Communication Systems and Link Budget

1. Communication Systems

2. Friis Transmission Equation

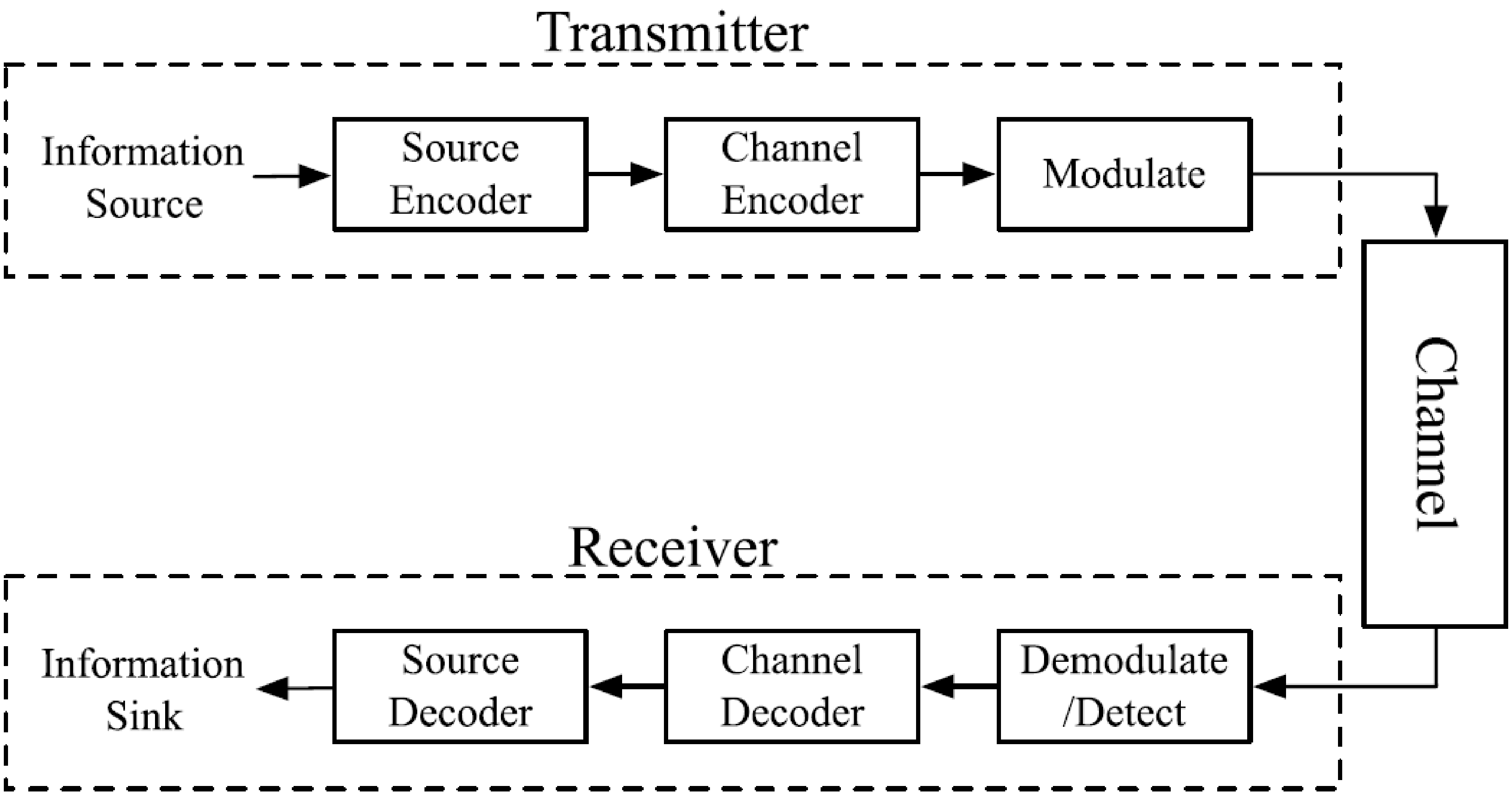
3. Receiver Figure

4. Link Budget

5. Code Problems

