Low Power Wireless Communication System Design Methodologies

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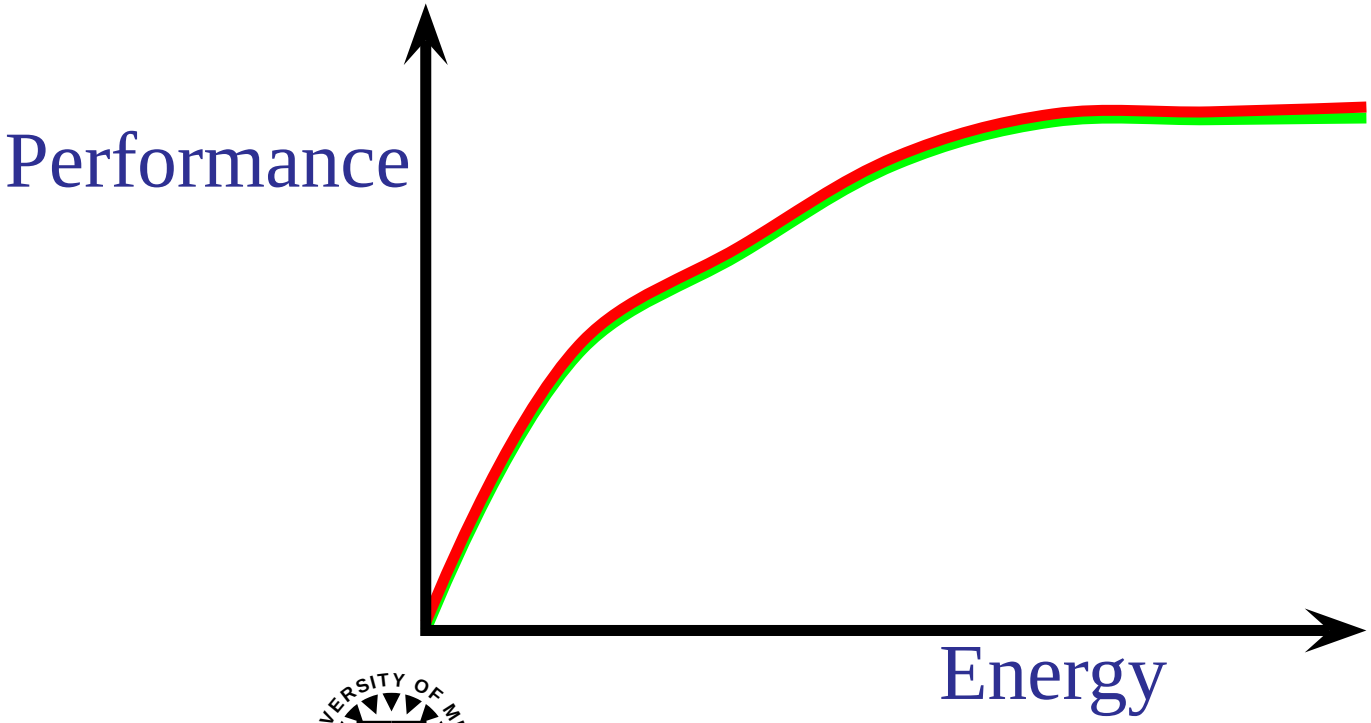
Objectives

- Determine the trade-off between performance and energy in a wireless communication network.



Observations

- The performance and energy consumption of a wireless network is determined by network protocol, physical layers design (coding and modulation) as well as propagation and device characterisitics

Observations

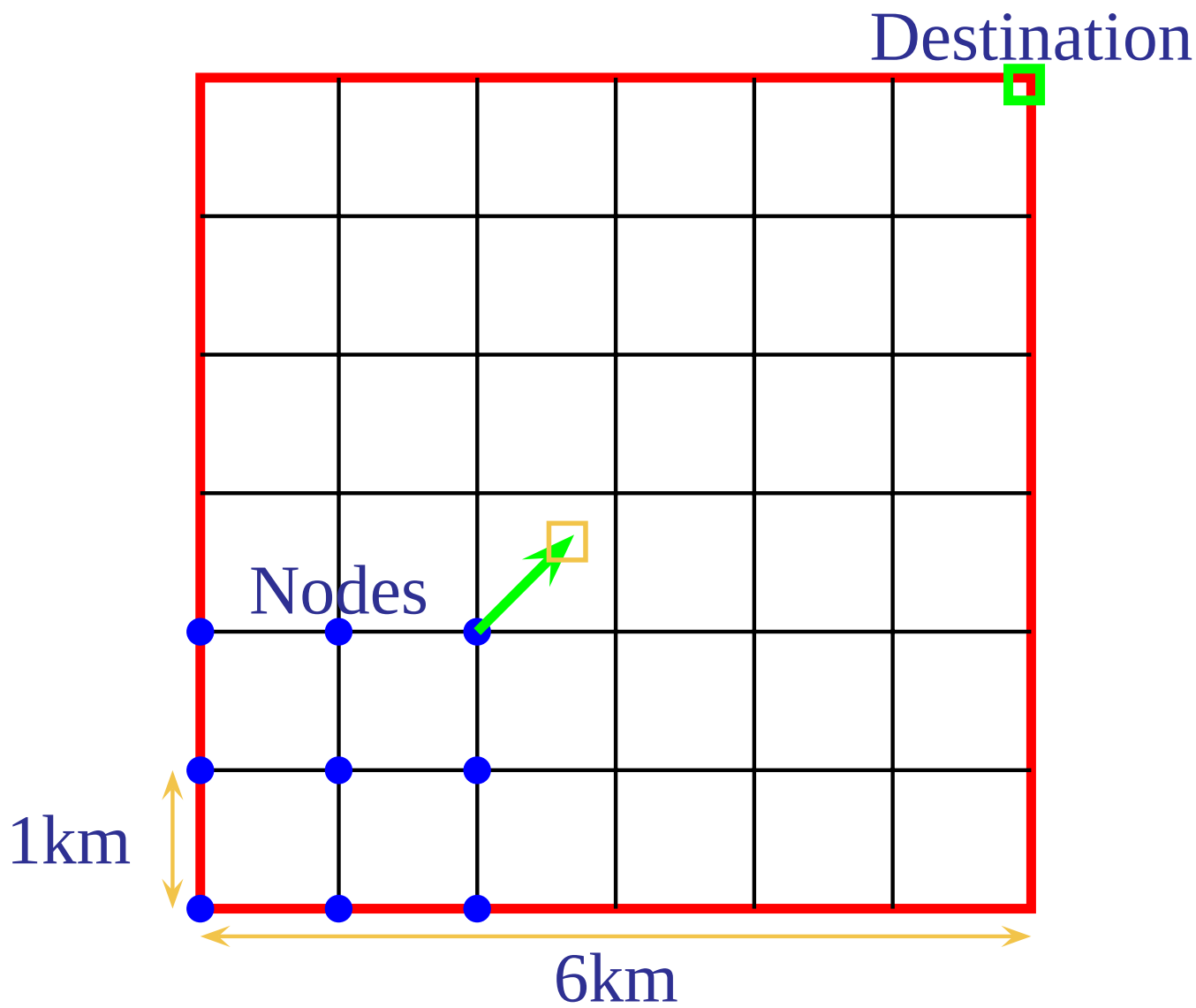
- Without a constraint on energy each of these subsystems can be optimized individually.
- By imposing an energy constraint the overall systems optimization requires a coupling between the different layers in the system hierarchy.

Objectives (cont.)

- Provide a methodology for *integrated* design, optimization and simulation of a communication system including the application layer, network protocol, data link layer protocols, physical layer and device layer.

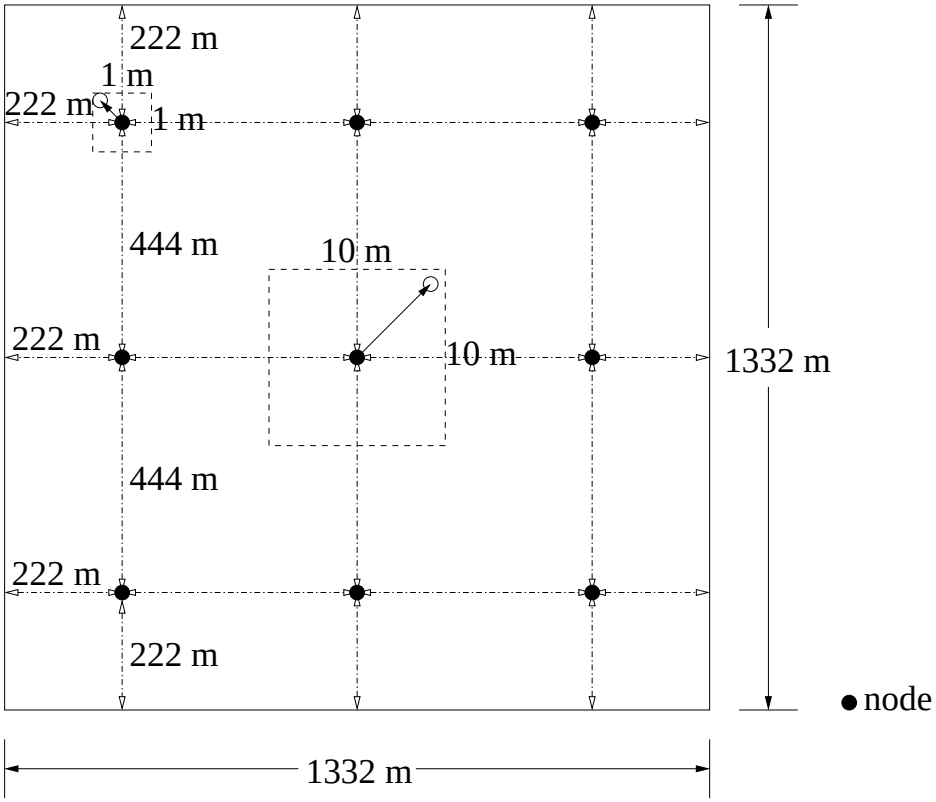
Example Scenario 1 (Application Layer)

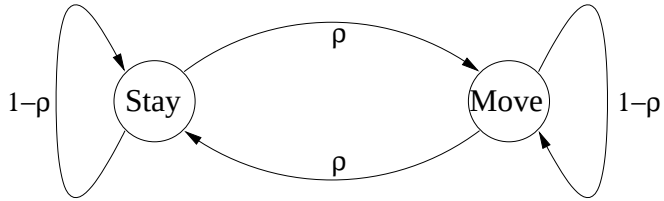
- Mobiles are initially located in a small geographical region and desire to keep track of the position of other nodes as nodes move toward a destination (situation awareness).
- Each node moves toward the destination (1 m/s) but with random variations (uniform over a 1 m^2 area) and knows its own position (through GPS).
- Each node has a finite amount of energy for transmission of messages and processing of received messages.


