Adaptive Energy-Saving for Multihop Wireless Networks

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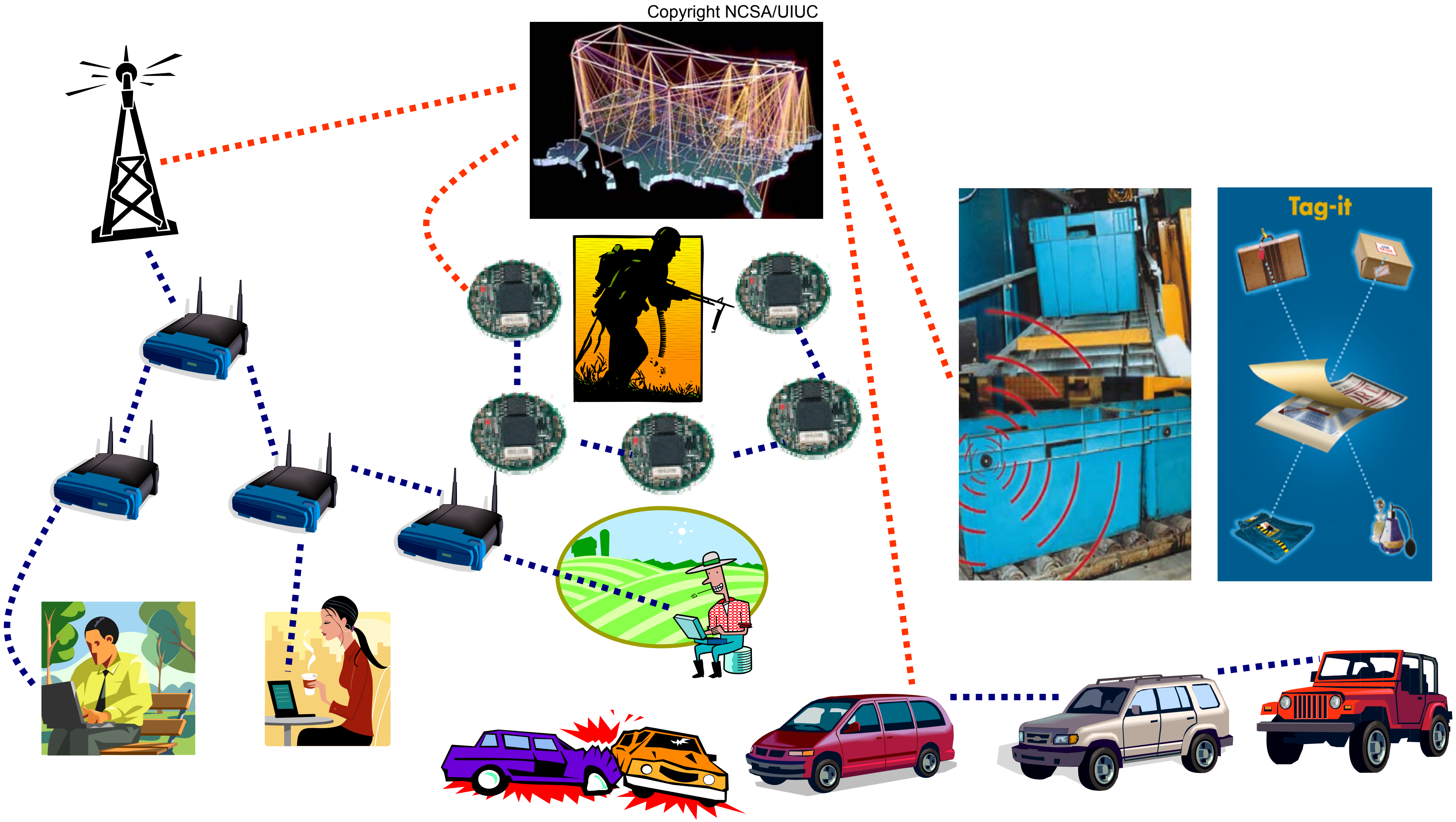
Wireless Networking: It’s Kind of a Big Deal

- “***The number of WiFi hotspots in the United States*** increased from 3,400 to 21,500 between 2002 and 2004 […] that number is expected to grow […] to 64,200 by 2008, ***a 31.5 percent compound annual growth rate***.” – David A. Gross,

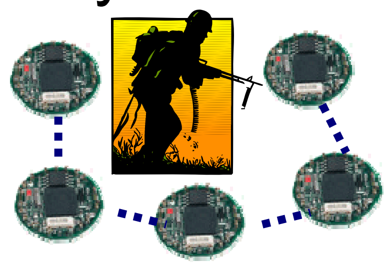
  US Ambassador Bureau of Economic and Business Affairs
- “***The number of RFID tags produced worldwide is expected to increase more than 25 fold*** between 2005 and 2010, reaching 33 billion, according to market research company In-Stat.” – EE Times
- “IDC now estimates there will be more than ***100 million Bluetooth devices worldwide*** by the end of the year, and In-Stat/MDR expects a compound ***annual growth rate of 60 percent*** from 2003 to 2008.” – CNET.com
- ***TinyOS*** Sensor Operating System: Typically ***50-200 downloads per day*** – TinyOS Website

Emerging Wireless Applications



Why Use Multihop Wireless?

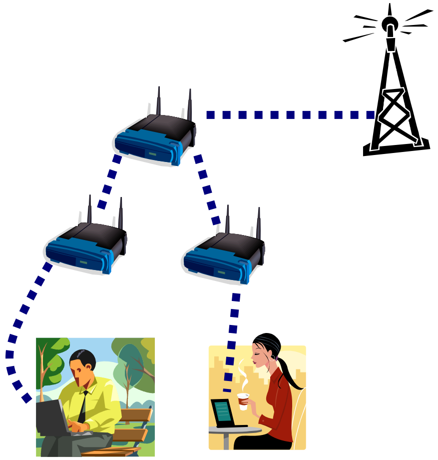
- Connectivity: Extend infrastructure at a low cost
  - Mesh and Community Networks
- Ease of Deployment: Extend infrastructure quickly
  - Disaster scenarios
  - Vehicular networks
  - Sensor networks
  - Military operations



- Performance: Increased capacity per node

(*W* = Channel Bitrate, *N* = Number of Nodes)

Single Hop Network	**Multihop Network** [Gupta00Capacity]
$O\left(\frac{W}{N}\right)$	$O\left(\frac{W}{\sqrt{N}}\right)$



Some Research Challenges

- Improve performance
  - Exploit diversity (e.g., multiple channels, bitrates)
- Making that last wire less necessary
  - The power cable has proved remarkably resilient in this “wireless” world
- Security and privacy
  - Resource constraints on cryptography
  - Tapping the channel to eavesdrop is much easier
  - Devices pushed farther away from a centralized, trusted infrastructure

Summary of My Work

- Energy efficient protocols for wireless interfaces to adaptively sleep and listen to the channel
- Exploiting channel diversity for secure key distribution in sensor networks
- Protocol implementation on sensor hardware

Talk Outline

- Background on Energy Efficient Design
- Adaptive Sleeping Protocol
- Adaptive Listening Protocol
- Secure Key Distribution
- Future Research

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The Importance of Energy-Saving Research

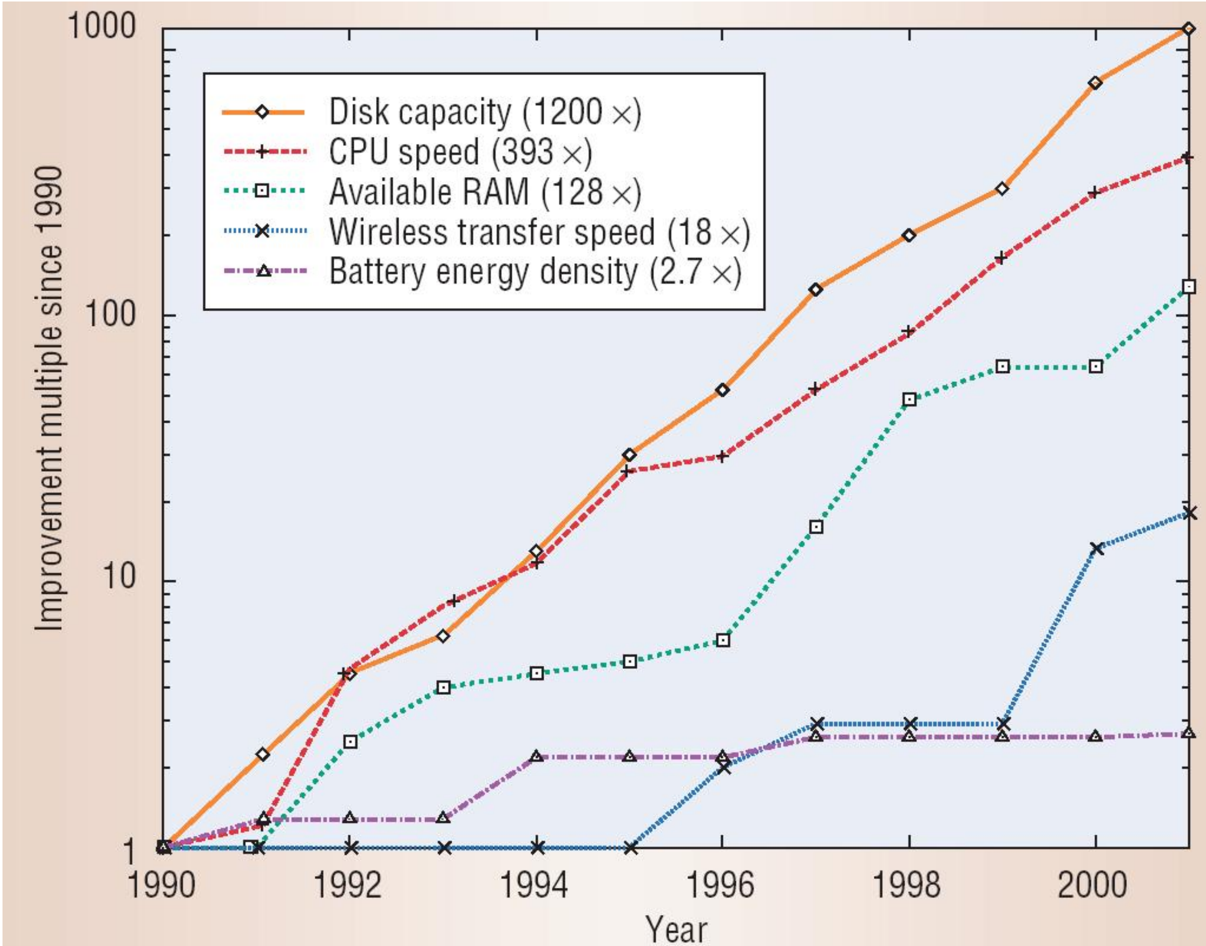
- ✓ Battery life is a concern for wireless designers and users
- ✓ Energy efficient devices needed for ubiquitous wireless networks to become a reality

Won’t Moore’s Law Save Us?

NO!!!

