Power-Aware Wireless Microsensor Networks

Eugene Shih

Benton H. Calhoun

Seong-Hwan Cho

Anantha Chandrakasan

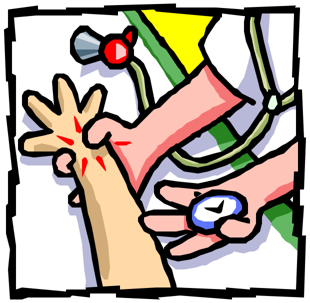
April 19, 2001

http://www-mtl.mit.edu/research/icsystems/uamps

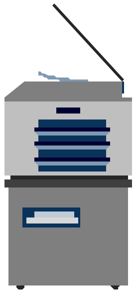
Sensor Network Applications

Indoor Home Sensing

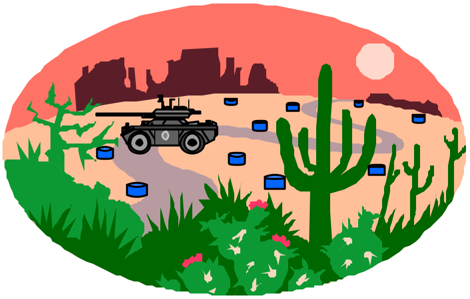
Medical Monitoring



Equipment Monitoring

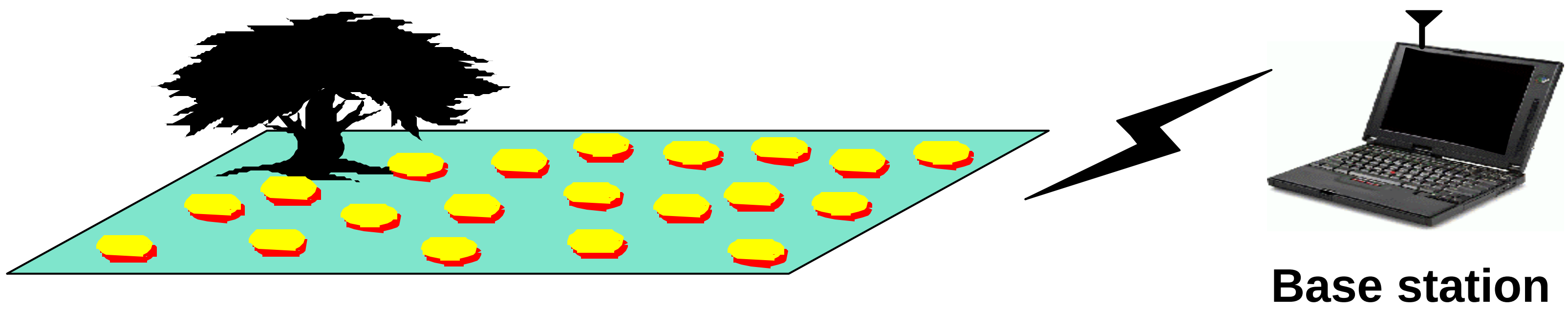


Vehicle Tracking



Design a universal substrate for power-aware data gathering from a massively distributed wireless network

Domain Characteristics



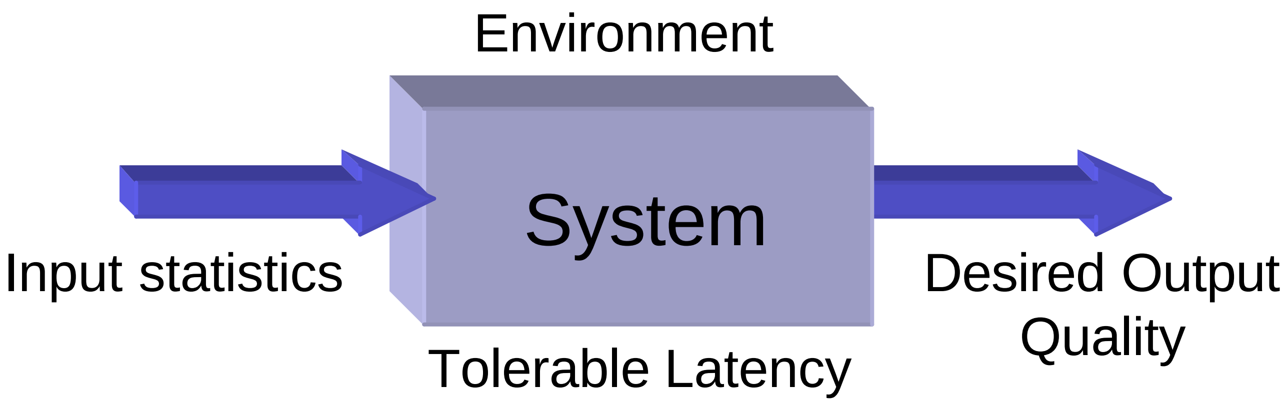
- Lots of static nodes
- Compact form factor
  - 1 cm^3
- Low rate sensing
  - < 10 kbps
- Deployed in high densities
  - 0.1 to 20 $nodes/m^2$
- Short links between sensors
  - 5 to 10 m
- Sensors far from base station
  - > 100 m
- Long lifetime
  - 1 to 5 years
- Battery replacement impossible

System Design Implications

- Tension between form factor and lifetime requirements
  - Thin-film battery has energy density of 2.5 J/mm^3
    - 128-pt FFT every second (low-power processor): 24 days
    - But, lifetime requirement is 1 to 5 years
- Key challenge: Ultra energy-efficient node
- Low-power design
  - Optimized for a particular, worse-case scenario

