Wireless Embedded Systems and Networking

Foundations of IP-based Ubiquitous Sensor Networks

Robust Embedded Networking

David E. Culler

University of California, Berkeley

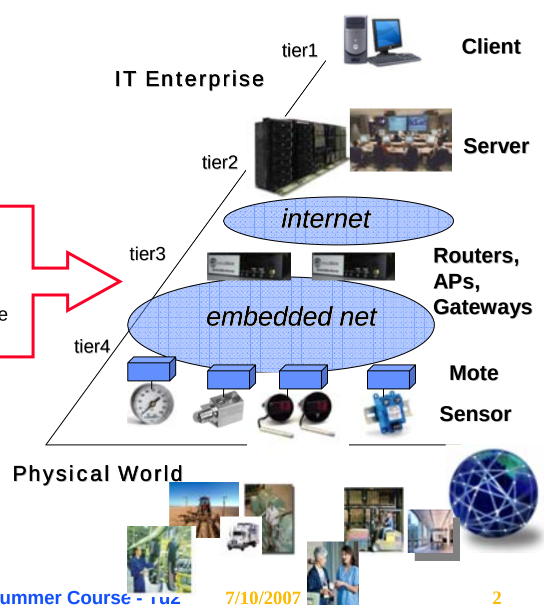
Arch Rock Corp.

July 10, 2007

Our Focus

Embedded Tier Networking

- Reliable, Low-Power Communication
- Self-Organized
- Despite uncertain environmental factors
- Among embedded devices, and to/from the infrastructure



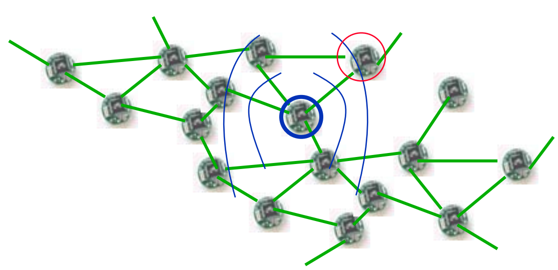
Communication Patterns

- **Internet**
  - **Many independent pt-pt streams**
- **Sensor Networks**
  - **Dissemination**
  - **Collection**
  - **Aggregation**
  - **Tree-routing**
  - **Neighborhood**
  - **Point-point**

The Emergence of Networking Abstractions and Techniques in TinyOS
Philip Levis, Sam Madden, David Gay, Joseph Polastre, Robert Szewczyk, Alec Woo, Eric Brewer, and David Culler, NSDI'04

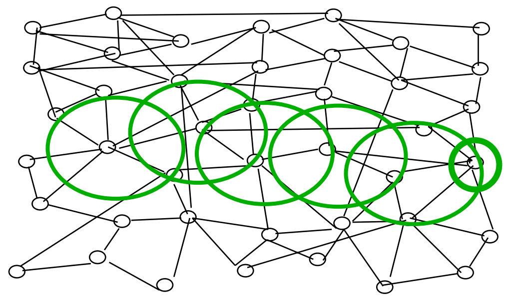
The Basic Primitive

- **Transmit a packet**
- **Received by a set of nodes**
  - **Dynamically determined**
  - **Depends on physical environment at the time**
  - **and what other communication is on-going**
- **Each selects whether to retransmit**
  - **Potentially after modification**
- **And if so, when**



Recall - Routing Mechanism

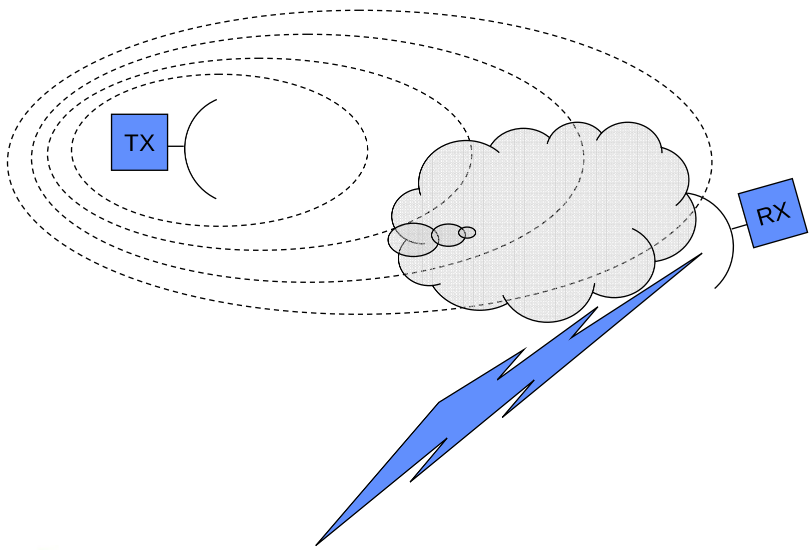
- Upon each transmission, one of the recipients retransmits
- What determines a good link?



