Energy and Bandwidth Efficiency in Wireless Networks

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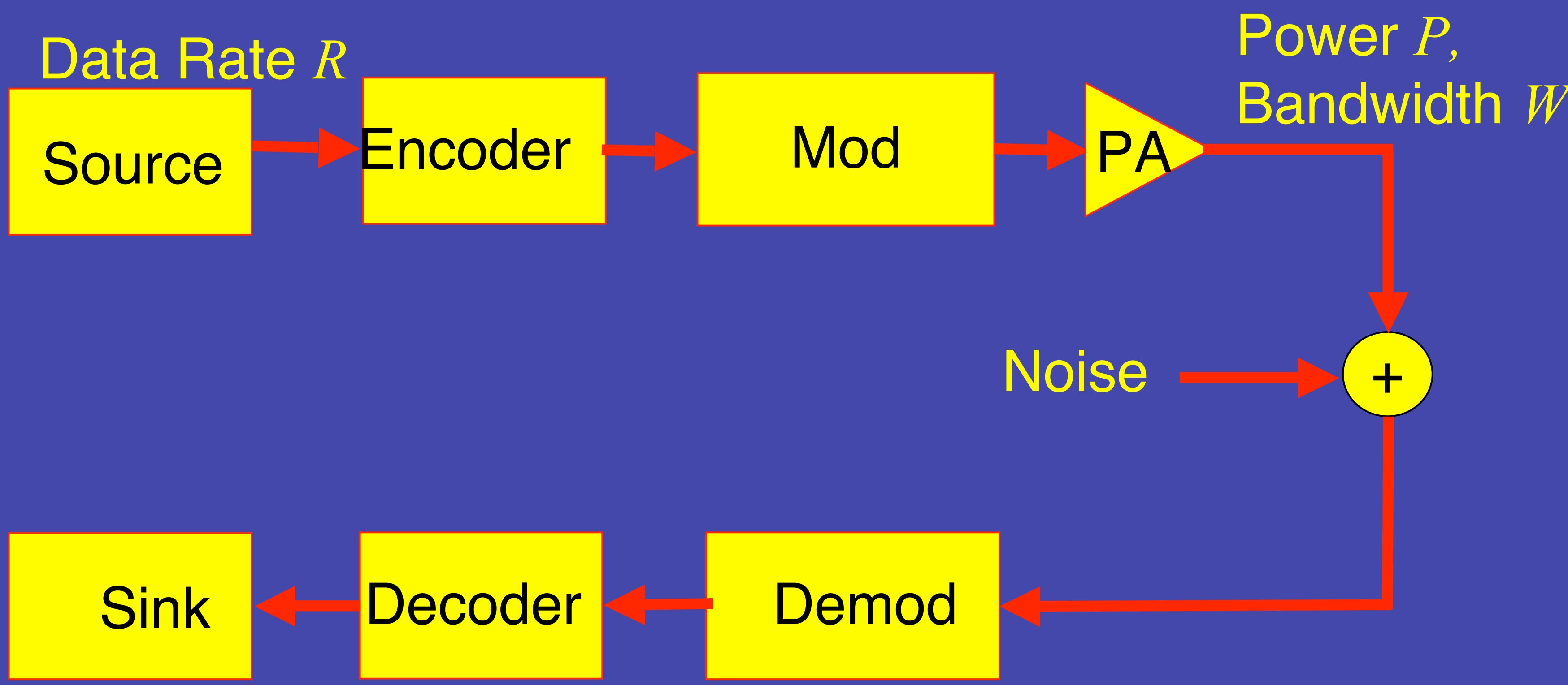
Outline

- Introduction/Background
- Device/Physical Layer/Network Layer Models
- Performance Measure
- Numerical Results

Communication Problem



Energy-Bandwidth Efficiency

- Shannon showed there is a fundamental tradeoff between energy efficiency and bandwidth efficiency for reliable communications
- R: Data rate (bits/second)
- P: Power (Joules/sec)
- N_0: Noise power spectral density (Watts/Hz)
- W: Bandwidth (Hz)

$$R < W \log_2\left(1 + \frac{P}{N_0 W}\right)$$

Shannon's Result

$$E_b = P/R$$

$$R/W < \log_2(1 + \frac{E_b}{N_0}\frac{R}{W})$$

$$\frac{E_b}{N_0} > \frac{2^{R/W} - 1}{R/W}$$

R/W: Bandwidth efficiency (bits/second/Hz)

E_b/N_0: Received energy per information bit-to-noise power spectral density ratio (dB)

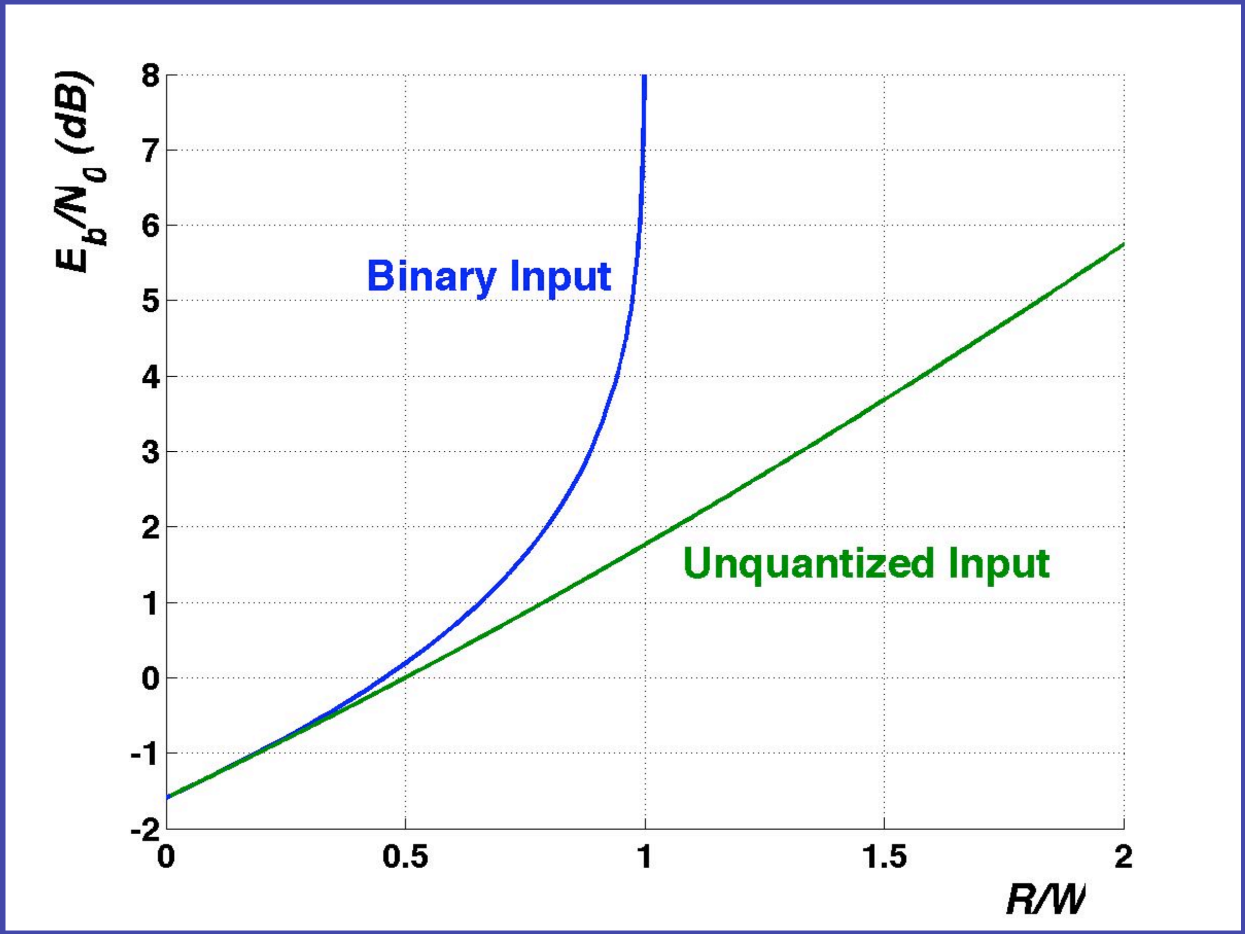
Shannon's Result for Binary Input (BPSK)

- When the signal alphabet is restricted to binary the capacity changes.