Approach of mAMPS is Power-Awareness

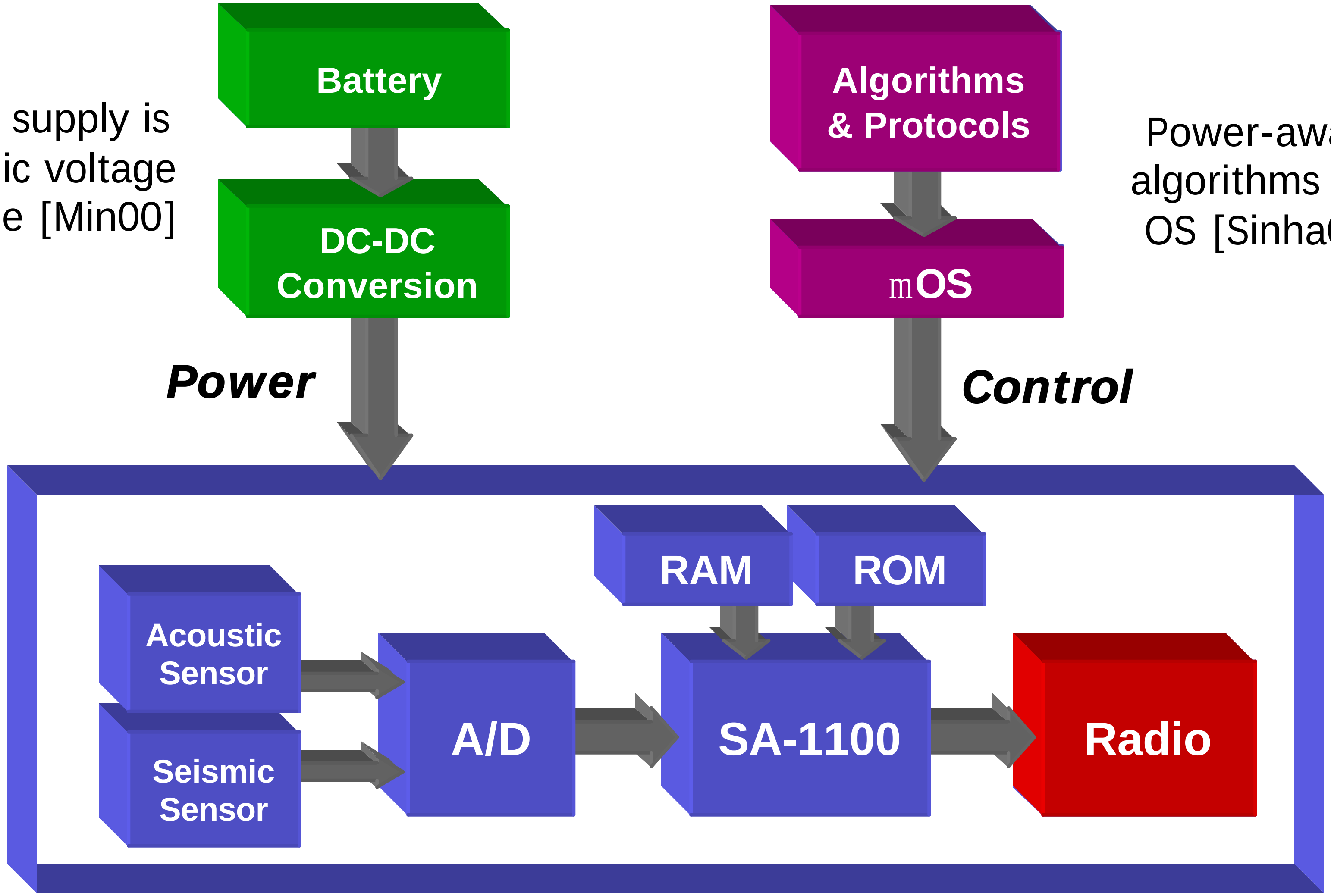
Power-Awareness vs. Low-Power



- Operating scenarios are diverse and dynamic
  - Changes in environment, signal statistics, etc.
  - Focus on adaptation to achieve desired output quality
- Power-aware system design explicitly adapts energy dissipation to changing scenario

Power-Aware Node Architecture

Power supply is dynamic voltage scalable [Min00]

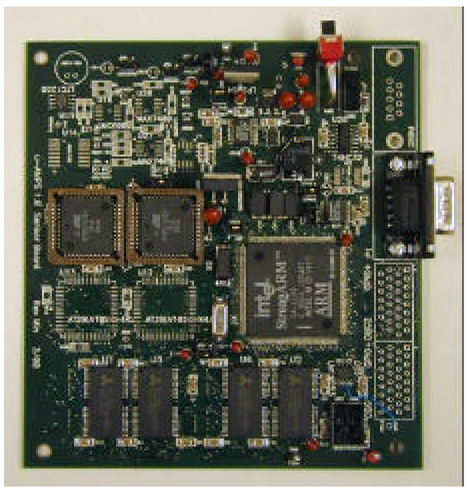


Power-aware algorithms and OS [Sinha00]

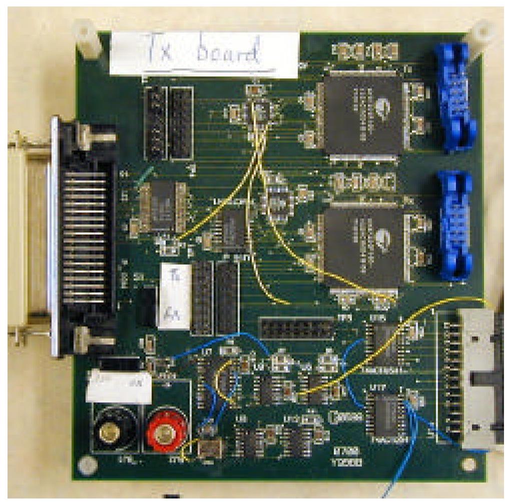
SA-1100 performs control and processing.
System adapts to scenario changes

mAMPS Node

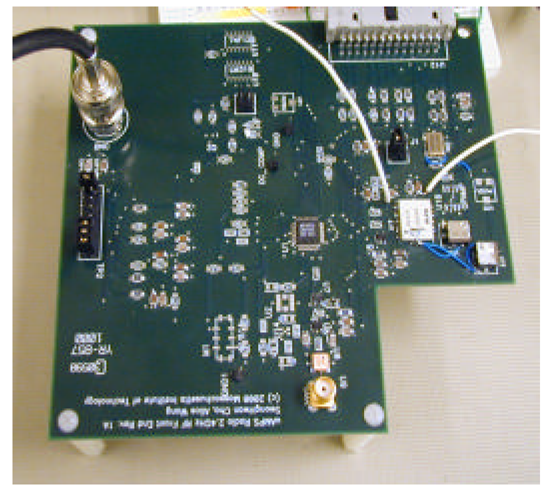
***m*AMPS: micro-Adaptive Multi-Domain Power-Aware Sensors**



