Cross-Layer Design and Analysis of Wireless Networks

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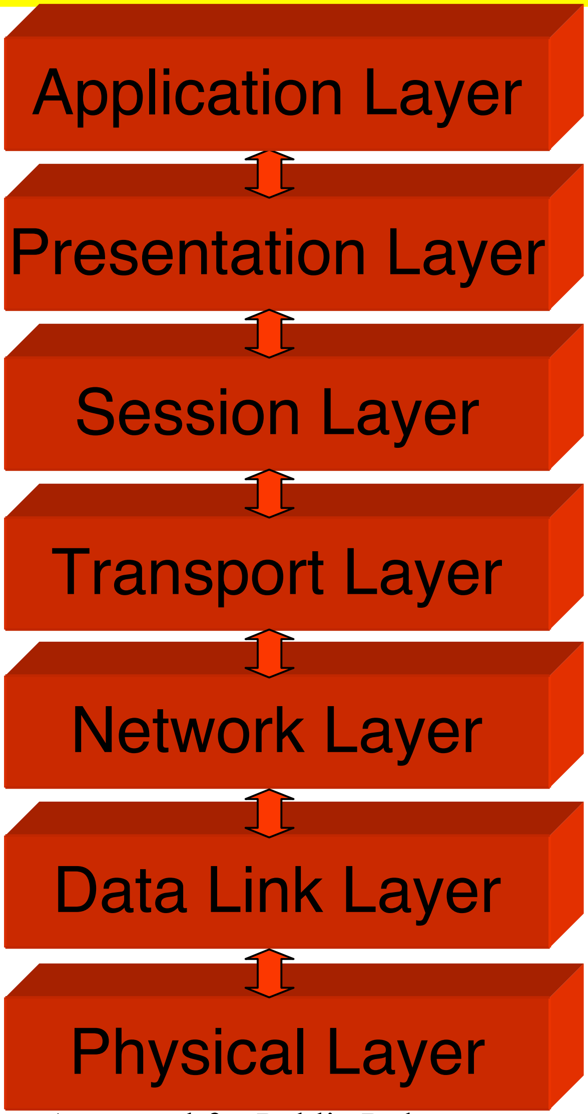
Outline

- Introduction
- Network and Physical Layer Design
- MAC and Physical Layer Design

Layered Approach



Why cross-layer design?

- Significant performance advantages (e.g. 10 dB in certain situations).
- Forces designers to consider other layers.
- Layers are coupled.

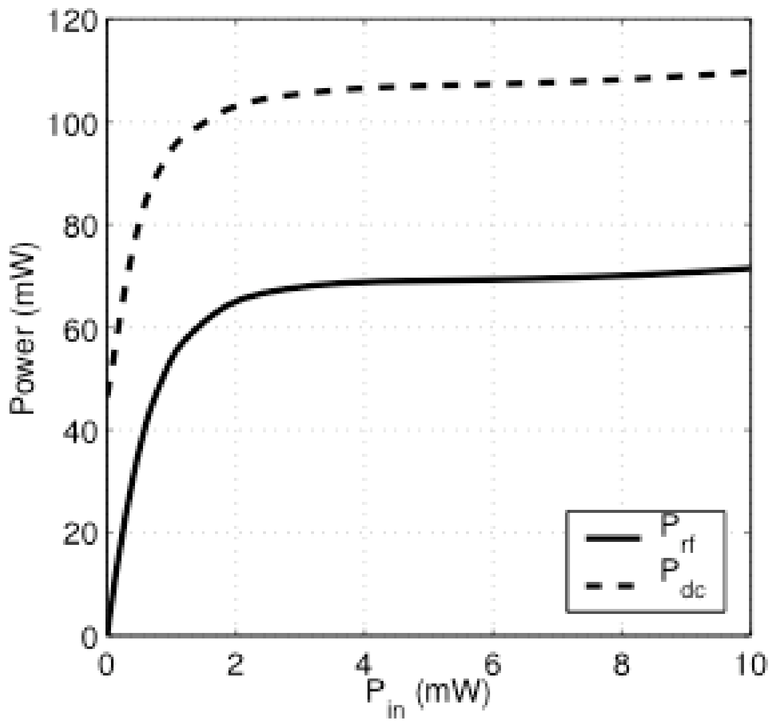
What causes coupling?

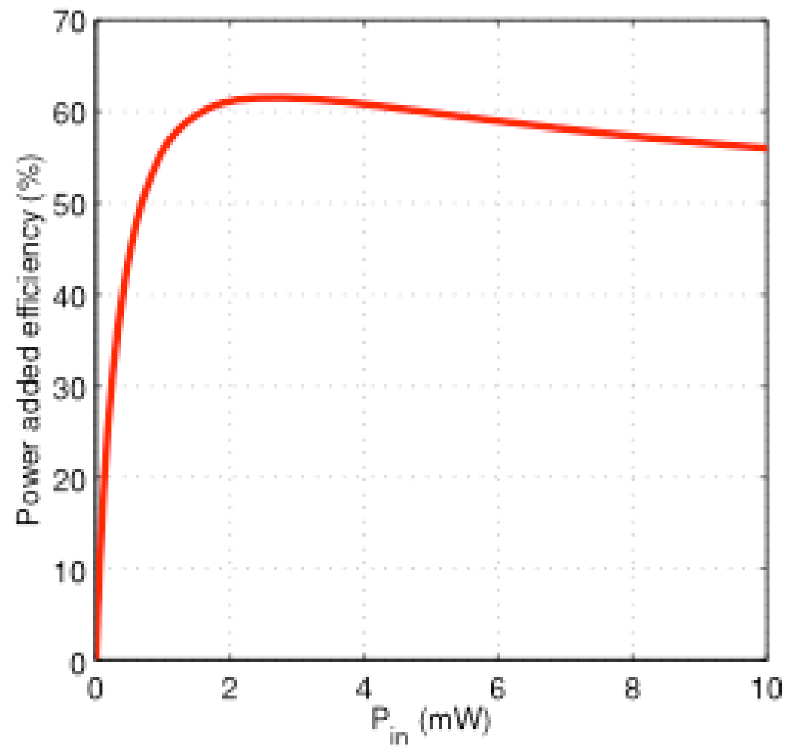
- Energy constraints.
- Delay constraints.
- …

Why not cross-layer design?

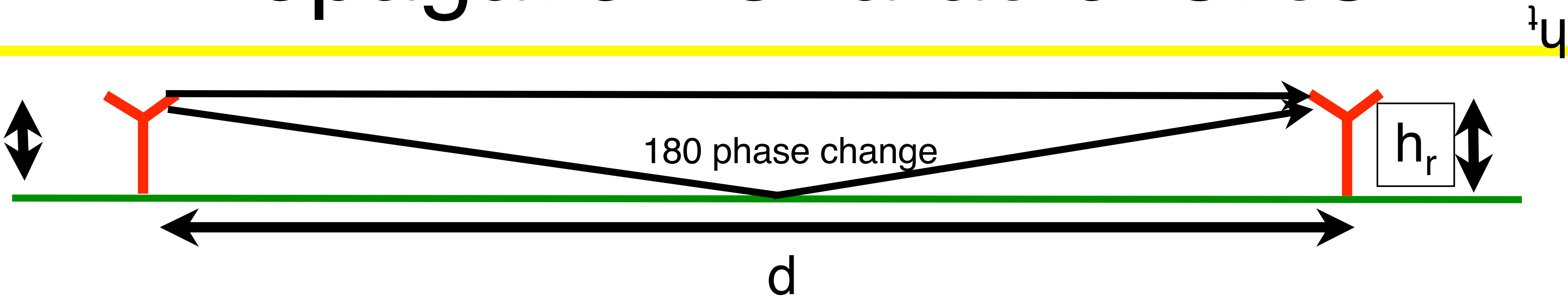
- Difficulty.
- Lack of insight into design.
- Generally requires near brute-force simulation/optimization if several layers are considered simultaneously.

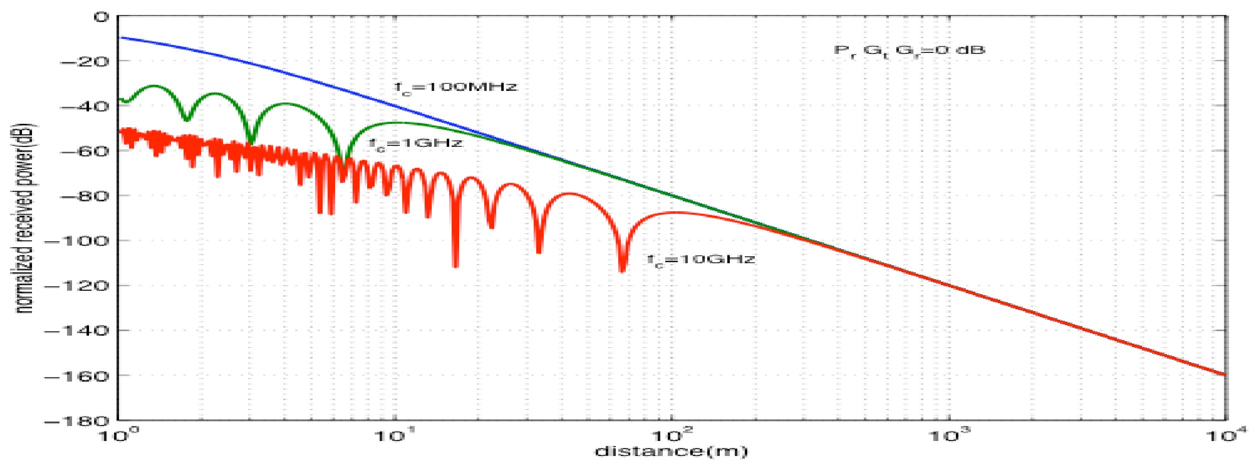
Amplifier Characteristics





Propagation Characteristics



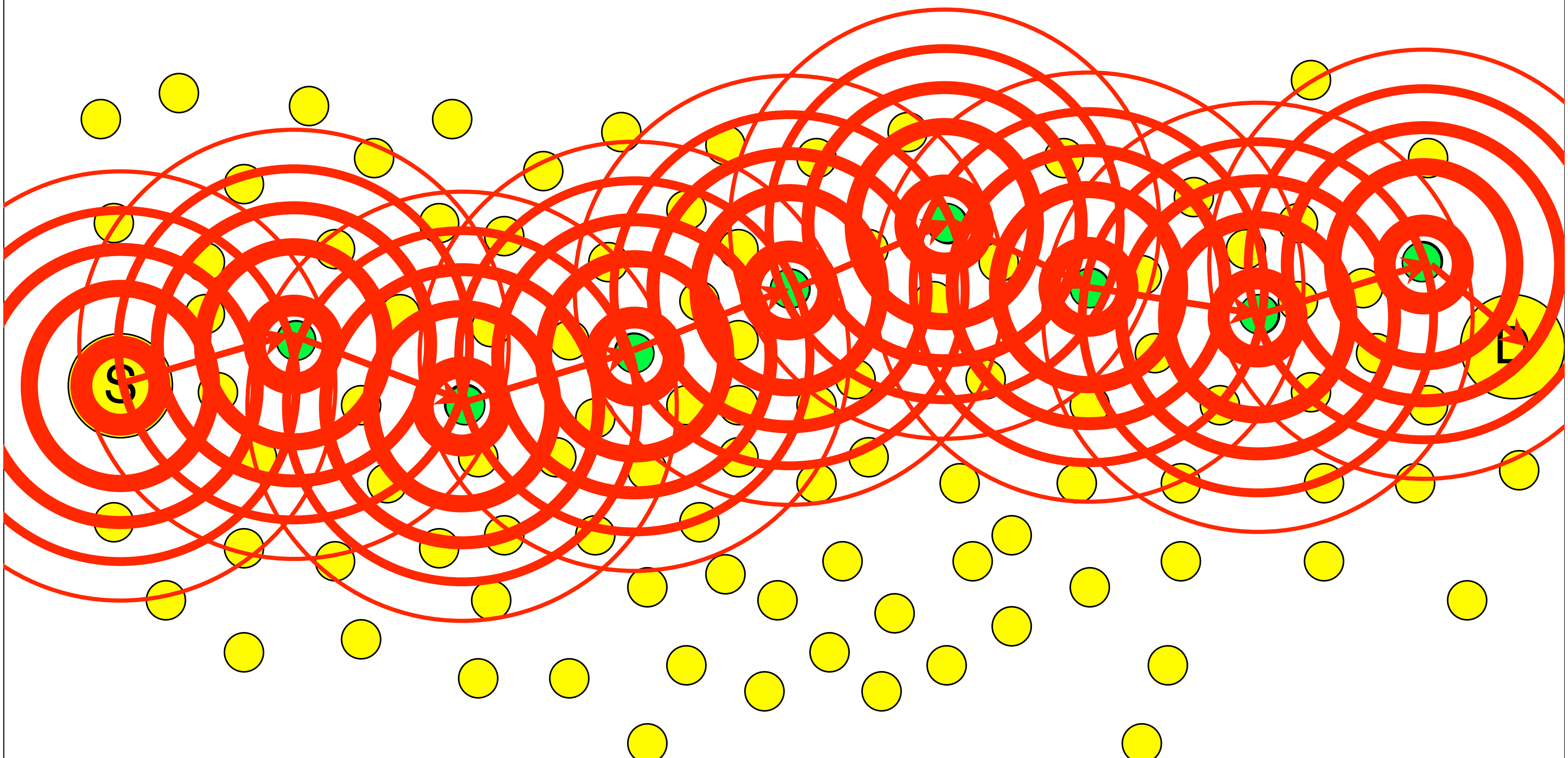


$$\boxed{P_r = P_t \left(\frac{\lambda_c}{4\pi d)}\right)^2 4 G_t G_r \sin^2\left(\frac{2\pi h_t h_r}{\lambda_c d}\right) \approx \frac{P_t G_t G_r h_t^2 h_r^2}{d^4}}$$

