Communications and Networking Session:

Cross Layer System Design for Sensor Networking

Dr. Jason Redi

BBN Technologies

Cambridge, MA

redi@bbn.com

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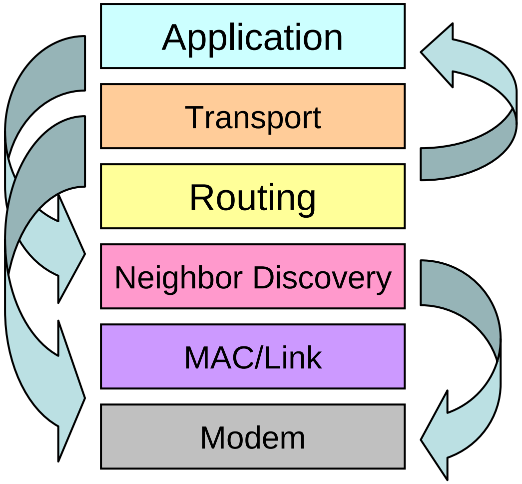
Relation Between Cross Layer and Sensing

- Sensors
  - Widely varying densities
  - Large numbers of nodes
  - Minimal resources (CPU, energy, bandwidith)

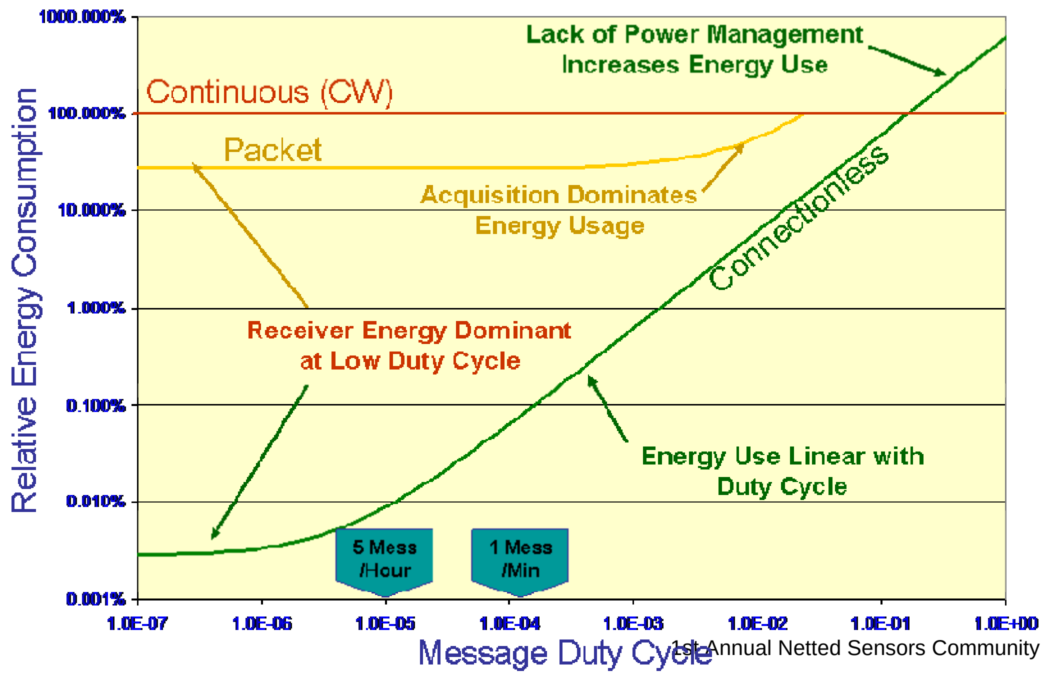
- Cross-layer
  - Network and software people compartmentalize information and algorithms.
  - Cross-layer is a philosophy of sharing information available in module A for the improved performance of module B.
  - Can provide potential performance benefit at cost of system complexity