Necessitates Energy-Saving Protocol Design

Log Scale



1200 x

393 x

128 x

18 x

2.7 x

From “Thick Clients for Personal Wireless Devices” by Thad Starner in *IEEE Computer*, January 2002

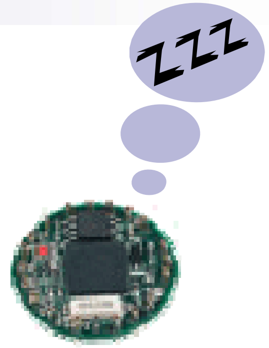
Energy Consumption Breakdown

From UIUC Vodafone Symposium	Data Traffic (Laptop)	Voice Traffic (Cell Phone)
Display	45%	2%
Radio Transmit	5%	24%
Radio Receive/Listen	10%	37%
CPU	40%	37%

Source: Nikhil Jain, Qualcomm

- Solution spans multiple areas of research: networking, OS, architecture, and applications
- Our work focuses on the networking component
- While applicable to laptops, our work is most beneficial to small/no display devices like sensors

How to Save Energy at the Wireless Interface

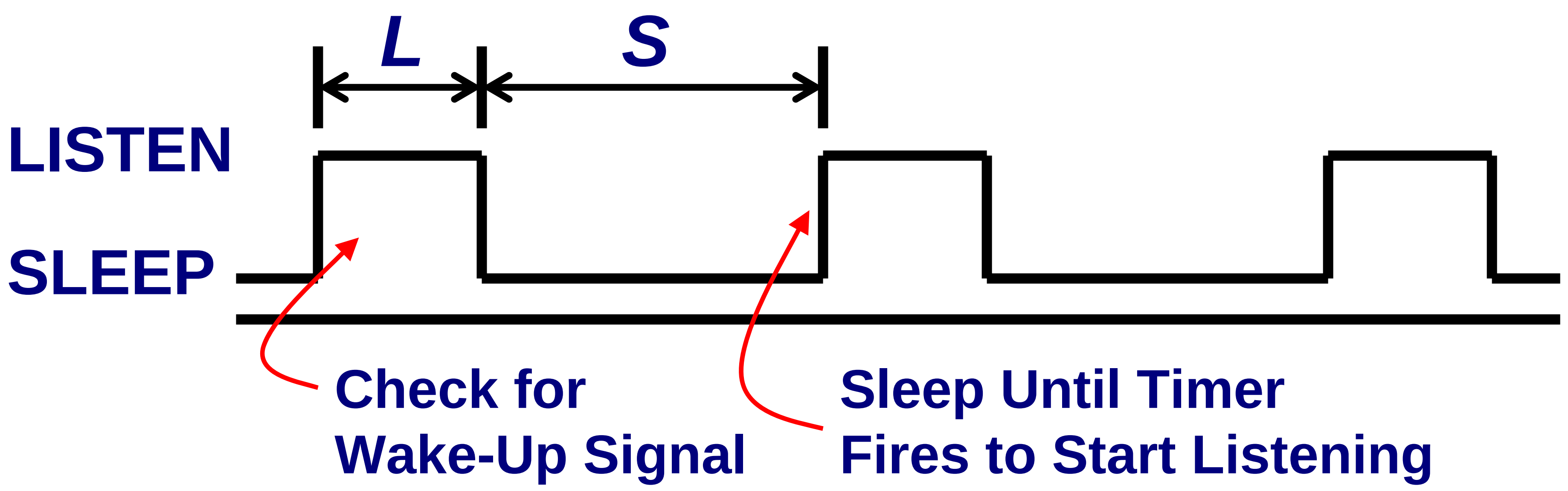


Specs for Mica2 Mote Radio

Radio Mode	Power Consumption (mW)
TX	81
RX/Idle	30
Sleep	0.003

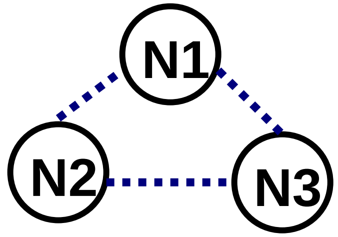
- Sleep as much as possible!
- Fundamental Question: *When should a radio switch to sleep mode and for how long?*

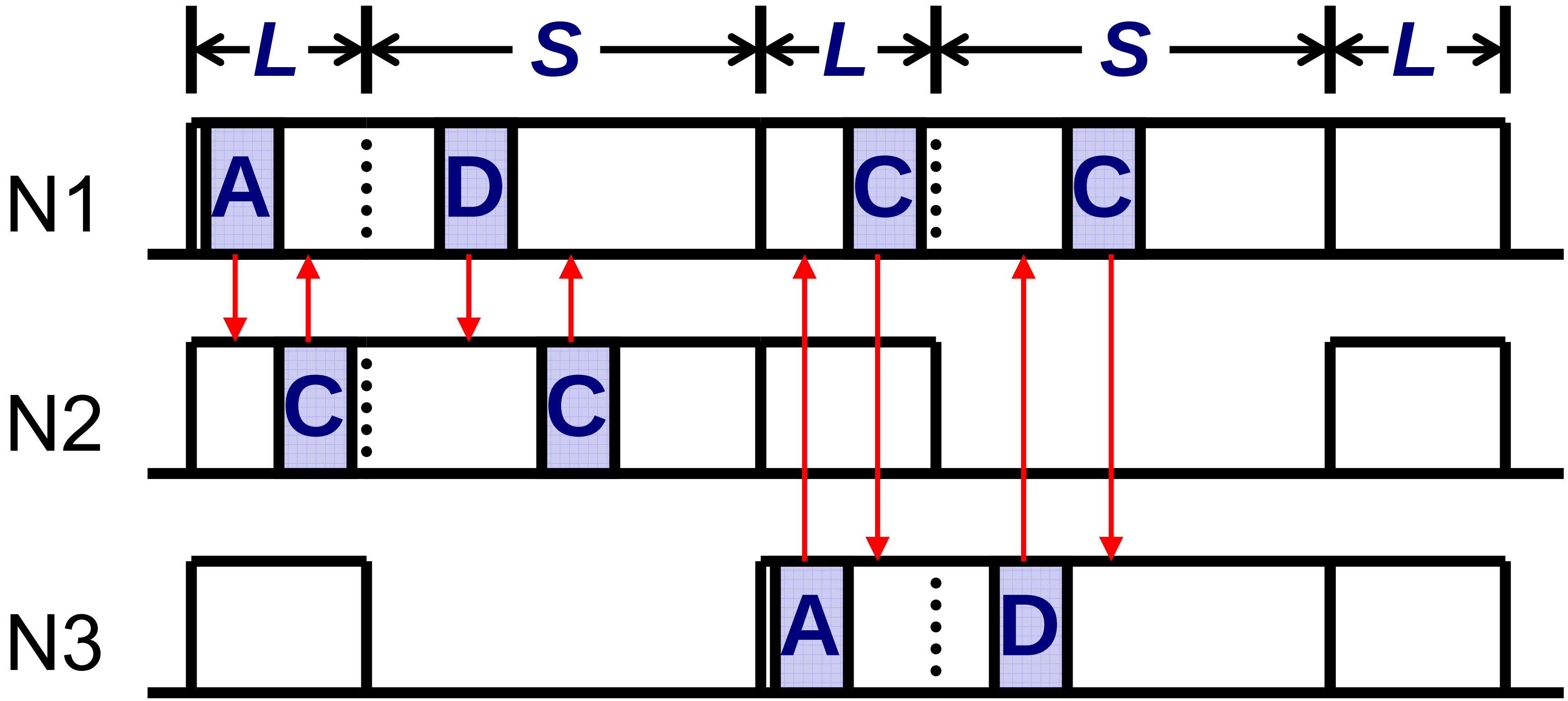
Common Power Save Protocol Design



- *L* and *S* are static values regardless of traffic
- Design used in IEEE 802.11 as well as sensor protocols (e.g., B-MAC and STEM)
- Used by both *in-band* and *out-of-band* protocols

