Coding and Modulation for the QRPP EME Channel

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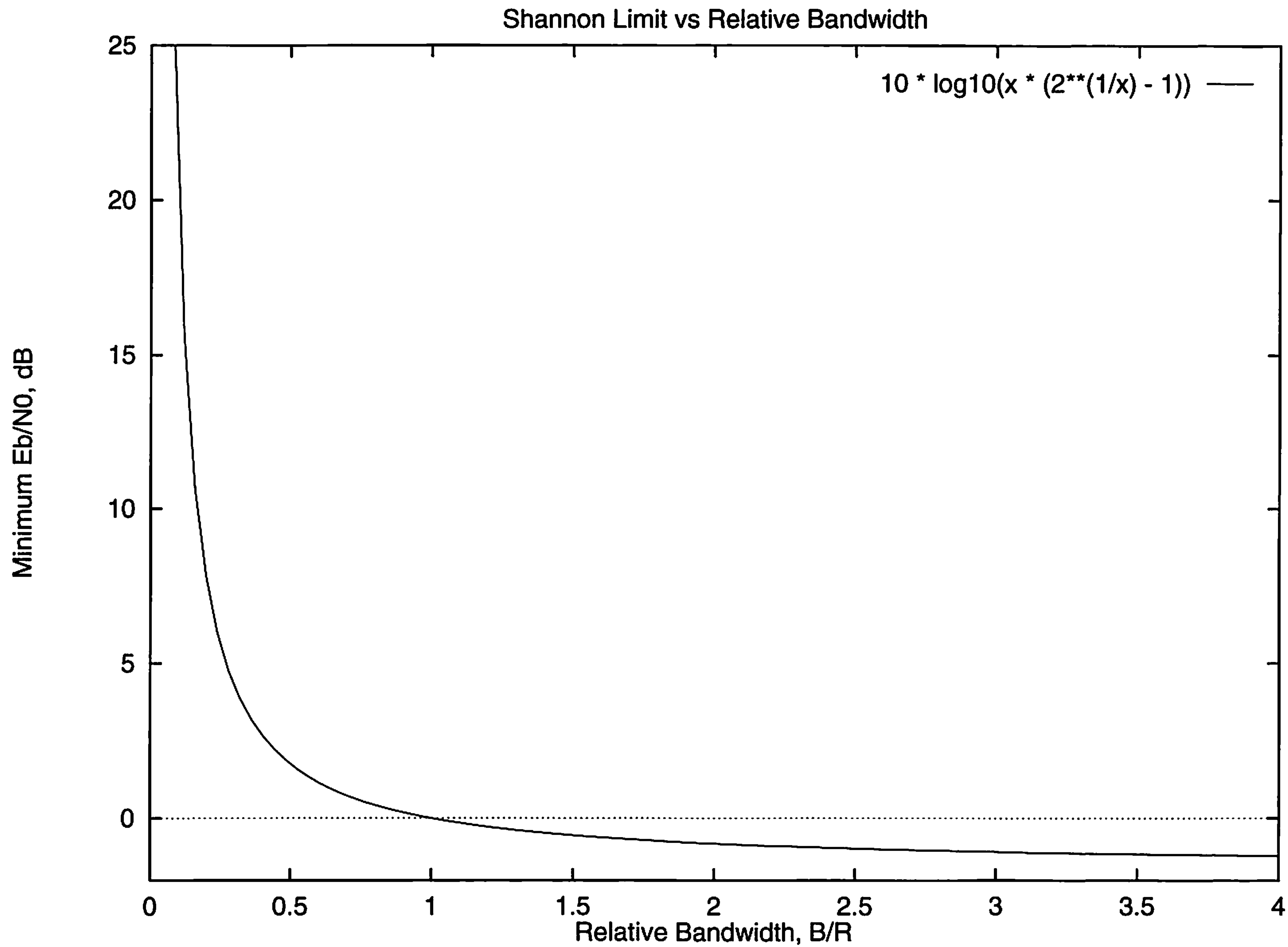
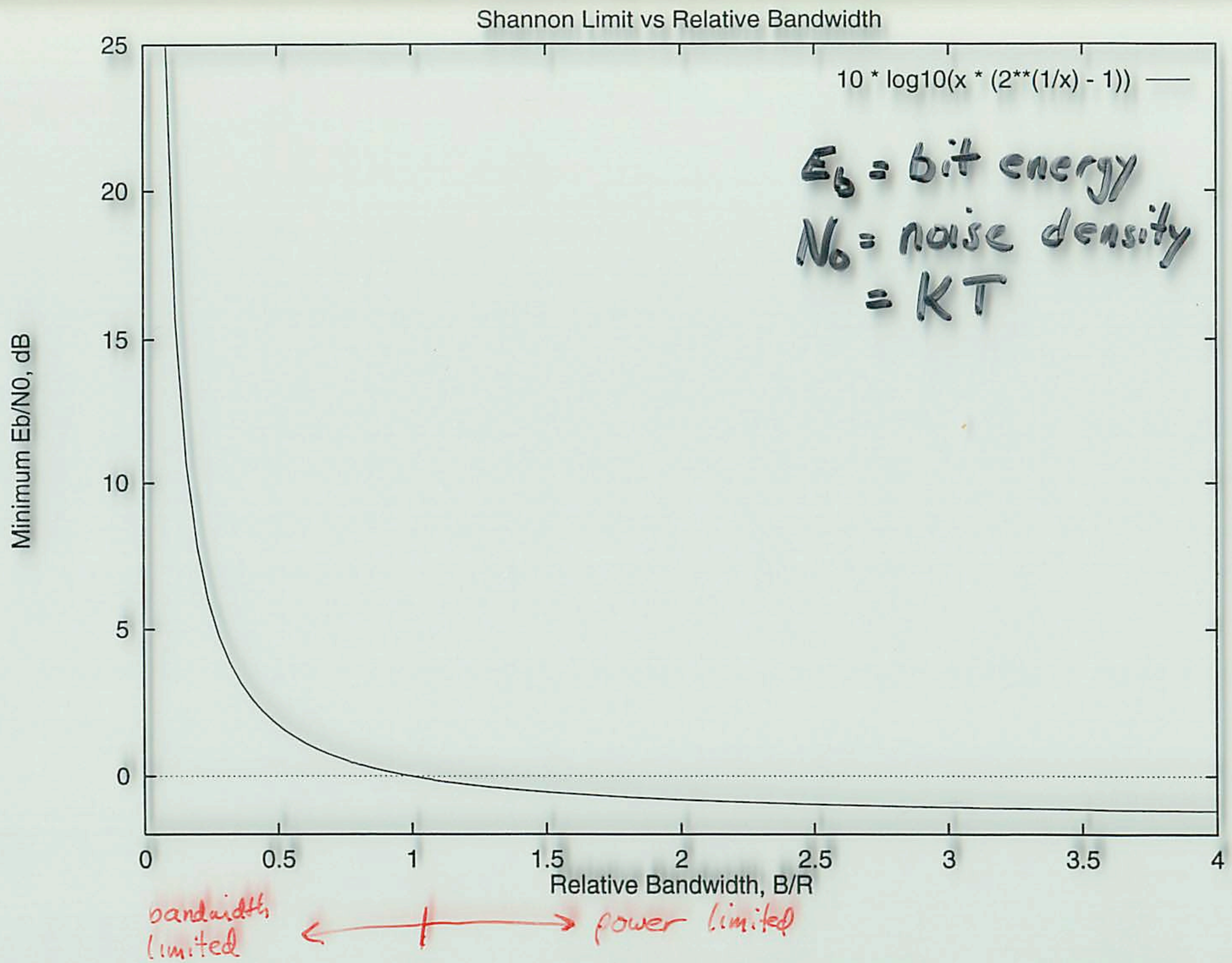
EME Channel Characteristics

- Extremely high path loss
- Extra bandwidth plentiful
  - classic power-limited channel
- Rayleigh fading
  - very similar to land mobile channel without direct path
- Typical coherence times of seconds on 2m
  - decreases approximately as $1/f$
- Typical coherence bandwidth of 500-1000Hz
  - relatively independent of frequency


Shannon Limit vs Relative Bandwidth
10 * log10(x * (2**(1/x) - 1))
Minimum Eb/N0, dB
Relative Bandwidth, B/R
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
3.5
4



