Wireless Sensor Networks: Past, Present and Future

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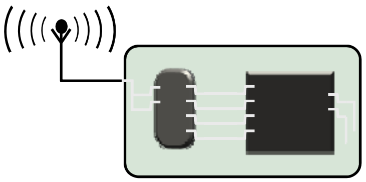
We Will Address…

- What are sensor networks?
- Why are sensor networks interesting?
- Why are sensor networks challenging?
- What is the state-of-the-art in sensor networking?
- What is network management, and why is adaptation crucial for sensor networks?
- What are the interesting research directions?

Wireless Sensor Networks

- Participants in “traditional” networks
  - Devices close to a human user
  - Interact with humans

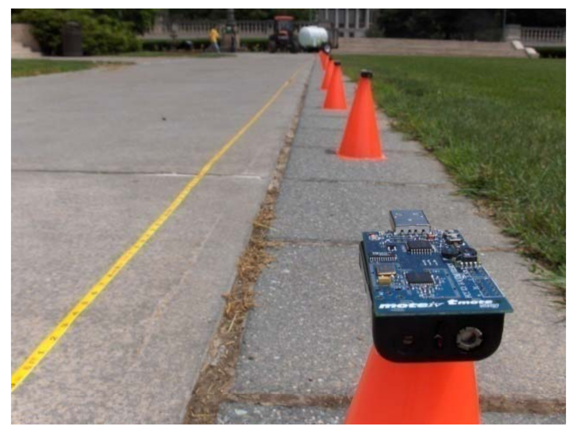


- Alternative concept
  - Focus on interacting with environment
  - Network is *embedded* in environment
  - Nodes in the network are equipped with sensing and actuation to measure/influence environment
  - Nodes process and communicate information

Wireless sensor networks (WSN)
Wireless sensor & actuator networks (WSAN)

Wireless Sensor Nodes

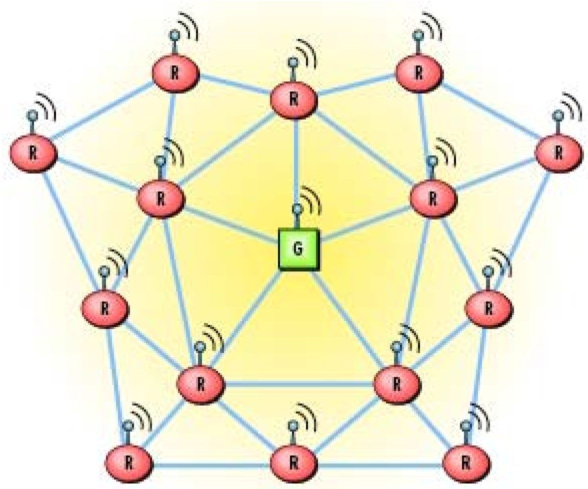
- Sensors monitor environment
  - Cameras, microphones, physiological, pressure, biological sensors, etc.
  - Sensor data limited in range and accuracy
- Sensor nodes
  - Sensor module (e.g., acoustic, seismic, image)
  - Digital processor for signal processing and network protocol functions
  - Radio for communication
  - Battery-operated



Wireless Sensor Networks

Networks of distributed data sources that provide information about environmental phenomena to an end user or multiple end users

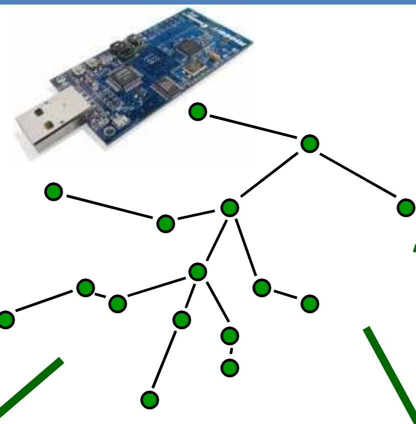
- Tens to thousands of nodes scattered throughout an environment
- Data routed via other sensors to
  - One or more sinks or base stations
  - Other sensors
- Unique characteristics
  - Ad hoc network
  - No end-to-end communication
  - Co-operative operation
  - Redundancy in information



WSN Advantages

- Networking sensors enables
  - Extended range of sensing → improved quality
  - Fault tolerance due to redundancy in data from different sensors
  - Distributed processing of large amounts of data
  - Duty-cycling individual nodes
  - Scalability: quality can be traded for system lifetime
  - Collaboration: nodes can help each perform a larger sensing task
- New wireless networking paradigm
  - Requires autonomous operation
  - Highly dynamic environments
    - Sensor nodes added/fail
    - Events in the environment
  - Distributed computation and communication protocols required

Sample Applications



Health monitoring

Structural Integrity

Environment Monitoring

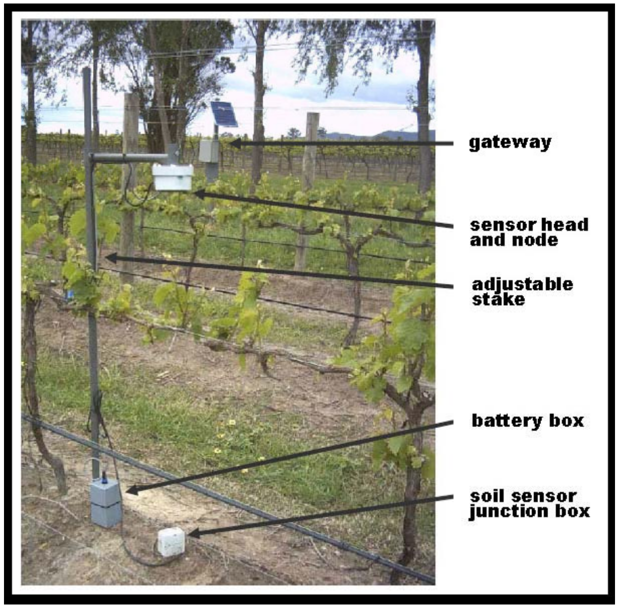
Security

Environmental Monitoring

- Raw sensor data or high level descriptions about environmental phenomena
- Example projects
  - ZebraNet: mobile nodes, on-board data storage
  - Ecology of rare plants in Hawaii: static nodes, low temporal resolution

Precision Agriculture

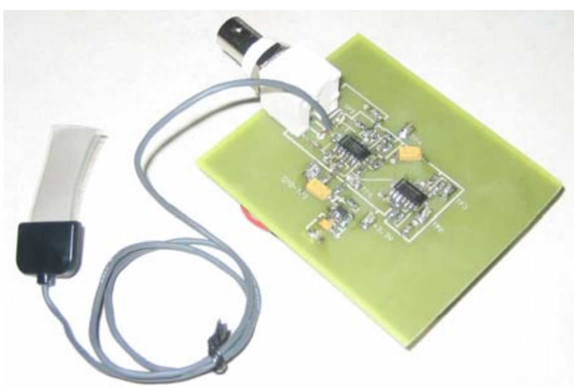
- Deliver fertilizer/pesticides/irrigation only where needed
- Grape Networks
  - California-based company: WSN covers 50 acres, > 200 sensors
  - WSN broadcasts
    - Location of the sensors
    - Temperature, humidity, light
    - Powdery mildew
    - Degree days
  - Sensors buried next to grapes
  - Can view data over web
  - Can set thresholds for automatic alerts
- Many similar projects on monitoring vineyards

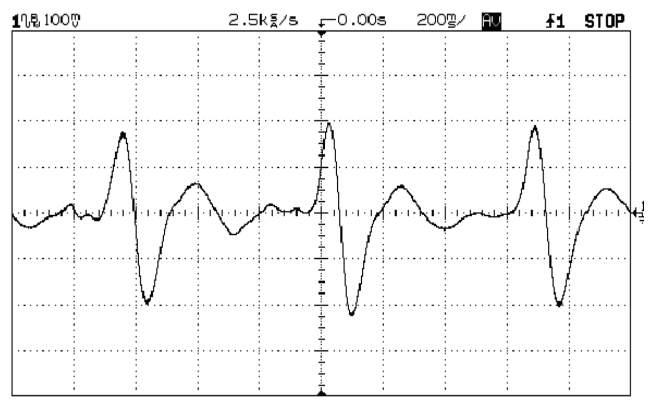


Source: http://blog.xbow.com/photos/uncategorized/2007/10/18/nodedeployment_2.jpg

Health Monitoring

- Sensors monitor vital signs
  - Blood pressure, heart rate, EKG, blood O2
- Sense, process, understand, control
- Requires protocols that are
  - Reliable, flexible, scalable, secure



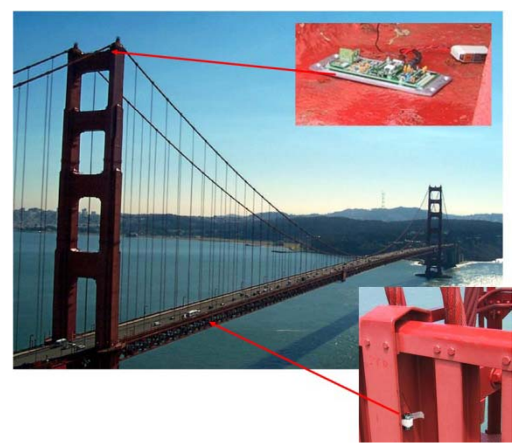


Other Applications

- Disaster relief operations
  - Deploy sensors in area hit by disaster (fire, earth quake, etc.)
  - Derive a “map” of safe/dangerous areas within building, grounds, etc.