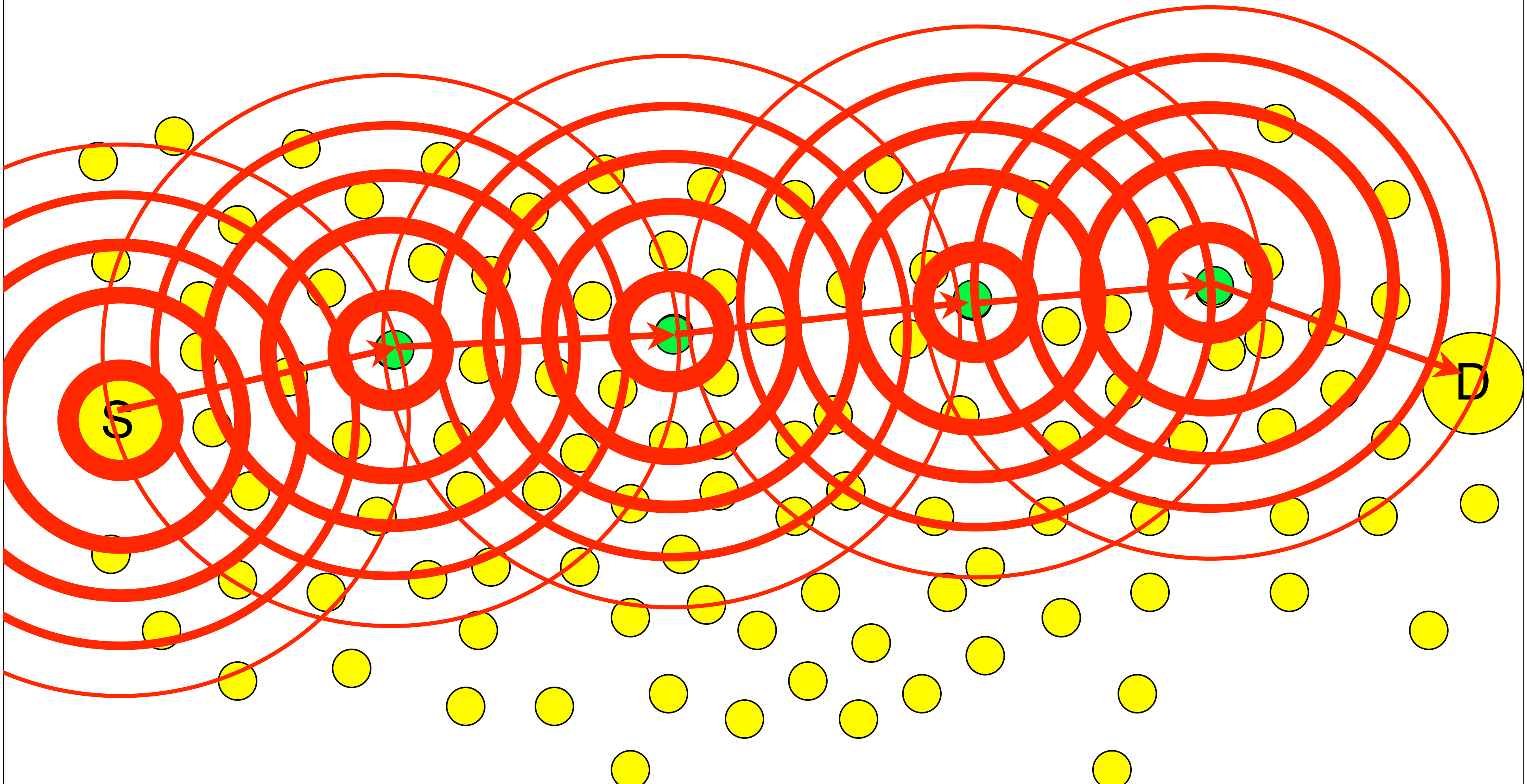
Two cross layer problems

- **Problem 1:** Network routing algorithm: For fixed total energy maximize the normalized throughput between source and destination while accounting for amplifier characteristics, physical layer performance and processing energy at receiver.
- **Problem 2:** Determine the tradeoff between energy and delay in wireless networks taking into account the MAC and physical layers.