Elements of Robust Communication

- Application: feasible workload
  - Packet rates, pattern, timing
- Network: finding and using good paths
  - Topology discovery and route selection
  - Route cost determination, selection
  - Forwarding
- Link: Framing, Media Management Protocol
  - On to receive during transmission
  - Frame structure, error detection, acknowledgement
  - Avoiding contention (MAC, CCA, Hidden Terminal)
  - Link quality estimation
- Physical: Signal to Noise Ratio
  - Device Transmission Power / Receive Sensitivity
  - Antenna design and orientation, obstructions, attenuation
  - Receive signal vs interference, noise, multipath
  - Modulation, channel coding

In a nutshell



Why Multihop Routing?

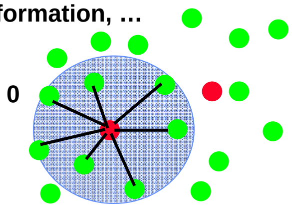
- **Power!**
  - Power to *transmit* distance D grows as D^3 or worse
  - Power to *route* distance D grows linearly
- **Bandwidth (spatial multiplexing)**
  - With n nodes in a single cell, each gets at most 1/n bandwidth
  - Many small cells => many simultaneous transmissions.
- **Reliability**
  - Individual links experience interference, obstacles, and multipath effects
  - Even short-range “wireless wires” require human nurturing
    - » IRDA, Bluetooth, WiFi, Cell Phone
  - Provides spatial diversity and receiver diversity
    - » rather than antenna diversity
  - Protocol level reliability

Connectivity

- **Much of the CS work on network protocols**
  - **Routing, cluster head formation, topology formation, …**

assumes a *unit disk* model

- **If Distance < R, Connectivity = 1, otherwise 0**



- **EM models based on fading, signal-to-noise ratio (SNR), modulation, and coding.**
  - **PRR (packet receive rate) for SNR (γ), frame size (*f*)…**

$$p = (1 - \frac{1}{2}\exp^{-\frac{\gamma}{2}\frac{1}{0.64}})^{8f}$$

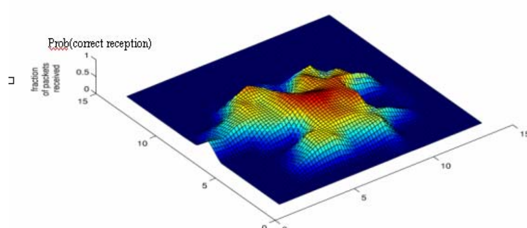
For Mica2 with FSK CC1000

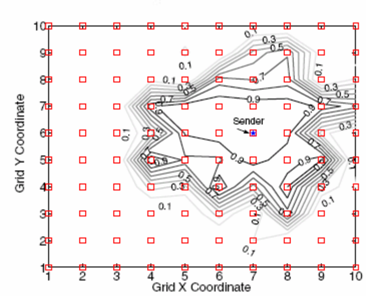
- **Nakagami and Rayleigh Fading**

$$PL(d) = PL(d_0) + 10nlog_{10}(\frac{d}{d_0}) + X_\sigma$$

Real World Example – open surface

- **2003 study of 100-200 first generation motes placed in regular grid in open tennis court.**
- **RFM 916 MHz ASK RF transceivers with simple whip antenna.**
- **Variation in Packet Receive Rate (PRR) from each transmitter.**





Taming the Challenges of Reliable Multihop Routing in Sensor Networks, Alec Woo and David Culler, ACM SenSys Nov. 2003.

D. Ganesan, B. Krishnamachari, A. Woo, D. Culler, D. Estrin, and S. Wicker, "An Empirical Study of Epidemic Algorithms in Large Scale Multihop ," Intel Research, IRB-TR-02-003, Mar. 14, 2002

Analytical Models with Mulipath

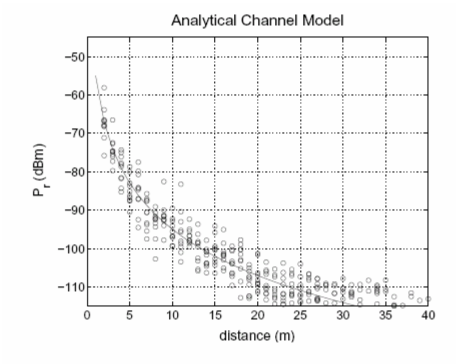


Fig. 1. Channel Model, $n = 4$, $\sigma = 4$, $P_t = 0\,dBm$

Path loss with distance d

$$PL(d) = PL(d_0) + 10nlog_{10}(\frac{d}{d_0}) + X_\sigma$$

Bit error rate

$$P_e = \frac{1}{2}\exp^{-\frac{\alpha}{2}}$$

$$SNR = \frac{E_b}{N_0}\frac{R}{B_N}$$

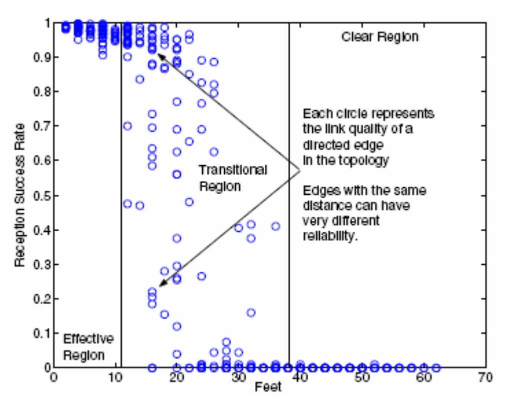
α (= $\frac{E_b}{N_0}$); R = 19.2 kbps; B_N = 30 kHz

PRR

$$p = (1 - \frac{1}{2}\exp^{-\frac{\gamma}{2}\frac{1}{0.64}})^{8f}$$

Marco Zuniga, Bhaskar Krishnamachari, "Analyzing the Transitional Region in Low Power Wireless Links", IEEE SECON 2004.