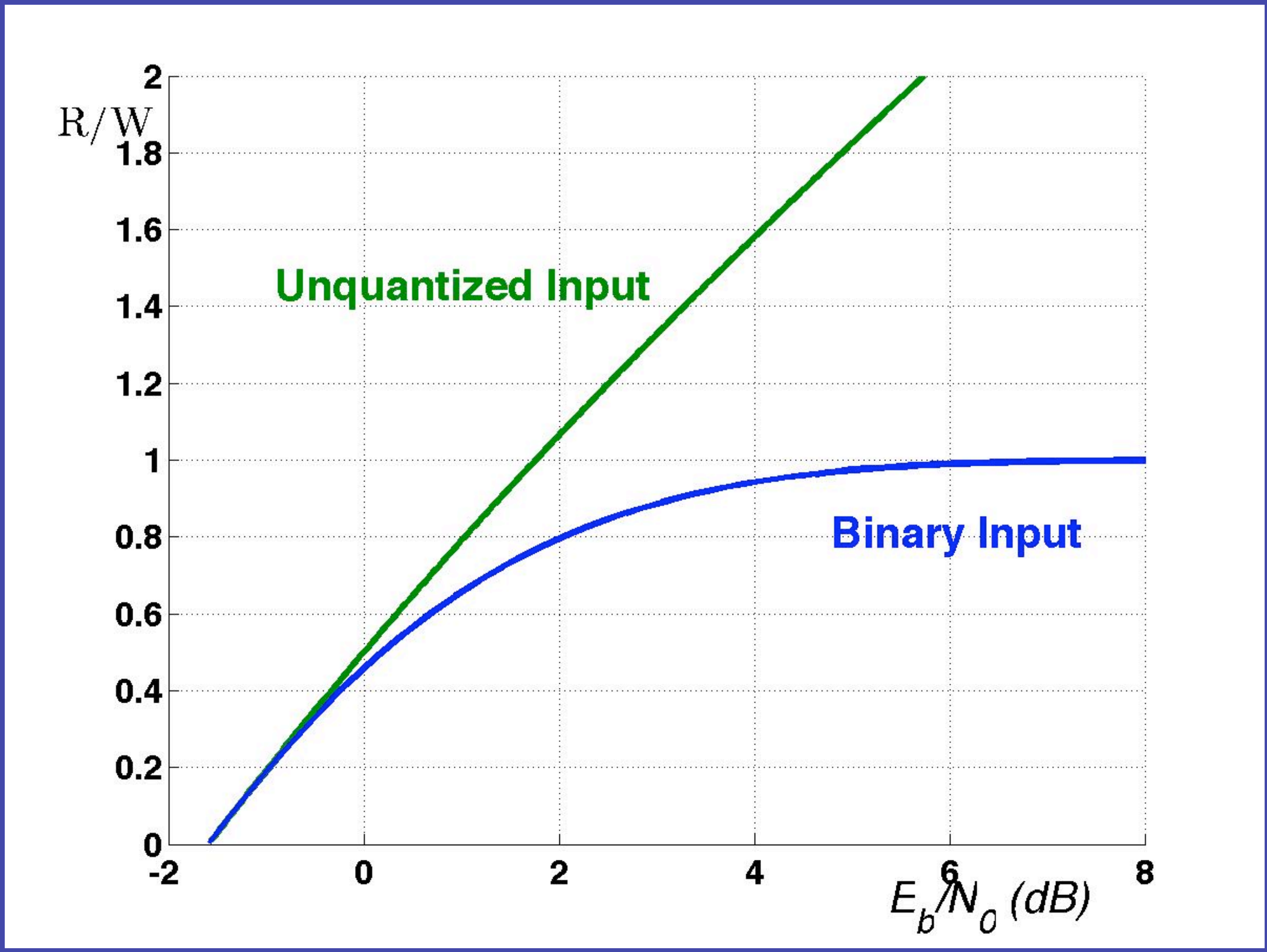
$$R/W < 1 - \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-(y-\beta)^2/2} \log_2(1 + e^{-2y\beta}) dy$$

$$\beta = \frac{E_b}{N_0} \frac{R}{W}$$

Energy-Bandwidth efficiency tradeoff



Energy-Bandwidth Efficiency Tradeoff



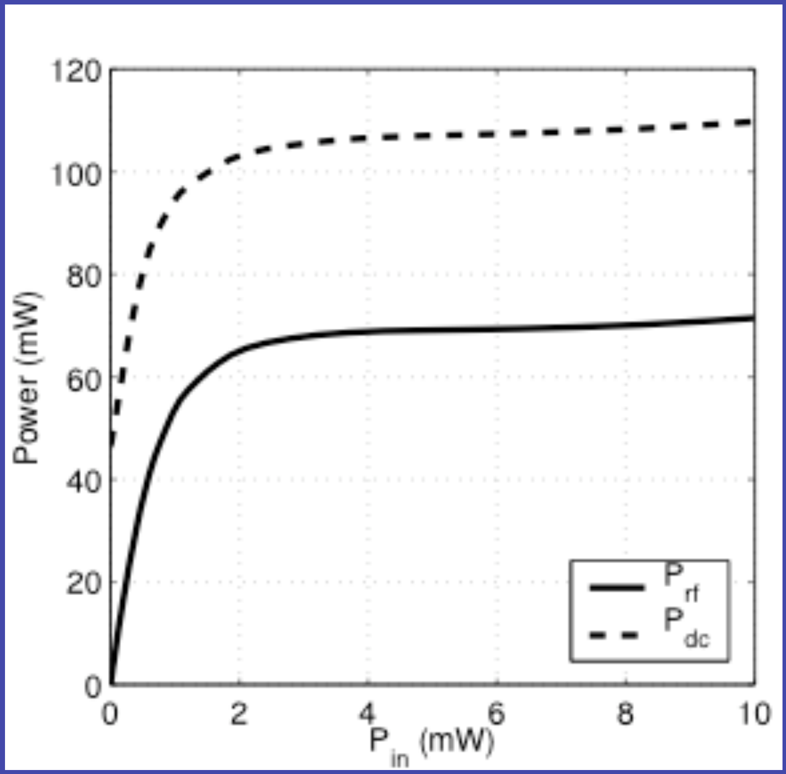
Shannon’s Assumption

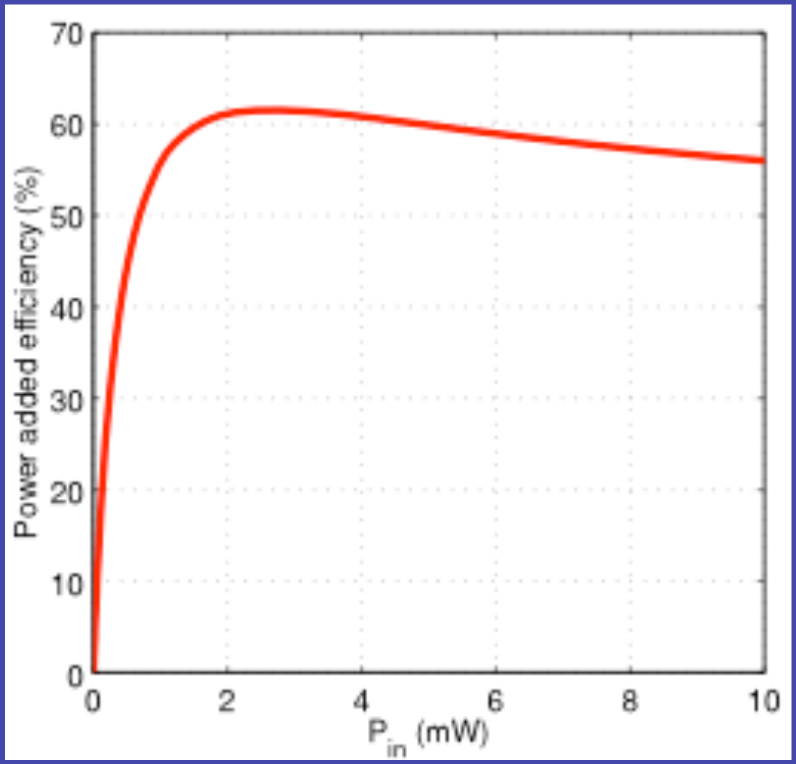
- Linear amplifier (Ideal, 100% efficient)
- Point-to-point link
- No receiver processing energy
- Infinite delay

Relaxed Assumptions

- Nonlinear amplifier (energy efficiency dependent of drive level)
- Multihop network (take into account propagation)
- Receiver processing energy

Power Amplifier

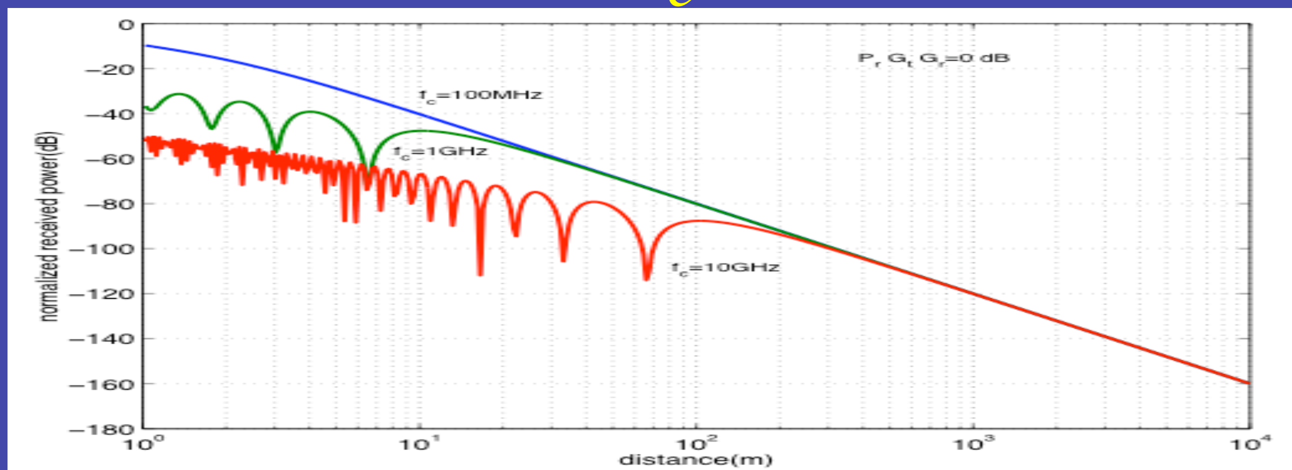




Power Amplifier

- Power amplifier is most energy efficient when driven into saturation (large output power).
- Power amplifier is least energy efficient at low input drive levels (low output power)

