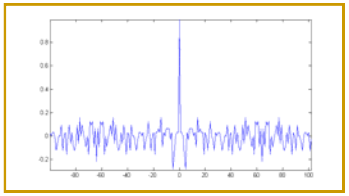
ECE 5660 – Spread Spectrum Communications
Spring 2008



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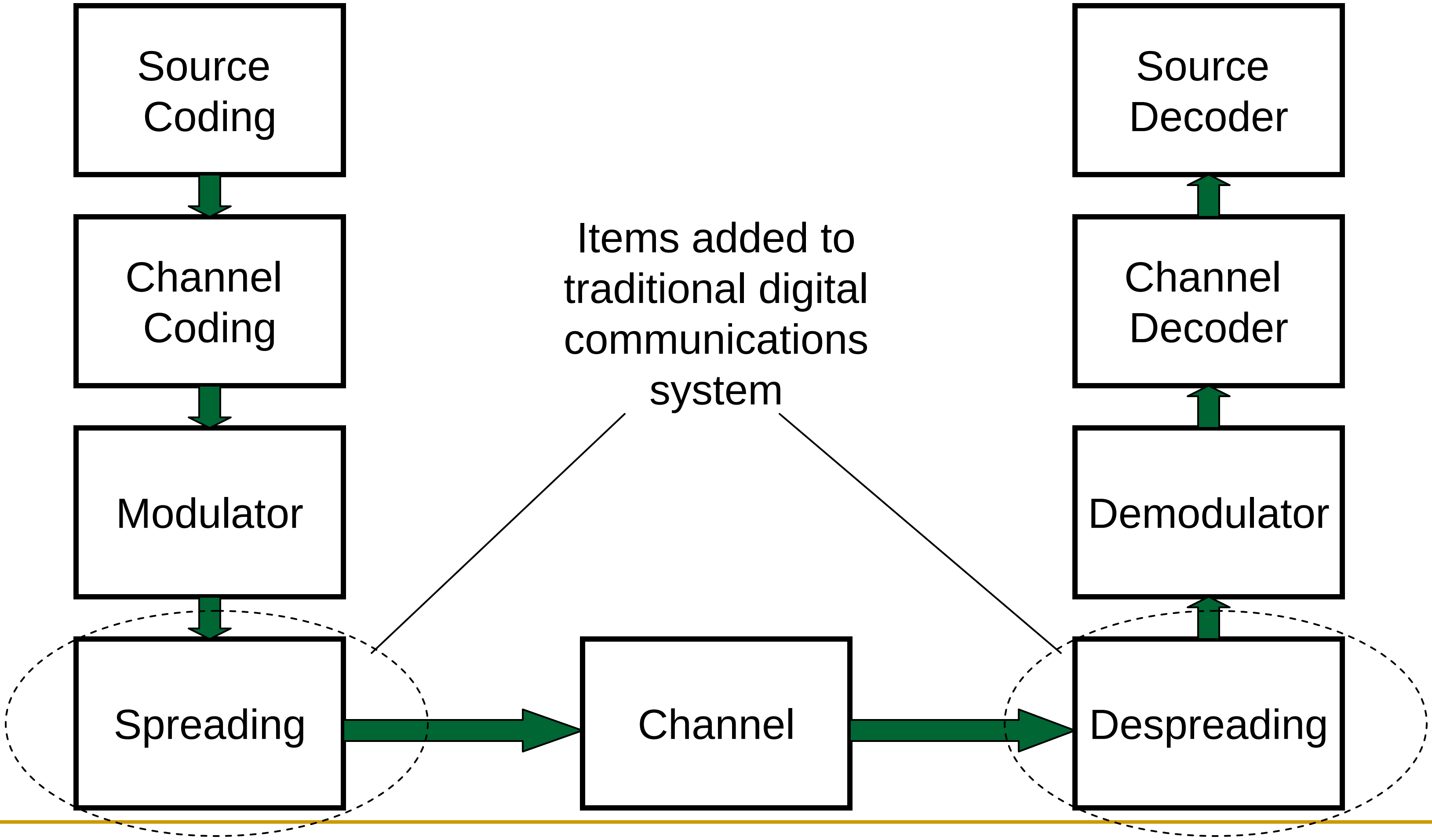
Lecture #2: Introduction to Spread Spectrum

What is Spread Spectrum?

- The digital communications techniques described last lecture are designed for communicating in an AWGN channel.
  - Bandwidth/energy efficiencies are optimized for this purpose
- Other channels of interest also exist such as those that are dominated by interference or severe multipath propagation
- Spread spectrum is a modulation scheme that provides better energy efficiency than traditional modulation schemes in many non-AWGN channels by sacrificing bandwidth efficiency
- Spread spectrum can be defined as any modulation scheme where:
  - The occupied bandwidth is much larger than the information bandwidth due to the use of a *spreading signal*
  - Demodulation is accomplished by correlating the received signal with a signal similar to the spreading signal (spreading waveform is independent of information waveform)

Block Diagram of Spread Spectrum Communications System



Items added to traditional digital communications system

Why Spread Spectrum?