PRR vs Distance in practice



(a) Reception probability of all links in a network with a line topology.

Example: TI CC2420

- IEEE 802.15.4 compliant
- 2400 – 2483.5 MHz RF tranceiver
- O-QPSK Direct Sequence Spread Spectrum (DSSS)
  - 250 kpbs data rate, 2 Mchips/s
- 0 dBm (1 mW) transmit power
- -95 dBm receive sensitivity
- 30/45 dB adjacent channel rejection
- 53/54 dB alternate channel rejection
- PIFA PCB antenna

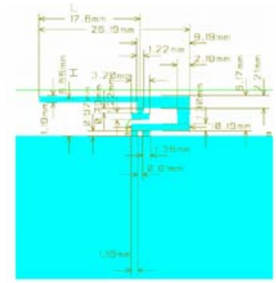


Figure 2: Antenna dimensions

http://focus.ti.com/lit/ds/symlink/cc2420.pdf

http://focus.ti.com/lit/ug/swru043/swru043.pdf

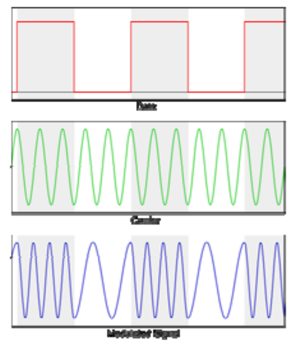
Real World Example

- Heavy metal environment
- Operating machinery
- Changing environment
- Electronic Equipment
- …

Channel Modulation

- **ASK - Amplitude Shift Keying**
  - Rene, Mica1 – RFM1000
- **FSK - Frequency Shift Keying**
  - Mica2 – CC1000
- **O-PSK - Orthogonal Quadrature phase-shift keying**
  - Telos, TelosB, MicaZ - 802.15.4

FSK



O-QPSK, RSSI, CCI/LQI

Figure 6. Modulation and spreading functions [1]

Symbol	Chip sequence ($C_0, C_1, C_2, \ldots, C_{31}$)
0	1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0
1	1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0
2	0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0
3	0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1
4	0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1
5	0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0
6	1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1
7	1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1
8	1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1
9	1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1
10	0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1
11	0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0
12	0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0
13	0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1
14	1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0
15	1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0

Table 3. IEEE 802.15.4 symbol-to-chip mapping [1]

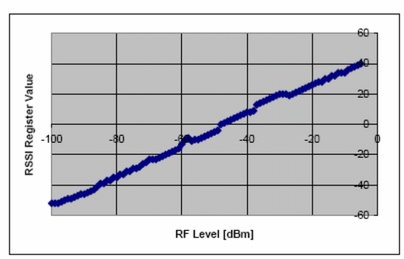
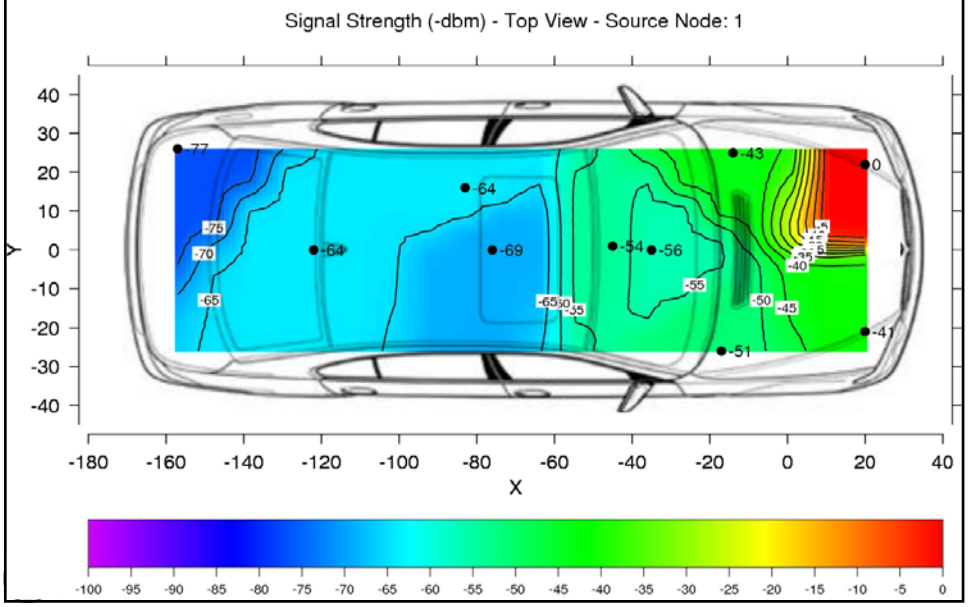