In-Band Protocol Example



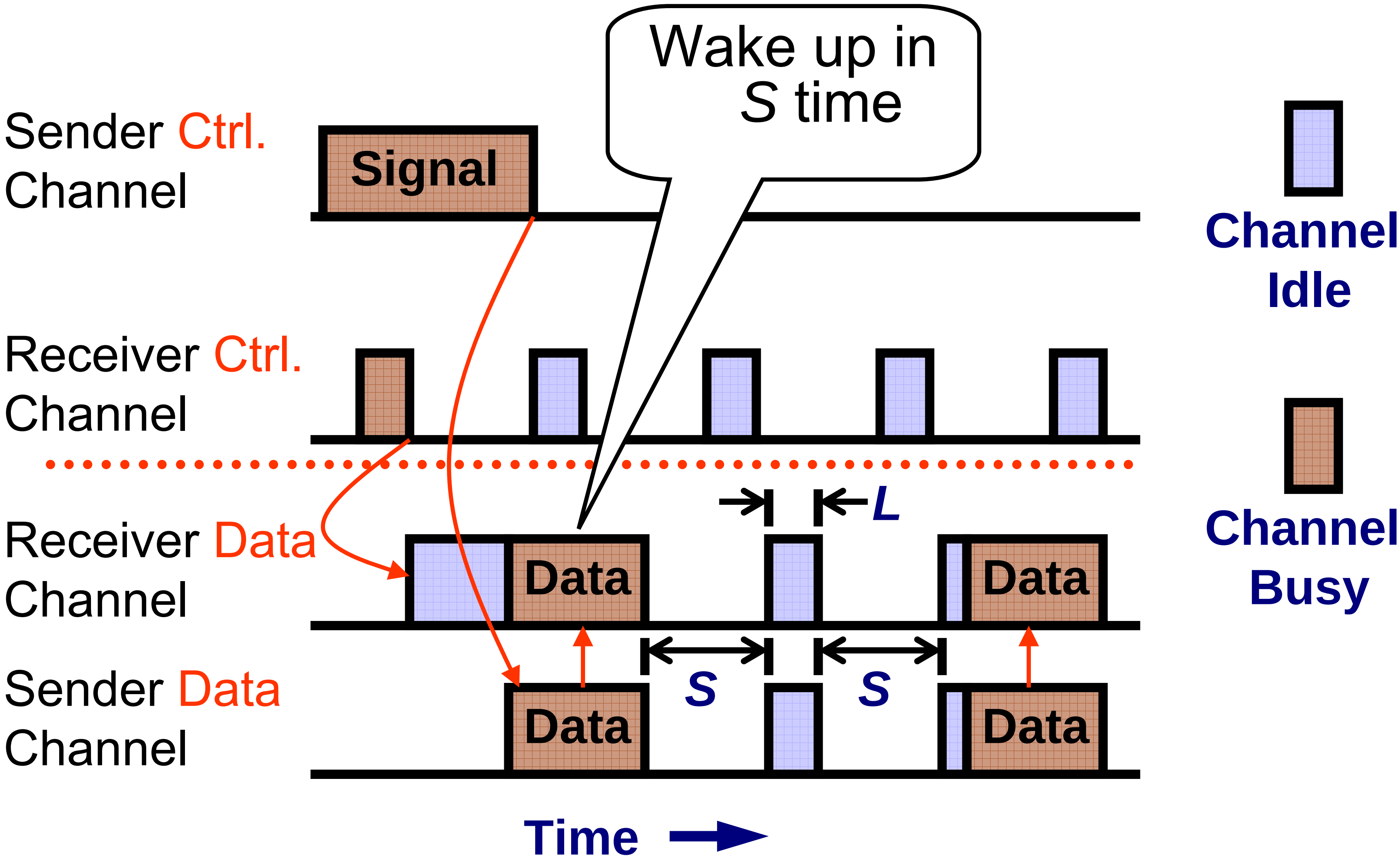


A = Advertisement Pkt

C = ACK Pkt

D = Data Pkt

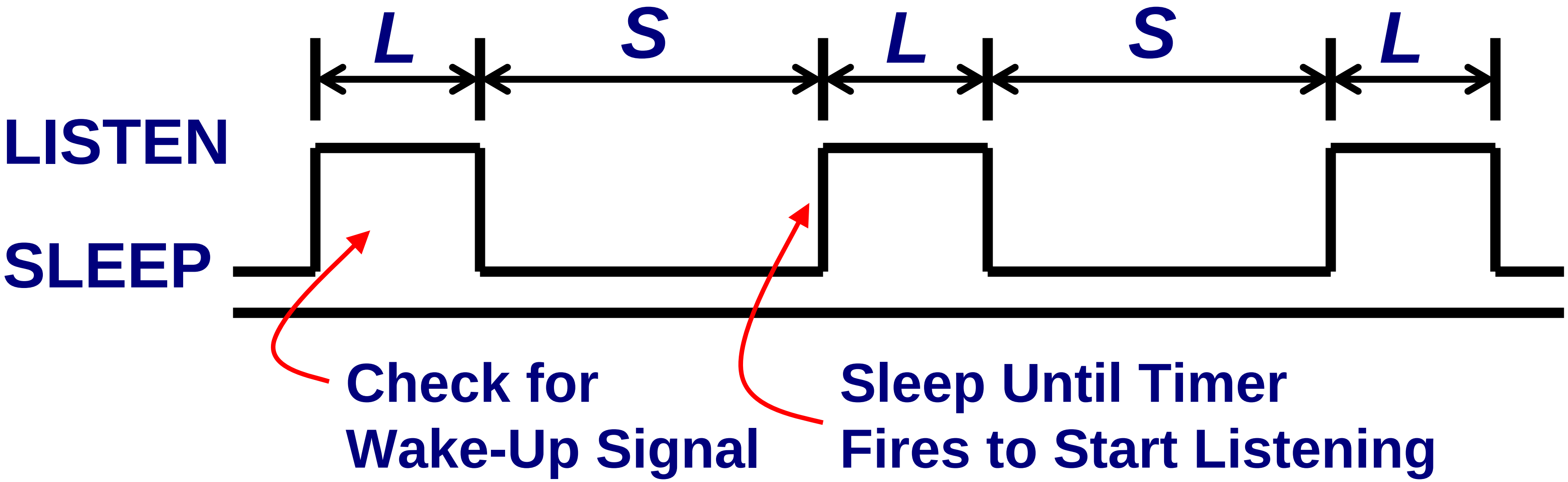
Out-of-Band Protocol Example



In-Band vs. Out-of-Band

- In-Band
  - Only requires one, half-duplex channel
- Out-of-Band
  - No synchronization required for control channel
  - Wake-up signaling does not interfere with data communication

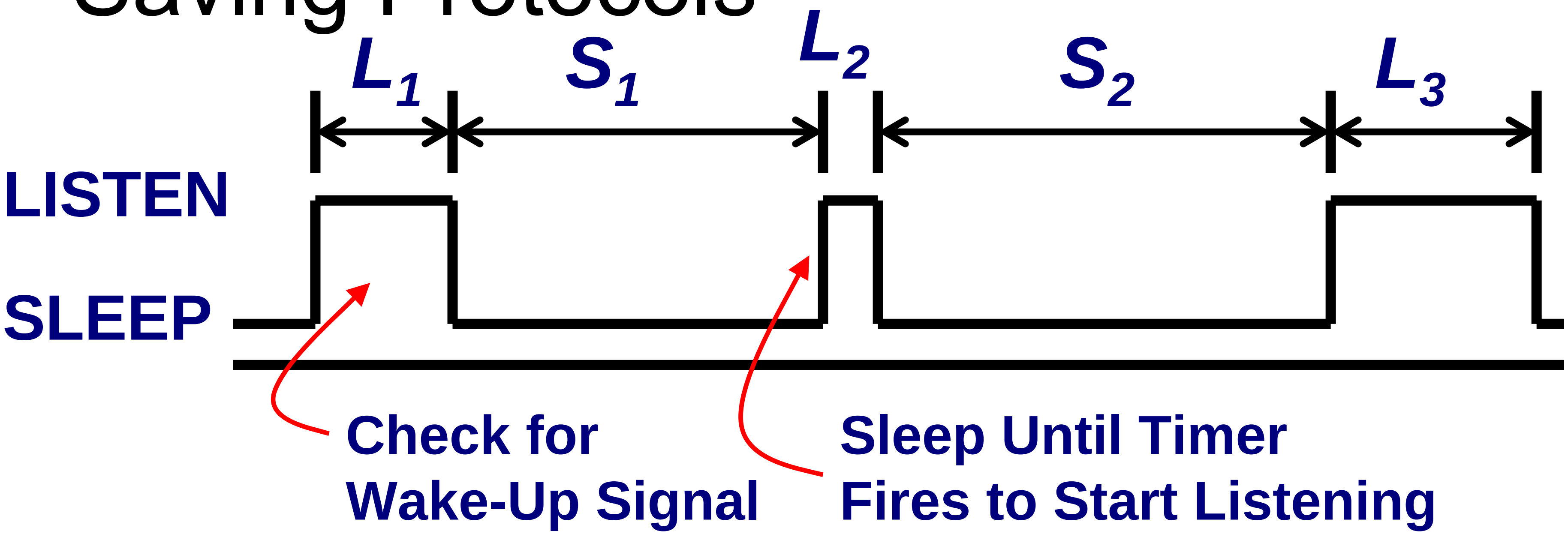
Problems With Static Values



- *L* too short: Wake-up signals are missed
- *L* too long: Wasted energy

- *S* too short: Wasted energy
- *S* too long: Increased latency

Our Approach: Adaptive Energy-Saving Protocols



- Adapt listening (*L*) based on channel state
- Adapt sleeping (*S*) based on traffic arrivals and desired latency

Protocol Design Space

	Adaptive Listening	Adaptive Sleeping
In-Band	Covered in this talk	Our multilevel routing work
Out-of-Band	Our in-band techniques are applicable	Covered in this talk

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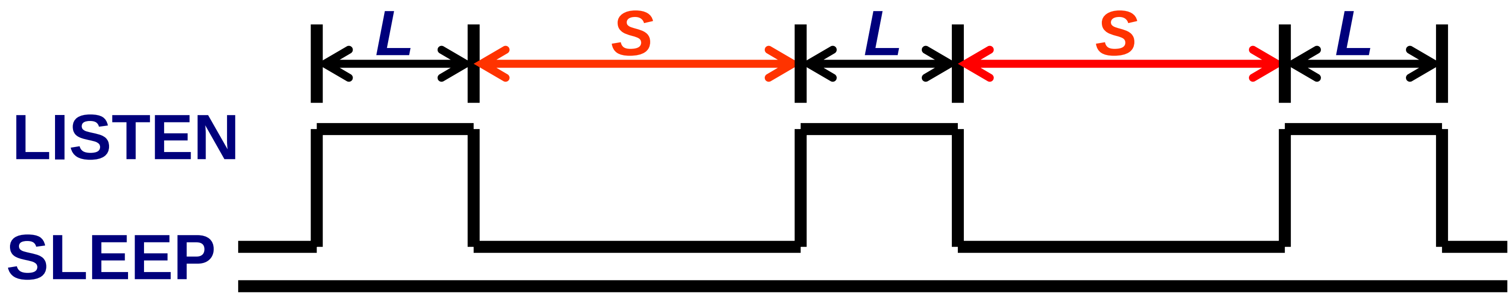

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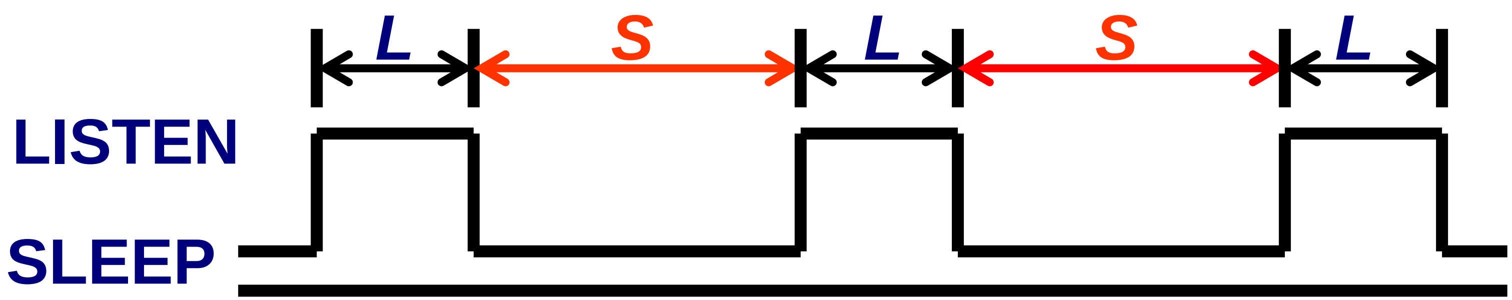


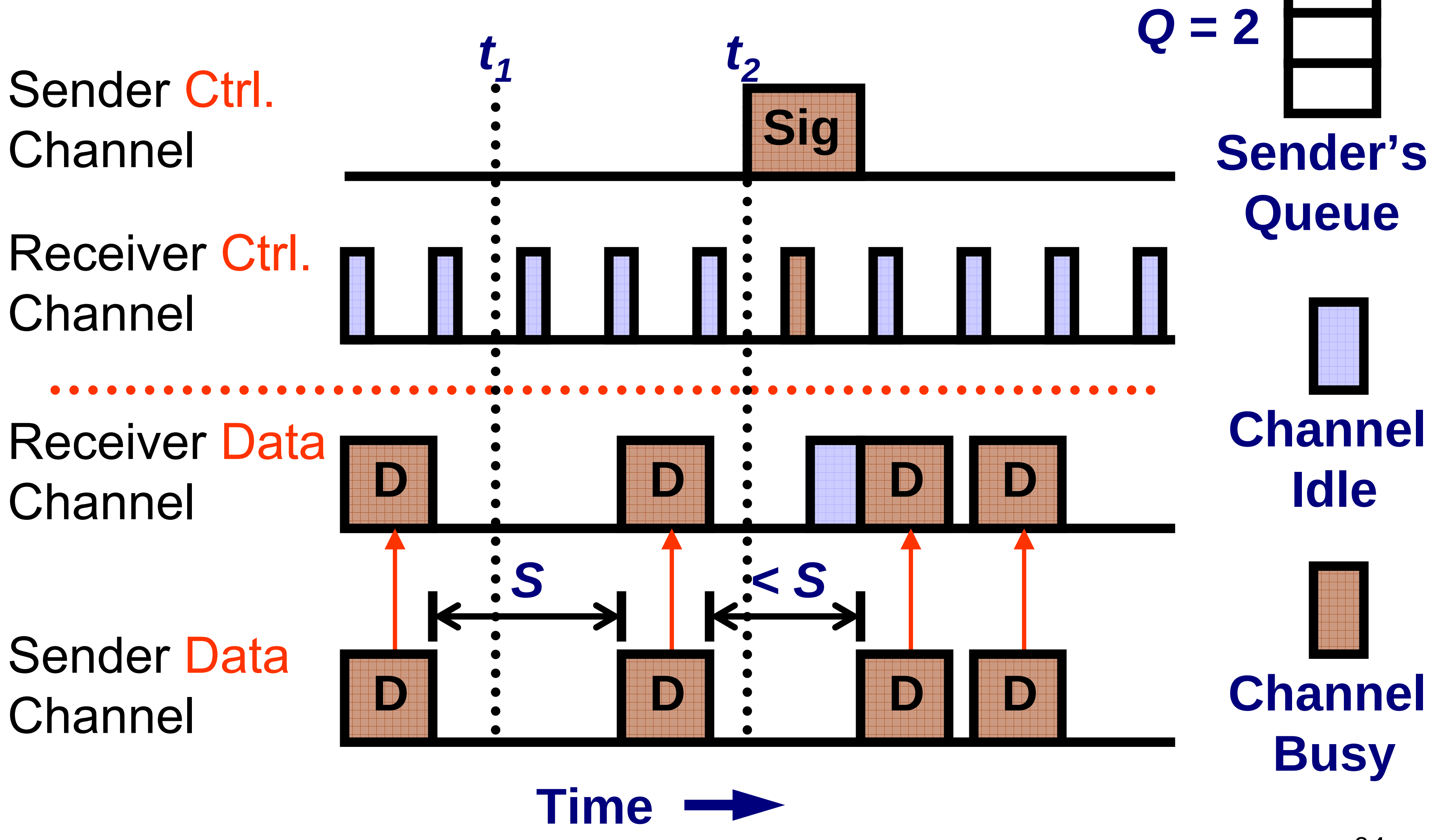
How Do You Choose *S*?