- Interference mitigation (sometimes called anti-jamming)
  - Improved performance in presence of interference
- Low probability of intercept (LPI)
  - Decrease the probability that an unintended receiver can detect presence of a signal
- Underlay Systems
  - Anti-jamming and LPI capabilities can be used in commercial scenarios as an *underlay system*
  - Spread spectrum system shares the spectrum on a secondary basis by causing negligible interference to existing system
- Multipath resistance
  - Improved performance in multipath fading channels
- Improved multiple access efficiency
  - CDMA
- Ranging capability

Terminology

- Spreading – increasing the signal bandwidth beyond data rate
- Direct Sequence Spread Spectrum (DS-SS)
  - Signal is spread by multiplying data signal by a pseudo-random signal with very high symbol rate
- Frequency-Hopped Spread Spectrum (FH-SS)
  - Signal is spread by changing the carrier frequency in pseudo-random fashion over large bandwidth
- Processing Gain
  - Measure of the performance improvement through the use of spread spectrum
  - Closely related to the bandwidth expansion (or spreading) factor
    - Some authors define processing gain to be bandwidth expansion
- Jammer - Intentional interferer
- Intercept - Reception by unauthorized receiver

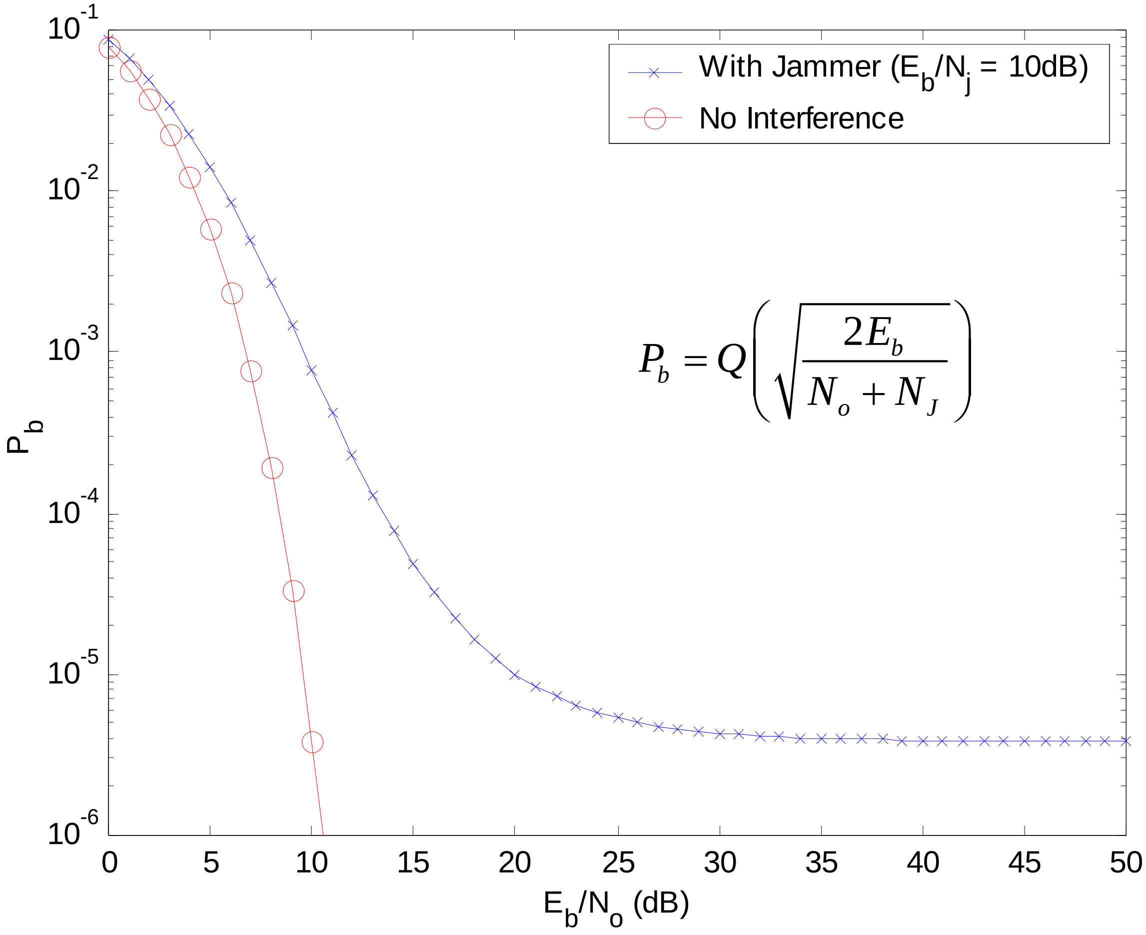
Jamming

- Consider a situation where a jammer is attempting to disrupt communications by transmitting a wideband noise-like signal.
- The jammer can increase its impact by pulsing the transmit signal using a duty cycle ρ.
- To see the impact of the jammer consider a BPSK modulation scheme which in an AWGN channel has performance

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_o}}\right)$$

E_b = energy per bit
N_o = one-sided noise power spectral density

Continuous Jamming



$$P_b = Q\left(\sqrt{\frac{2E_b}{N_o + N_J}}\right)$$

- N_j = interference density
- In the presence of interference with constant E_b/N_j an error floor is oberved vs E_b/N_o
- At high received powers, performance is limited ('interference limited')

Pulsed Jamming

- Define
  - J = average received power from the jammer
  - W = transmit bandwidth of the jammer (equal to the desired signal bandwidth)
  - $N_J = J/W$ = one-sided jammer power spectral density
  - ρ = duty cycle of jammer
- When the jammer is not transmitting the BER is