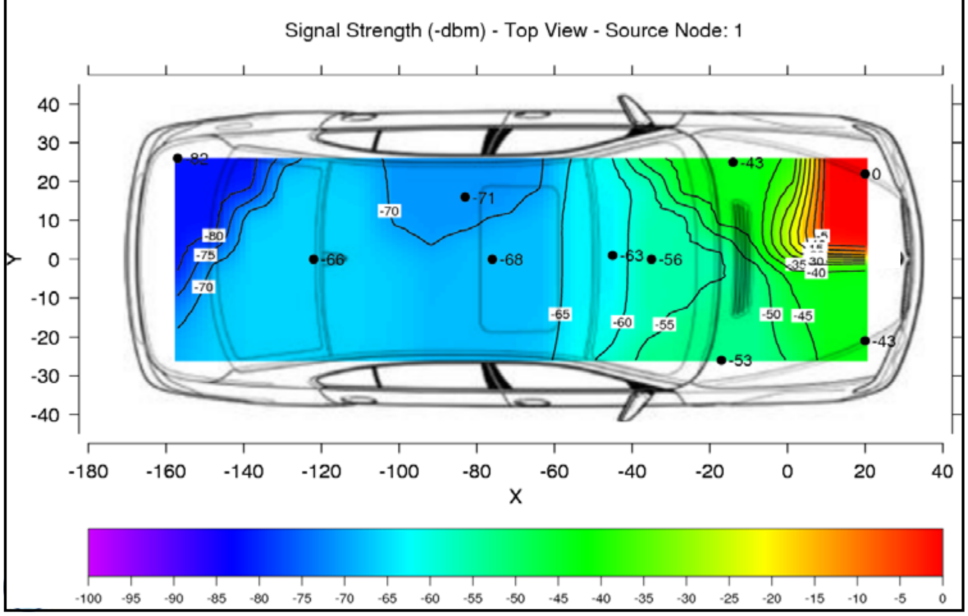
Figure 27. Typical RSSI value vs. input power

- **Chip Correlation Indicator**

RSSI - Stationary



RSSI - Driving



IEEE 802.15.4 Frame Format

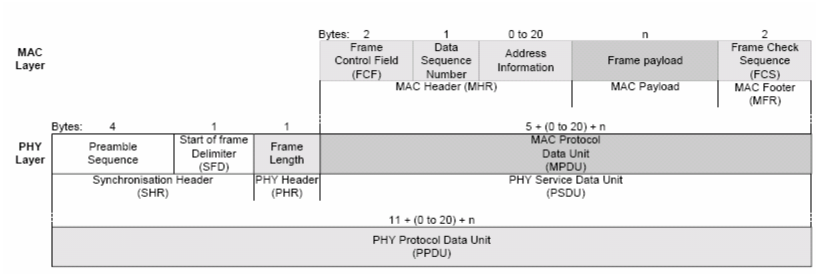
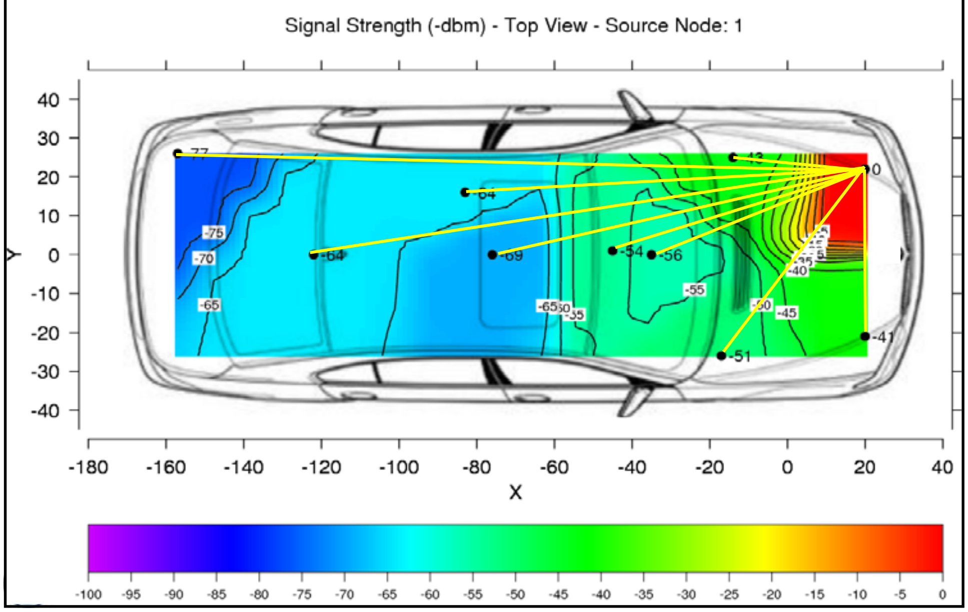
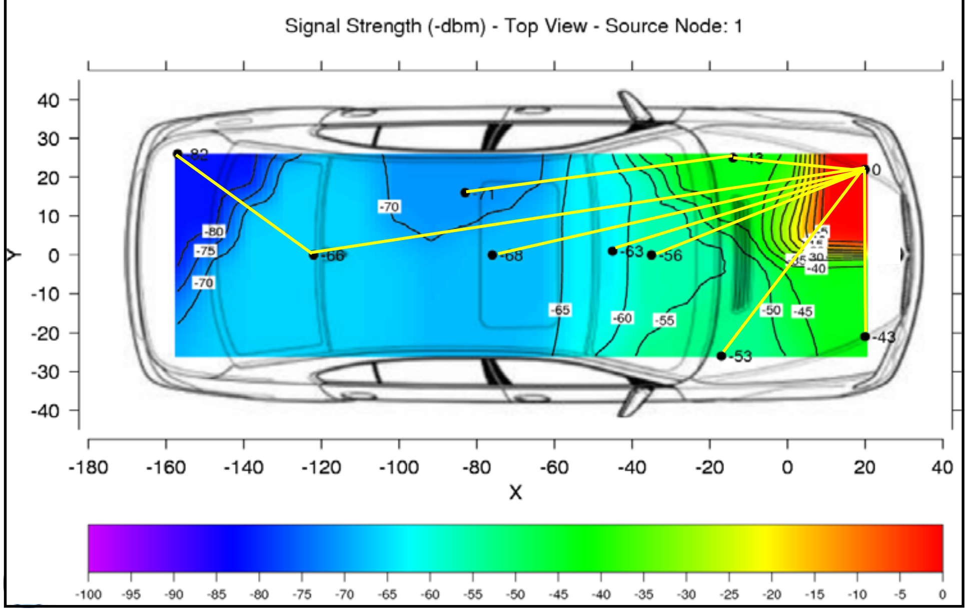


