Cross-Layer Interactions and Optimizations in Wireless Networks

Catherine Rosenberg

Joint work with Vivek Mhatre (now at Intel, UK), Sunil Kulkarni (now at Google, USA), Jeongjoon Lee (now at LG, Korea), and Aravind Iyer (Purdue).

Outline

- Introduction: wireless vs. wireline
- Cross-layer integration: a necessity but also a challenge
- Examples in single hop networks
  - Cellular networks: inter-cell interference
  - WLAN: power saving mode
- Examples in multi hop networks
  - Let's first talk about MAC
  - Sensor networks: an address-light, integrated MAC and routing protocol
  - Sensor networks: optimal routing and link scheduling
  - Ad hoc networks: capacity
- Conclusions

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Wireless vs. Wireline Networks

- **Wireline systems**
  - Reliable channel and very high capacity
  - Core router: Gbps - Tbps
  - Requirement: **simplicity** and **scalability**
- **Wireless systems**
  - Limited natural resource (spectrum) ➔requirement: **spectrum efficiency**
  - **Shared channel** ➔ requires elaborate **MAC protocol**
  - Difficult channel:
    - **Channel attenuation**: wireless signal power is subject to path loss, location dependent shadowing, time-varying fading, all of which attenuate the signal
    - **Additive interference:** wireless signals can be decoded and received at acceptable error rates only if the signal-to-interference-and-noise ratio (SINR) is adequate
  - **Limited device capabilities** (often): Finite battery energy, possibly low processing power

Introduction

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Why Wireless Networking?

- *Ease of deployment* (often coupled with energy issues)
- Support of *mobility*
- *On-demand, seamless* connectivity between *individuals* and their *environment*
  - *On-demand:* connection should be available whenever there is a need for it
  - *Seamless:* connectivity should be maintained despite mobility and wireless channel variations
  - *Individuals:* are users equipped with wireless devices such as laptops, cell-phones or PDAs
  - *Environment:* includes homes, offices, manufacturing facilities, farms, hospitals, all possibly equipped with wireless-capable sensors and actuators

Introduction

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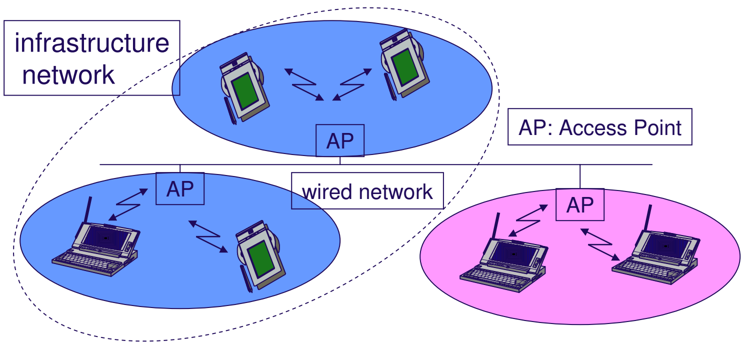
Introduction

Current Wireless Networks

- Single hop:
  - Cellular Networks: voice and data services, excellent coverage, great penetration
  - Wireless LANs: data services, Wireless LAN “hotspots” used in campuses, coffee shops, airports
  - Wireless PANs: wireless keyboard, mouse, headphones, etc



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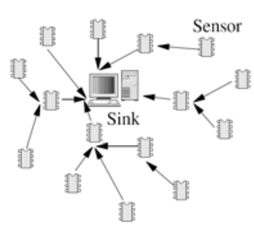
Introduction

Current Wireless Networks

- Multi-hop: distributed, no infrastructure
  - Sensor Networks:
    - Application specific networks of wireless nodes
    - Mainly deployed for distributed monitoring of a signal of interest
    - Objective is collaborative rather than individual
    - Many-to-one data flow
  - Ad Hoc Networks:
    - An ad-hoc network has no specific task except communication
    - Individual nodes have their own objectives
    - Any-to-any data flow