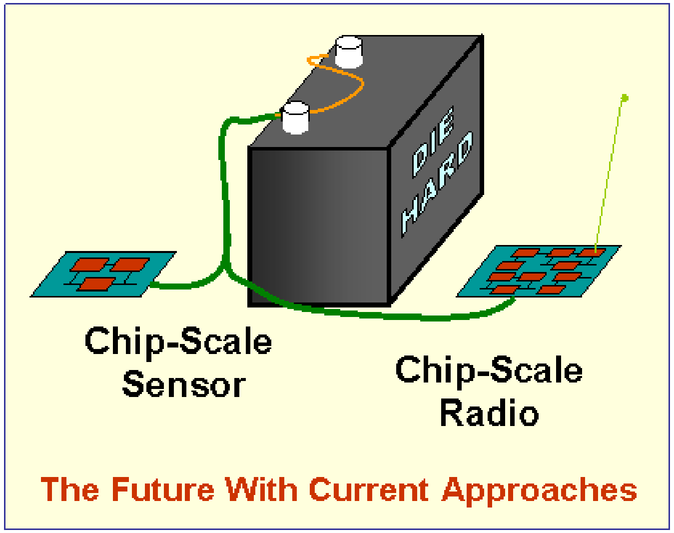


- This talk will overview some cross-layer methods used in one particular sensor networking program

DARPA Connectionless Networks Program

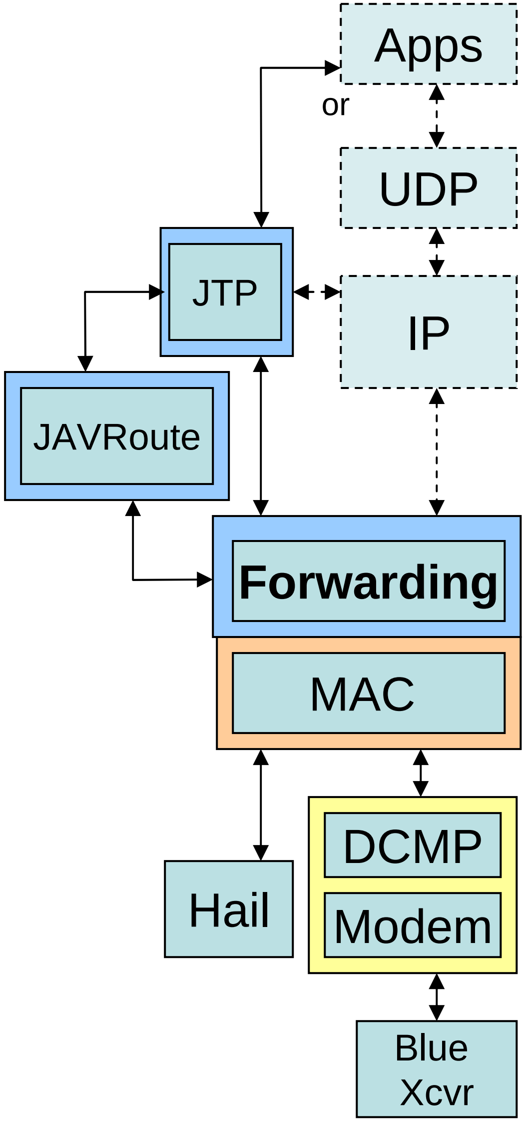
- Size/Weight/Power of Sensing and Digital Components Continues to Drop
- Energy Required to Send a Bit Remains Constant
  - Driven by Shannon's Law and Physics
- Energy Required by RF Link and Network Topology Limits Lifespan, Miniaturization, Covertness, …
- Systems designed for high offered load are energy inefficient at low loads
  - But we need high offered load *too*





JAVeLEN

- Joint Architecture Vision for Low Energy Networking (JAVeLEN)
- Two Example Methods for Cross-Layer Sensor Networks
  - End-to-End Transport protocol with mid-hop operation
  - Dynamic Time Synchronization



Observations about Multi-hop

- **Wireless BER is so bad that we use P2P-ACKs for unicast packets.**
  - We can *overload* P2P-ACKs to handle some error cases (e.g. queues full).
- **A to B and B to A paths are usually the same**
  - Therefore E2E Packets and E2E-ACKs will flow over the same nodes.
  - If path does not change, any retransmissions will flow over the same nodes and the original transmission.
  - Useful to cache packets in mid-path to response to E2E-NAKs early in the path.
- **Things the Network "knows":**
  - Reachability
    - Can help with establishment and disconnection indication.
  - Path length
    - Can help with initial determination of bandwidth-delay product.
  - Hop-by-Hop costs
    - JAVeLEN estimates energy and link utilization and reports that as hop-by-hop costs.
    - Can help with estimate of non-congestion wireless packet losses.
  - Network Topology
    - Can help with identifying backup or alternative paths.
  - Any of this information might still be temporarily wrong or changing.