Source: http://www.disasterlogistics.org/assets/images/Turkey_Earthquake_103.jpg

- Intelligent buildings (or bridges)
  - Reduce energy waste by proper HVAC control
  - Predict structure failures



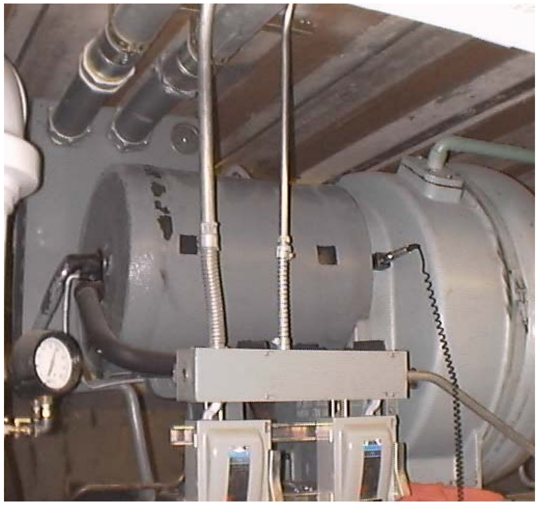
Source: http://ds.informatik.rwth-aachen.de/teaching/ws0607/labsn

Other Applications

- Facility management
  - Intrusion detection into industrial sites
  - Control of leaks in chemical plants

Source: http://www.merl.com/projects/images/zigbeeipm.jpg

- Machine surveillance and preventive maintenance
  - Monitor machines for signs of wear and tear
  - Create automatic alerts



Source: http://www.vafmechanical.com/400ch210.jpg

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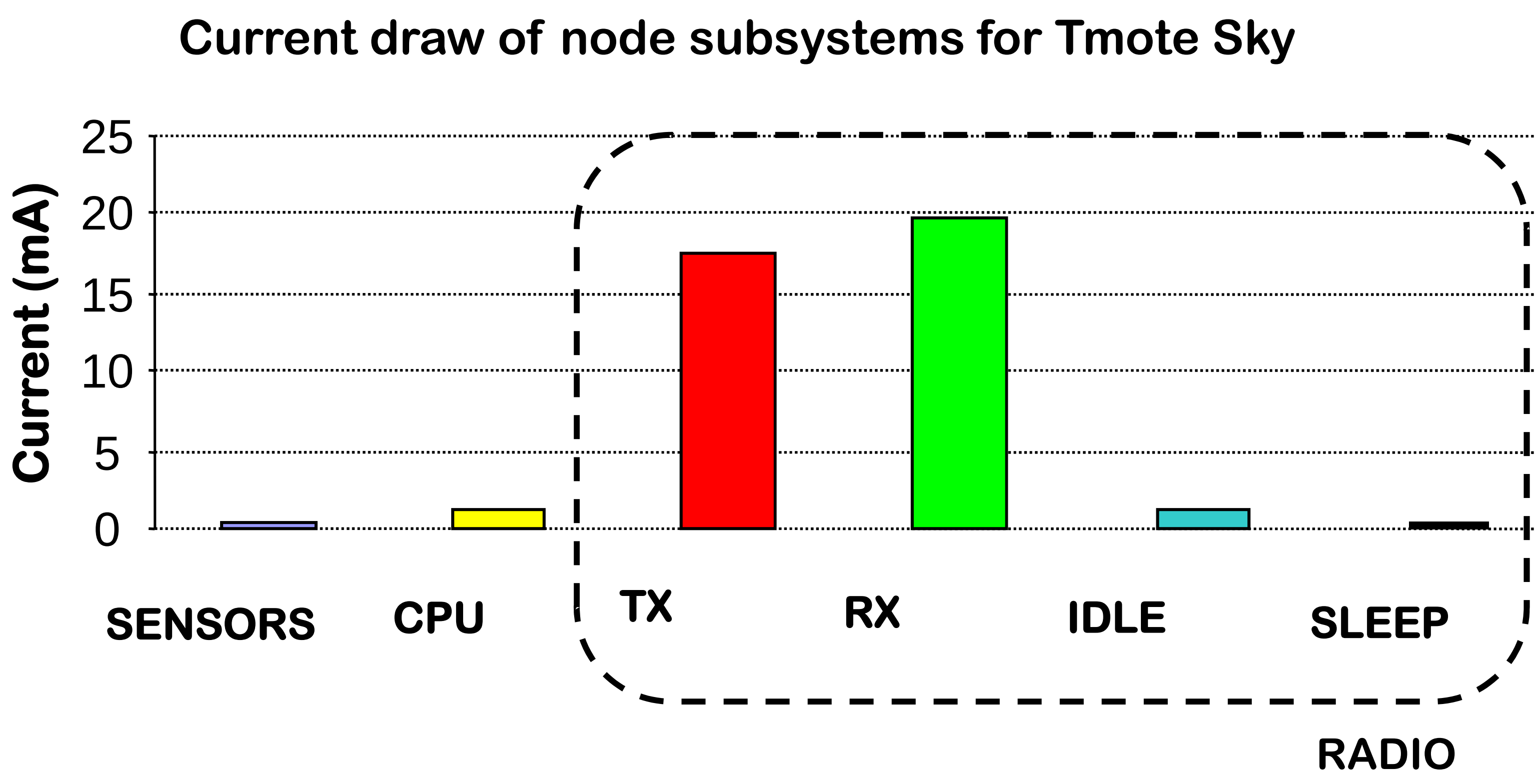
WSN Limitations

- WSNs extremely *resource-limited*
  - Goal is to control use of resources while maintaining application's required quality of service (QoS)
  - Limited in bandwidth, energy, computational power, memory
- Communication
  - Bandwidth is limited and must be shared among all the nodes in the sensor network
  - Spatial reuse essential
  - Efficient local use of bandwidth needed
  - Application should influence data sent in a network
    - TCP assumptions of fair-share of bandwidth no longer valid

WSN Limitations (cont.)

- Sensor energy
  - Each sensor node has limited energy supply
    - Nodes may not be rechargeable
    - Eventually nodes may be self-powered
  - Energy consumption in sensing, data processing, and communication
    - Communication often the most energy-intensive
    - For some sensors (e.g., imagers), sensing may also be energy-intensive
    - Must use energy-conserving protocols

Sensor Node Current Draw



- Operating voltage: 2.1 – 3.6 V

WSN Limitations (cont.)

- Sensor device
  - Computation: many sensors use simple processors → cannot handle complex signal processing or protocol operations
  - Memory: many sensors have small memory → code must be efficient, intelligent storage protocols needed for data storage
  - Buffers: limited memory implies small buffers → need intelligent buffer management to ensure important data not lost due to overflow

Evaluating WSNs

- What are the performance metrics for WSNs?
- System lifetime
  - How to define lifetime? Application-specific, each application will have its own definition of when network stops supporting application
  - E.g., time until network partition
  - E.g., time until probability of missed detection exceeds a threshold
- Quality of result of sensor network
  - Application-specific measure
  - Latency of data transfer
  - SNR of aggregate data signal
  - Probability of missed detection or false alarm
  - Coverage probability
  - Tracking accuracy

Evaluating WSNs (cont.)

- Fault tolerance/reliability
  - Network should be robust to individual node failures
  - Failures due to running out of energy, hardware failures, malicious intercept of sensor, etc.
- Scalability
  - Protocols must scale to thousands or millions of sensor nodes
  - Requires intelligent management of high densities of nodes
- Security
  - Especially important in some sensitive applications
- Cost
  - Goal is to provide long-lasting networks that support QoS for low cost!

Evaluating WSNs (cont.)