A Sensor Network

An Ad Hoc Network

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Cross-Layer Integration

Tension between Performance and Architecture

- Success of Internet is due to its architecture
  - Hierarchy of layers
  - Peer-to-peer protocols
  - Allows plug-and-play
  - Longevity
  - Important for proliferation of technology
- Performance: The short term vision
  - " Putting a link between layer A and layer B can improve performance by x%"
  - Consequences of this approach
    - Spaghetti code
    - Not modular
    - Not upgradeable
    - No longevity
    - High per unit cost: Value of a communication medium = Number of adoptees
- Architecture: The long term view
  - Mass production = Reduced cost over long term
- Tension between Performance and Architecture

This slide is courtesy of P.R. Kumar

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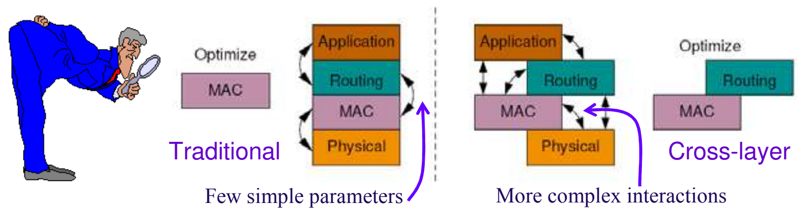
Cross-Layer Integration

Cross-layer Interactions and Integration

- Traditional (wired) network design follows *layering*; each layer optimized *separately*; no cross-layer integration
- Examples of cross-layer interactions in wireless:
  - Data-rate supported by a wireless link depends on interference (which depends on traffic at neighbors)
  - "Best" set of routes depends on current wireless link characteristics
- Cross-layer design can take *advantage* of these interactions
- Cross-layer design allows *integration* of layers; protocol functions can be *jointly* optimized



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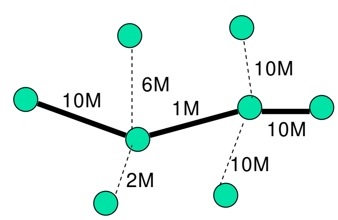
Cross-Layer Integration

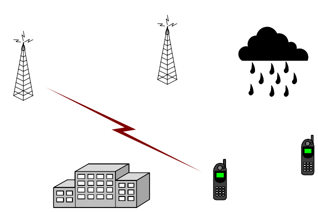
Wireless Networks: A More Complex Interaction Between Layers

Cross-layer solutions are necessary because of the difficulty in summarizing the lower layers

- *Wireline networks*:
  - Single value can be used to summarize the capacity of a link
  - This value can be used by higher layers (e.g., used by transport layer for congestion control or used for routing)



- *Wireless systems:*
  - Bandwidth/capacity no longer a fixed constant
  - Interference
  - Time-varying channel condition (e.g., mobility and fading)
  - No easy way for the higher layer to describe functioning of lower layers
- This affects routing, scheduling, congestion control, etc.



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Questions without Answers

- What are the consequences of cross-layer integration?
- What is the longevity of the solutions?
- What is the reusability of the solutions?

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Examples in Single Hop Networks

Areas for Cross-Layer Integration

- TCP modifications for energy efficiency
- Adaptive power MAC protocols
- Opportunistic Scheduling
- **Power saving mode and scheduling**
- **Inter-cell interference, SINR estimation, and scheduling**

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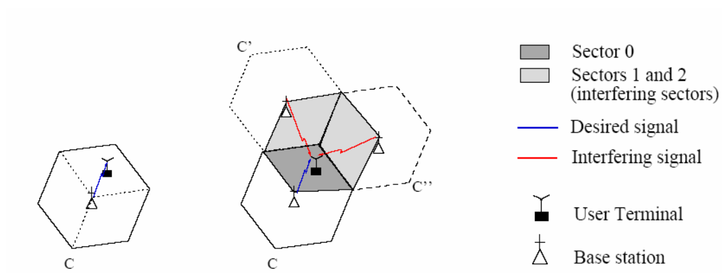
V. Mhatre and C. R; "Impact of Network Load on Forward Link Inter-cell Interference in Cellular Data Networks", submitted to IEEE Transactions on Wireless Communications