Destination
Nodes
1km
6km

Example Scenario 2 (Application Layer)

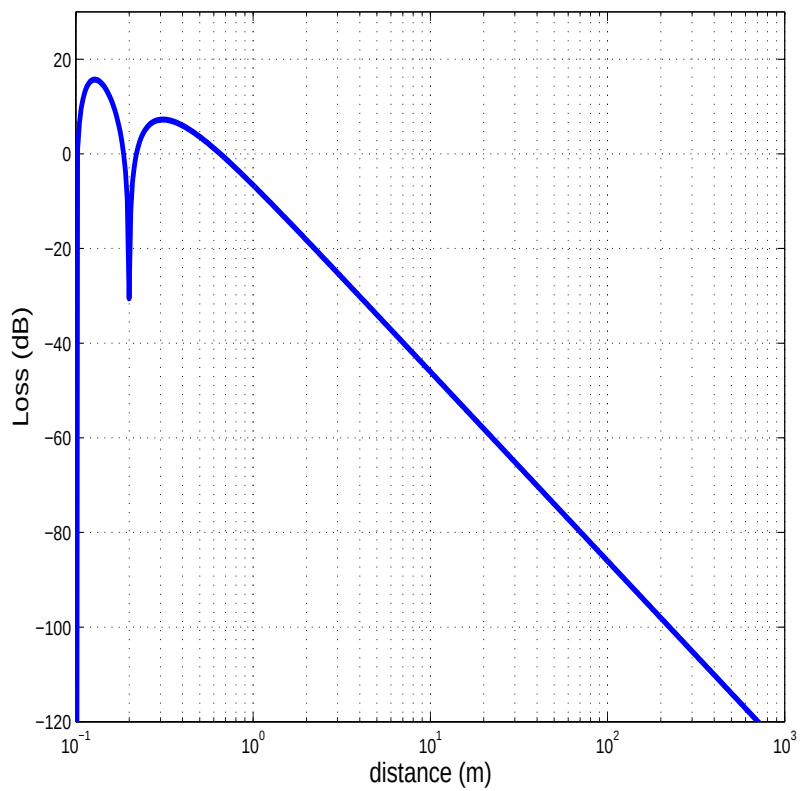
- All nodes are initially deployed in a region of size 1332 m $\times$ 1332 m and move within this region.
- The mobility of each node is characterized by a two-state discrete-time Markov chain.
- In each of these states, each node's motion is subject to random disturbance in the x and y coordinates, where the disturbance is parameterized by a scaling factor of 1 m in the state *Stay* and 10 m in the state *Move*.
- Each node has a finite amount of energy for transmission of messages and processing of received messages.


222 m
1 m
222 m
1 m
444 m
10 m
222 m
10 m
1332 m
444 m
222 m
222 m
1332 m
node


ρ
1−ρ
Stay
Move
1−ρ
ρ

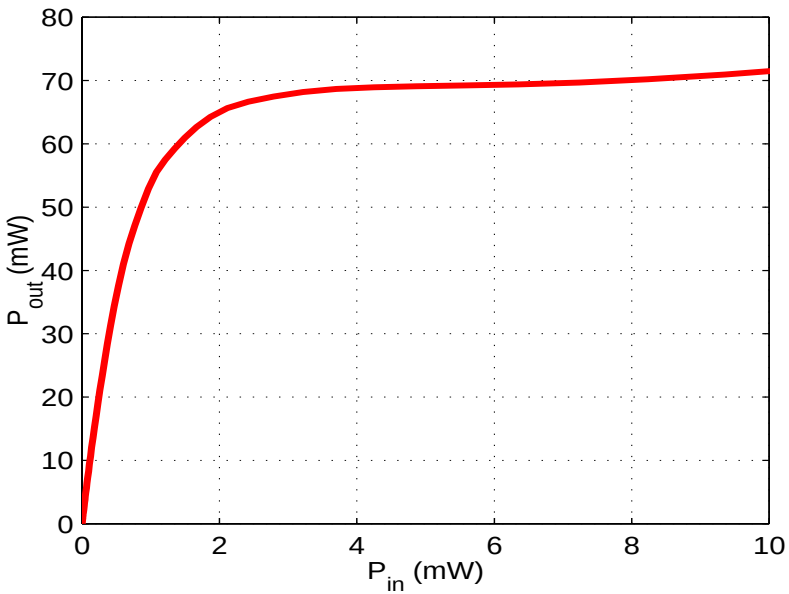
Propagation Effects

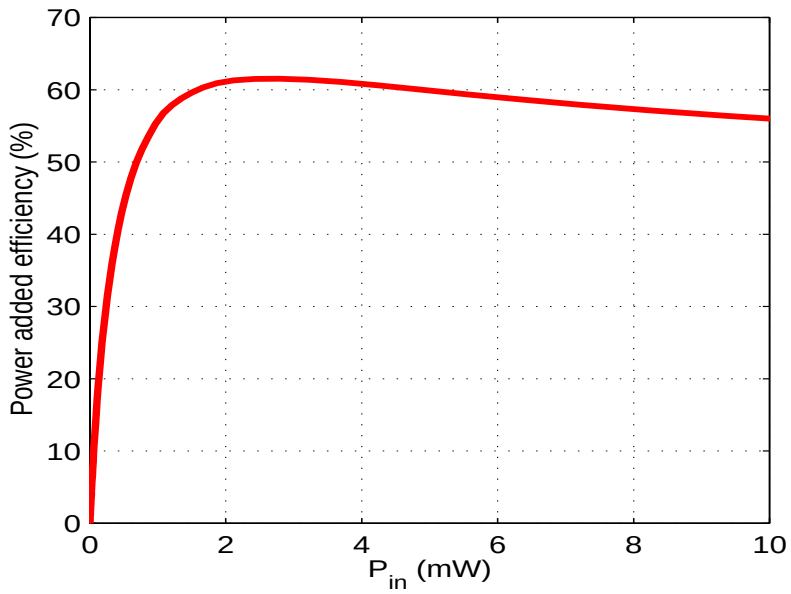
- Propagation decreases the received power proportional to d^4.



Amplifier Effects

- The amplifier has low efficiency at low drive levels and high efficiency at high levels.





Observations

- The propagation effect would seem to imply that routing the messages would be power efficient with low power for each link.
- The power efficiency curve would suggest that a single broadcast strategy would be power efficient since the amplifier is not efficient at low drive levels.
- Higher amplifier intermodulation products at high drive levels cause increased interference.
- What is the routing algorithm/amplifier drive level for optimum performance for a given energy constraint?

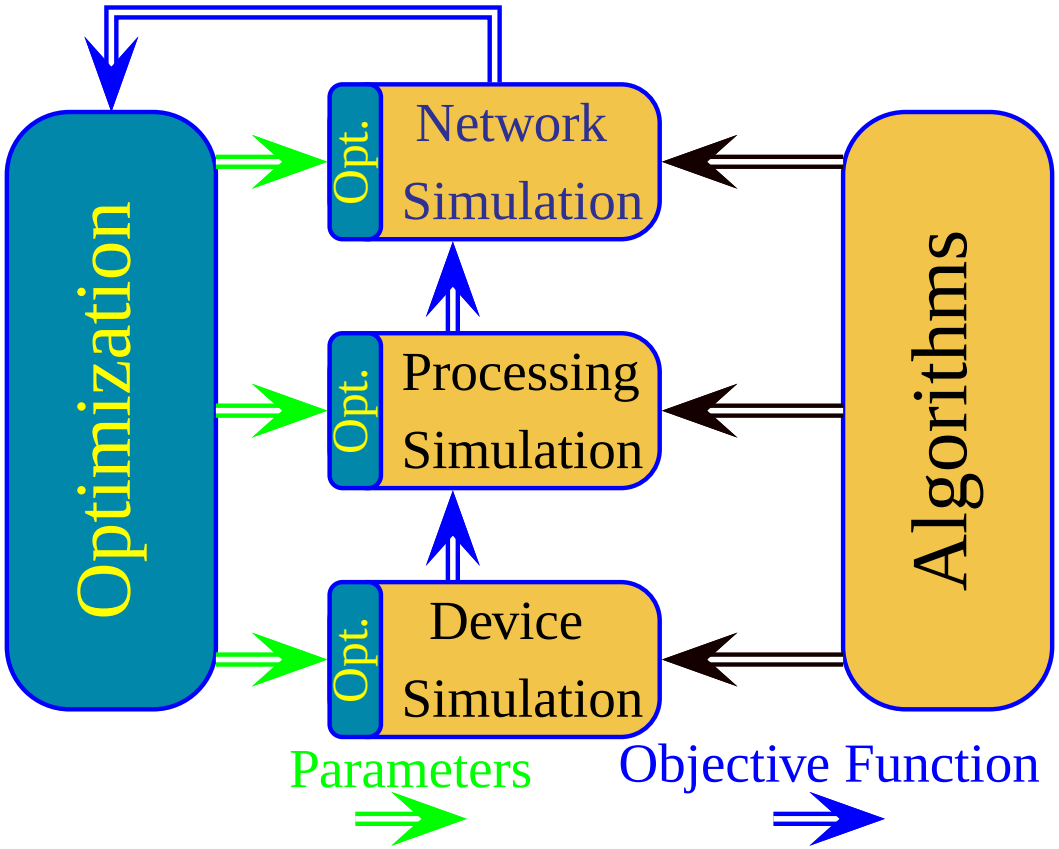
Methodology

- To determine tradeoff between performance and energy for complex systems an appropriate combination of simulation and optimization is necessary. The systems are generally too complex for nice analytic formulation and thus require simulation.
- The number of parameters is very large so efficient optimization and simulation is necessary.