Processor



Baseband



Radio

*m*AMPS Prototype

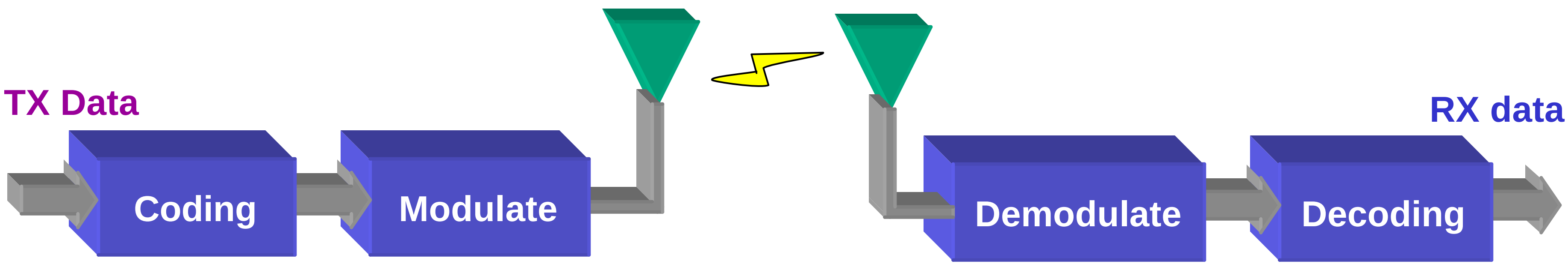
[Seong-Hwan Cho, Rex Min, Eugene Shih, Alice Wang]

Communication Link Abstraction

- Nodes communicate with one another in the network
- Channel will introduce errors, received signal will be corrupted
- Desired output quality:
  - Probability of error P_b
- Cost:
  - Energy dissipated

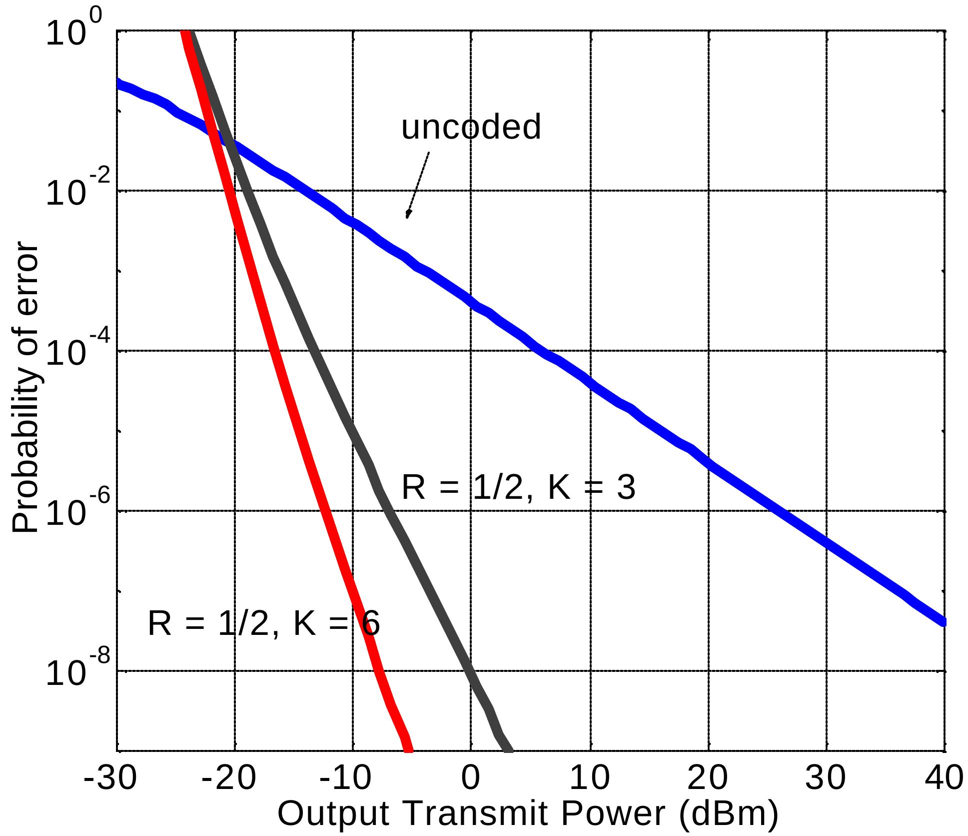
How can we meet desired output quality while minimizing energy dissipation?

Achieving Desired Quality



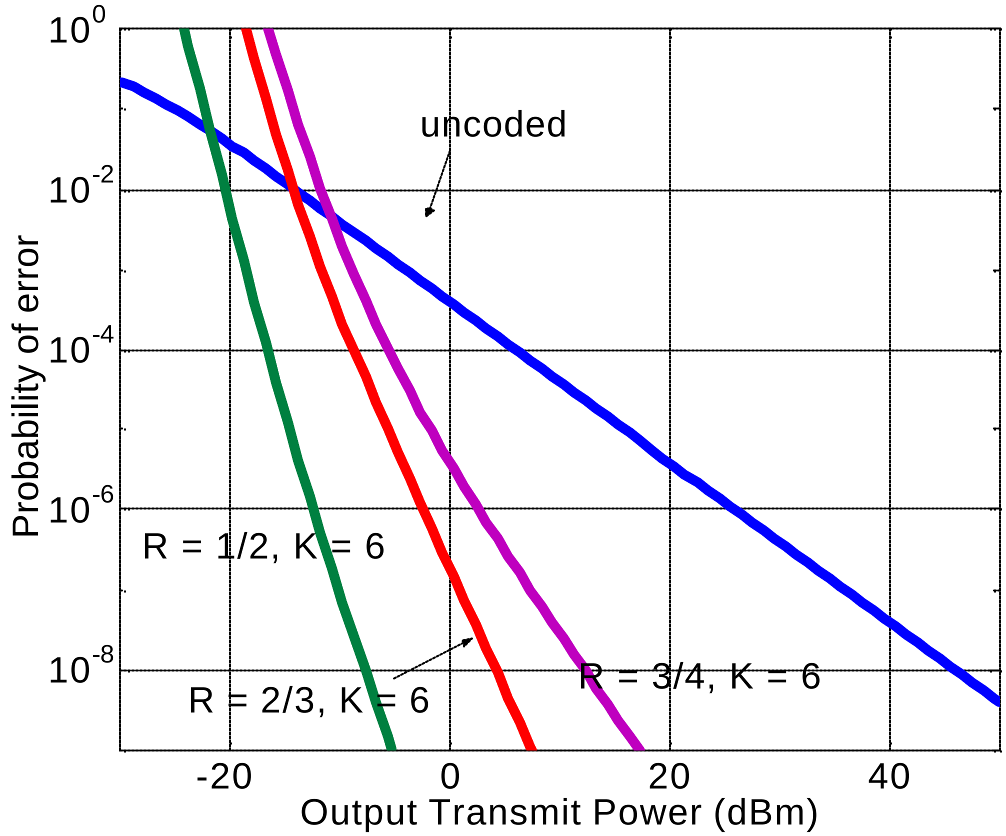
- Variety of techniques to achieve desired performance
  - Modulator/Demodulator
    - Different transmitter and receiver architectures
    - Increase transmit power
  - Add more processing
    - Equalization
    - Forward Error Correction
- Approach: Investigate trade off between transmit power and forward error correction to achieve a given output quality
  - Convolutional codes: characterized by rate (R) and constraint length (K)