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_o}}\right)$$

- When the jammer is transmitting the BER is

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_o + N_J/\rho}}\right)$$

- Thus the average BER is

$$P_b = (1-\rho)Q\left(\sqrt{\frac{2E_b}{N_o}}\right) + \rho Q\left(\sqrt{\frac{2E_b}{N_o + N_J/\rho}}\right)$$

Worst Case Pulse Jamming

- In a jamming environment, typically $\frac{E_b}{N_o} >> \frac{E_b}{N_J}$

  thus

$$P_b \approx \rho Q\left(\sqrt{\frac{2E_b\rho}{N_J}}\right)$$

- We would like to examine the worst case. Thus, we can use the upper bound for the *Q*-function

$$P_b \le \frac{\rho}{\sqrt{4\pi\rho E_b / N_J}} e^{-\rho E_b / N_J}$$

- This function is maximized at $\rho = \frac{N_J}{2E_b}$

- Thus,

$$\boxed{P_b^{\max} = \frac{1}{\sqrt{2\pi e}} \frac{1}{2E_b / N_J}}$$

Worst Case Pulse Jamming (cont.)

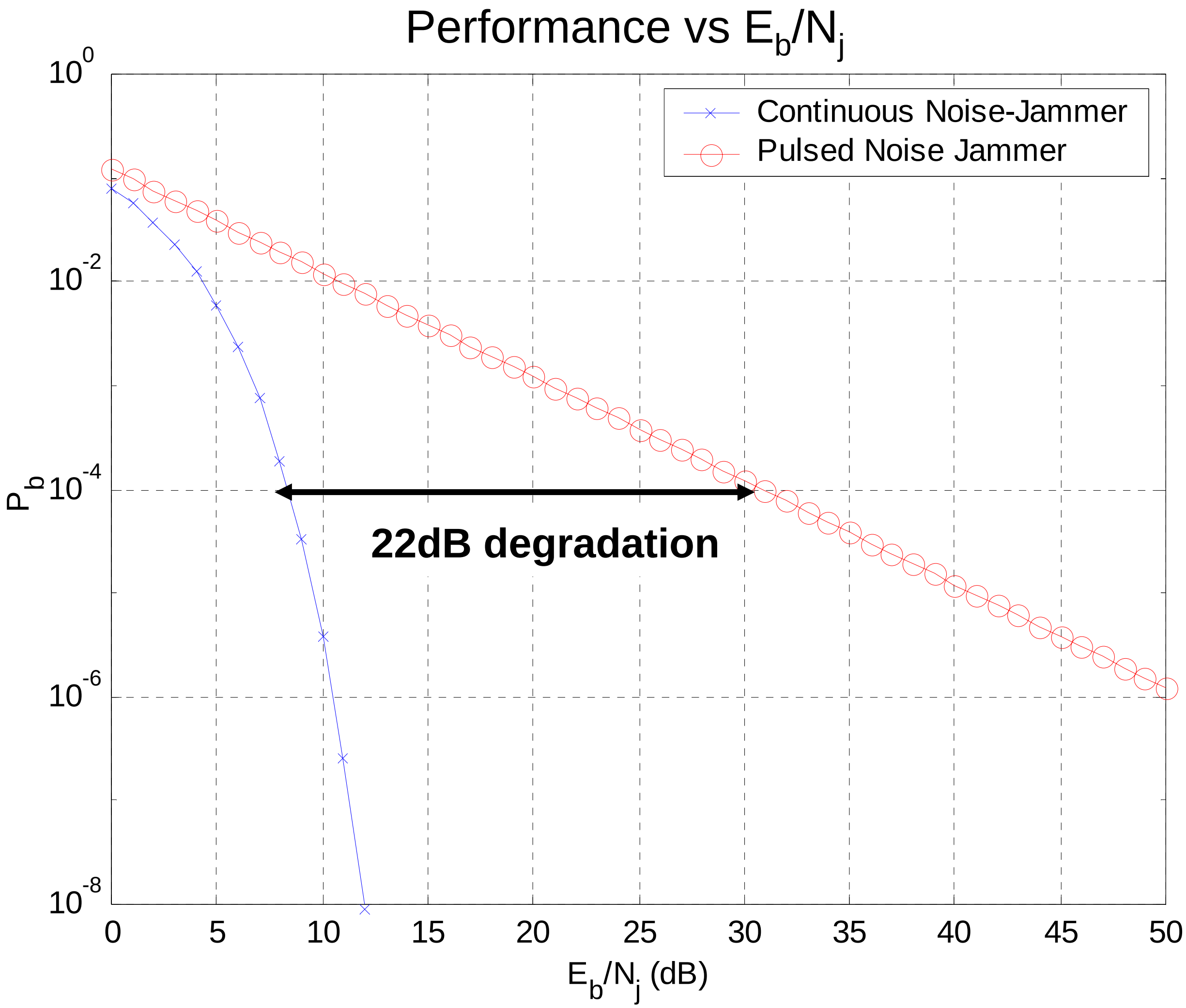
- Now, comparing to the case where the jammer does not pulse (ρ = 1):

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_J}}\right)$$

$$P_b^{\max} = \frac{1}{\sqrt{2\pi e}}\frac{1}{2E_b / N_J}$$

- Optimally pulsing changes exponential relationship between P_b and E_b/N_J to an inverse linear relationship

Impact of Pulse Jamming



- Optimal pulsing allows jammer to severely degrade performance of system
- While optimal jamming is difficult to achieve, we can see the type of degradation possible
- Employing spread spectrum and coding will overcome this problem