Methodology (cont.)

- We break the problem into layers and are investigating the simulation/optimization problem and the coupling between layers.

Performance Optimization Methodology



Optimization Criteria

Scenarios/Requirements

Battery Capacity

Protocol

Compression Type

Coding Type

Modulation Type

Frequency

Antenna Model

Amplifier Models

Optimization

- How often should nodes transmit their location packets?
- How much energy should be allocated to the receiver for processing packets?
- At what drive level should the amplifier operate?

Single-hop Transmission Protocol at Network I

- Each node carries a battery with a certain capacity and broadcasts its position awareness packet every T seconds.
- The mobile network uses time division multiple access (TDMA), where each node in the network has its own transmission time slot.
- After a transmission, the node retransmits the same packet with probability q if there is enough energy left in the battery and enough time left in its transmission time slot for one packet transmission.

Multi-hop Routing Protocol at Network Layer

- Each node updates its link information to its neighbors every T_r seconds and calculates its routing table similar to what is done in OSPF.
- In order to take advantage of omni-directional antenna, the routing protocol stores the largest transmit power for a node to reach its neighbors along with its routing table.
- Each node transmits its position awareness packet to its neighbors every T_g seconds using the power calculated above.

Goal for Network Layer

Let $\underline{w}_k^{(j)}$ be the actual position of node j at time index k, and $\underline{\hat{w}}_k^{(i,j)}$ be node i's estimate of node j's position at time index k.

Define the estimation error

$$\underline{e}_k^{(i,j)} = \underline{w}_k^{(j)} - \underline{\hat{w}}_k^{(i,j)}, \tag{1}$$

and

$$J^{(i)} = E\left[\frac{1}{K(I-1)} \sum_{j=1, j\neq i}^{I} \sum_{k=1}^{K} \left\| \underline{e}_k^{(i,j)} \right\|\right], \tag{2}$$

where I is the total number of nodes in the network and K is the time horizon under consideration.

Define the objective function

$$J = \frac{1}{I} \sum_{i=1}^{I} J^{(i)}. \tag{3}$$

The constraint on energy is

$$\max_{1 \leq i \leq I} E^{(i)} \leq E. \tag{4}$$

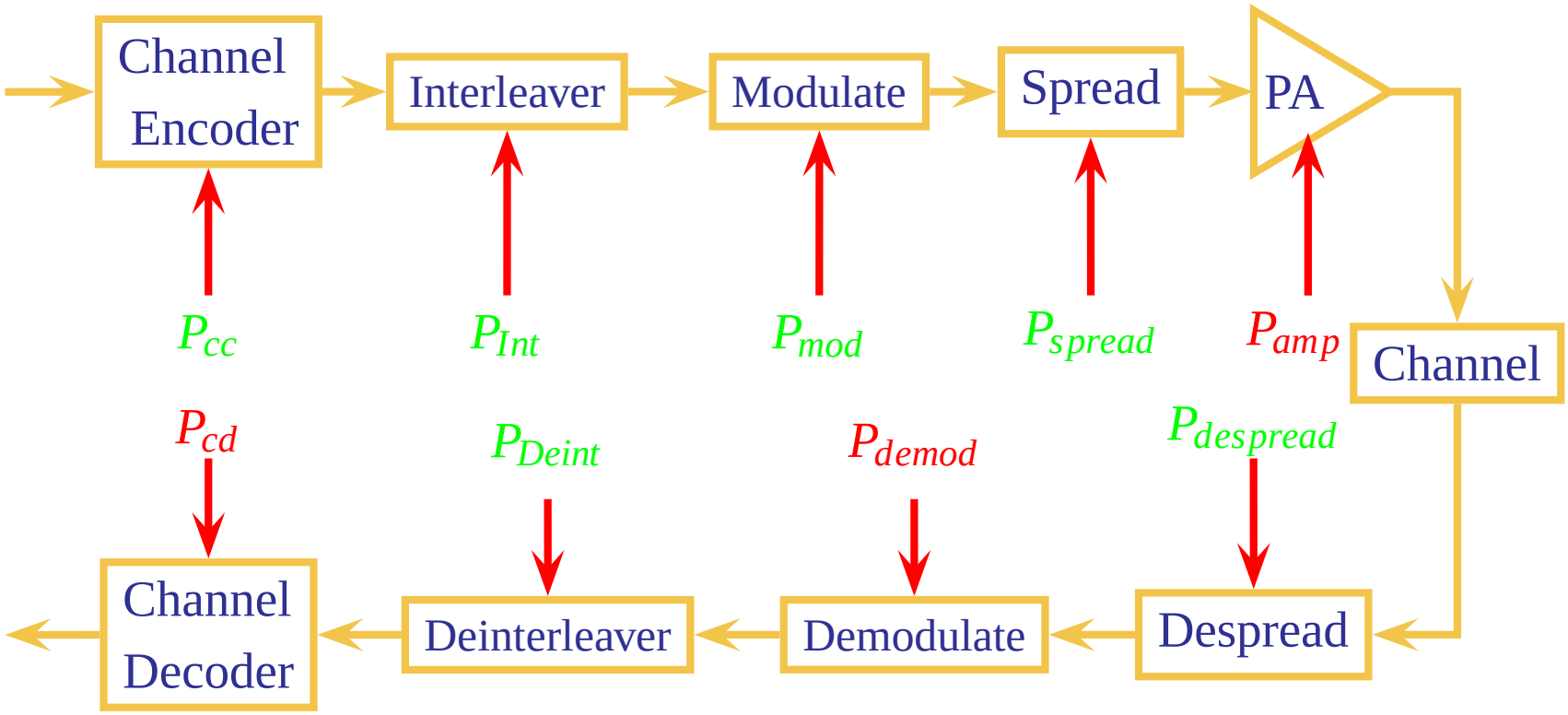
Our integrated design is to find

$$[T^*, q^*, E_{ct}^*, E_{cr}^*] = \arg \min_{\substack{[T,q,E_{ct},E_{cr}] \\ \max E^{(i)} \leq E}} J(T, q, E_{ct}, E_{cr}) \quad (5)$$

and the corresponding performance

$J^* = J(T^*, q^*, E_{ct}^*, E_{cr}^*)$.

Processing Layer Block Diagram



Goal for Processing Layer

Compute the packet error probabilities as a function of the transmitter and receiver energy and received SNR optimized over other parameters.

$$
\begin{aligned}
P_e &= f_P(E_{ct}, E_{cr}, SNR) \\
&= \min_{N_M, N_D} g_P(E_{ct}, E_{cr}, SNR, N_M, N_D)
\end{aligned}
$$

N_M = bits of quantization for demodulator

N_D = bits of quantization for decoder.

Initial Models for Processing Layer

- Convolutional, Turbo, (Golay or Hadamard, other Block) Channel Code
- BPSK Modulation with Raised Cosine Filtering
- Frequency-Hopped Spread-Spectrum
- AWGN,(Flat (Ideal) Rayleigh, Pine Street, American Legion Drive, Measurements)
- Tapped Delay Line Matched Filter (Equalization)
- Coherent Demodulation
- Viterbi Decoding, Iterative Decoding, (Hadamard/Golay) Decoding

Parameters for Optimization

- Block Length of Packet
- Preamble Size (for synchronization)
- Number of Bits/Hop
- Sample Rate at Input to Equalizer/Matched Filter
- Number of Bits of Quantization at Input to Equalizer/Matched Filter
- Number of Bits of Quantization for Coefficients in Equalizer/Matched Filter

Parameters for Optimization (cont.)

