Cross-Layer Design and Analysis of Wireless Networks

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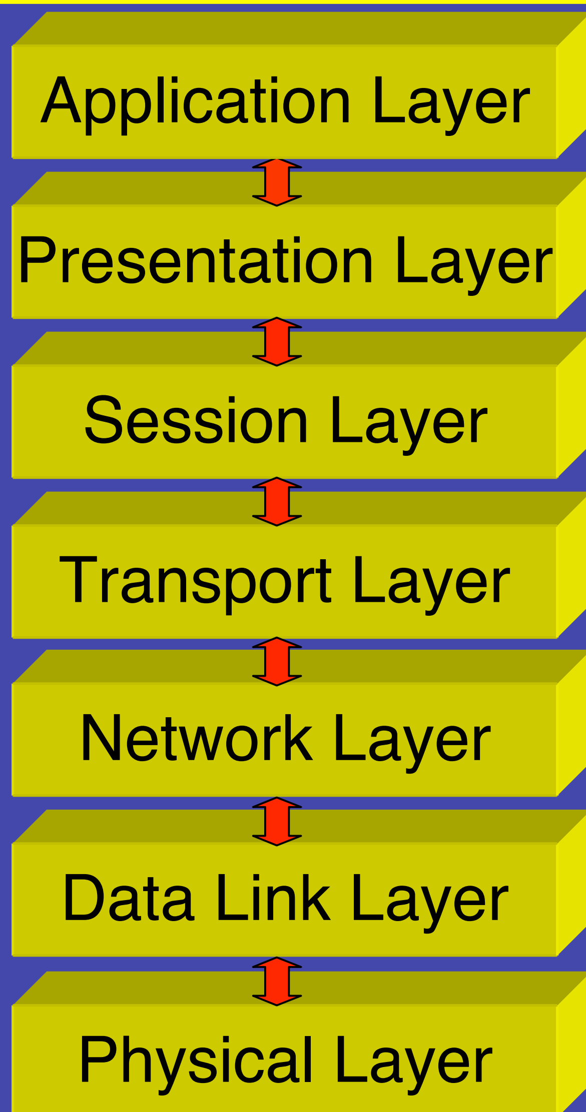
Outline

- 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.

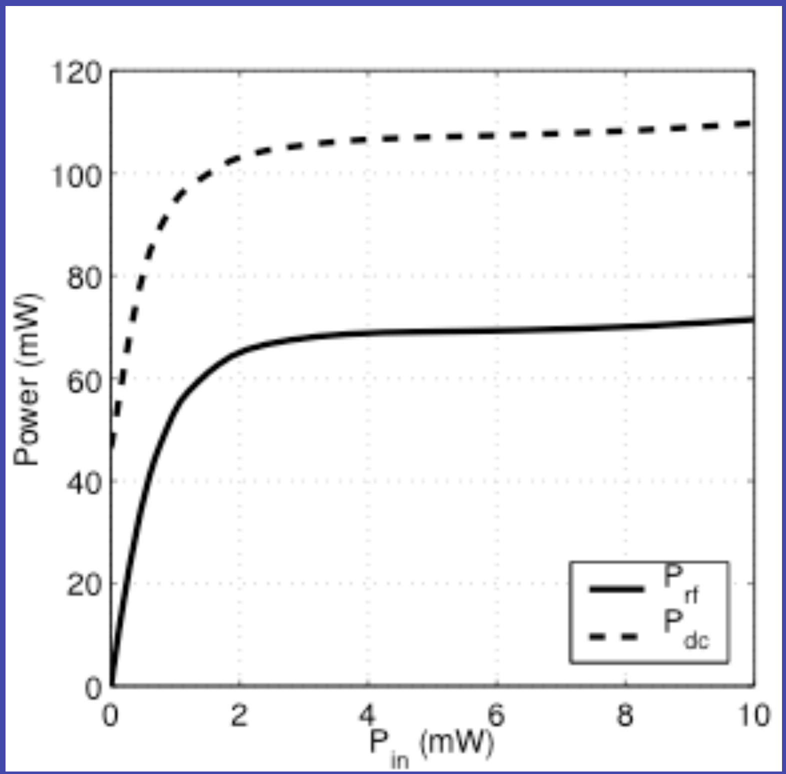
What causes coupling?

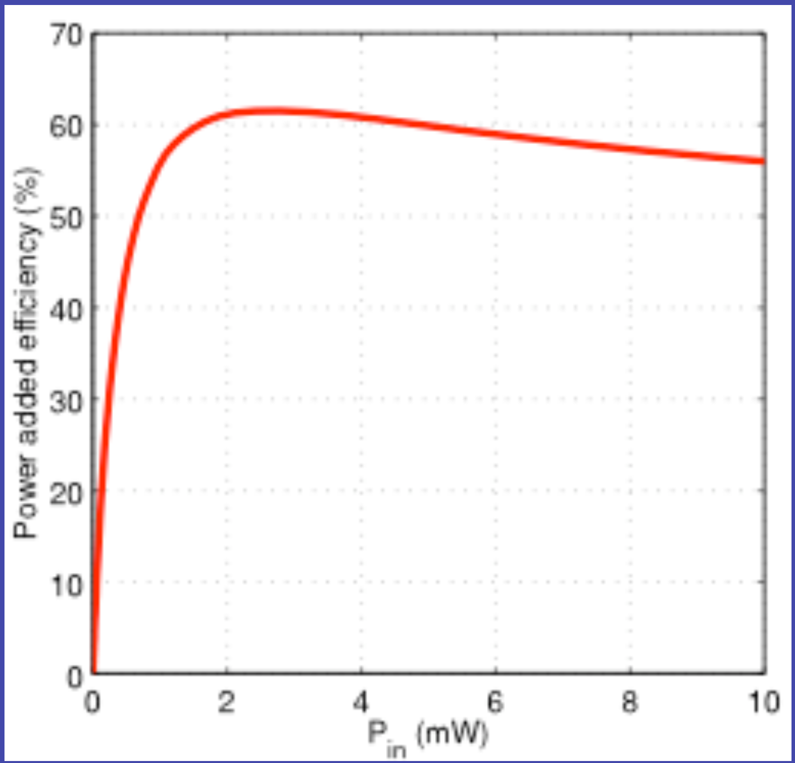
- Energy constraints.
- Delay constraints.
- …

Why not cross-layer design?

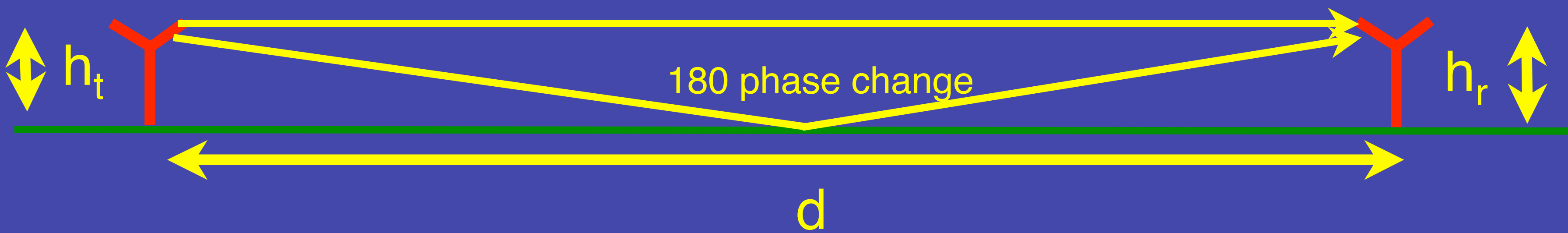
- Difficulty.
- Lack of insight into design.
- Generally requires near brute-force simulation/optimization if several layers are considered simultaneously.