Bandwidth Expansion

- Let us now consider the problem in terms of S/J or the ratio of received signal power to received jamming power (ignoring noise).
- Recall that $E_b = ST_b$ and $N_j = J / W$

Continuous Jammer

$$P_b = Q\left(\sqrt{\frac{2ST_b}{J/W}}\right)$$

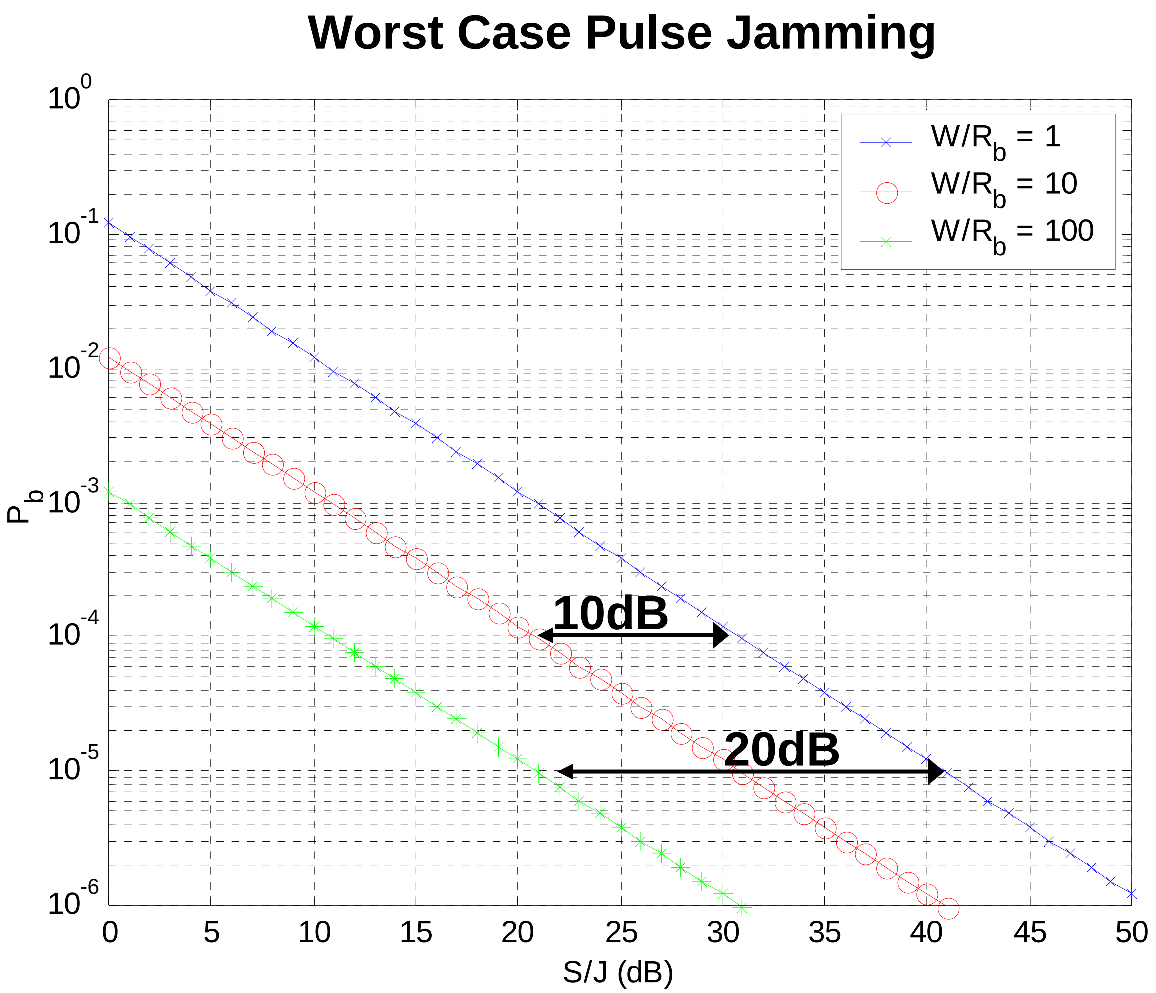
$$= Q\left(\sqrt{2\frac{S}{J}\frac{W}{R_b}}\right)$$

Optimal Pulsed Jammer

$$P_b^{\max} = \frac{1}{2\sqrt{2\pi e}}\frac{J}{S}\frac{R_b}{W}$$

We see that for a constant amount of jamming power we can improve our performance by increasing bandwidth *W* without increasing data rate. This is termed bandwidth expansion.