Reconsidering the need for an End-to-End protocol

- **"A funny thing happened on the way to the destination…"**
- **Exceeded retransmissions in mid-path**
  - No CTS (for RCDA) or no ACK (for DA only)
    - Might mean that node is no longer there
  - Got CTS, but no ACK
    - Node is there, but congestion likely
    - Can wait and try later (but not too long) OR
    - Try an alternative path
  - Nodes can measure local RF energy (if non-spread), correlation (if spread), and promiscuous packets to estimate if area is typically "busy".
- **Arrived at node in mid-path OK, *but:***
  - No next-hop
    - Path to destination lost during packet's travels
    - Can send along alternative route (source route) OR,
    - Can send explicit NAK back to source (assuming path to *source* still exists)
  - No space in queues
    - Solution – don't allow packets if no space available. Use a NAK packet and push problem back to previous hop.
    - Either wait, send along alternative path, or send NAK back to source.

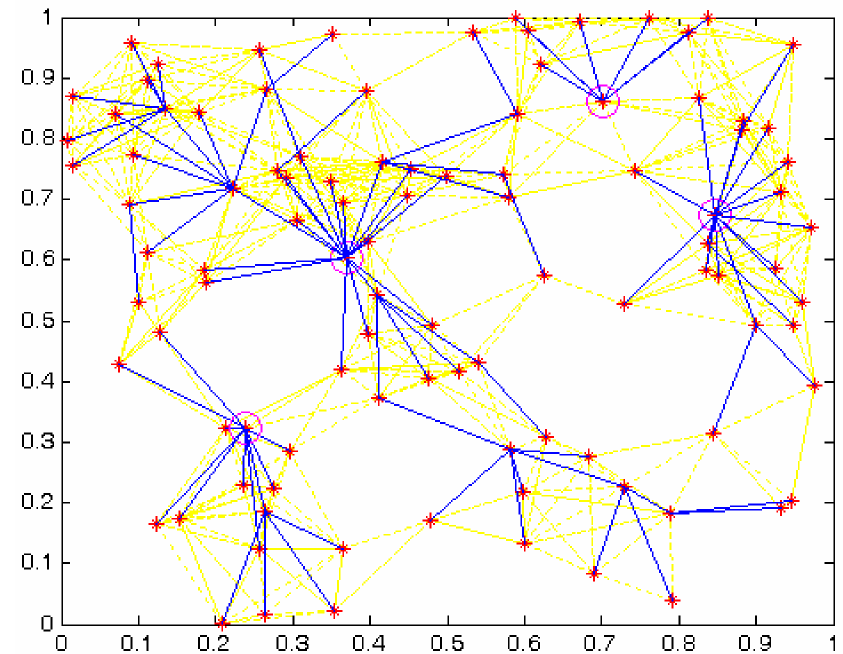
Solutions to E2E Packet Losses

- **Arrived at node in mid-path OK, *but: (con't)***
  - Node destroyed or rebooted
    - Everything seems OK, but packets just never gets past one particular hop.
    - Only solvable with E2E acknowledgements
  - Internal error in node (surprisingly common – [StonePartridge01])
    - Hardware or software pointer corrupted, Bus timing errors, etc.
    - Only solvable with E2E acknowledgements

- **Summary**
  - Need both E2E-ACKs and P2P-ACKs
    - P2P-ACKs deal with lousy wireless BER, E2E-ACKs deals with errors P2P can't catch
  - Send E2E ACK
    - Have Non-ACK'd data and no new data is received for a period of time or
    - Received *X* packets without sending E2E-ACK.
    - Sequence numbers indicate missing data for more than 2x expected delay.
    - End of stream indication received.
  - Overload P2P-ACKs
    - Provide Data NAK to indicate no route, queue full, etc.
    - Allows previous hop to make alternative decision.
  - Overload E2E-ACKs
    - Informs source to stop injecting data.
    - Informs nodes along the path to drop packets (and caches) to the dest.