Figure 17. Schematic view of the IEEE 802.15.4 Frame Format [1]

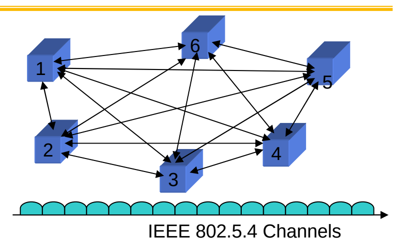
Network - Stationary

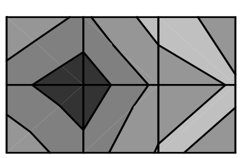


Network - Driving



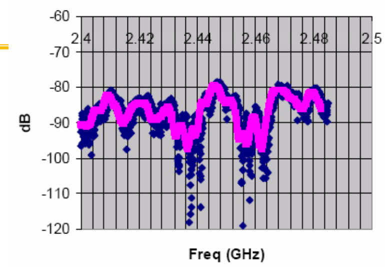
Industrial Setting (Sexton)

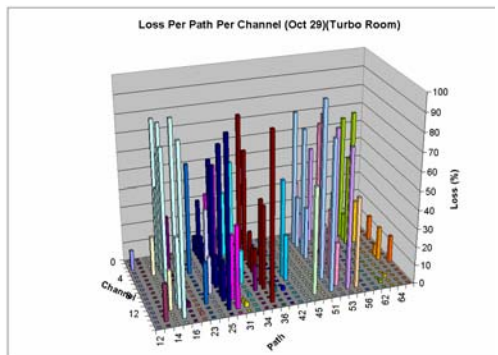




Channel Fading

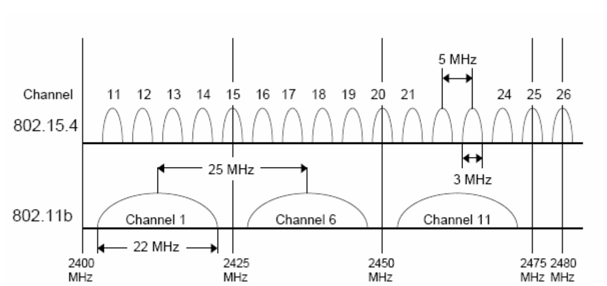
- **Multipath effects**
  - Varies by position
  - Varies by frequency
  - Varies over time
- **Overcome with diversity**
  - Time diversity
    - » Retransmission
  - Spatial Diversity
    - » Multiple antennas
  - Path diversity
    - » Alternative receivers
  - Frequency diversity
    - » Spreading, Multiple channels





Radio Channel Quality in Industrustrial Wireless Environments, Dan Sexton, et. al SICON'05

WIFI Relationship



Variations over time

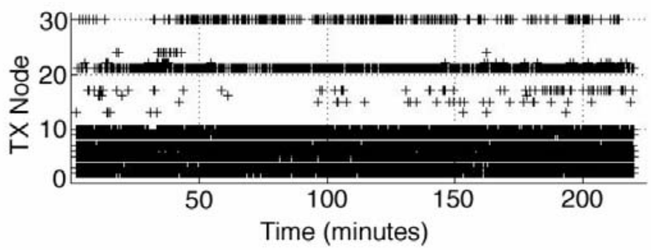


Figure 1. Packet reception over time (x axis) at node 4 from all other 29 nodes (y axis). Every packet received is marked by a '+'. Some nodes such as 2 and 3 have almost consistent packet reception while node 30 has packet reception that varies over time.