Cellular Inter-cell Interference

- CDMA-HDR like system, one user served at a time over forward link
- **Inter-cell interference** from (usually 2) base stations of adjacent cells
- Interfering signals are the forward link signals of the neighboring cells
- The higher the **network load** in the neighboring cells, the higher the **interference**, and vice-versa
- **Cross-layer Problem:**
  - Characterize interference as a function of interfering network load
  - Use this relationship for better channel estimation, which is used in turn for scheduling and retransmission



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Cellular Inter-cell Interference

- Base station transmits a pilot signal periodically
- Terminal measures the SINR of the pilot signal, predicts SINR in the next slot, sends estimation to base station
- Base station serves terminal at a rate corresponding to the predicted SINR
- All the base stations are GPS synchronized, and transmit pilots **synchronously**
- During pilot measurement, interfering signals are **continuously** present
- During actual data transfer, interfering signals are present **intermittently**

Current SINR estimation based on pilot measurement (Scheme A)

$$Pilot\ SINR = \frac{\mathbf{G}_0^2 A^2 T_c^2}{2N_0 + \frac{1}{3}\mathbf{G}_1^2 A^2 T_c^2 + \frac{1}{3}\mathbf{G}_2^2 A^2 T_c^2}$$

$$Actual\ SINR = \frac{\mathbf{G}_0^2 A^2 T_c^2}{2N_0 + \frac{1}{3}\mathbf{G}_1^2 A^2 \rho_1 T_c^2 + \frac{1}{3}\mathbf{G}_2^2 A^2 \rho_2 T_c^2}$$

Scheme A over-estimates interference, i.e., under-estimates SINR.
Can we do better?

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V. Mhatre and C. R; "Impact of Network Load on Forward Link Inter-cell Interference in Cellular Data Networks", submitted to IEEE Transactions on Wireless Communications

Results

- Simulate channel from each base station and terminal with:
  - Path loss
  - Time-varying log-normal shadowing
  - Time-varying Rayleigh fading
- Multi-slot packets and **Hybrid-ARQ**
- Terminal type: Pedestrian (3 Kmph)
- Simulation parameters taken from CDMA-HDR system settings.

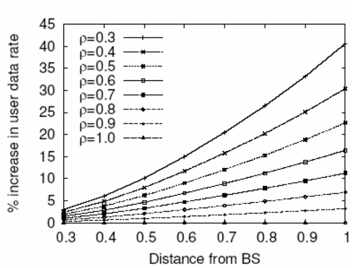

Figure: Pedestrian Path Loss Model

The improved SINR estimation scheme builds on top of current scheme, it requires

- ✓ **Traffic load measurement on BS**
- ✓ **Addl messaging from BS to term**

Results in more accurate, and higher SINR estimates

Results in **higher throughput**, mostly for users dominated by interference

- ✓ Terminals located near cell boundary
- ✓ Vehicular users

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In summary

V. Mhatre and C. R; "Impact of Network Load on Forward Link Inter-cell Interference in Cellular Data Networks", submitted to IEEE Transactions on Wireless Communications

- **Cross-layer interaction**: information from network layer (network load) to better estimate a physical layer parameter (SINR) which is used by the base station during opportunistic scheduling.
- **Trade-off**: more signaling between base stations, need to measure loads for better efficiency and fairness.