Propagation Characteristics

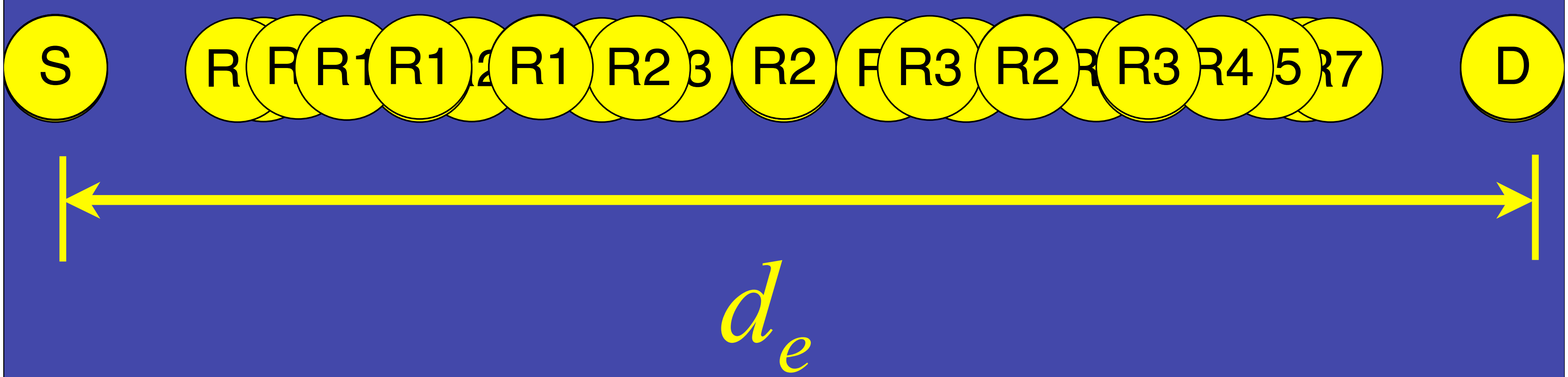


$$P_r = P_t\left(\frac{\lambda_c}{4\pi d_e}\right)^2 4 G_t G_r \sin^2\left(\frac{2\pi h_t h_r}{\lambda_c d_e}\right) \approx \frac{P_t G_t G_r h_t^2 h_r^2}{d_e^4}$$

Propagation Characteristics

- Amount of energy necessary to go a distance d_e increases as d_e^{4}.

Simplified Network Model



Performance Measure

- Without Spatial Reuse
  - Energy Efficiency
  - Bandwidth Efficiency
  - Transport Efficiency

Goal

- We want to find the relation between energy consumption and bandwidth efficiency for a network taking into account amplifier characteristics, propagation characteristics, receiver processing energy.

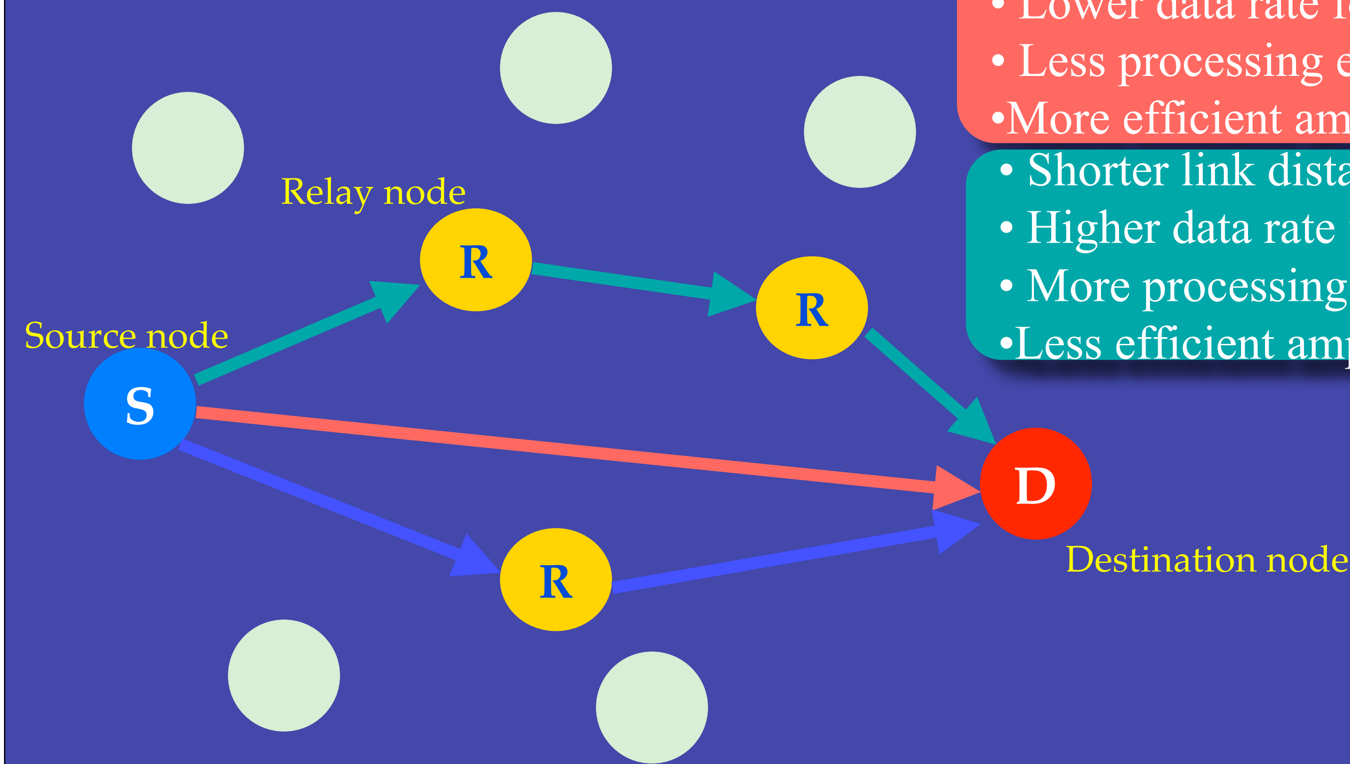
Goal

- We want to optimize over amplifier drive level and the distance between nodes in routing packets from the source to the destination.

An Illustrative Example:

- Longer link distance => lower received SNR
- Lower data rate for each hop
- Less processing energy usage
- More efficient amplifier operation

- Shorter link distance => higher received SNR
- Higher data rate for each hop
- More processing energy usage
- Less efficient amplifier operation



Choose route to
- Minimize energy usage
- Maximize bandwidth efficiency

RX Processing Energy

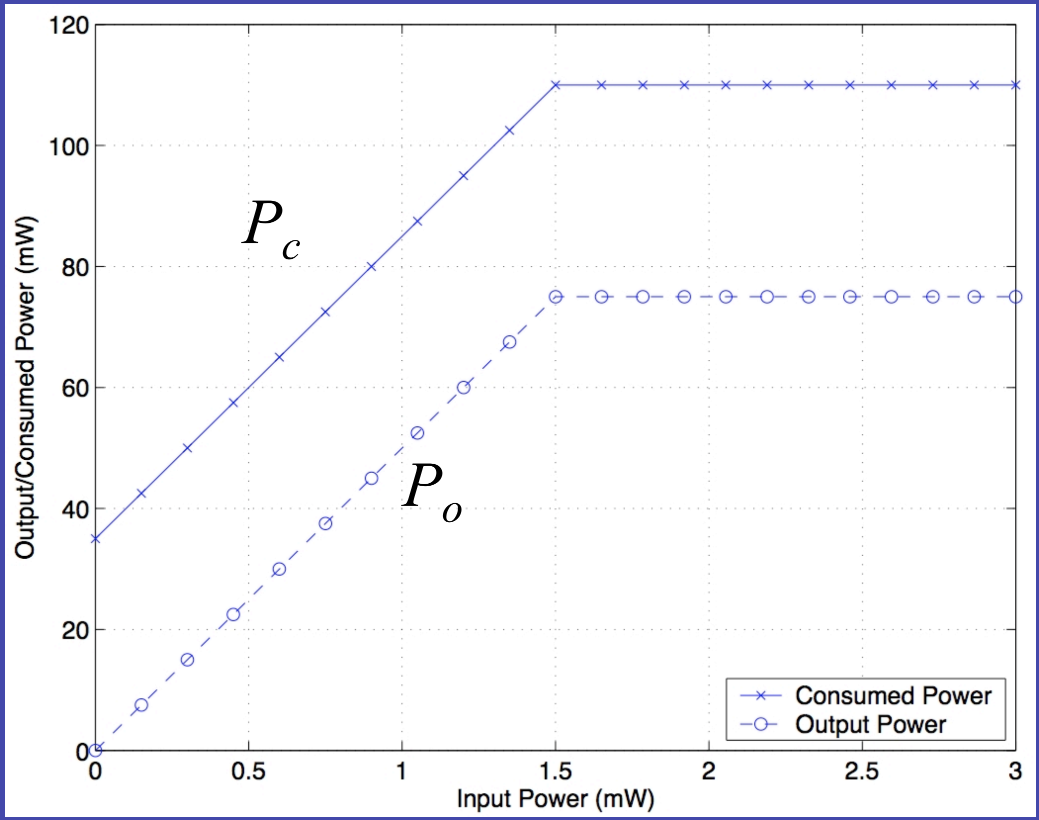
- Assume a fixed power consumption of receiver (P_{rp}).
- Lower rate codes => receiver is on for a longer period of time for a given number of information bits.
- Large number of hops => large amount of receiver energy consumption.