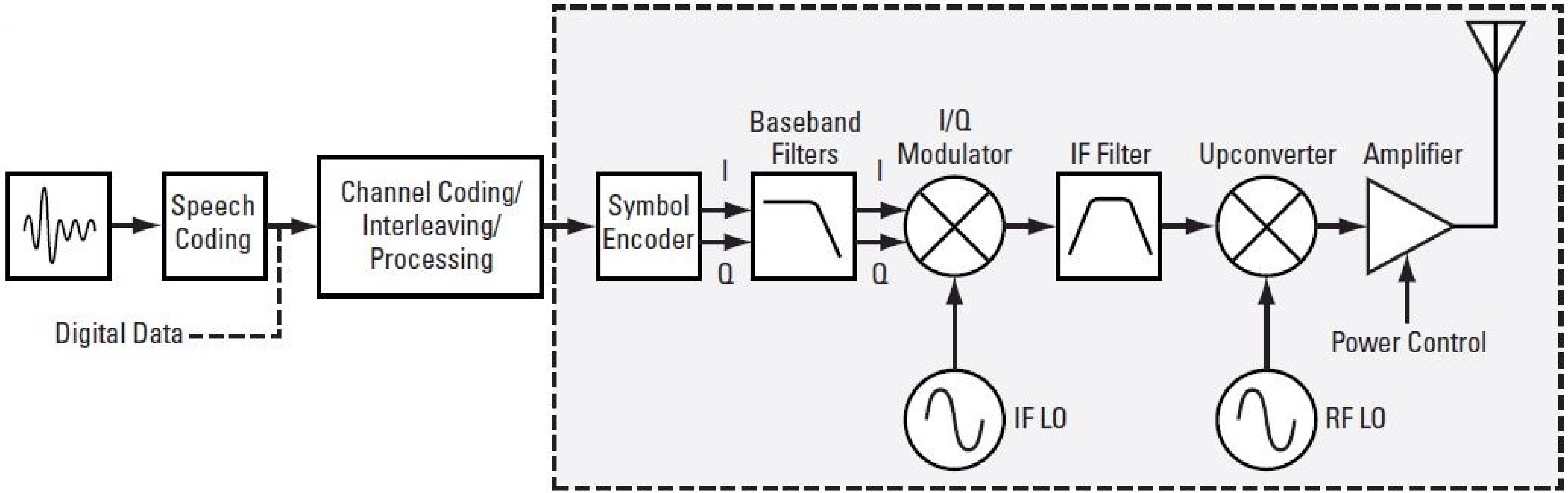
1. Communication Systems

❑ Block Diagram of a Communication System



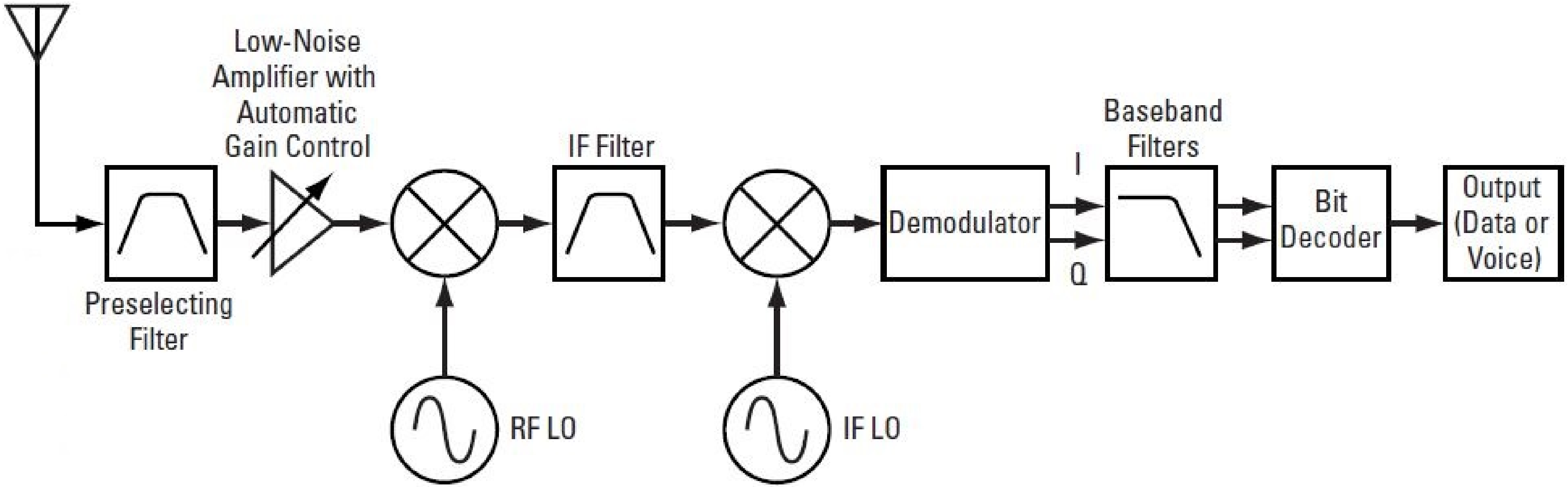
1. Communication Systems

