Cross-Layer Interactions and Optimizations in Wireless Networks

Catherine Rosenberg

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

Wireless vs. Wireline Networks

Introduction

- **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

3

Why Wireless Networking?

Introduction

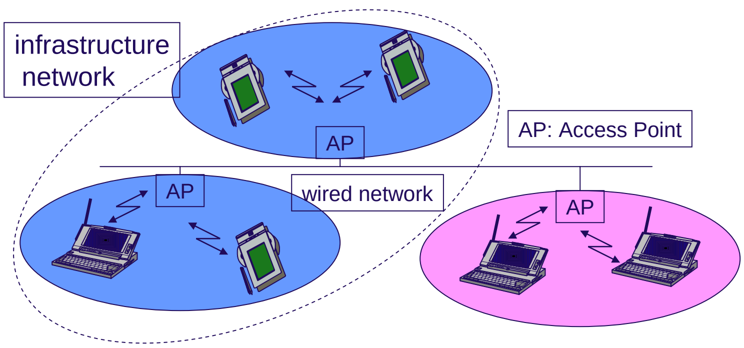
- *Ease of deployment* (often coupled with energy issues)
- Support of *mobility*
- *On-demand, seamless* connectivity between *individuals* and their *environment*
  - *On-demand:* connection should be available whenever there is a need for it
  - *Seamless:* connectivity should be maintained despite 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

4

Introduction

Current Wireless Networks

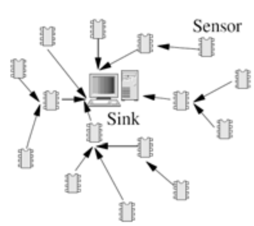
- Single hop:
  - Cellular Networks: voice and data services, excellent coverage, great penetration
  - Wireless LANs: data services, Wireless LAN “hotspots” used in campuses, coffee shops, airports
  - Wireless PANs: wireless keyboard, mouse, headphones, etc



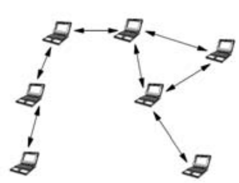
Introduction

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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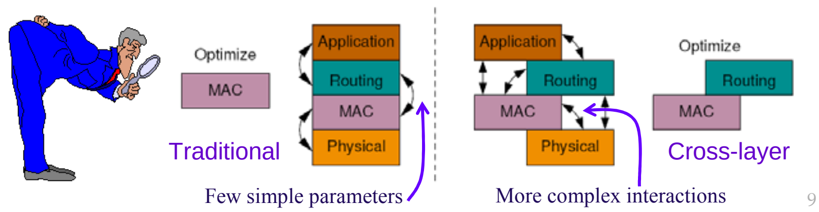
Tension between Performance and Architecture

- 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

Cross-layer Interactions and Integration

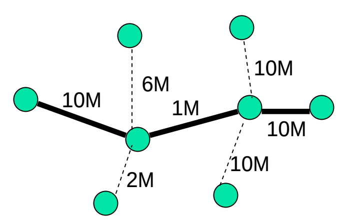
- Traditional (wired) network design follows *layering*; each layer optimized *separately*; no cross-layer integration
- Examples of cross-layer interactions in wireless:
  - Data-rate supported by a wireless link depends on interference (which depends on traffic at neighbors)
  - "Best" set of routes 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



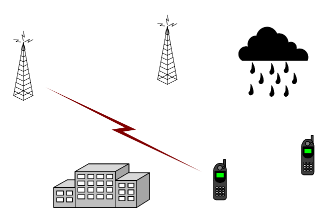
Wireless Networks: A More Complex Interaction Between Layers

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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Cross-Layer Integration