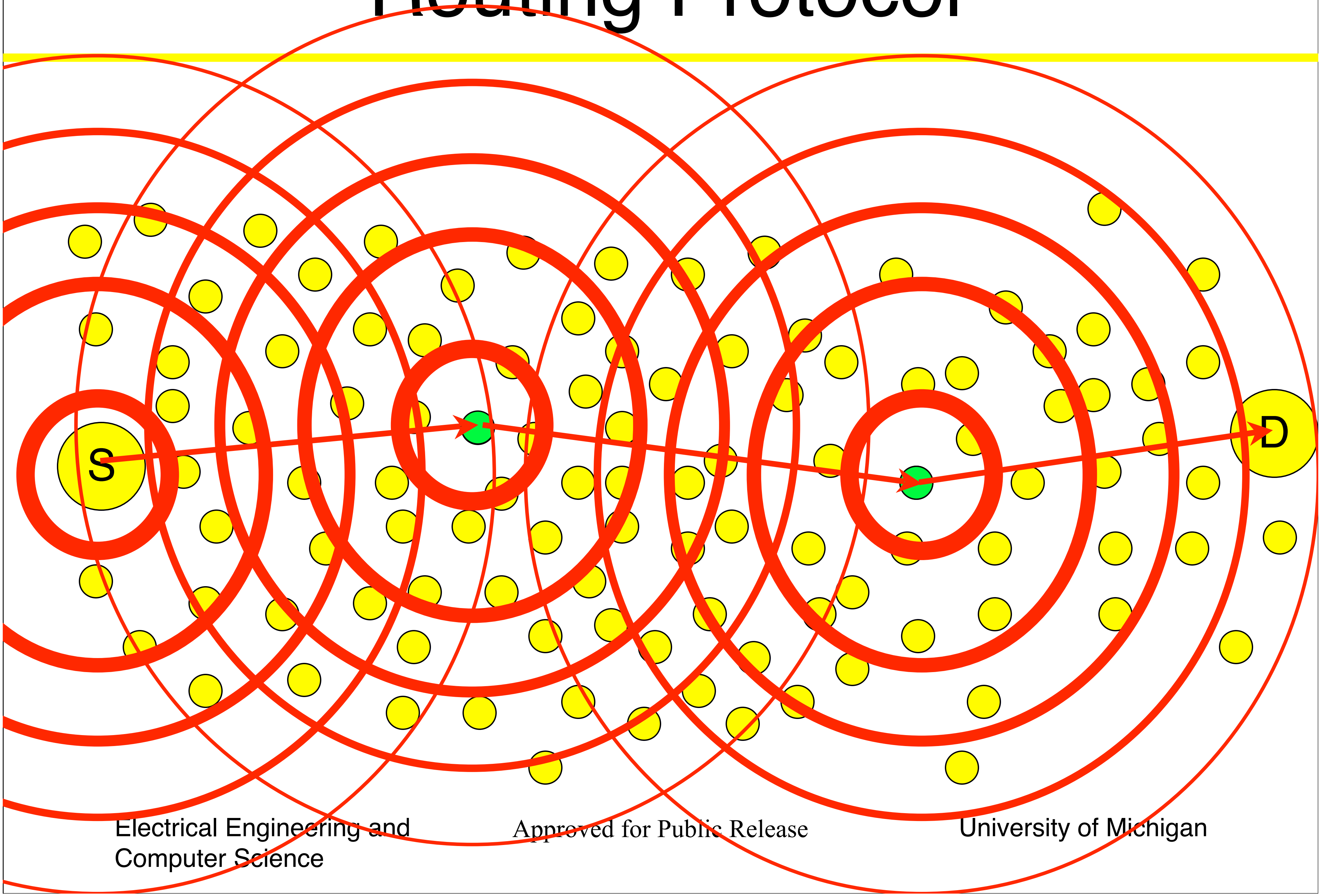
Routing Protocol



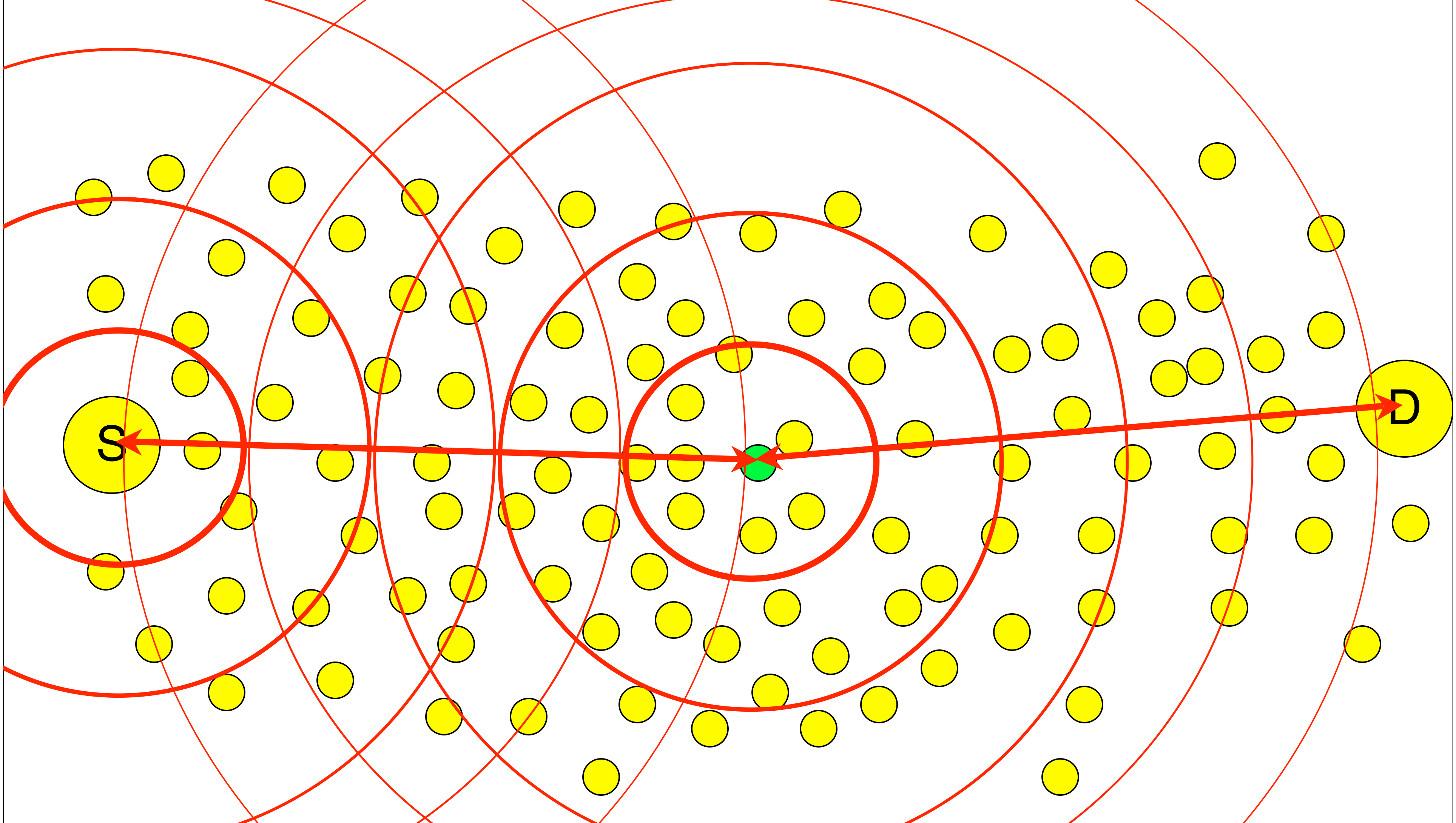
Routing Protocol



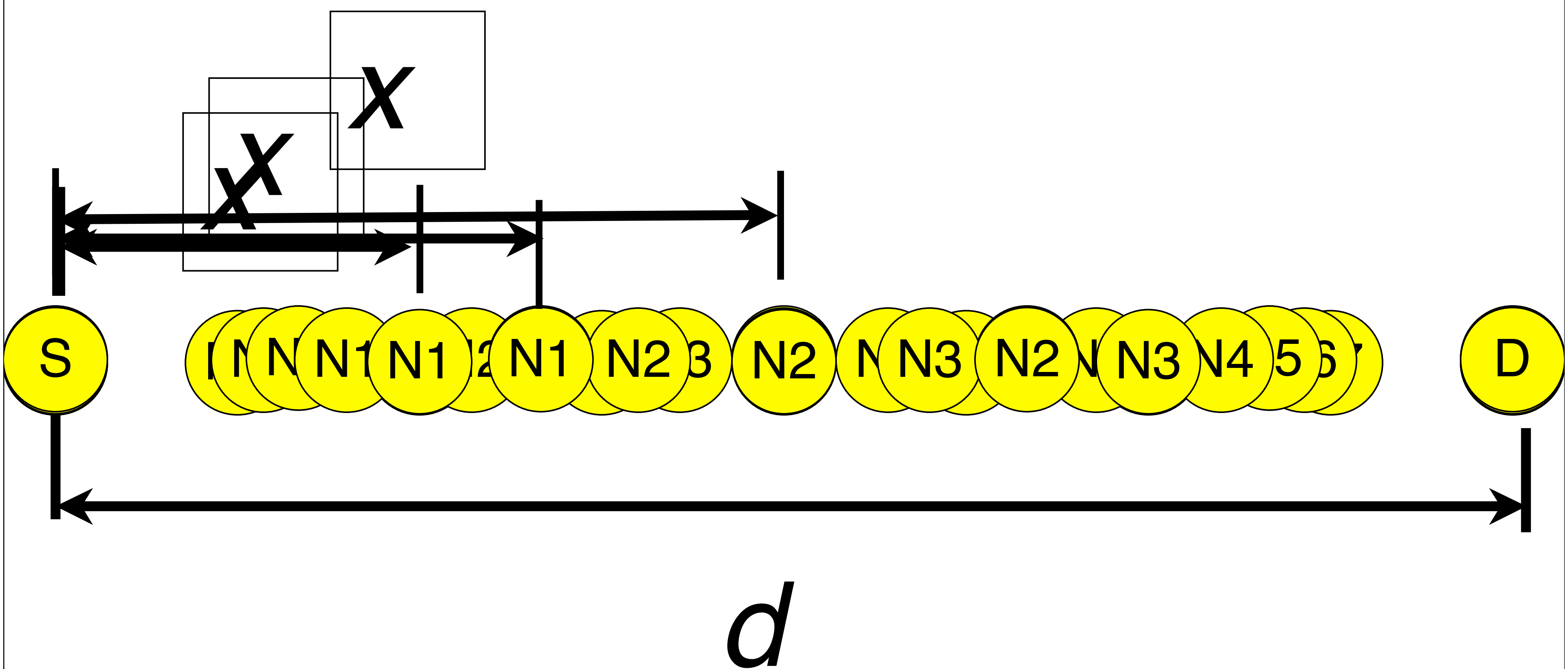
Routing Protocol



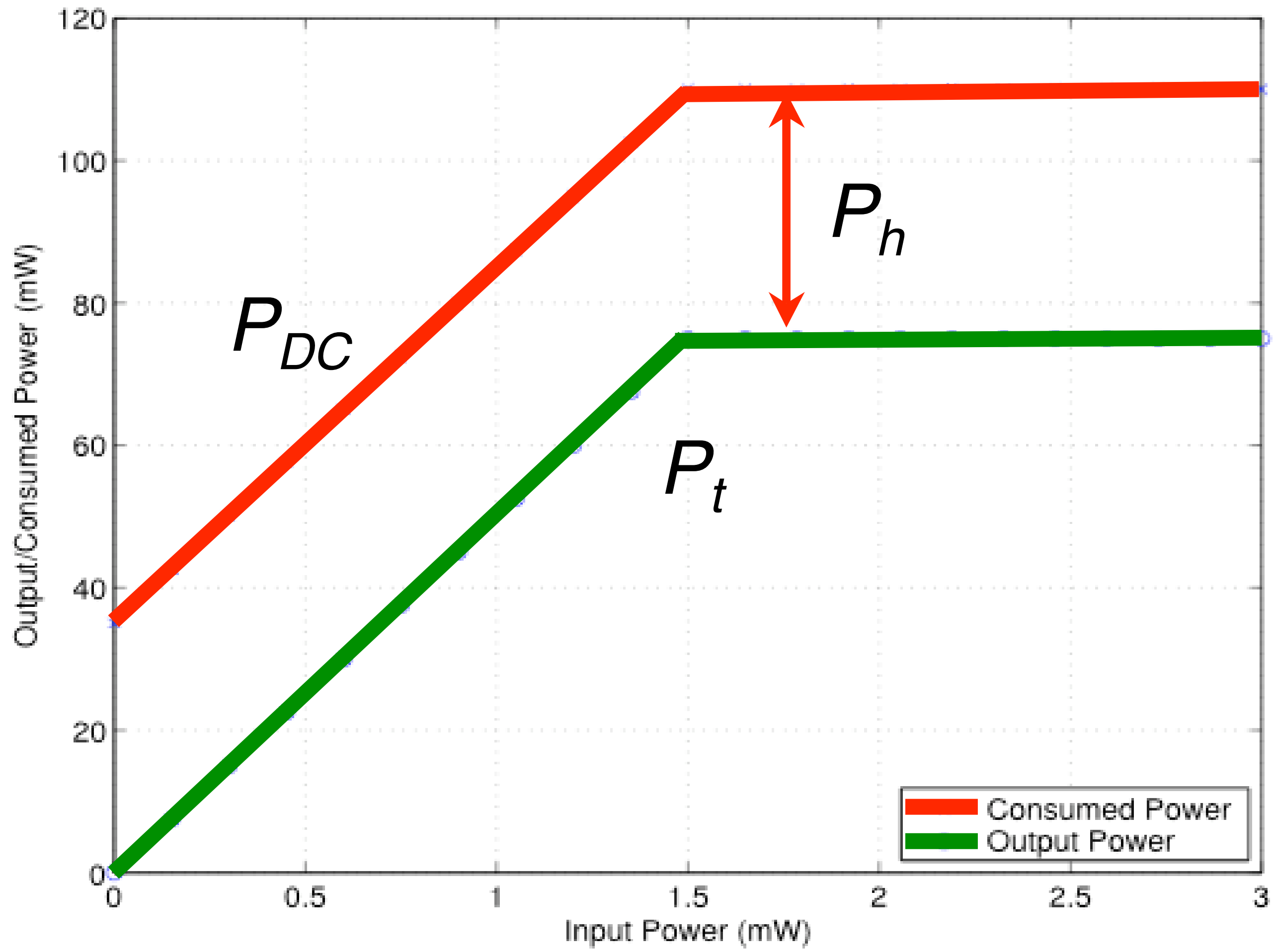
Routing Protocol



Simplified Network Model

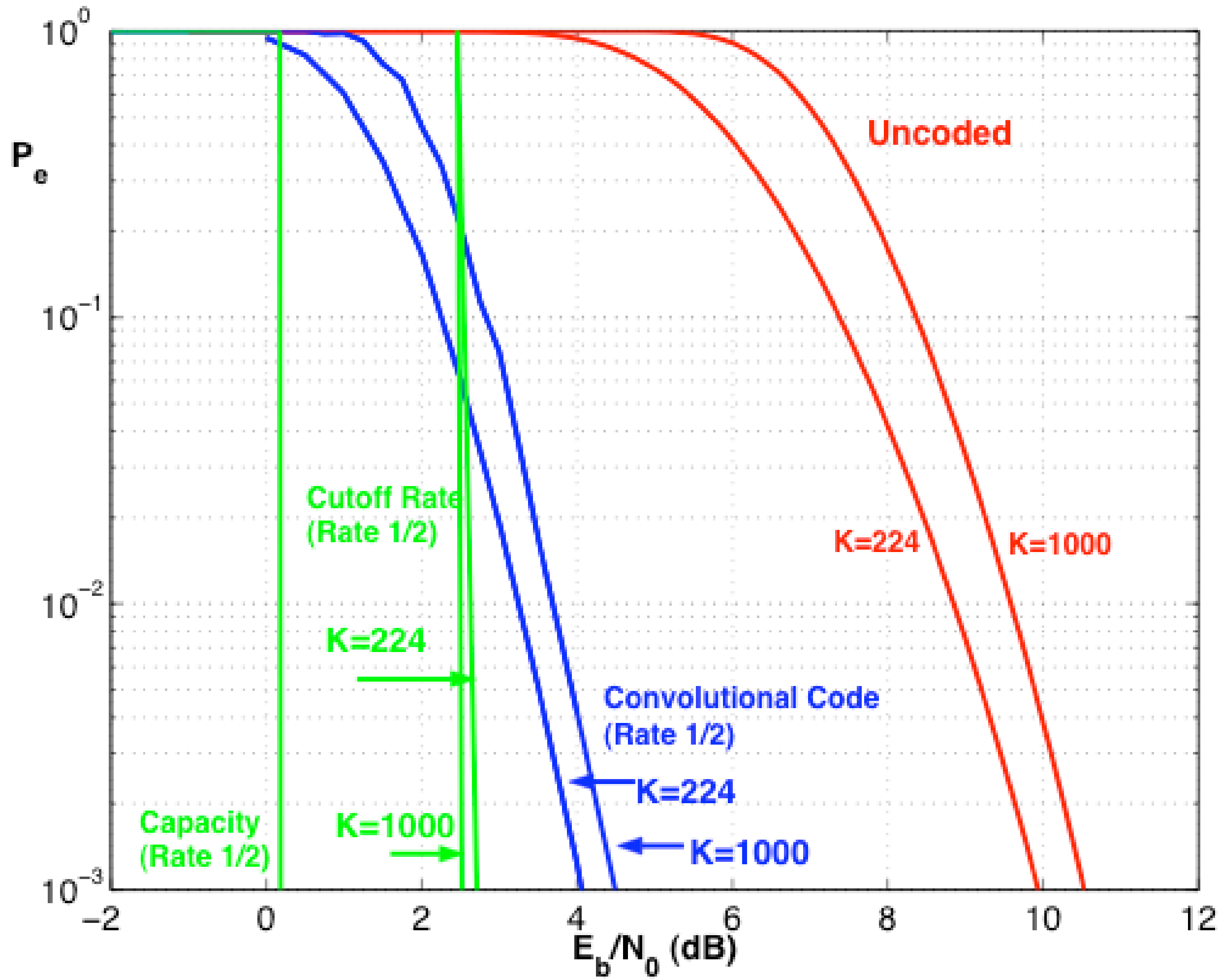


Amplifier Model



P_{in}

Packet Error Rate (Packet Length=224)



Assumptions/Notation

- Total energy available for all the nodes in the linear network =B (joules).
- Independent errors at different nodes.
- Energy E_r for processing each packet at a receiver.
- Number of hops=k.
- Packet duration $=T_p$.
- Code rate $=R$ (bits/channel use).
- $P_{DC}=f(P_{in})$.