- Tradeoffs can be made among these parameters
  - Can reduce quality of result of sensor network to increase system lifetime
  - Can increase security (uses more energy) at the expense of a shorter system lifetime or lower quality sensing results
  - Can support scalability by adding higher cost sensor nodes (e.g., with longer range for transmitting data out of the WSN)
- Important to understand application goals
  - Design decisions should be made accordingly

Some History…

- Networking sensors dates back to 1970's
  - Small scale systems
  - Large, expensive, power-hungry sensors
  - Wired implementations
  - Uses: primarily machine monitoring
- Research into current-day large-scale, low-power wireless sensor networks began in mid-90's, exploded in early 2000's
- Evolved from advances in several areas
  - Radio/communication efficiency
  - Mobile ad hoc networking
  - Embedded computing/pervasive computing
  - MEMS devices (sensors)
  - Low-power hardware design (VLSI)
  - Data mining
  - Distributed detection and distributed signal processing
- Crossroads led to WSNs

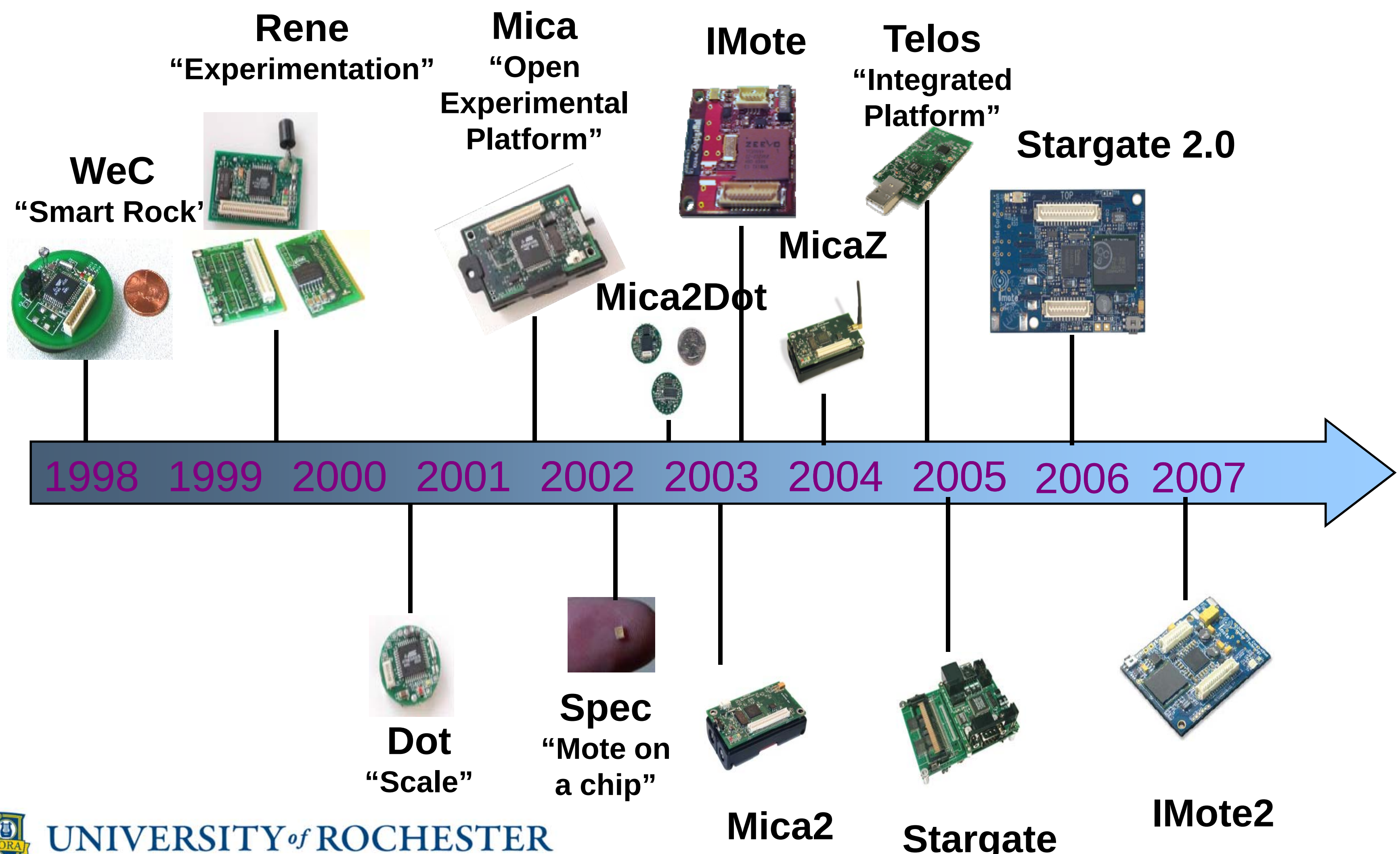
Some Early Projects

- DARPA ISAT (Information Science and Technology) study 1997-1998 – primary driver for research on WSNs in US
- WINS project
  - UCLA and Rockwell Science Center
  - Focus on developing low-power electronics
  - Some of the first wireless sensor devices
- μAMPS project
  - MIT
  - Focus on developing low power sensor nodes, signal processing algorithms and networking capabilities for large-scale systems
- TinyOS, motes, etc.
  - Berkeley
  - Developed commercial hardware ("motes"), open-source software for running motes (TinyOS)
  - Easily programmable, full function devices – enabled much research and implementation with real systems

Current Projects

- Too numerous to list!
- Literally thousands of research projects devoted to all aspects of WSN design
  - Hardware
  - Software
  - Networking
  - Signal processing
  - Data analysis
  - Etc., etc.
- Hundreds of commercial applications
  - Precision agriculture
  - Weather monitoring
  - Health monitoring
  - Machine/structure monitoring
  - Security and surveillance
  - Logistics control
  - Military applications

Sensor Motes Timeline



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Source: D. Pompili, "Wireless Sensor Networks: Introduction and Applications"

Current State-of-the-Art in Sensor Hardware

Crossbow MICAz mote
http://www.xbow.com

Sentilla Tmote Sky
http://www.sentilla.com

Crossbow/Intel Imote2
http://www.xbow.com

Ember EM250
http://www.ember.com

ETH BTNode
http://www.btnode.ethz.ch

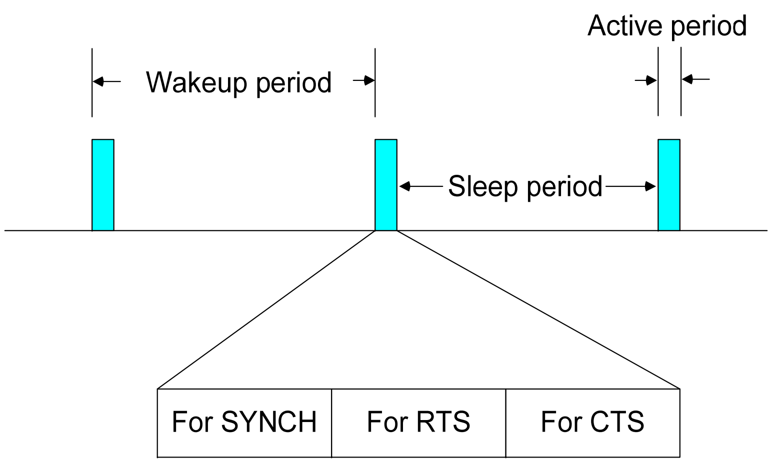
Crossbow IRIS 2.4 GHz
http://www.xbow.com

Current State-of-the-Art in Sensor Networking

- Thousands of different protocols for WSNs
- 10 top-tier conferences dedicated entirely to WSN research
  - Additional 10 or so workshops
  - Many networking and communications conference also feature tracks or special sessions on WSNs
  - 1 journal dedicated to WSN research, several others often feature WSN research
- What makes wireless sensor networking so unique?

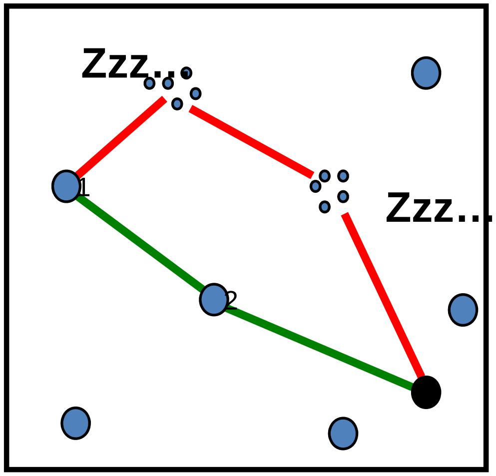
Design Issues– MAC

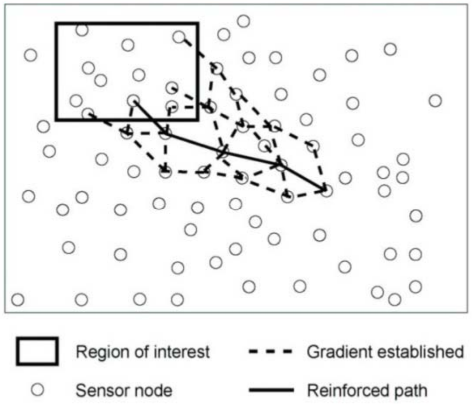
- Cooperative nature of sensor networks
  - Fairness not an issue
  - Sensors should not compete for limited bandwidth
- Exploit traffic patterns
- Energy efficiency extremely important
  - Reduce idle listening
  - Reduce unnecessary reception
- Example protocols
  - Scheduled: TDMA protocols, LEACH
  - Contention-based: S-MAC, T-MAC, DMAC, TRAMA, STEM
  - Low-power listening: B-MAC, X-MAC, STEM, C-MAC