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25
20
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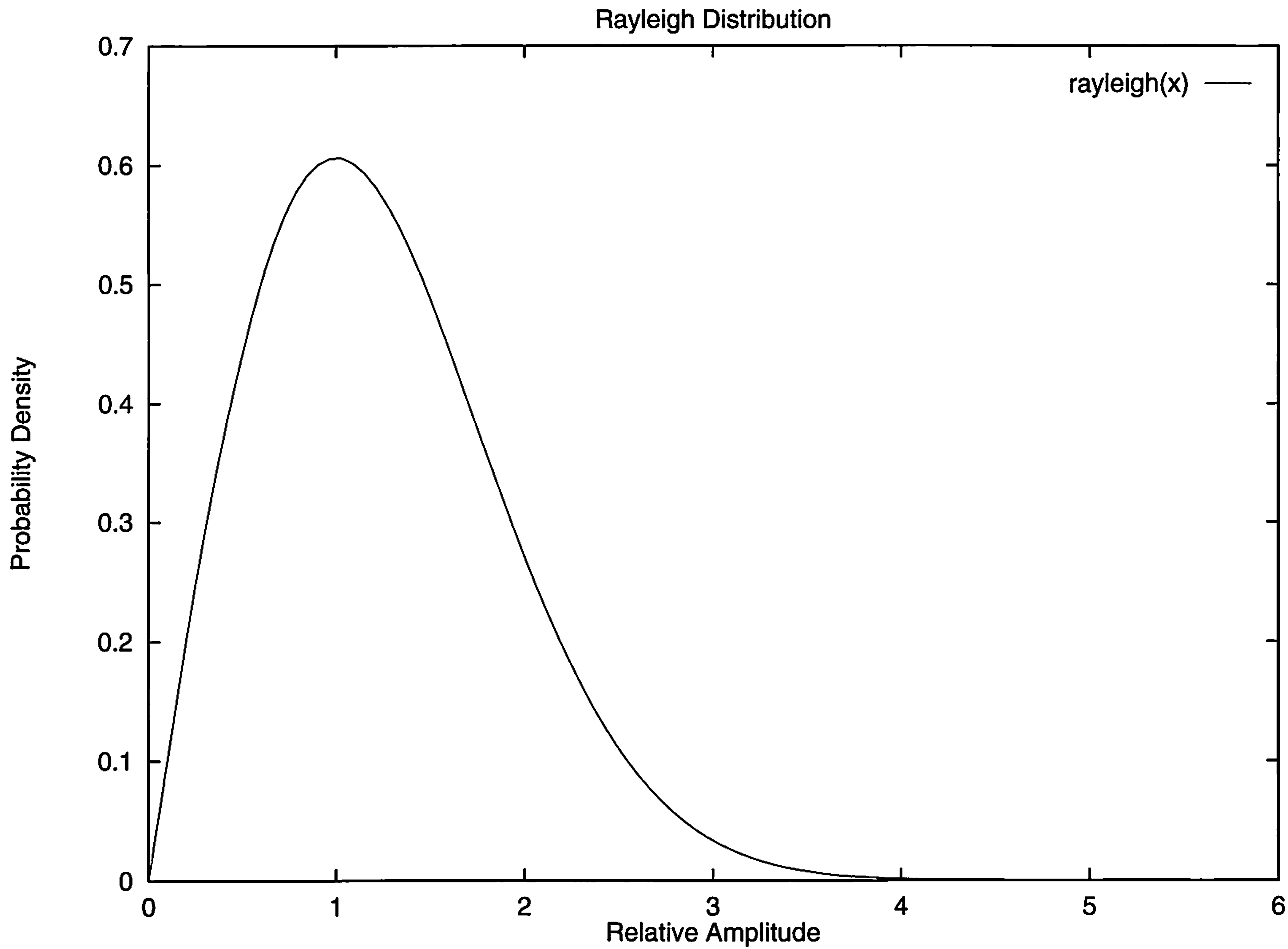
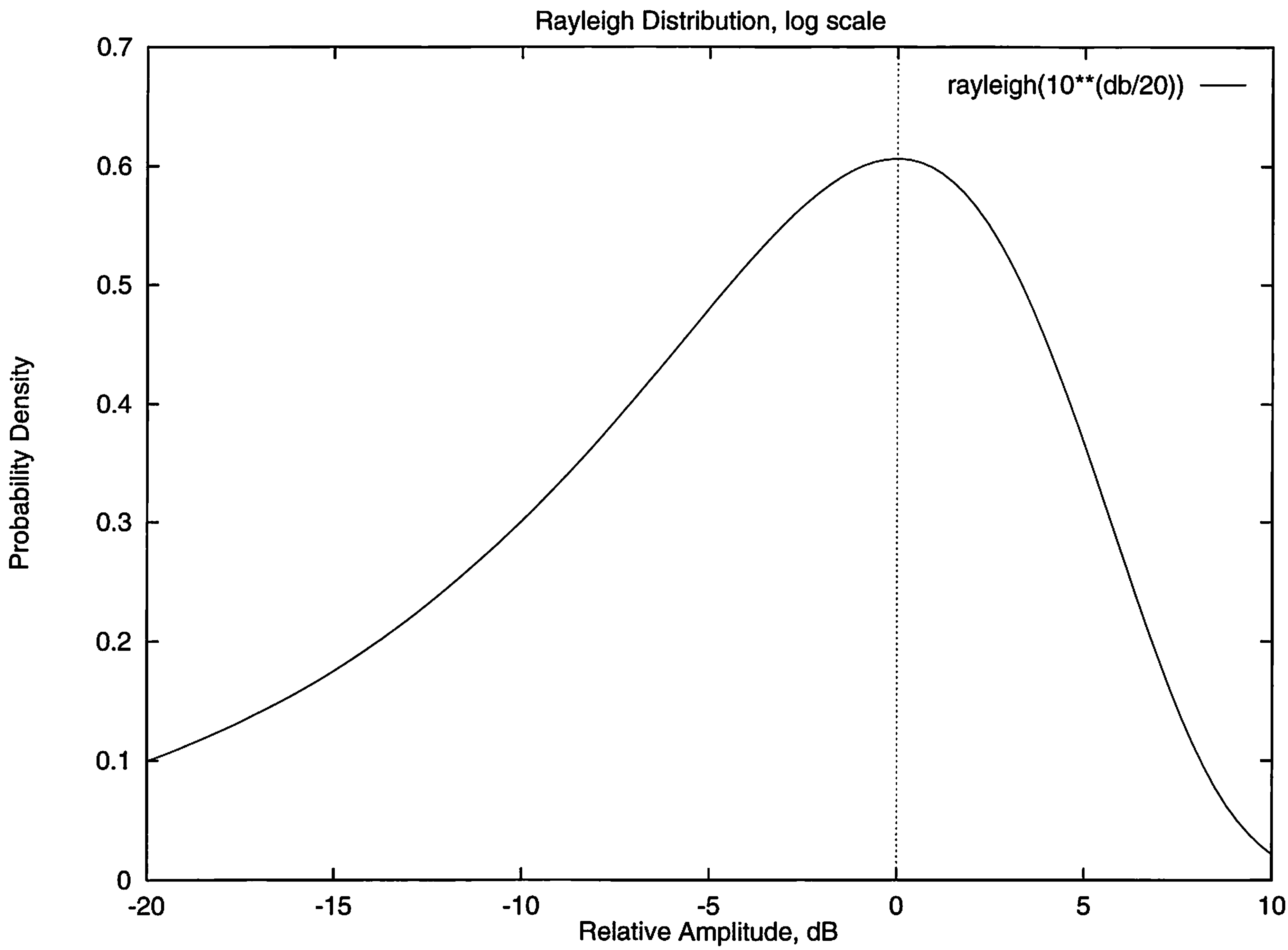
