs

- We have also devised fault-tolerant topology control algorithms, $FLSS_k$, to preserve *k*-connectivity.
- LMST and its variations can be deployed in the in-car wireless devices to derive (on the fly) wireless topology of adequate density and route redundancy.
- Reliable and delay-bounded *k*-hop broadcast/geocast (required in security applications) can be developed on power-controlled topologies
- Ning Li and Jennifer C. Hou, ``Localized fault-tolerant topology control in wireless ad hoc networks'' *IEEE Trans. on Parallel and Distributed Systems*, special issue on *Localized communication and topology protocols for ad hoc networks*, Vol. 17, No. 4, pp. 307--320, April 2006.



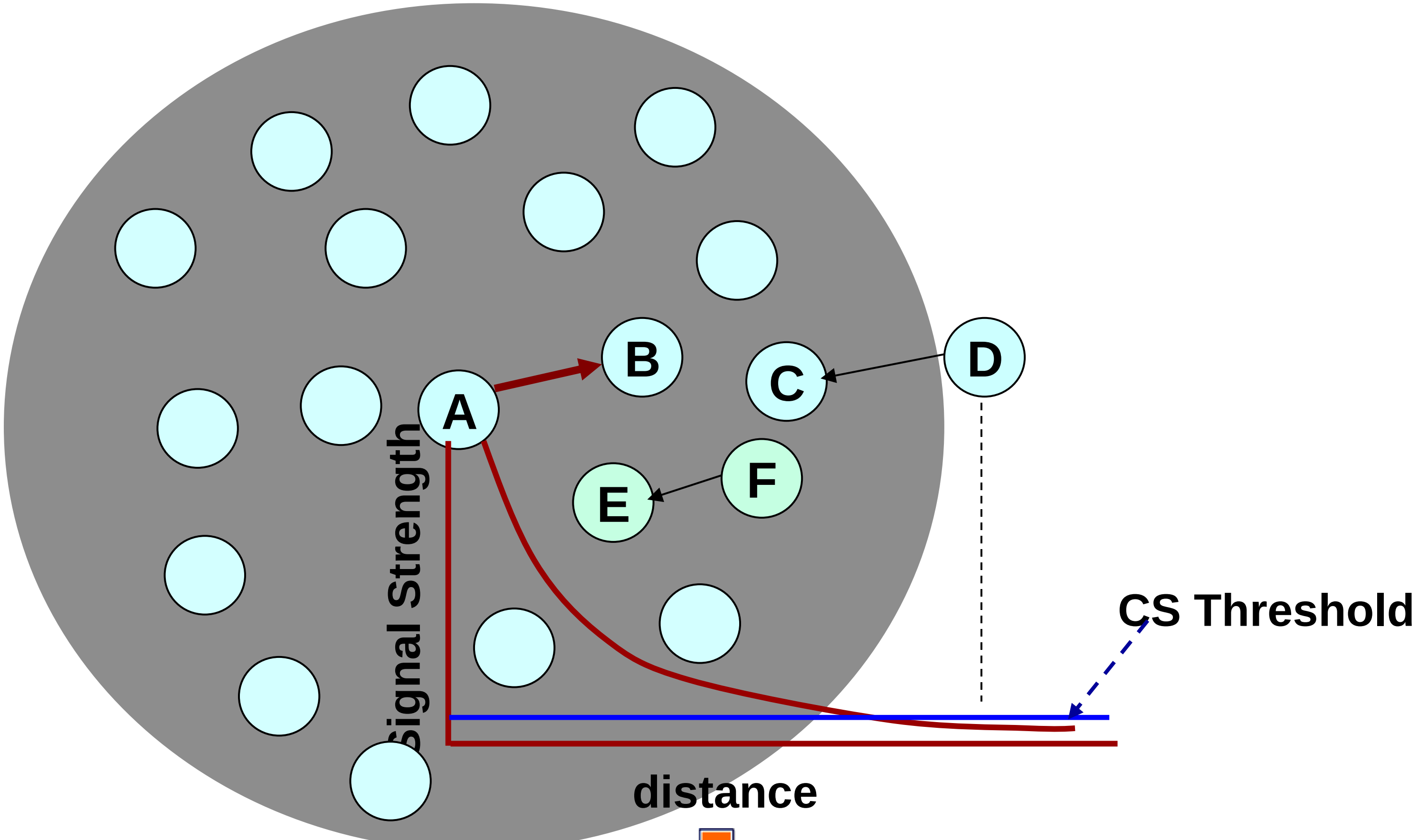
(d) EER.



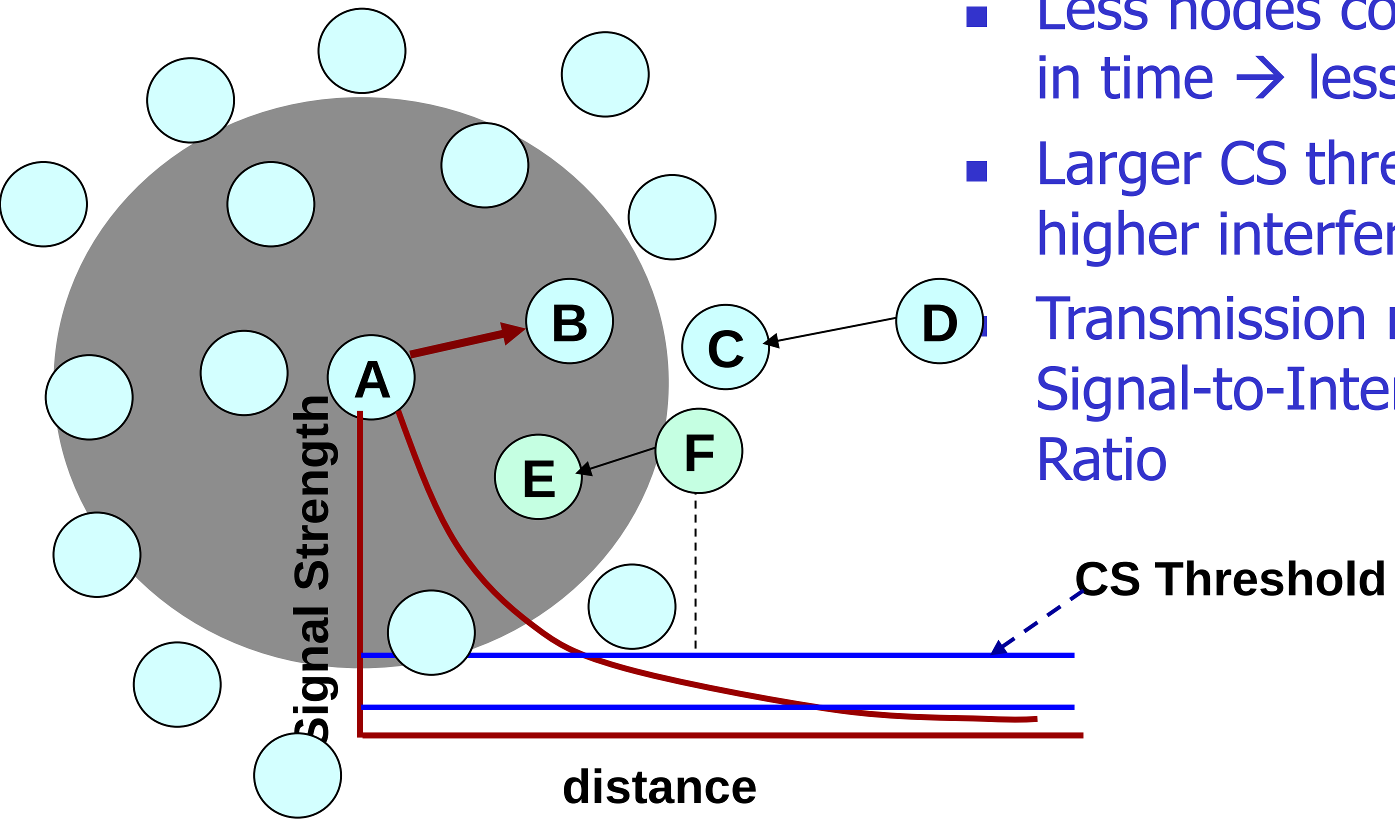
(c) Average degree.