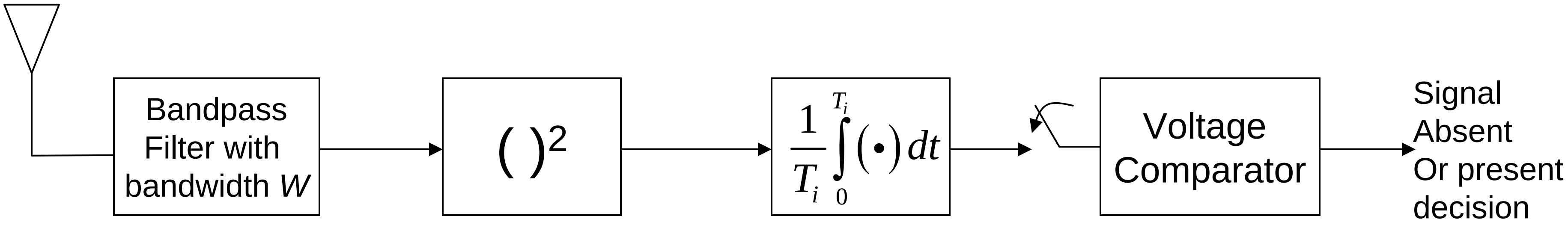
Impact of Bandwidth Expansion



- Performance is improved by a factor directly proportional to bandwidth expansion W/R_b. Thus, W/R_b is often called the *processing gain*.
- Similar gain is obtained with continuous jamming

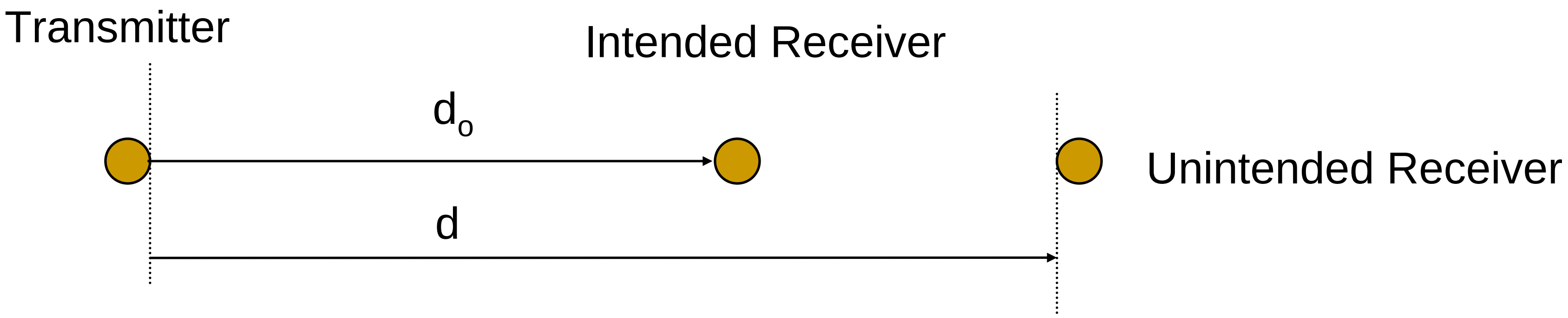
Low Probability of Detection

- There are situations where communications need to be carried out without the knowledge of a third party.
- Note that this is a more strict requirement than *secure communications* since we do not want the third party to even know communication is taking place.
- This is termed *Low Probability of Detection Communication*
- A common method of detecting the presence of a signal is the use of a radiometer:



Low Probability of Detection

- Assume that an unintended receiver knows the frequency band of the intended receiver and attempts to detect the presence of a transmission with an energy detector



Impact of Bandwidth

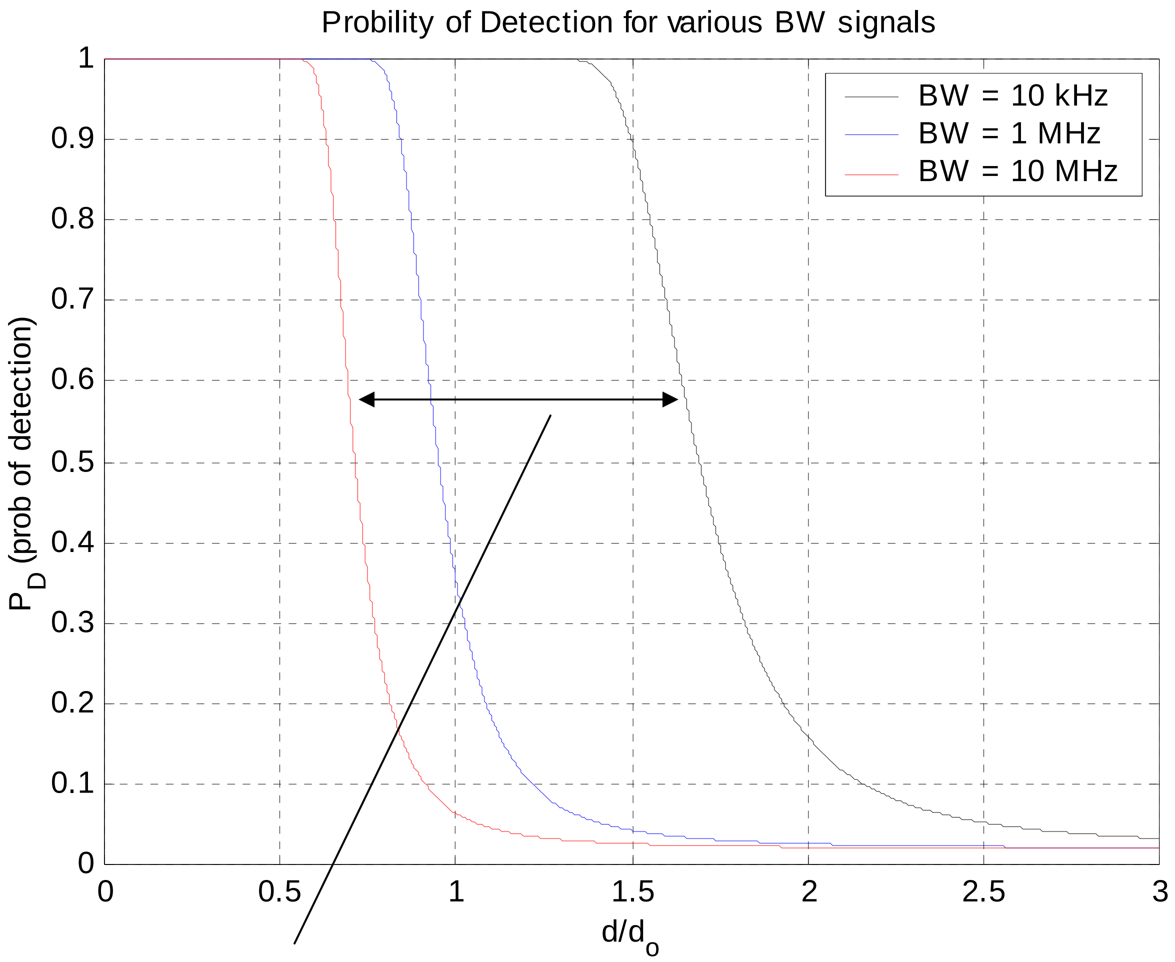
- The probability of detection (i.e., the probability that the interceptor detects that transmission is taking place) can be shown to be