Dynamic Time Synchronization

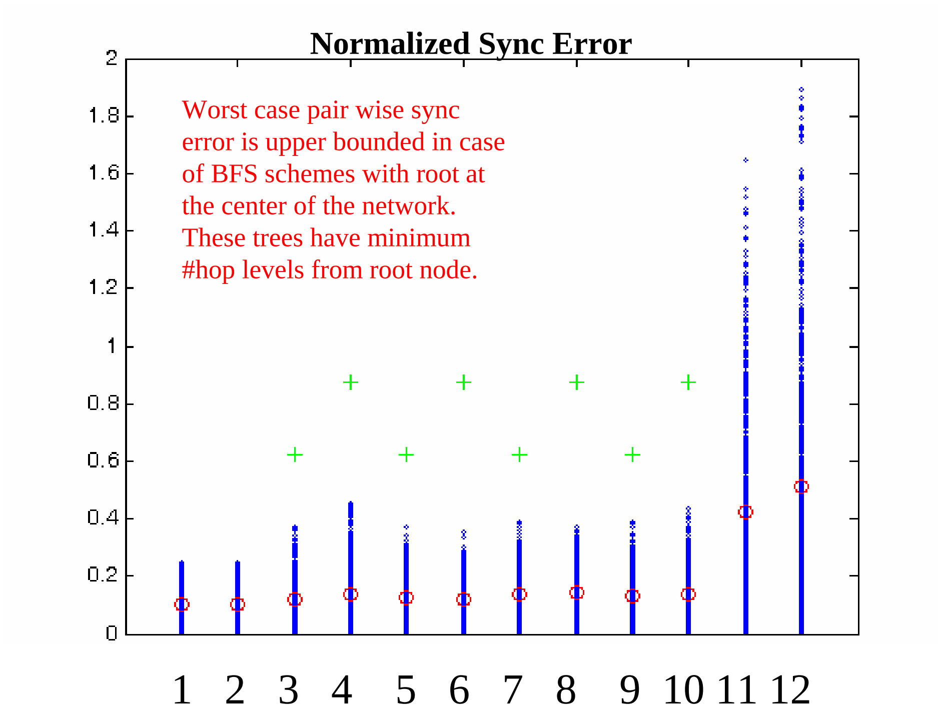
- **Background**: Low offered load environments need sync for shutting down receivers according to slots.
- **Problem:** Real clocks have time drift
  - 1ppm clock in 100kbps radio drifts 0.1 bit time per second, two nodes drift 120kbps in a week.
- **Solution:**
  - Dynamic time synchronization
    - Election of leader/root
    - Computation of energy efficient "sync-tree"
    - Slot-alignment messages along sync-tree
    - Maintenance of tree and slot re-synchronization