- If energy is our only concern then *S* can be arbitrarily large
  - However, the queue may become large
- Since sensors are resource limited, we address this queue constraint
  - If a device's queue reaches a threshold, *Q*, then it must start transmitting packets soon

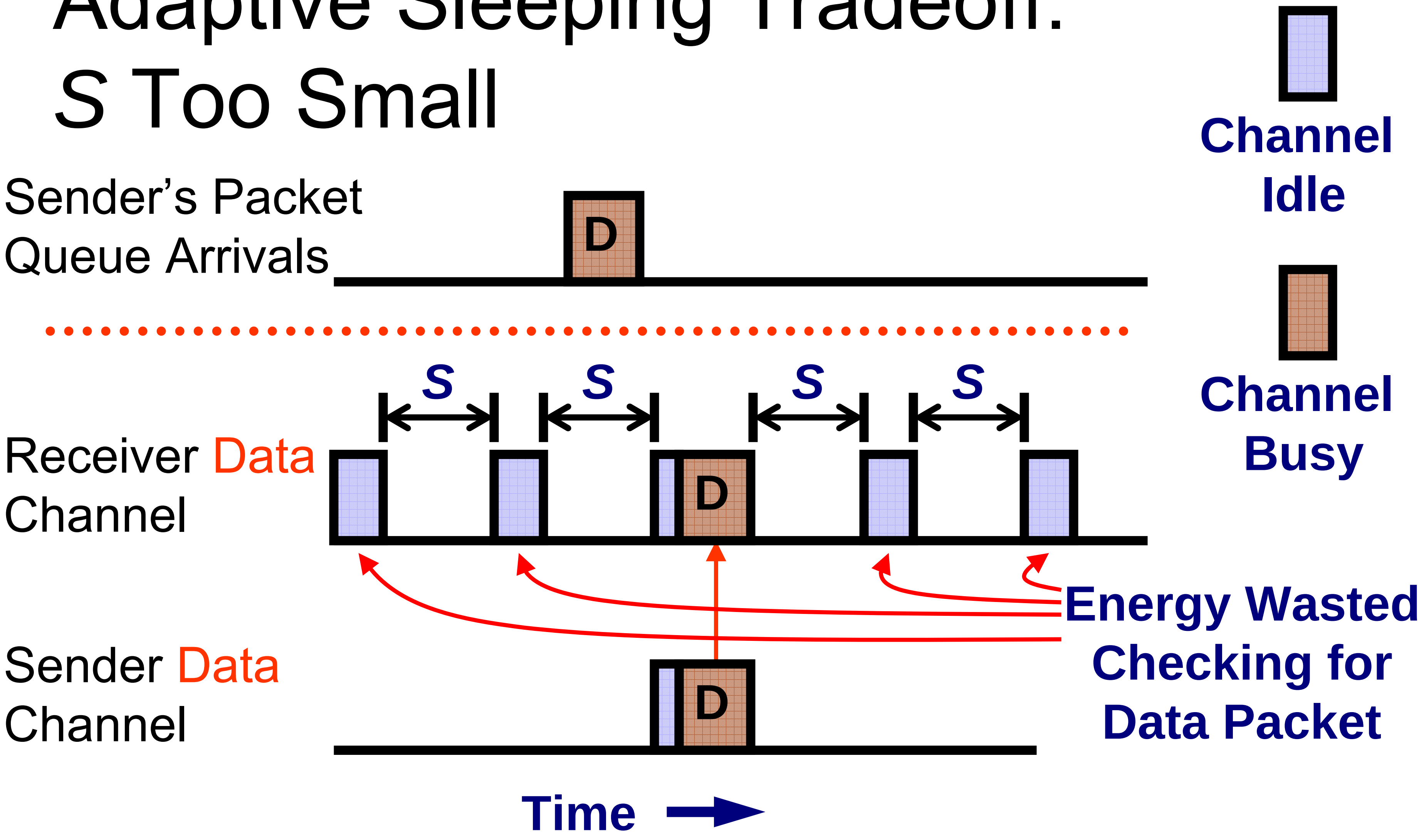
Adaptive Sleeping Overview

- Sender and receiver schedule a future wake-up time based on the traffic rate
- If the sender's queue reaches *Q* packets before a scheduled wake-up:
  - Then the sender wakes up the receiver via the out-of-band control channel
- All nodes periodically check control channel for wake-up signal
  - If signal detected → Turn on data radio
  - If data packet is for another node → Data radio returns to sleep

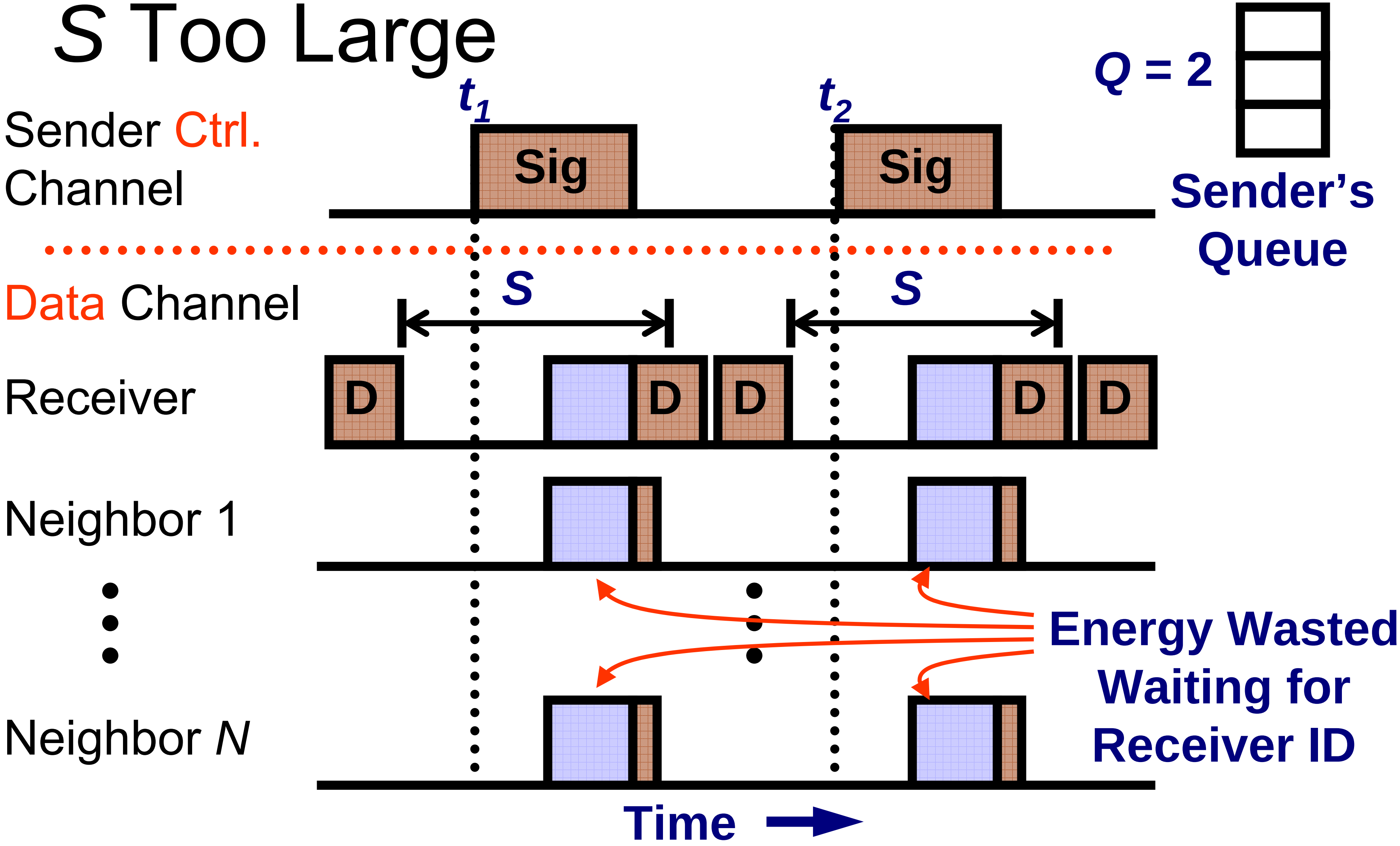
Adaptive Sleeping Example



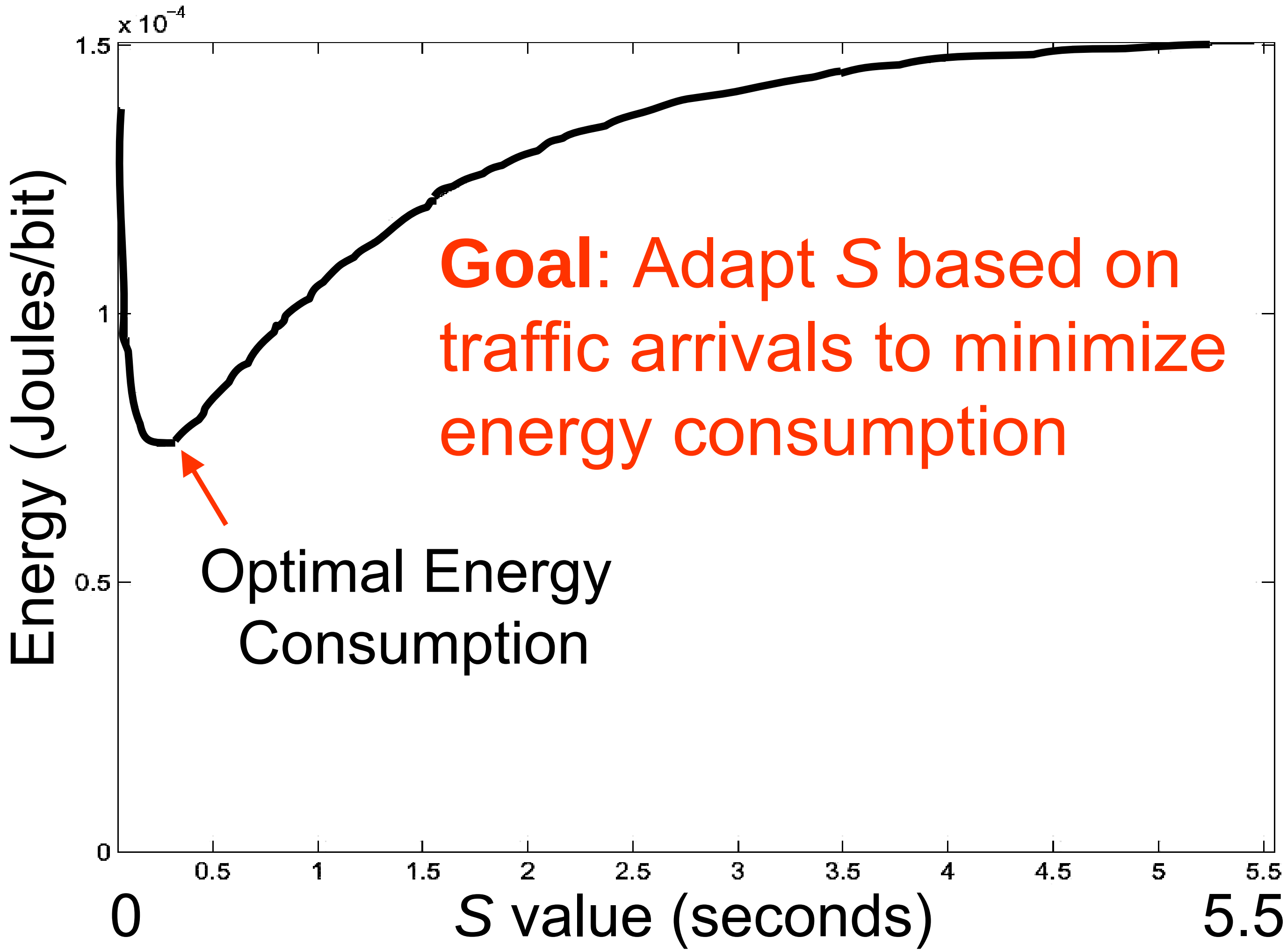
Adaptive Sleeping Tradeoff: *S* Too Small