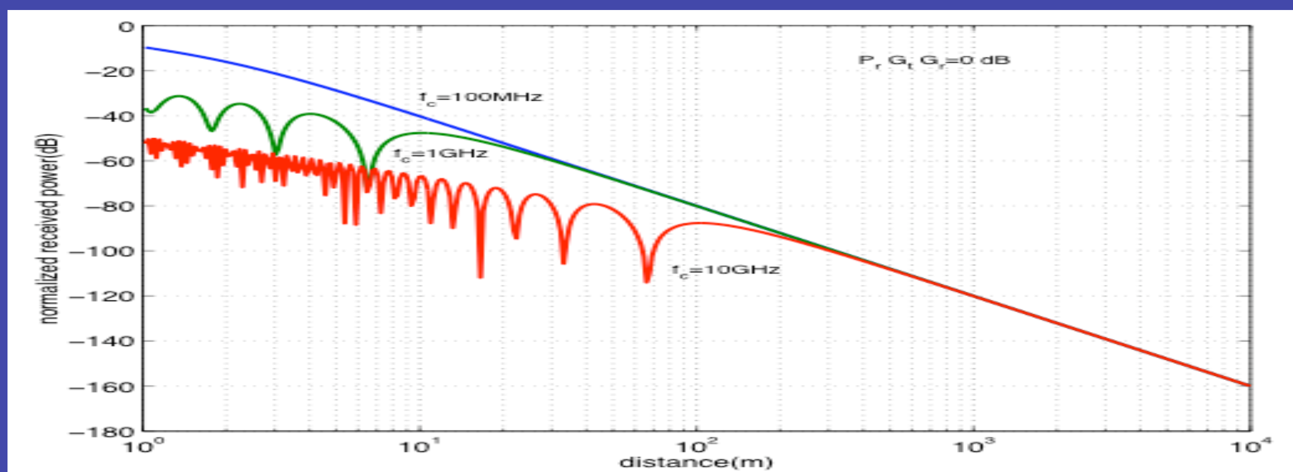
Amplifier Characteristics





Propagation Characteristics



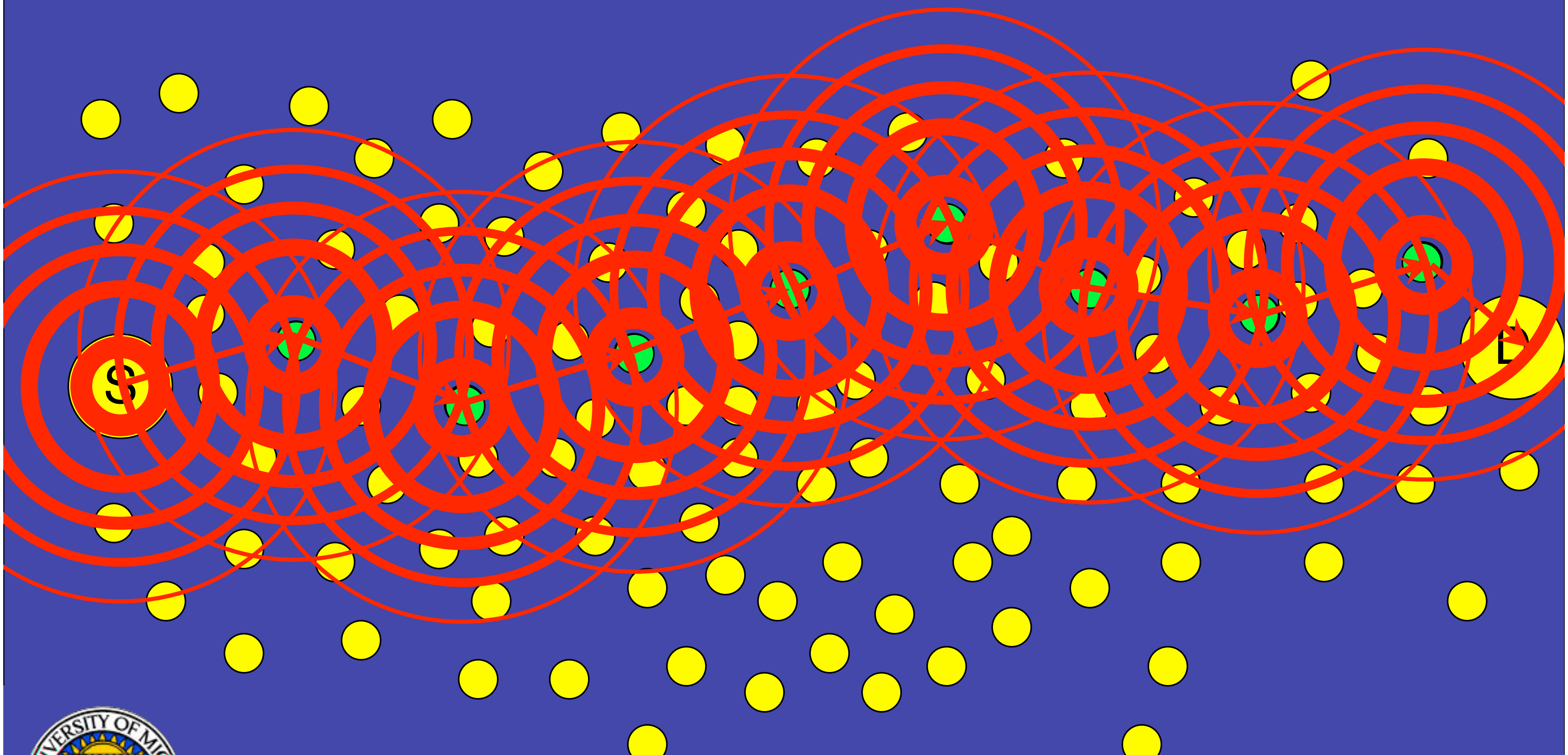


$$P_r = P_t\left(\frac{\lambda_c}{4\pi d)}\right)^2 4G_tG_r\sin^2\left(\frac{2\pi h_t h_r}{\lambda_c d}\right) \approx \frac{P_tG_tG_rh_t^2h_r^2}{d^4}$$

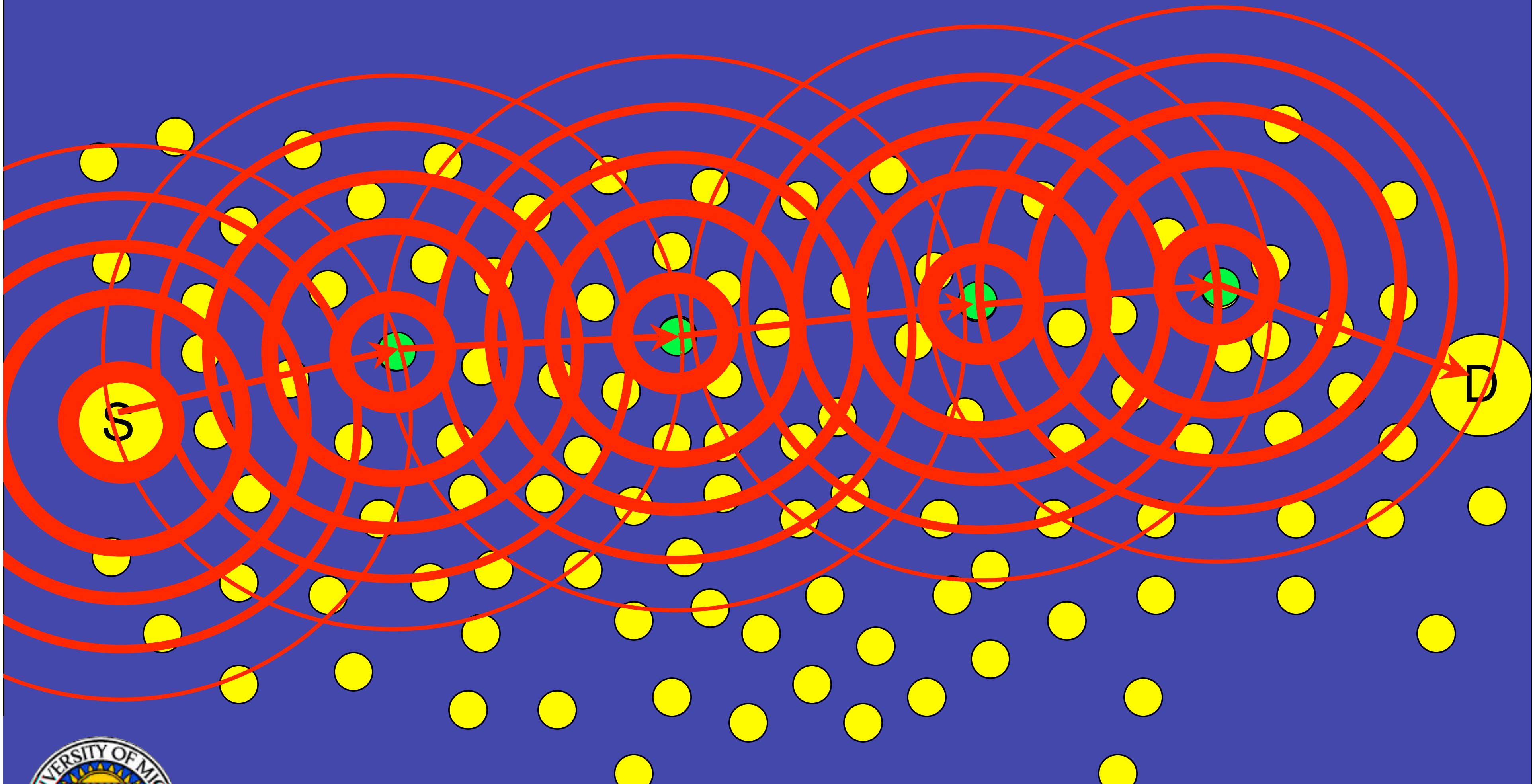
Two cross layer problems

- **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



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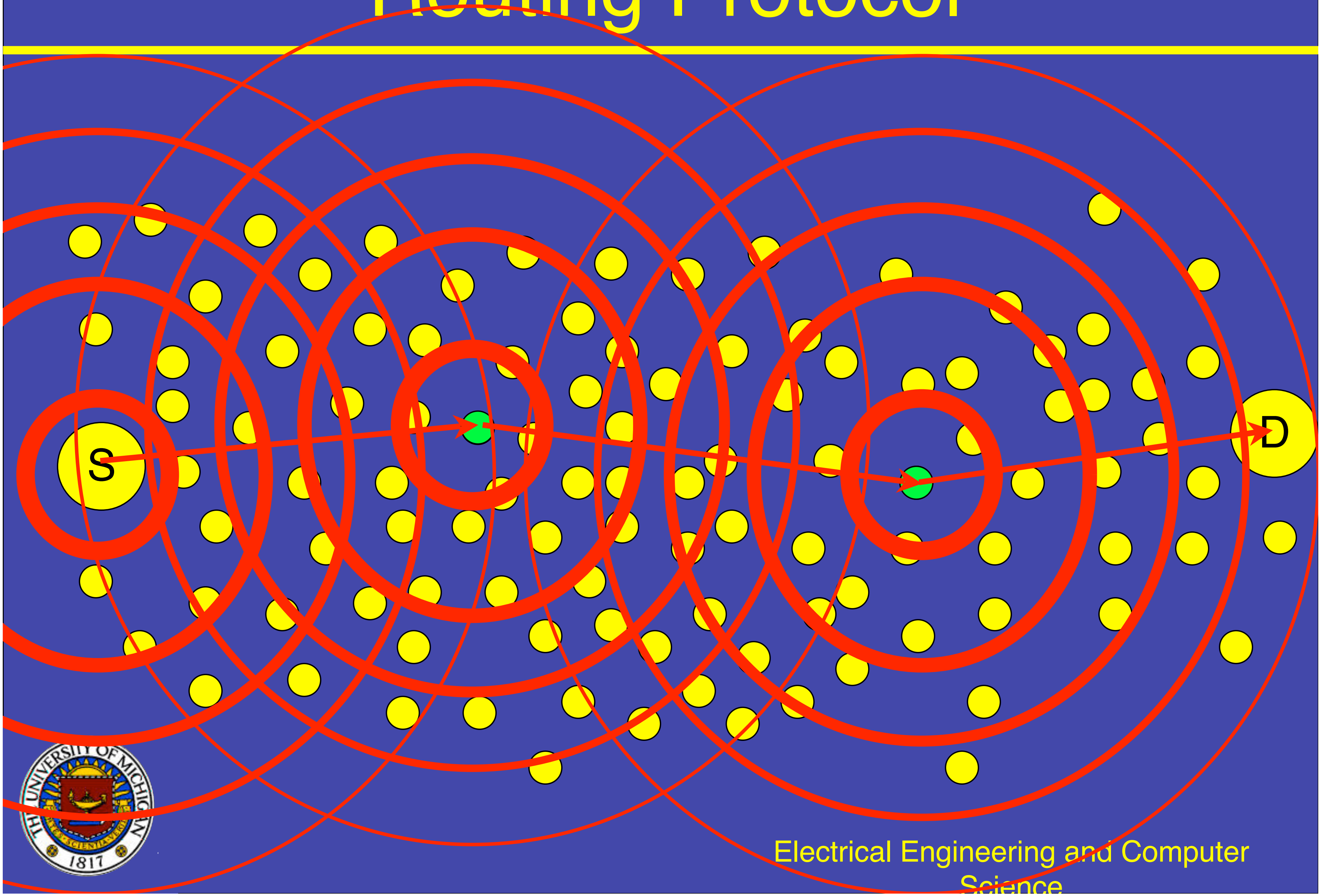
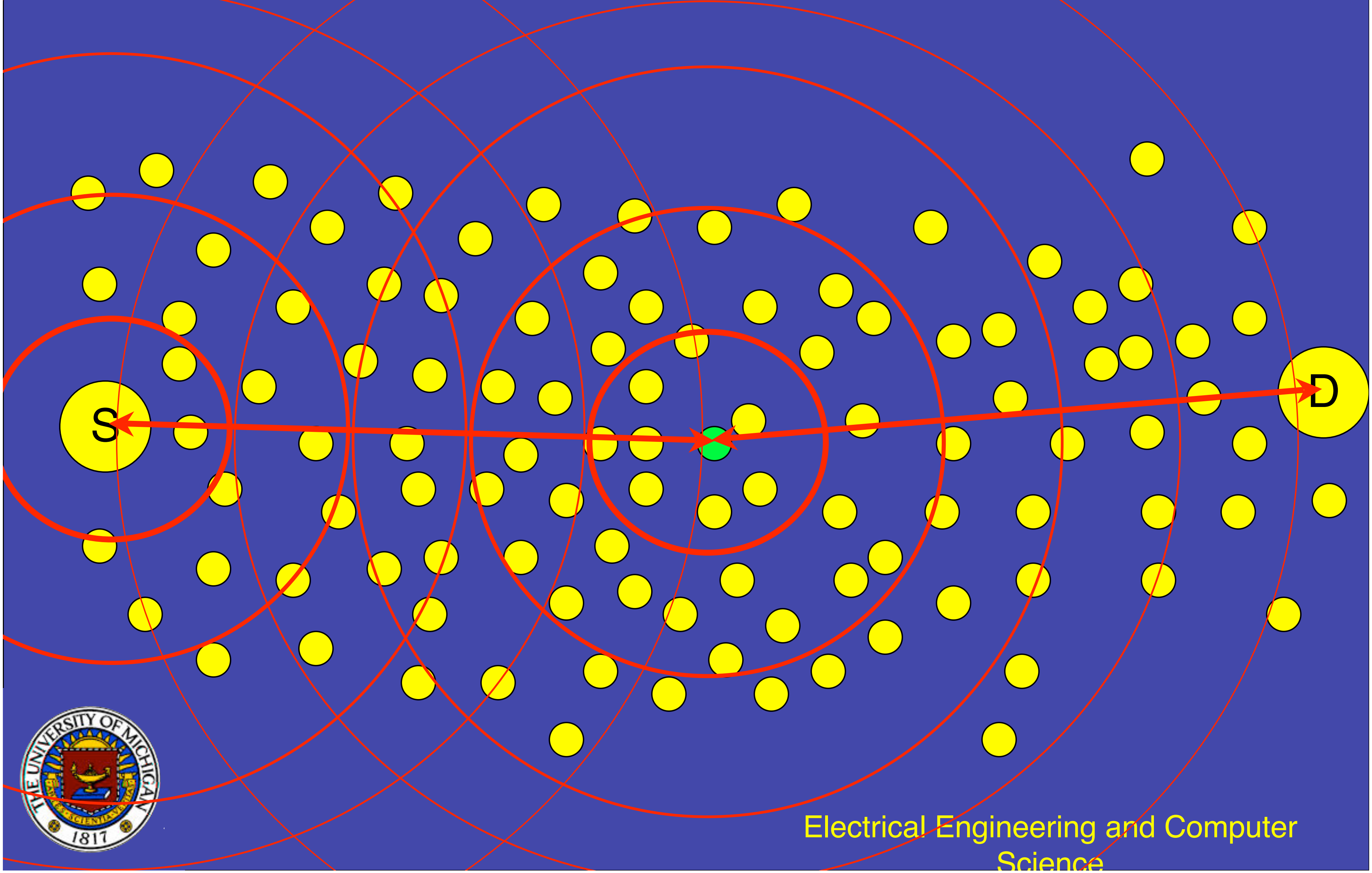
Routing Protocol