Circled nodes are "local roots"
One among them will be elected the leader

Sync-trees

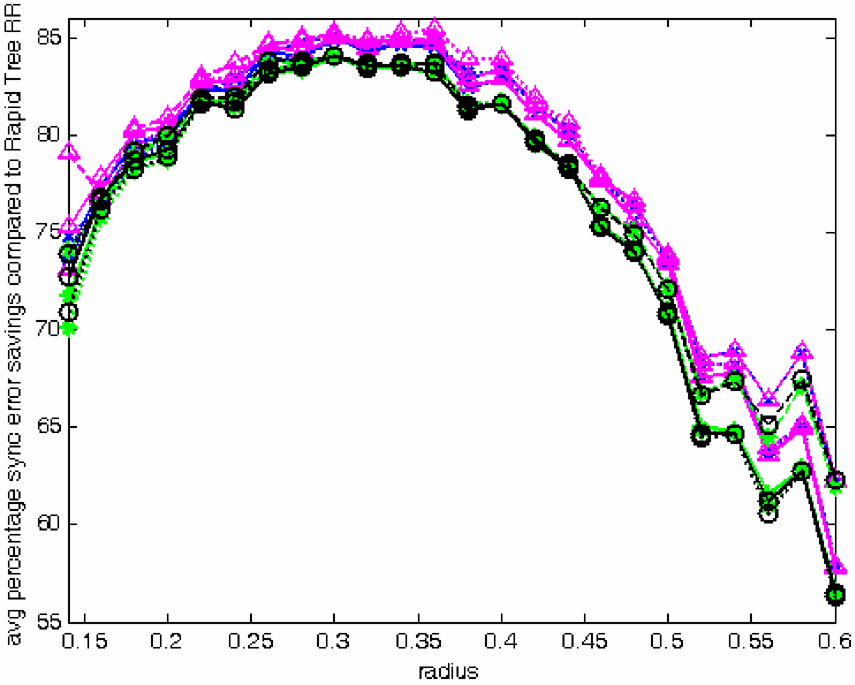
- Sync-tree : a spanning tree of the network topology graph
- Several optimality considerations
  - Minimize worst case pair wise sync error between any two neighboring nodes in the network topology (influences guard time provisioning)
  - Minimize number of transmitting nodes in the tree (Should minimize the #slot-align message transmissions during later phases of the protocol.)
- It is hard to construct a tree that satisfies all the above properties → Use heuristics



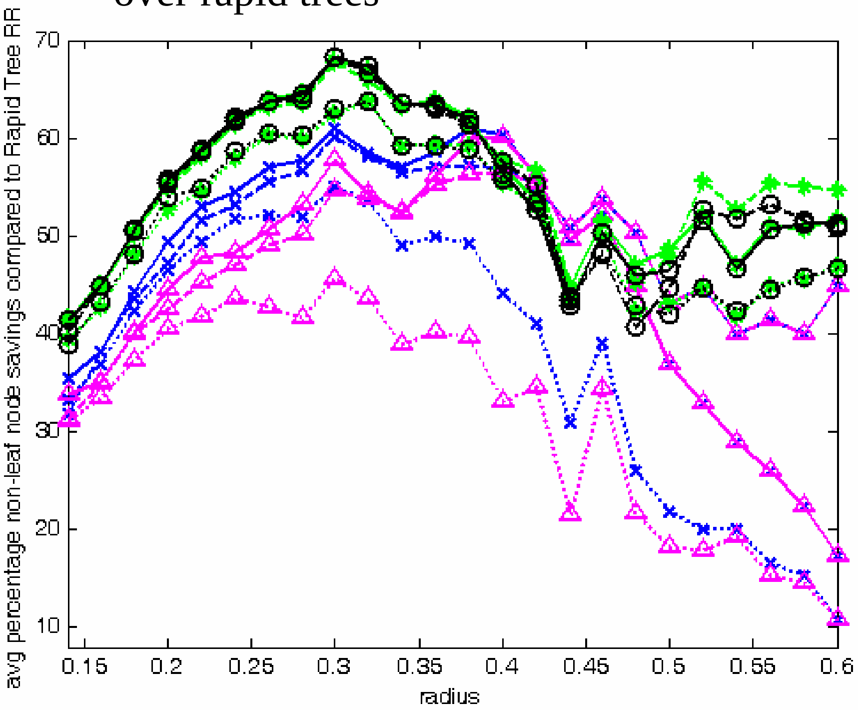
1: Min-distance Dijkstra (center root)
2: Min-distance Dijkstra (random root)
3: Min-hop Dijkstra (center root)
4: Min-hop Dijkstra (random root)
5: BFS (center root)
6: BFS (random root)
7: BFS node-sorted (center root)
8: BFS node-sorted (random root)
9: BFS edge-sorted (center root)
10: BFS edge-sorted (random root)
11: Rapid (center root)
12: Rapid (random root)

Performance Evaluation

% savings in worst case sync-error of BST trees over rapid trees



% savings in number of transmissions for slot-align messages of BST trees over rapid trees



Conclusions

- Sensor systems have new and complex networking needs.
- Sensor networks require holistic (re)thinking about networking system design.
- Many cross-layer methods are available, but all must be balanced against real benefit and complexity.