❑ Block Diagram of a Digital Communications Transmitter



1. Communication Systems

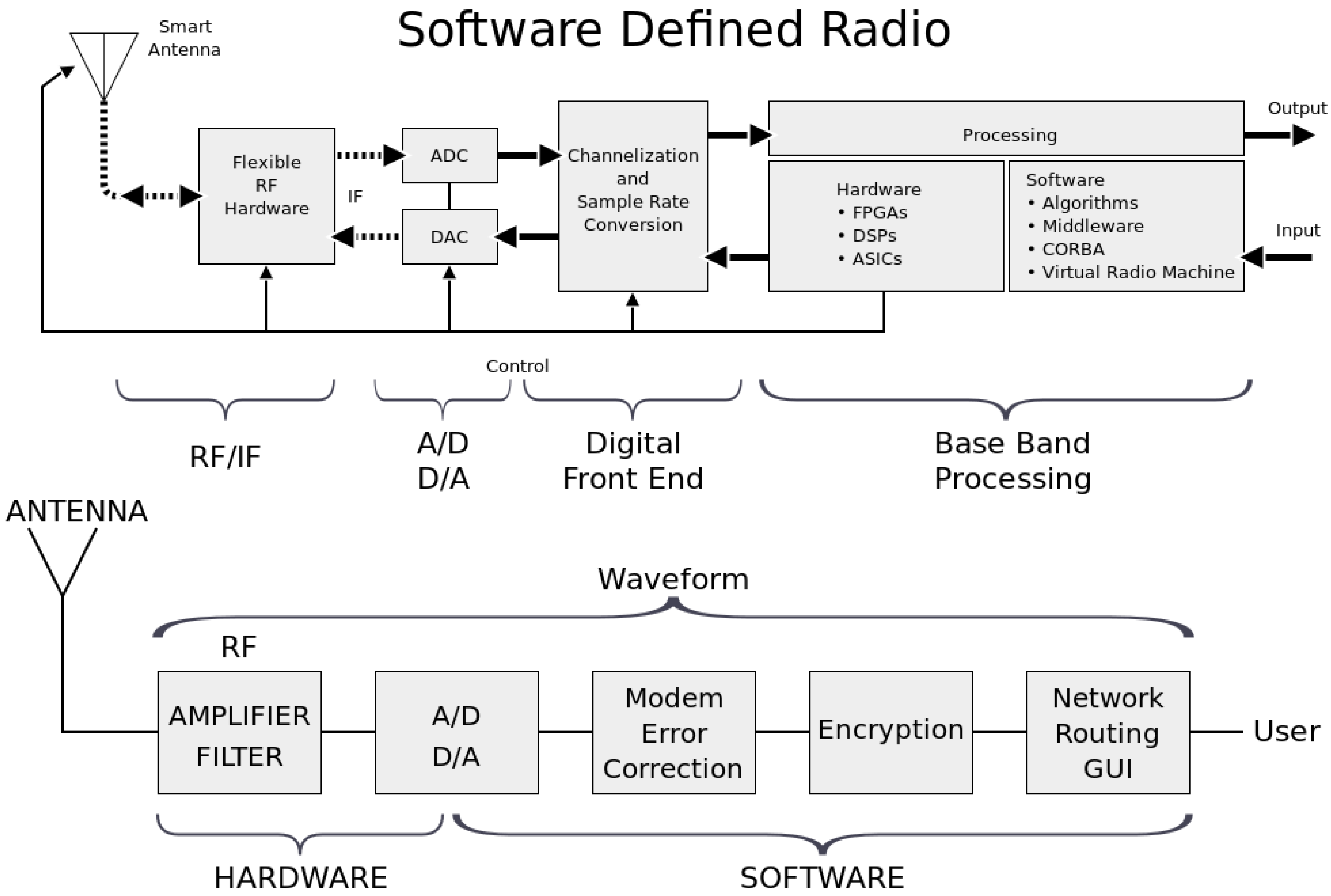
- Block Diagram of a Digital Communications Receiver