Spatial Reuse Through Controlling CS Threshold

- The “contending area” can also be adapted through tuning
  - the carrier-sensing threshold



How CS Threshold Controls Contending Area



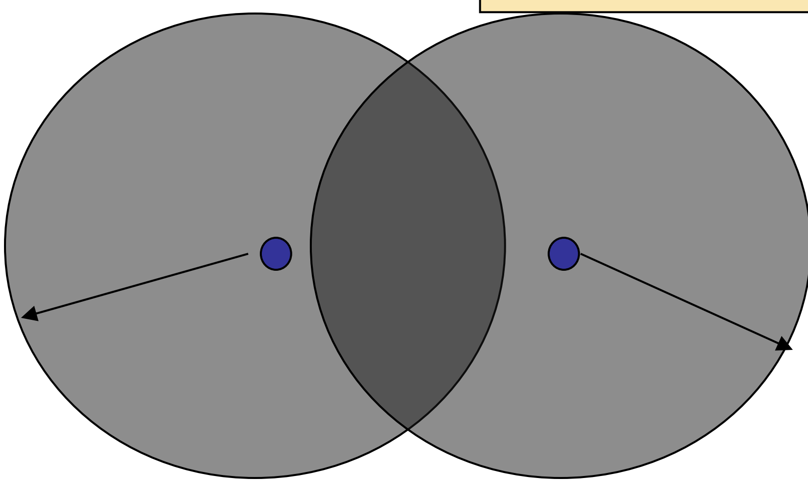
- Larger CS threshold leads to smaller contending area
- Less nodes compete the channel in time → less collisions
- Larger CS threshold also leads to higher interference
- Transmission rate depends on Signal-to-Interference-Noise Ratio

Benefits of Smaller Contending Area

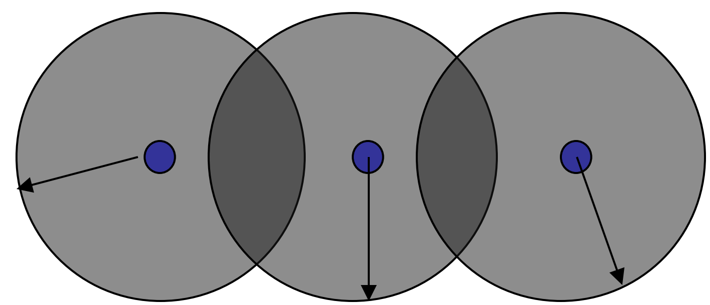
- Reduced MAC overhead

  → Better utilization of each communication link
- More spatial reuse
- At the cost of higher interference level and lower transmission rate

What is the optimal CS Threshold?
How does it relate to the transmit power?



High rate links



Low rate links

Tuning Transmit Power or Carrier Sense Threshold

- One can increase the level of spatial reuse by either reducing the transmit power or increasing the carrier sense threshold ➔
  - Is there a relation between the transmit power and the carrier sense threshold?
  - Does increasing the transmit power have the same effect of increasing the carrier sense threshold?

Network Capacity as a Function of Transmit Power and Carrier Sense Threshold

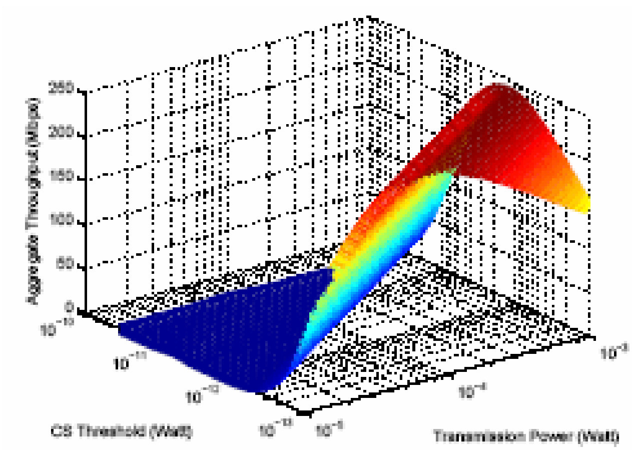
Increasing Fu

Constants

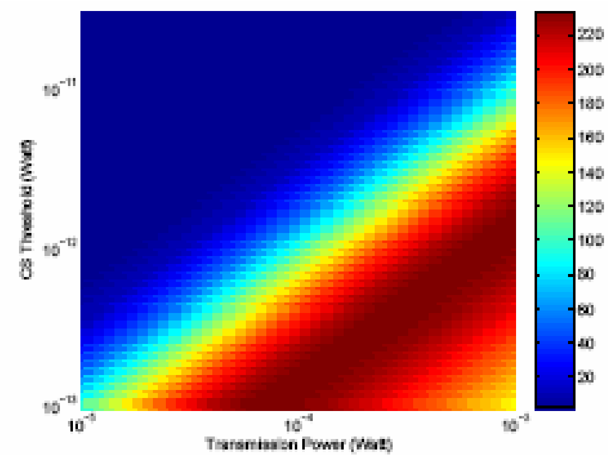
D

$$\Gamma_n = C_0 \cdot \left(\frac{T_{CS}}{P_{Tx}}\right)^{\frac{2}{\theta}} \cdot \log_2\left(1 + f\left(C_1 \cdot \left(\frac{P_{Tx}}{T_{CS}}\right)^{\frac{1}{\theta}}\right)\right)$$

Spatial Reuse | **Link Capacity**



(a) Network capacity as a function of P_{tx} and T_{cs}



(b) Optimal ratio between CS Threshold and Power

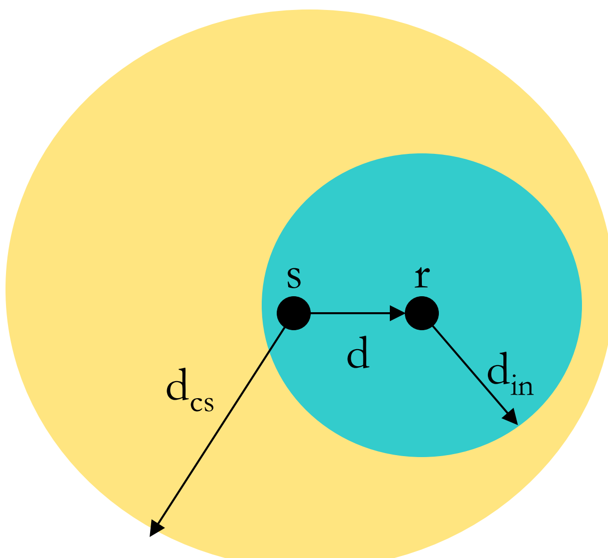
Determination of Optimal Carrier Sense Threshold

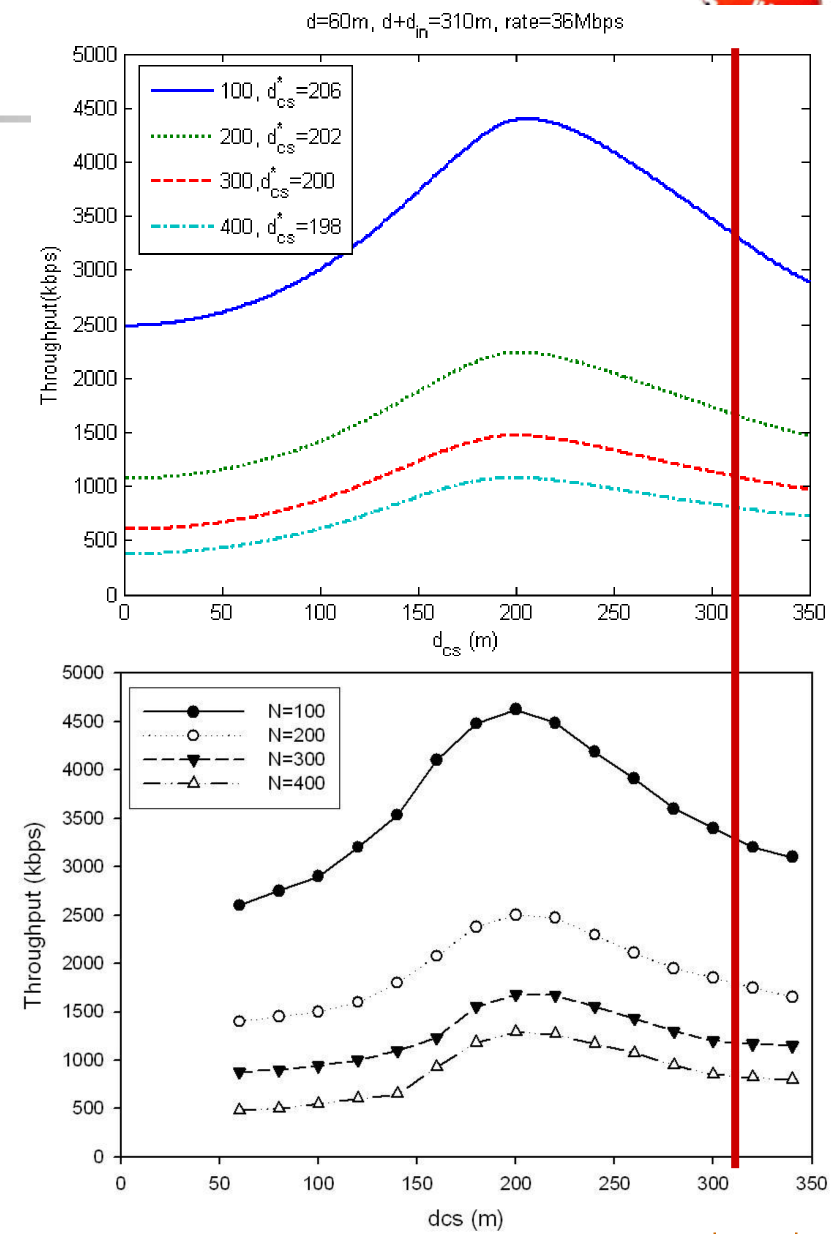
- When the transmit power decreases or the carrier sense threshold increases, the SINR decreases as a result of smaller received signal and the increased interference level.
  - Can the tradeoff between the increased level of spatial reuse and the decreased data rate each node can sustain be quantified?