Performance Measure

- Expected number of successfully received bits per unit bandwidth and time.

$$\frac{E_p}{N_0} = \frac{G_t G_r h_T^2 h_r^2}{N_0 (d/k)^4} T_p (P_{DC} - P_h)$$

$$S = \left(\frac{BR}{k(T_p P_{DC} + E_r)} \right) P_s\left(\frac{E_p}{N_0}, R\right)^k$$

Number of packets that can be transmitted end-to-end

Number of Hops

Packet Success Probability

Energy used per hop (transmission and reception)

Optimization

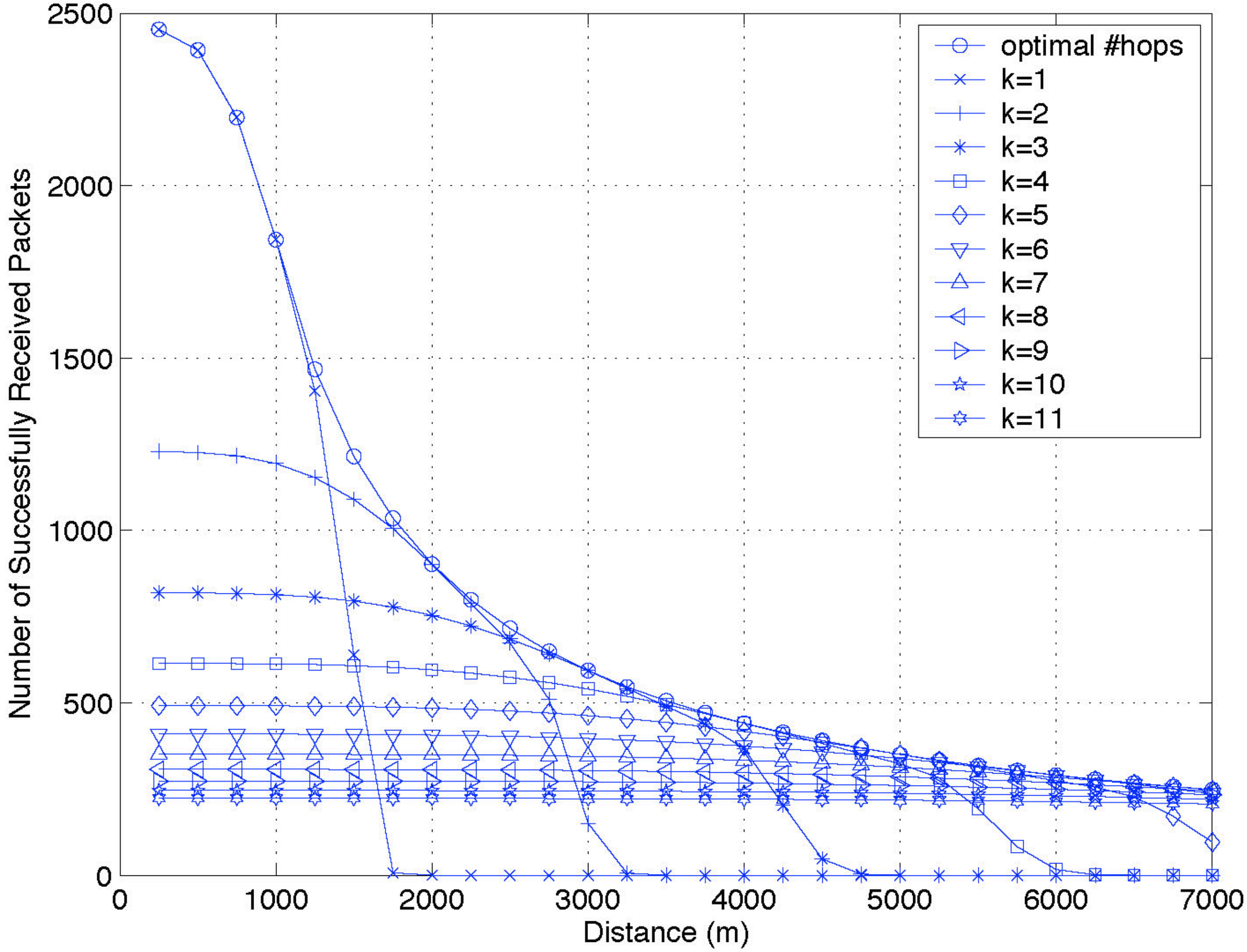
$$S^* = \max_{P_{in},R,k} S(P_{in}, R, k)$$

Main Result (large *d*)

$$S^* = \frac{\delta}{d}$$

- Functional form of throughput independent of
  - Error Control Coding Scheme
  - Modulation
  - Channel (Fading, Propagation Characteristics)
  - Amplifier Characteristics
- Specific constant δ depends on all of the above.

Throughput vs. Distance (Uncoded)



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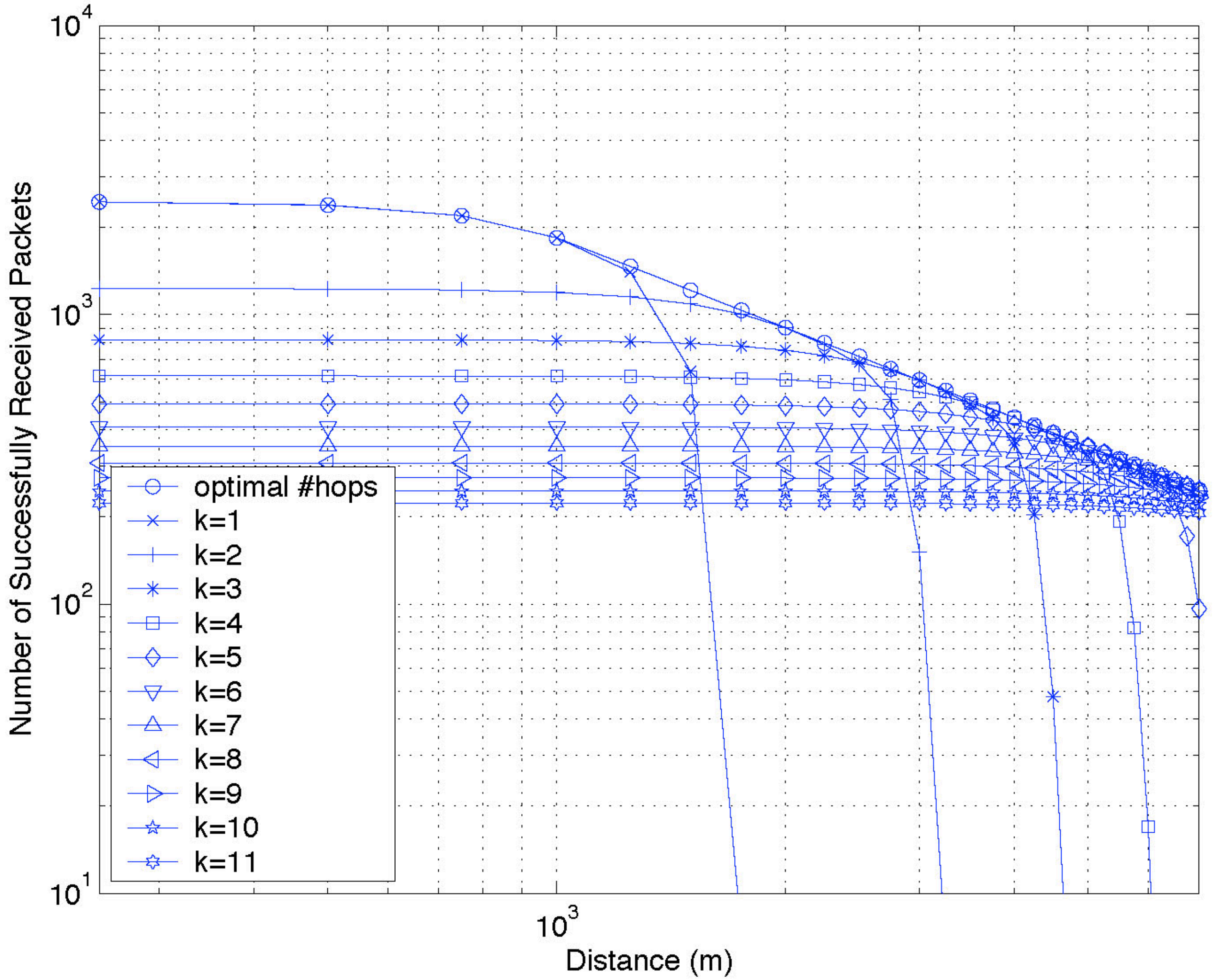
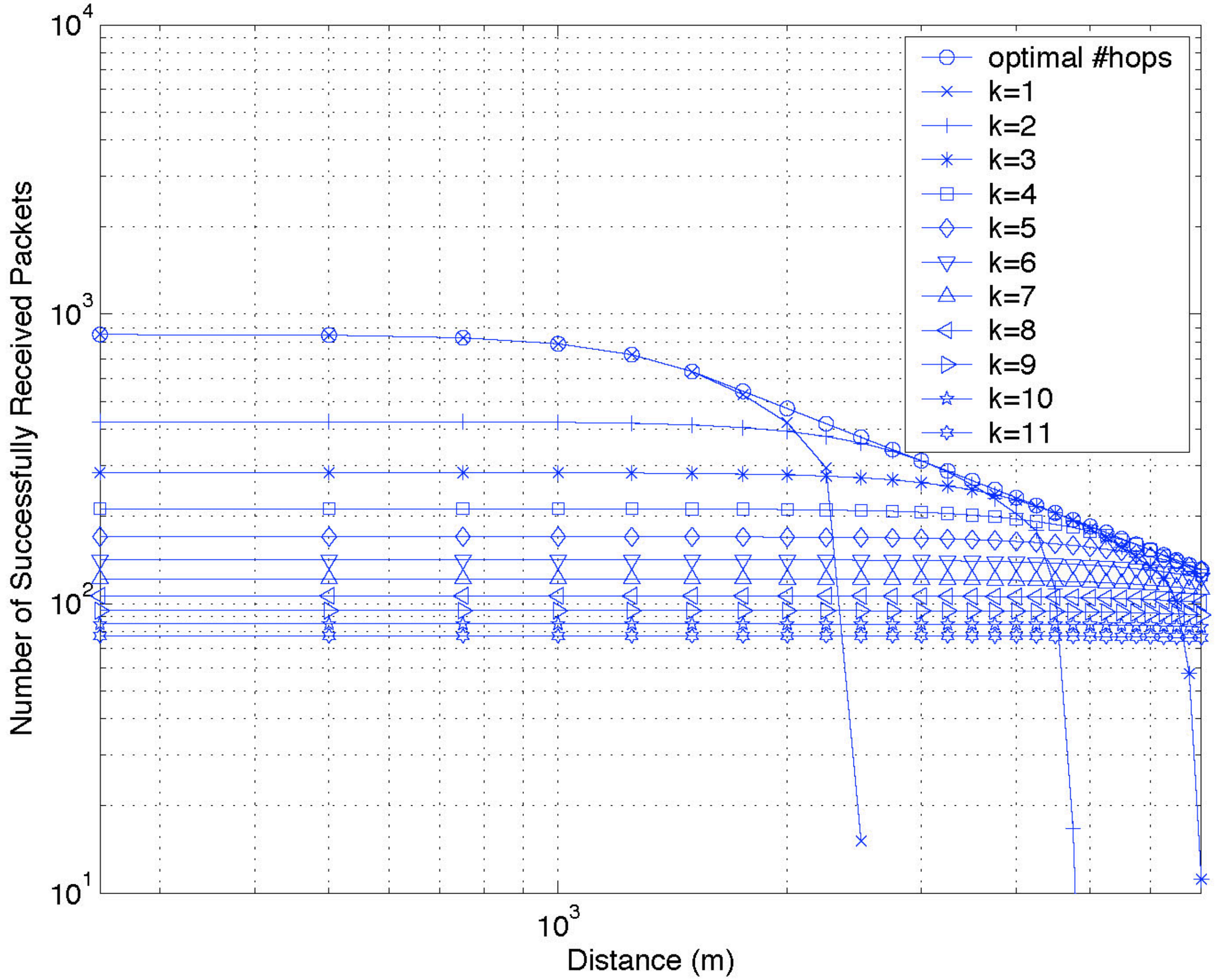
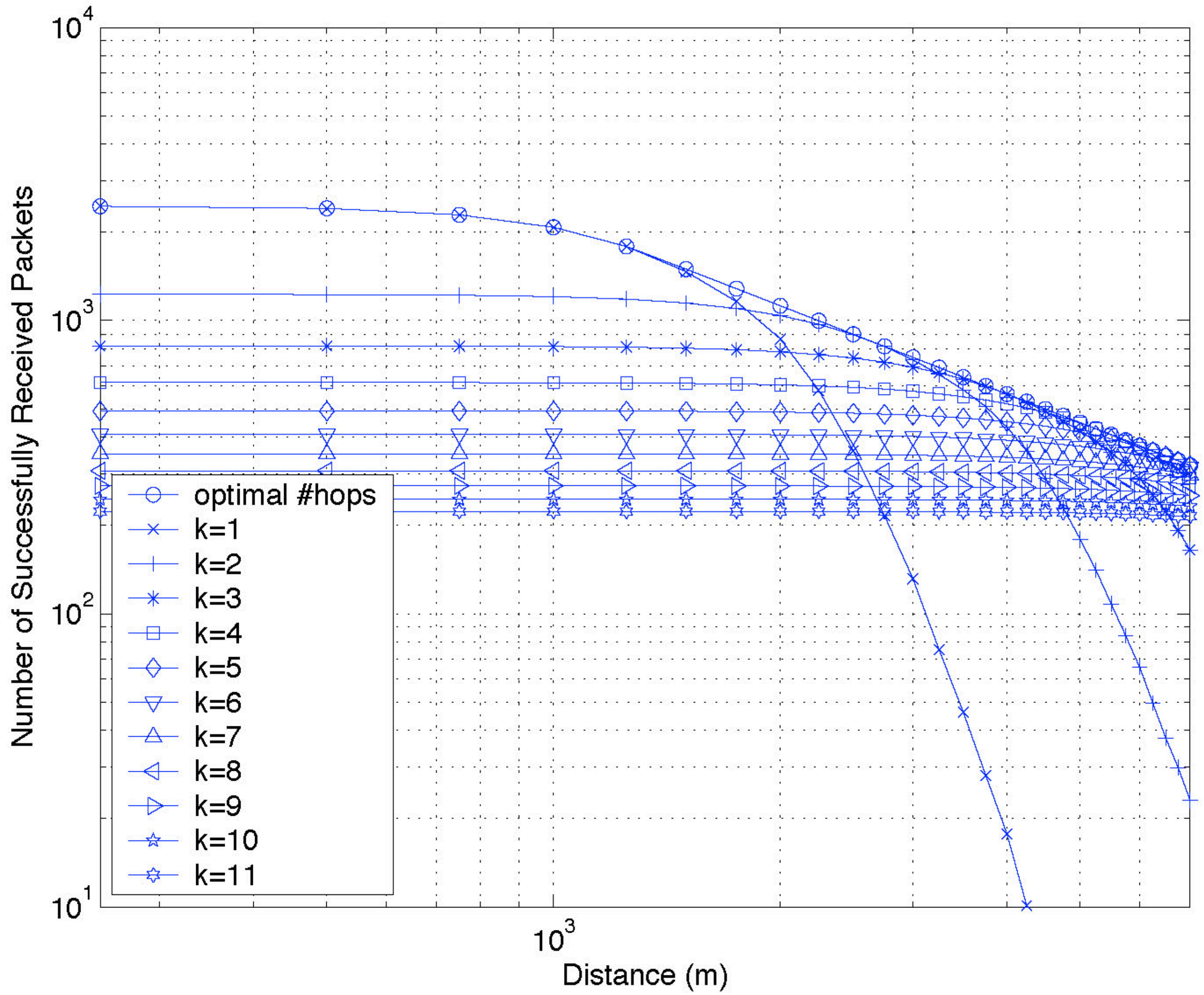