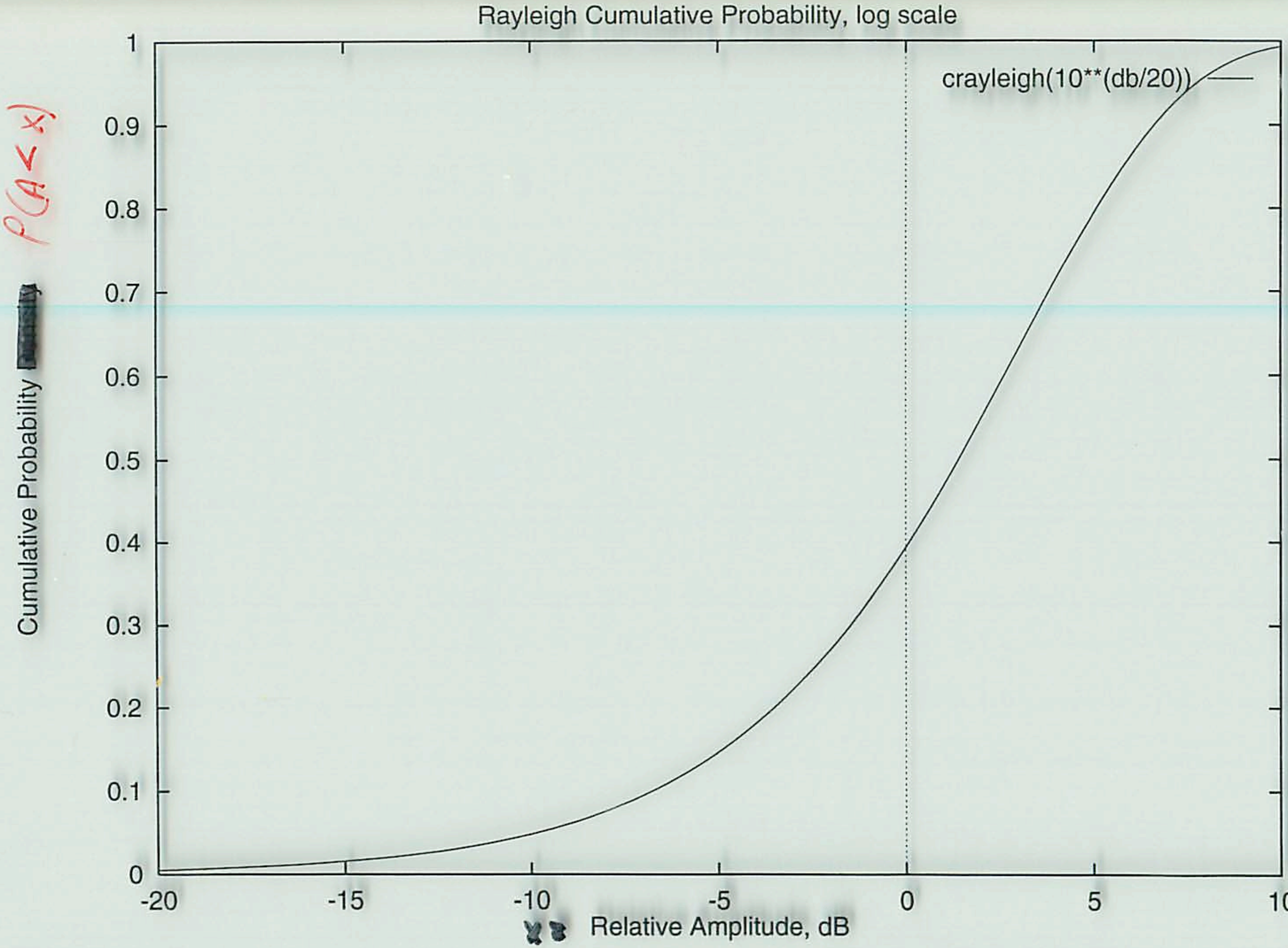
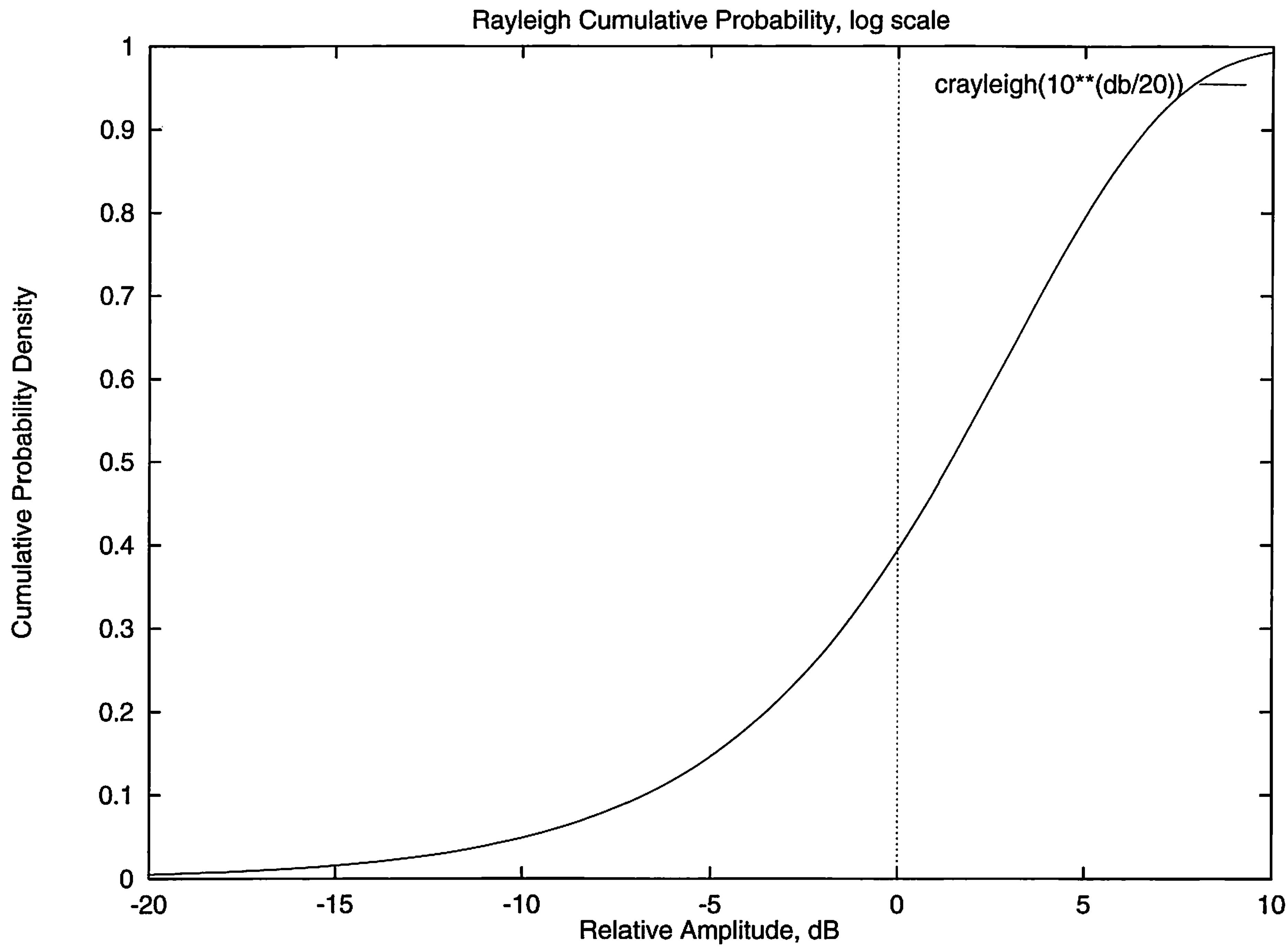
1
1.5
2
2.5
3
3.5
4
Eb = bit energy
N0 = noise density
= KT
bandwidth limited
power limited