Routing Protocol



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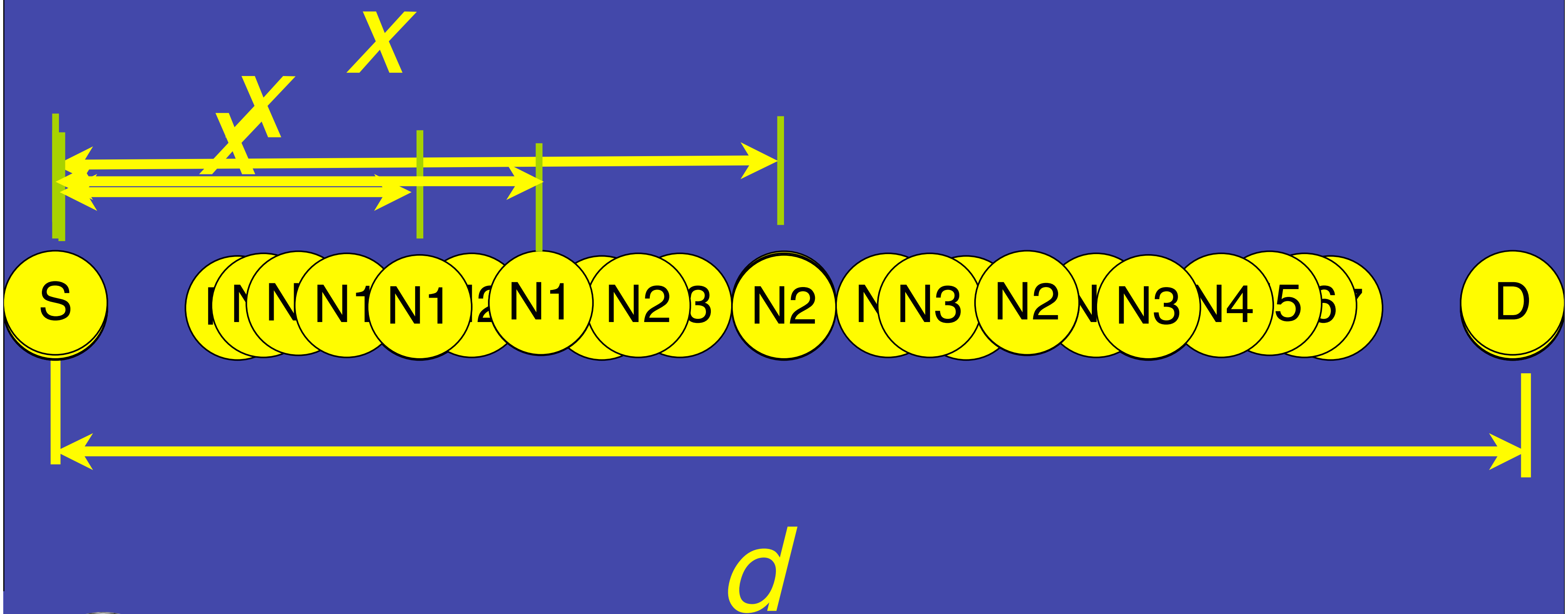
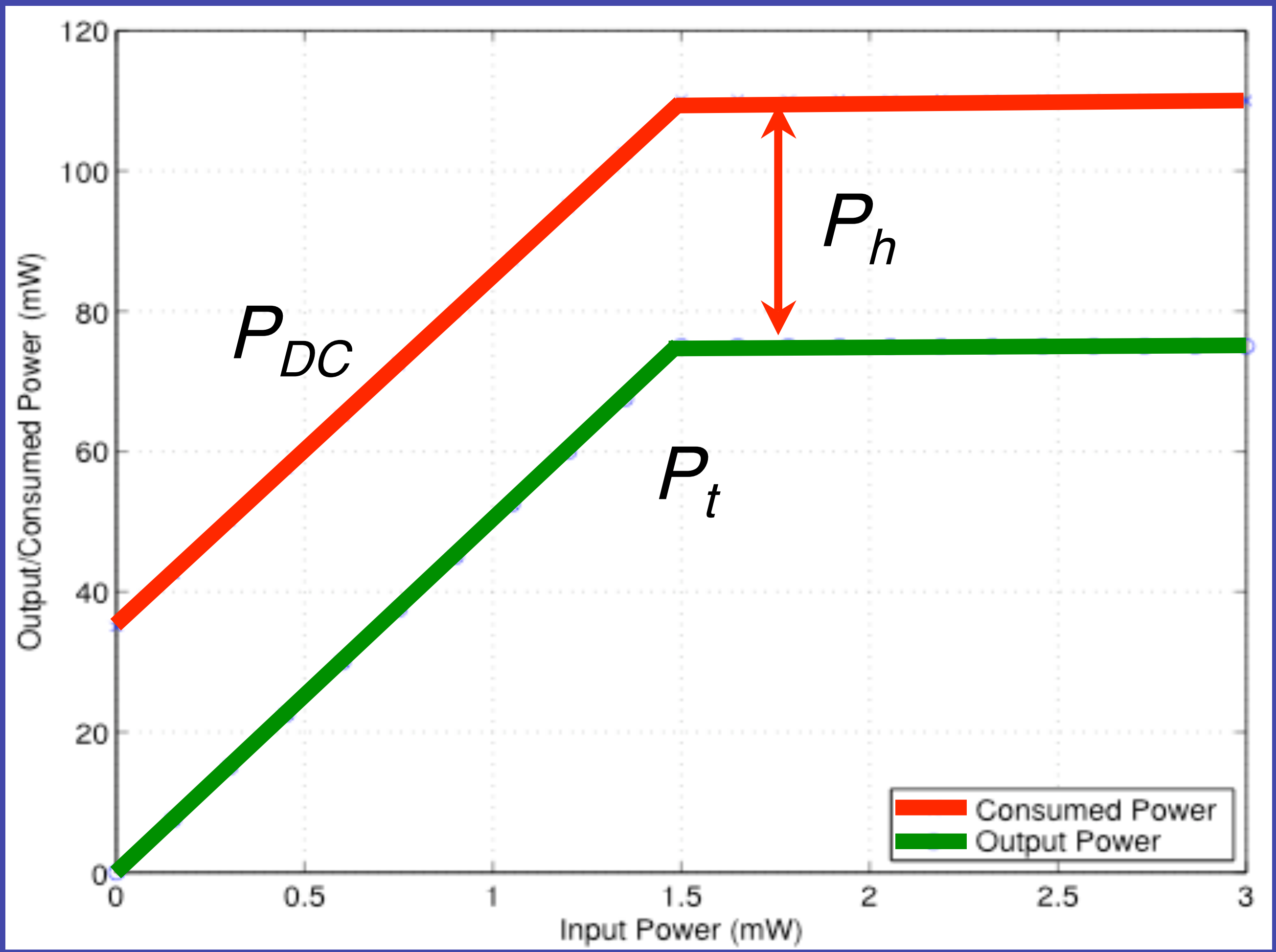
Simplified Network Model

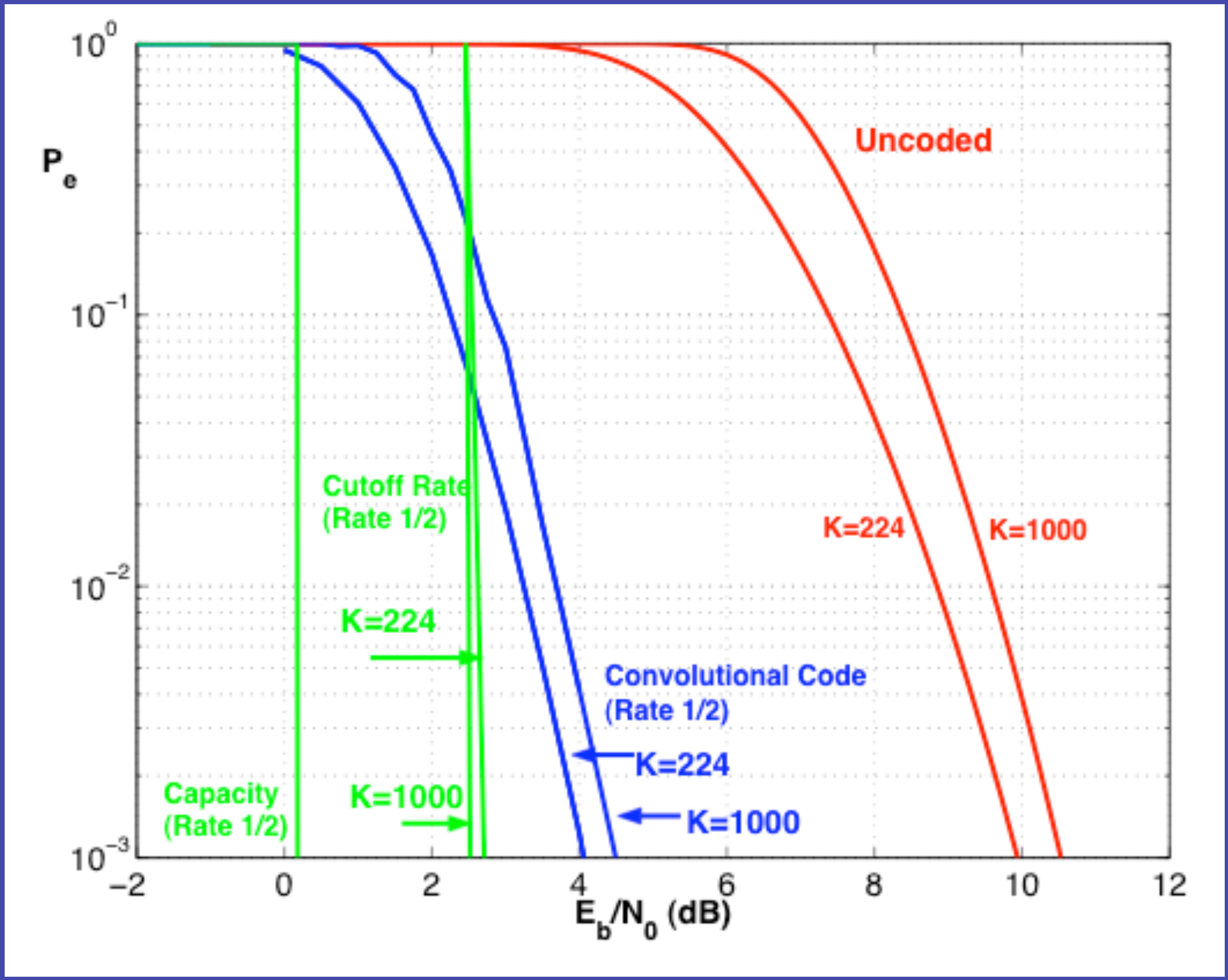


Amplifier Model



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 and

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

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

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

Number of Hops

Energy used per hop (transmission and reception)