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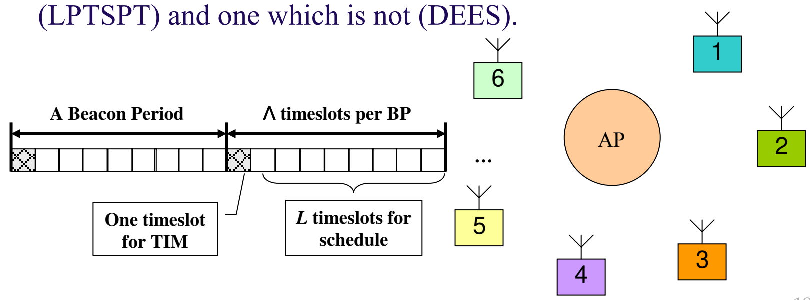
J. Lee, C. R, and E. K. P. Chong, "Energy Efficient Schedulers in Wireless Networks: Design and Optimization," to appear in Mobile Network and Applications (MONET)

WLAN: Power Saving Mode

- For WLAN, IDLE mode power consumption is significant.
- Need to avoid wasting power in IDLE mode.
- How to? ➔ Put the wireless interface in SLEEP mode whenever possible.
- We focus on the downlink, we try to schedule packets so as to minimize total energy while respecting a constraint on mean delay.
- We propose 2 heuristics, one which is work conserving (LPTSPT) and one which is not (DEES).



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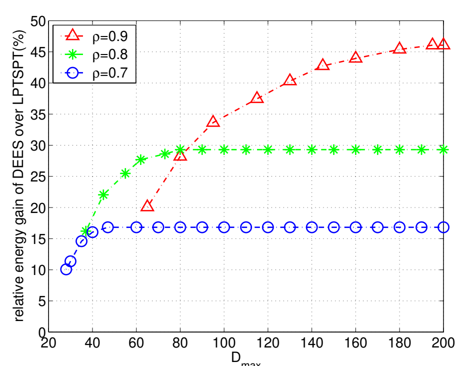
WLAN: Power Saving Mode

If we optimize the system, i.e., we choose the best beacon period duration for each heuristic and for each pair (ρ, D_{max}), then the non-work conserving scheduling does better most of the time (i.e., as long as the delay constraint is not too tight).



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In summary

- **Cross-layer interaction**: information on energy status to be taken into account by base station during scheduling.
- **Trade-off**: more complexity and more signaling (TIM), need for a beacon period, multiple users with different objectives.

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Areas for Cross-Layer Integration

Examples in Multi-Hop Networks

- Several suggestions for cross-layer design
  - Transmit power based routing
  - Battery life based routing
  - Traffic based sleeping strategies
  - TCP modifications for energy efficiency
  - Routing for improving network lifetime
  - Adaptive power MAC protocols
  - QoS schemes based on routing and MAC parameters
  - **MAC and routing**

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Examples in Multi-Hop Networks

Let's First Talk About MAC

- Central to all multi-access wireless networks is the MAC protocol.
- In single hop networks, MAC is well understood, not in multi-hop.

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A. Iyer and C. R.; "Understanding the Key Performance Issues with MAC Protocols for Multi-hop Wireless Networks", accepted to Special Issue on MAC in Wireless Communications And Mobile Computing

MAC Protocols: Two Functional Components

- Useful to separate MAC protocols into two functional components
- **Collision avoidance**
  - Uses protocol handshakes via control messages and/or busy-tone signals
  - Goal is to *reserve* the channel for the duration of the data transmission
  - Example: RTS/CTS exchange in IEEE 802.11
  - Responsible for efficiency; poor collision avoidance can lead to
    - High number of data packet collisions
    - Poor overall throughput
- **Contention resolution**
  - Uses mechanisms such as persistence and/or backoff
  - Goal is to tune the aggressiveness with which nodes attempt to *access* the channel
  - Example: BEB mechanism in IEEE 802.11
  - Responsible for efficiency and fairness; poor contention resolution can lead to
    - High number of control packet collisions
    - Unfairness between flows, and between links

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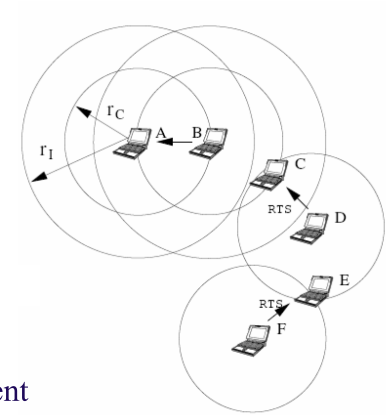
MAC Protocols for Multi-hop Wireless Networks