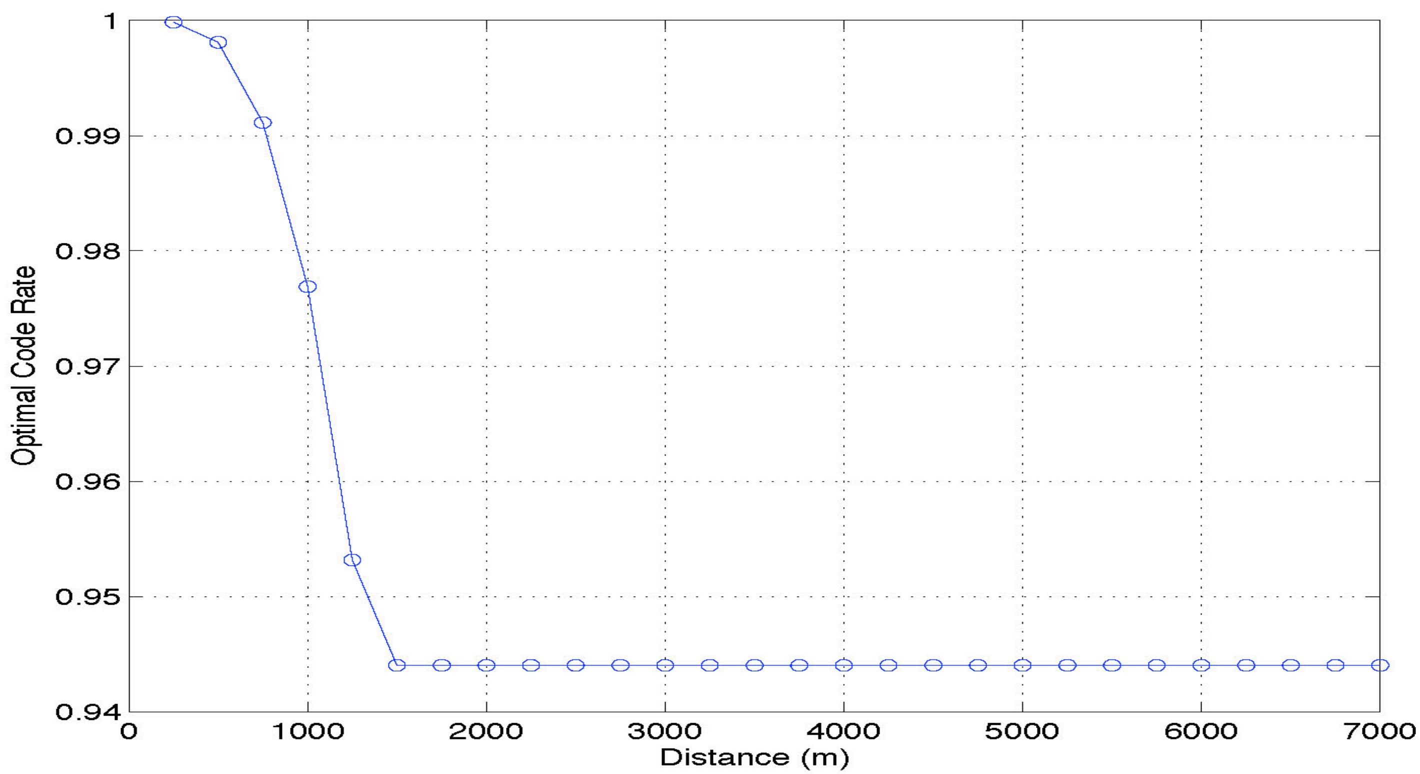
Throughput vs. Distance (Convolutional Code, Rate 1/2)



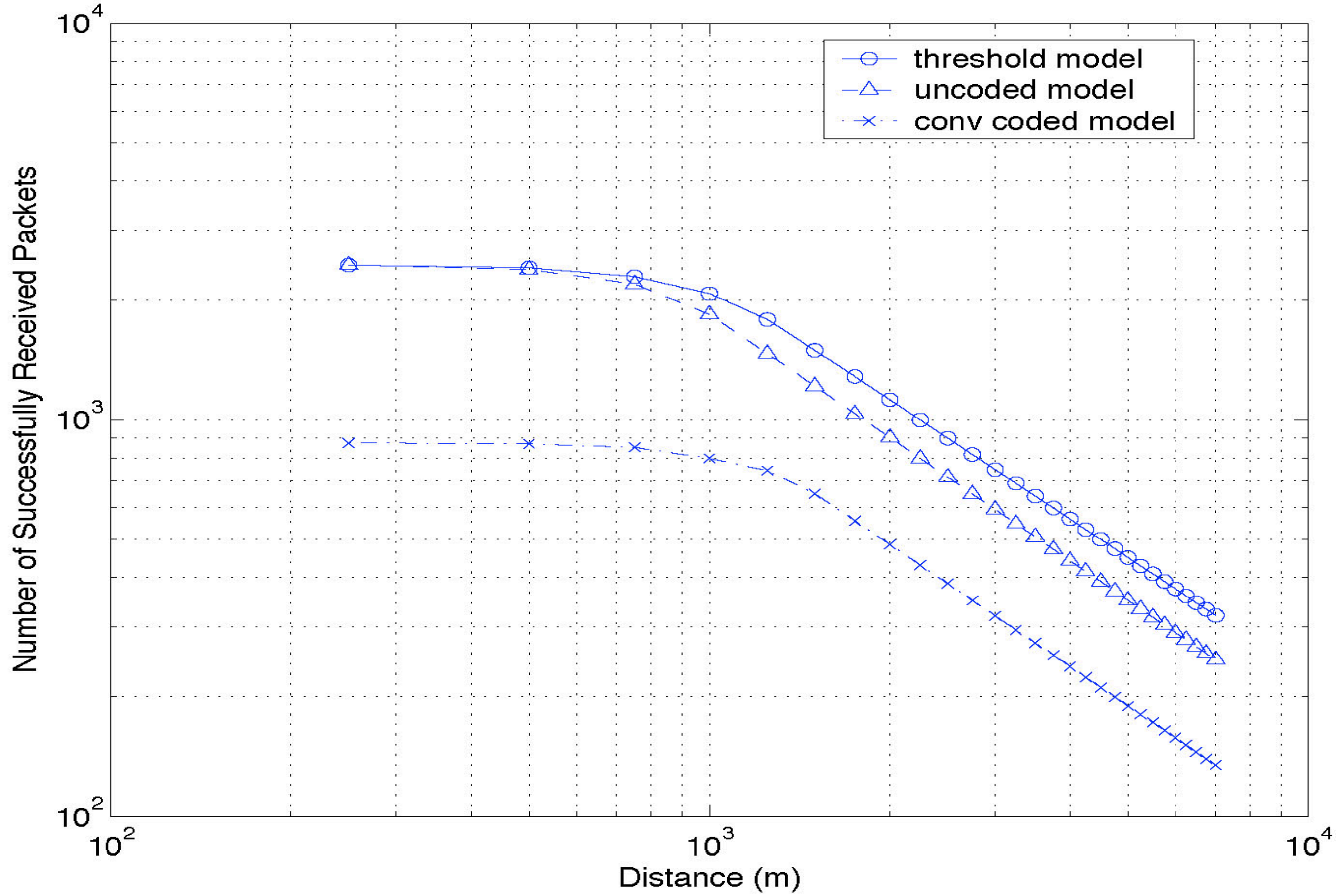
Throughput vs. Distance (Capacity at Optimum Rate)



Optimum Rate vs. Distance



Throughput vs. Distance (Comparison)