1. Communication Systems

❑ Block Diagram of a Software-Defined Radio

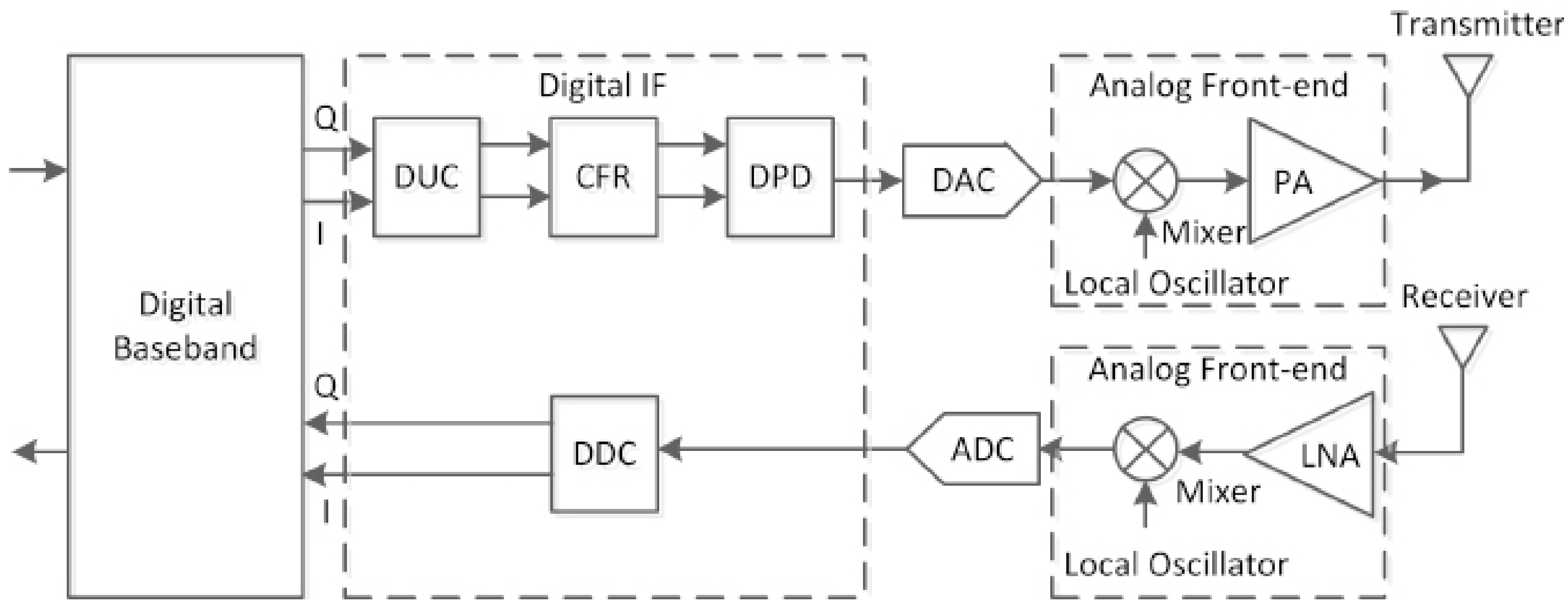
Source: inst.eecs.Berkeley.edu/~ee15a/sp15/Labs/wireless/