Desired Quality: Effect of Coding (I)

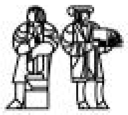


- Convolutional codes decreases transmit power for fixed P_b
- Fix rate, varied constraint length
  - Longer constraint length = Better performance

Desired Quality: Effect of Coding (II)

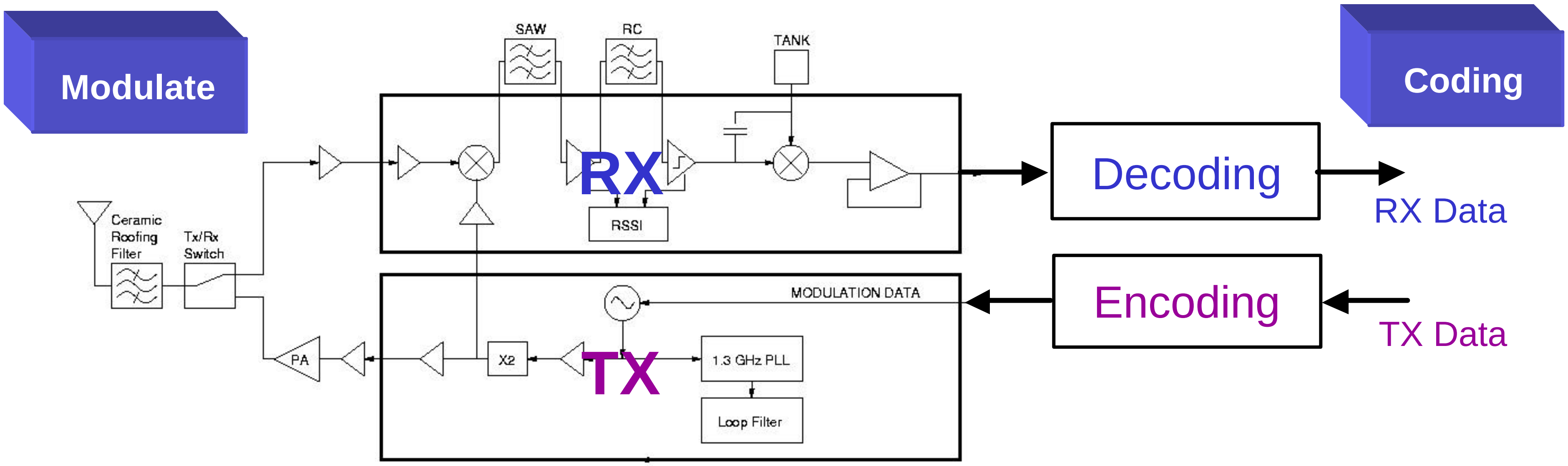


- Fix constraint length, change rate
  - Higher rate decreases performance due to less redundancy