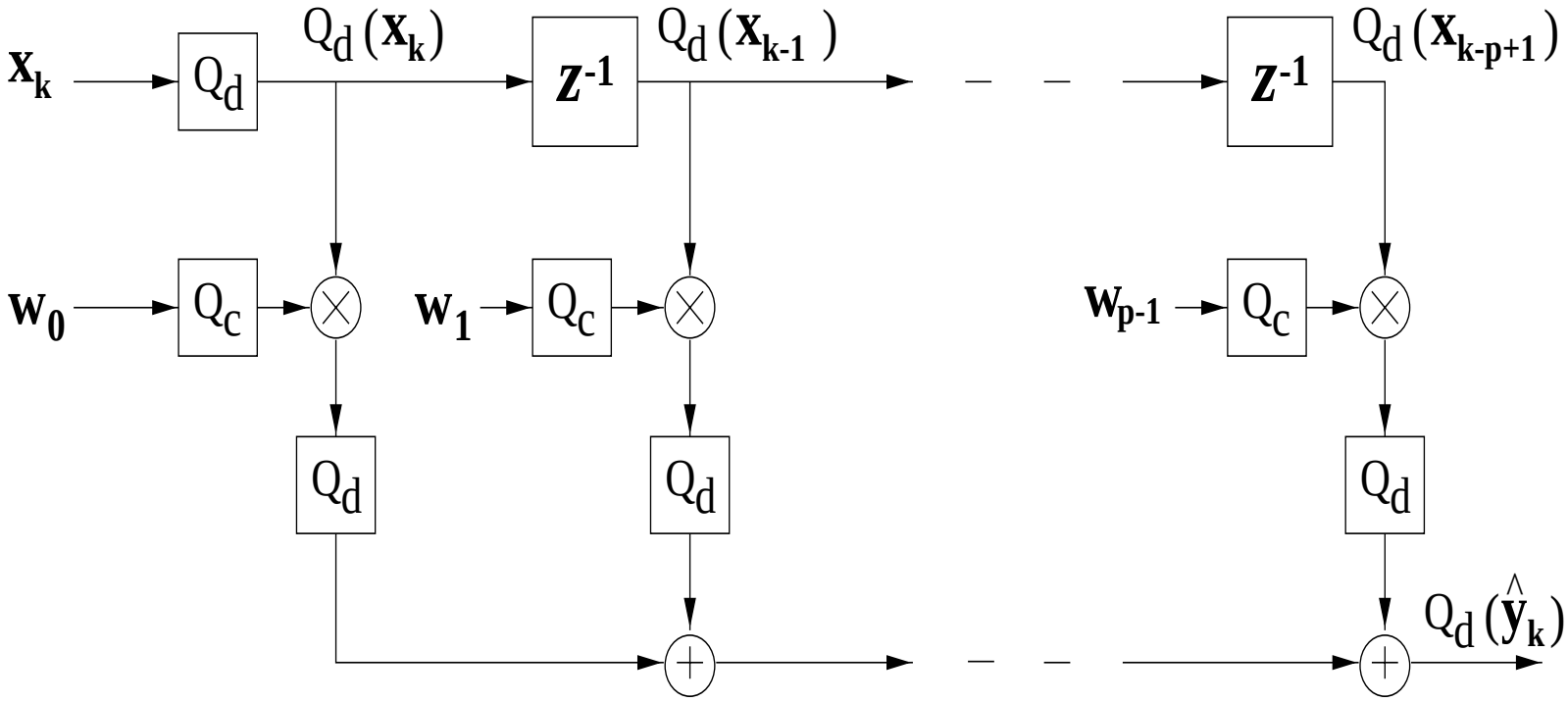
- Number of Taps in Equalizer/Matched Filter
- Bits of Quantization at Output of Equalizer/Matched Filter (Input to Decoder)
- Number of Bits Quantization in Decoder Metric (e.g. Turbo or Convolutional or Golay or Hadamard)
- Number of Iterations for Iterative Decoder

Processing Energy Estimation

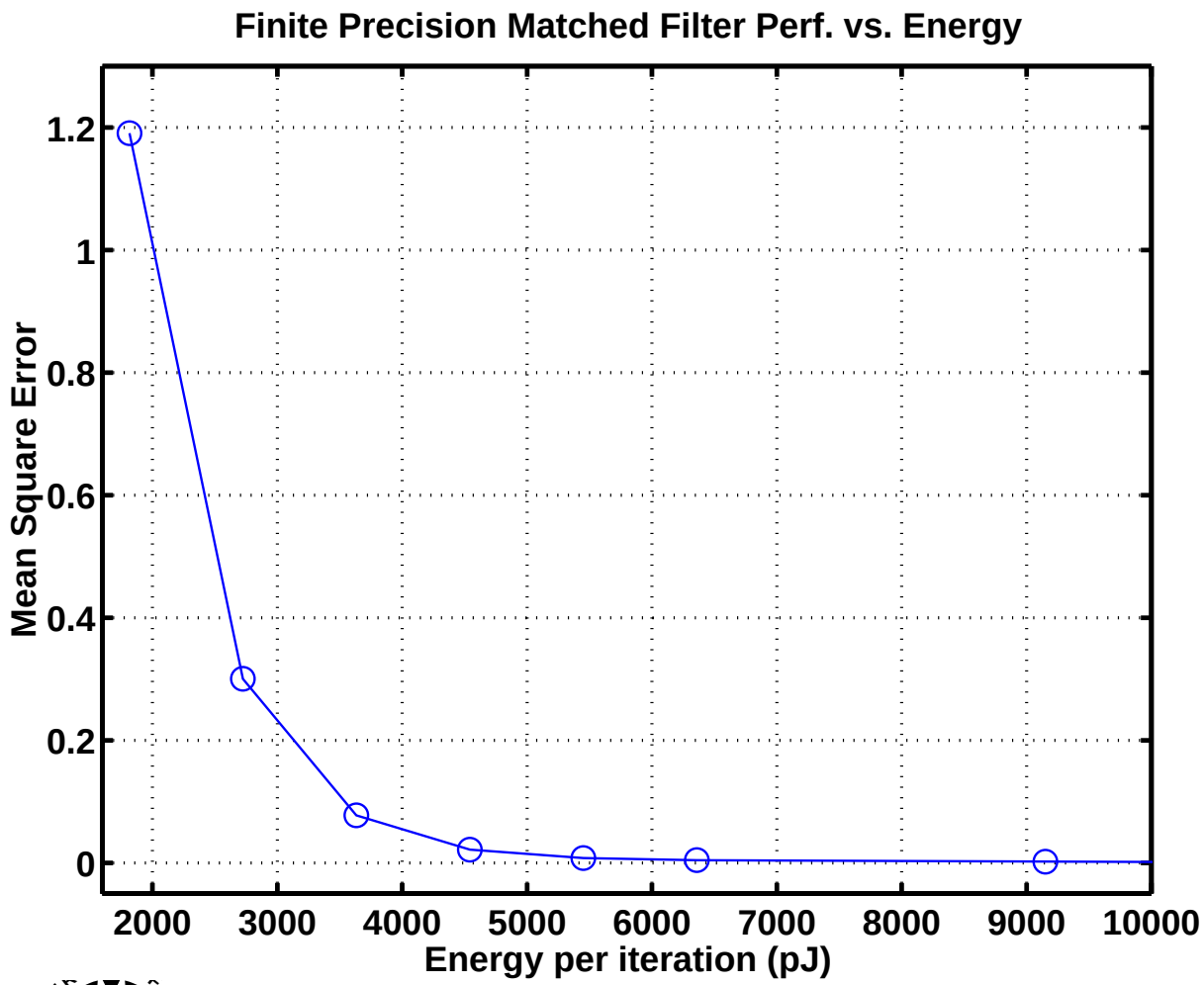
- Energy dissipation of digital circuitry is estimated based on 0.6 μm standard cell technology.
- Energy for the computation intensive algorithm is estimated by summing the energy of the operations. The energy for each individual operation is individually synthesized using Epoch CAD tool.

- Power/Energy consumption for the algorithm containing intensive memory access or highly interconnected structure are estimated from the actual circuit layout synthesis (e.g. turbo decoding, convolutional decoding).
- The supply voltage of the circuit used for the algorithm implementation are scaled to handle the range of operating speeds to get the lowest possible energy.