- Collision Avoidance: Problems
  - Hidden Terminal
  - Deaf Terminal
  - Exposed Terminal
  - Link Layer Congestion
- Desirable collision avoidance features
  - Perfect Collision Avoidance
  - No Link Layer Congestion
  - Link Layer Acknowledgement
  - Full Spatial Reuse



Problems with Collision Avoidance
(assuming fixed communication and interference ranges)

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Collision Avoidance: Impact of Problems

- Evaluation Methodology
  - Table 1 compares different protocols based on desirable collision avoidance features
  - Event-driven simulations for different protocols
  - Use throughput as a metric
  - We do not propose a new protocol; only an objective evaluation

Table 1

Protocols / Features	DUCHA	RI-BTMA	802.11
Perfect Collision Avoidance	Yes	Yes	No
Maximum Spatial Reuse	Yes	Yes	No
Link Layer Acknowledgement	Yes	No	Yes
No Link Layer Congestion	Yes	No	No

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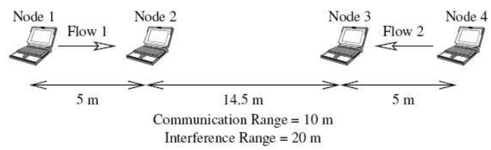
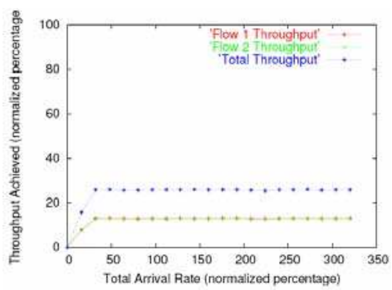
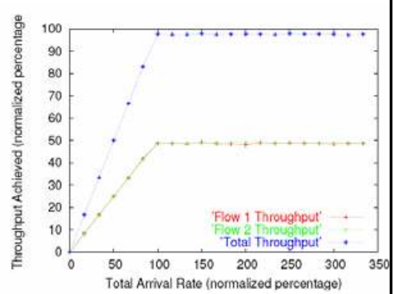
Collision Avoidance: Impact of Problems (contd.)



- Throughput vs. Arrival Rate for IEEE 802.11 (left) and DUCHA (right)





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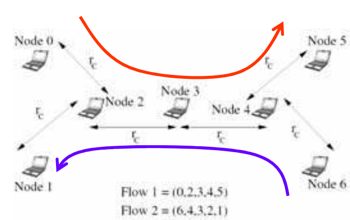
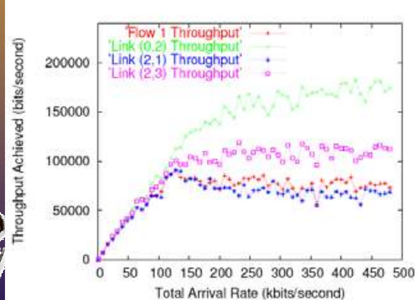
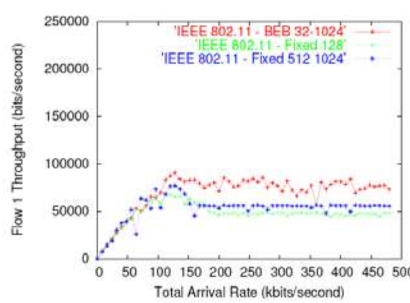
Impact of Contention Resolution

- IEEE 802.11 Throughput
  - for different links (left)
  - for different contention resolution schemes (right)







Impact of Contention Resolution (contd.)