- Kyung-Joon Park, LaeYoung Kim, Jennifer C. Hou, and Tamer Baser, ``Distributed control of physical carrier sense in CSMA/CA wireless networks," *IEEE Journal on Selected Areas in Communications (JSAC),* to appear.

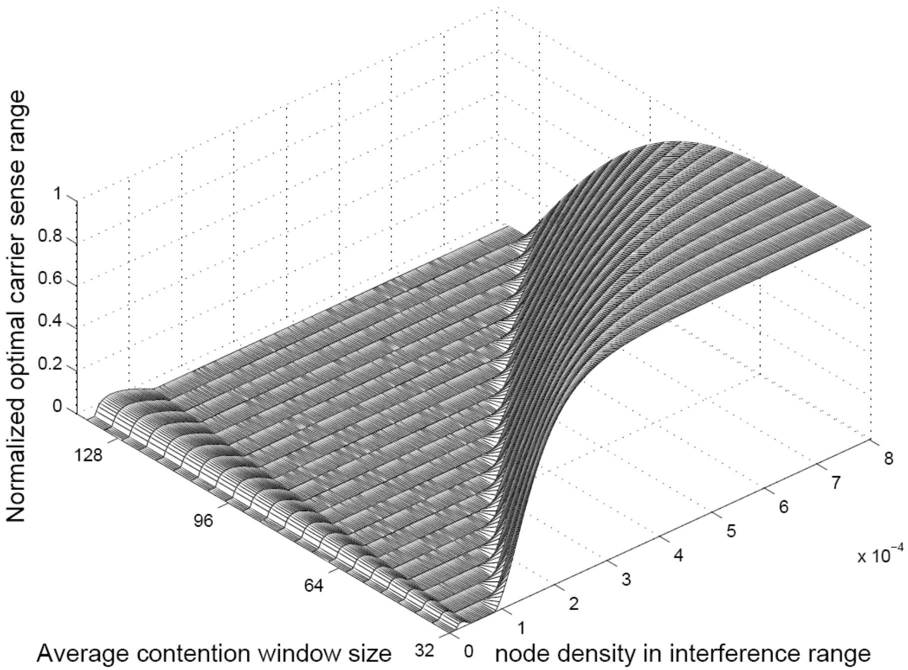
Effect of Carrier Sense

- When $d_{cs} > d + d_{in}$, the per-node throughput S decreases with the increase of d_{cs}
- The optimal d_{cs}^* exists in [0, $d + d_{in}$]

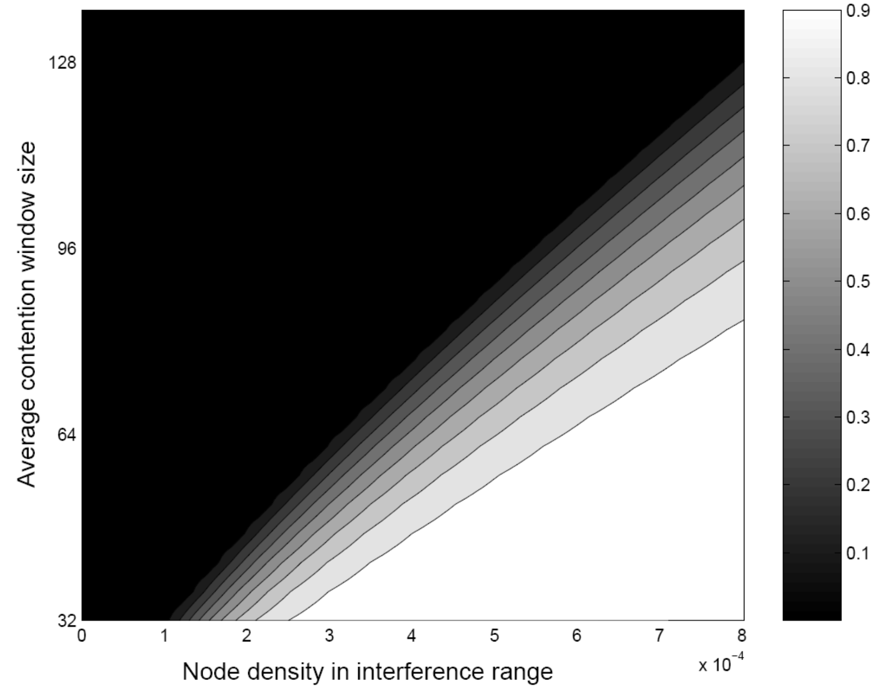




Normalized X^* as function of node density and contention window size



(a) Normalized optimal carrier sense range



(b) Contour plot of normalized optimal carrier sense range

Routing Metrics

- Routing protocols based on the hop count often choose long, lossy links that give low throughput.
- Routing metrics that are more sophisticated than the hop count need to be used to locate paths with high throughput and low loss rates.

  ➔ This boils down to the issue of how to exploit MAC/PHY characteristics to better quantify the quality of a route.

Example Routing Metric

- Estimated Transmission Time (ETT) metric.
  - ETT predicts the total amount of time it would take to send a data packet along a route.
  - Each mesh node sends periodic broadcasts at each available 802.11b bit-rate.
  - *ETT for a given link* = expected time to successfully send a 1500-byte packet at that link's highest-throughput bit-rate, including the time for the number of retransmissions predicted by the measured delivery probabilities.

Highest-throughput bit-rate = *bit-rate with highest (delivery prob. X bit-rate)*

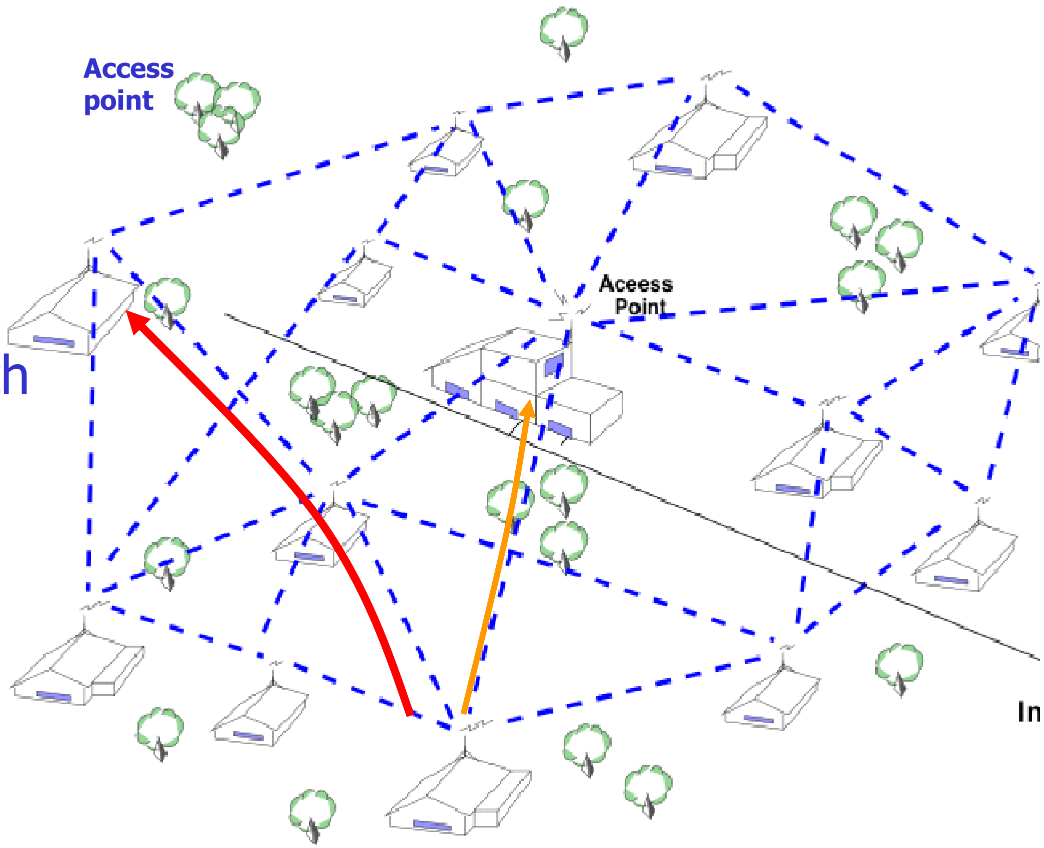
  - *ETT for a route* = sum of ETTs for each of the route's links