Communication View: Coding Always Wins

Energy Cost of Communication



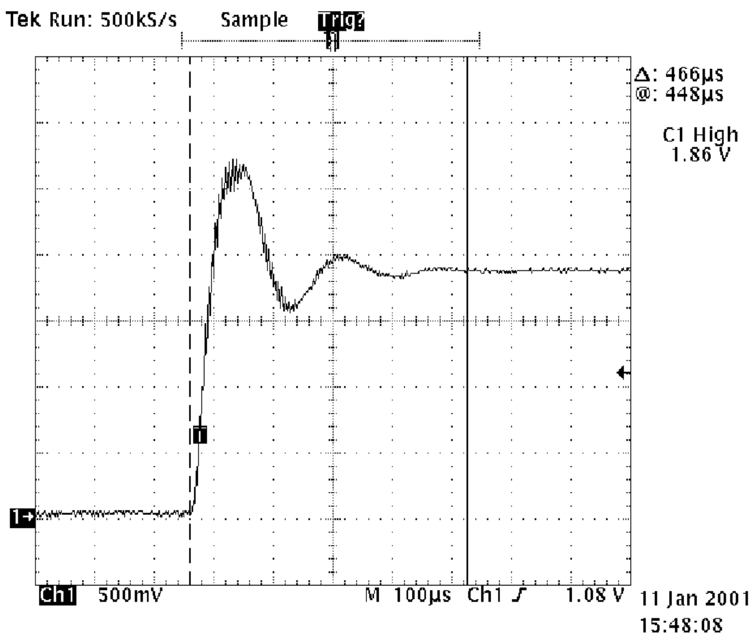
$$E_{radio} = E_{rx} + E_{tx}$$

$$E_{FEC} = E_{FEC}^{(e)} + E_{FEC}^{(d)}$$

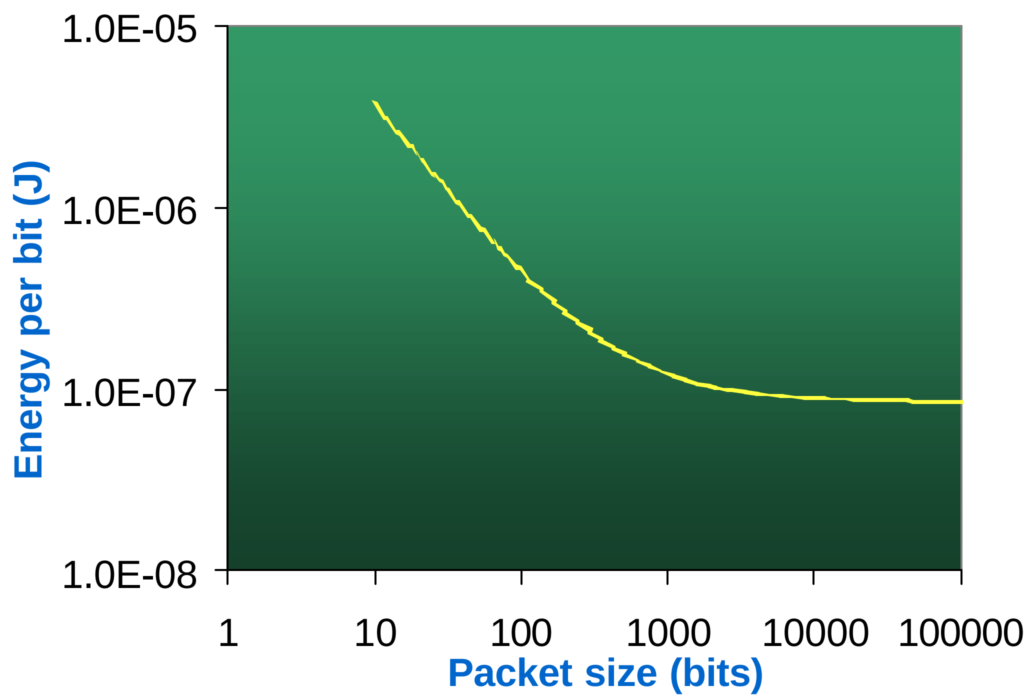
$$E_{radio} = [P_{rx}(T_{on} + T_{startup})] + [P_{tx}(T_{on} + T_{startup}) + P_{out}(T_{on\text{-}tx})]$$

$$E_{total} = E_{radio} + E_{FEC}$$

Radio Startup Time



Startup time is 466 µs



- High energy per bit for small packets due to startup energy domination
- Ensure packets lengths are long enough
  - 10000 bit packets to mitigate startup cost

Model Parameters

Fixed Parameters

P_{tx}	81 mW
P_{rx}	180 mW
$T_{startup}$	$466\ \mu s$

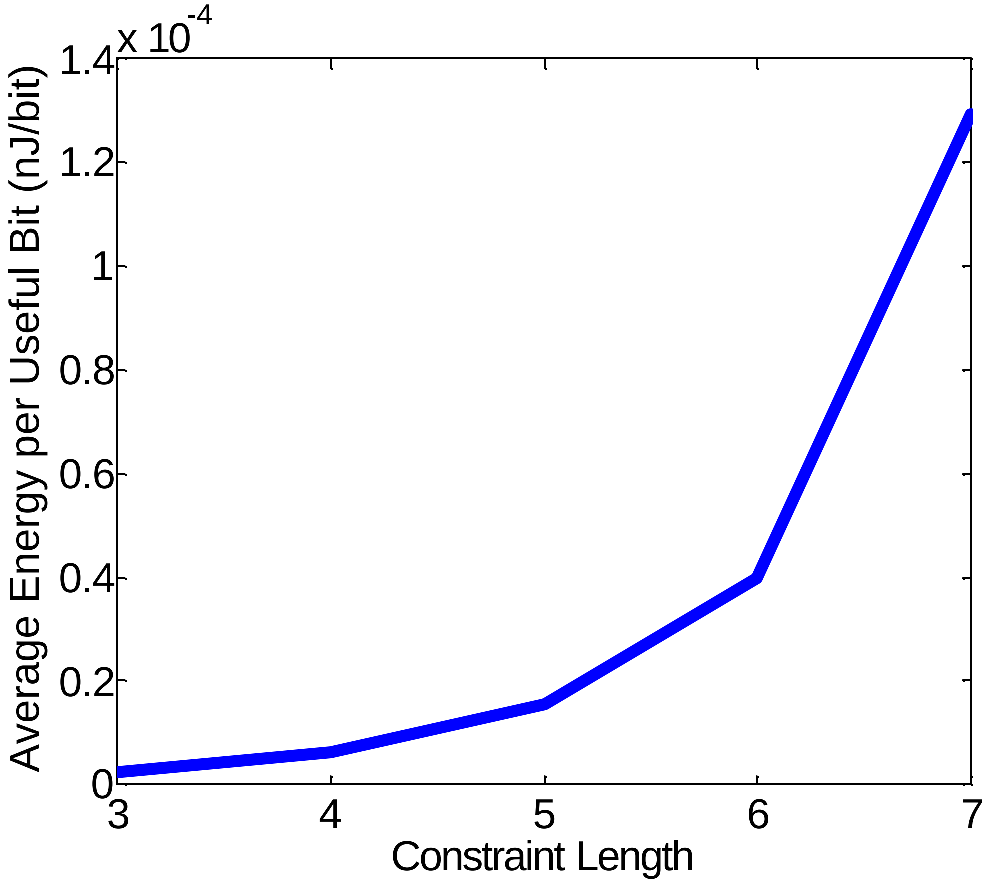
Tunable Parameters

P_{out}
T_{on}
E_{FEC}

- Fixed parameters
  - Characteristics of the radio front-end
- "Tunable" parameters
  - P_{out}: transmit output power
  - T_{on}: time transmitter and receiver need to be on
    - Related to the length of the packet
    - When FEC is added, the length of the packet increases
  - E_{FEC}: depends on code used and underlying fabric or architecture

Coding Energy: SA-1100

- Encoding energy is negligible
- Decoder (Viterbi) energy increases with constraint length
  - Number of states is proportional to 2^{K-1}
- Change of rate does not affect E_{FEC}
  - Essentially, the same Viterbi decoder is used for same constraint length