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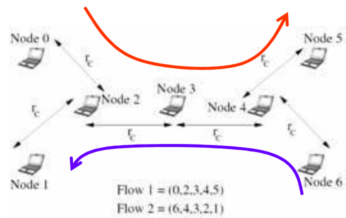

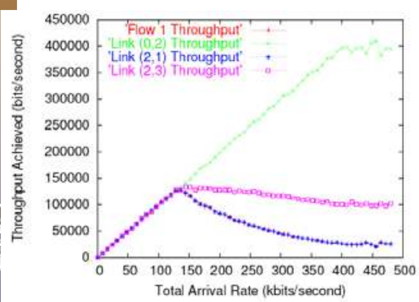

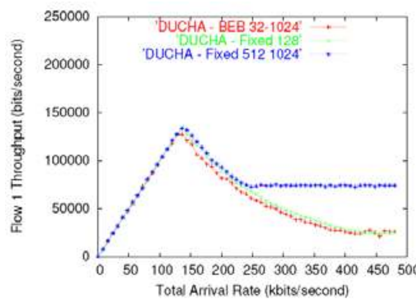

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Impact of Contention Resolution (contd.)

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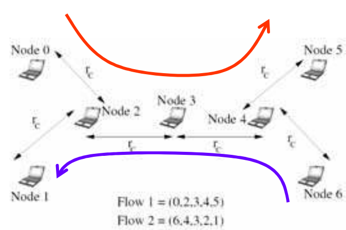
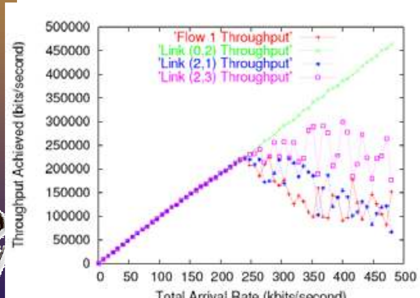
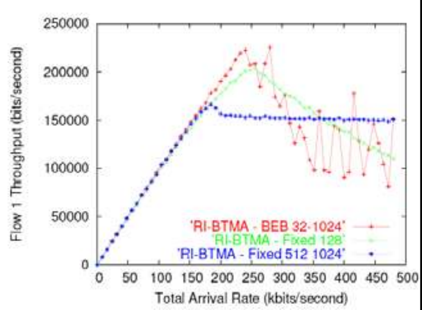
- RI-BTMA Throughput
  - for different links (left)
  - for different contention resolution schemes (right)







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Evaluation of MAC Protocols: Summary

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- Achieving perfect collision avoidance (or in practice, close to perfect) is extremely important
  - IEEE 802.11 showed a lot of throughput degradation
- Link layer congestion may be relatively insignificant, provided perfect collision avoidance is achieved
  - RI-BTMA showed very good performance
- Designing the right contention resolution is very important
  - DUCHA achieves less throughput than IEEE 802.11, if coupled with bad contention resolution
  - Optimal routing and link scheduling (coming up) may be a guideline for designing contention resolution schemes

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Sensor Networks for Event Detection

S. Kulkarni, A. Iyer and C. R; "An Address-light, Integrated MAC and Routing Protocol for Wireless Sensor Networks," accepted in IEEE/ACM Transactions on Networking

- Applications: Intruder detection, detecting breach of security, detecting anomalies in manufacturing plants, etc
- Key Common Feature: Infrequency of events
  - Network remains idle most of the time
  - On detecting event, report has to reach sink promptly
- Design Theme: save energy in every possible way
  - **Addressing:** assignment and exchange of per-node addresses in a dense network is very expensive
  - **Routing:** data flow is many-to-few; take advantage of it
  - **MAC:** reduce idle-listening; power-saving mode should have little or no coordination or message exchanges
  - **Integrate** MAC and routing
- Result: AIMRP – An Address-light, Integrated MAC and Routing Protocol

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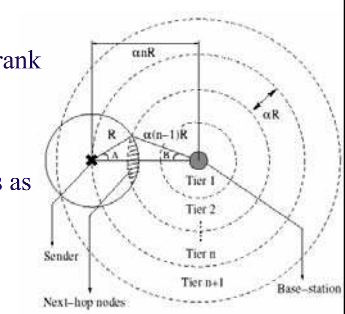
AIMRP: Cross-layer Design and Performance

S. Kulkarni, A. Iyer and C. R; "An Address-light, Integrated MAC and Routing Protocol for Wireless Sensor Networks," accepted in IEEE/ACM Transactions on Networking