Rayleigh Distribution
rayleigh(x)
Probability Density
Relative Amplitude
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6



Rayleigh Distribution, log scale
rayleigh(10**(db/20))
Probability Density
Relative Amplitude, dB
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
-20
-15
-10
-5
0
5
10


Rayleigh Cumulative Probability, log scale
crayleigh(10**(db/20))
Cumulative Probability [redacted]
P(A < x)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-20
-15
-10
-5
0
5
10
[redacted] Relative Amplitude, dB

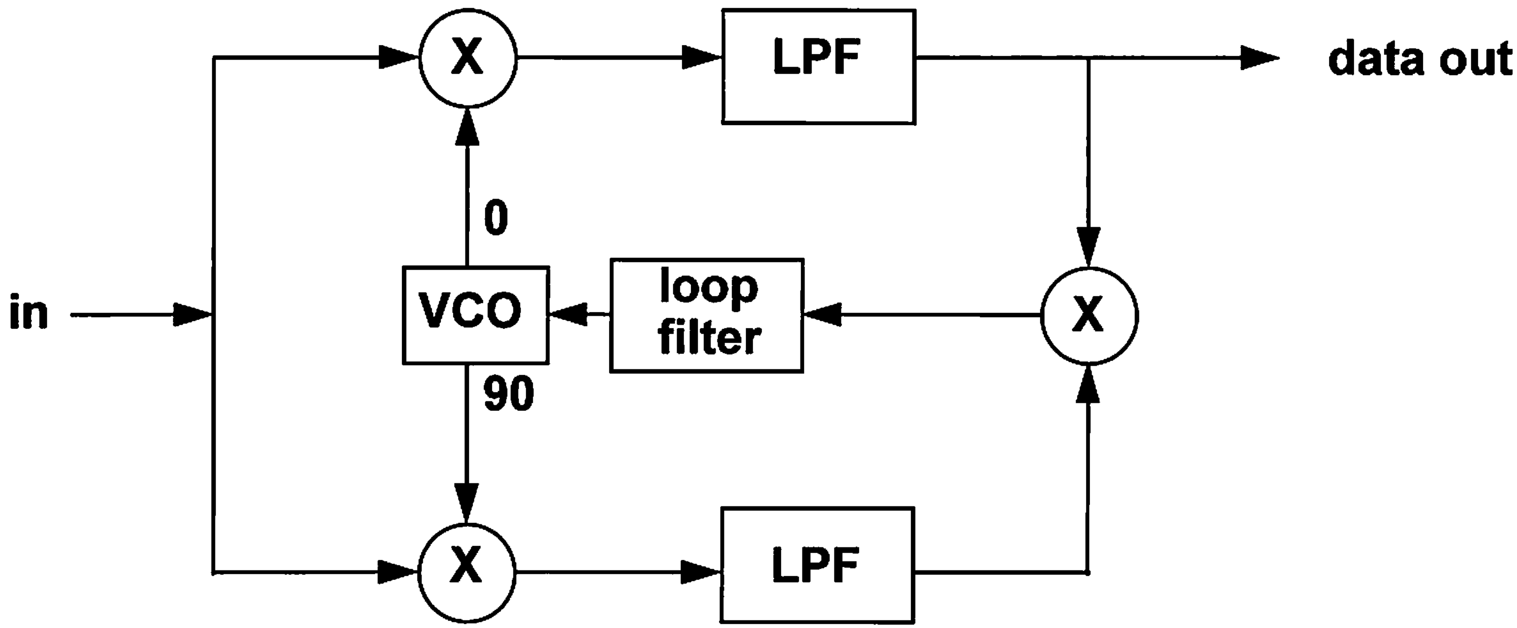


Rayleigh Cumulative Probability, log scale
crayleigh(10**(db/20))
Cumulative Probability Density
Relative Amplitude, dB
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-20
-15
-10
-5
0
5
10

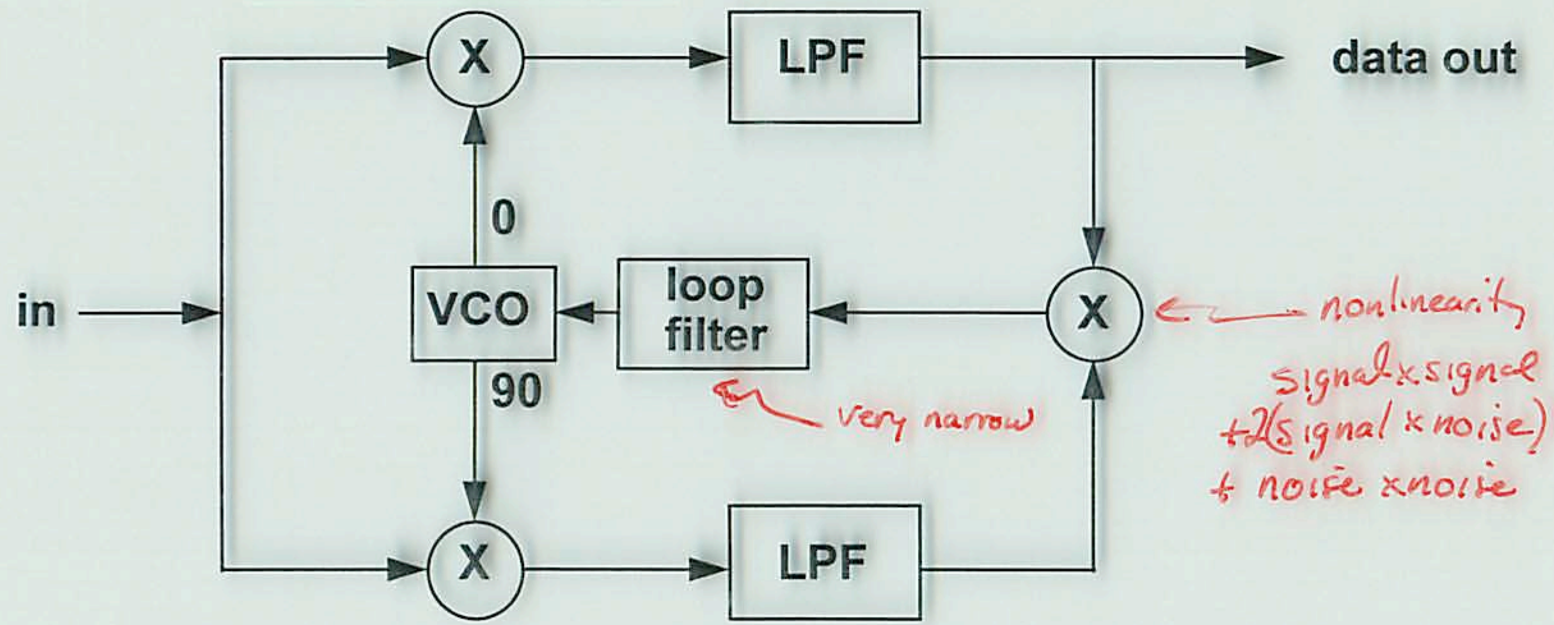
Stuff That Probably Won't Work

- Coherent, suppressed carrier BPSK & QPSK, with or without FEC
  - Carrier phase stability requirements are extreme at low data rates; coherence time of channel is much too short
- Noncoherent BFSK without FEC
  - E_b/N_0 requirements too high
- Ordinary CW
  - signals aren't even audible!

Binary Costas Loop



Binary Costas Loop



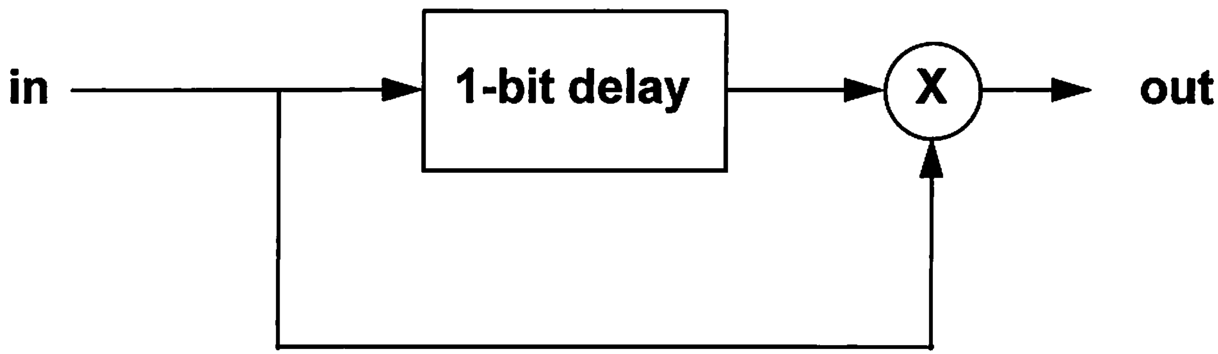
Stuff That Might Work

- Coherent, residual carrier BPSK with strong FEC
  - Long-time standard with NASA deep space probes
- BFSK with strong FEC
- Differentially detected BPSK with strong FEC
  - better than BFSK

BPSK


+90 deg
Carrier suppressed, must be regenerated nonlinearly
-90 deg
+71.6 deg
Residual carrier @-10dB, can be directly tracked
-71.6 deg