Adaptive Sleeping Tradeoff: *S* Too Large



Adaptive Sleeping Tradeoff



Adaptive Sleeping Analysis

- Based on analysis, we found that *S* is optimized according to the equation:

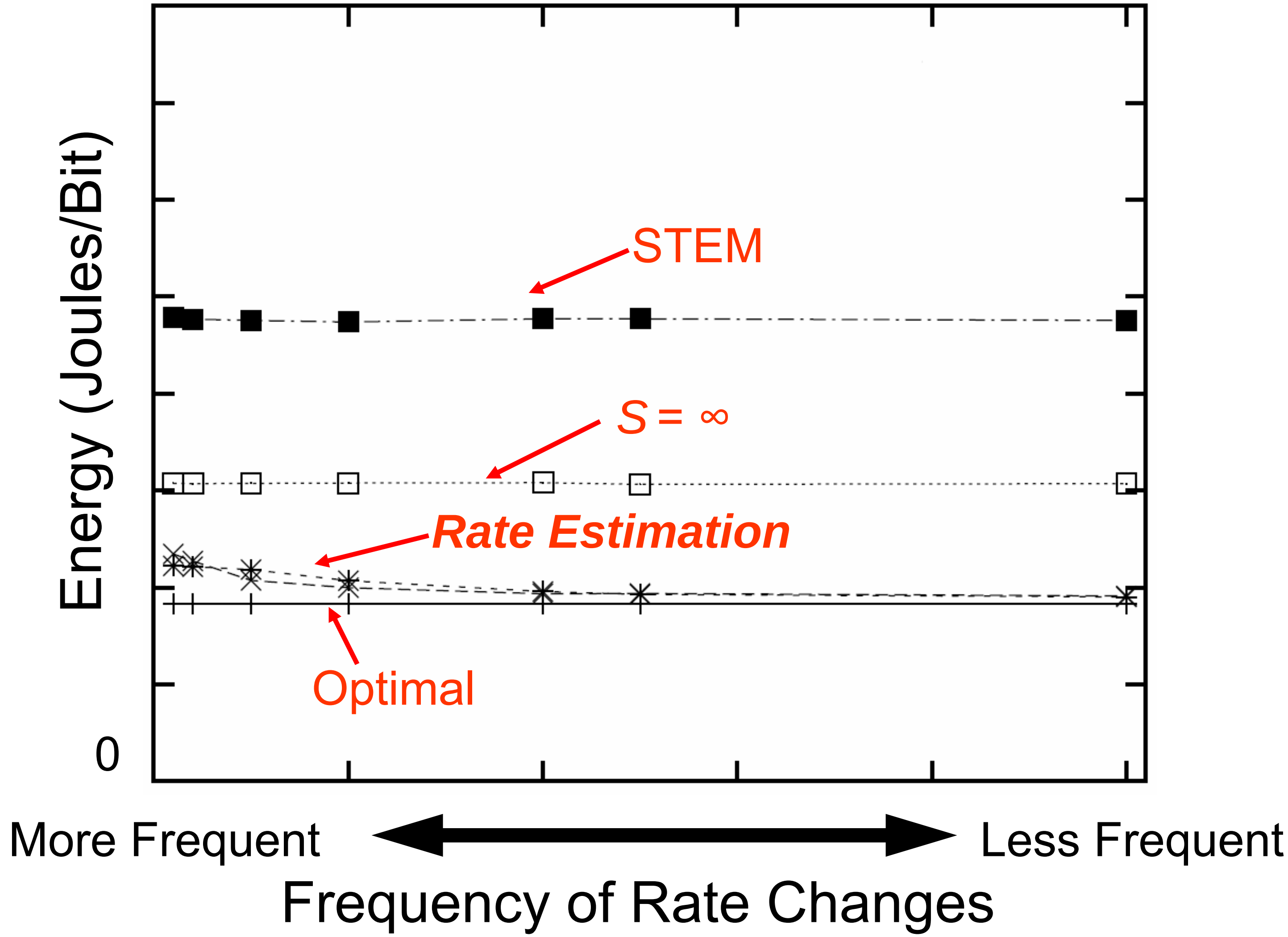
$$S = \gamma\,(1/R)$$

- *R* = Packet arrival rate at sender
  - Can be estimated with a weighted moving average
- γ = Function of *Q* and the number of neighbors of the sender (*nbrs*)
  - Can be calculated offline when *Q* and *nbrs* are known

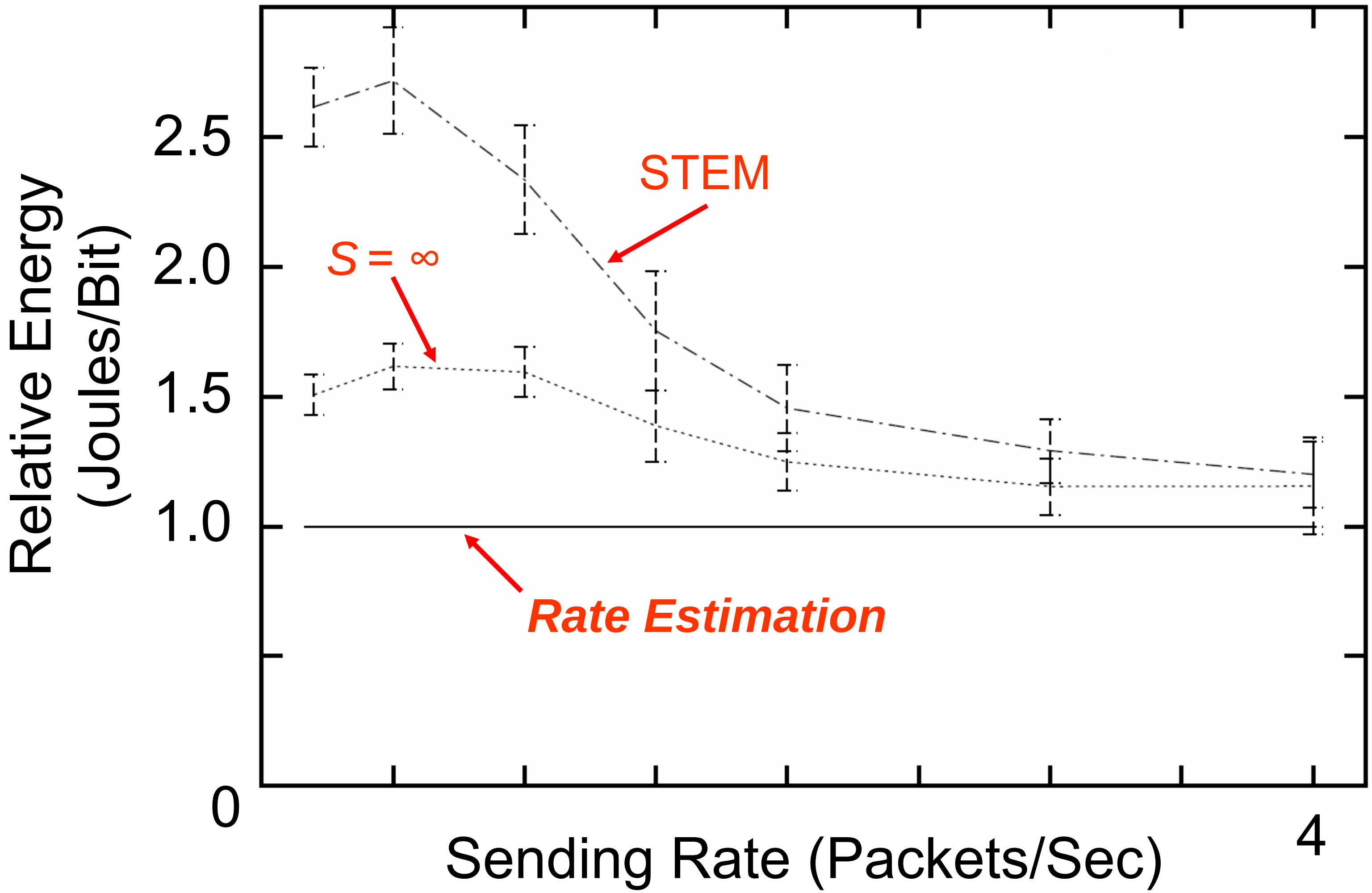
Adaptive Sleeping Results

- Simulated using *ns-2* and Poisson traffic
- Rate Estimation
  - Proposed protocol with Q=2.
- Optimal
  - Optimal value of S which minimizes energy
- $S = \infty$
  - No timeout triggered wake-ups. Out-of-band wake-ups occur when Q=2 packets are in the queue.
- STEM
  - Out-of-band protocol proposed in [Schurgers02Optimizing]. Special case of our protocol with $S = \infty$ and Q=1.