- Lightweight Addressing:
  - Random ids for MAC; Tier-ids for Routing
- Routing Mechanism:
  - Forwarding towards decreasing tier rank
  - Hop-by-hop routing using anycast querying
- Integration with MAC:
  - RTR – "anycast" message (functions as RTS and route request)
  - CTR following a backoff (multiple possible next-hop nodes)
- Power-saving Mode:
  - Absolutely no coordination among sensors: sleep independently of each other
  - Dimension wake-up frequency to satisfy latency
- Performance Summary:
  - AIMRP: $E_{hop} = 12.64\text{mJ}$ $E_{report} = 65.22\text{mJ}$ $P_{avg} = 0.74\text{W}$
  - S-MAC: $E^S_{hop} = 23.37\text{mJ}$ $E^S_{report} = 65.44\text{mJ}$ $P^S_{avg} = 4.13\text{W}$



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In summary

S. Kulkarni, A. Iyer and C. R; "An Address-light, Integrated MAC and Routing Protocol for Wireless Sensor Networks," accepted in IEEE/ACM Transactions on Networking

- **Cross-layer interaction**: Combining addressing, routing, power saving mode, and MAC for energy efficiency. A completely integrated solution.
- **Trade-off**: optimized but very application-specific.
- Difficult to find a benchmark to compare against.

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A. Iyer and C. R.; "Optimal Routing and Link Scheduling for Interference-Limited Wireless Sensor Networks", submitted to Infocom

Sensor Networks for Data Gathering

- Aim: To design a routing and link scheduling algorithm to maximize the lifetime of a data-gathering sensor network
- Applications: Habitat monitoring, monitoring of weather conditions, collecting data about crops or livestock, etc
- Key Common Features:
  - Constant flow of data from sensors to sink(s)
  - Loose latency constraint on an individual data unit
- Design Challenges: cross-layer interactions
  - Optimal routing depends on link capacities
  - Link capacities depend on link scheduling because of interference
  - Link scheduling has to satisfy flow conservation which depends on the routing
- Our Approach:
  - Network flow optimization framework
  - Routing and link scheduling via dual decomposition

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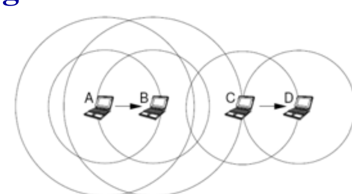
A. Iyer and C. R.; "Optimal Routing and Link Scheduling for Interference-Limited Wireless Sensor Networks", submitted to Infocom

Models and Algorithm



Links (A,B) and (C,D) contend with each other

- Algorithm:
  - During the control subslot, a **contention-free set of links** is activated to maximize
    $\sum_{l\in\mathcal{L}} \lambda_l w_l$ where $w_{(j,n)} = q_j - q_n - e_{tx}\epsilon_j - e_{rx}\epsilon_n$
    where q_n is related to the queue length and ε_n to the energy consumed at node *n*
  - This problem is NP-hard; we use a greedy heuristic
  - During the data subslot, the activated links communicate data
- Insights: Algorithm illustrates the importance of –
  - **Multi-hop routing** to evenly distribute relaying burden
  - **Spatial reuse** *i.e.,* scheduling contention-free links in parallel
  - **Priority** to back-logged links; **discouraging** energy-depleted ones

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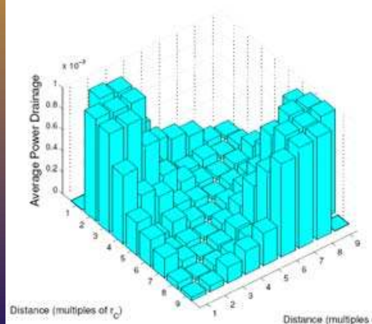
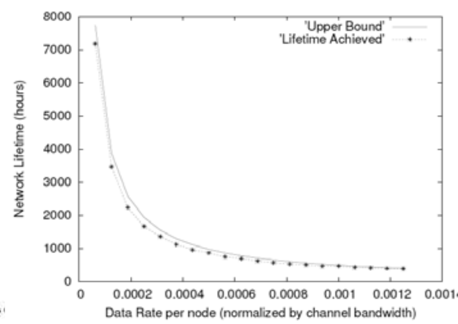
Simulation: Two Sink Grid Topology