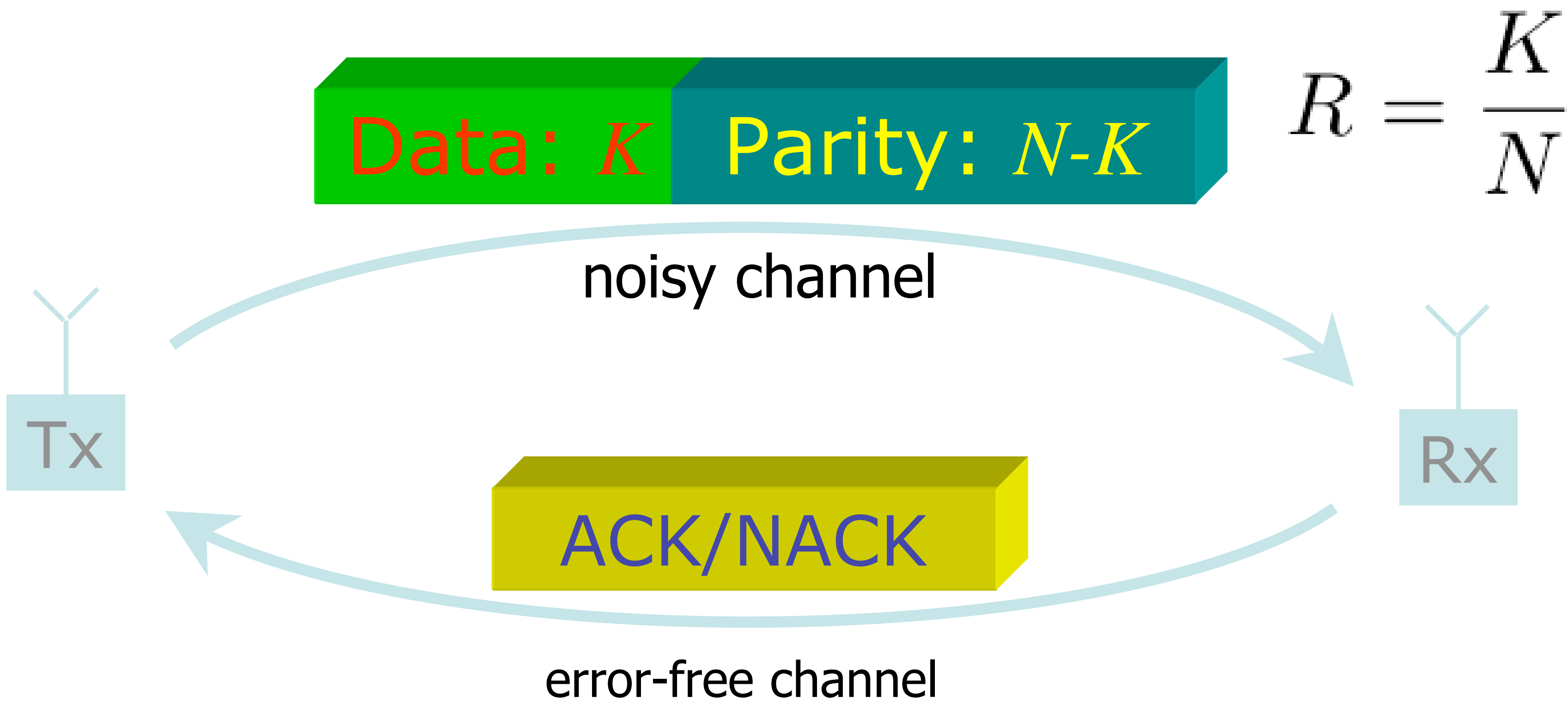
Conclusion: First Problem

- Optimum rate in AWGN close to 1.
- Uncoded better than rate 1/2 coded at optimum distance but requires higher density of nodes.
- Amplifier operating point is not an extreme point of amplifier characteristics.
- For other channels (e.g. faded channels) optimum rate will likely decrease.
- This problem encompasses physical layer and network layer issues.

Second Problem

- Determine the tradeoff between energy and delay in wireless networks taking into account the MAC and physical layers.

ARQ Protocol



Average Energy and Average Delay

$$\frac{\bar{E}_b}{N_0} = \frac{\frac{E_c}{N_0 R}}{1 - P_e(\frac{E_c}{N_0}, R)}$$

$$\bar{D} = \frac{N}{1 - P_e(\frac{E_c}{N_0}, R)}$$

Goal

- For a fixed number of information bits, *K*, determine the optimal number of coded bits, *N*, to minimize the delay.
- Note: The *N* that minimizes the delay also minimizes the energy.

$$\min_N \bar{D} = \min_N \left[\frac{N}{1 - P_e(\frac{E_c}{N_0}, \frac{K}{N})} \right]$$

Packet Error Probability Bounds

$$P_e(\frac{E_c}{N_0}, R) \leq 2^{-N(R_0-R)} = 2^K 2^{-NR_0}$$

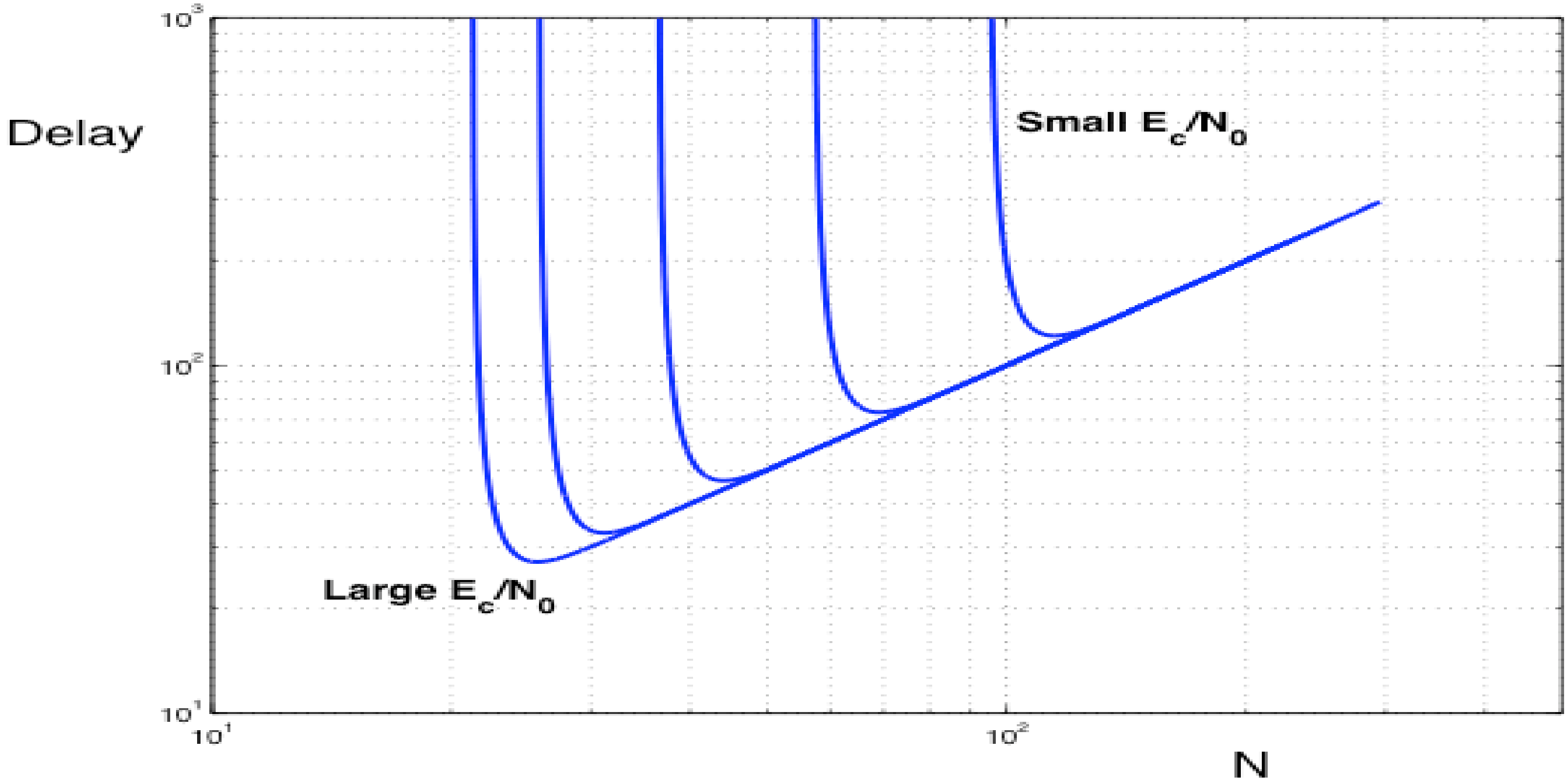
For an additive white Gaussian noise channel

$$R_0 = 1 - \log_2(1 + e^{-\frac{E_c}{N_0}})$$

Notes

- Turbo codes and LDPC codes can achieve better than the cutoff rate.
- Convolutional codes are far from cutoff rate for large block length.
- Reed-Solomon codes have near exponential dependence on N

Delay vs. Blocklength



Main Result

For large *K* (compared to 1) at the optimum packet length (N^*) the resulting error probability is a constant.

$$P_e\left(\frac{E_c}{N_0}, \frac{K}{N^*}\right) = \frac{1}{1 + K\ln(2)}$$

Delay-Energy Tradeoff

$$R^* = \frac{R_0}{1 + \frac{1}{K}\log_2(1 + K\ln(2))}$$

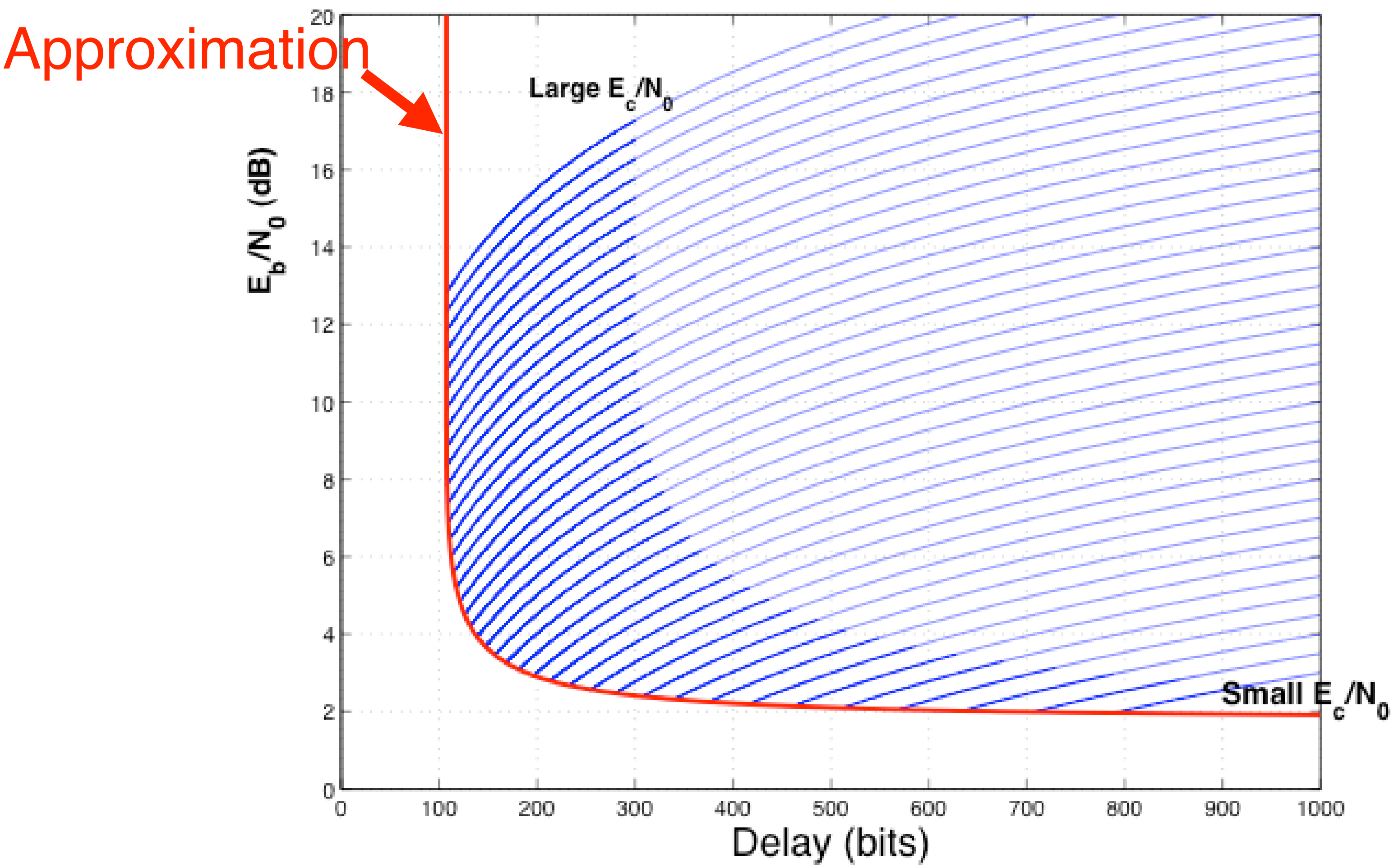
$$D^* \approx \frac{K}{R_0}\left[1 + \frac{\log 2(K\ln(2))}{K}\right]$$

$$\frac{E_b^*}{N_0} \approx \frac{E_c}{N_0 R_0}\left[1 + \frac{\log 2(K\ln(2))}{K}\right]$$