$$P_d = \Phi\left\{\left[\frac{S}{N_o}\sqrt{\frac{T_i}{W}} - \Phi^{-1}\left(1 - P_{fa}\right)\right]\right\}$$

  - S = received power
  - T_i = integration time of interceptor
  - P_{fa} = probability of false alarm
  - W = bandwidth of signal
  - N_o = noise power spectral density
  - $\Phi(x) = \int_{-\infty}^{x} \exp\left(-\frac{1}{2}y^2\right) dy$

- P_d is directly proportional to received power S (and thus data rate) and integration time T_i
- P_d is inversely proportional to bandwidth W
- Thus, if we increase W while leaving data rate (and thus S) constant, the probability of intercept will decrease

Probability of Detection



Increasing the bandwidth decreases the probability of detection or forces the eavesdropper to be closer

- P_{fa} = 2%
- d/d_o = distance of interferer relative to desired receiver
- E_b/N_o = 7.25dB
- R_b = 10kbps
- T_i = 10ms
- Path loss exponent = 4

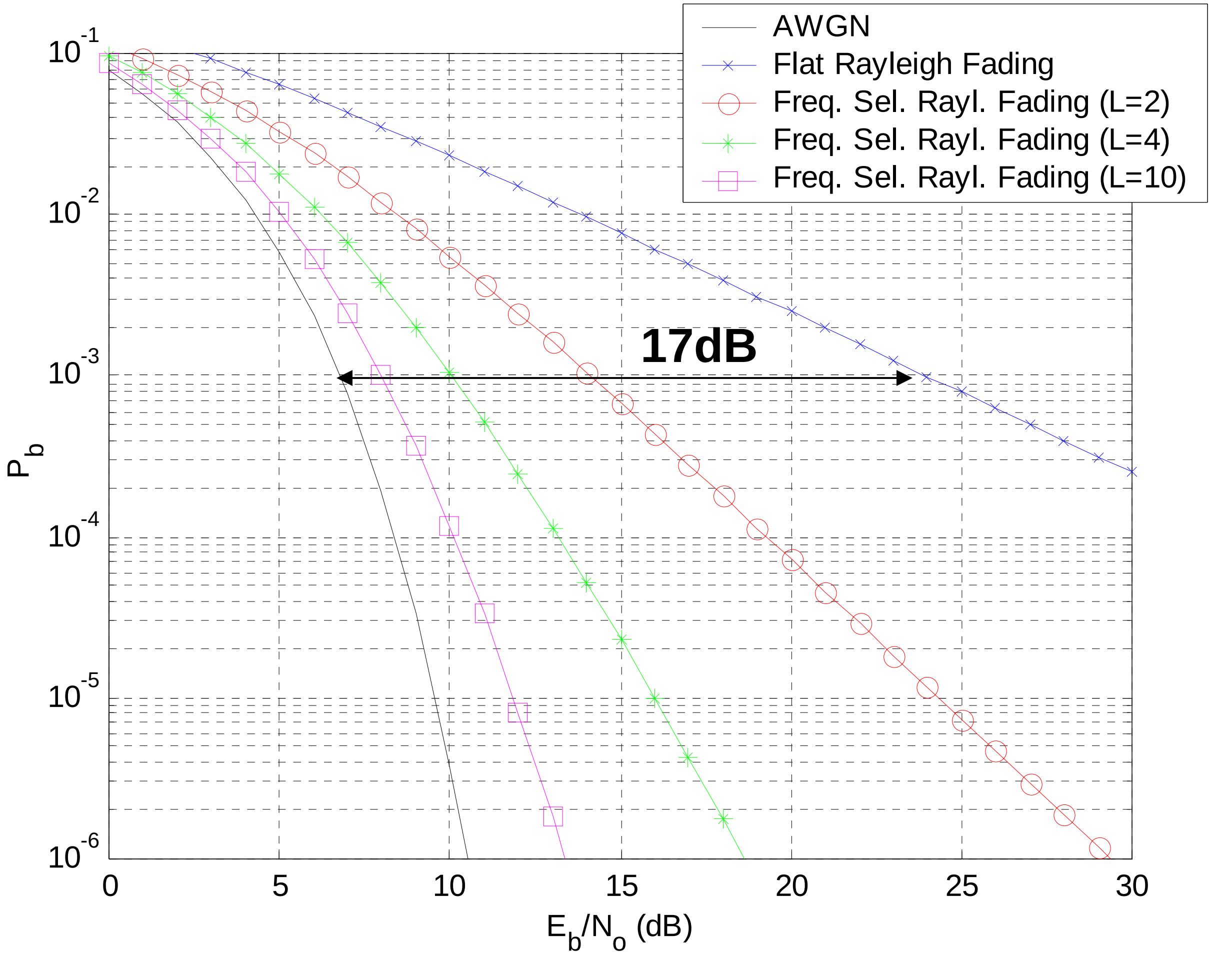
Multipath

- Multipath in wireless channels leads to constructive and destructive interference due to phase differences between multipath echoes
- In a narrowband system, all paths arrive at indistinguishable time differences and thus all paths interfere with each other. This leads to *Rayleigh fading.*
- The relative delays of the multipath determine the coherence bandwidth of the channel.
- Narrowband systems have a signal bandwidth smaller than the channel coherence bandwidth and thus the whole band fades simultaneously (flat fading)

Multipath Resistance

- By increasing the bandwidth of the signal beyond the coherence bandwidth of the channel, the whole band will not fade simultaneously (*frequency selective fading).*
- This causes waveform distortion which typically requires the use of an equalizer.
- However, by using spread spectrum the distortion is rendered benign and the frequency selective fading becomes a source of diversity.
- This diversity can be exploited through the use of a Rake receiver with DS-SS or by fast frequency hopping (using coding with hopping)

Multipath Resistance (cont.)



- Flat fading causes a loss of ~17dB at $P_b=10^{-3}$.
- We can recover 9dB with spread spectrum if two equal power paths are present
- The loss is reduced to 3dB if 4 equal power paths are present

CDMA

- The previously mentioned uses of spread spectrum were primarily used in the military where bandwidth efficiency is not an issue.