$$t = \frac{1}{\sum_i \frac{1}{t_i}}$$

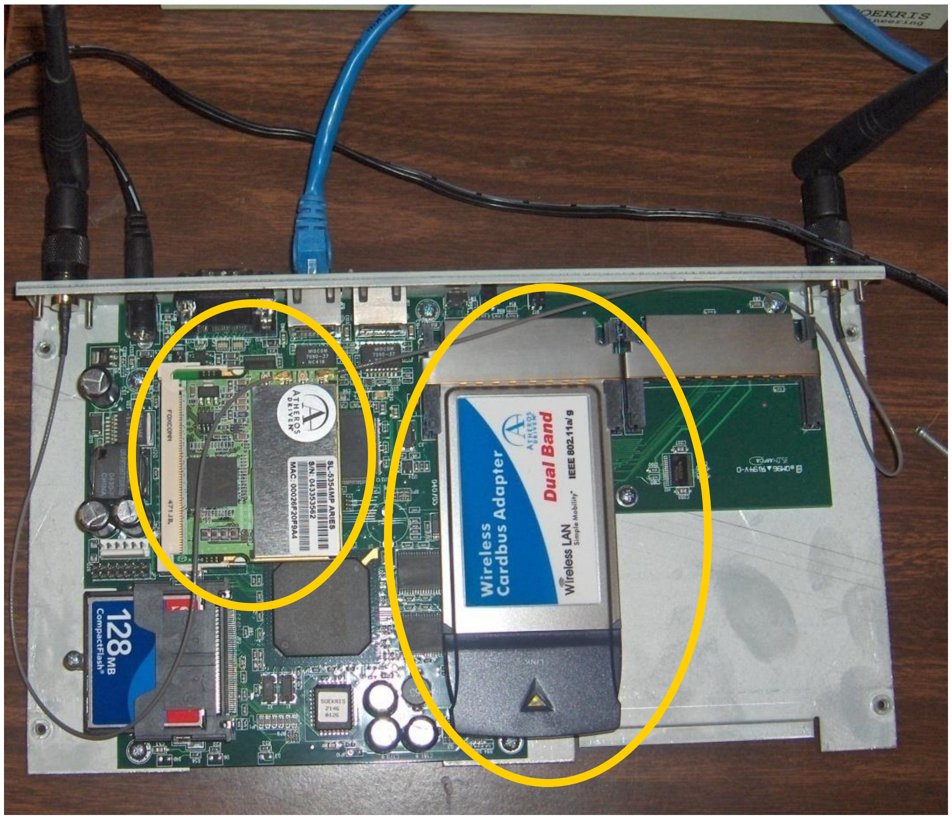
t : e2e throughput
t_i : throughput of hops

Multi-radio, Multi-Path Routing

- There may be multiple Internet gateways.
- The routing decision is complicated by one more dimension → which Internet gateway to connect.
- Devices can be equipped with multiple interfaces, each of which can be assigned different channels.