- 81 (9x9) grid topology with 2 sinks at opposite corners
- Average power drainage of different nodes (left)
- Lifetime achieved as a function of per node rate of sensor traffic arrivals (right)





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In summary

- **Cross-layer interaction**:
  - Routing and link scheduling are tightly coupled; packet forwarding decisions are taken per-slot via link activation
  - Information about network traffic (captured by q_n) and device energy levels (captured by ε_n) is used for scheduling
- **Trade-off**:
  - Control messages required to exchange information and achieve link scheduling

Outline

- Introduction: wireless vs. wireline
- Cross-layer integration: a necessity but also a challenge
- Examples in single hop networks
  - Cellular networks: inter-cell interference
  - WLAN: power saving mode
- Examples in multi hop networks
  - Let's first talk about MAC
  - Sensor networks: an address-light, integrated MAC and routing protocol
  - Sensor networks: optimal routing and link scheduling
  - **Ad hoc networks: capacity**
- Conclusions

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Capacity of Ad Hoc Networks: Related Work

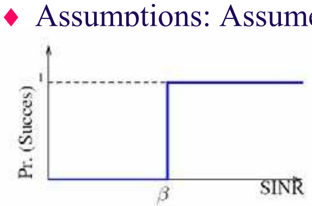
Gupta, IEEE Trans. Info Theory, 2000

- n nodes deployed randomly and uniformly over fixed area
- Random source-destination pairs
- Limited transmit power ➔ multi-hopping
- Observation: Relaying load lowers network capacity

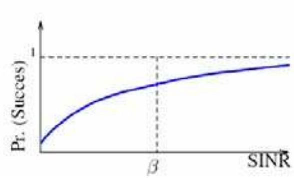
Main Result [Gupta, IEEE Trans. Info Theory, 2000]

Per node capacity of a random ad hoc network is $\Theta\left(\frac{1}{\sqrt{n \log n}}\right)$,
and this bound can be achieved.

- Assumptions: Assume PER is 0 if SINR ≥ β



Reality ➔



- Even with SINR ≥ β, PER ≠ 0 on each link! Do the capacity results change under such a link layer model?

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V. Mhatre and C. R; "The Capacity of Random Ad Hoc Networks under a Realistic Link Layer Model", submitted to IEEE Trans on Information Theory

Capacity of Random Ad Hoc Networks under a Realistic Link Layer Model

- Throughput is $O\left(\frac{1}{n}\right)$ and not $\Theta\left(\frac{1}{\sqrt{n \log n}}\right)$
- **Moral of the story**: Besides relaying load, cumulative PER is also important in determining the capacity of large multi-hop networks
- Can we do better? YES
- How? Use reduced spatial reuse, i.e., K_n colors instead of K colors, and $K_n \to \infty$
- Then throughput scales as $\Theta\left(\frac{1}{K_n \sqrt{n \log n}}\right)$

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In summary

- **Cross-layer interaction**: Impact of link layer (cumulative packet loss) on network layer (capacity) .
- **Trade-off**: none since this is an "off-line" computation. This is just a better model giving us better insights.

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Outline

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- Conclusions

The Cross-layer Integration Challenge

Cross-Layer Integration

- Cross-Layer integration needed to improve *efficiency*
- Layers are coupled
  - Potential loss of *modularity*
  - Could lead to complex and fragile overall design
- Longevity issue
  - Short term versus long term perspective
- Interactions: warning!
  - Layers can interact
  - Loops can be formed

➔ be careful before leaping into cross-layer design

To obtain papers

Please go to my web site at:
www.ece.uwaterloo.ca/~cath

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THANK YOU!

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