- However, it can be shown that spread spectrum can be beneficial in commercial applications such as cellular where spectral efficiency is important.
- If multiple users occupy the same bandwidth using spread spectrum signals, we call this *Code Division Multiple Access.*
- Unlike Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) we do not provide *orthogonal* channels for each user in the system.
- What is the advantage of this?

Capacity of FDMA

- Let us assume the use of separate frequency bands for each user in the system (i.e., FDMA).
- Let us further assume the use of a modulation scheme with k bits per symbol which is used to achieve a bit rate R_b for K simultaneous users in a total bandwidth of B_T.
- Assuming optimal pulse shaping with PSK or QAM, the bandwidth requirement per user is equal to the symbol rate
  - $B_u = R_s = R_b / k$.
- For FDMA the number of users that can be supported (assuming k=1) is the total bandwidth divided by the bandwidth per user:

$$\boxed{K_{FDMA} = \frac{B_T}{B_u} = \frac{B_T}{R_b}}$$

Capacity of TDMA

- In a pure TDMA system, each user occupies the entire bandwidth but only for a fraction of the time. Thus, $B_u = B_T$
- Each user transmits at a symbol rate $R_s = B_T$ (again assuming optimal pulse shaping) during a fraction $1/K$ of the time and thus achieves a date rate of

$$R_b = \frac{kR_s}{K}$$

- If each user must achieve a data rate of R_b, than the number of users that can be supported is (again assuming that k=1):

$$\boxed{K_{TDMA} = \frac{R_s}{R_b / k} = \frac{B_T}{R_b}}$$

which is the same as in *FDMA*

Capacity of CDMA

- In a CDMA system all users occupy the same bandwidth simultaneously. Since the signals are typically uncoordinated the channels are not orthogonal and the system is *interference limited.*
- Let us examine the *uplink* of a CDMA system where each user transmits at a bit rate of R_b in a bandwidth of B_T Hz and is received with equal power P.
- The total interference power seen by each signal is $I = (K-1)P$.
- The interference spectral density is I / B_T

Capacity of CDMA (cont.)

- In order to achieve an adequate performance level, each user must have a specified value of E_b / I_o.
- This is found as:

$$\frac{E_b}{I_o} = \frac{PT_b}{(K-1)\, P/B_T} = \frac{B_T / R_b}{K-1}$$

- This then determines the capacity of a CDMA system:

