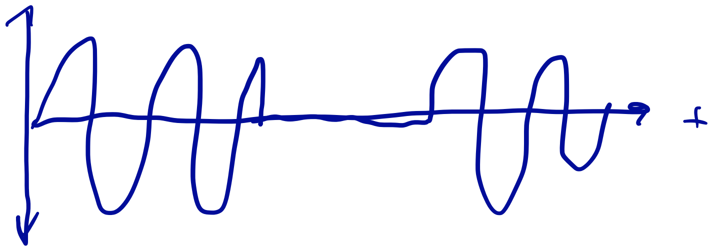
Communication

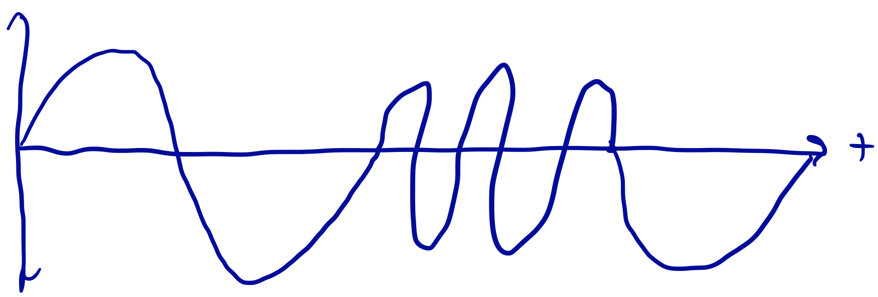
- How do we transmit data with a radio signal?

$$s(t) = A\cos(2\pi f t + \phi)$$

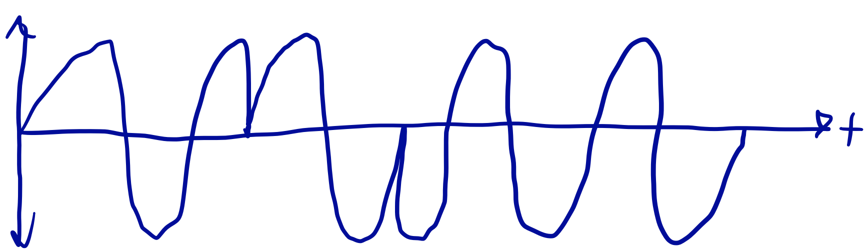
* Change A ⇒ "Amplitude shift keying" (ASK)



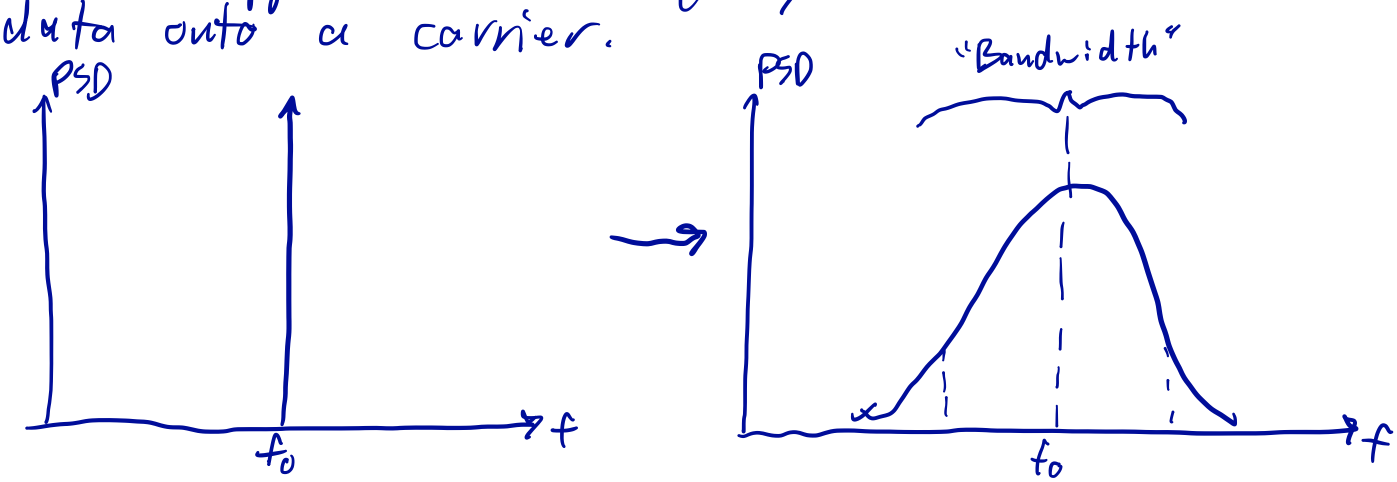
* Change f ⇒ "Frequency shift keying" (FSK)



* Change ϕ ⇒ "Phase-shift keying" (PSK)



* What happens in the frequency domain when we modulate data onto a carrier.



- Bandwidth (measured in Hz) is proportional to data rate in bits/sec.

- Constant of proportionality is called "spectral efficiency."