Differential BPSK Demod

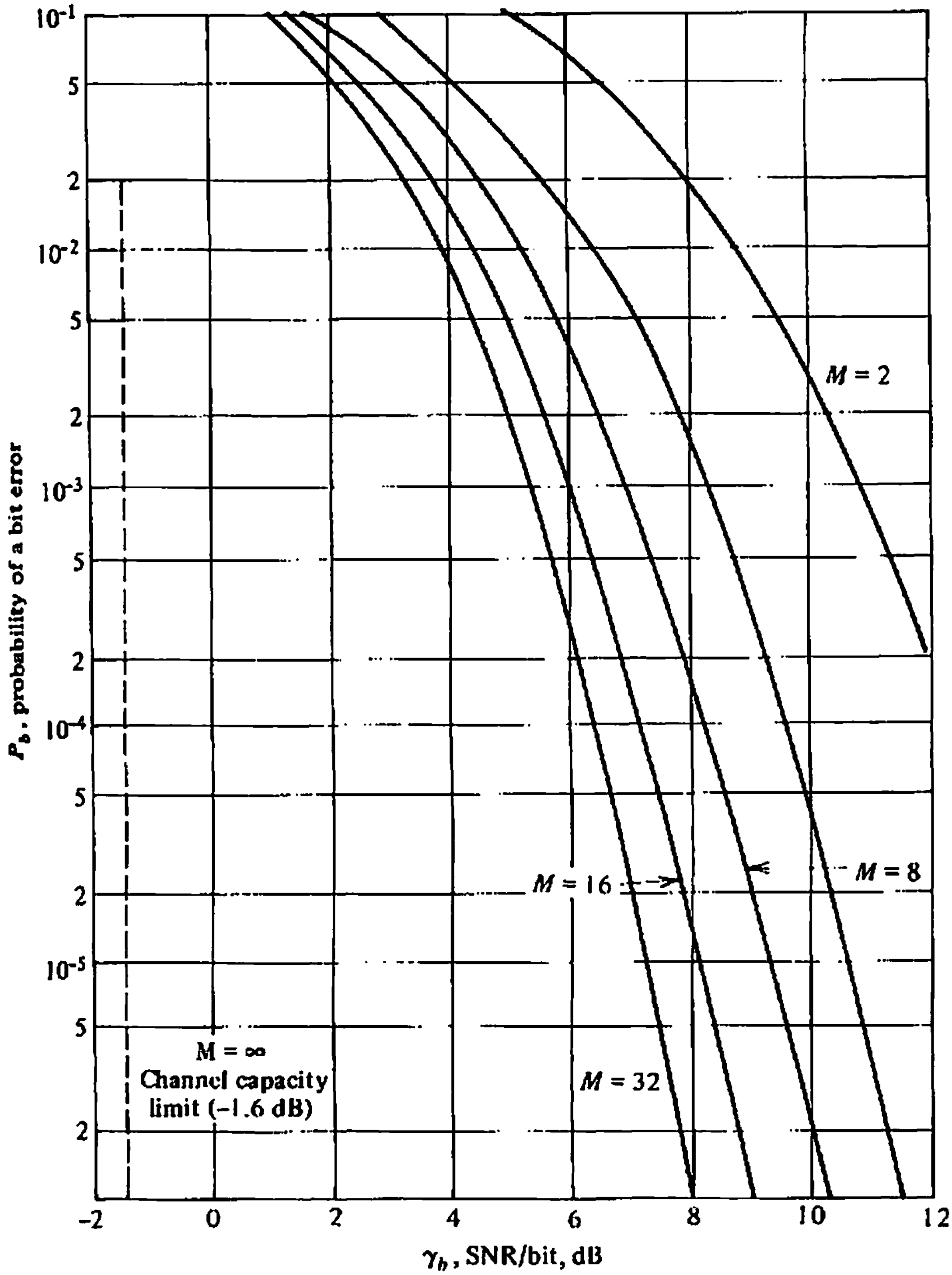


What Definitely Will Work

- Noncoherently demodulated M-ary orthogonal FSK (MFSK) with strong FEC and interleaving
  - extension of ordinary 2-tone FSK to many more tones, usually a power of 2
- Technology is actually quite old, but impractical for amateurs until modern PCs
  - British Foreign Office "Piccolo" system was 32-ary FSK
  - Coded 8-ary FSK common in military anti-jam FH radio
  - Qualcomm CDMA cellular system uses 64-ary Walsh spread spectrum variant for mobile-to-cell (reverse) link

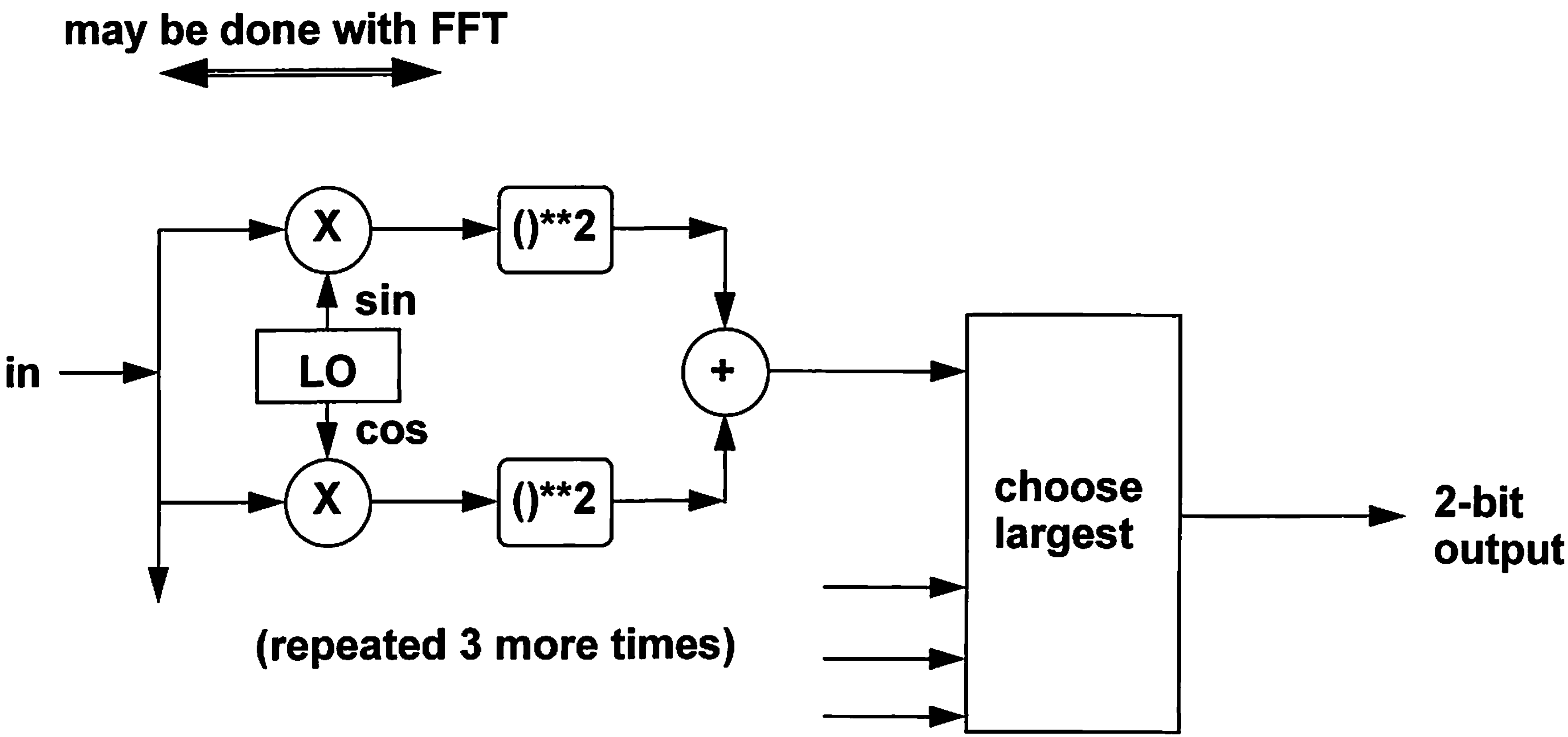
Why M-ary FSK?