System Model

- Assumptions
- Power Amplifier Model
- Signal Attenuation Model

Power Amplifier Model

- Linear at low input power levels.
- Saturation at high power levels
- Constant amount of power turned into heat
- P_h=35mW, P_{sat}=75mW,
- ρ=50 (17 dB), P_1=1.5mW



Power Amplifier Model

- Radiated Power

$$f_o(P_{in}) = \begin{cases} \rho P_{in}, & 0 \leq P_{in} \leq P_1 \\ P_{sat}, & P_1 < P_{in} \leq P_{max} \end{cases}$$

- Consumed Power

$$f_c(P_{in}) = f_o(P_{in}) + P_h$$

Propagation Model

Inverse power law

$$P_r = \beta \frac{P_o}{d^\eta}$$

For numerical results β=*1*, η=*4*.

Energy Consumption

- Encoder K information bits mapped into N coded bits, rate $R=K/N$.
- k hops between transmitter and receiver
- E_p energy per coded bit

$$
\begin{aligned}
E_t &= k(E_{tx,b} + E_{rcvr,b}) \\
&= \frac{kN(f_c(P_{in})T_s + E_p)}{K}
\end{aligned}
$$

Bandwidth Efficiency

- B_{eff}= expected number of correctly decoded (end-to-end) bits per channel use.
- $P_s(R,E_b/N_0)$= probability of packet success per hop which depends on the code rate R and the received SNR.

$$B_{\text{eff}} = R[P_s(R, \frac{E_b}{N_0})]^k$$

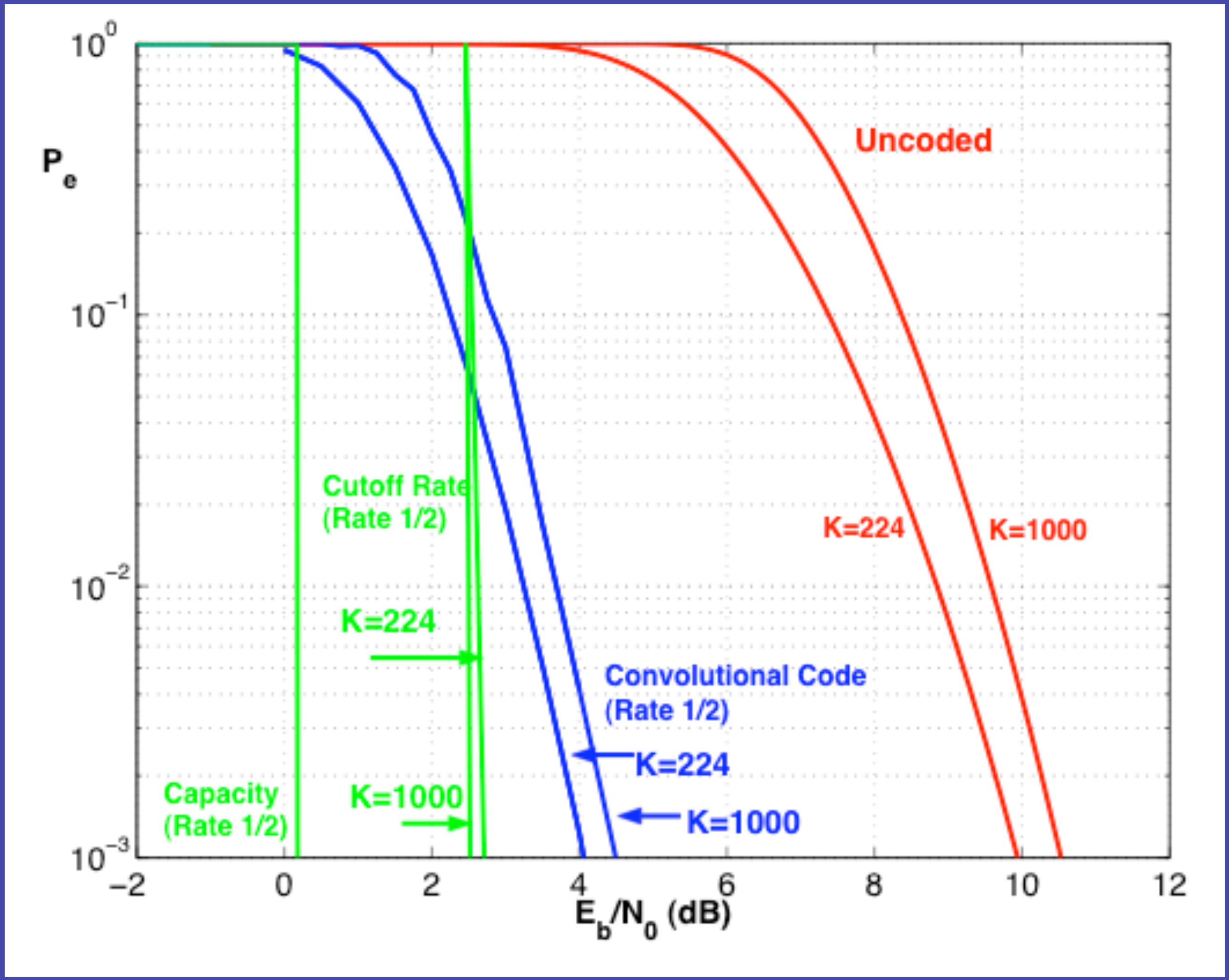
Physical Layer Models

- Threshold Model

$$P_s(R, \frac{E_b}{N_0}) = \begin{cases} 0, & \frac{E_b}{N_0} < \Gamma \\ 1, & \frac{E_b}{N_0} > \Gamma \end{cases}$$

- Coded Model
- Uncoded Model
- $P_e = 1 - P_s$

Physical Layer Model (AWGN)



Transport Efficiency

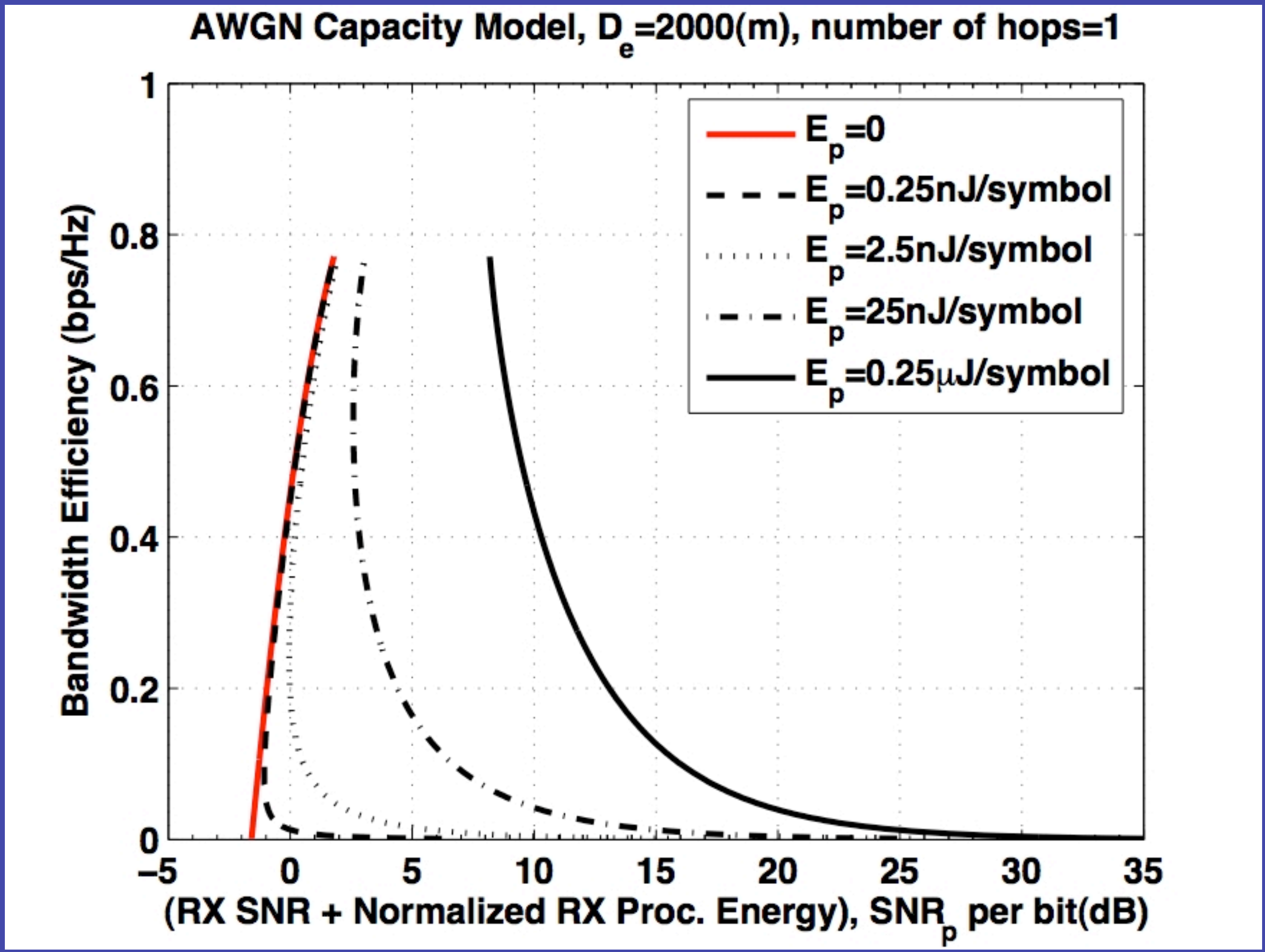
- Often it is desirable to have a single measure of a network performance.
- A measure of performance capturing energy use and bandwidth efficiency is the transport efficiency.