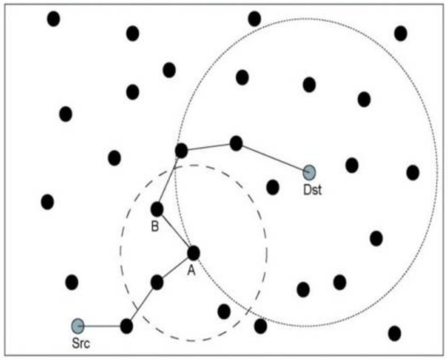


Design Issues– Routing

- Different traffic models
- Data dissemination rather than P2P routing
- Data-centric rather than address-centric
- Location-aware sensors
- Resource-aware routing needed
- Exploit local aggregation
- Time-varying channels leads to necessity for dynamic routing approaches
- Types of routing in WSNs
  - Resource-aware routing
  - Data-centric routing
  - Geographic routing
  - Clustering







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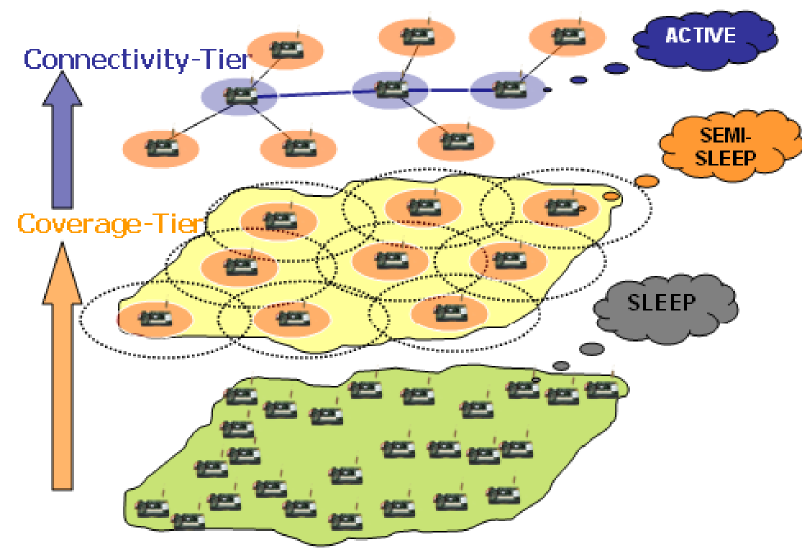
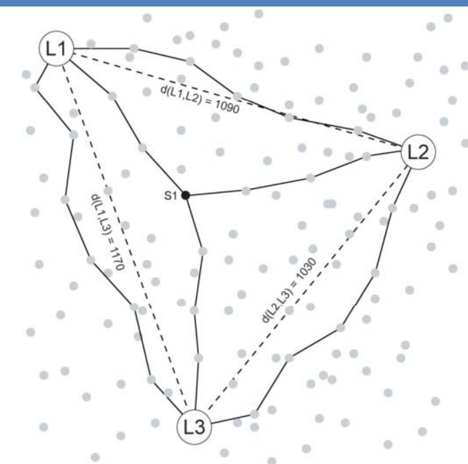
Design Issues– QoS Management

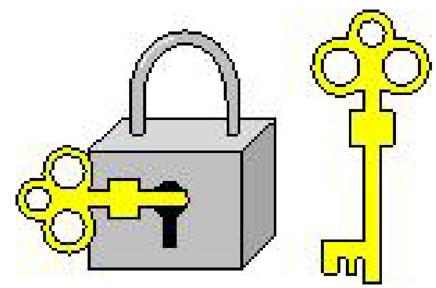
- QoS determined by content of data rather than amount
- Transport layer
  - Intelligent congestion management
  - Throttle back irrelevant data rather than each node's sending rate
- Sensor selection
  - Ensure the correct sensors provide data
  - E.g., coverage: each location monitored by at least K sensors



Design Issues– Services

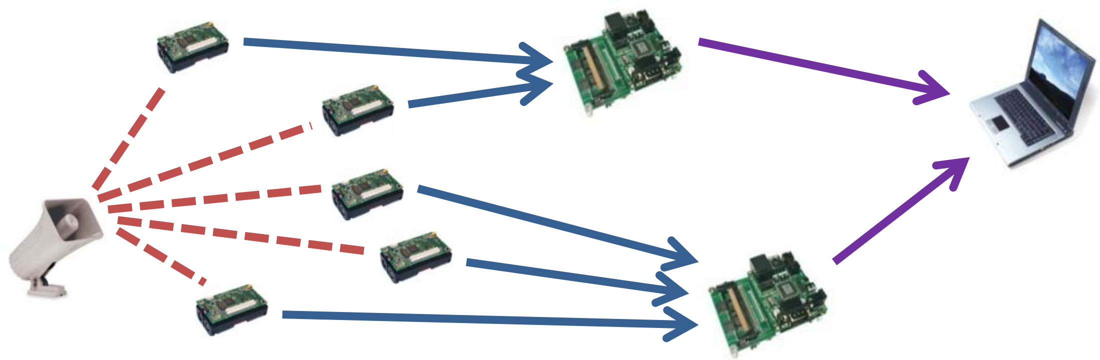
- Localization
  - Needed to determine where events occur
  - Often times, only relative position is necessary
- Time synchronization
  - Needed to determine if event sensed by two sensors is in fact the same event
  - Needed to determine object speed
- Security
  - Should be thought about from the inception of the network
  - Use scalable and application-specific security to ensure “the right” data protected





Adapting WSNs

- Goal: Support WSN applications by providing only required data
- Network requirements
  - Flexible
  - Robust
  - Long-lived
- Network limitations
  - Channel bandwidth
  - Radio energy



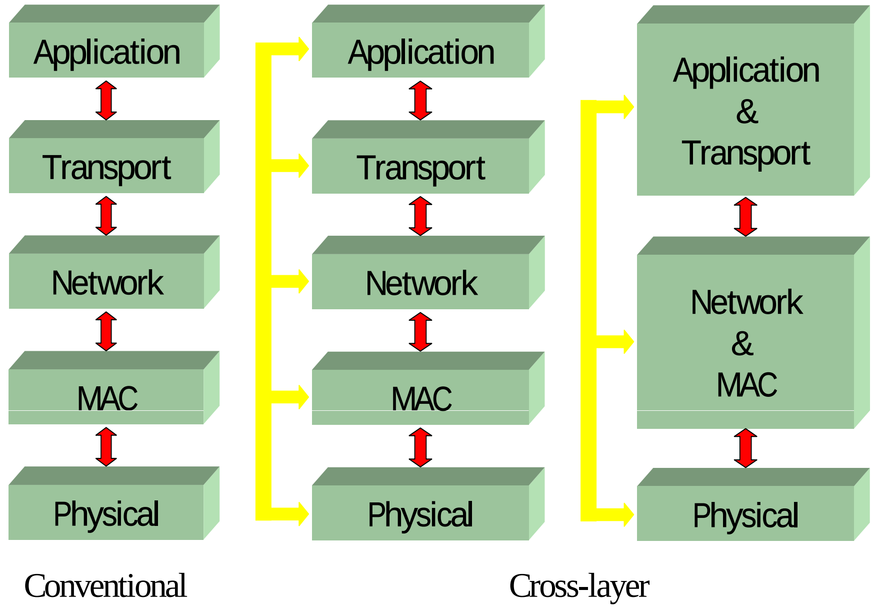
Network and radio resources must be managed on multiple levels to provide required QoS while efficiently using limited resources

WSNs Must Adapt

- To changes in
  - Application goals
  - Network conditions
  - Sensed phenomena
  - Environmental conditions
  - Available resources
- Need an architecture to allow protocols' parameters to be adjusted dynamically
  - E.g., if intrusion detected, enable more frequent reports for radios close to detected activity
  - May need to reduce reports from other, non-critical sensors until either enough information gathered or the threat is over
  - Protocols must be flexible to support such changes quickly, seamlessly
- Challenges
  - Sharing information among protocols
  - Translating application goals into protocol parameters
- University of Rochester's current research on transformative architectures
  - X-Lisa information sharing architecture
  - MiLAN middleware