- Increasing M decreases E_b/N_0 requirements at the expense of extra bandwidth
- Each "tone" carries $\log_2 M$ bits, so we can "invest" that much more energy in each tone
  - still no need for a phase reference between symbols
- Improvement is rapid at first -- 8-ary FSK is actually better than perfect coherent BPSK at 10^{-5} BER -- but it eventually slows down
  - reaches Shannon limit of -1.6dB at M=infinity

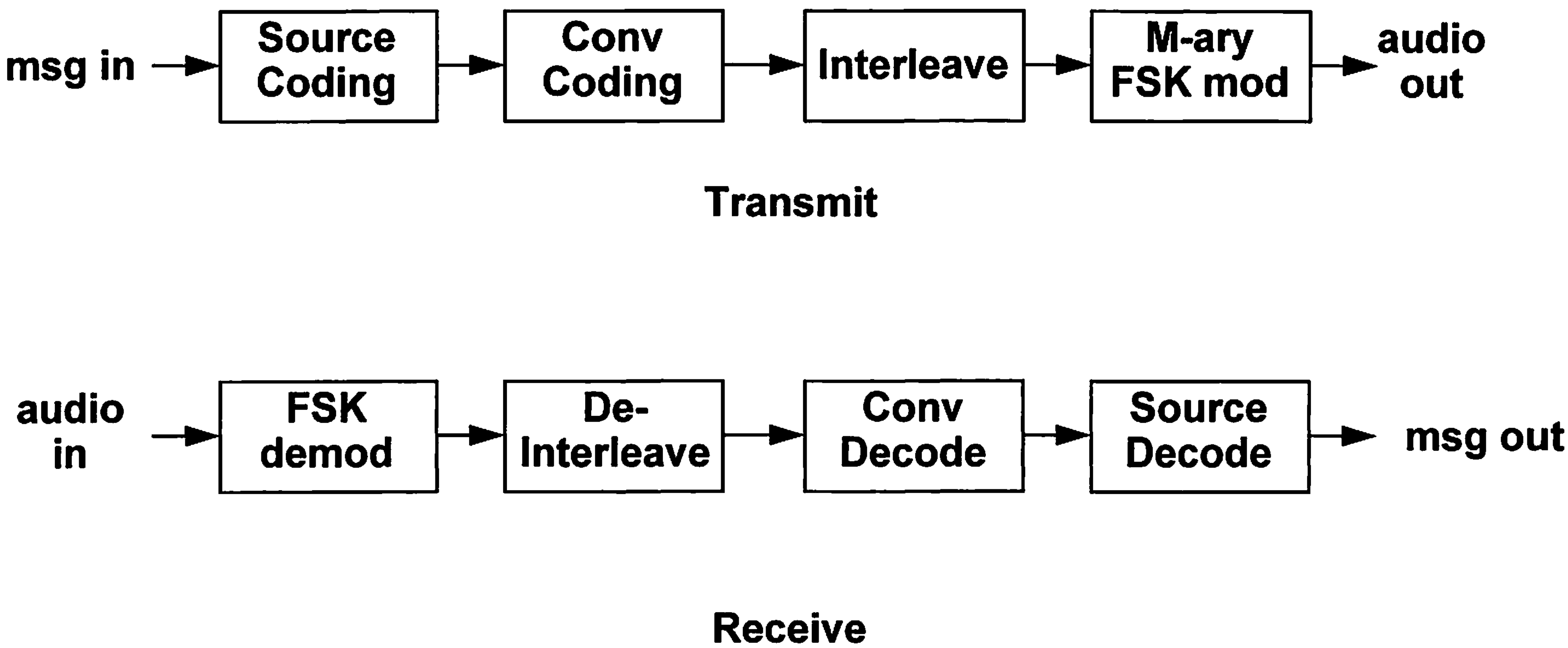


Probability of a bit error for noncoherent detection of orthogonal signals.