Packet Success Probability

Optimization

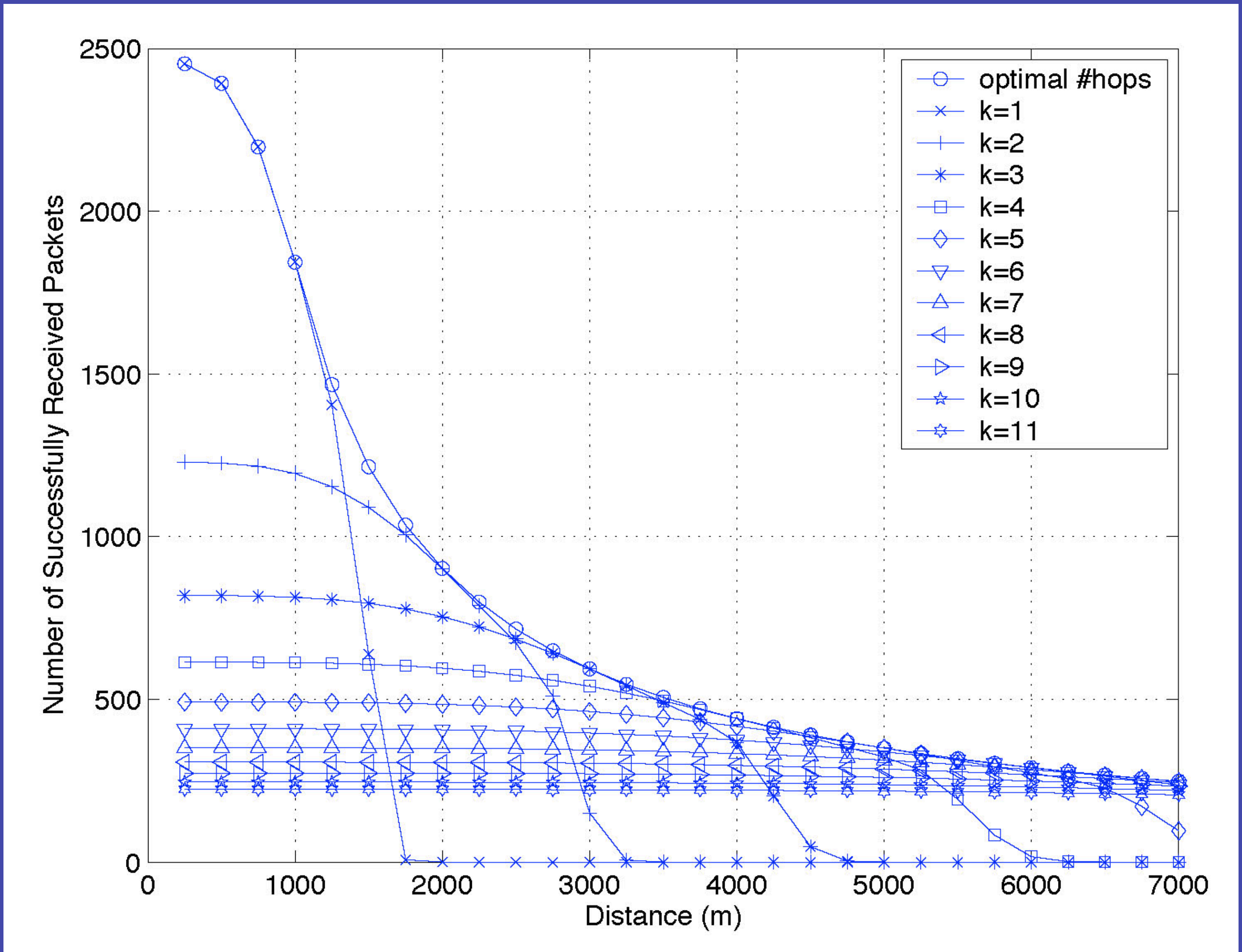
$$S^* = \max_{P_{in}, R, k} S(P_{in}, R, k)$$

Main Result (large *d*)

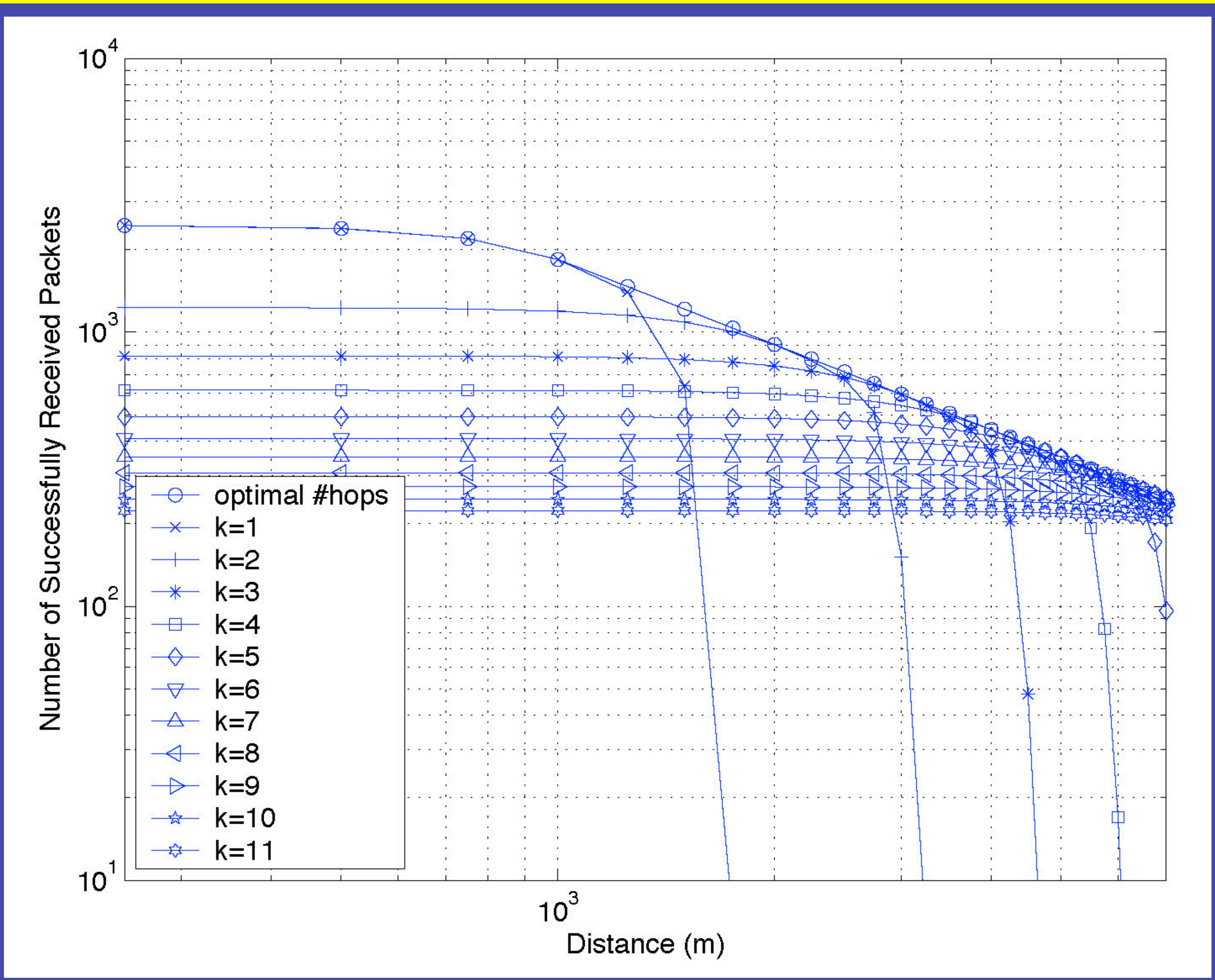
$$S^* = \frac{\delta}{d}$$

- 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.

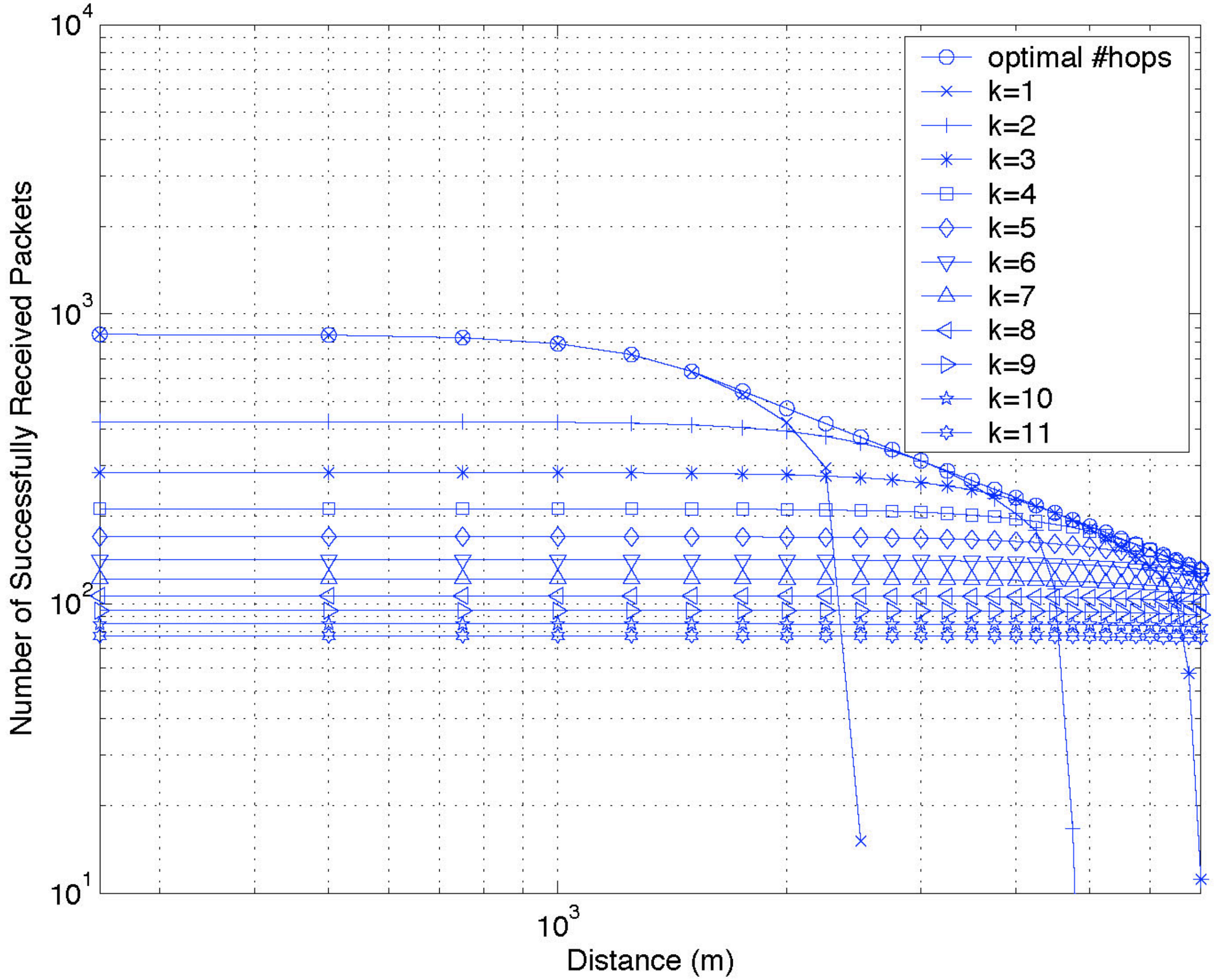
Throughput vs. Distance (Uncoded)