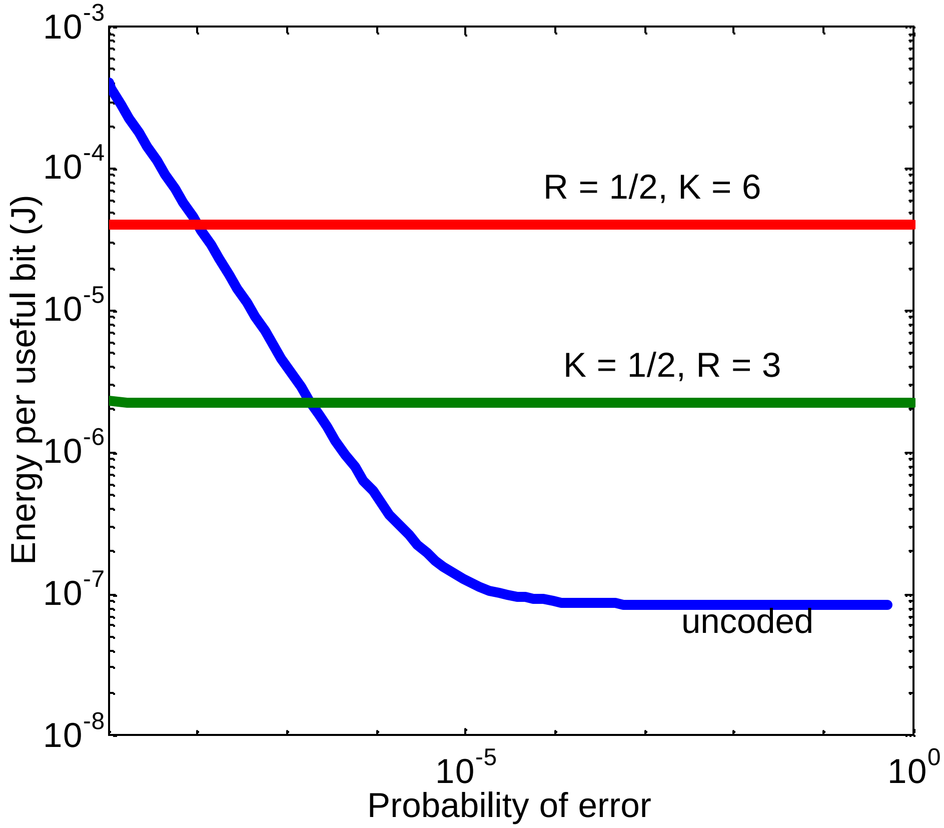


R = ½, K = 3	2200 nJ/bit
R = ½, K = 6	40000 nJ/bit

Energy vs. P_b: Changing Constraint Length

- Fix rate, change constraint length
  - Fixed number of bits transmitted ⇒ radio on time is fixed
- Computation energy dominates for high error

Component	Energy
Radio (0 dBm) $P_b \approx 10^{-3}$	85 nJ/bit
R = ½, K = 3	2200 nJ/bit
R = ½, K = 6	40000 nJ/bit