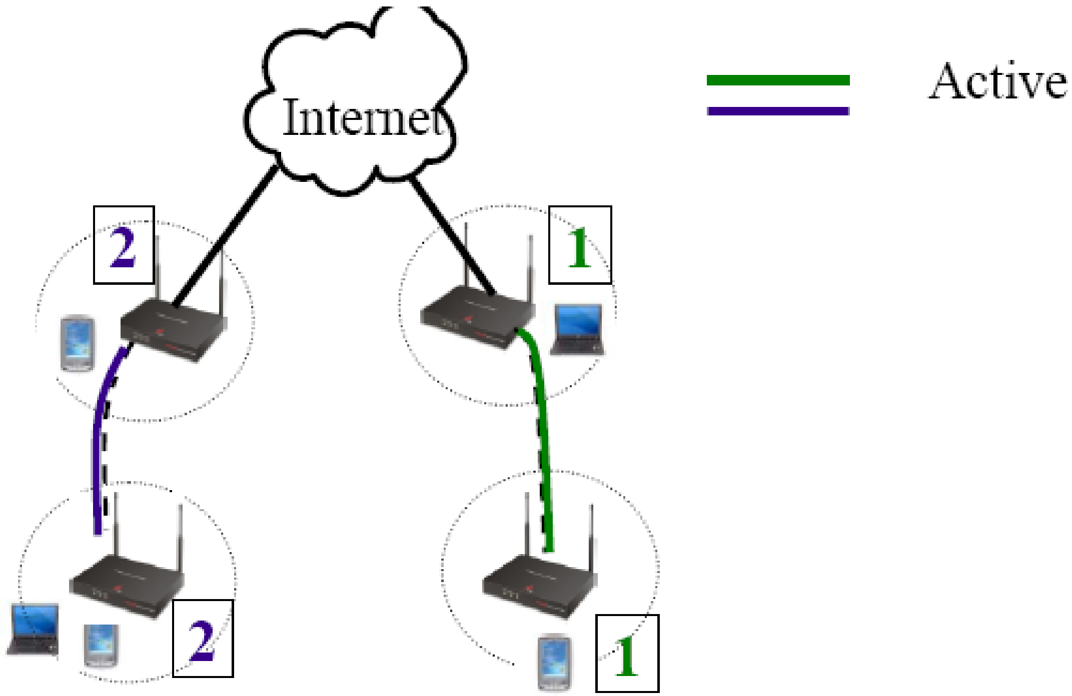
Multi-radio, Multi-path Routing



Soekris net4521 device

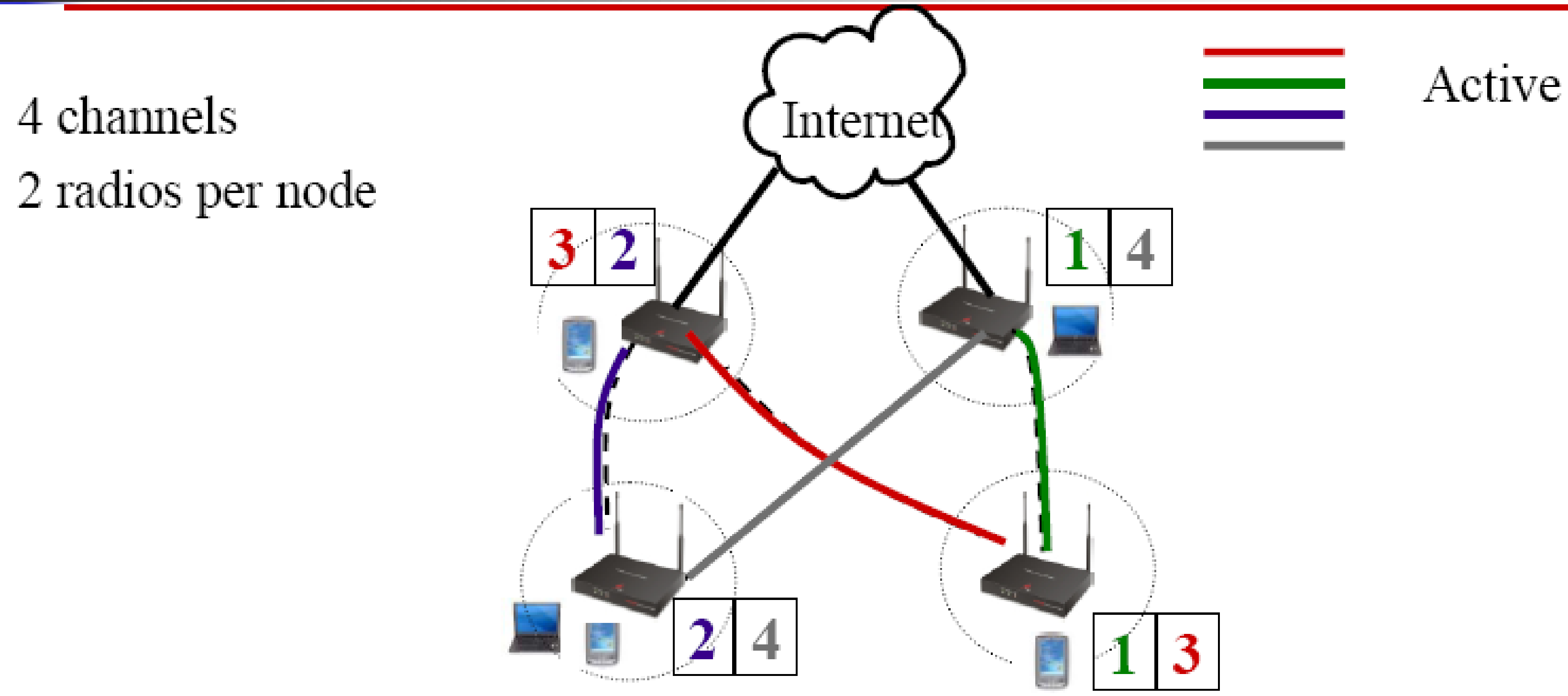
- IEEE 802.11 has multiple channels
  - 12 in IEEE 802.11a, 3 non-overlapping in IEEE 802.11b
- The routing decision can be further complicated by assigning different channels to interfaces and finding high-throughput routes on different channels.

Benefit of Using Single Interface and Multiple Channels



- Multiple channels can be used to mitigate interference and enable simultaneous transmissions.
- When used with single radio nodes network partition may result.

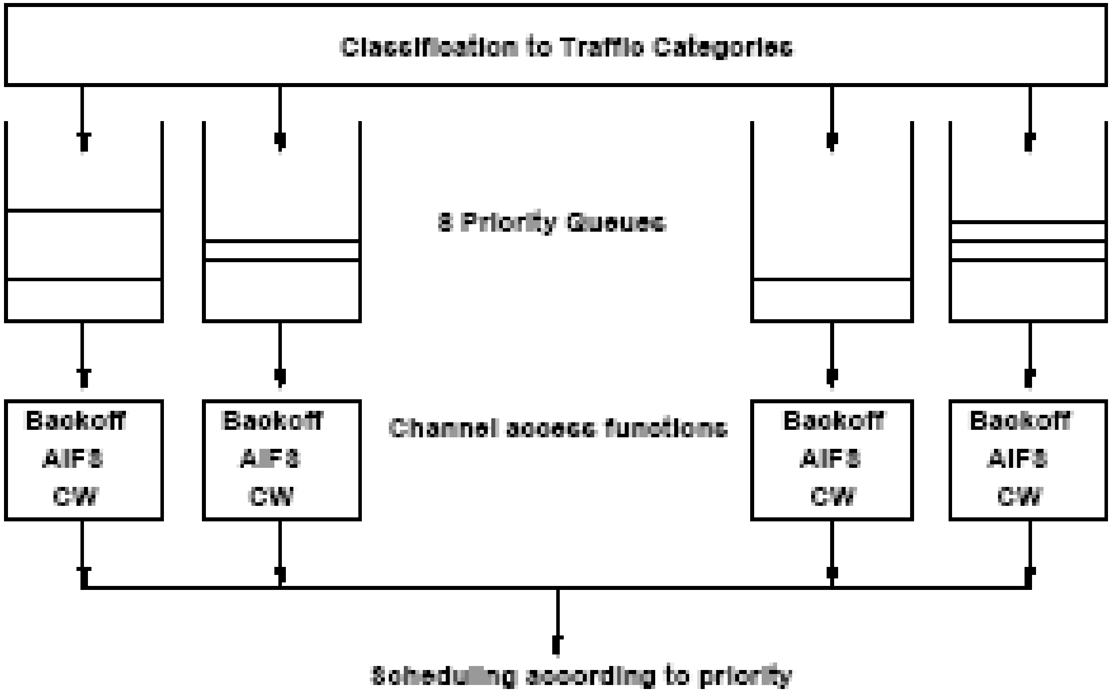
Benefit of Using Multiple Interfaces and Multiple Channels



- With sufficient radios and sufficient channels, interference can be completely eliminated.
- Channel assignment becomes crucial

QoS Provisioning in IEEE 802.11e

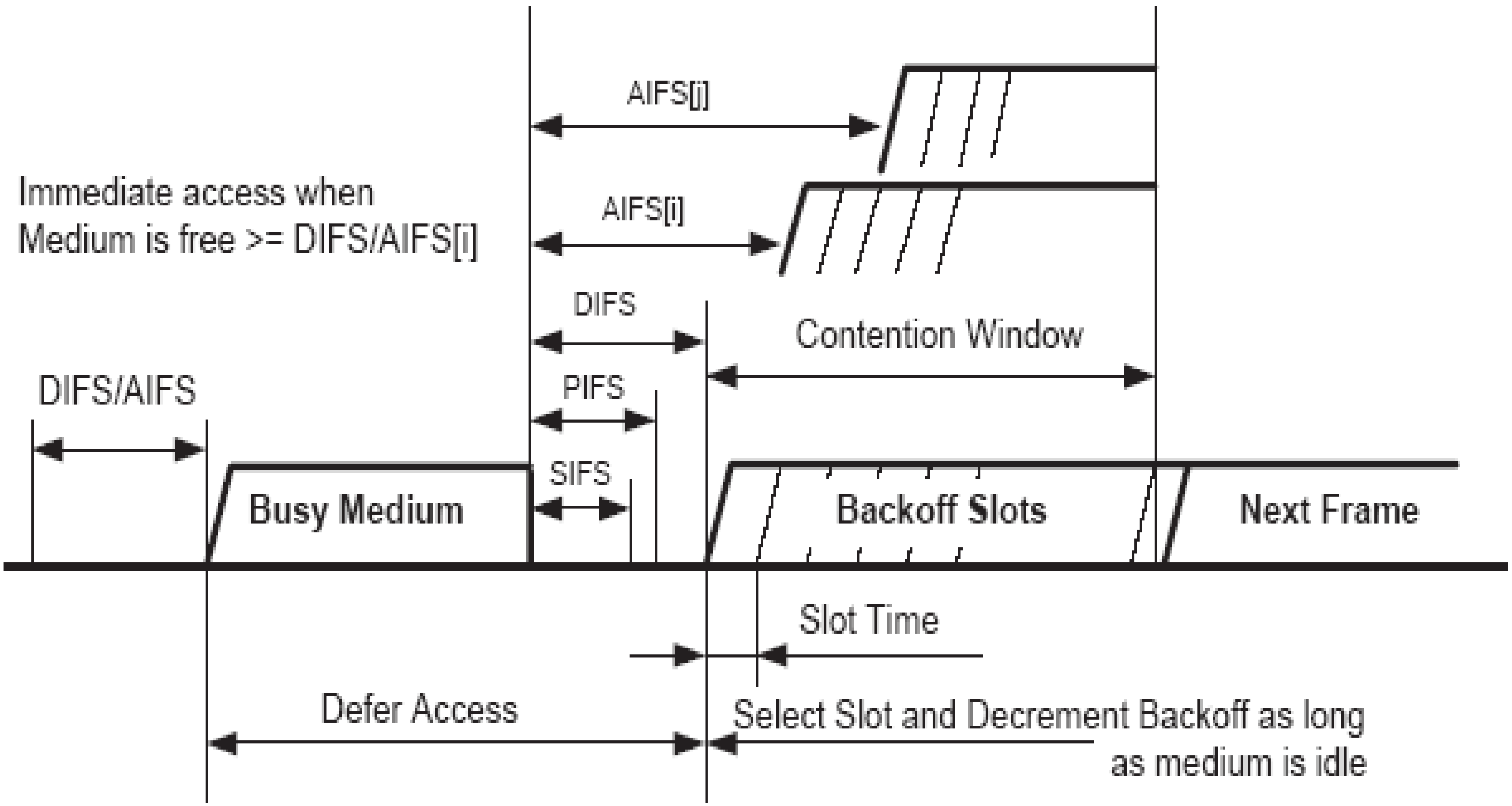
- QoS provisioning
  - A total of eight user priority levels are defined. Each priority is mapped to an access category (AC), which corresponds to one of the four transmit queues.
  - Each queue is served by an independent channel access function that specifies the IFS value to be used for sensing the idle medium, and the contention window parameters (such as CWmin and CWmax).