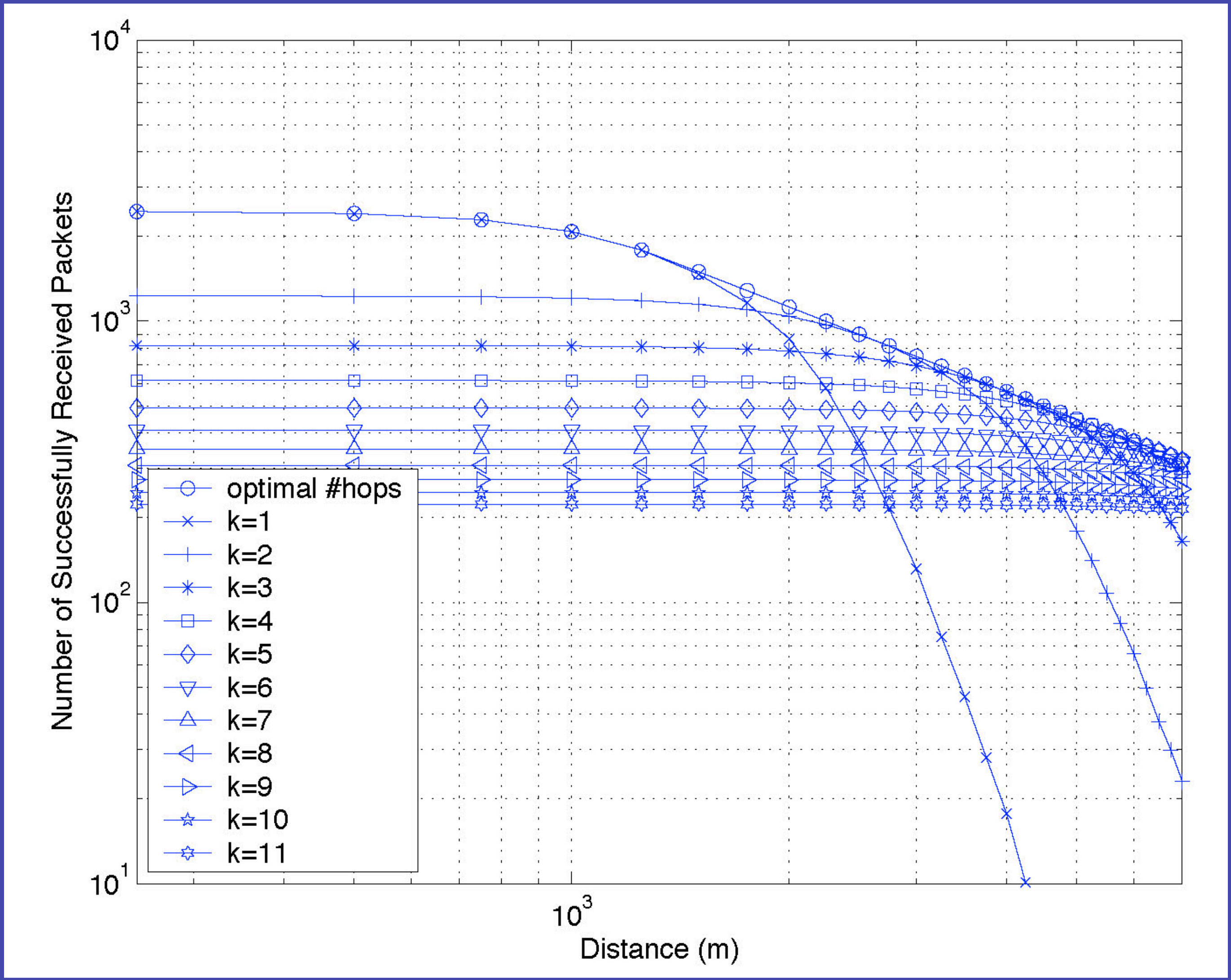
Throughput vs. Distance (Uncoded)



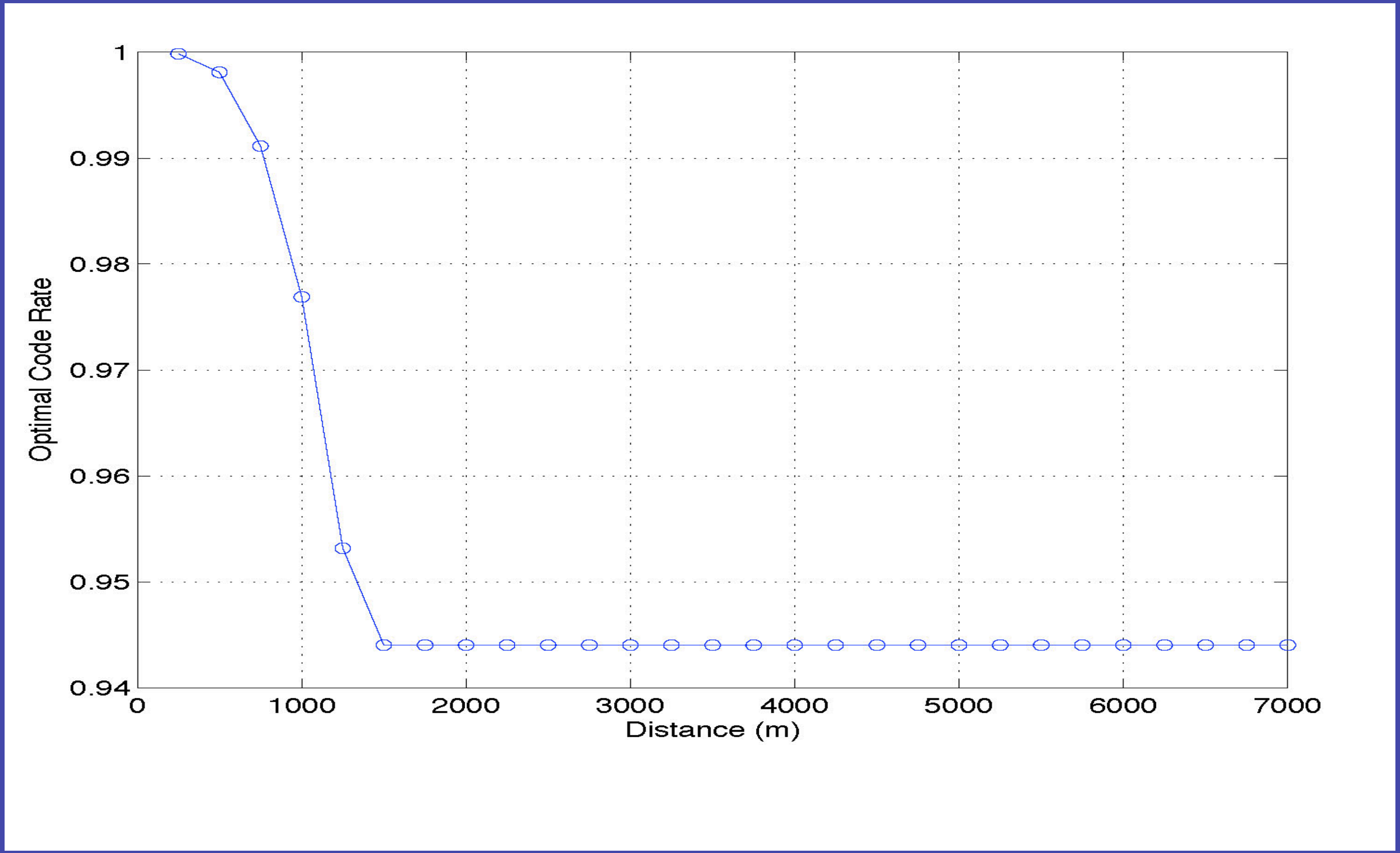
Throughput vs. Distance (Convolutional Code, Rate 1/2)



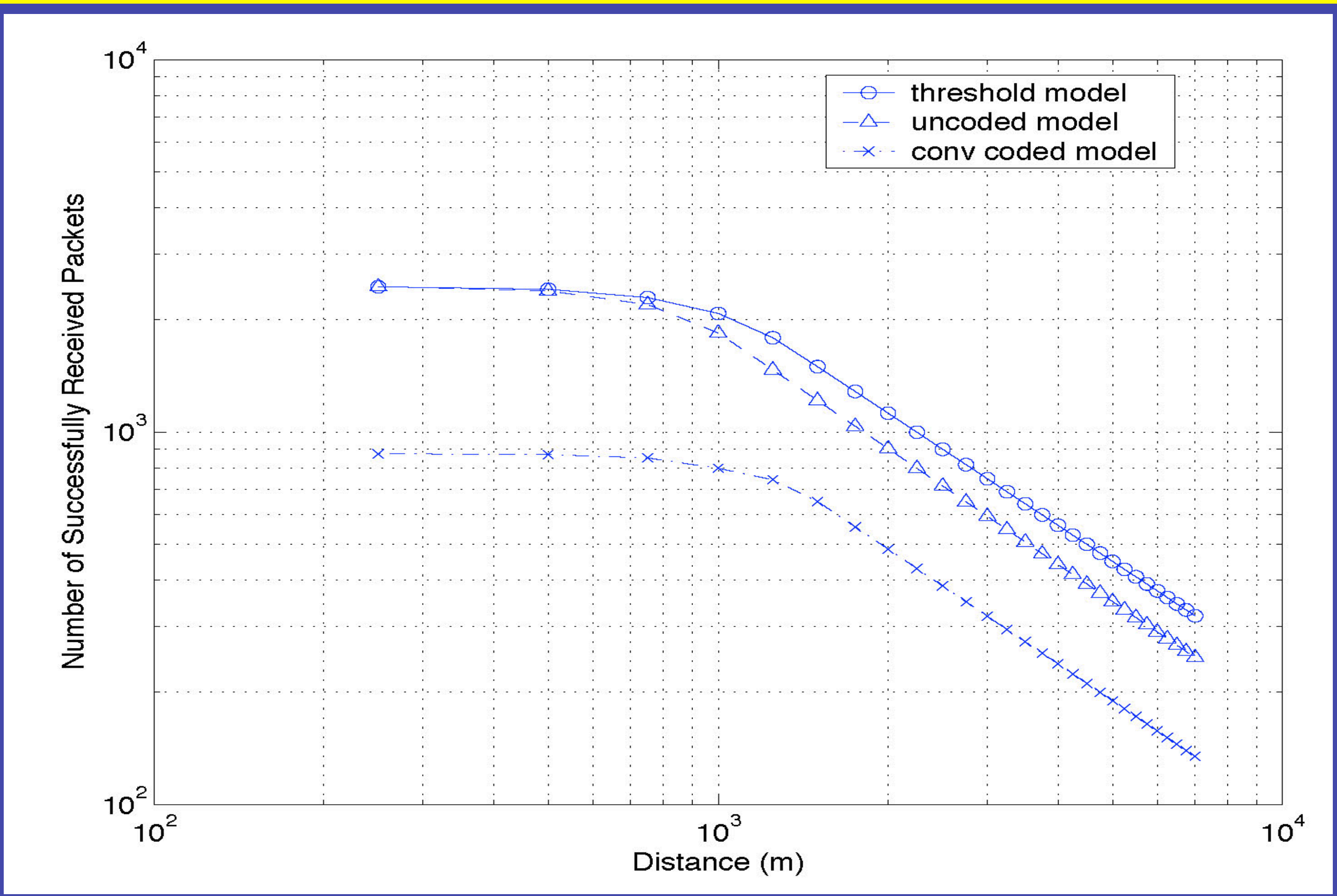
Throughput vs. Distance (Capacity at Optimum Rate)