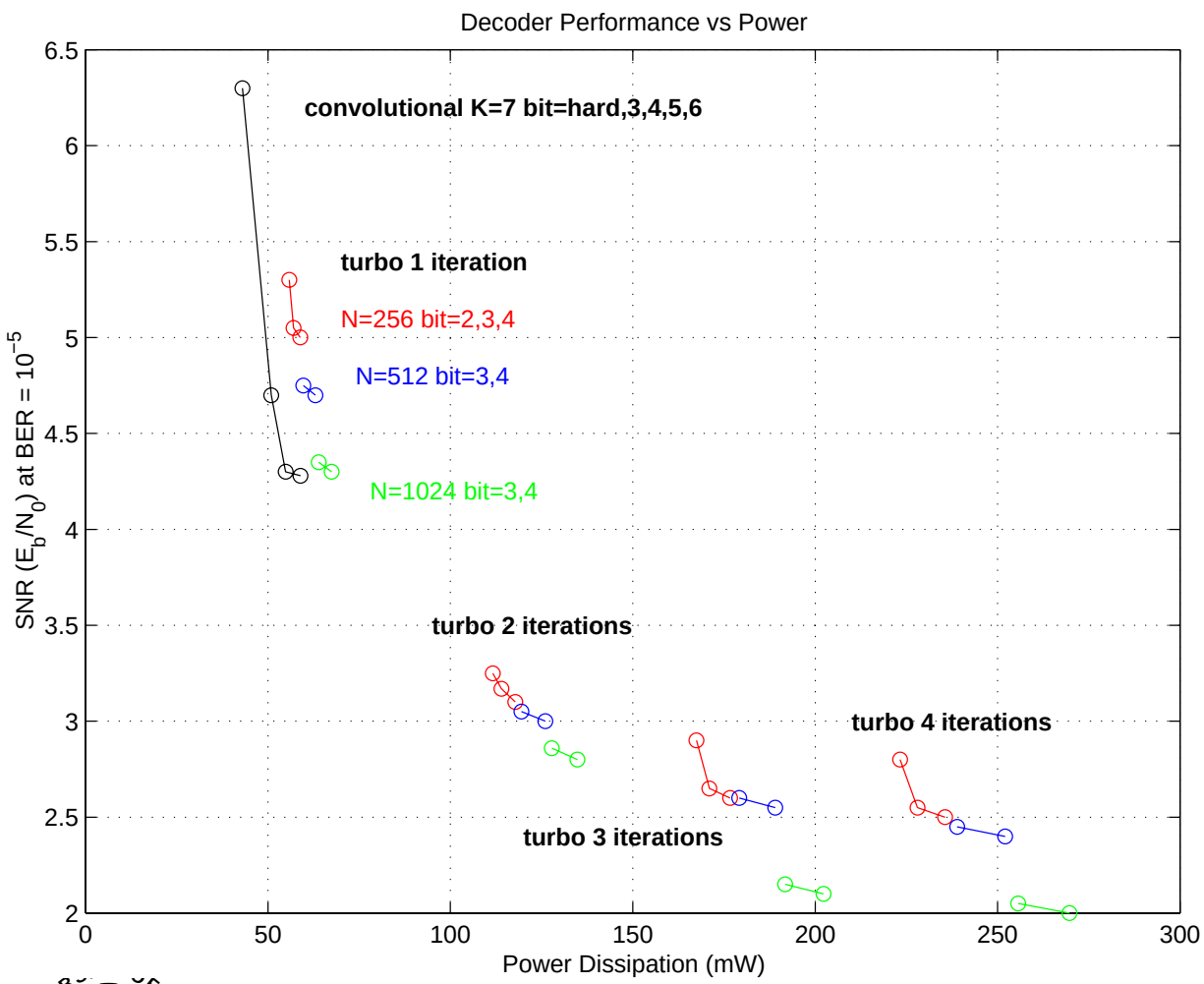
Matched Filter Structure



MSE Performance for Matched Filter Alone



Power Performance Tradeoffs for Codes



Initial System Assumptions

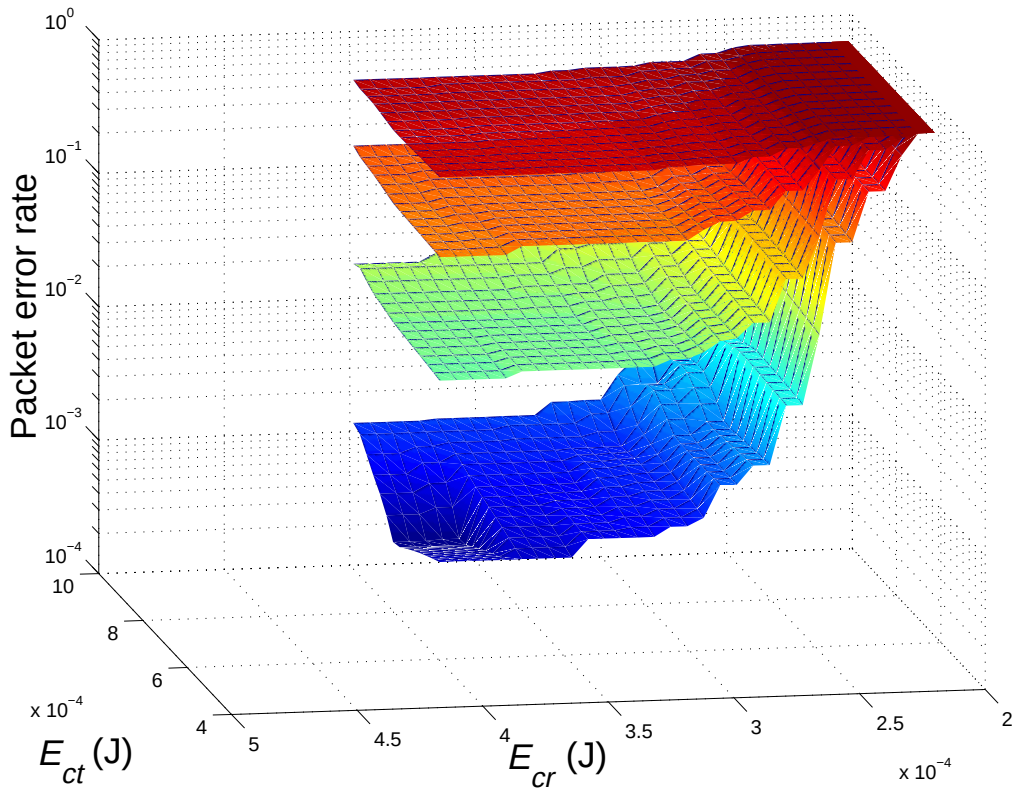
- Packet length of 224 (252) information bits or 460 (512) channel bits
- Constraint length 7 convolutional code (Turbo code)
- BPSK modulation with square root raised cosine filter (rolloff=0.3)
- Transmitter filter implemented with 19 taps (infinite quantization)

- Symbol duration 20μs.
- Frequency-hopped with 23 (32)bits/hop, 20(16) hops per packet
- Nonlinear amplification (model from device layer)
- Additive white Gaussian noise channel

Initial System Assumptions (cont.)

- Variable signal energy-to-noise density ratio (SNR)
- Ideal down conversion (frequency dehopping)
- Matched filter implemented with a tap delay line model with 19 taps and N_D bits of quantization for the coefficients and the input sampled at four times the data rate.
- Convolutional decoder with N_E bits of quantization
- Variable receiver processing energy constraint

Packet Error Probability vs. E_{ct}, E_{cr}



Packet Error Probability for SNR= 1,2,3,4 dB

Notes

This plot shows the bit error rate as a function of the receiver processing energy constraint and the transmitter amplifier energy constraint. The surfaces are, from top down, SNR=1 dB, 2 dB, 3dB, and 4 dB. The grids are interpolated.

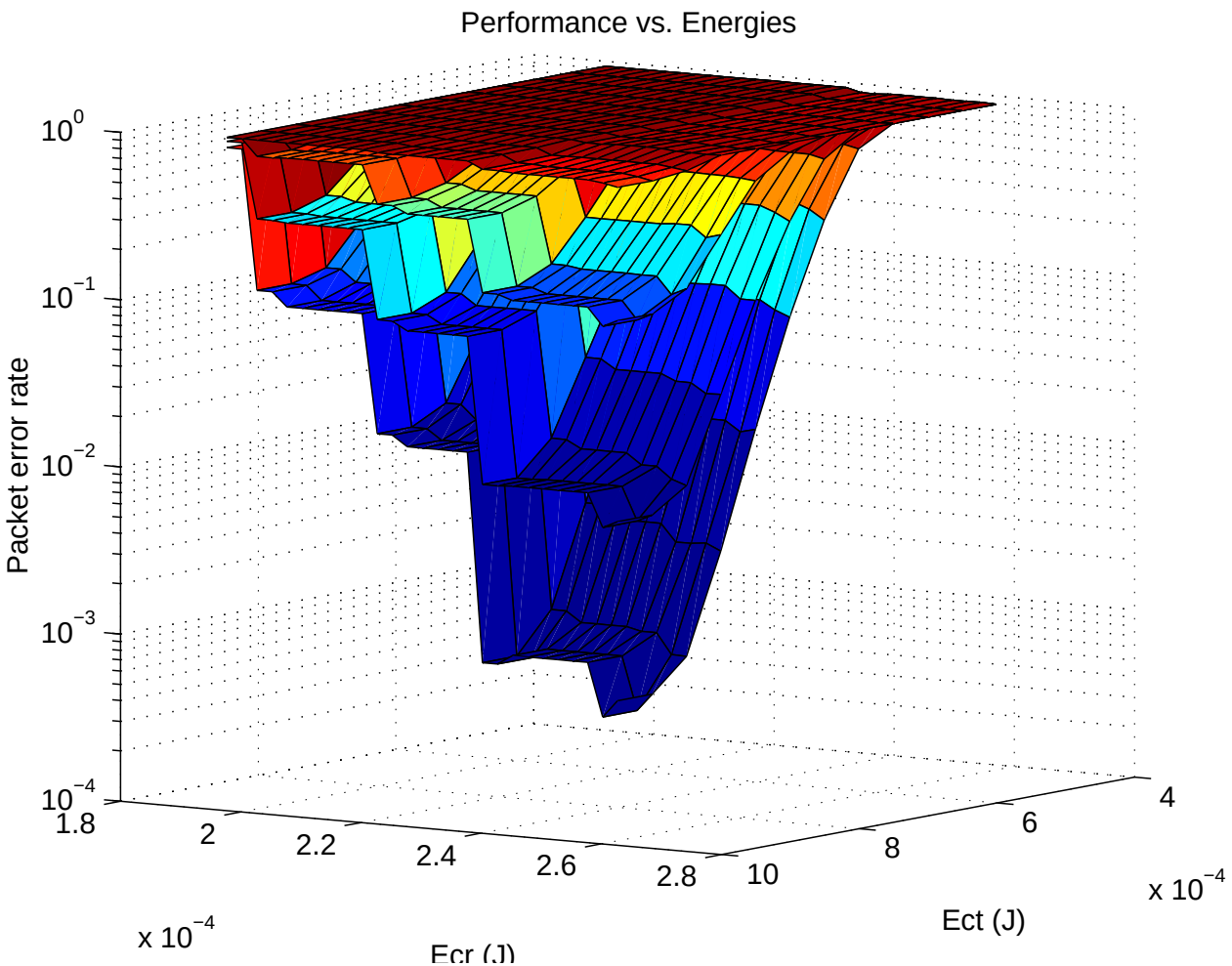
Objective Function

Next we renormalize our results by relating the received SNR to E_{ct}, $N_0 = -174$dBm/Hz and a noise figure of 3 dB.