Protocol Architectures

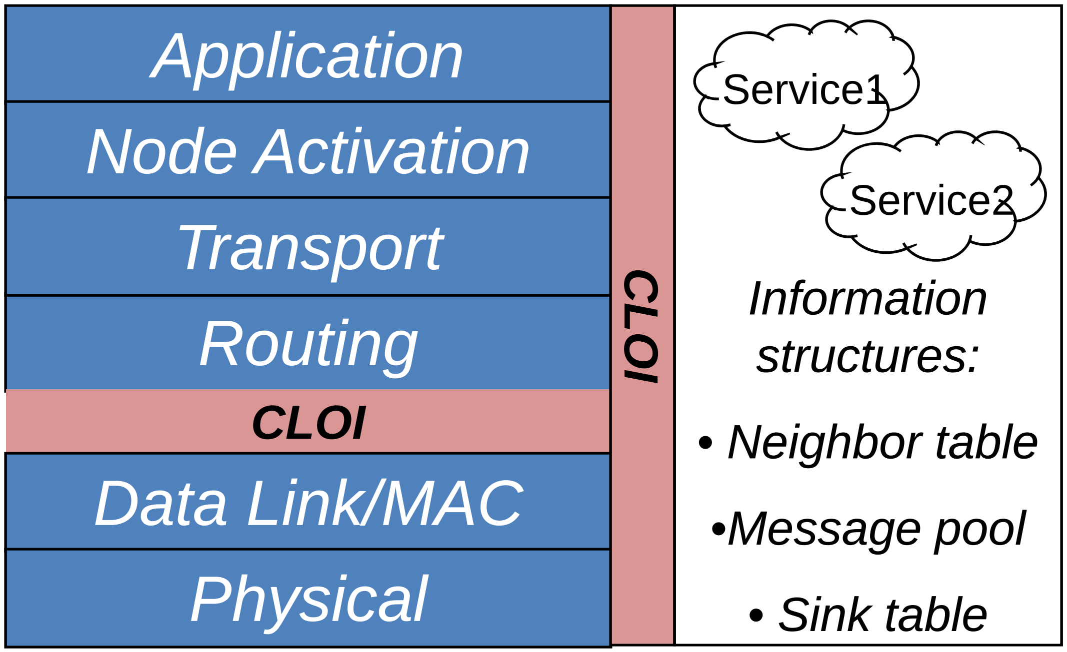
- Cross-layer design: two or more layers cooperate to improve network's response
  - Layer fusion: operations from two or more layers performed jointly
  - Information sharing: several layers share information
- No standardized cross-layer architecture



- Our goal: develop a new architecture that maintains layered structure for flexibility while supporting network-aware and application-aware protocol parameter setting

X-Lisa: X-layer Information Sharing Architecture

- Maintain layered stack but enable information sharing
- Cross-layer optimization interface (CLOI)
  - Repository for information that can be used for optimizations
  - Provides services
- Enables layers to
  - Share predefined set of information
  - Re-focus on main functions



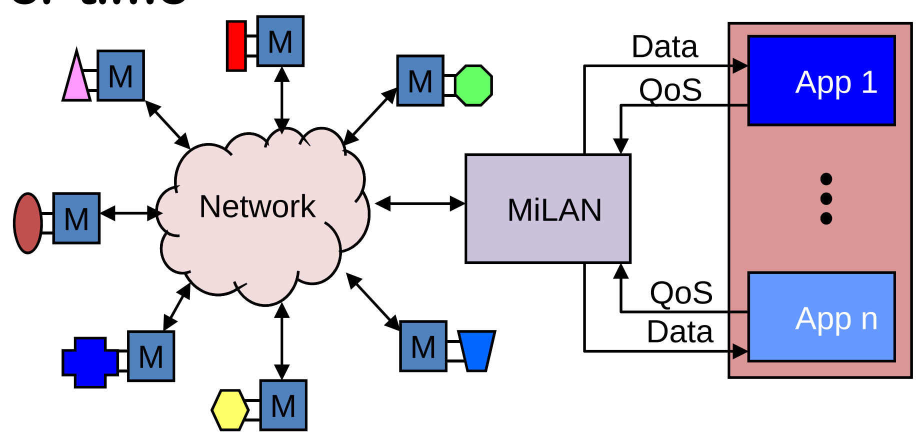
Discussion

- CLOI is not proactive
  - Provides information to all layers
  - Lets protocols act on information
- X-Lisa allows sharing structures: saves space
- Information exchange costs energy: find best value-for-cost
- X-Lisa provides
  - Structured yet flexible architecture
  - Enables protocols to focus on basic functions
  - Allows protocols to optimize parameters based on current network conditions
- Missing
  - Need to add a connection between the possibly time-varying application goals and the protocols– MiLAN

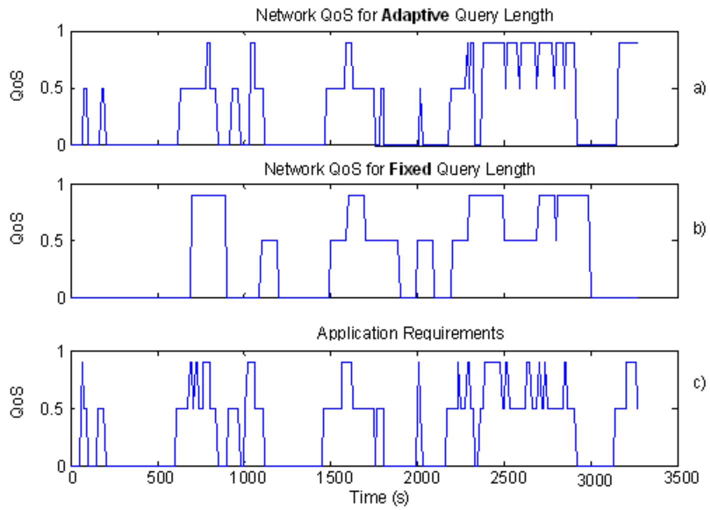
MiLAN: Middleware Linking Applications and Networks

Applications/users should *not* need to keep track of low-level components, but *should* influence how network is reconfigured over time

- Take input from
  - Application/users (on goals and performance)
  - Network (on physical limitations and cost)
- Use information to optimize protocol parameters
- Adjust protocol parameters over time
- Enable trade-off of performance for cost

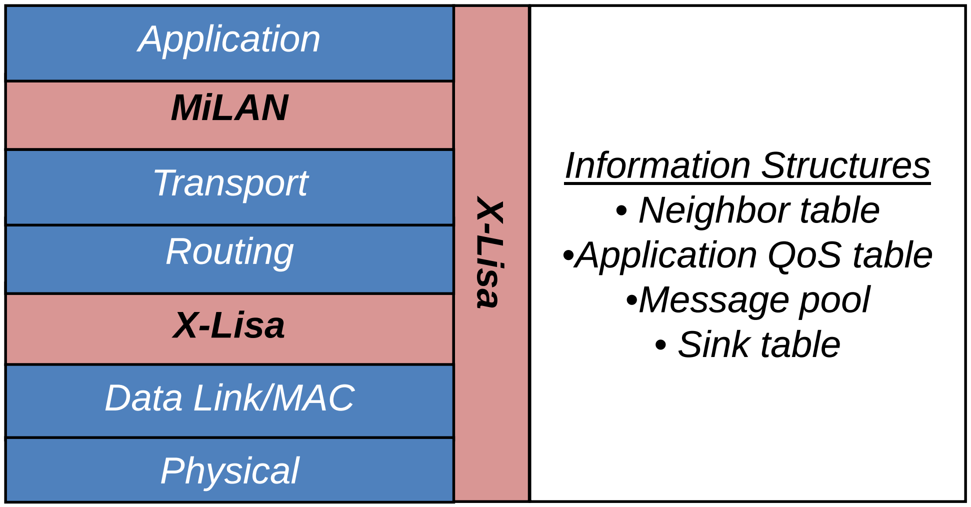


Application-aware Decisions



- Initial work shows large promise when protocol parameters adapted based on application-level information
- Need to integrate MiLAN with X-Lisa to enable both application-aware and network-aware decisions

Enabling Adaptive and Efficient Networks



- X-Lisa
  - Provides means to update network protocols
  - Allows all protocols to maintain consistent view of the network
  - Enables easy access to relevant network and application information
- MiLAN
  - Translates application goals to protocol QoS parameters
  - Allows application to "control" network operation
  - Dynamic adjustments as application goals change