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

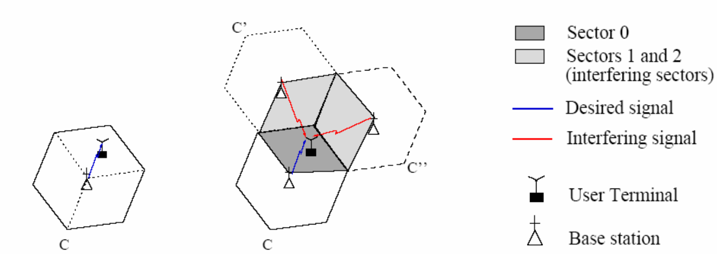
- TCP modifications for energy efficiency
- Adaptive power MAC protocols
- Opportunistic Scheduling
- **Power saving mode and scheduling**
- **Inter-cell interference, SINR estimation, and scheduling**

13

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



14

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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?

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.

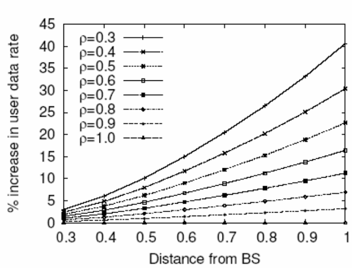

Figure: Pedestrian Path Loss Model

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

- **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.

17

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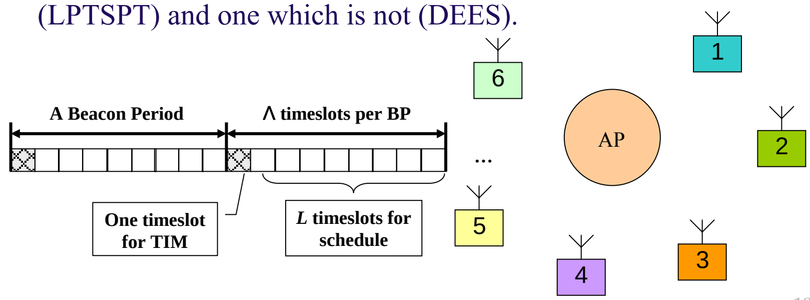
18

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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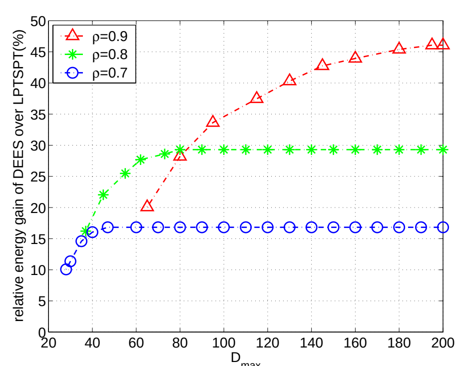
WLAN: Power Saving Mode

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.

21

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Examples in Multi-Hop Networks

Areas for Cross-Layer Integration

- 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**

23

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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.

25

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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

26

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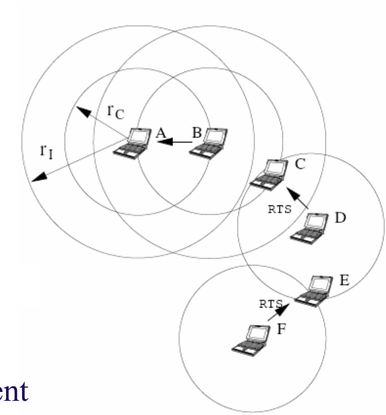
MAC Protocols for Multi-hop Wireless Networks

- 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	DUCHA	RI-BTMA	802.11
Features			
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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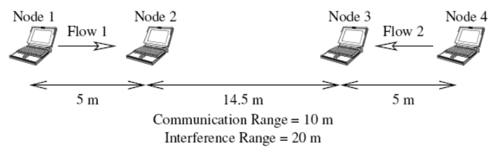
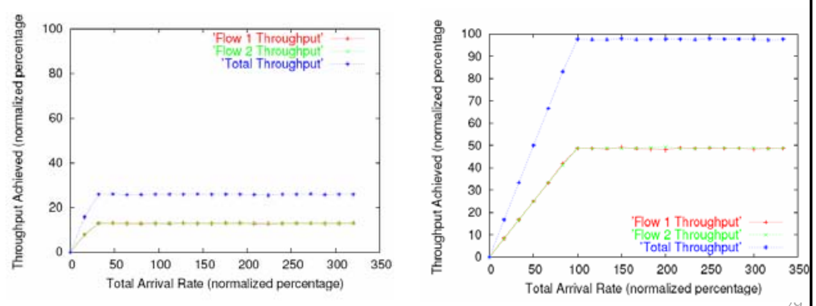
Collision Avoidance: Impact of Problems (contd.)