1. Communication Systems

❑ Another Block Diagram of a Software-Defined Radio

Source: cblelectronics.com



Friis Equation Origins

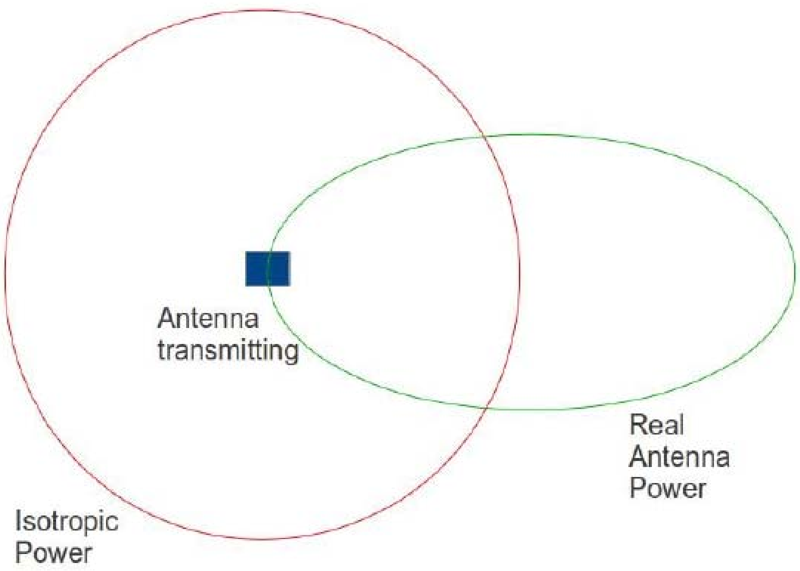
- Derived in 1945 by Bell Labs worker Harald T. Friss
- Gives the amount of power an antenna received under ideal conditions from another antenna
  - Antennas must be in far field
  - Antennas are in unobstructed free space
  - Bandwidth is narrow enough that a single wavelength can be assumed
  - Antennas are correctly aligned and polarized

Simple Form of Friis Equation

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

- P_r : Power at the receiving antenna
- P_t : output power of transmitting antenna
- G_t, G_r: gain of the transmitting and receiving antenna, respectively
- λ: wavelength
- R: distance between the antenna

Power Density at Receiving Antenna Aperture



Multiplying by gain of the transmitting antenna gives a real antenna pattern

$$p = \frac{P_t}{4\pi R^2} G_t$$

EIRP (Effective Isotropically Radiated Power)

$$\mathrm{EIRP} = P_t G_t \ (\mathrm{W})$$

2. Friis Transmission Equation

❑ Received Power

- G_t in natural unit (not in dB)

$G_t\,(\mathrm{dB}) = 10\log_{10} G_t$

$G_t = 10^{G_t\,(\mathrm{dB})/10}$

- If receiving antenna has an effective aperture of A_{eff} the power received by this antenna (P_r) is

$$P_r = p\,A_{eff}$$

thus:

$$P_r = \frac{P_t}{4\pi R^2} G_t A_{eff}$$

❑ Antenna Effective Aperture

- The effective aperture of an antenna can be written as

$$A_e = \frac{\lambda^2}{4\pi} G$$

plugging in:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

2. Friis Transmission Equation

❑ Free-Space Loss

$$\text{Free-Space Loss} = \left(\frac{\lambda}{4\pi R}\right)^2$$

- Low frequency better? Yes, in some cases.

- But antenna will be larger at low frequencies.

❑ Power in dBm

P (dBm) = 10log10[P (W)/0.001 (W)]

1 mW = 0 dBm

10 mW = 10 dBm

1 μW = −30 dB

Modifications to Friis equation (Complicated Form)

$$\frac{P_r}{P_t} = G_t(\theta_t, \varphi_t) G_r(\theta_r, \varphi_r) \left(\frac{\lambda}{4\pi R}\right)^2 (1 - |\Gamma_t|^2)(1 - |\Gamma_r|^2) |\boldsymbol{a}_t \cdot \boldsymbol{a}_r^*|^2 e^{-\alpha R}$$

- G_t , G_r : modifications to gain of antennas in which the antennas “see” each other.
- Γ_t and Γ_t are the reflection coefficients of the antennas
- $\mathbf{a}_t$ and $\mathbf{a}_r$ are the polarization vectors of the antennas
- α is the absorption coefficient of the medium