Optimum Rate vs. Distance



Throughput vs. Distance (Comparison)



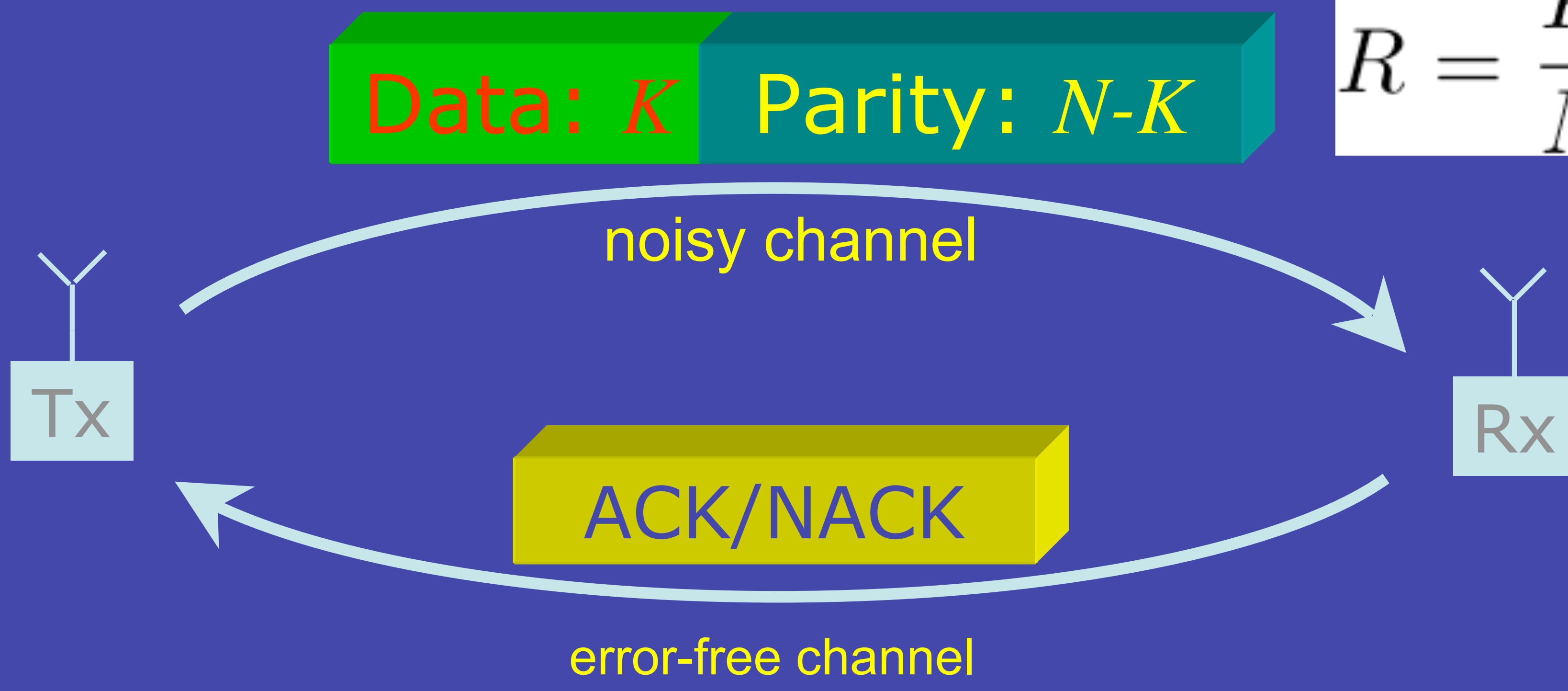
Conclusion: First Problem

- 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



$$R = \frac{K}{N}$$

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

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

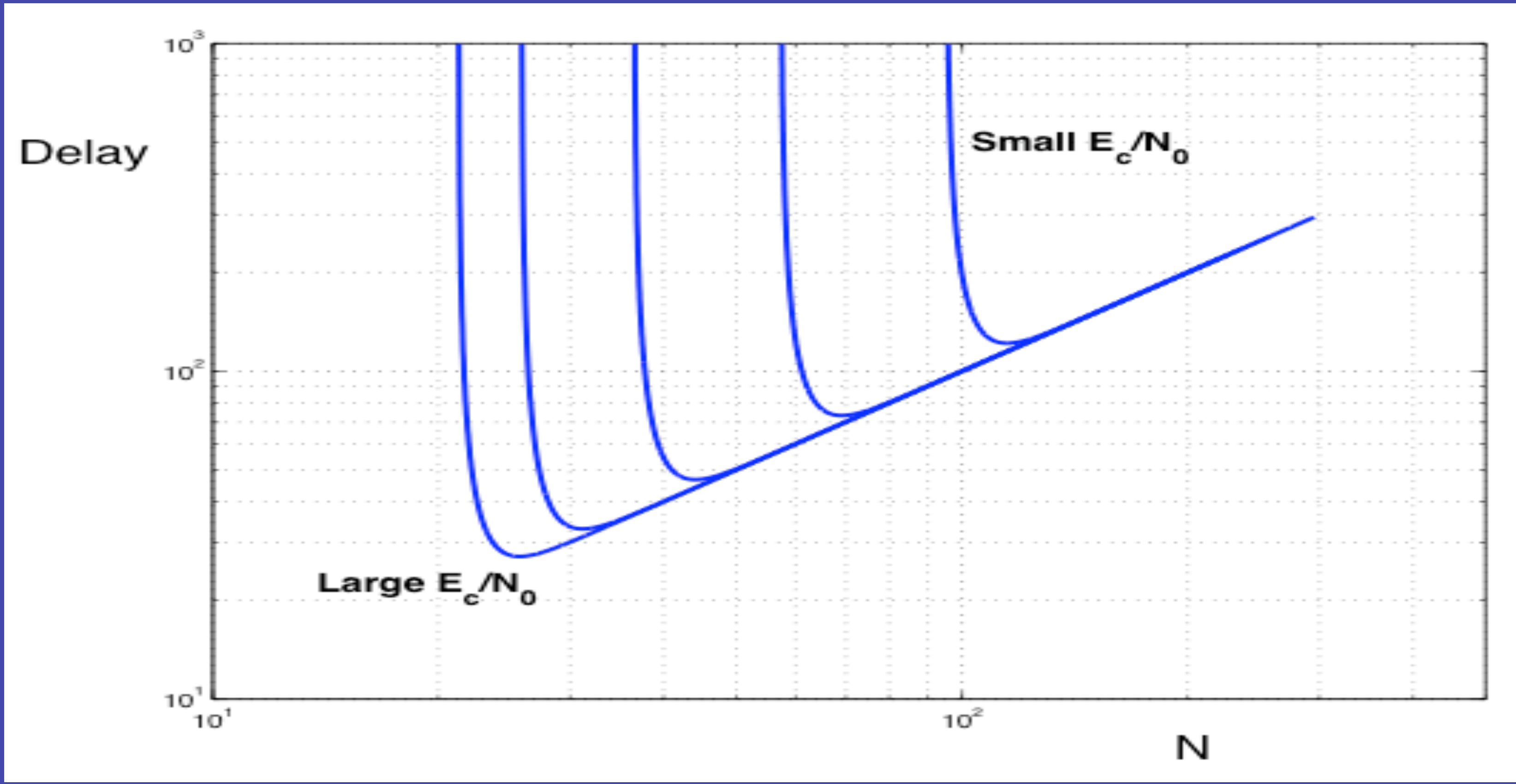
For an additive white Gaussian noise channel

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

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

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

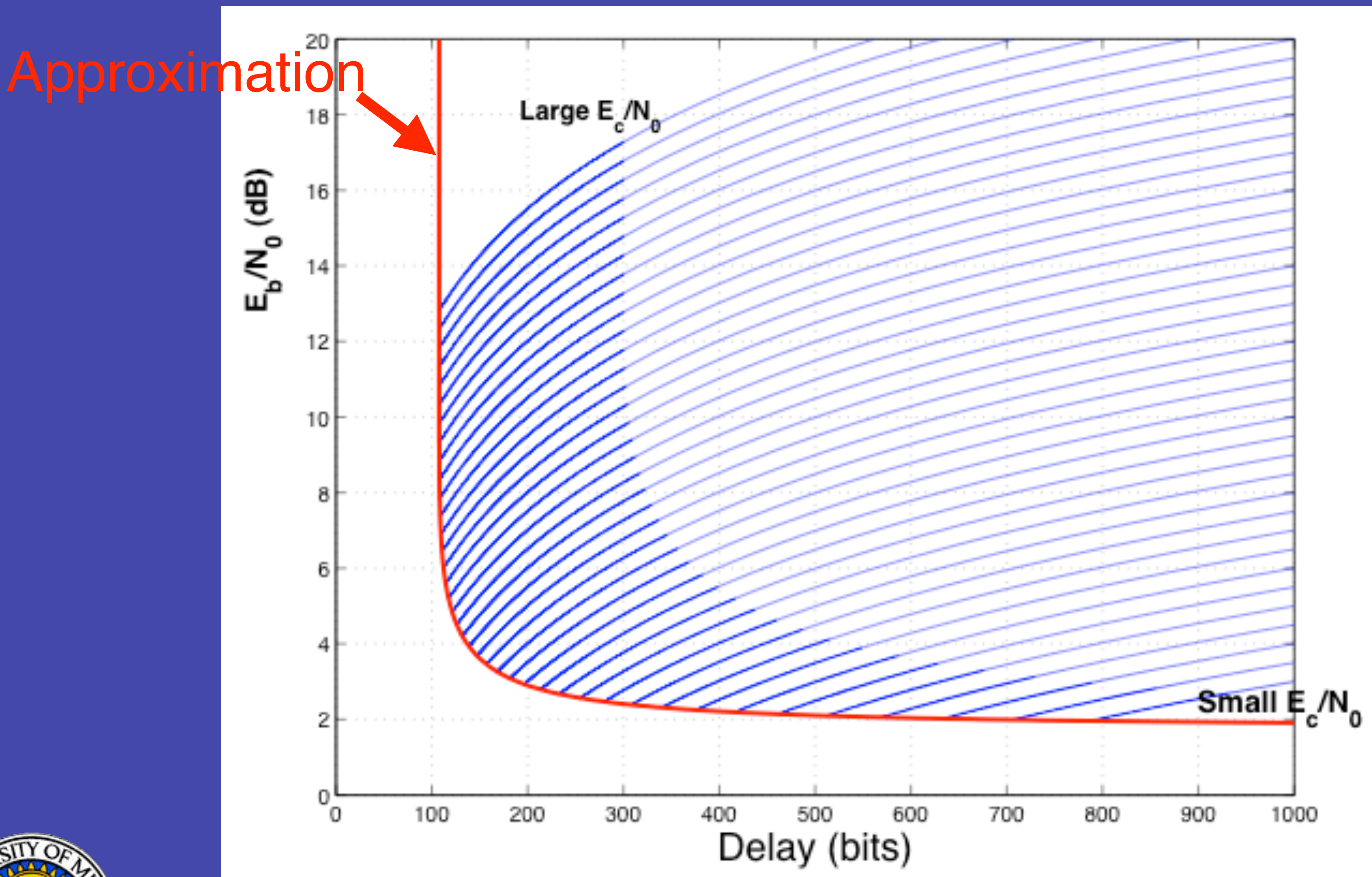
$$D^* \approx \frac{K}{R_0}\left[1 + \frac{\log 2(K\ln(2))}{K}\right]$$