Adaptation Rules

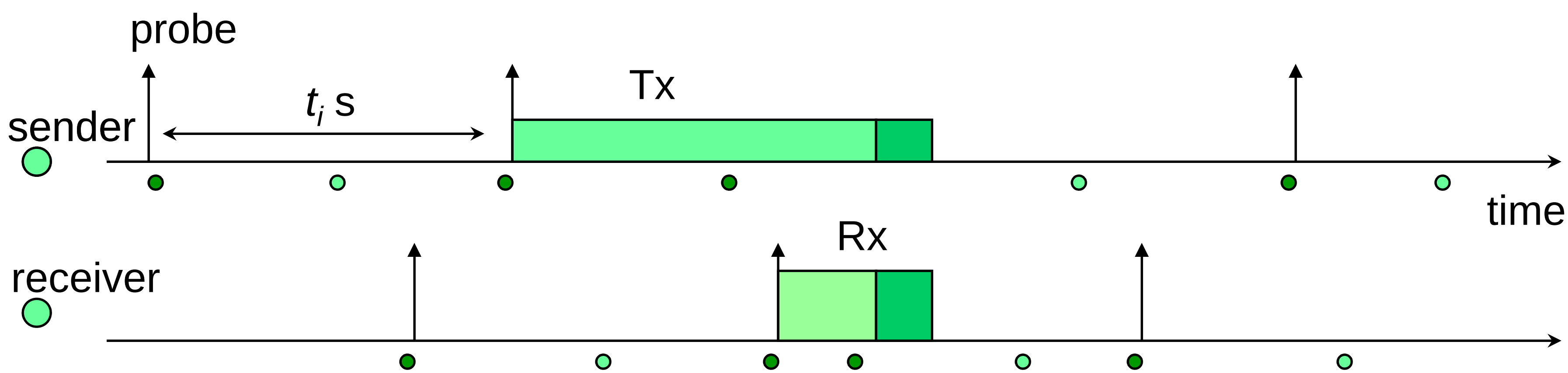
- Given appropriate architecture (MiLAN and X-Lisa), question becomes *how* to adapt protocols, algorithms
- Look at adaptation of individual protocols' parameters
  - Need to determine:
    - *How* parameters should be changed
    - *When* parameters should be changed
    - *Sensitivity* of parameter adjustments
- Also need to look at joint optimization
  - Multiple protocols (e.g., MAC and PHY)
  - Protocols with algorithms, such as distributed source coding (DSC)
- Initial work looking at adaptation of the MAC and PHY layers shows this approach beneficial…

PHY, MAC and Energy Consumption

- Overall energy consumption is dominated by energy required for communication
- PHY and MAC layers are the "closest" layers to energy consumption
  - PHY and MAC designs greatly impact the overall energy consumption
- We need to find PHY and MAC schemes that provide
  - Minimum overall energy consumption in the network
  - Maximum utility for the WSN application
  - Adaptability to changes in network and application requirements

Low Power Listening MAC Protocols

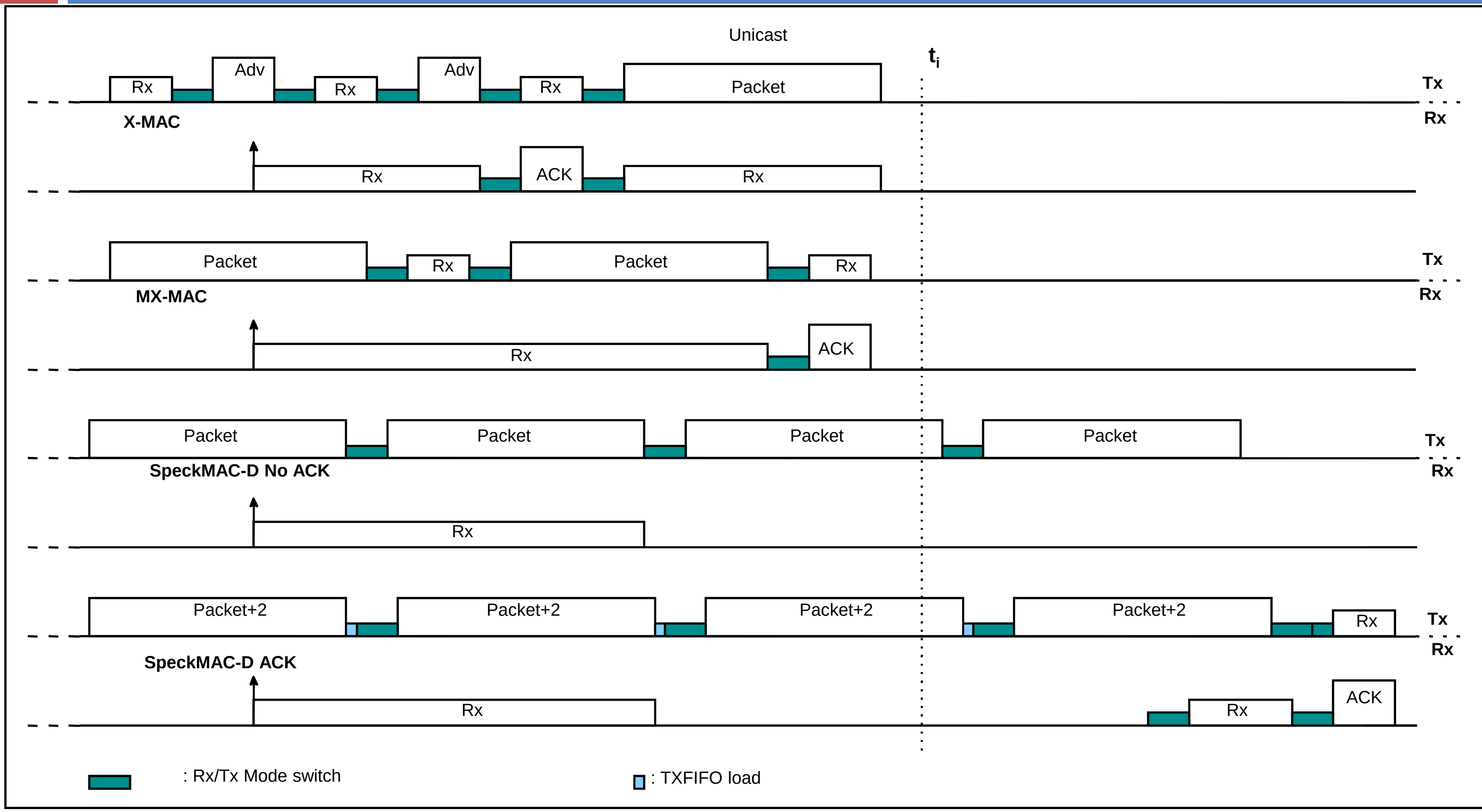
- Idle listening consumes much energy
  - Previous MAC protocols use periodic sleeping, but synchronization required
- B-MAC first introduced low power listening
  - Radio probes channel every t_i s
  - Sleeps between CCAs (clear channel assessments)
  - Long preamble > t_i sent before data packets



X-MAC/SpeckMAC/MX-MAC

- X-MAC
  - Repeatedly sends small advertisement packets
  - Embed target address to announce packet transmission
  - Destination must send an acknowledgment
- SpeckMAC
  - Repeats packet itself to act as a long preamble
- MX-MAC
  - Sends data packet instead of advertisements
  - Easy to adapt to broadcast

LPL Schedules



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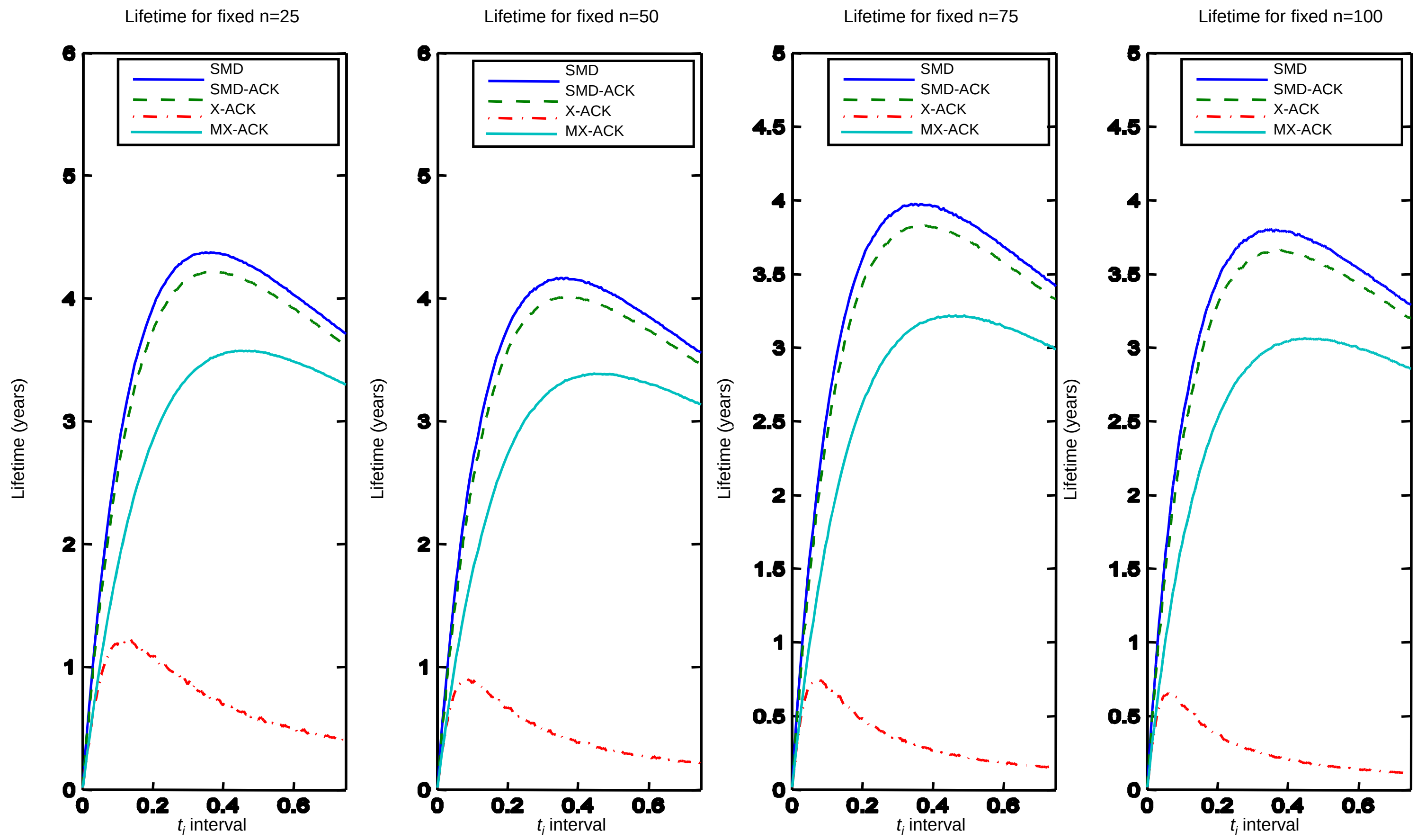
Broadcast Results