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



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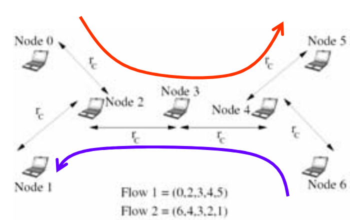
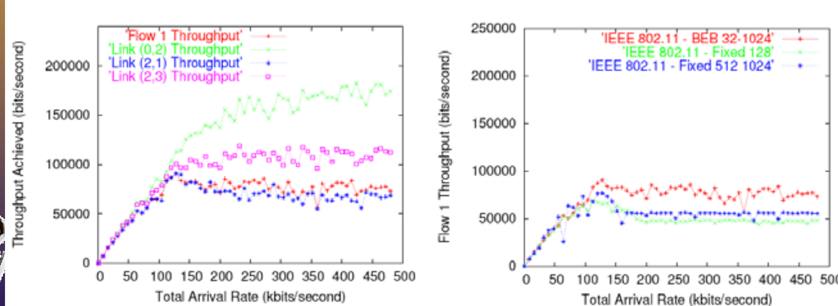
Impact of Contention Resolution

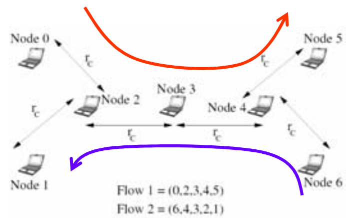
- IEEE 802.11 Throughput
  - for different links (left)
  - for different contention resolution schemes (right)

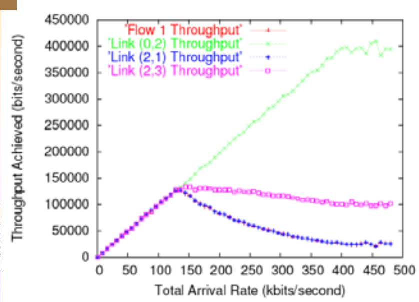


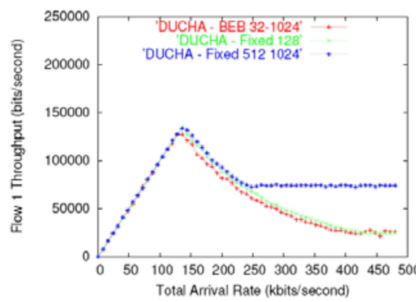


Impact of Contention Resolution (contd.)

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







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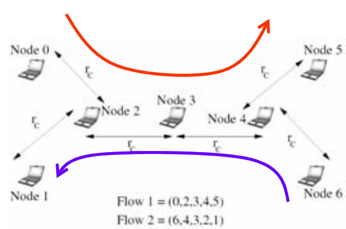
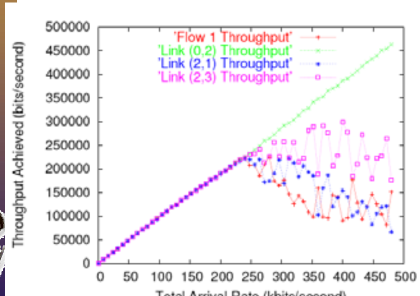
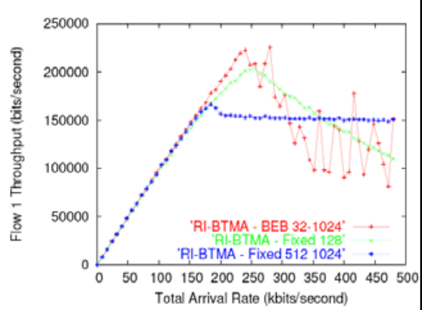
31

Impact of Contention Resolution (contd.)