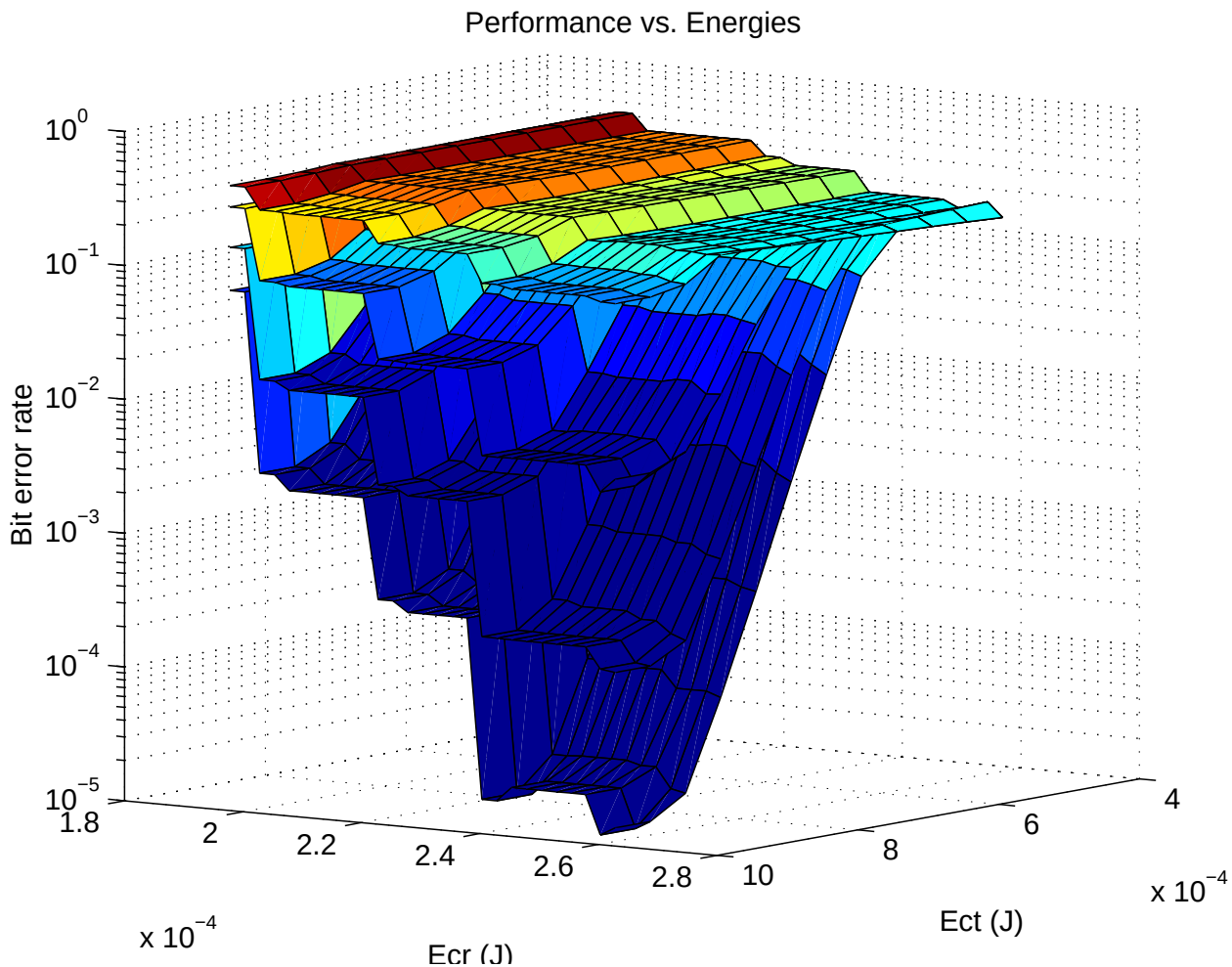
$$SNR = \frac{P_{out} T_s G_t G_r h_t^2 h_r^2 \eta_r \eta_t}{d^4 N_0}$$

where $P_{out} = f_1(E_{ct})$.

Objective Function



Objective Function



Objective Function

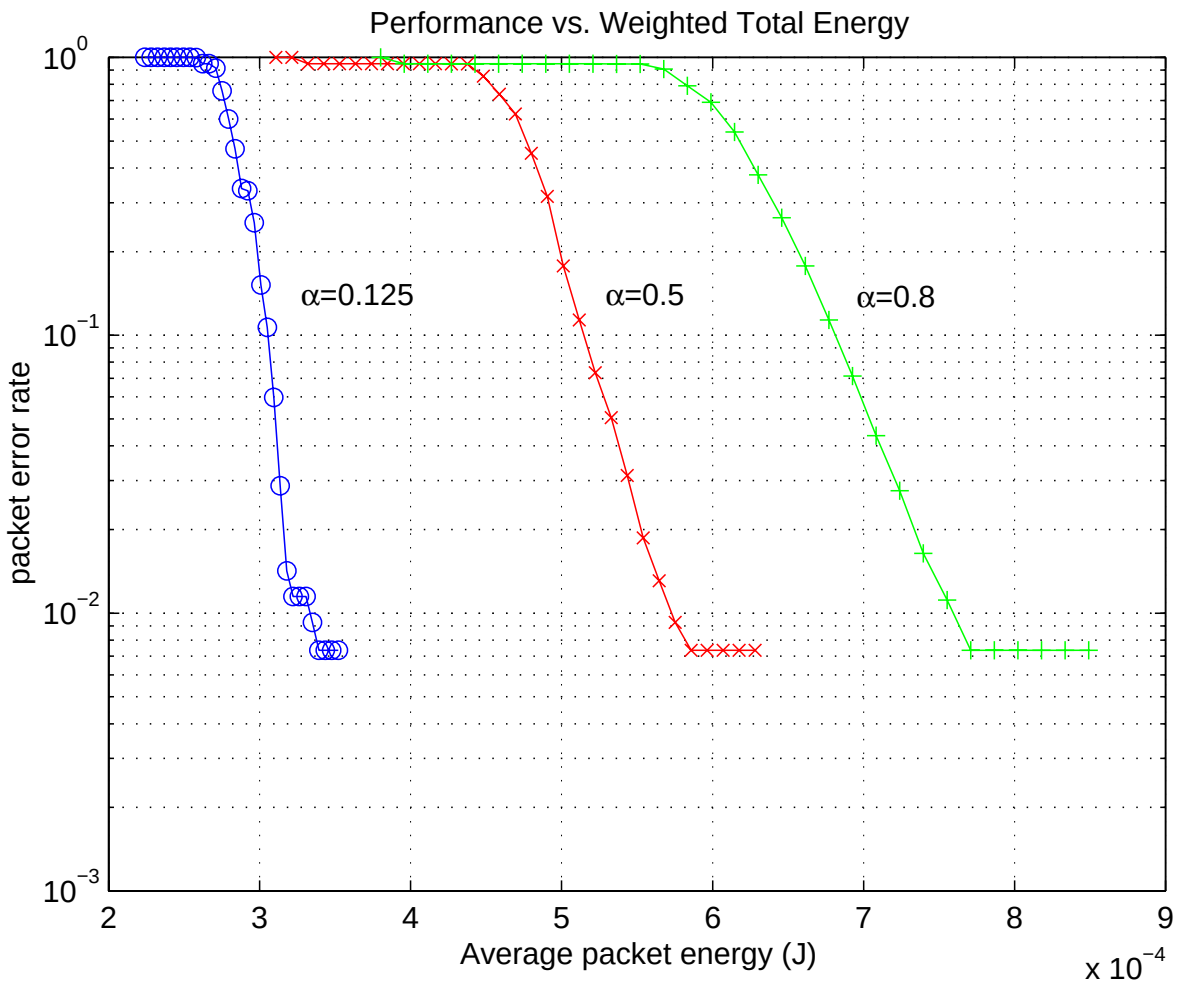
Consider the case where each node is transmitting a fraction α of the time and receiving packets a fraction $1-\alpha$ of the time. We optimize the design to get the lowest packet error rate for a given average energy per packet. In other words, for E given, find the optimal performance subject to

$$\alpha E_{ct} + (1-\alpha)E_{cr} < E$$

This gives the solution to the above optimization

problem using the processing layer model and channel propagation model given above.

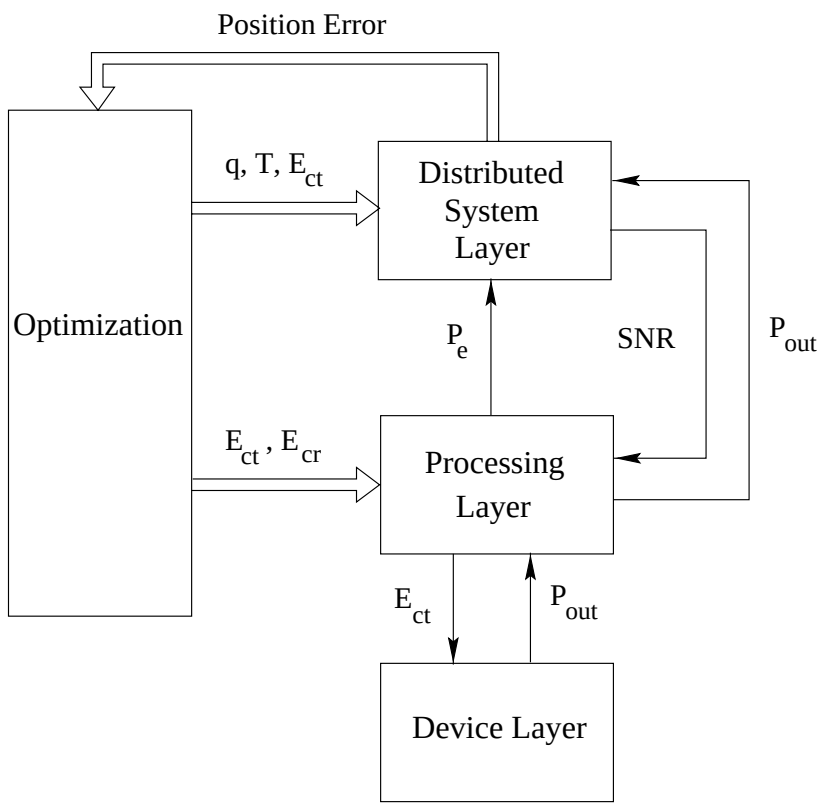
Objective Function



Simulation Times

In order to produce the simulation 5 different P_{in} drive levels were chosen, and 5 different SNR's were chosen and then optimized over the parameters (bits of quanitzation for matched filter and decoder). This resulted in about 250 different simulations which takes about 3 days running on 20 Sparc Ultra 10s.