(b) Implementation model

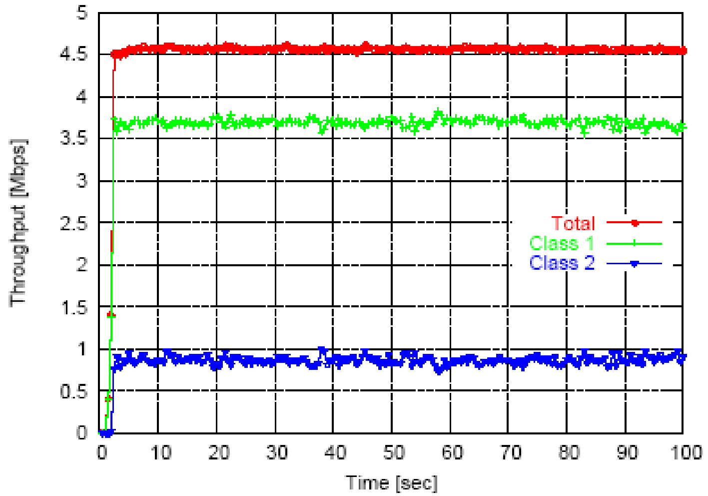
- Data transmission from high-priority flows will be favored by assigning appropriate IFS values and contention window parameters to increase their probability of gaining medium access.

Inter Frame Spacing

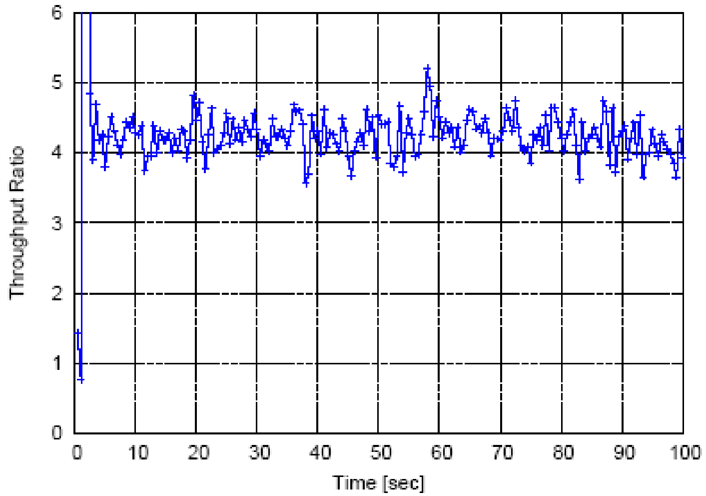


Our Work on QoS Provisioning

- Through analytical modeling, we show that service differentiation (i.e., proportional throughput ratios among different classes) can be achieved, while maximizing the total channel utilization.



(a) Throughput



(b) Throughput ratio

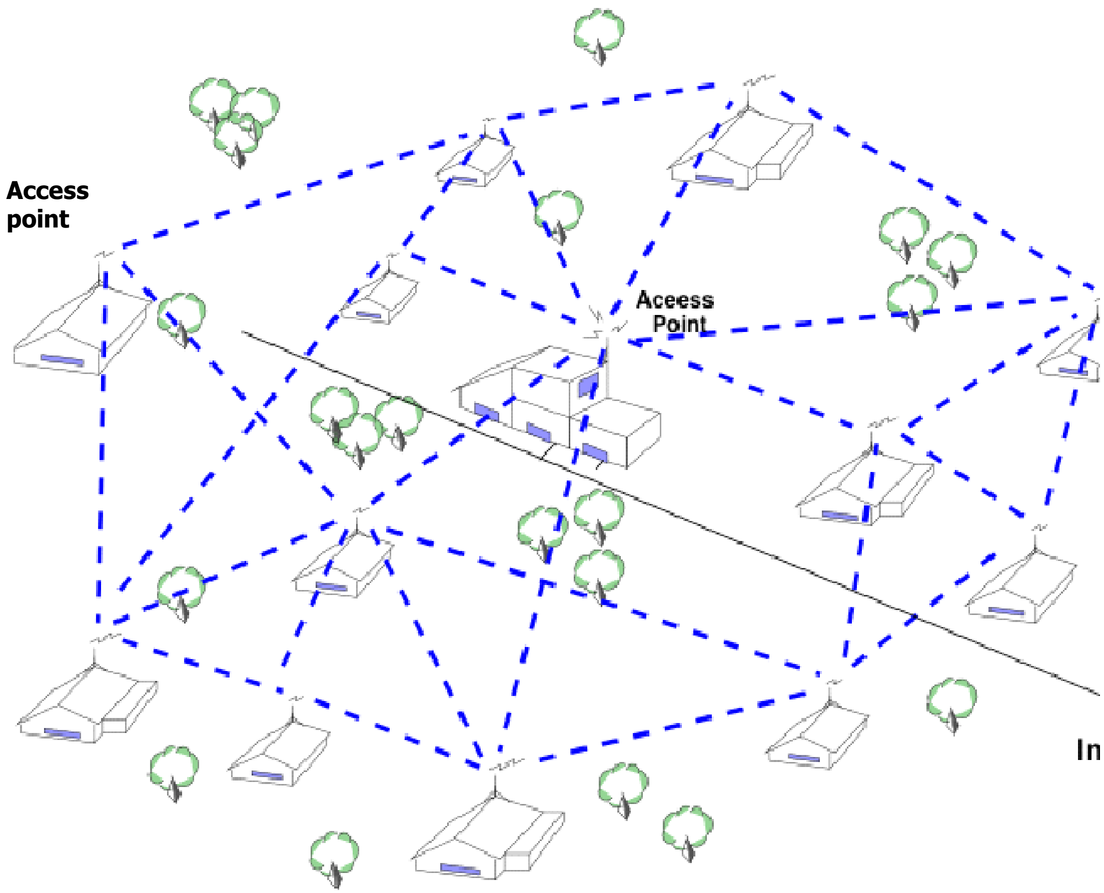
Performance Modeling of MAC Activities in Multi-hop Wireless Networks

Performance Modeling

- We will discuss how to characterize the PHY/MAC data transmission activities with the use of probability, renewal theory, continuous-/discrete-time Markov chains.
  - Single-hop networks (WLANs)
  - Multi-hop wireless networks
- We will also discuss asymptotic capacity analysis (i.e., how does the network behave with respect to connectivity, critical power consumption, and lifetime, if the number of nodes approaches infinity)
  - With/without infrastructure
  - With/without multiple channels
  - With/without mobility

Case Study I: Wireless Mesh Networks

Wireless Mesh Networks



- Is targeted to solve the well-known last-mile problem for broadband access.
- Most of the nodes are stationary.
- Only a fraction of nodes have direct access, and serve as gateway to the Internet.
- Nodes serve as relays forwarding traffic and maintain network-wide Internet connectivity.

Current State of Art

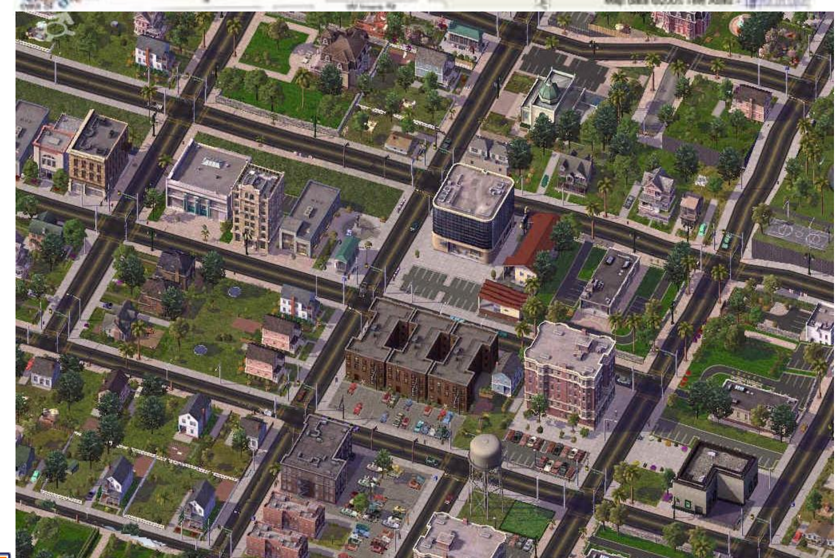
- Wi-Fi clouds have been planned for large cities
  - Bay Area Wireless User Group (BAWUG) http://www.bawug.org
  - Champaign-Urbana Community Wireless Nework http://cuwireless.net
  - MIT Roofnet http://pdos..csail.mit.edu/roofnet/doku.php
  - Seattle Wireless http://www.seattlewireless.net
  - Wireless Leiden in Sweden http://www.wirelessleiden.nl
- Chaska, Minnesota
  - One of 29 Wi-Fi clouds in U.S.
  - 18K people, 16 square miles
  - Built in a few weeks at the cost of $600K
  - Service charge is $15.99 / month

Urbana Champaign Wireless Community Networks

- We are currently working with Champaign-Urbana Wireless Community Network to deploy a 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.