•**Understanding the causes of packet delivery success and failure in dense wireless sensor networks,** Kannan Srinivasan, Prabal Dutta, Arsalan Tavakoli, and Philip Levis

Received Signal Strength ?

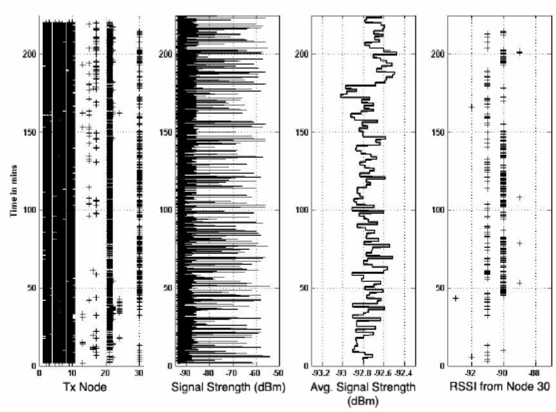


Figure 4. Observed behavior at node 4. The first plot on the left shows packet loss over time. The second plot shows the measured signal strength of the channel, which shows very, short-lived spikes. The third plot shows the singnal strength of the channel averaged over 400 samples (40s), which shows that there are not significant variations. The last plot, on the right, shows the RSSI distribution of packets received from node 30 over time.

Noise

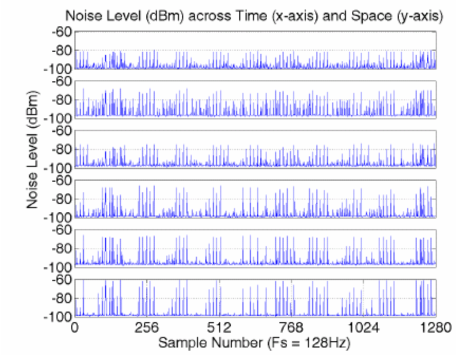
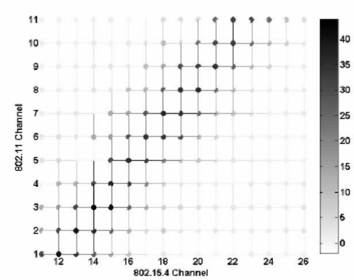


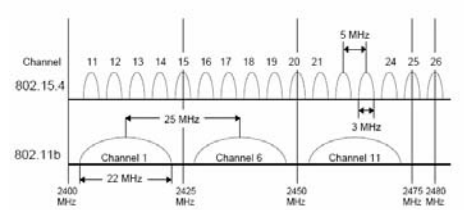
Figure 6. Sampled signal strength over 10 seconds and across six motes.

- **Periodic WiFi beacon**

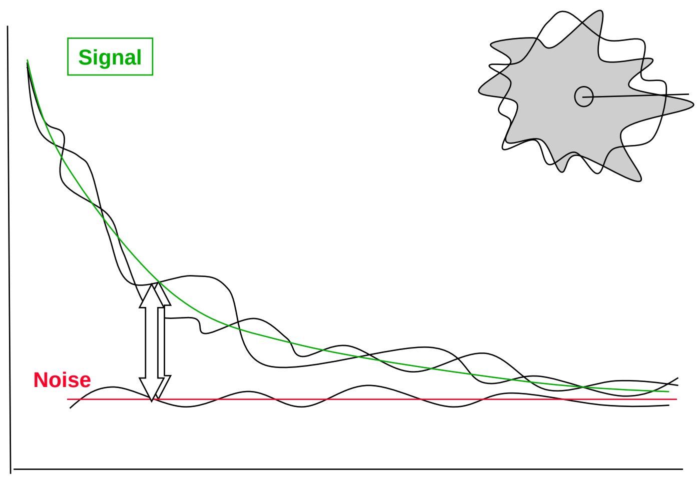
802.11 / 802.15.4 Interference



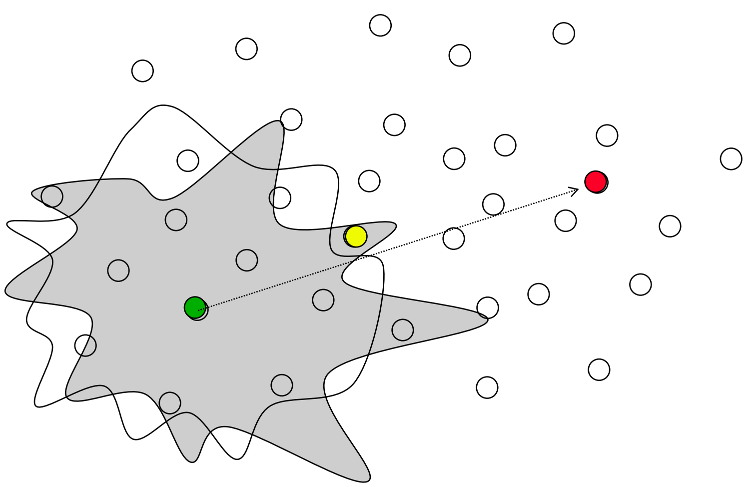
(b) Measured 802.11b interference with 802.15.4 (dBm).