Adaptive Sleeping: Time-Varying Traffic Rate Results



Adaptive Sleeping: Multihop Topology Results



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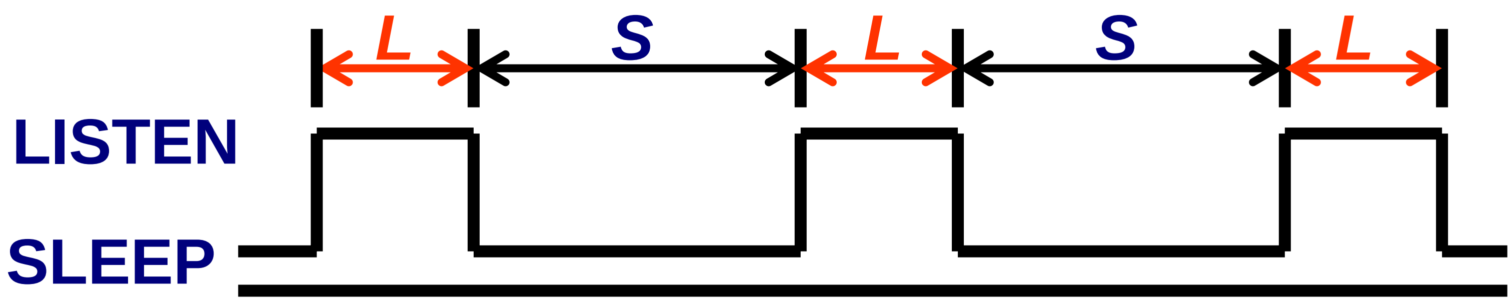

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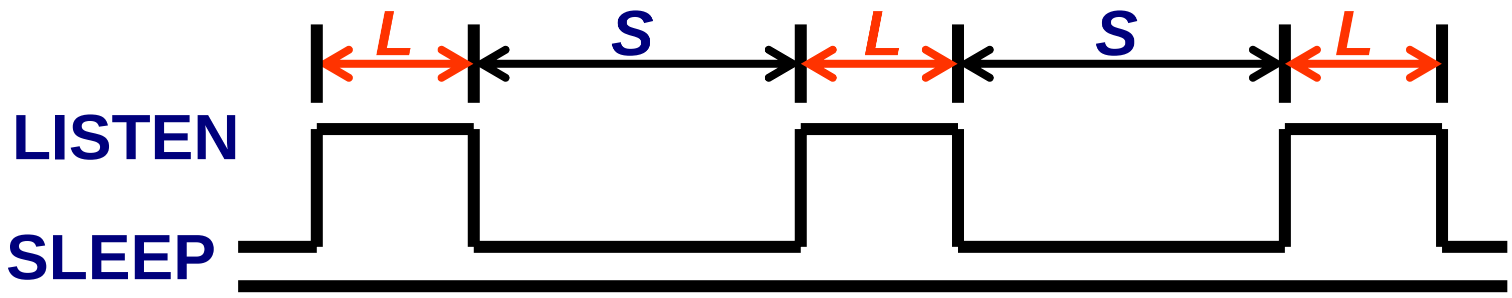
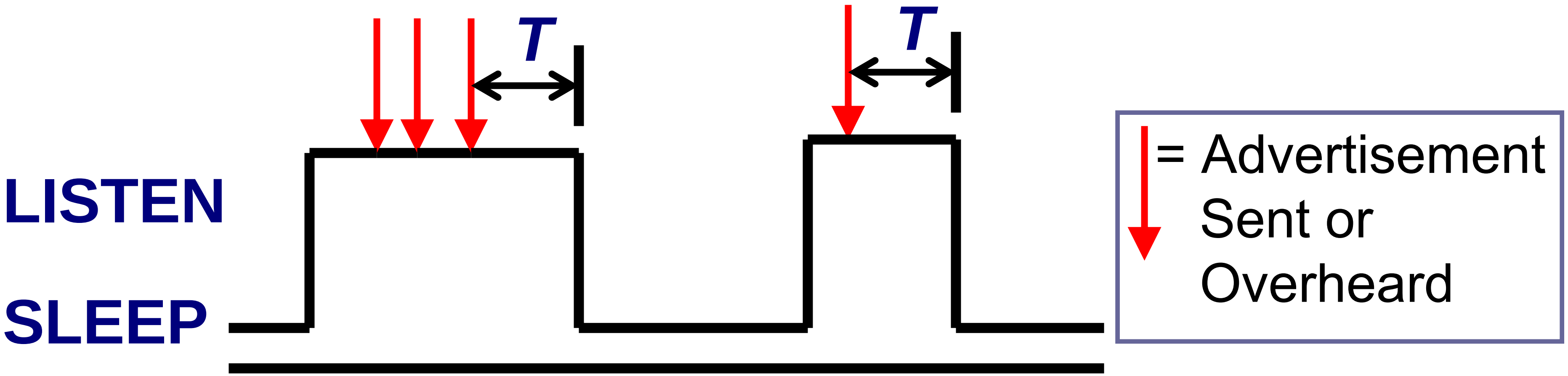


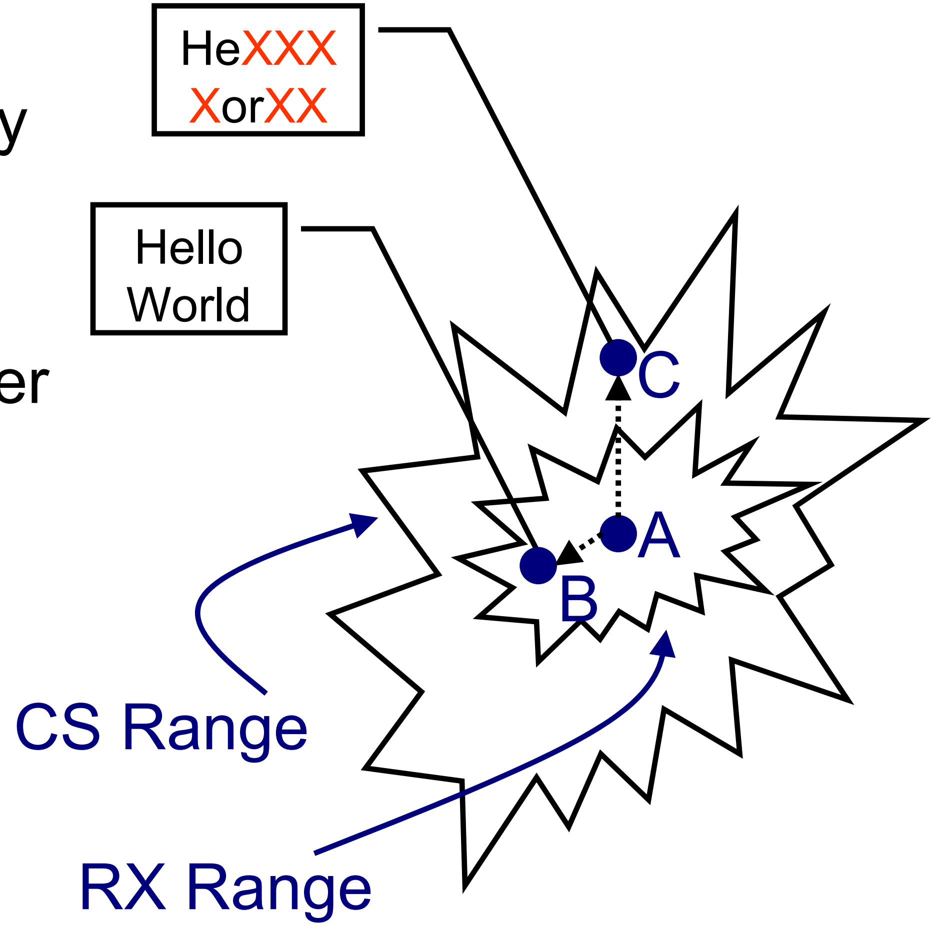
Our Approach to Adaptive Listening



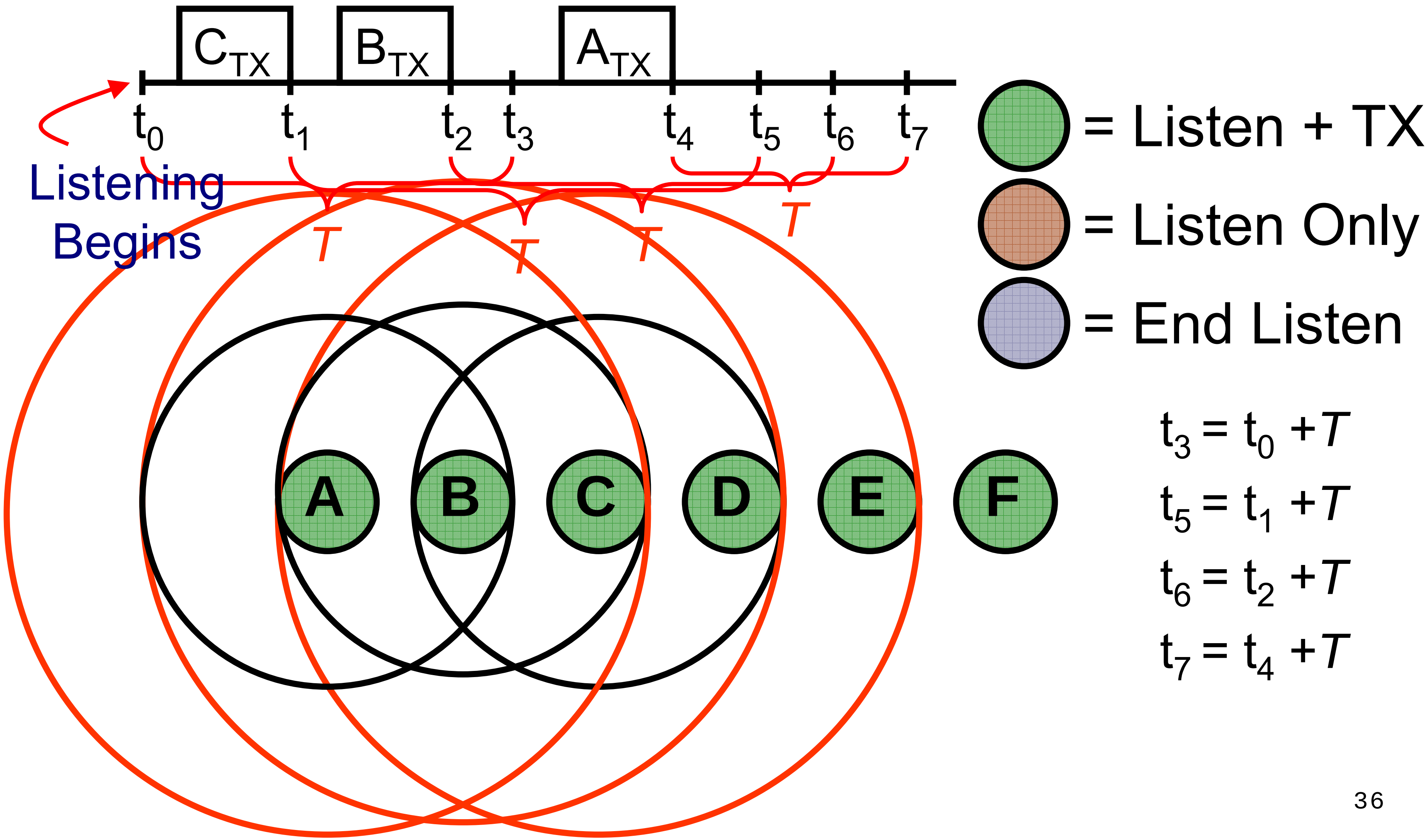
- Use physical layer carrier sensing to extend the listening period for advertisements
- Previous work has proposed dynamic listening periods for 802.11 power save, but ours is the first for single radio devices in multihop networks

Adaptive Listening Background: RX Threshold vs. CS Threshold

- RX Threshold: received signal strength necessary for a packet to be correctly received
- CS Threshold: received signal strength to consider the channel busy
- We assume that usually CS range ≥ 2*RX range
  - If this is not true, our technique gracefully degrades to a fixed listening interval scheme