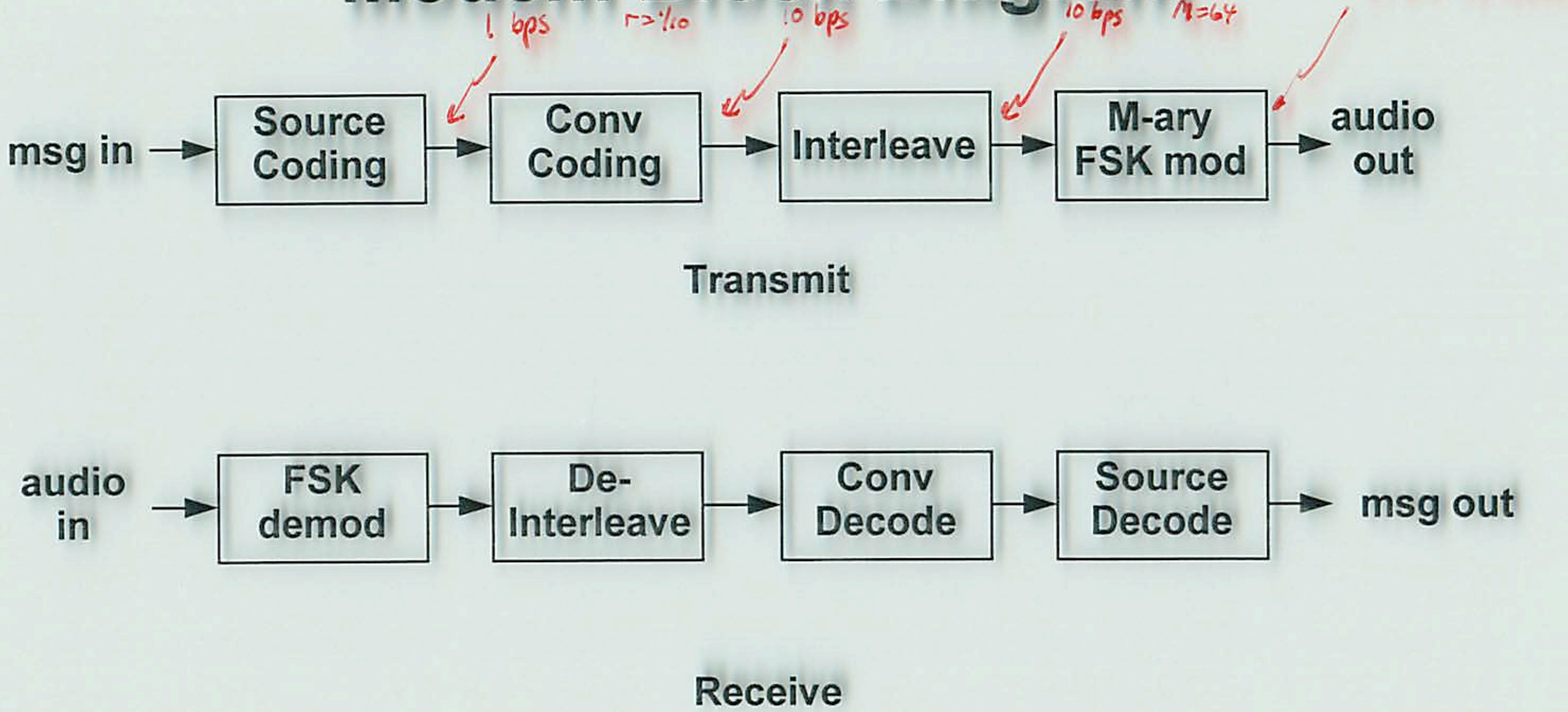
Noncoherent 4-ary FSK Demod



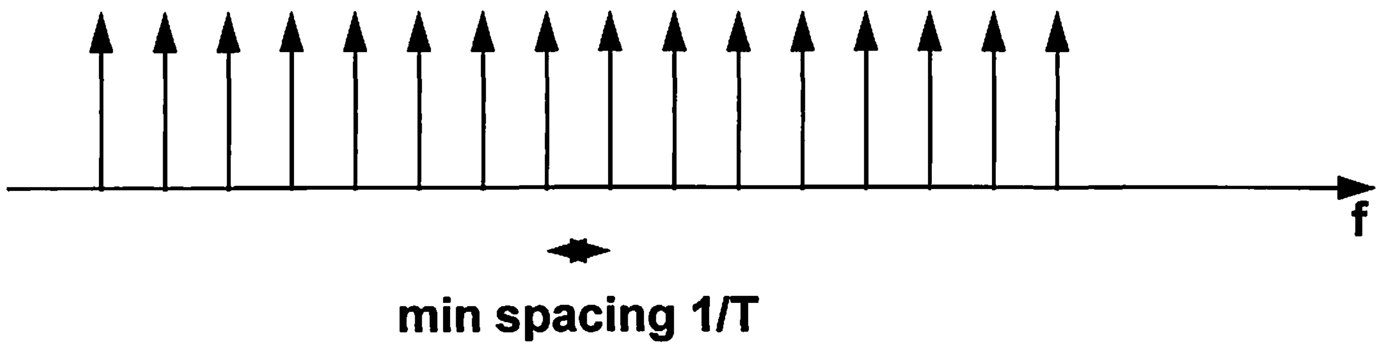
Modem Block Diagram



Modem Block Diagram



16-ary Tone Spacing

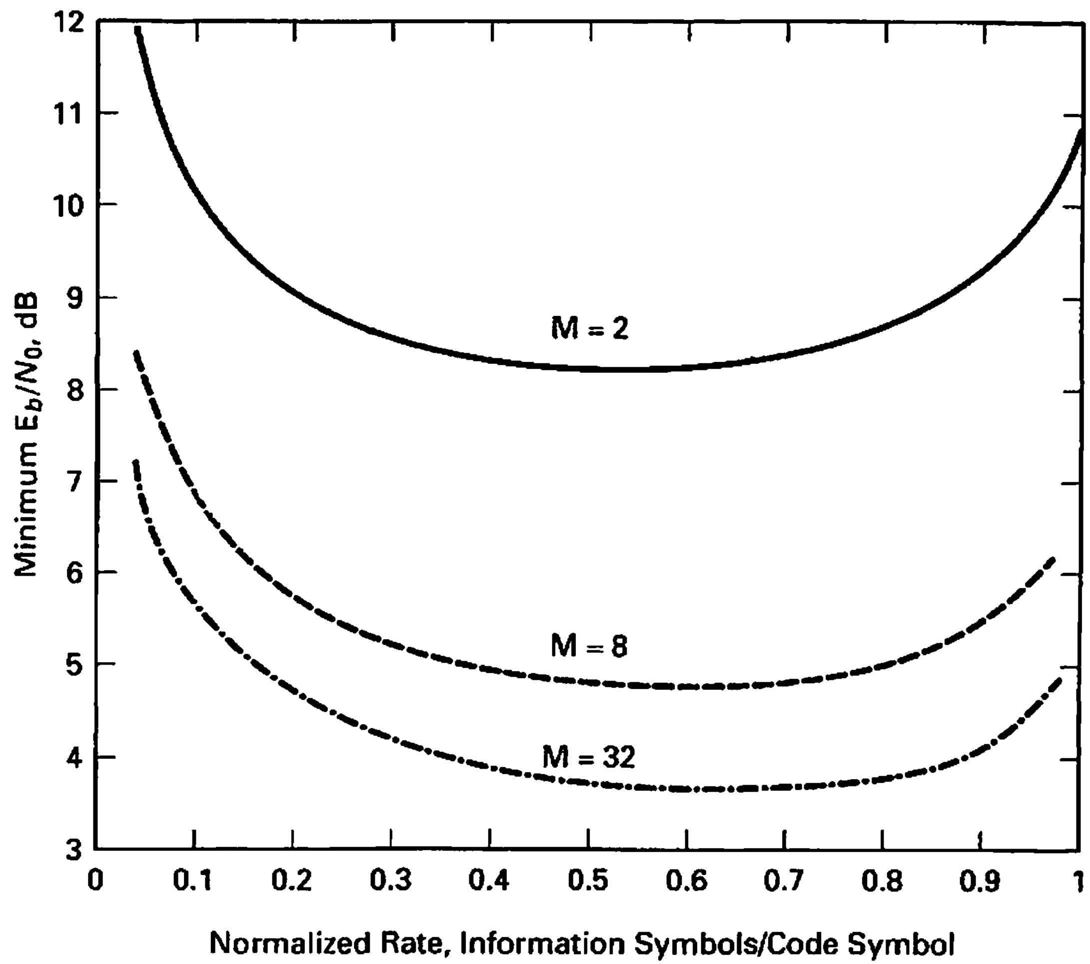


min total bandwidth = M/T = $r*M/\log_2(M)$; r = data rate

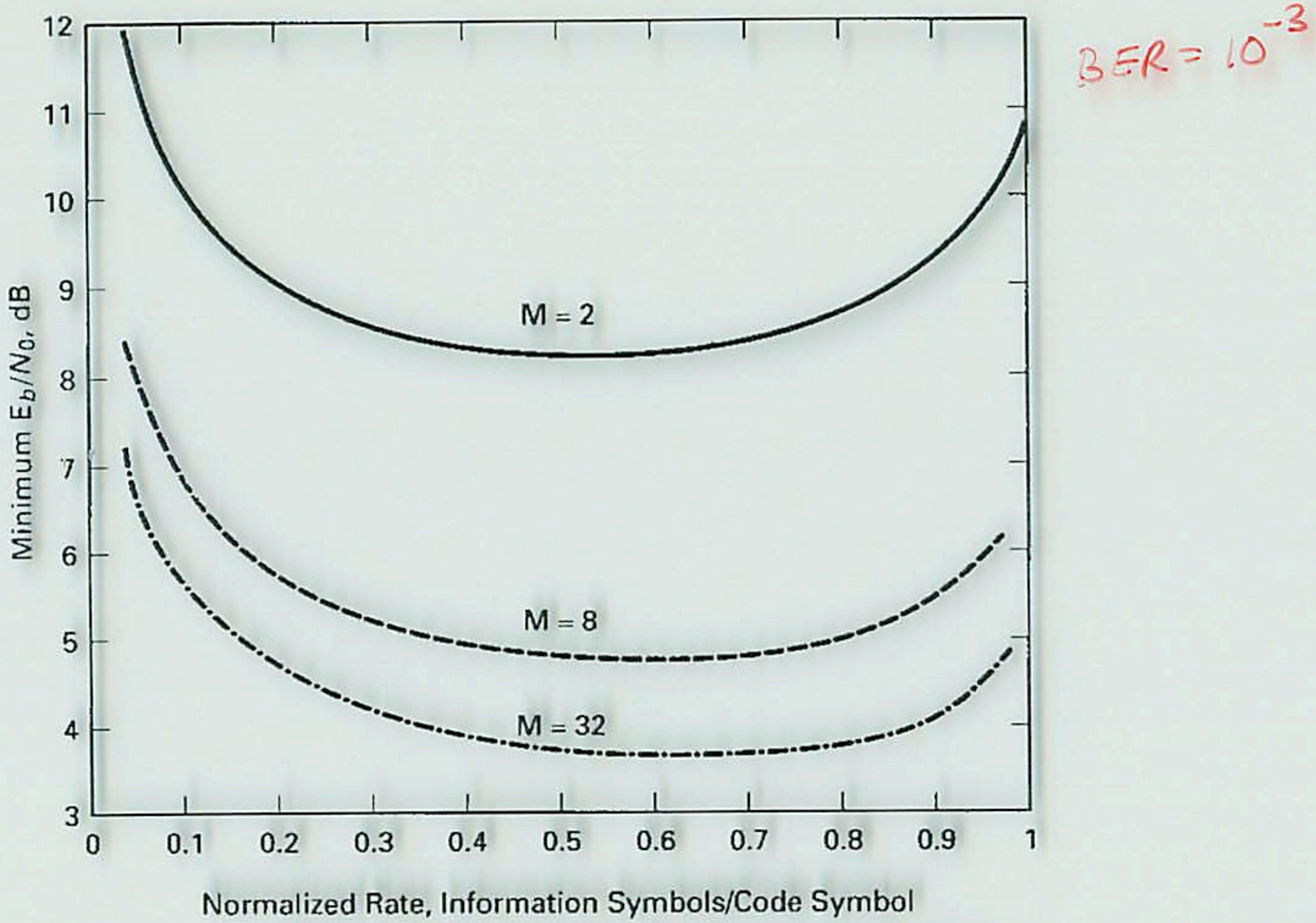
Coding with MFSK

- Forward error correction coding (FEC) can further improve MFSK performance
- Unlike ideal coherent PSK, there is an optimum “code rate” (redundancy ratio) for each value of M due to demodulator thresholding
- For a non-fading channel this is about rate 1/2 for a very wide range of M
  - for M=64, E_b/N_0=3.5 dB is possible
- For a Rayleigh fading channel, this is about rate 1/10 for M=64
  - Needed E_b/N_0 is about 6.5 dB

Noncoherent Thresholding



Minimum E_b/N_0 versus rate, M orthogonal signals, noncoherent detection AWGN.