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

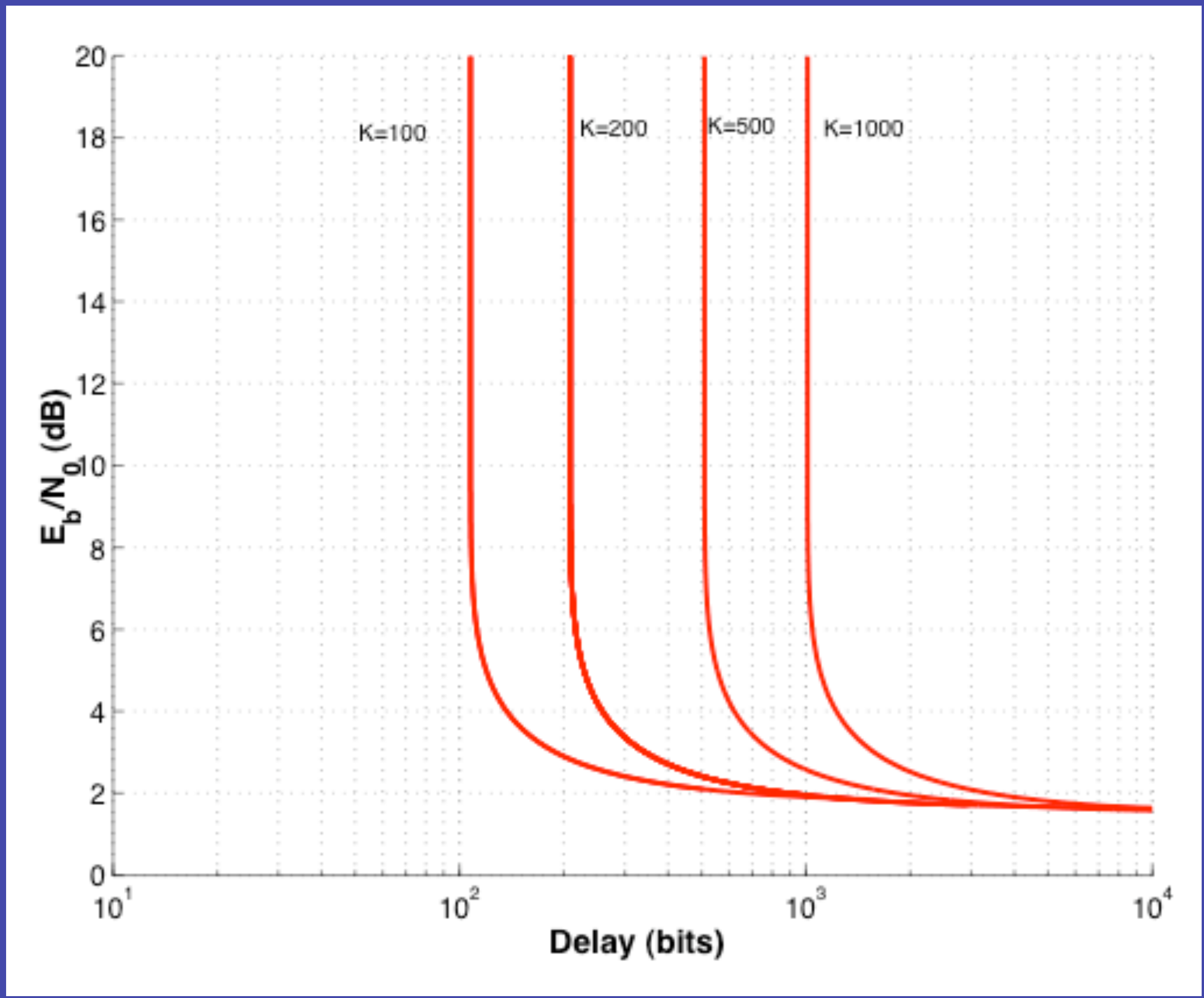
Comments on Result

- 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

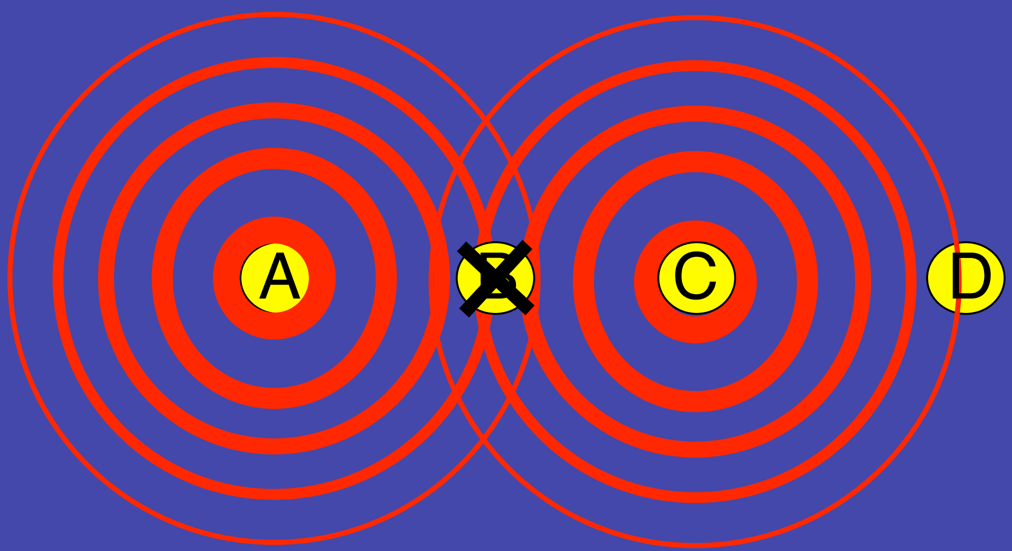


Delay-Energy



Extension to Include MAC Layer

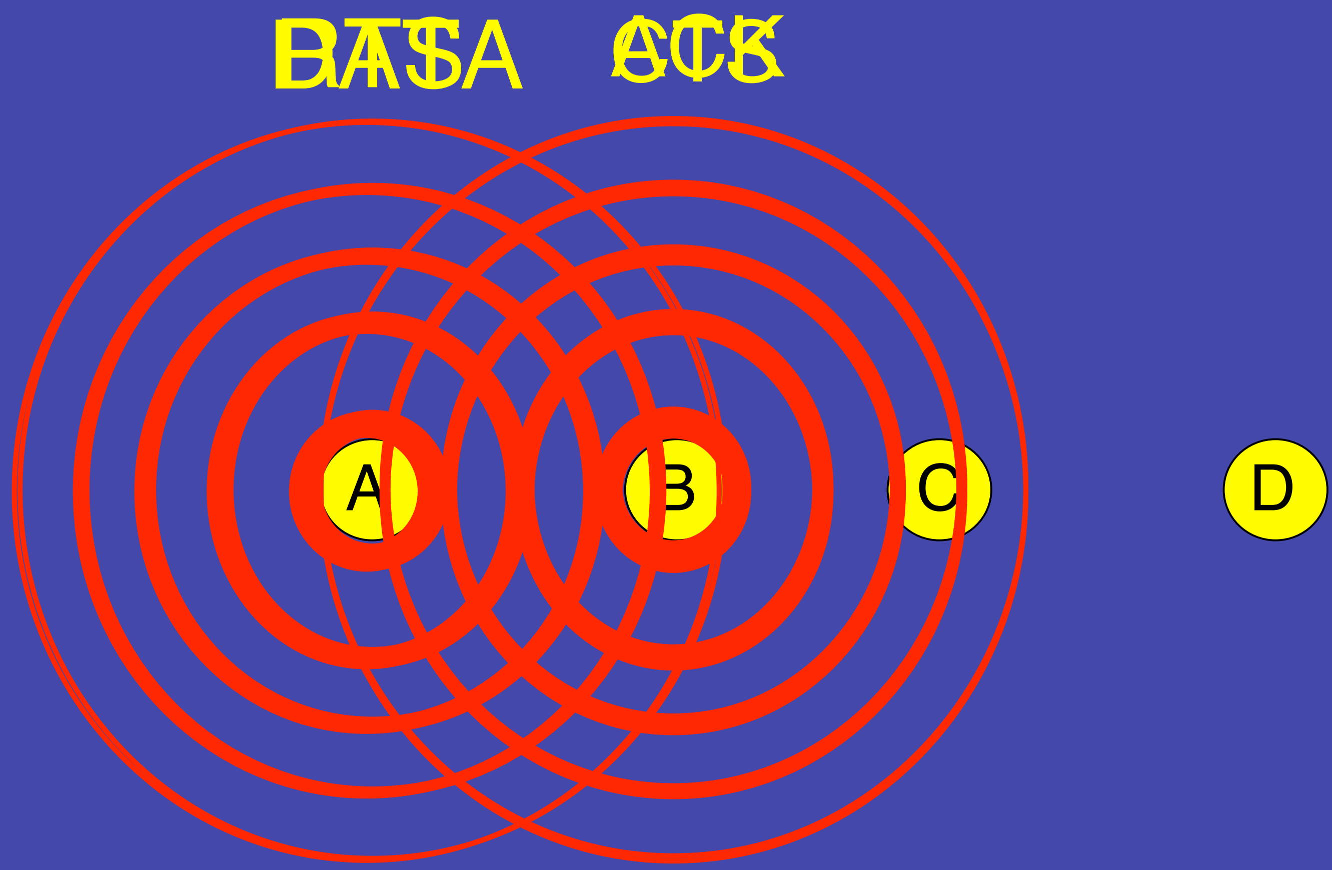
Node A wants to transmit a message to Node B. Node C wants to transmit a message to Node D. Without coordination Node C's signal will interfere with A's transmission to Node B. Node C might start it's transmission after A has already begun transmitting because C can not hear Node A's signal. This is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