Overall Optimization and Simulation



Overall Optimization and Simulation

Step 1: Optimization program determines parameters E_{ct}, E_{cr}, T, q.

Step 2: Device and processing layer determines P_{out}, E_{at}, E_{ar} amplifier output power.

$$
\begin{aligned}
P_{out} &= f_1(E_{ct}) \\
E_{at} &= f_2(E_{ct}) \\
E_{ar} &= f_3(E_{cr})
\end{aligned}
$$

This is actual energy per packet consumed (which might be less than the energy constraint)

Overall Optimization and Simulation

Step 3: Distributed system (network) layer determines SNR.

$$SNR = \frac{P_{out} T_s G_t G_r h_t^2 h_r^2 \eta_r \eta_t}{d^4 N_0}$$

where

P_{out} = amplifier output power

T_s = channel symbol duration

G_t = transmitter antenna gain

G_r = receiver antenna gain

h_t = transmitter antenna height

h_r = receiver antenna height

η_t = transmitter antenna efficiency

η_r = receiver antenna efficiency

d = distance

N_0 = thermal noise power density

Overall Optimization and Simulation

Step 4: Processing layer determines P_e, packet error probability. This is actually done off line resulting in a function f_4^* used by the network layer:

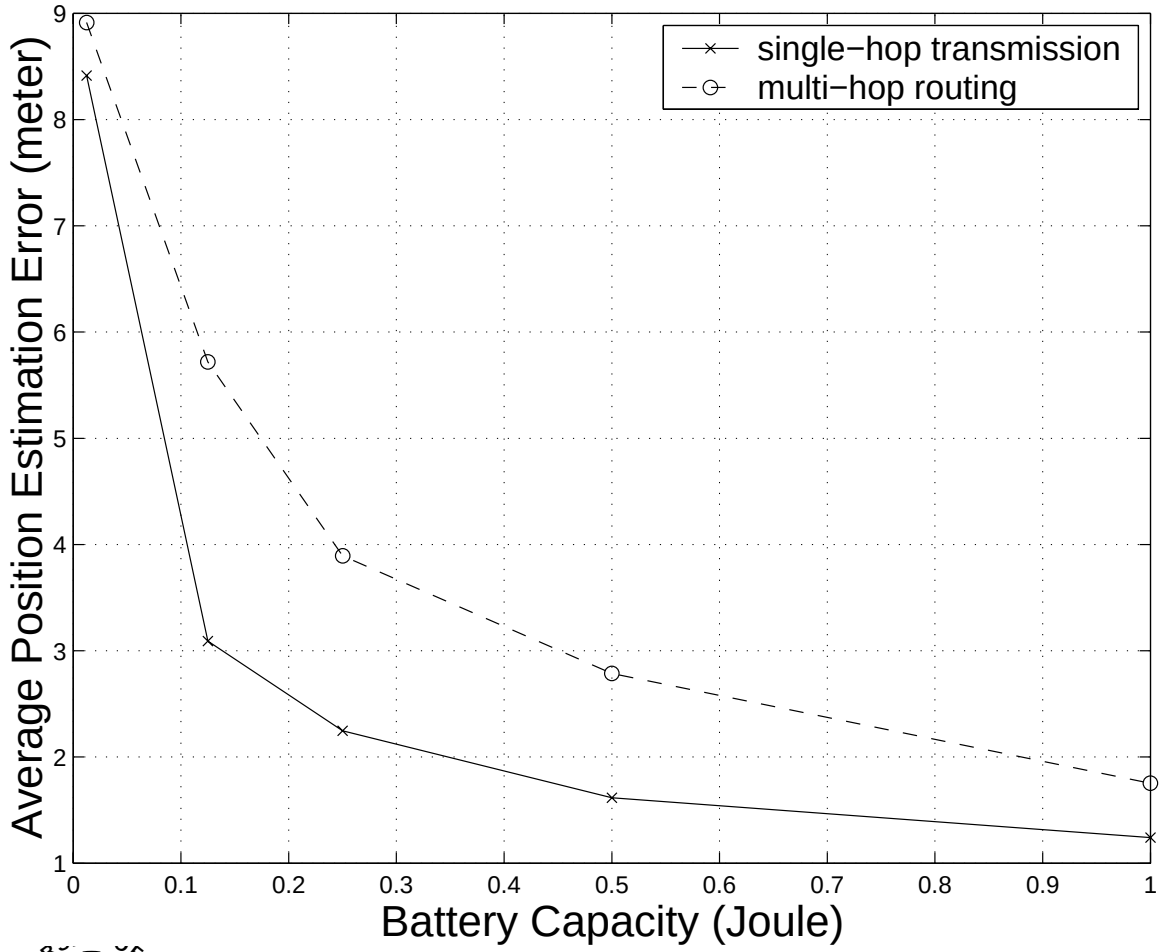
$$P_e = f_4^*(E_{ct}, E_{cr}, SNR)$$

Step 5: Network layer uses P_e to determine if the simulated packet transmission leads to a correct reception or not; it then updates the position error.

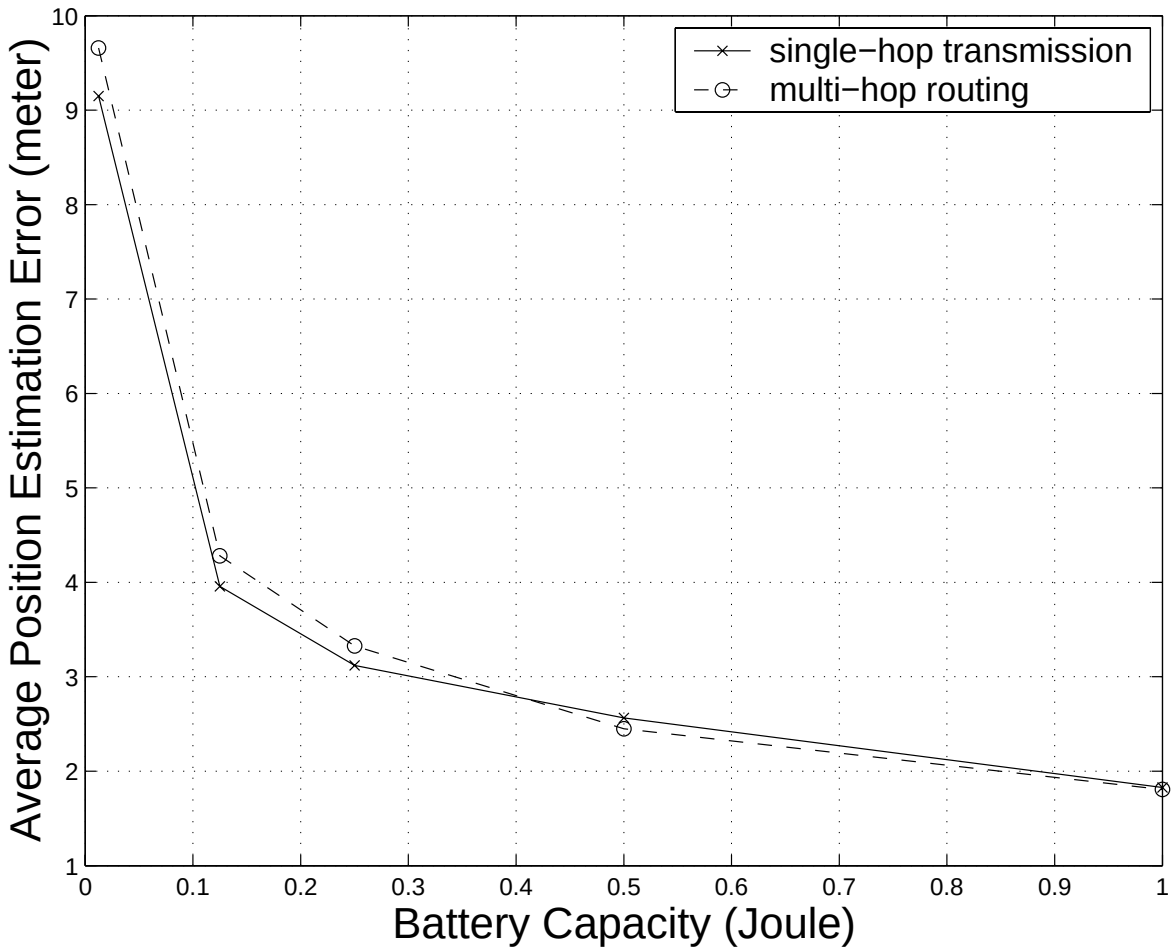
Overall Simulation and Optimization

- For a given parameter set run 40 parallel simulations of network performance (mean-square error). Use the first 30 that finish.
- Use simulated annealing with the hide-and-seek algorithm to determine parameters values for each iteration

MSE vs. Energy (1km x 1km drop zone)



MSE vs. Energy (2km x 2 km drop zone)



Comparison of Design Methodologies

- Alternative Design 1 (AD-1)

  We partially decouple the optimization by imposing a constraint on the packet error probability for the transmission between the two most distant nodes.