Using Carrier Sensing for Adaptive Listening



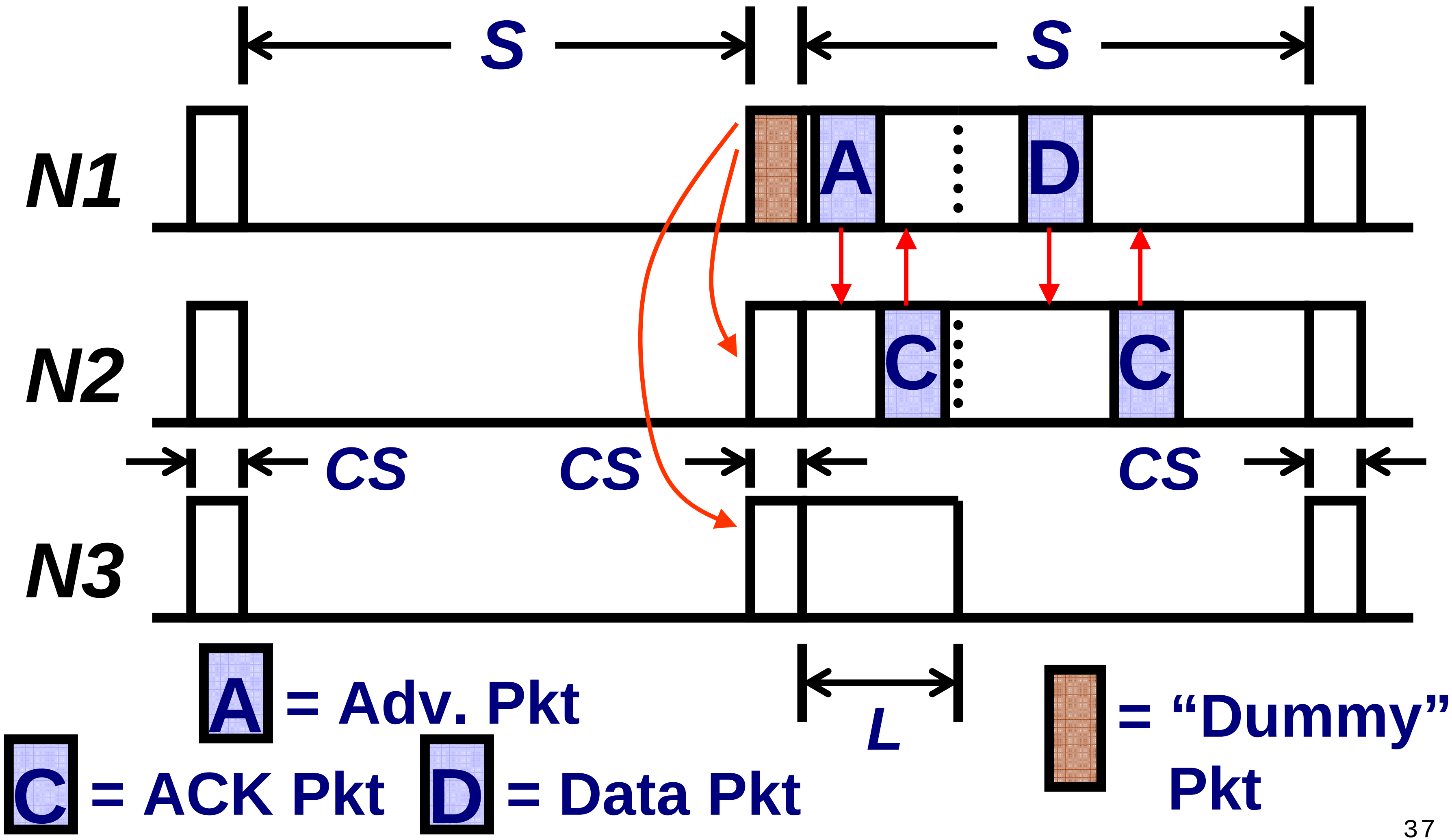
$t_3 = t_0 + T$

$t_5 = t_1 + T$

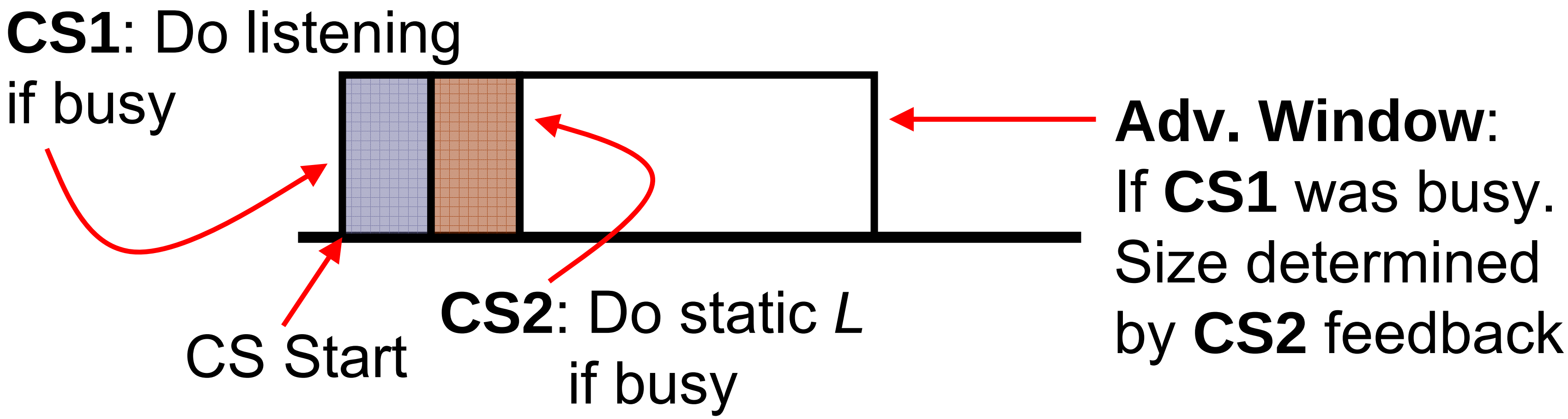
$t_6 = t_2 + T$

$t_7 = t_4 + T$

Adaptive Listening: Additional Carrier Sensing Signaling



Adaptive Listening: Putting It All Together

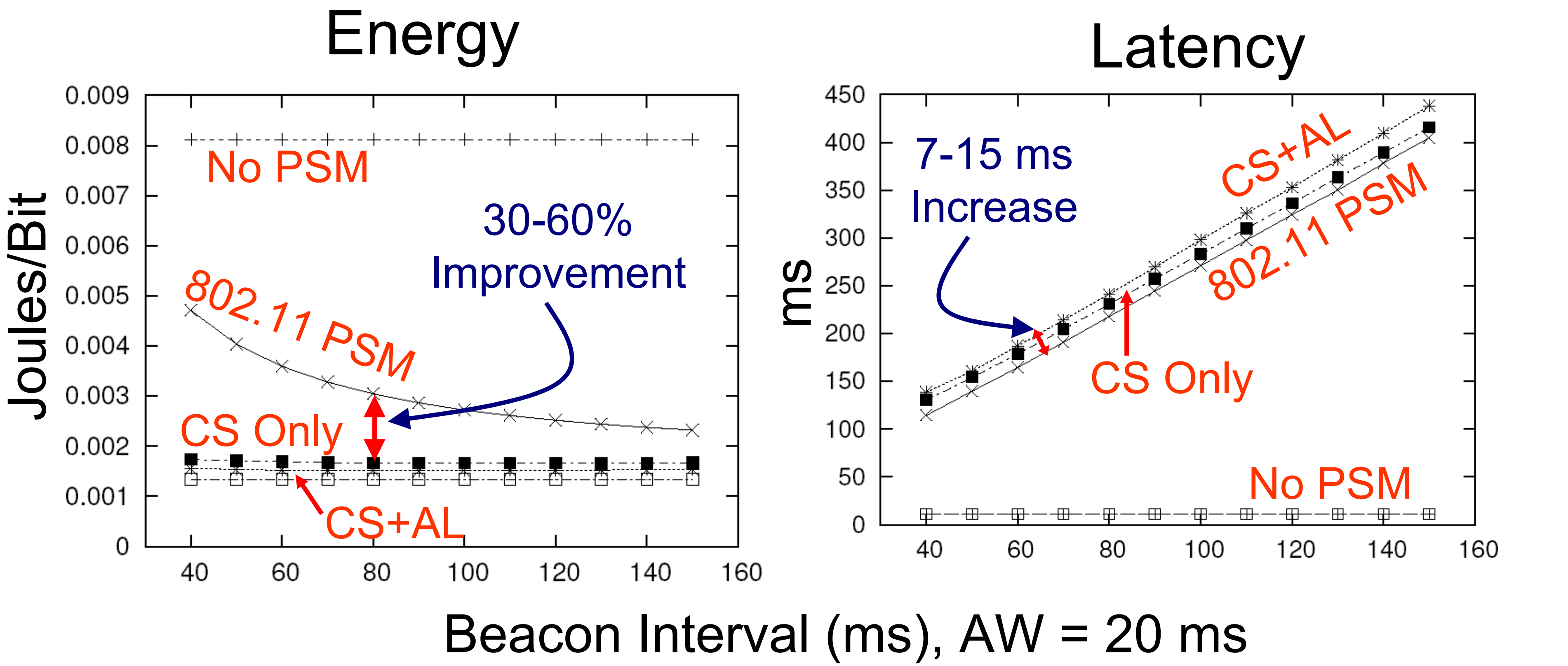


- First CS period indicates whether advertisement window is necessary
- Second CS period indicates whether window size should be fixed or adaptive
  - If a sender repeatedly fails using adaptive listening, it can fallback to the original protocol

Adaptive Listening Results

- Simulated using *ns-2*
- Five flows with source and destination selected uniformly at random
  - Low traffic = 1 kbps per flow
  - Higher traffic = 10 kbps per flow
- CS Only = Carrier sense signaling at beginning of advertisement window only
- CS+AL = Carrier sense signaling at beginning plus adaptive listening

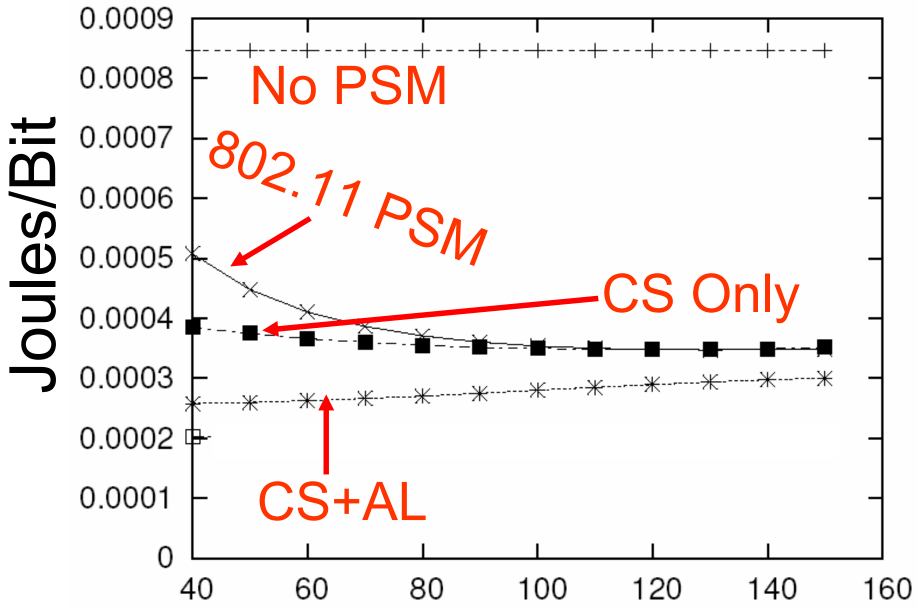
Low Traffic Results



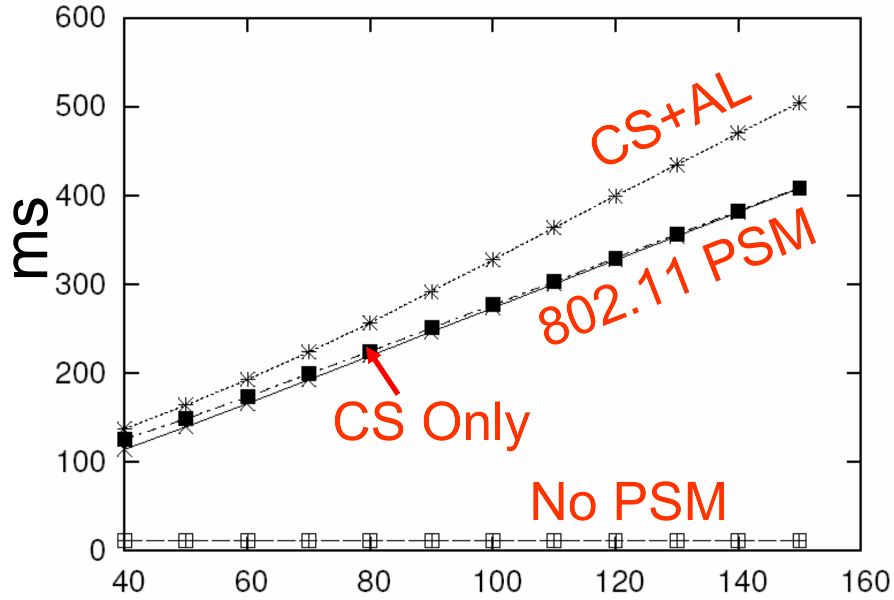
Latency Increase: (1) Additional CS periods, (2) Packets arriving during AW, (3) For adaptive listening, postponed advertisements

Higher Traffic Results

Energy



Latency



Beacon Interval (ms), AW = 20 ms

Differences from Lower Traffic: (1) More Adv. windows have at least one packet, (2) More contention means more deferred Advs.