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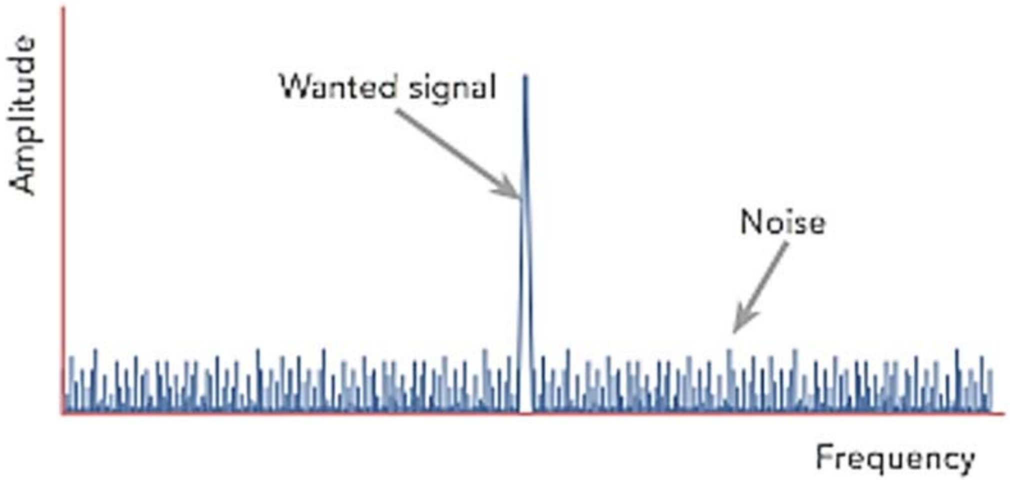
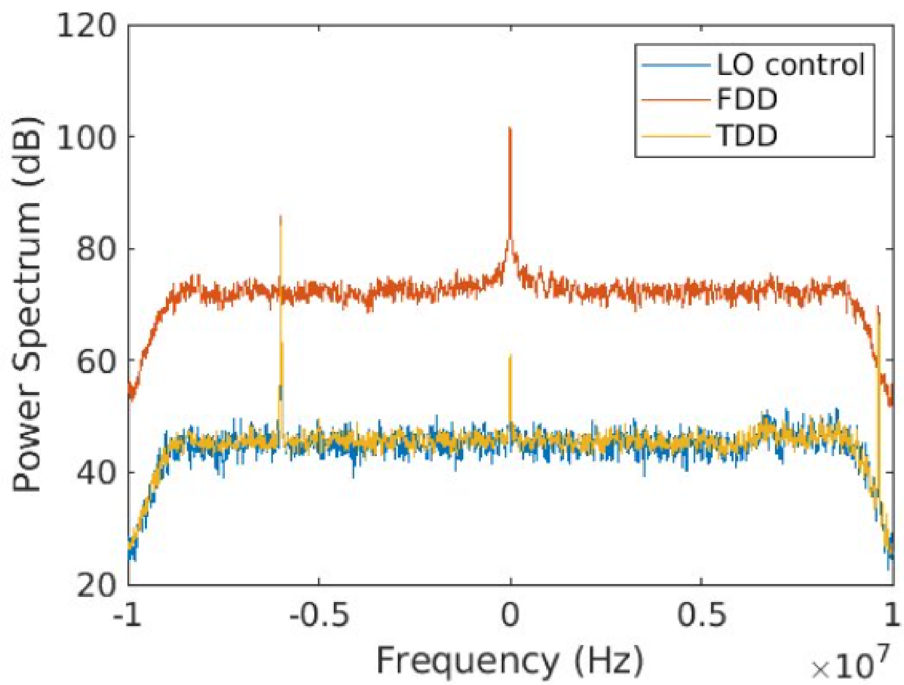
3. Receiver Noise





3. Receiver Noise

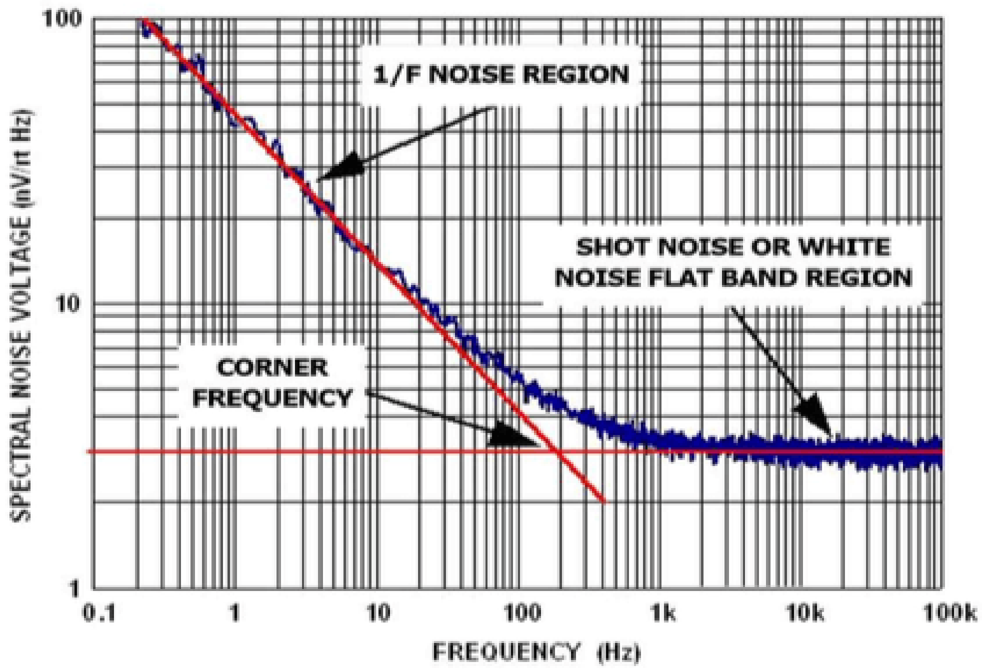
$N = kT_sB$: Thermal (or White) noise power at receiver