$$\mu(k, R, P_{in}) = \frac{B_{eff}}{E_t}$$

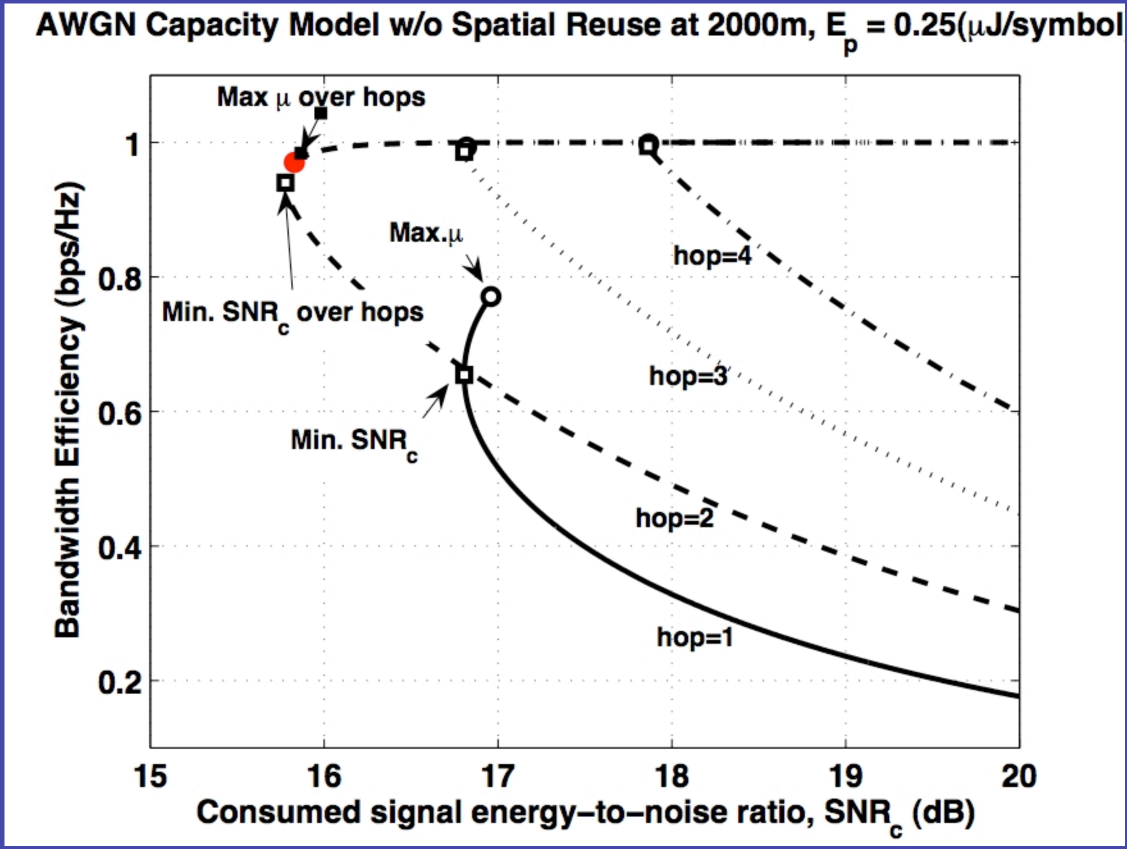
- Transport efficiency is the bits/second/Hz possible per unit energy.
- The transport efficiency depends on the number of hops, the code rate and the operation of the amplifier.

Energy-Bandwidth Efficiency (Single Hop)

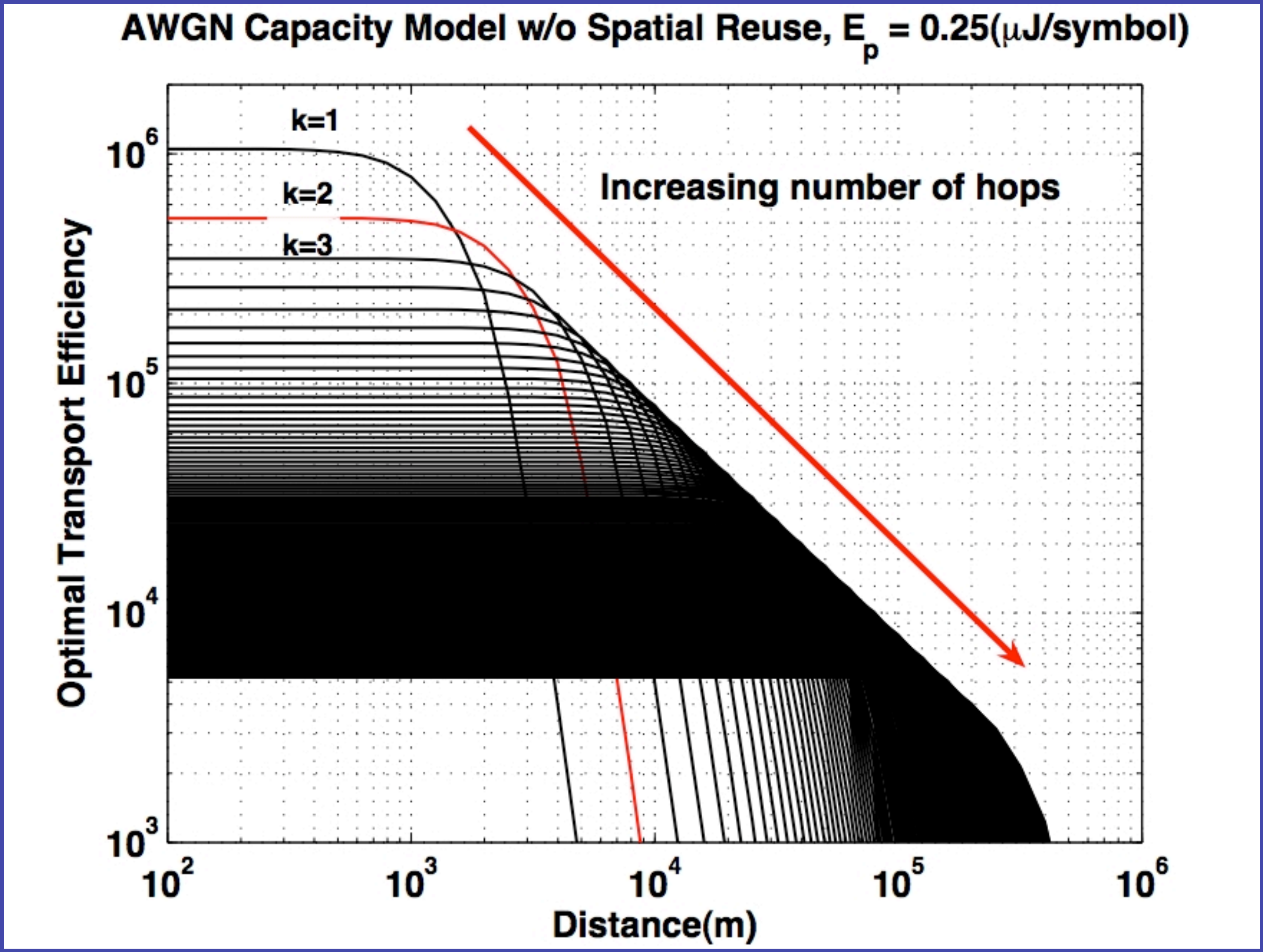
E_p=.25μJ/symbol @50Ksymbols per second corresponds to 125 mWatts receiver processing power