Optimization AD-1

We first consider the following optimization problem at the processing layer:

$$[\hat{E}_{ct}, \hat{E}_{cr}] = \arg \min_{\substack{[E_{ct}, E_{cr}] \\ P_e(E_{ct}, E_{cr}, SNR_f) \leq 10^{-2}}} E_{ct} + E_{cr}.$$

Goal for AD-1

The goal in this first step is to minimize the total energy (transmitter and receiver) needed for the longest possible (worst-case) transmission distance in order to maintain a packet error probability of 0.01.

The objective for AD-1 is to find

$$[\tilde{T}, \tilde{q}] = \arg \min_{\substack{[T,q] \\ \max E^{(i)} \leq E}} J(T, q, \hat{E}_{ct}, \hat{E}_{cr}),$$

and its corresponding optimal parameters:

$$J(T^*, q^*, E^*_{ct}, E^*_{cr}) \leq J(\tilde{T}, \tilde{q}, \hat{E}_{ct}, \hat{E}_{cr}).$$

Alternative Design 2 (AD-2)

In alternative design 2, we completely decouple the optimization at the network and processing layers.

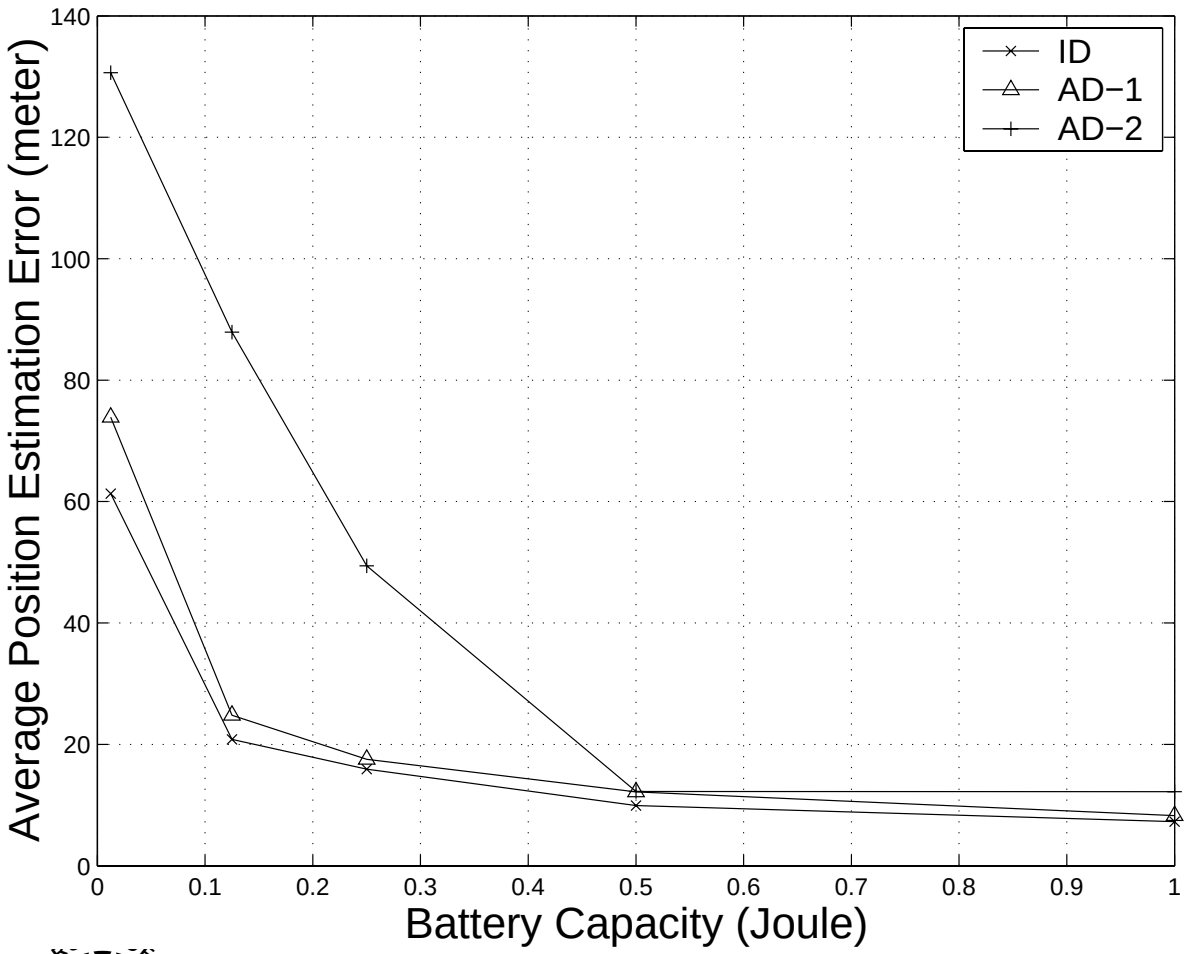
We proceed as follows: (i) we optimize E_{ct} and E_{cr} as in AD-1; and (ii) we select the parameter values $T^o = 60$ s and $q^o = 0.01$ at the network layer, without doing any optimization.

Comaprison of Designs

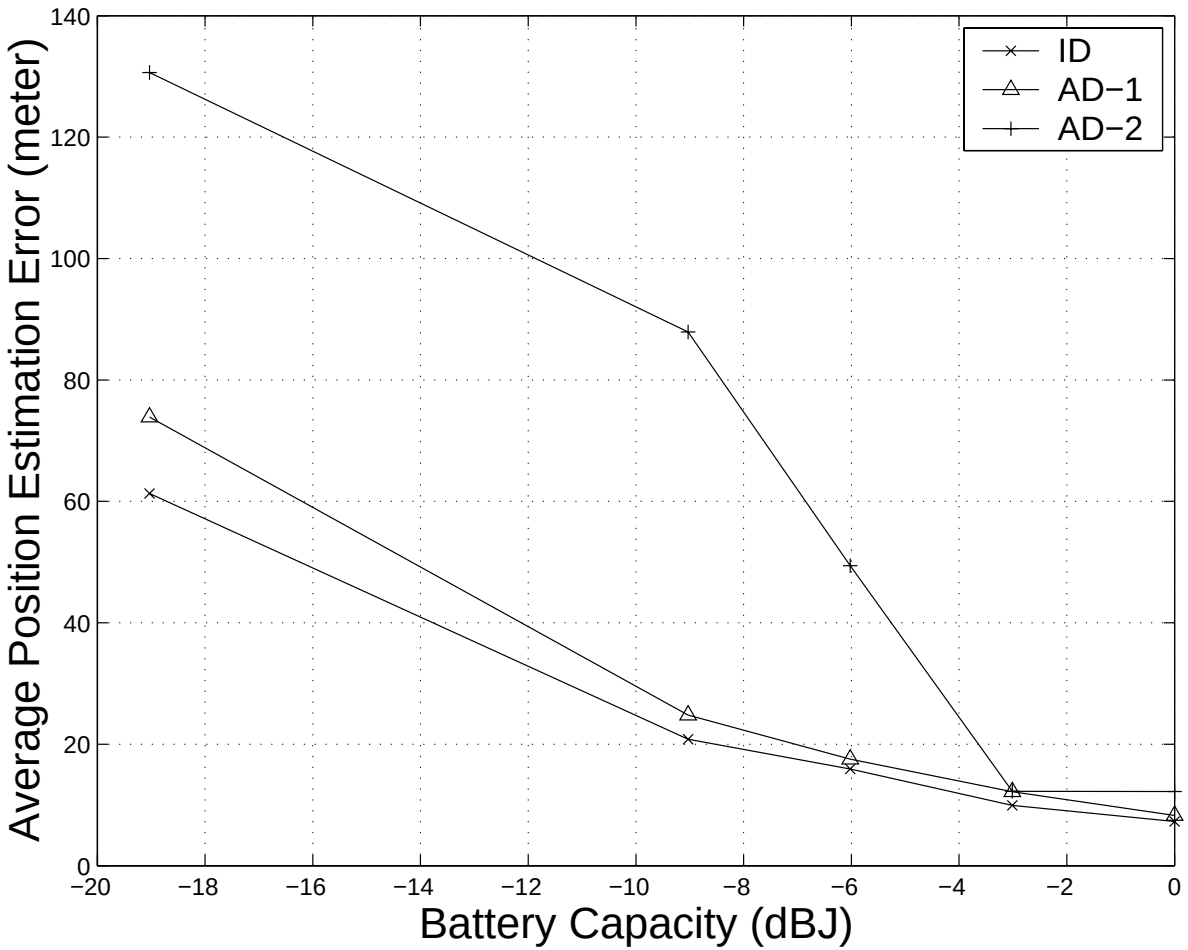
It should be obvious that

$$J(T^*, q^*, E^*_{ct}, E^*_{cr}) \leq J(\tilde{T}, \tilde{q}, \hat{E}_{ct}, \hat{E}_{cr}) \leq J(T^o, q^o, \hat{E}_{ct}, \hat{E}_{cr}).$$

Design Comparison (1km x 1km drop zone)



vs. Energy (1km x 1km drop zone)



Conclusions

A methodology for optimizing and simulating a wireless communication network including, application layer, network protocol, processing layer and device layer with significantly lower computation than a brute force approach has been achieved.

Conclusions

The methodology has been verified for an example scenario. The methodology allows us to compare different types of routing algorithms taking into account device effects (amplifier nonlinearity, for example) as well as power consumption of digital circuitry.

Conclusions

By comparing different design methodologies, we conclude that our integrated design outperforms the other designs by jointly optimizing paremeters at different layers rather than by simply guessing or optimizing parameters at different layers separately.

Conclusions

Adaptability of protocols to energy availability can save significant energy. The amount of gain of the integrated approach will change for different scenarios.

Publication

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