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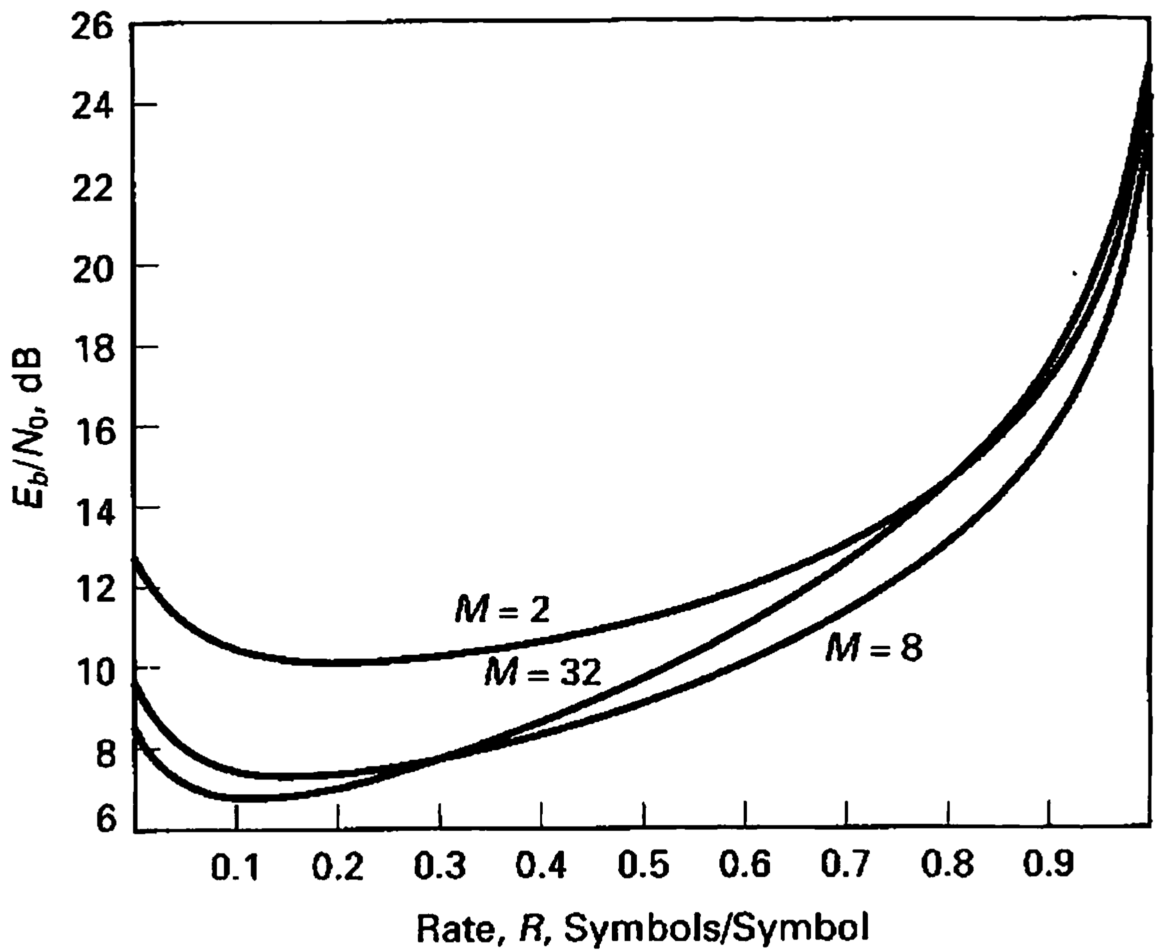
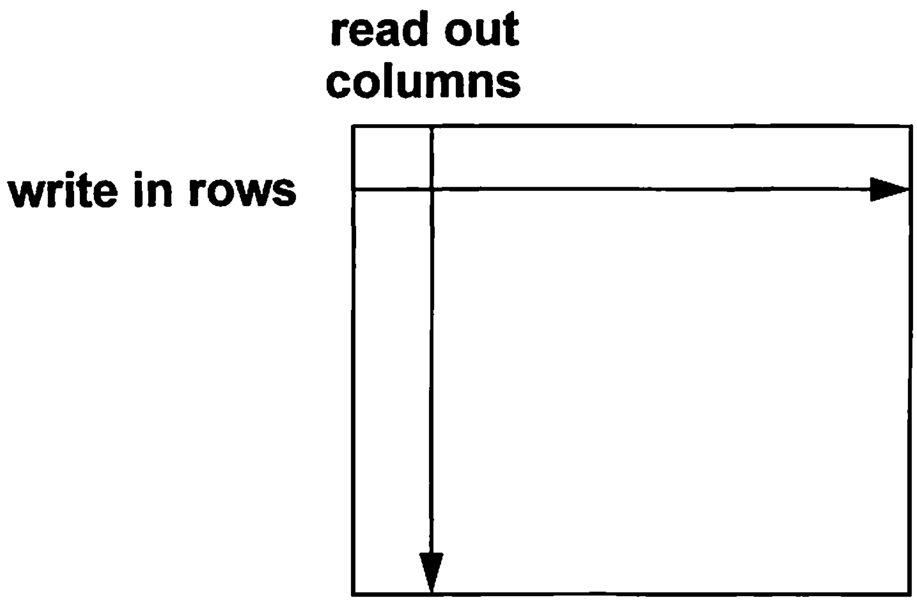


Minimum energy loci versus rate, Rayleigh channel, M-ary orthogonal signals, noncoherent detection.

Interleaving

- Interleaving simply rearranges the order in which code symbols are transmitted
  - scatters error bursts into "random" single errors



Convolutional Coding

- One of the most powerful FEC techniques
- Two major decoding methods:
  - Viterbi (maximum likelihood)
  - Fano (sequential)
- Each has its place
- Decoding is relatively CPU-intensive, but is now easy on modern PCs
  - K=7 r=1/2 Viterbi @ 155 kb/s on Pentium 90
  - K=32 r=1/2 Fano @ 200-400 kb/s (slower near threshold)
- Suggest Viterbi for EME
  - Can use larger K
  - Use "tail biting" to remove usual tail overhead

Design of Oscar-Class 70cm EME Link

- RF Output Power = 150W (+21.76 dBW)
- TX Antenna Gain = +19.1 dBi
- Path Loss (average) = 261.2 dB
- RX Antenna Gain = +19.1 dBi
- RX Power = -201.24 dBW
- System T = 100K (-208.6 dBW/Hz)
- RX C/N_0= +7.36 dB-Hz
  - far too weak to hear!

Link Design, cont

- C/N_0 = +7.36 dB-Hz
- Assume E_b/N_0 = 7dB
- Data Rate = +0.36 dB-bps ~= 1bps
- Choose FEC rate r=1/10 -> 10 code sym/sec
- Choose M=64:
  - 6 bits/"tone"
  - symbol duration = 6/10 = 600 millisec

Comments

- M=64 is not necessarily optimal, but should work
  - Not a lot of literature on very large M
- Symbol time is less than coherence time
  - but we're close; this is our most serious limitation
- Symbol time long enough for delay spread to not be a factor
  - If it was, we could chirp or frequency hop
- Symbol time long enough for easy symbol synch with GPS and computer moon tracking

Scaling to Higher Speeds

- "Full scale" EME stations should support ~300bps with these techniques
- M=64 implies ~64KHz RF bandwidth, with ISI due to delay spread on short symbols
- Could go to M > 64 to lengthen symbol and further reduce E_b/N_0, but would need even more bandwidth
- Some form of spread spectrum seems essential to maximizing potential of large EME stations

Scaling to Lower Speeds

- Coherence time a serious barrier
- Could keep M=64 and lower the FEC code rate to give a supportable user data rate
- This FEC rate would be well below the optimum for a Rayleigh fading channel, implying a significant noncoherent combining loss and greater E_b/N_0, hence an even lower data rate
- We'd definitely try the operators' patience!