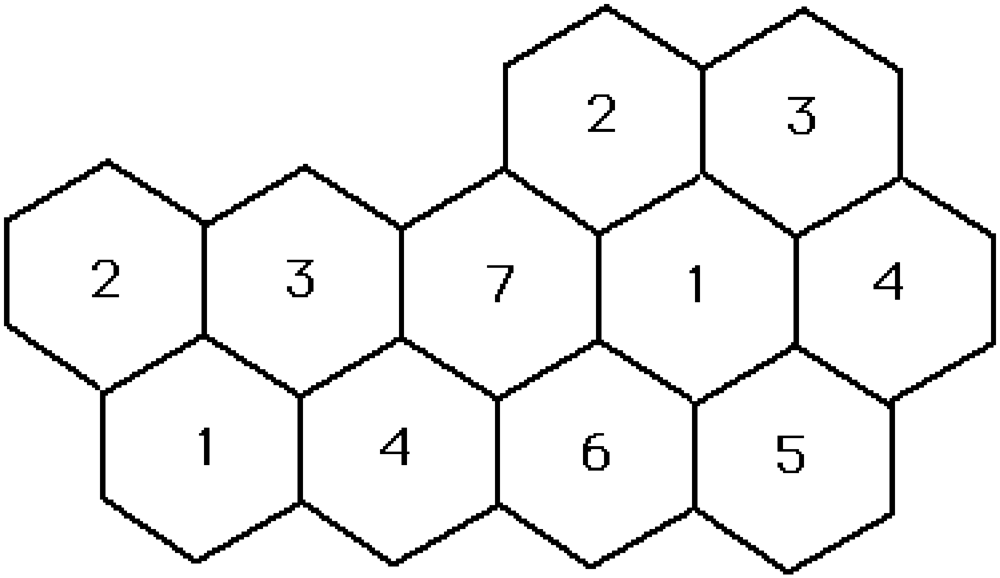
$$\boxed{\begin{aligned} K_{CDMA} &= \frac{B_T/R_b}{E_b/I_o} + 1 \\ &\approx \frac{B_T}{R_b}\frac{I_o}{E_b} \end{aligned}}$$

Capacity of CDMA and Frequency Reuse

- Now, since the required E_b/I_o is almost certainly greater than 1, we can see that the system capacity of CDMA appears to be inferior to TDMA and FDMA. In fact for a typical required E_b/I_o of 6dB, we see that it is smaller by a factor of 4.
- However, this analysis ignored the idea of frequency reuse.
- In cellular (and several other wireless systems) frequency bands are reused in geographically separated areas (typically called 'cells') to achieve greater spectral efficiency.
- Thus, only a fraction of the frequencies can be used in a given area.

Frequency Reuse Patterns

- TDMA and FDMA require a frequency reuse pattern
- Must have sufficient spatial separation to reuse frequency and avoid high probability of interference.



Ex: Reuse pattern of 7

Frequency band is divided up into a number of bands and reused.

This reduces the number of channels by the reuse factor *Q*

Impact of Frequency Reuse

- The capacity per cell in TDMA and FDMA systems is thus reduced by the reuse factor Q:

$$\boxed{K_{TDMA} = K_{FDMA} = \frac{1}{Q}\frac{B_T}{R_b}}$$

- In typical TDMA/FDMA systems, this reuse factor is 7 with sectored antennas or 12 with omni directional antennas.

Frequency Reuse in CDMA

- In CDMA *universal frequency reuse* is employed which means that the reuse factor Q = 1.
- This increases the interference seen at the base station by a factor f. Thus, in the universal frequency reuse case we have

$$\frac{E_b}{I_o} = \frac{PT_b}{\left(K-1\right) {}^{P}\!/_{B_T} \left(1+f\right)}$$

- Thus, the capacity is

$$\boxed{K_{CDMA} \approx \frac{B_T}{\left(1+f\right)R_b}\frac{I_o}{E_b}}$$

Voice Activity

- It has been well documented that a typical speaker in a telephone conversation is only active some fraction *v* of the time (typically *v* = 3/8)
- In TDMA/FDMA systems it is impractical to efficiently reallocate channels during moments when the channel is inactive.
- However, in CDMA we can take advantage of voice activity simply by suppressing transmission while the speaker is inactive. This reduces the amount of interference seen at the receiver by a factor of *v.*
- The capacity of CDMA is then

$$\boxed{K_{CDMA} \approx \frac{B_T}{v\left(1+f\right)R_b}\frac{I_o}{E_b}}$$

Impact of Sectored Antennas

- Sectored antennas reduce the amount of interference seen at the receiver.
- In TDMA/FDMA systems three-sector antennas allow a reduction in the reuse factor from 12 to 7. However, in CDMA it reduces interference by an amount directly related to the antenna gain *G.* Thus, we now have a CDMA capacity of

$$\boxed{K_{CDMA} \approx \frac{B_T}{v\left(1+f\right)R_b/G}\frac{I_o}{E_b}}$$

Capacity Comparison

- Assuming the use of sectored antennas, the reuse of TDMA/FDMA is 7 and the capacity per cell is

$$\boxed{K_{TDMA} = K_{FDMA} = \frac{1}{7}\frac{B_T}{R_b}}$$

- With a typical E_b/N_o requirement of 7dB, a voice activity factor of $v = 3/8$, a three sector antenna gain of 4dB (5dB minus 1dB scalloping loss), and an out-of-cell interference factor $f = 0.6$, we get a CDMA capacity per cell of

$$\boxed{K_{CDMA} \approx \frac{B_T}{R_b}}$$

- Which is nearly on order of magnitude improvement! Further, if we can reduce the E_b/N_o requirements we can directly improve system capacity.

Applications of Spread Spectrum

- Military Systems
  - LPI Communications
  - Jam-resistant communications
- Cellular Systems (CDMA)
  - IS-95 2nd Generation Standard
  - WCDMA and cdma2000 3rd Generation Standards
- WLAN
  - 802.11 (original standard)
- GPS
  - Used for high precision position location

Conclusions

- In AWGN channels, traditional modulation methods are more bandwidth efficient than spread spectrum and equally energy efficient
- However, traditional modulation schemes do not perform well in other channels such as
  - Jamming environment
  - Multipath fading
- Spread spectrum communications methods are much more efficient in such channels
- Spread spectrum is also beneficial for
  - Multiple access
  - Low probability of intercept
  - Ranging