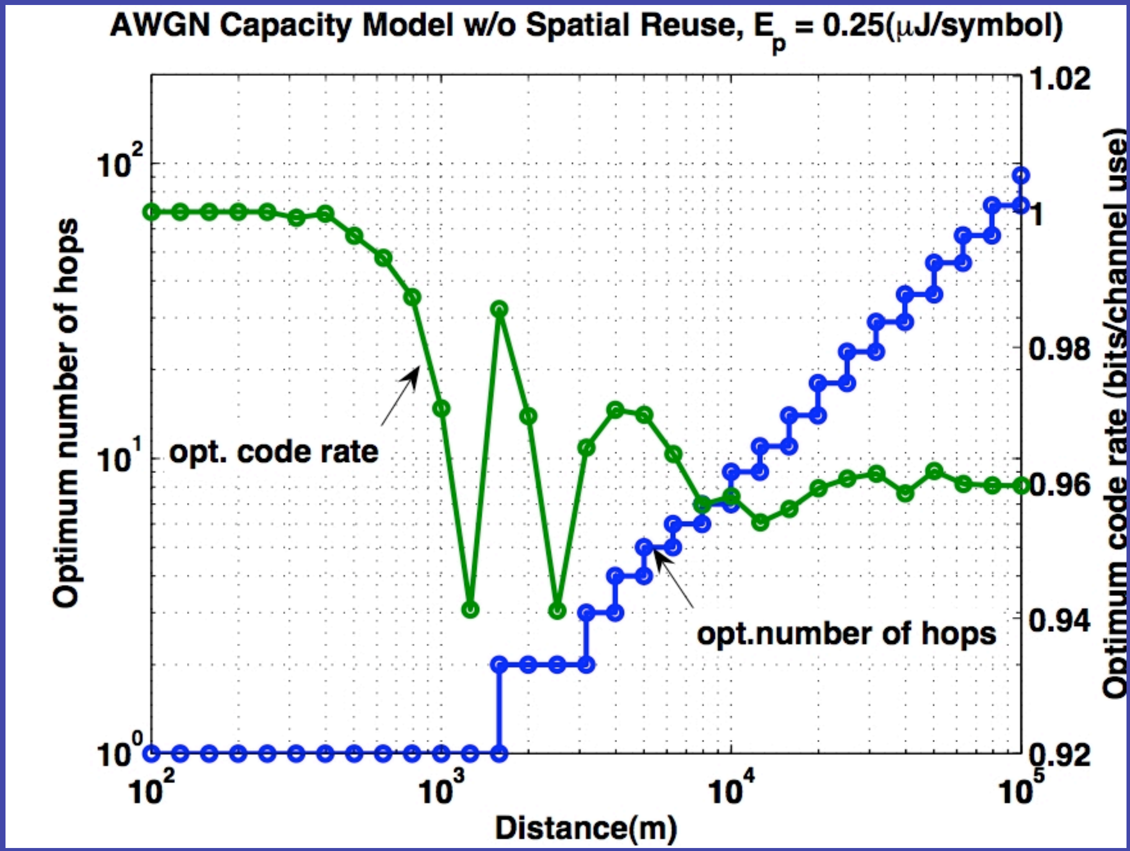


Energy-Bandwidth Efficiency (multi-hop)



Transport Efficiency vs. Distance




AWGN Capacity Model w/o Spatial Reuse, E_p = 0.25(μJ/symbol)
Optimum number of hops
Optimum code rate (bits/channel use)
Distance(m)
opt. code rate
opt.number of hops
10^0
10^1
10^2
10^3
10^4
10^5
0.92
0.94
0.96
0.98
1
1.02

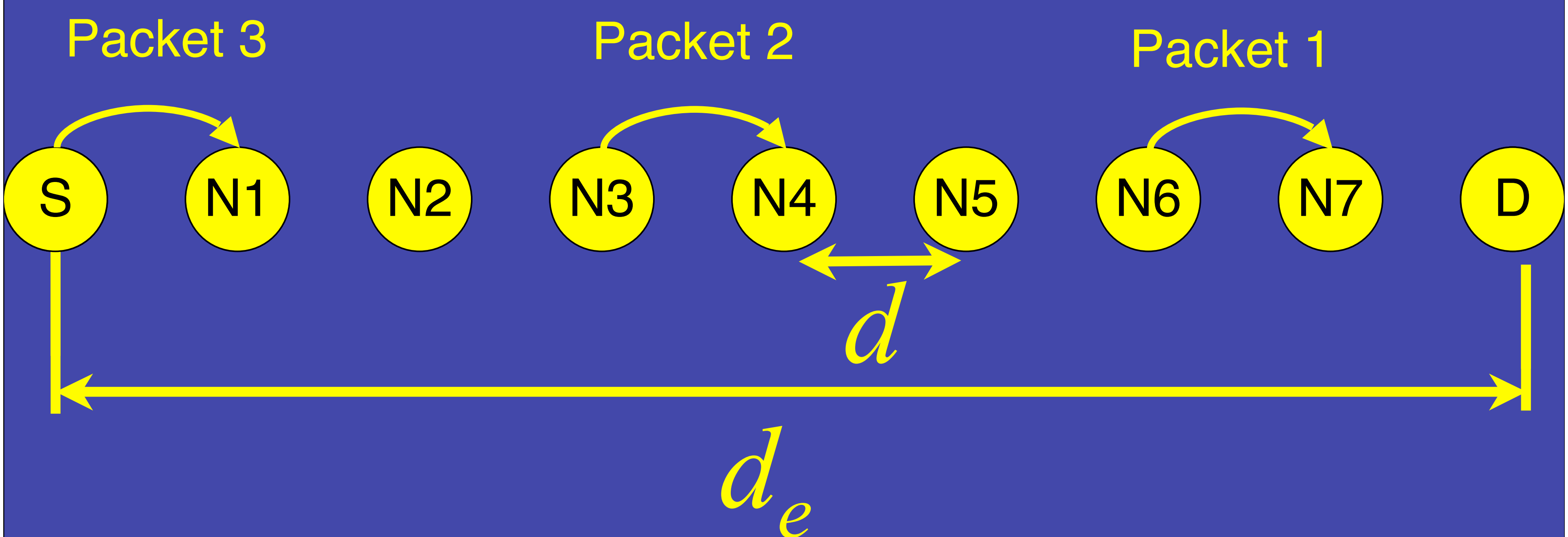
Conclusion Without Spatial Reuse

- Transport efficiency decreases only inverse linear with distance for any power propagation law, amplifier characteristic, coding/modulation technique.

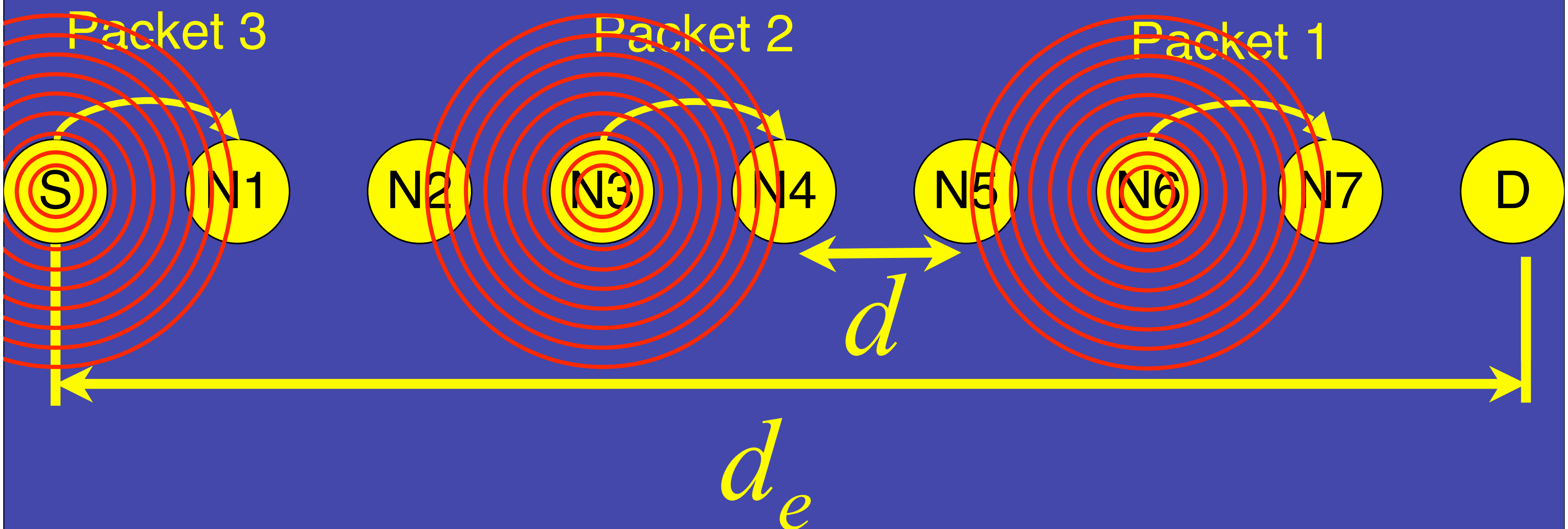
$$\max_{k, P_{in}, R} \mu(k, R, P_{in}) = \frac{\delta}{d_e}$$

- The constant depends on the coding, the propagation model, the amplifier model.
- Same results holds for any functional dependence of error probability on SNR, any amplifier model, propagation characteristics.