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







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Evaluation of MAC Protocols: Summary

- 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

33

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34

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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

Sensor Networks for Event Detection

- 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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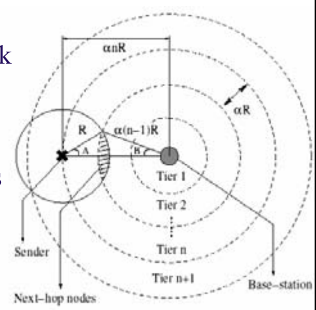
AIMRP: Cross-layer Design and Performance

- 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: $E^S_{hop} = 23.37\text{mJ}$ $E^S_{report} = 65.44\text{mJ}$ $P^S_{avg} = 4.13\text{W}$

36

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In summary

- **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.

37

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38

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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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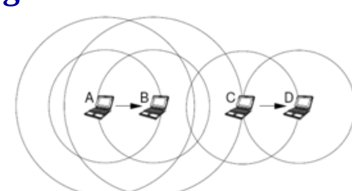
Models and Algorithm



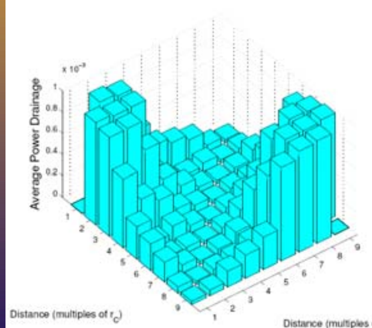
Links (A,B) and (C,D) contend with each other

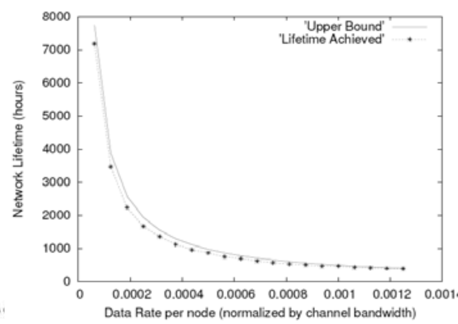
- Algorithm:
  - During the control subslot, a **contention-free set of links** is activated to maximize
    $$\sum_{l \in \mathcal{L}} \lambda_l w_l \text{ where } w_{(j,n)} = q_j - q_n - e_{tx}\epsilon_j - e_{rx}\epsilon_n$$
    where q_n is related to the queue length and ε_n to the energy consumed 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

Simulation: Two Sink Grid Topology

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

- 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)





In summary

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

- **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

43

Capacity of Ad Hoc Networks: Related Work

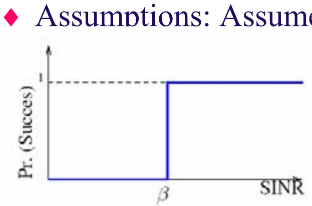
Gupta, IEEE Trans. Info Theory, 2000

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

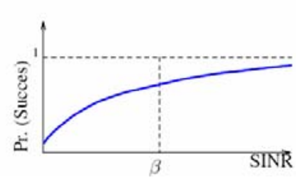
Main Result [Gupta, IEEE Trans. Info Theory, 2000]

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 $\geq \beta$



Reality ➔



- Even with SINR $\geq \beta$, PER $\neq 0$ on each link! Do the capacity results change under such a link layer model?

44

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

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

- 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 $\Theta\left(\frac{1}{K_n \sqrt{n \log n}}\right)$

45

In summary

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

- **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.

46

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The Cross-layer Integration Challenge

- 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

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49

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THANK YOU!

50