Adaptive Energy-Saving Summary

- Static sleep and listening intervals can degrade energy efficiency
- We propose adaptive power save methods that can benefit both out-of-band and in-band protocols
  - Adaptive Sleeping [IEEE WCNC 2004, IEEE Trans. on Mobile Computing 2005]
  - Adaptive Listening [IEEE MASS 2005]

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Leveraging Channel Diversity for Key Establishment [IEEE Infocom 2006]

- Symmetric keys are favorable for resource constrained devices, but distribution is difficult
- Our idea: Exploit multiple channels available

Leveraging Channel Diversity for Key Establishment [IEEE Infocom 2006]

- Given K channels:

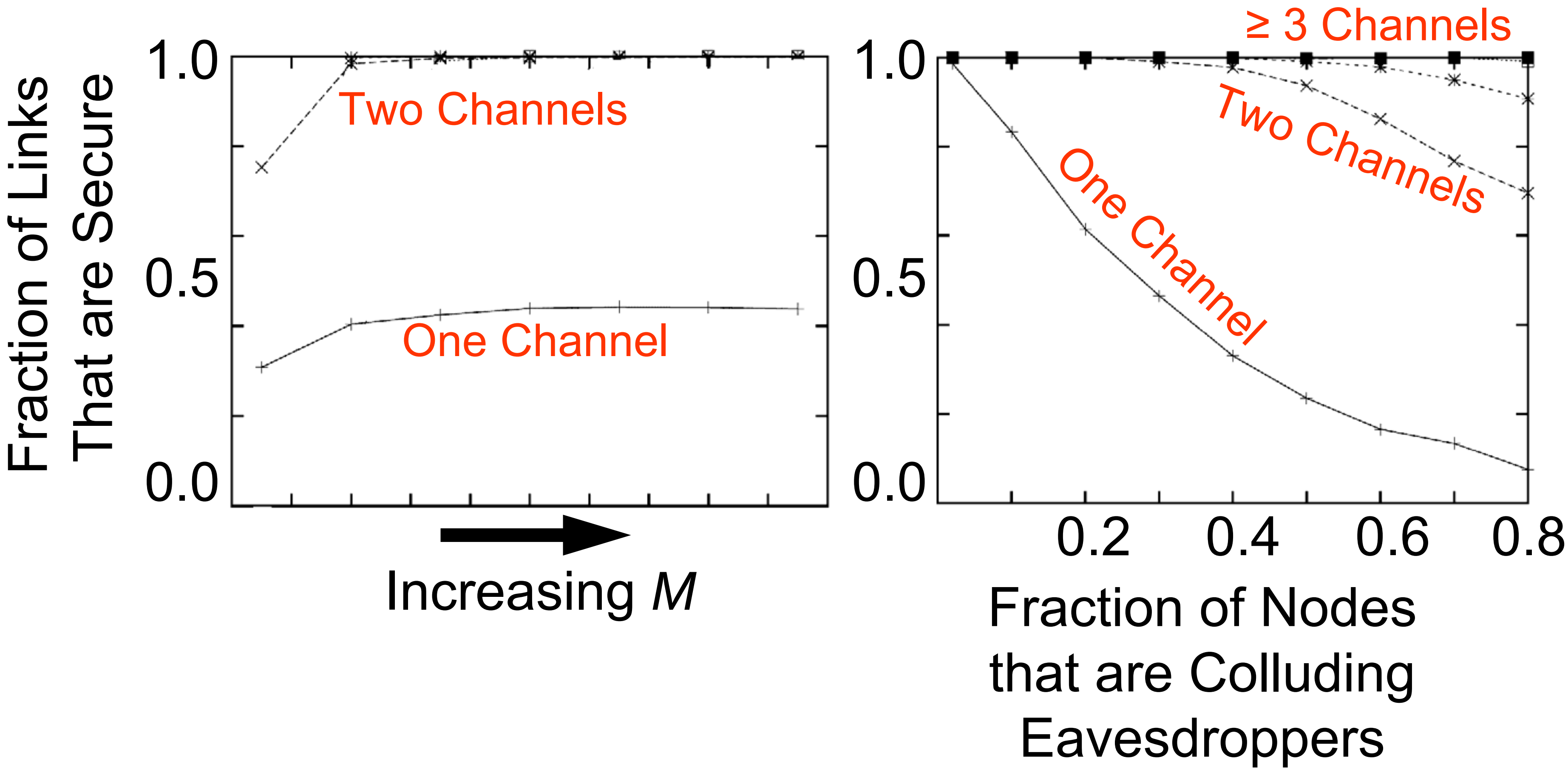
  Pr(Eve hears Bob's packet | Alice hears Bob's packet) = $1/K$

- If Alice hears M of Bob's packets, then the probability that Eve heard *all* of those packets is $(1/K)^M$

- As $(1/K)^M \rightarrow 0$:

  The packets Alice heard can be combined to create Alice and Bob's secret key

Leveraging Channel Diversity for Key Establishment [IEEE Infocom 2006]



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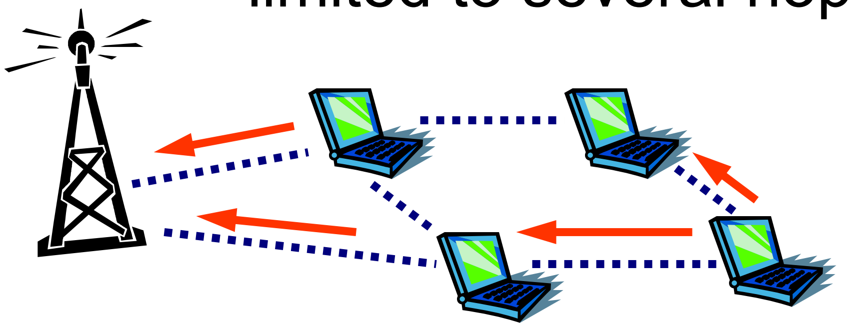
Future Research: Multihop Wireless Networks

- Performance
  - Efficient use of physical-layer diversity
  - Opportunistic channel usage
  - Integrating application knowledge in network protocol design
- Security and Privacy
  - Physical-layer diversity to counter attackers
  - Distributed detection of misbehavior

Future Research: Multihop Wireless Networks

- Experimental testbeds
  - Test protocols in a realistic setting
  - Address implementation issues
  - Prior experience
    - Implementation in TinyOS on sensor hardware
    - User-level routing protocol for hybrid networks limited to several hops from access point



Research Summary

- Adaptive Energy-Saving Protocols

	Adaptive Listening	Adaptive Sleeping
In-Band	[IEEE MASS 2005]	Multilevel routing [IEEE Broadnets 2004]
Out-of-Band	Our techniques are applicable	[IEEE WCNC 2004, IEEE Trans. on Mobile Computing 2005]

- Secure Key Distribution [IEEE Infocom 2006]
- Energy-Latency Tradeoff for Broadcast Dissemination [IEEE ICDCS 2005]
- Implementation on Sensor Hardware

Thank You!

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Sources (1/2)
(Ordered by First Appearance)

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  - http://www.state.gov/e/eb/rls/rm/2005/48757.htm
- *Report: RFID production to increase 25 fold by 2010* in EE Times
  - http://tinyurl.com/aangg
- *CNET's quick guide to Bluetooth headsets* on CNET.com
  - http://tinyurl.com/dslev
- TinyOS Community Forum: Stats
  - http://www.tinyos.net/stats.html
- NCSA/UIUC Internet Visualization Graphic
  - http://tinyurl.com/d7qgr

Sources (2/2)

- Champaign-Urbana Community Wireless Network (CUWiN)
  - http://cuwireless.net/
- DakNet
  - http://www.firstmilesolutions.com/products.php?p=daknet

Properties of Preamble Sampling

- No synchronization necessary
  - We require synchronization
- Larger preambles increase chance of collisions
  - We restrict CS signals to a time when data is not being transmitted
  - In our technique, interference is tolerable between CS signals
- Broadcasts require preamble size be as long as a BI → Exacerbates broadcast storm
  - We do not require extra overhead for broadcast
- Only one sender can transmit to a receiver per BI
  - We allow multiple senders for a receiver per BI

Is time synchronization a problem?

- Motes have been observed to drift 1 ms every 13 minutes [Stankovic01Darpa]
- The Flooding Time Synchronization Protocol [Maróti04SenSys] has achieved synchronization on the order of one microsecond
- Synchronization overhead can be piggybacked on other broadcasts (e.g., routing updates)
- GPS may be feasible for outdoor environments
- Chip scale atomic clocks being developed that will use 10-30 mW of power [NIST04]

Transition Costs Depend on Hardware [Polastre05IPSN/SPOTS]

Mote Radio Model	Wake-Up Time (ms)	TX/RX/ Sleep (mW)	Bitrate (kbps)
TR1000 (*1998-2001*)	0.020	36/12/ 0.003	40 ASK
CC1000 (*2002-2004*)	2	42/29/ 0.003	38.4 FSK
CC2420 (*2004-now*)	0.580	35/38/ 0.003	250 O-QPSK

Related Work

- Carrier Sensing
  - B-MAC [Polastre04SenSys]: Make the packet preamble as large as the duty cycle
  - WiseMAC [ElHoiydi04Algosensors]: Send the packet preamble during the receiver's next scheduled CS time
  - We apply CS to synchronous protocols
- Dynamic Listening Periods
  - T-MAC [VanDam03SenSys]: Extends S-MAC to increase the listen time as data packets are received
  - DPSM/IPSM [Jung02Infocom]: Extends 802.11 for dynamic ATIM windows in single-hop environments
  - We use physical layer CS to work in multihop environments without inducing extra packet overhead

Other Research

- Adaptive Framework for Energy-Saving Broadcast [IEEE ICDCS 2005]
  - Probabilistic protocol gives flexibility to choose tradeoffs in energy, latency, reliability, and overhead for broadcast dissemination
- Routing using multiple power save states
  - Metrics to find energy-efficient states for nodes on a path while achieving a desired latency