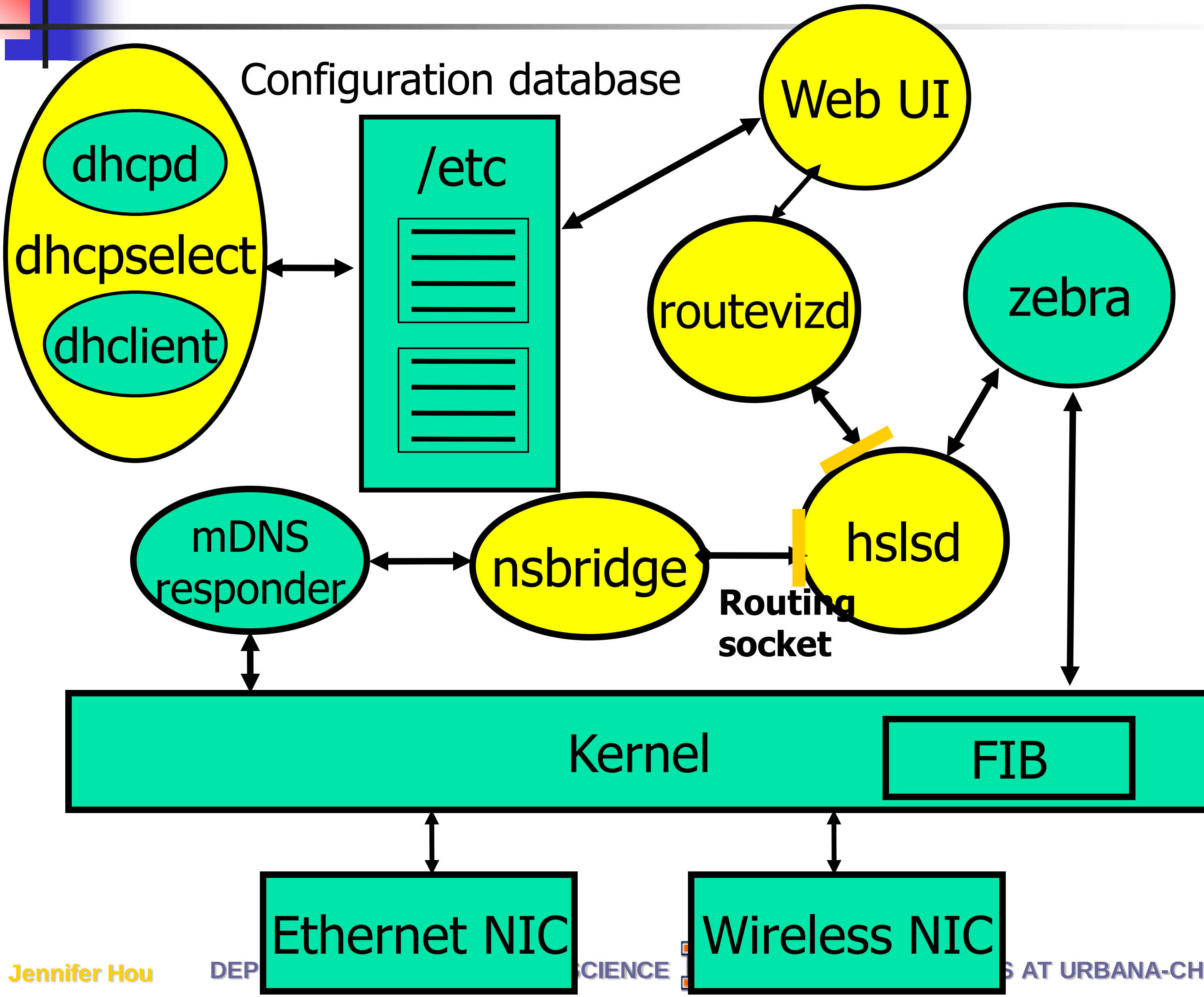


**Supported by NSF Computing Research Infrastructure program.*

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

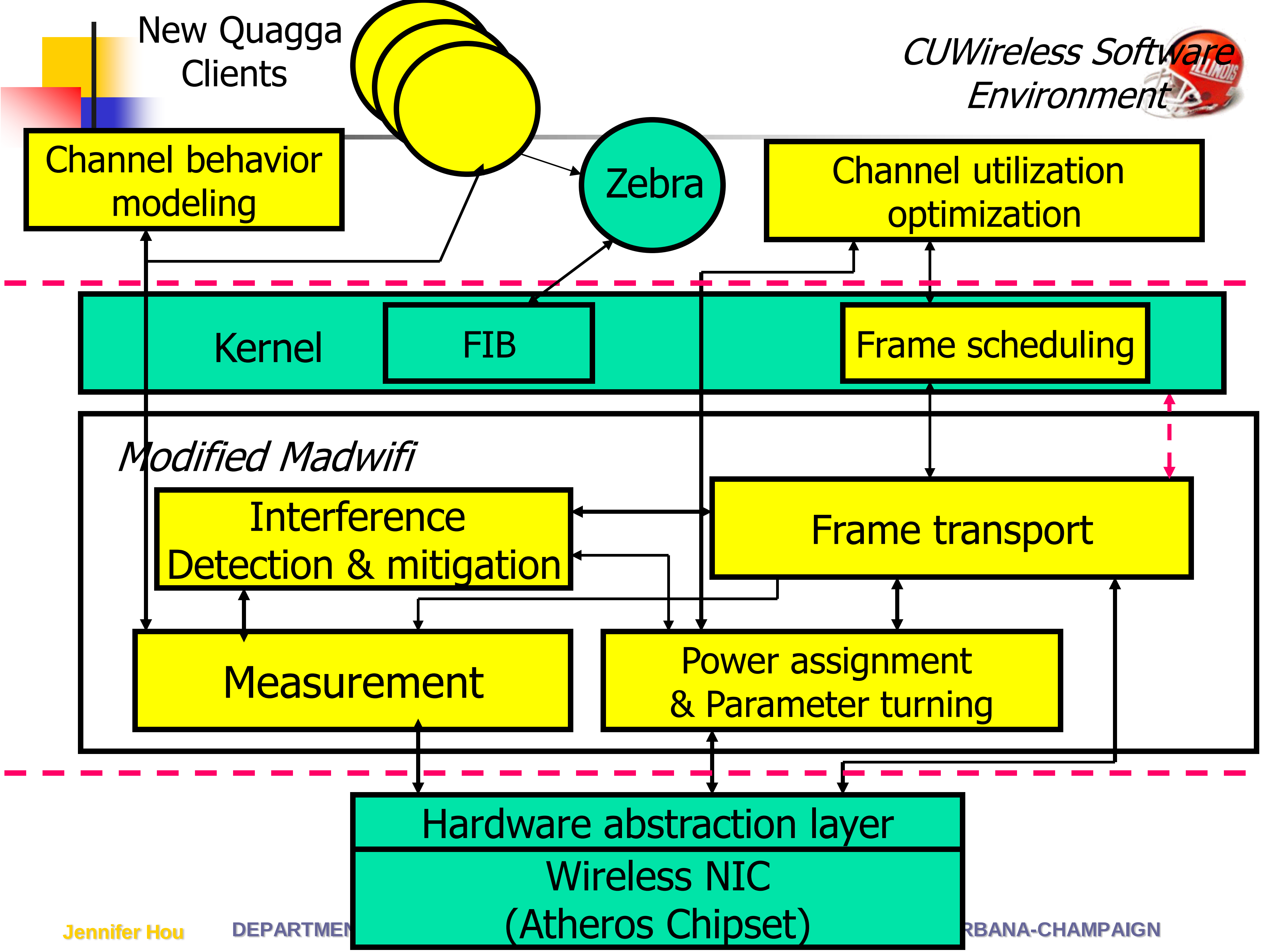


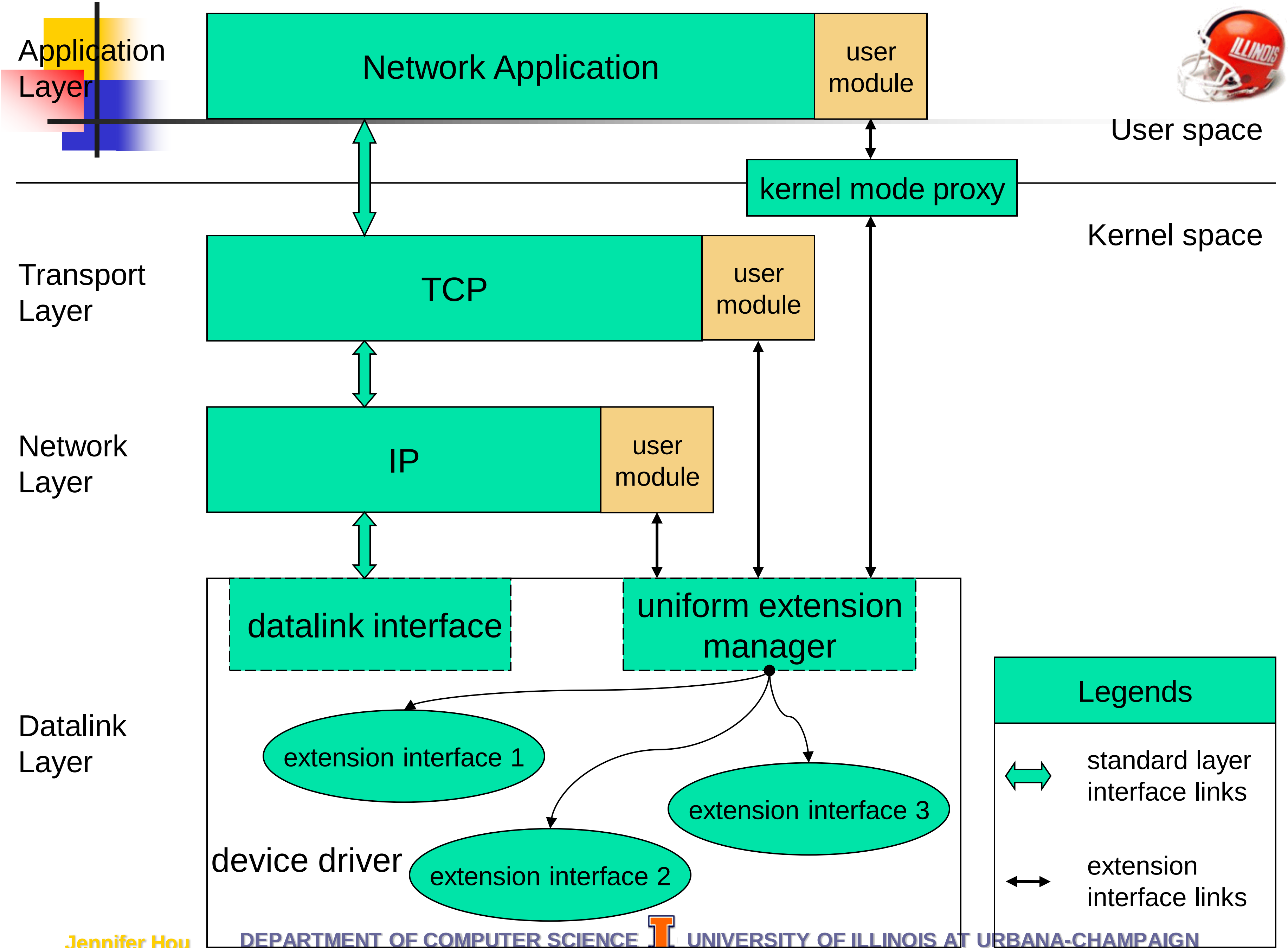
Design/Implementation of Driver Support

Rationale for Transparent Device Driver

- In order to optimize network performance, PHY/MAC attributes should be exported to higher layer protocols in order to
  - enable cross layer design and optimization,
  - promote spatial reuse through tuning of PHY/MAC parameters,
  - allow implementation of new MAC functions other than those provided by IEEE 802.11.
- Because new MAC functions may be in conflict with existing ones that have been implemented in the firmware of most IEEE 802.11 interface cards, there should be mechanisms for disabling selected MAC functionalities in the firmware and/or setting various parameters that are originally controlled by the firmware.

CUWireless Software Environment




Application Layer
Network Application
user module
User space
kernel mode proxy
Kernel space
Transport Layer
TCP
user module
Network Layer
IP
user module
Datalink Layer
datalink interface
uniform extension manager
extension interface 1
extension interface 3
extension interface 2
device driver
Legends
standard layer interface links
extension interface links

Internals of TDD

- An extension interface
  - registers (unregisters) itself with the extension manager via *RegisterExtInterface() (UnregisterExtInterface()).*
  - registers (unregisters) its set/get handlers with the extension manager via *RegisterSetHandler() (UnregisterSetHandler()).*
- A cross-layer module
  - finds whether or not an extension interface exists via *FindExtension().*
  - sets/gets the value of certain PHY/MAC parameters exported by an extension interface via *GetExtParam()* and *SetExtParam().*
- The uniform extension manager maintains
  - (i) the definition record of all the supported events in an event definition tree; and
  - (ii) the list of subscribers of each event.
- An extension interface generates and delivers an event to the uniform extension manager by calling *TriggerEvent().*
- A cross-layer control module (un-)subscribes to an event with a callback function by calling *AddEventHandler()* (*RemoveEventHandler()).*

APIs Exported by Extension Manager

Category	Function name	Function description
Extension management	RegisterExtInterface() UnregisterExtInterface()	Register/unregister an extension interface module.
	FindExtension()	Query whether an extension interface identified by a unique name or id exists. Return a handle to the interface if it exists.