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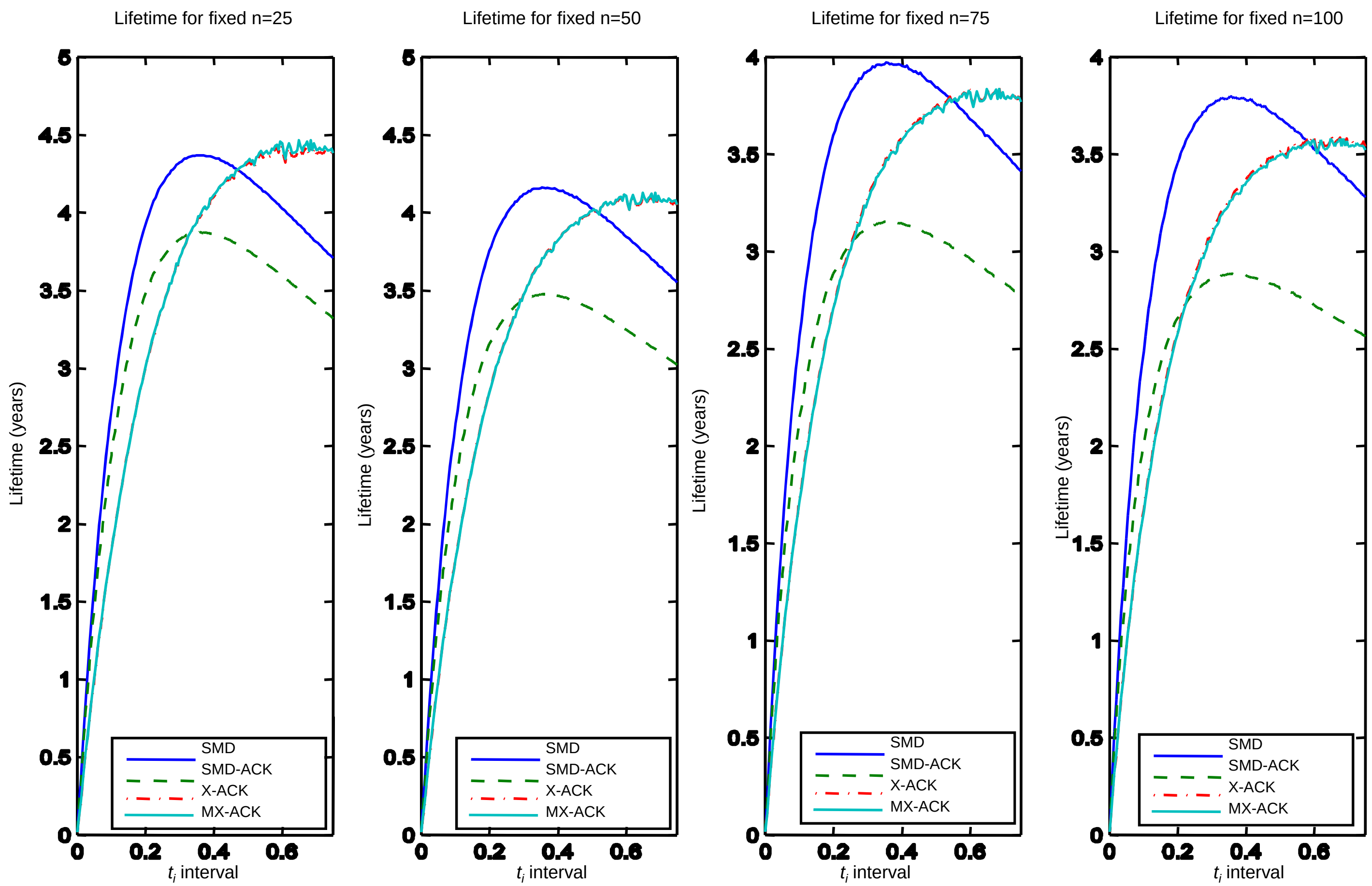
Unicast Results



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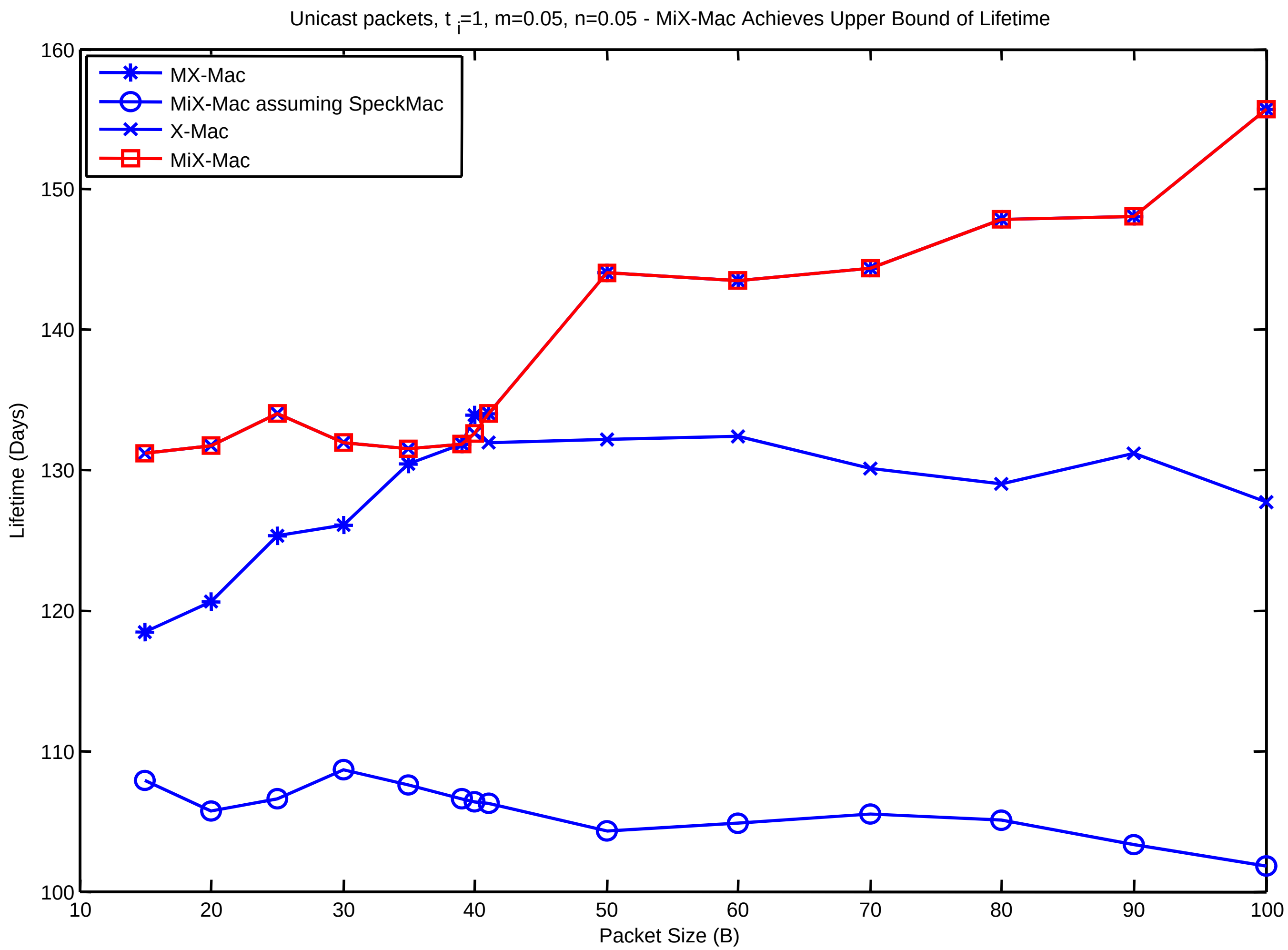
MiX-MAC: Adapting the MAC Schedule to Network Conditions