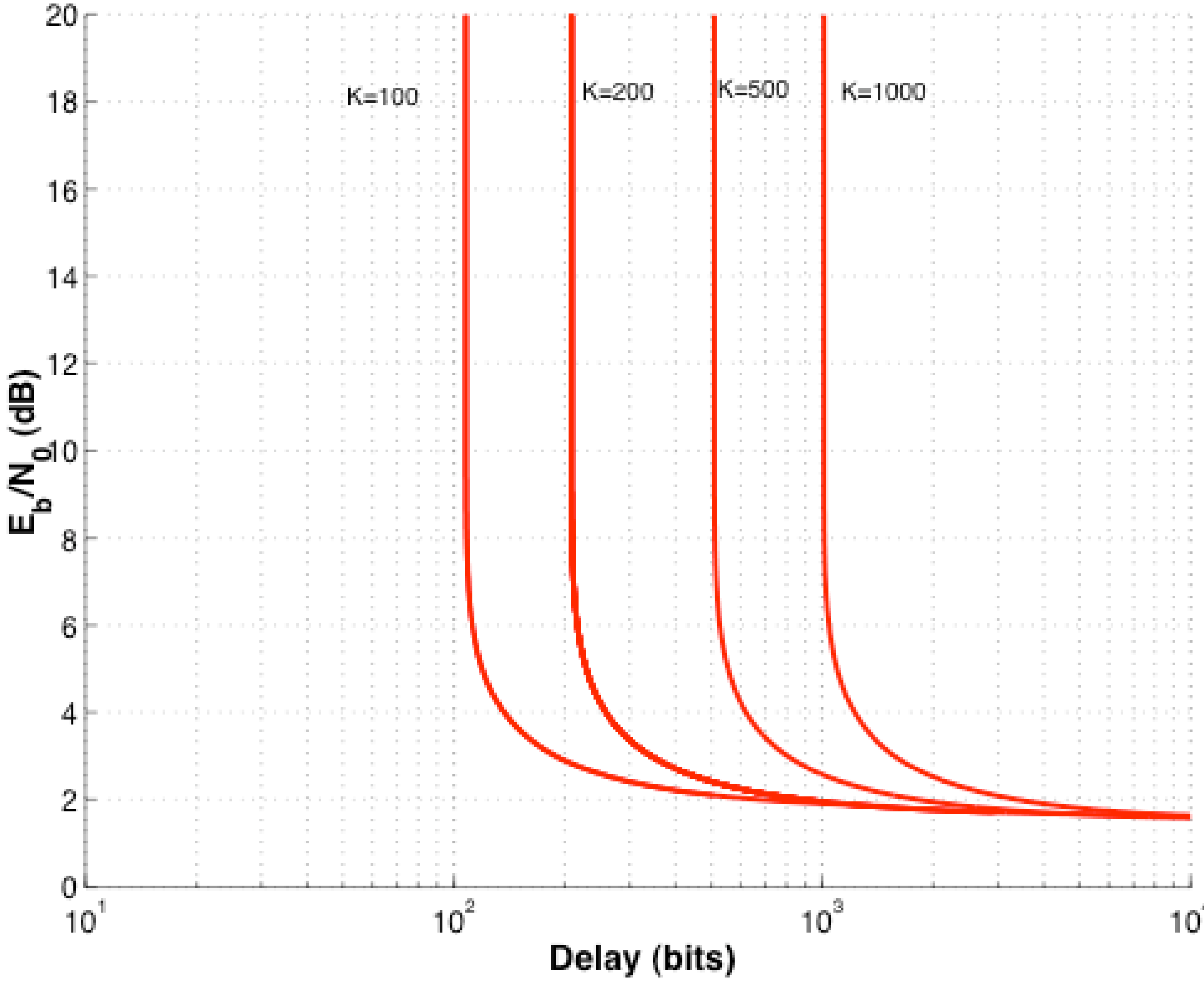
Comments on Result

- This result is independent of the channel model and modulation technique (e.g. coherent, noncoherent, faded) except that the channel is memoryless.
- The resulting minimum average energy and delay depend on the above characteristics.
- Result implies that larger payloads (K) should try to achieve a smaller error probability.

Example: K=100

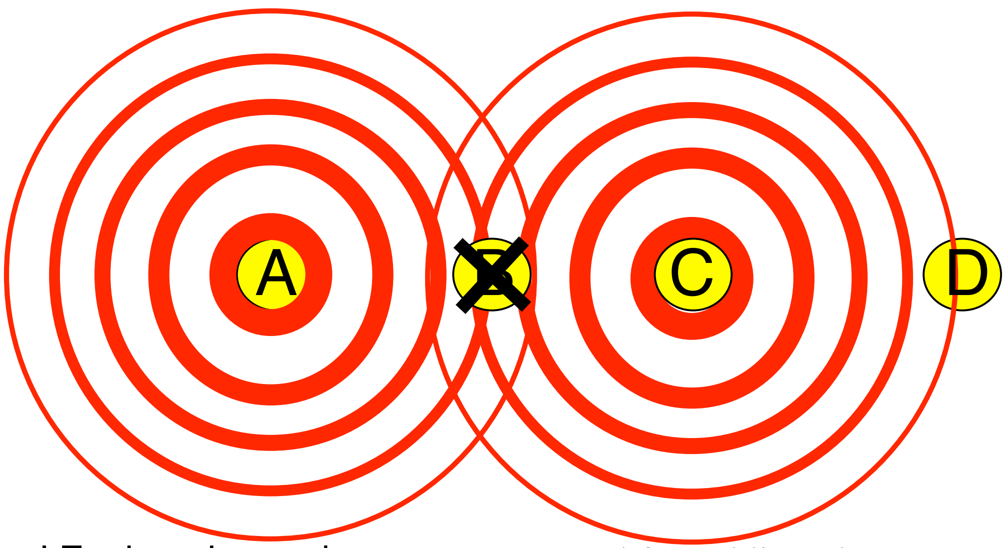


Delay-Energy



Extension to Include MAC Layer

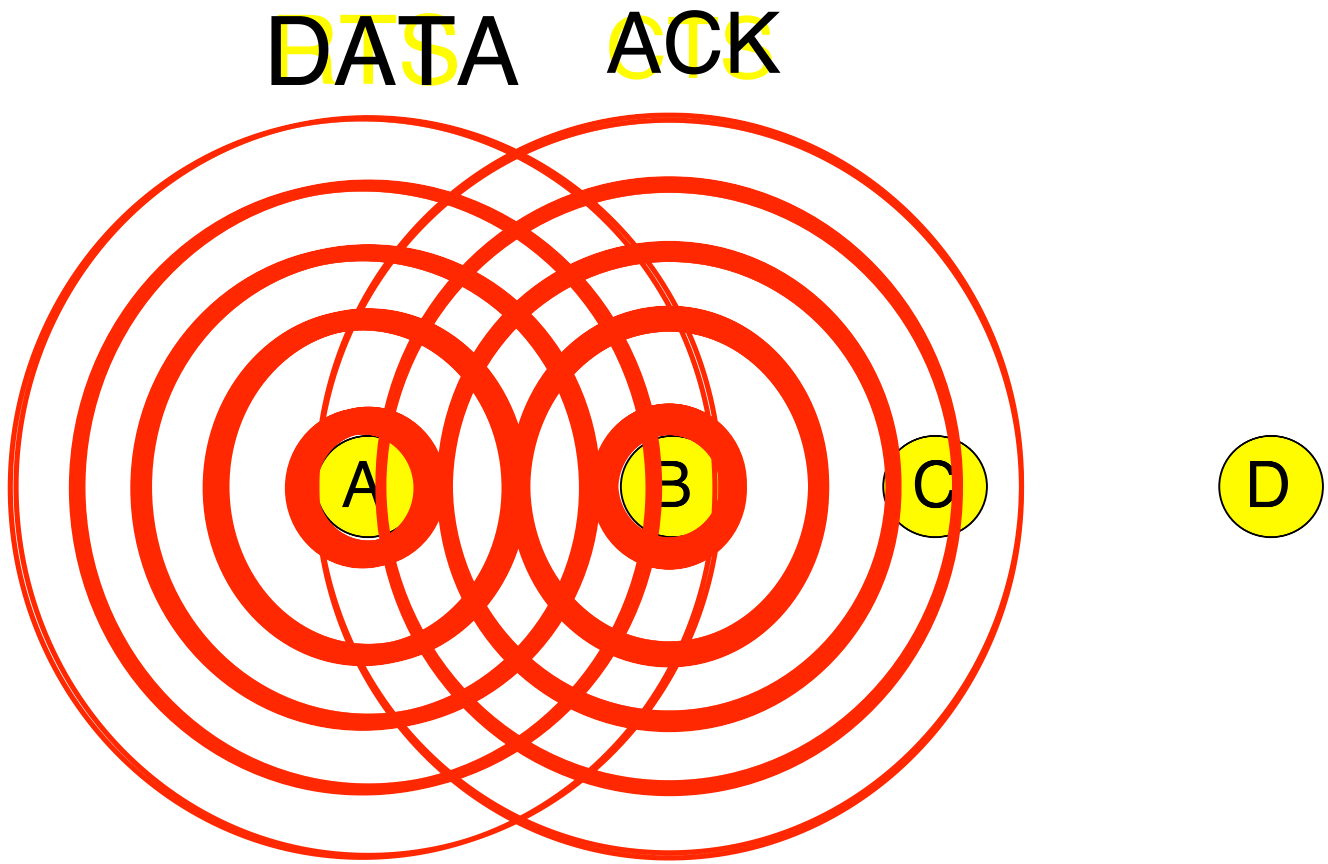
Node A wants to transmit a message to Node B. Node C wants to transmit a message to Node D. Without coordination Node C's signal will interfere with A's transmission to Node B. Node C might start it's transmission after A has already begun transmitting because C can not hear Node A's signal. This is the hidden node problem.



RTS/CTS Mechanism

- A transmits to B an RTS (request-to-send) packet.
- If B successfully decodes the RTS packet then B transmits a CTS (clear-to-send) packet indicating the upcoming transmission of data from A to B.
- Both A and C hear the CTS and now A knows that it is clear to send a packet to B.