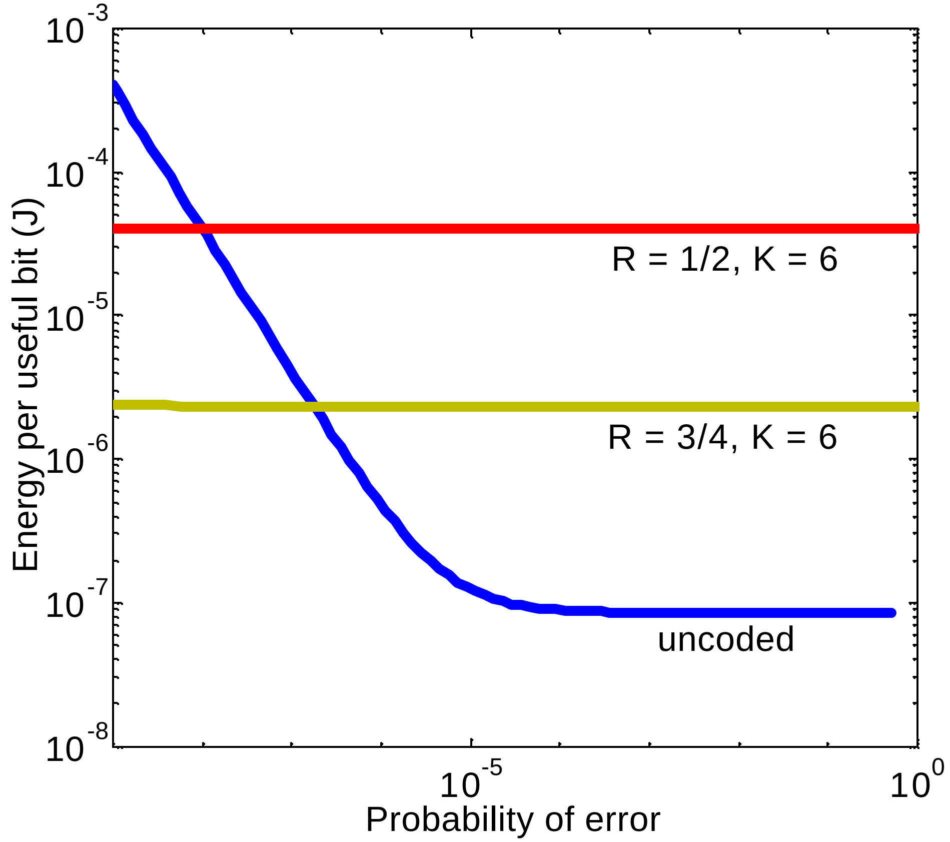


- Amplifier energy dominates at low error

Optimal strategy depends on desired quality

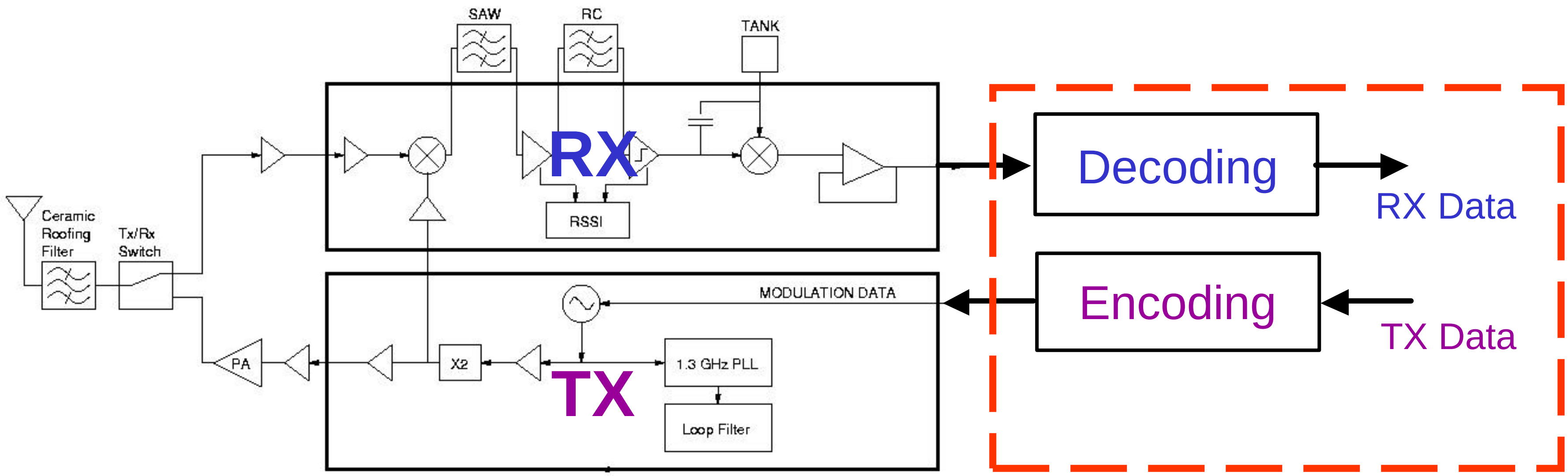
•MIT• μAMPS •PROJECT•

Energy vs. P_b: Changing Rate



- Fix constraint length, vary rate
  - Same decoding energy
  - Rate change implies less bits transmitted

Changing Fabric: SA-1100 to ASIC



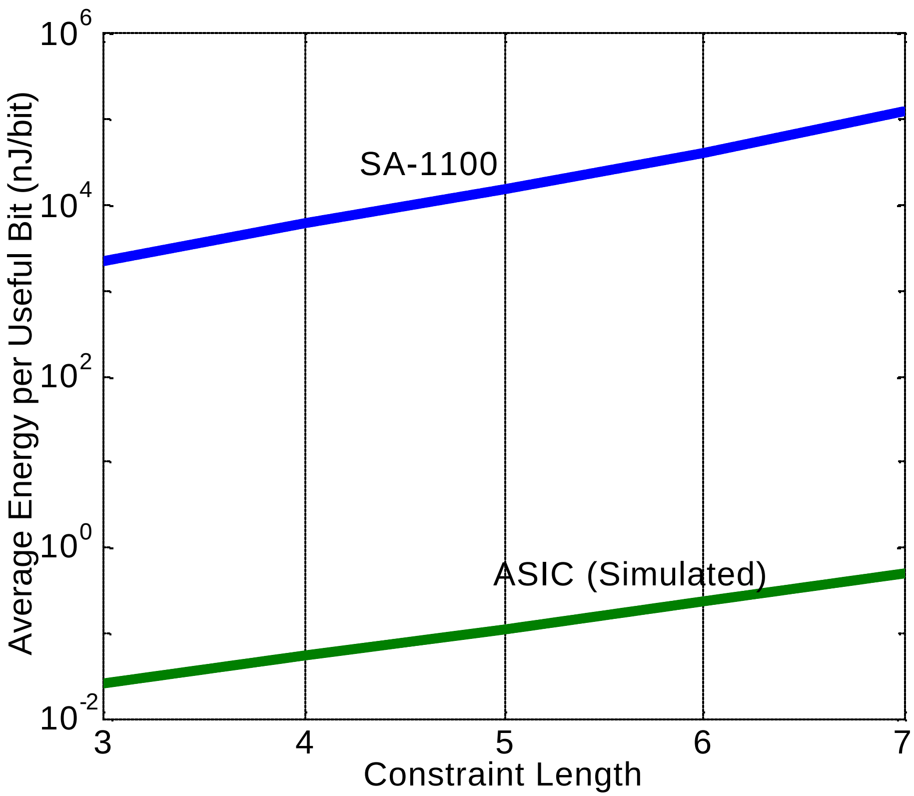
$$E_{radio} = E_{rx} + E_{tx}$$

$$E_{radio} = [P_{rx}(T_{on} + T_{startup})] + [P_{tx}(T_{on} + T_{startup}) + P_{out}(T_{on\text{-}tx})]$$