The Amoeboed "cell"



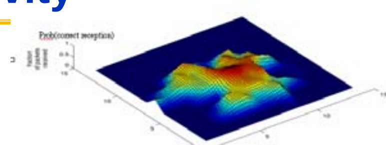
Which node do you route through?



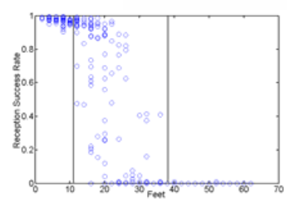
What does this mean?

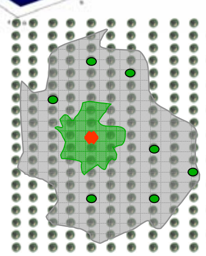
- **Always routing through nodes "at the hairy edge"**
  - **Wherever you set the threshold, the most useful node will be close to it**
- **The underlying connectivity graph changes when you use it**
  - **More connectivity when less communication**
  - **Discovery must be performed under load.**
  - **Topology determination is a continuous process of discovery and validation**

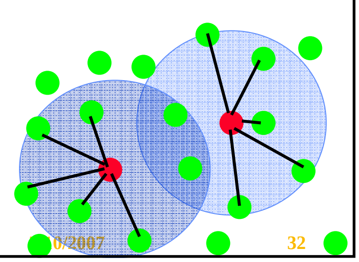
Complexity of Connectivity



- **Direct Reception "Neighborhood"**
- **Non-isotropic**
- **Large variation in affinity**
  - **Asymmetric links**
  - **Long, stable high quality links**
  - **Short bad ones**
- **Varies with traffic load**
  - **Collisions**
  - **Distant nodes raise noise floor**
  - **Reduce SNR for nearer ones**
- **Many poor "neighbors"**
- **Good ones mostly near, some far**

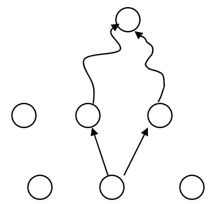






Basics of "Mesh Routing"

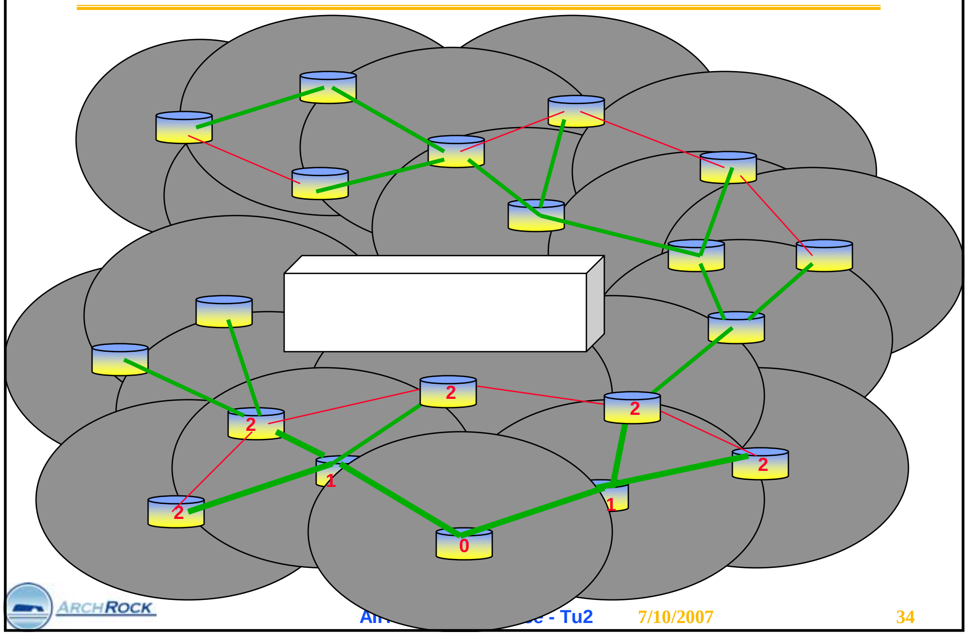
- Discover the network by "flooding" from a point
  - Typically a gateway "root" node
- Reverse the links to establish "parent" for each node
  - Actually hear from many potential parents
- Data collection by routing up the tree to the root
- Maintain a "good tree" by monitoring quality of links to potential parents and estimate of path from parent to root
  - Distributed Bellman-Ford
  - Cost-based routing



Not new to wireless sensor networks!
In the traditional wireless networking domain:
- DSR – dynamic source routing
- DSDV – destination sequenced distance vector routing
- AODV – Ad-Hoc On-demand Distance Vector Routing
- OLSR – Optimized Link State Routing

Mostly assumes a binary "link" relationship!