- Table in SMAD gives values for all common modulations

- PSK is very common because it has high spectral efficiency

- GPS uses BPSK - shift of 180° represents a bit transition
  Binary

- Satellite TV uses QPSK - 90° phase shifts

"Gains and Losses"

Losses:

- Atmospheric Attenuation (depends on frequency)
- Free space loss (inverse square law)
- Line losses
- Polarization losses
- Rain fade (depends on frequency)

Gains:

- Transmit + Receive antennas
- Signal processing

$$P_T \times \frac{1}{L_L} \times G_T \times \frac{1}{L_{FS}} \times \frac{1}{L_A} \times G_R = P_R$$

- Usually expressed in dB:

$$P_T - L_L + G_T - L_{FS} - L_A + G_R = P_R \quad \text{in dBW or dBm}$$

Antenna Gain:

- Antenna gain is measured in dBi – dB gain vs. isotropic
- Antenna gain measures how focused the power is in one direction.

Antenna gain is ratio of area of beam vs. whole sphere.

- Higher gain ⇒ narrower beam ⇒ more precise pointing requirements.

Some examples:

- ½ wave dipole ≈ 2 dBi gain
- Typical dish ≈ 30 dBi
- Arecibo ≈ 60 dBi

Free Space Loss:

- Signal falls off like $1/r^2$ with distance

$$1/r^2 \rightarrow 10 \log_{10}(1/r^2) = -20 \log_{10}(r) \text{ in dB}$$

- By convention, FSL also includes antenna aperture, which varies with frequency:

speed of light

$$FSL = \left(\frac{\lambda}{4\pi r}\right)^2 = \left(\frac{c}{4\pi r f}\right)^2$$

in dB: $147.55 - 20 \log(r) - 20 \log(f)$

for r in meters, f in Hz

Noise:

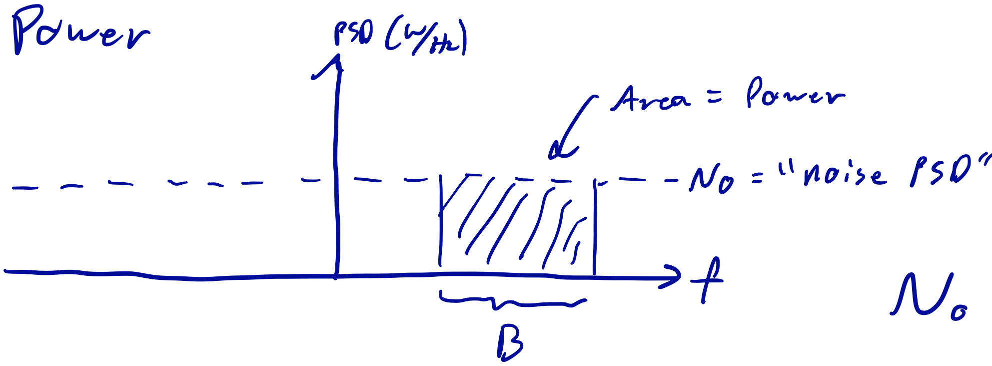
- What stops us from detecting arbitrarily weak signals

Noise is Everywhere!

- Solar Radiation
- Cosmic rays
- Other signals
- Thermal Noise

- Thermal noise is caused by random motion of electrons
- Typically modeled as white noise (equal power at all frequencies)
- Usually measured in units of temperature (Kelvin)
  - For terrestrial signals $T \approx 300\,K$
  - For deep space signals $T \approx 150\,K$

Noise Power



Boltzmann's Constant

$$N_0 = K_B T$$

$$N = N_0 B = B K_B T$$

noise power (W)

- The receiver itself also adds noise. Usually measured in terms of "noise figure".

Example:

Voyage 1:

- Most distant spacecraft ever built

  120 AU $\approx 1.8 \times 10^{10}$ Km from Earth

- 20 W transmitter $\approx$ 13 dBW

- 3.66 Meter dish (High gain antenna)

- S-band ~ 2.4 GHz ~ 13 cm. wavelength

- Assume 100 KHz receiver bandwidth

* Transmitter antenna Gain:

$$G_T = \frac{\pi^2 d^2}{\lambda^2} e_A$$

d = diameter
λ = wavelength
e_A - efficiency ≈ 0.7

$$\approx 37.4 \text{ dBi}$$

* Free Space Loss:

$$L_{FS} = 147.55 - 20\log(r) - 20\log(f) \approx -305.2 \text{ dB}$$

* Receive Antenna Gain:

NASA DSN dish ~ 70 m $\Rightarrow G_R \approx 63$ dBi

* Received signal power $P_R \approx -191.8$ dBW

* Noise Power:

$$N = BK_BT = (100\times10^3)(1.38\times10^{-23})(150) \approx 2.07\times10^{-16} W$$

$$\approx -156.8 \text{ dBW}$$

* Signal-to-Noise Ratio:

$$\frac{S}{N} = -191.8 - (-156.8) \simeq -35 \text{ dB}$$

$\Rightarrow$ Noise is ~ 3000× stronger than signal!!

Shannon Limit

- Sets the theoretical limit on data rate for a given communication channel

$$C = B \log_2\left(1 + \frac{S}{N}\right)$$

"Channel Capacity" (bits/sec)

Not in dB

$$C = (100 \times 10^{-9}) \log_2\left(1 + \frac{1}{3000}\right) \simeq 45.6 \text{ bits/sec.}$$

* Actual Voyager 2 data rate $\simeq$ 16 bits/sec.

* In real life we can usually achieve about half the Shannon limit.