RTS/CTS Mechanism



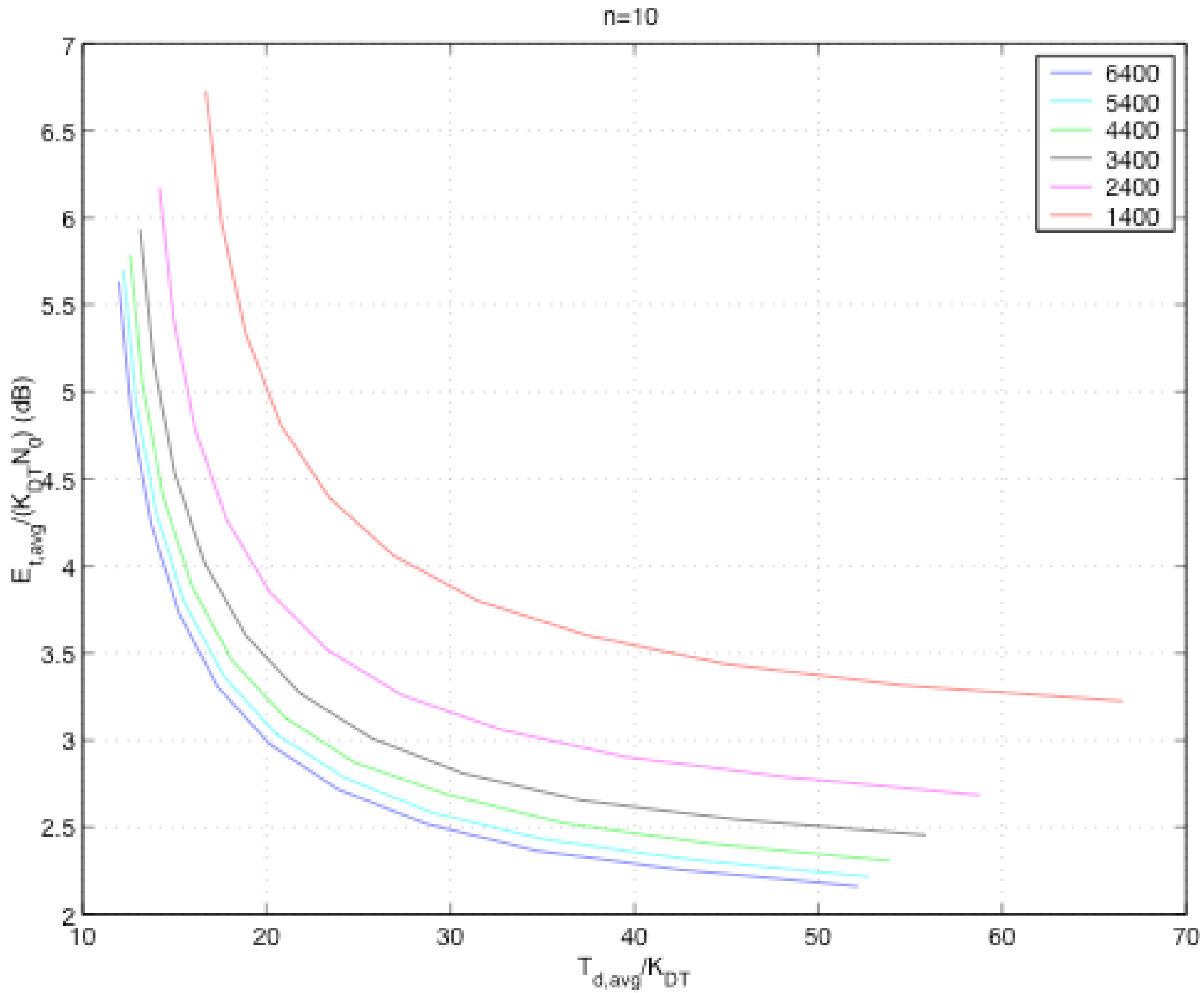
Problem

- Determine the delay vs. energy for different number of users.
- For fixed data length, RTS, CTS,ACK lengths determine optimal packet sizes N_{DATA}, N_{RTS}, N_{CTS}, N_{ACK}.
- Similar approximations for large K can be obtained for optimum $P_{e,RTS}$, $P_{e,CTS}$, $P_{e,ACK}$

Result

- We have developed an analytical framework to evaluate the joint distribution of energy and delay of the RTS/CTS protocol in a noisy channel.
- Similar approximations to single user case.
- Assumptions
  - All n users have packets ready (heavy-load assumption).
  - All users can hear all other users.
  - Memoryless channel.
  - No multiuser reception/detection capability.
  - Only transmit energy is considered.

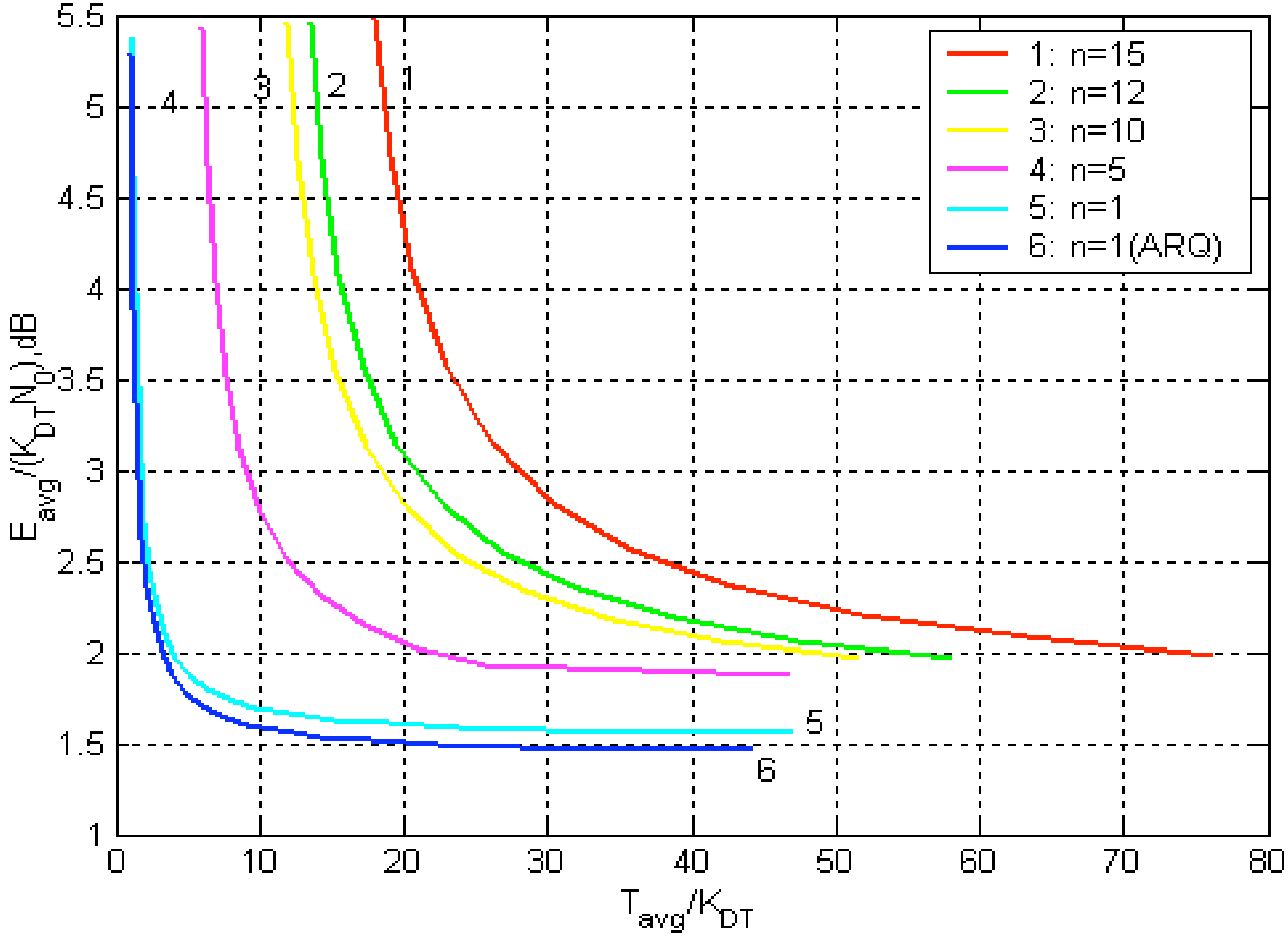
Numerical Results (10 users)



Interpretation

For short packets the fractional overhead to access the channel becomes larger.

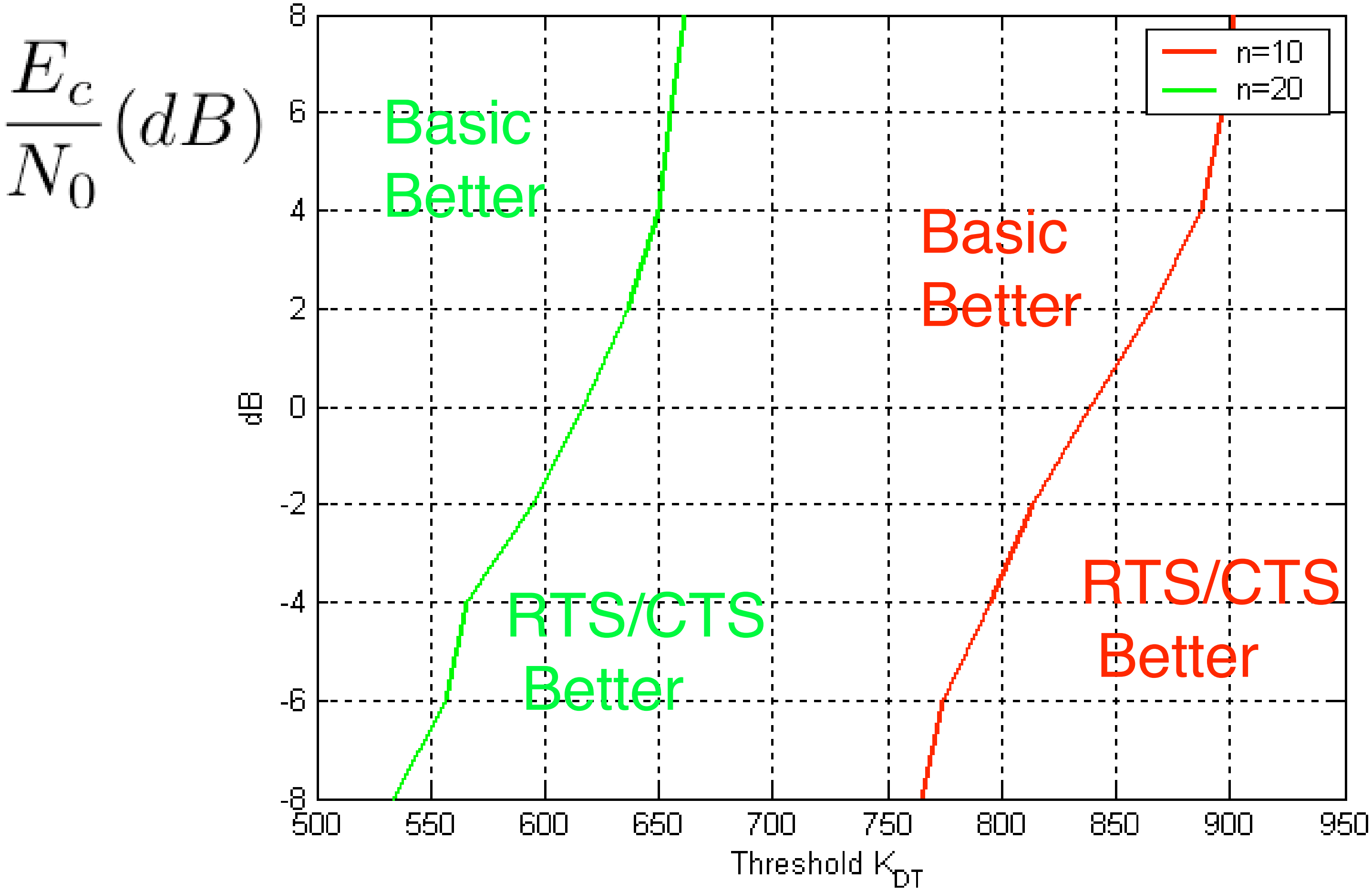
Numerical Results (K_{DT}=6400)



“Basic Protocol”

- Eliminate RTS/CTS
- Listen before send.
- If collision of data packet then wait a random (exponential) backoff time before retransmission.

Comparison with “Basic Protocol”



Interpretation of Results

- For a larger number of users there is a lower threshold for switching between the basic protocol and RTS/CTS protocol
- For larger energy per coded bit, the transmission rate becomes larger. The larger rate implies a shorter time to transmit a given number of bits. A shorter duration for transmission of the data packet increases the relative burden needed to transmit the RTS/CTS packets. So the threshold of packet length where RTS/CTS is better becomes larger.

Conclusion

- Have shown certain invariants (optimum distance, optimum error probability).
- By considering a couple layers joint design/optimization and analysis is possible.
- Insight into performance analysis can be obtained.
- Still need to consider many other factors (power control, data rate control, multiple-access capability of modulation and coding).
- There are many open and interesting problems in cross-layer design.