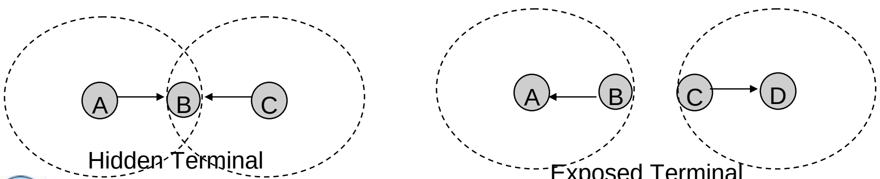
Self-Organized Spanning Tree



Lessons from our study of links

Classic Media Access Control

- CSMA wireless MAC
  - MACA, MACAW, IEEE 802.11
  - Listen (CCA - clear channel assessment)
  - If channel busy, back off (exponentially) and retry
  - Send RTS – request to send
  - Wait for destination to respond with CTS (clear to send)
  - On CTS, send data packet
  - and on overhearing CTS to another backoff
- TDMA
  - Divide time into periodic slots
  - Assign slots for individual nodes to transmit

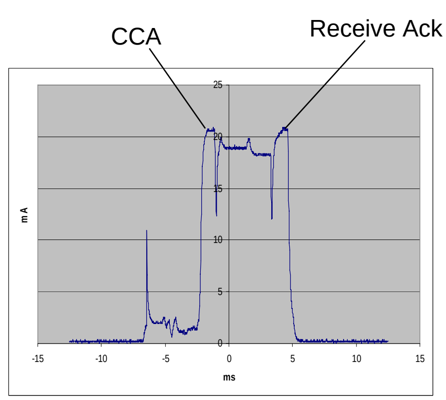


Lesson 1: Listen

- MACs deal with mitigating high contention
  - In low duty cycle networks, contention is low regardless
  - Can occur due to highly correlated behavior
    - » Example: all node sample periodically
    - » Separate sample from report, shift phase
- WSN packets are not the only thing on the air
- CCA essential for determining noise also
  - Don't transmit over a noisy (or busy) channel
  - Required even with TDMA techniques
- Low-Power Wireless Packets are small
  - IEEE 802.15.4 limit 127 bytes
  - PRR drops rapidly with frame size!
  - Handshake is extremely energy expensive
- In a mesh, hidden terminals and exposed terminals are EVERYWHERE

Lesson 2: Link Level Retransmission

- There will be packet loss, even on good links
- PRR(h hops) = PRR^h
- Link-level acknowledgements are essential.
  - Provides ability to estimate the quality of the link!



Lesson 3 – Asymmetric Links

- Asymmetric Links are common
  - Non-isotropic antenna, propagation, multipath
  - Variations in transmit power or receive sensitivity among nodes
  - Variations in noise level at receiver and transmitter
- Cannot assume the reverse link is good
  - Verify it!
  - Continuously

Lesson 4 – Variation in Time

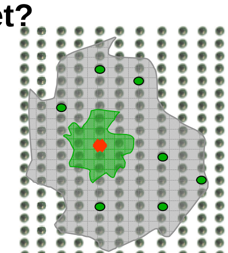
- Link quality varies in time due to many factors
- Changing physical environment.
- Changing RF noise
- Changing traffic from other nodes
  - Essentially additional noise, but right in the channel
- Cannot expect to determine connectivity in advance and just use it.
  - Zigbee route determination?
  - TSMP connectivity "survey"?

Lesson 4: Care in Discovery

- Flooding the network to determine connectivity creates huge amount of contention, collision, and noise.
  - Broadcast storm problem
- Produces uncertain link connectivity.
- Reversal is especially dubious.

Lesson 5: Reception ≠> Link

- Reception of a packet from a node does not imply the link is good.
- Will infrequently receive good packets even on a bad link.
- Many nodes far away => will frequently receive a packet from one of them.
- Neighbor table cannot contain an entry for everyone that a node has heard from!
- Must track only a small important subset?



Lesson 6: No Reception ≠> No Link

- Capture Effect
- A node will receive packets with low signal strength (at least if the noise is low)
- If a strong packet appears at the receiver while it is in the middle of processing a weak packet
  - Both will be lost
- And collision ≠> loss
  - If a weak packet arrives while receiving a strong packet, the strong packet will be received if the weak does not exceed the SNR threshold.

Exploiting the Capture Effect for Collision Detection and Recovery
Whitehouse, K.; Woo, A.; Jiang, F.; Polastre, J.; Culler, D.
Embedded Networked Sensors, 2005. EmNetS-II. The Second IEEE Workshop on
Volume , Issue , 30-31 May 2005 Page(s): 45 - 52

Lesson 7: Determining Link Quality

- RSSI, LQI, and Packet Sequence numbers tell receiver about the inbound link.
- Need to reply to the sender for it to know if that is a good link.
- The 2-way exchange provides way to filter out asymmetric links.
- Link ACKs inform sender about outbound link.

Summary

- Many of the best protocols are opportunistic
  - Use whatever connectivity occurs
- Topology determination and route selection is a constant and gentle process
  - Passive monitoring wherever possible
  - Use every piece of information available to track quality
- Concentrate link estimation on the few important candidates.
- Additional network density helps reliability
  - If the media management is done right