$$E_{FEC} = E_{FEC}^{(e)} + E_{FEC}^{(d)}$$

$$E_{total} = E_{radio} + E_{FEC}$$

Computation Cost: SA-1100 vs. ASIC



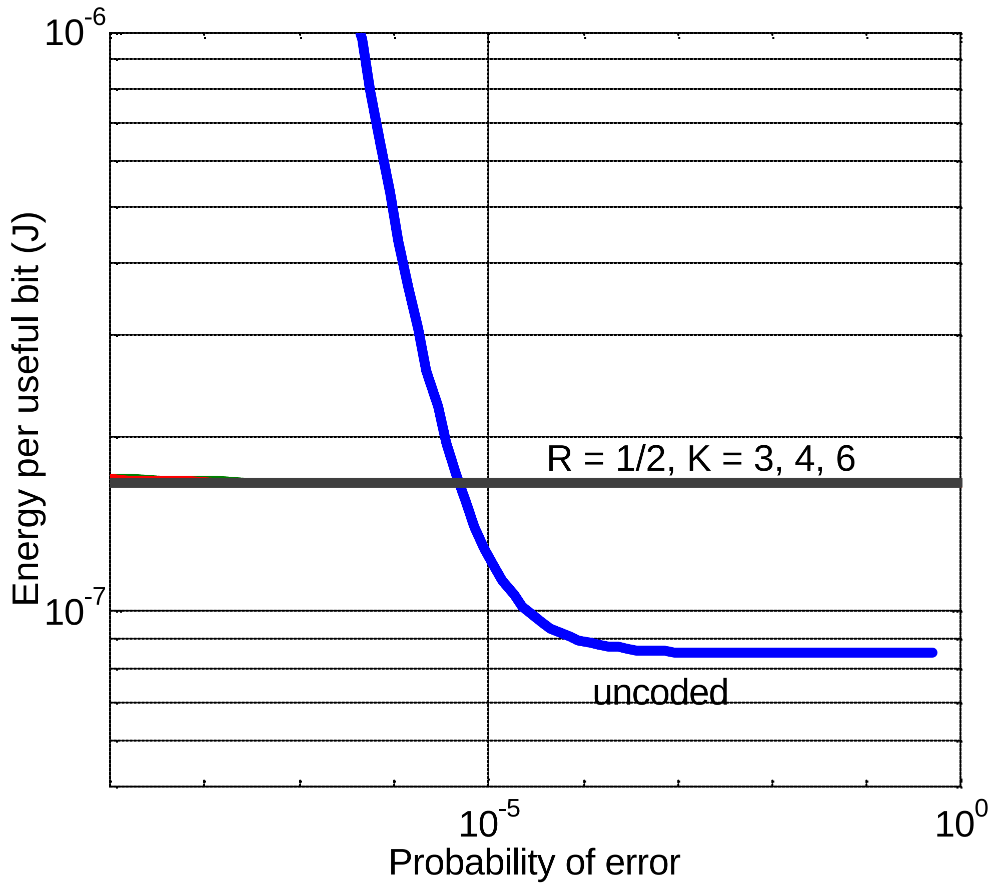
	R = ½ K = 3	R = ½ K = 6
ASIC (nJ/bit)	0.026	0.225
SA-1100 (nJ/bit)	2200	40000

- Viterbi decoder on SA-1100 is inefficient
  - Not optimized for ACS operation
- Decoding energy is 3 to 5 orders less

Energy vs. P_b: Changing Constraint Length

- Fix rate, change constraint length
  - Computation is cheap
  - Radio energy is still expensive
- Coding increased on-time of transceiver and transceiver is dominant

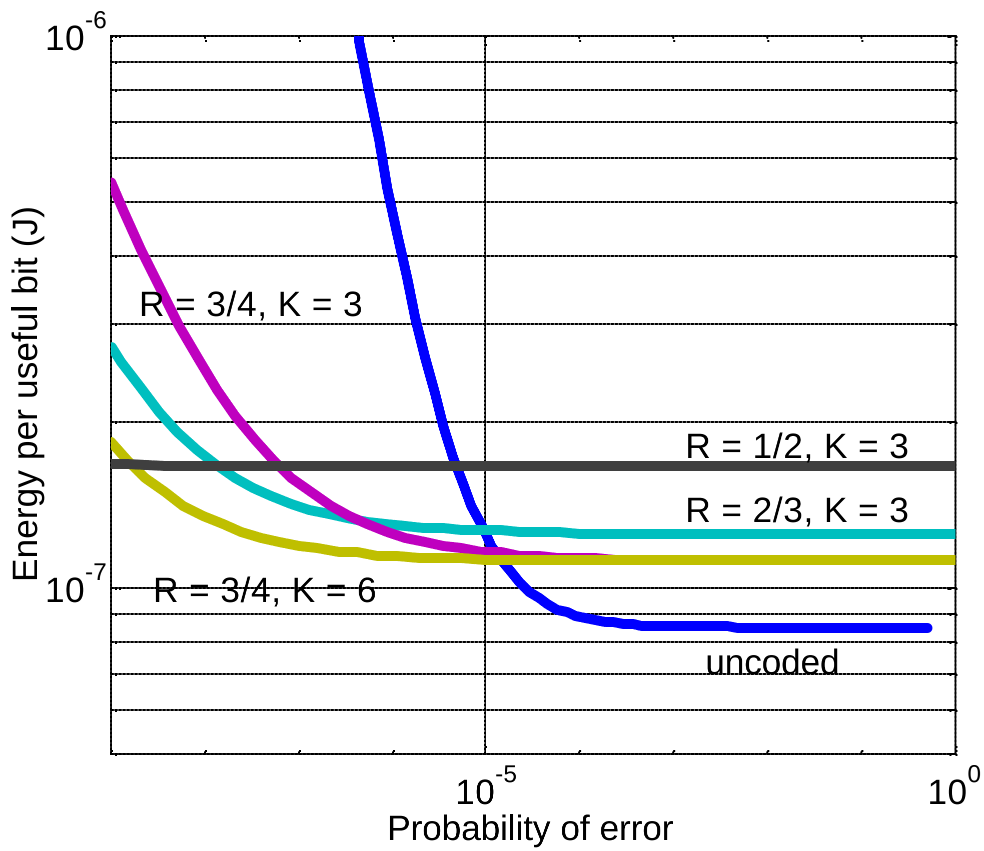
Component	Energy
Radio (0 dBm) $P_b \approx 10^{-3}$	85 nJ/bit
R = ½, K = 3	0.026 nJ/bit
R = ½, K = 6	0.225 nJ/bit



Energy vs. P_b: Increase Rate

- Higher rate implies less data to send
  - Bigger impact since radio energy dominates
- Strategy varies depending on desired probability of error
- Same Viterbi decoder is used
  - Easier to adapt

Range	Strategy
$P_b > 10^{-5}$	Uncoded
$10^{-6} < P_b < 10^{-5}$	R = 2/3, K = 3
$10^{-8} < P_b < 10^{-6}$	R = 3/4, K = 3
$P_b < 10^{-9}$	R = 1/2, K = 3



Summary

- Key challenge in wireless sensor networks
  - Nodes are energy-constrained
- Power-aware techniques critical to achieve long lifetimes
  - Techniques need to be applied at many different parts of system
- Optimal power-aware communication strategy is dependent on:
  - Scenario (desired output quality)
  - Fabric
- Computation is free, focus on communication