Register parameter set/get handlers	RegisterSetHandler() UnregisterSetHandler()	Register or unregister a set handler to the uniform extension manager.
	RegisterGetHandler() UnregisterGetHandler()	Register or unregister a get handler to the uniform extension manager.
Access to extension parameters	GetExtParam()	Get the value of an extension parameter by invoking the registered get handler.
	SetExtParam()	Set the value of an extension parameter by invoking the registered set handler.
Event Subscription and delivery	TriggerEvent()	Generate an event and deliver it to the subscribers.
	AddEventHandler() RemoveEventHandler()	Subscribe to an event with a callback handler function.

Case Study II: Vehicular Ad-hoc Networks

Leveraging WMNs for VANETs (Infrastructure Wise)

- The city-wide wireless mesh network CUWiN can be used to study
  - (i) how wireless coverage improves as the GW node (e.g., roadside gateway) density increases.
  - (ii) how a moving vehicle routes traffic through different roadside gateways without service disruption.
- Inexpensive wireless nodes can be installed in vehicles to
  - (i) empirically evaluate various security applications in vehicle-to-vehicle transmission.
  - (ii) empirically evaluate the data throughput that can be attained for commercial applications.

Vehicular Ad-Hoc Networks

- To mitigate the possibility of traffic accidents and highway congestion, safety and convenience applications using sensors and wireless technologies are currently being design/developed.
  - Stopped or slow vehicle advisor
  - Emergency electronic brake light
  - V2V post crash notification
  - Road feature notification
  - Cooperative violation warning
  - Parking availability notification
  - Service annoucement
- Wireless communication can also be used to create commercial opportunities by providing auto tele-informatics applications.
  - Real-time video relay
  - Everywhere Internet

Possible Research Topics in VANETs

- To ensure reliable and predictable broadcast/geocast (required in security applications), MAC-level interference/collision has to be mitigated ➔ the need for power control
  - Research in power control and carrier sense tuning can be readily applied by each vehicle.
  - The transparent device driver support can be readily used to realize power control, carrier sense tuning, and channel assignment.
- QoS provisioning research is required to provide prioritized services to safety, convenience, and commercial applications.
- Context-Assisted Routing that takes into account of road condition (road length, car density on the road, AP positions) is required.

Comments?