Spatial Reuse (Linear Case)



Spatial Reuse



Spatial Reuse

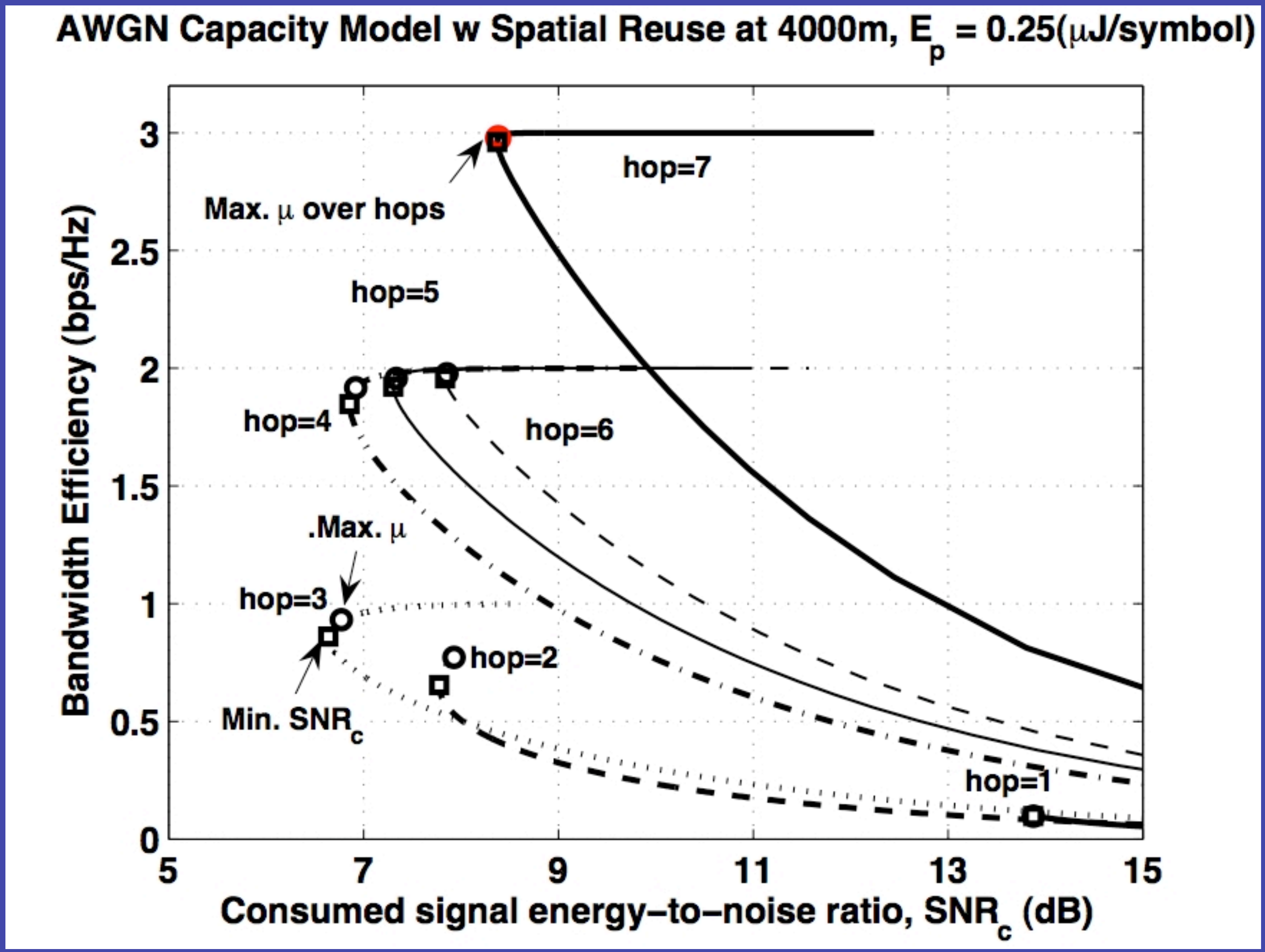
- L=minimum hop separation for concurrent transmissions.
- Ω =number of simultaneous transmissions.

$$\Omega \approx \frac{k}{L}$$

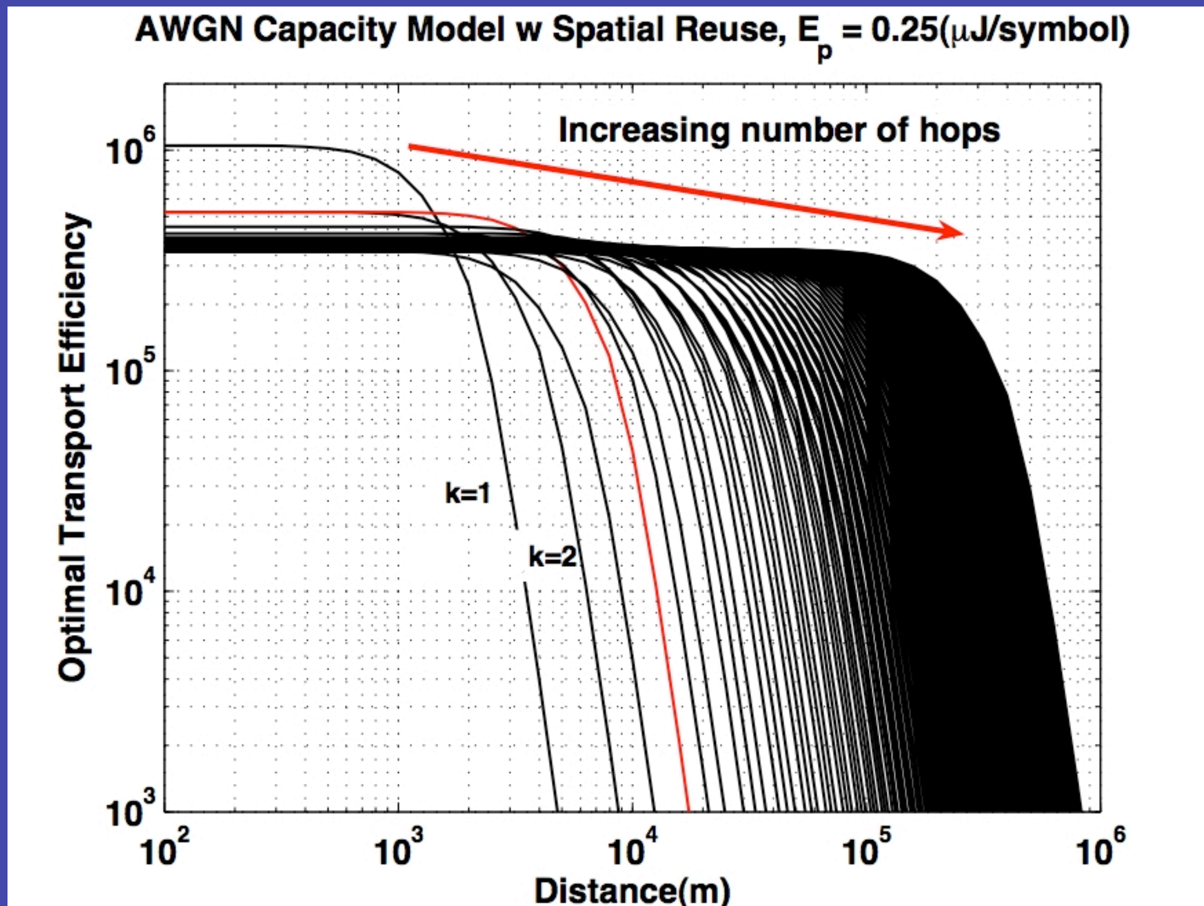
- Accounting for interference from two other transmissions with L=3 yields

$$SINR = \frac{\beta P_{out} T_s d^{-\eta}}{N_0 + \beta P_{out} T_s [(2d)^{-\eta} + (4d)^{-\eta}]}$$