- MiX-MAC uses a look up table
  - t_i
  - Packet size
  - Rx/Tx ratio
  - Broadcast / unicast nature of packet
- Adopts schedule performing best from pool of compatible MAC protocols
  - SpeckMAC-D
  - MX-MAC
  - X-MAC
- Receiver does not need to know schedule of sender
  - Only sends an ACK when required
- MiX-MAC achieves upper bound of node lifetime for all t_i

MiX-MAC Achieves the Upper Bound of Node Lifetime



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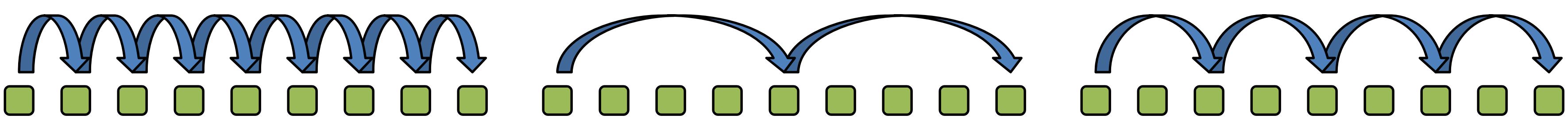
Adaptive PHY Design

- Traditional PHY design: minimize *Transmit Power (SNR)*
- Energy Aware PHY design: minimize *Energy Consumption*
  - Include processing energy consumption
  - Consider *Energy per Successfully Delivered Bit per Meter (ESBM)*
- Adapt to network topology and conditions
  - Number/length of hops
  - Channel conditions



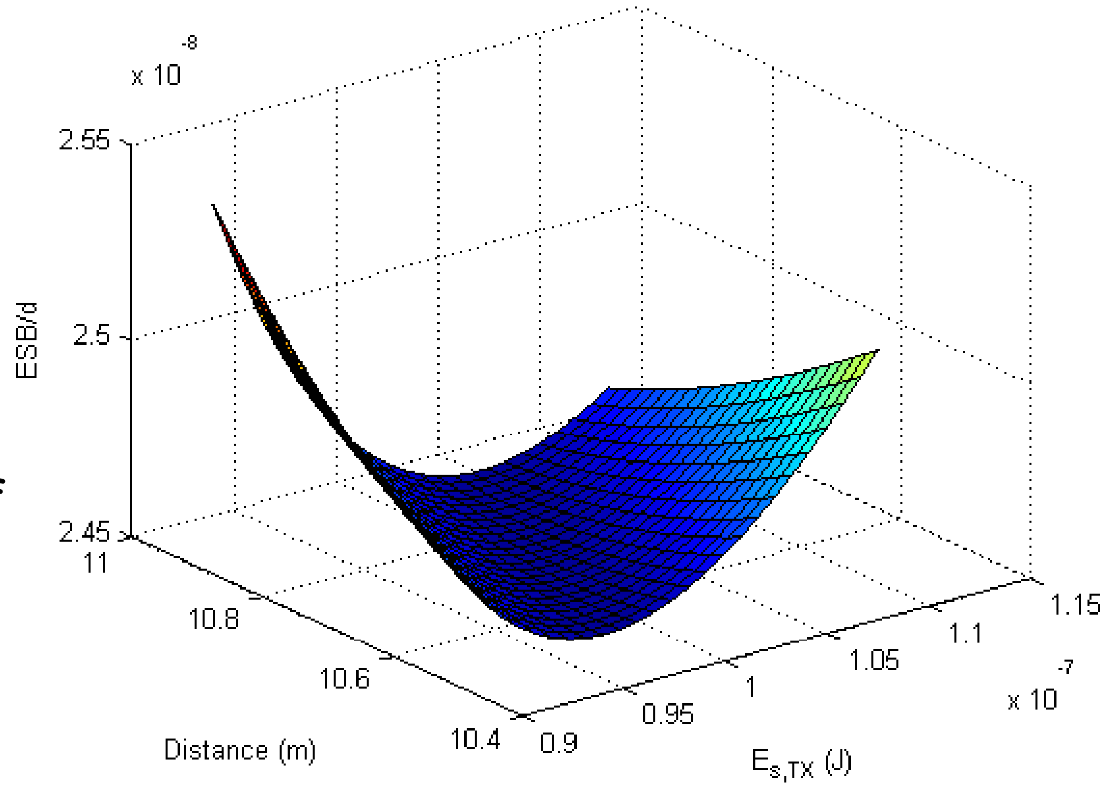
Short hops: High energy consumption due to large number of hops

Long hops: High energy consumption due to high energy consumption for each hop

Optimum hops: Optimum trade-off point between consumption of each hop and number of hops

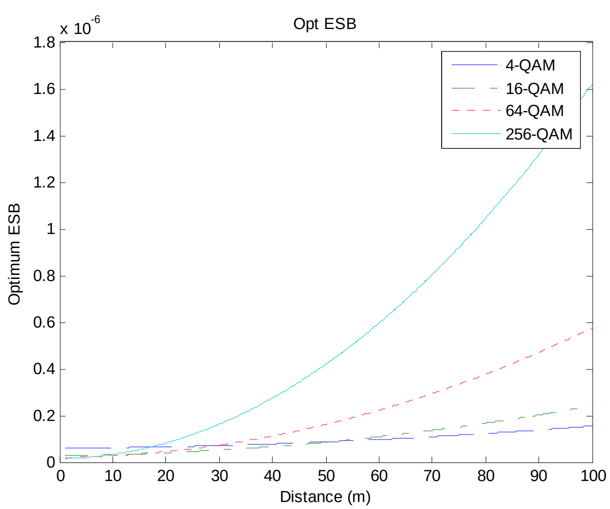
Optimizing ESBM

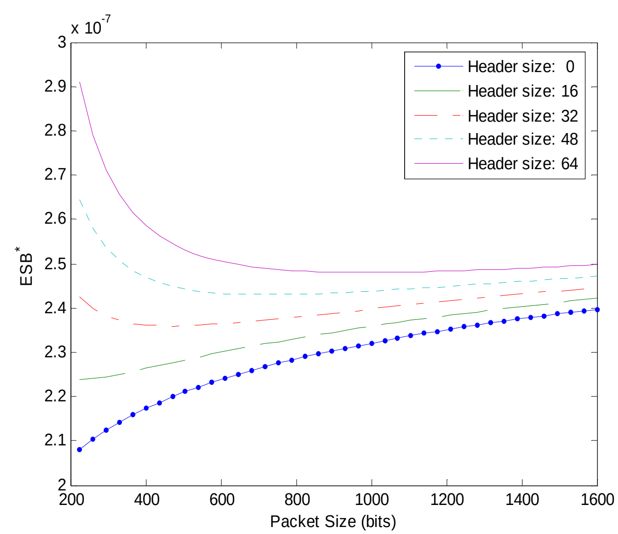
- Clear optimal transmit power to minimize energy for successful data transfer
- Optimal point a function of
  - Energy dissipation model
  - Channel model
  - Receiver sensitivity



Adaption Possibilities at PHY

- In addition to transmit power, can adapt
  - Hop distance
  - Packet size
  - Modulation type
  - Modulation order (e.g., change M for M-ary modulation)
- Determining optimal PHY requires network-level and application-level information → X-Lisa/MiLAN





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Need for Future Research

- With all the advances in sensor networks from the hardware to the network protocols to the algorithms, it is in some ways surprising that sensor networks are still not mainstream (like the Internet, cell phones, WiFi, etc.)
- Implies much research still needed!
- Sensor networks need to become
  - Easier to set up
  - Easier to maintain
  - Longer lifetimes
  - Greater flexibility
  - Connection to other networks
  - Cheaper

Future Research Needed

- Appropriate QoS model
  - What are good QoS parameters and how can these be described efficiently for use in protocol optimizations?
  - Automation of translation of QoS goals into protocol parameters → applications for WSNs will become much easier to design!
- Supporting heterogeneous applications
- Closing the loop via actuation
- Distributed and collaborative signal processing
- Data fusion and data mining for new information from data
- Supporting new medium
  - Underground WSNs
  - Underwater WSNs
- Integration of WSNs with other networks: Internet, WiFi, WiMAX, etc.
- Enhancing reliability at all levels of the protocol stack
- Protocols for self-powered sensors
- Securing WSNs
- Visual sensor networks