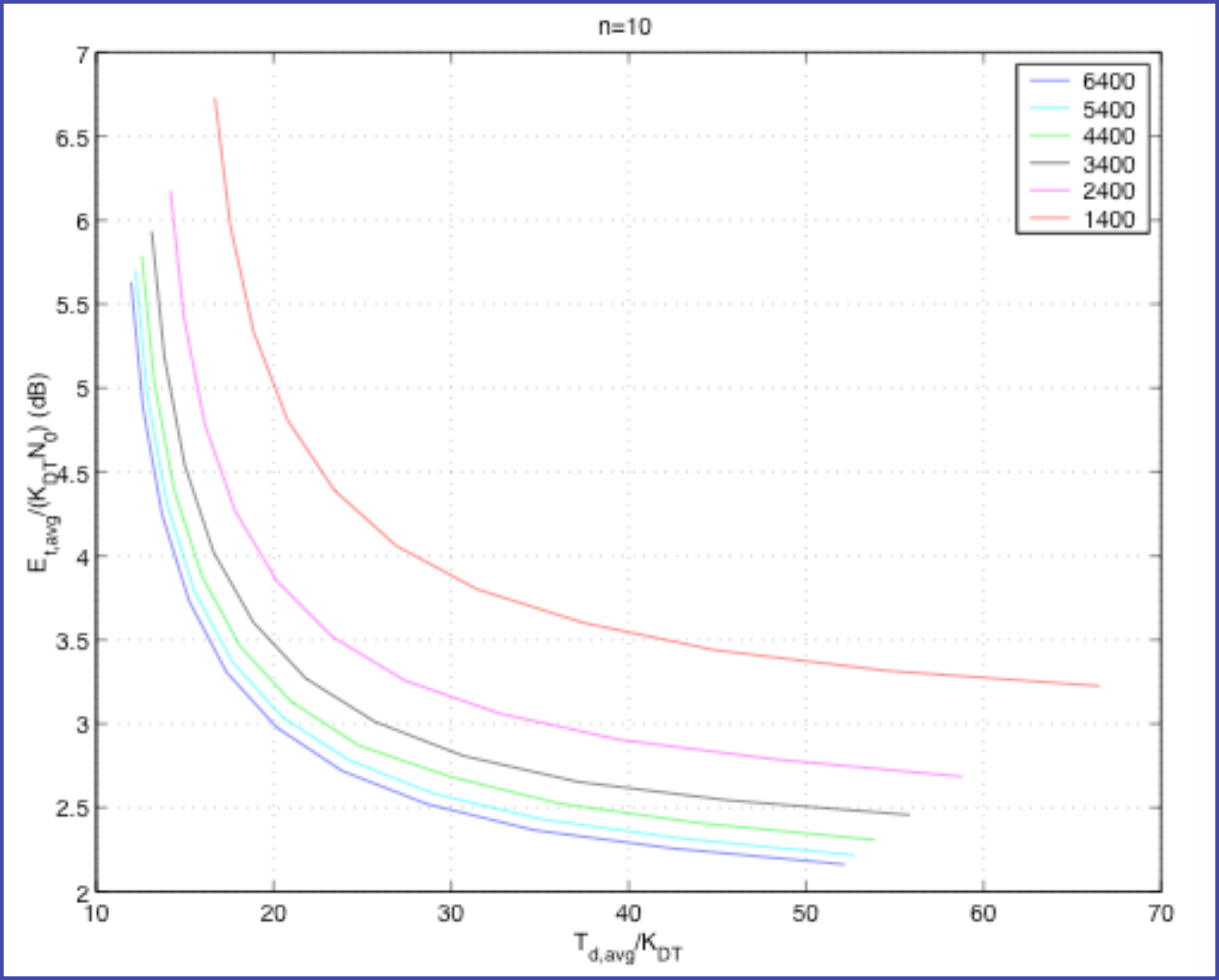
Problem

- 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.

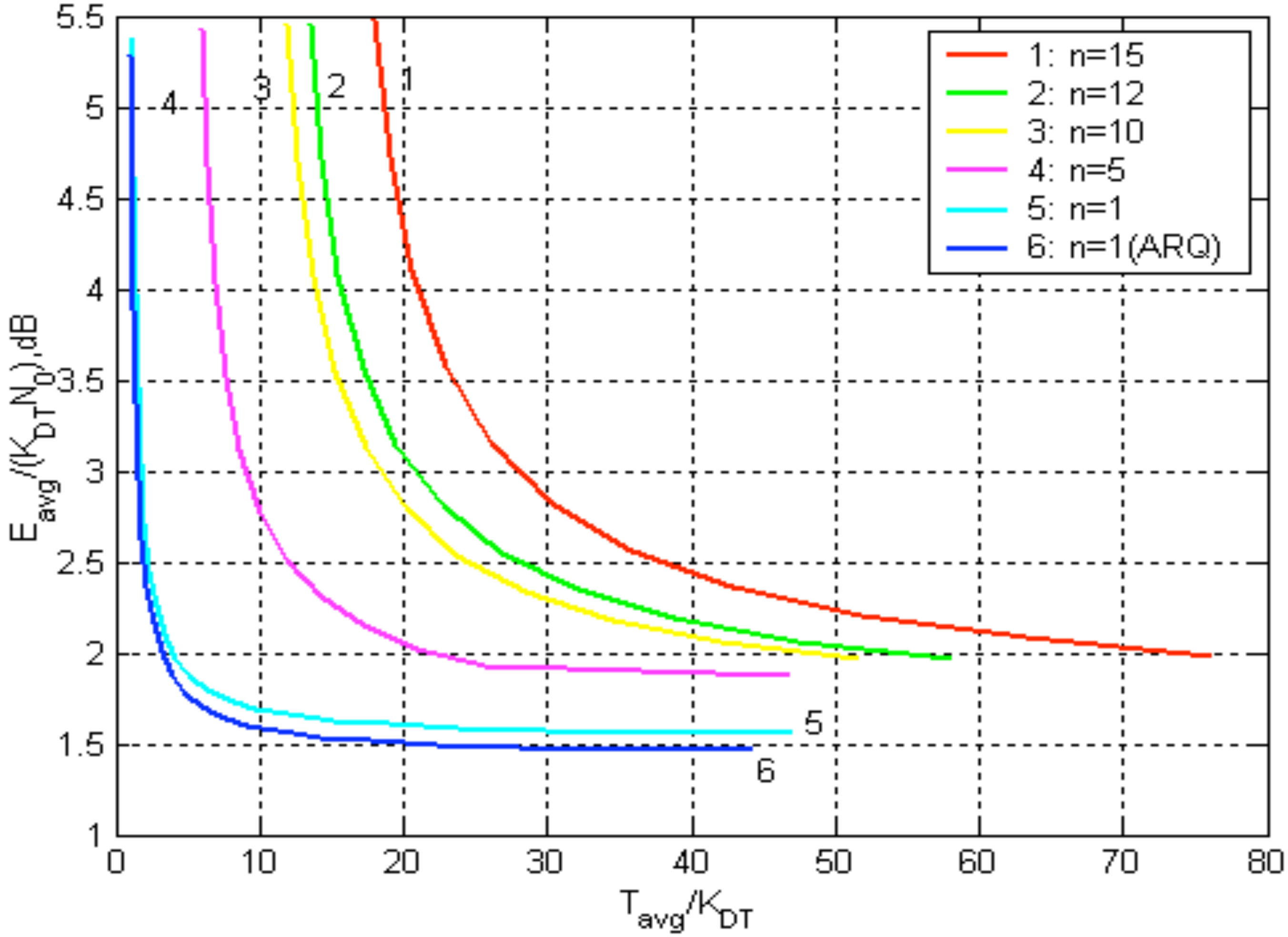
Numerical Results (10 users)



Interpretation

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

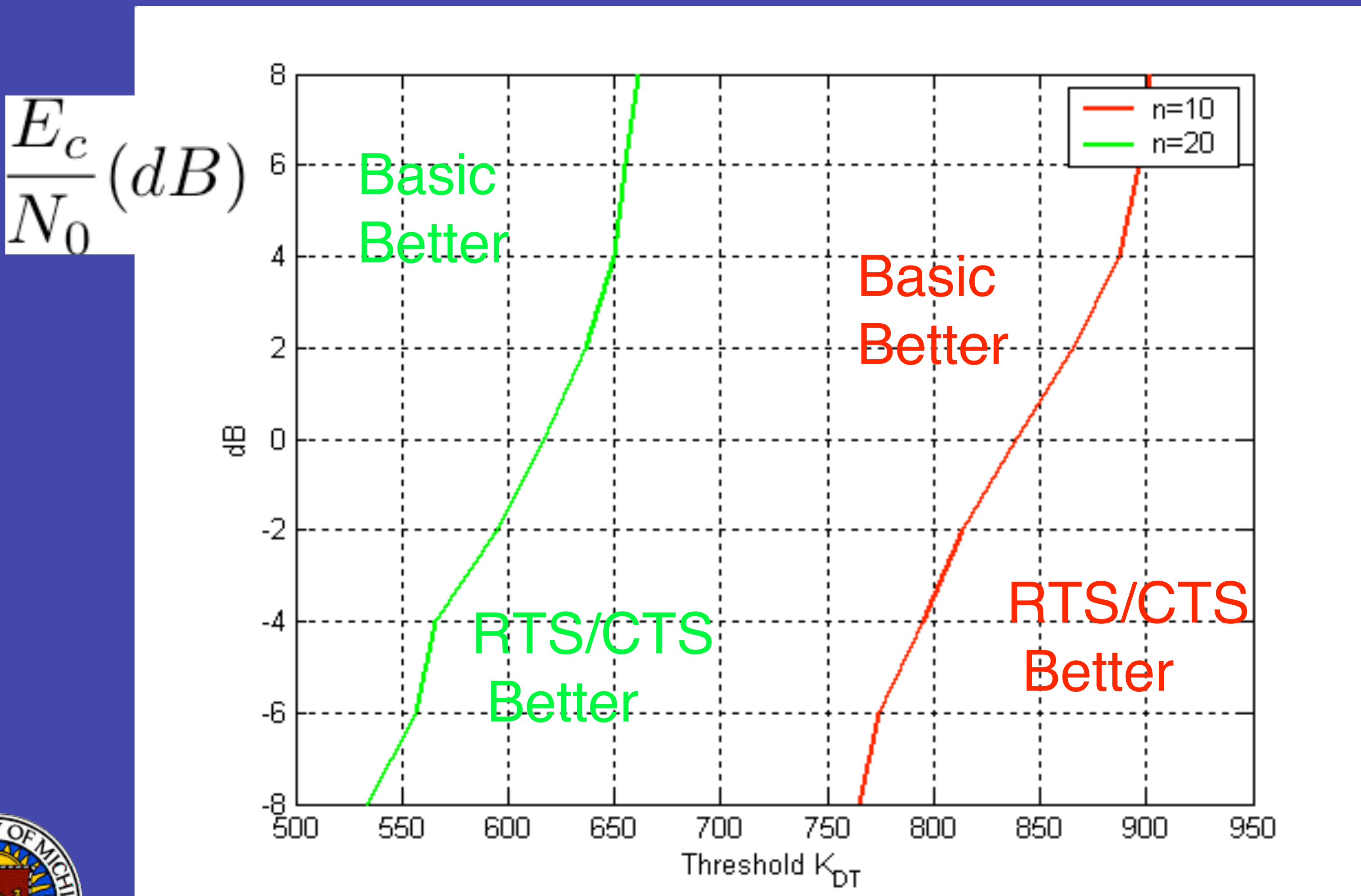
Numerical Results (K_{DT}=6400)



“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.