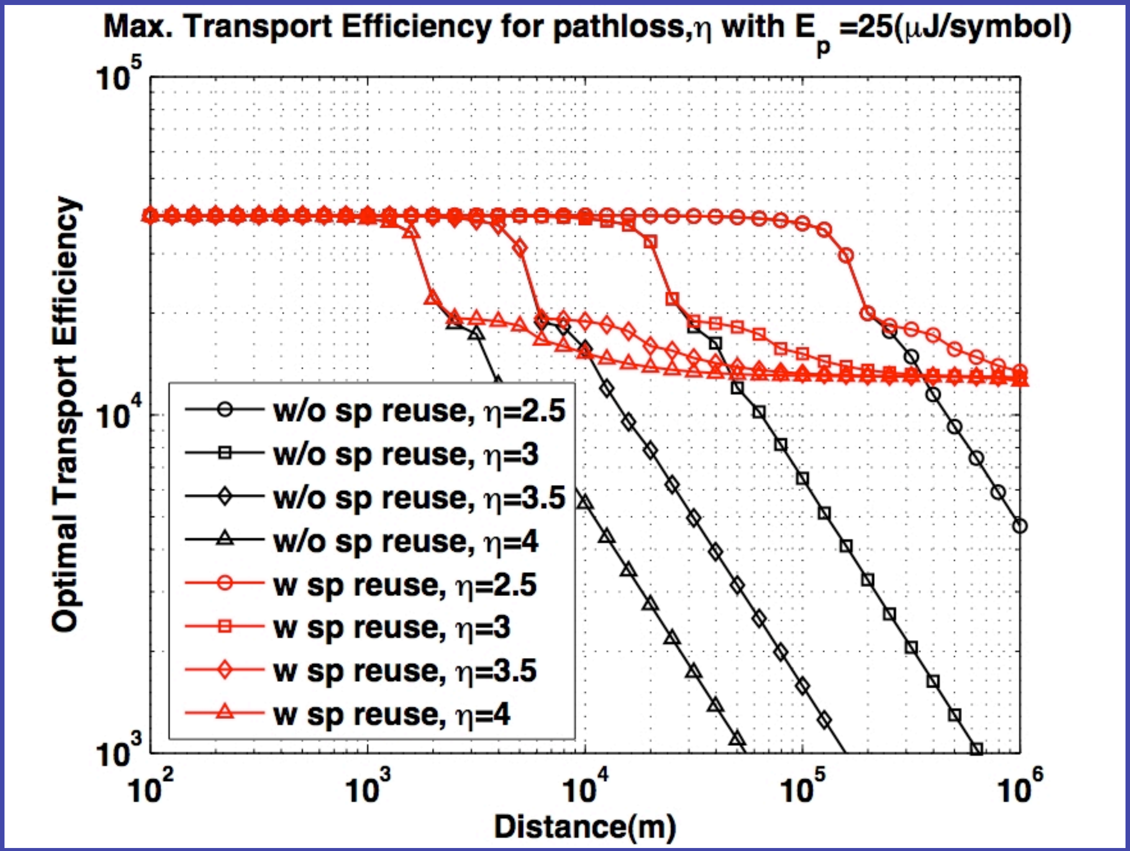
Energy-Bandwidth Efficiency



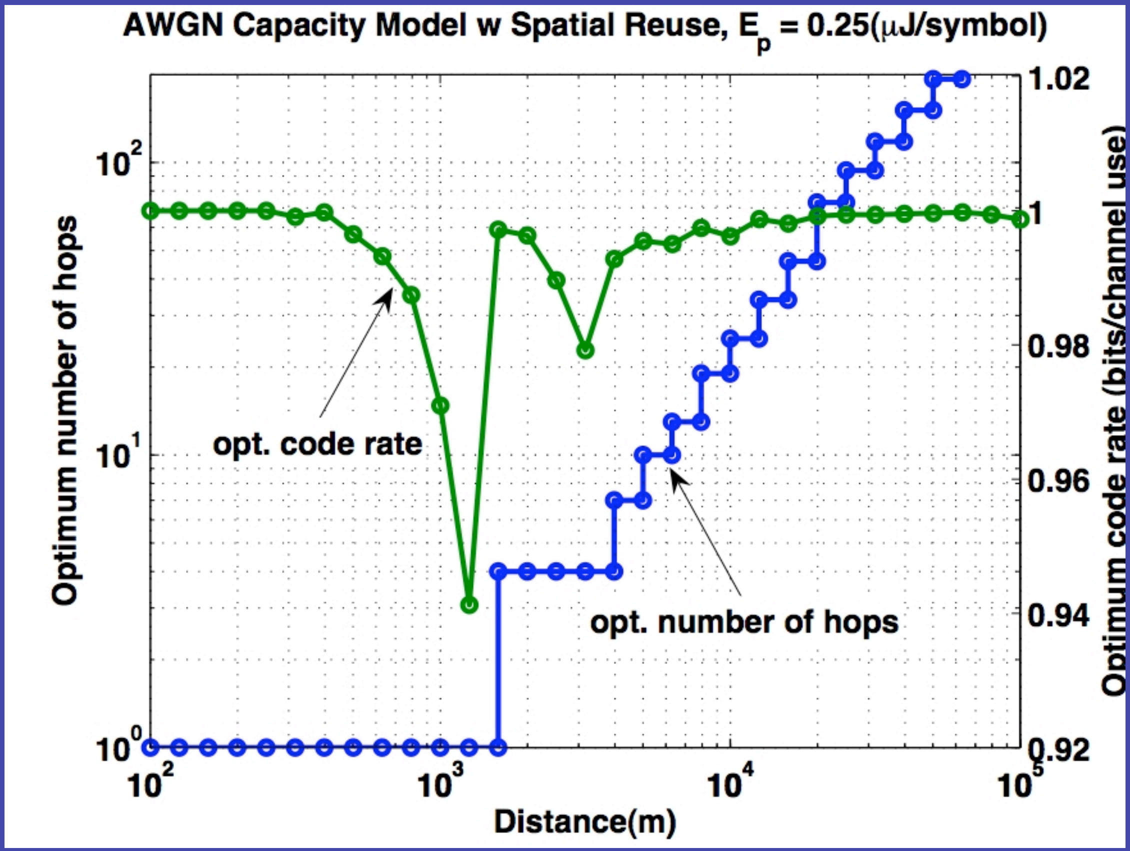
Numerical Result



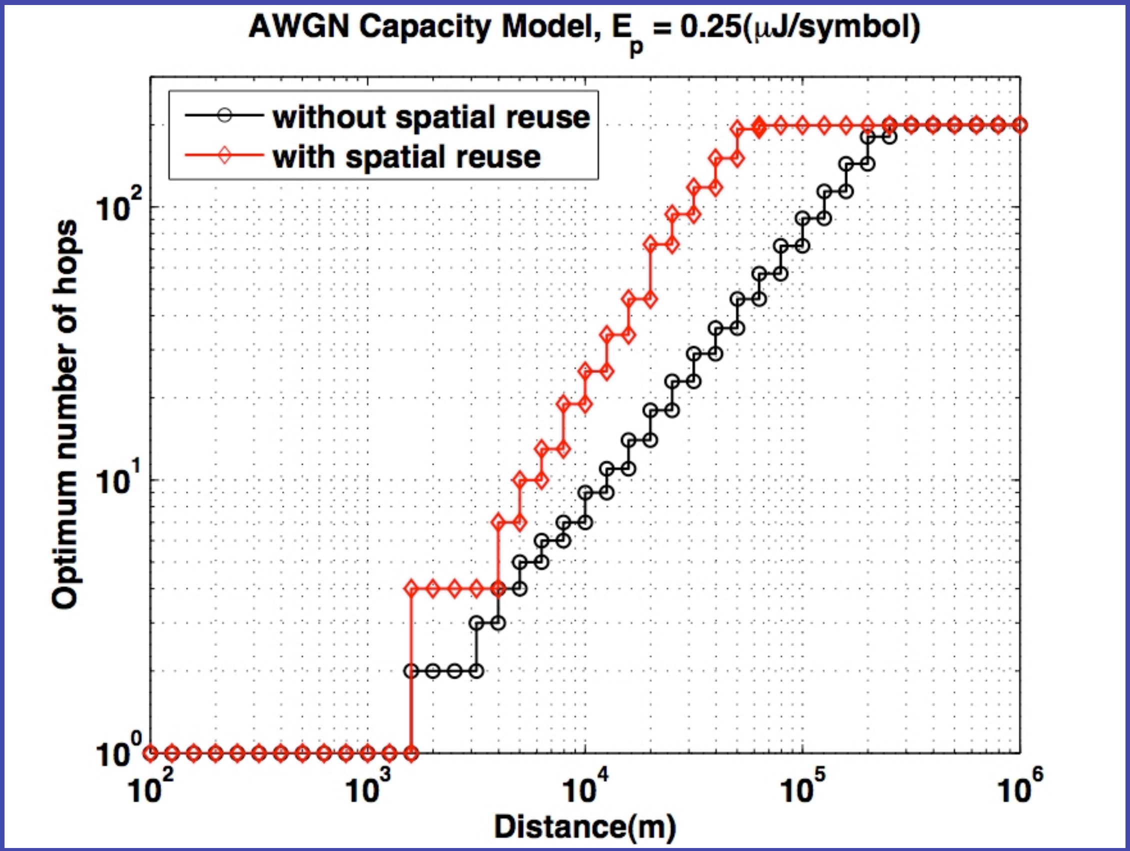
Transport Efficiency vs. Distance



Optimization Parameters with Spatial Reuse



Comparison of Optimum Number of Hops



Conclusions

- The tradeoff between energy and bandwidth efficiency for wireless networks has been quantified incorporating amplifier model inefficiency, propagation and network routing.
- Results indicate relatively short distances, high rate coding are desirable.
- Analysis technique easily applicable to fading and other modulation techniques as well as to specific codes.
- Results might change (lower code rates) if time/frequency selective fading is included but the fundamental relationship with distance does not change.

Conclusions

- There are many extensions necessary
  - Include MAC layer
  - Include spatial distribution of nodes as opposed to infinite density of node
  - Include mobility (energy to update routing path)
  - Find practical ways to achieve performance limits.