$k = 1.38 \times 10^{-23}$ J/K : Boltzmann constant

T_s: receiver noise temperature (K)

B: receiver bandwidth (Hz)

$$N\ (\text{dBm}) = 10\log_{10}\frac{N(\text{W})}{0.001(\text{W})} = 10\log_{10}\frac{N(\text{W})}{1\ \text{mW}}$$



4. Link Budget

In this course we have focused on narrowband radio systems where a sinusoidal signal is assumed. In practise, the sinusoid acts as a carrier for the information signal, which is the true "signal". Hence, strictly speaking, the SNR refers to this power of the recovered signal power to noise power. We will use the term *carrier-to-noise ratio (CNR)* to refer to the received carrier power. Here, we will use the symbol c to refer to the received carrier power and n to the noise power.

Friis' formula can be written as

$$C = EIRP \left(\frac{\lambda}{4\pi r} \right)^2 \frac{G_r}{l}$$

where l is other losses over and above the free-space loss, and EIRP has been defined previously as the product of the transmit power and transmit gain (effective radiated isotropic power). It could be polarization loss factor, impedance mismatch loss, diffraction loss, plane-earth reflection loss, etc. including a combination of these effects.

4. Link Budget

The carrier-to-noise power ratio is found by setting $N = kT_S B$:

$$\frac{C}{N} = EIRP \left(\frac{\lambda}{4\pi r}\right)^2 \frac{G_r}{lkT_S B}$$

It is common to represent the CNR over 1 Hz of signal bandwidth ($B = 1$ Hz), so that the resulting expression can simply divided by the bandwidth to get the ratio:

$$\frac{C}{N_0} = EIRP \left(\frac{\lambda}{4\pi r}\right)^2 \frac{1}{lk} \frac{G_r}{T_S}$$

In dB, this expression becomes

$$\left[\frac{C}{N_0}\right]_{\mathsf{dB}} = EIRP - FSL - L + \left[\frac{G_r}{T_S}\right]_{\mathsf{dB}} + 228.6 \qquad \text{(units: dB-Hz)}$$

where $10\log(1/k) = 228.6$ dBW/K-Hz. Note that receive antenna's gain and the receiver temperature are grouped together as a ratio that is often called the *receiver figure of merit*. This

4. Link Budget

per-Hz form of the CNR is useful since the CNR can be found for any signal bandwidth by simply subtracting $10\log B$:

$$\left[\frac{C}{N}\right]_{\text{dB}} = EIRP - FSL - L + \left[\frac{G_r}{T_S}\right]_{\text{dB}} + 228.6 - 10\log(B) \qquad \text{(units: dB)}$$

Hence, a link budget is obtained by "accounting" for each of these terms in a budget in dB units, where losses are "negative" and gains are "positive". Usually, L must be expanded into a larger summation of terms to account for each of the loss effects that we have studied in detail in this course.

Link Margin

As discussed in class, some additional margin is usually provided for in the implementation of the system so that it can deal with worst-case fading caused by the atmosphere and other effects. The margin is usually introduced by increasing a combination of the transmit power, transmit antenna gain, and receive antenna gain. Often, it is the margin that is of most interest in the budget, since it tells you how much room is built into the link budget. If the minimum required CNR CNR_{req} is known, the margin is simply the difference in dB between the actual CNR and the required CNR:

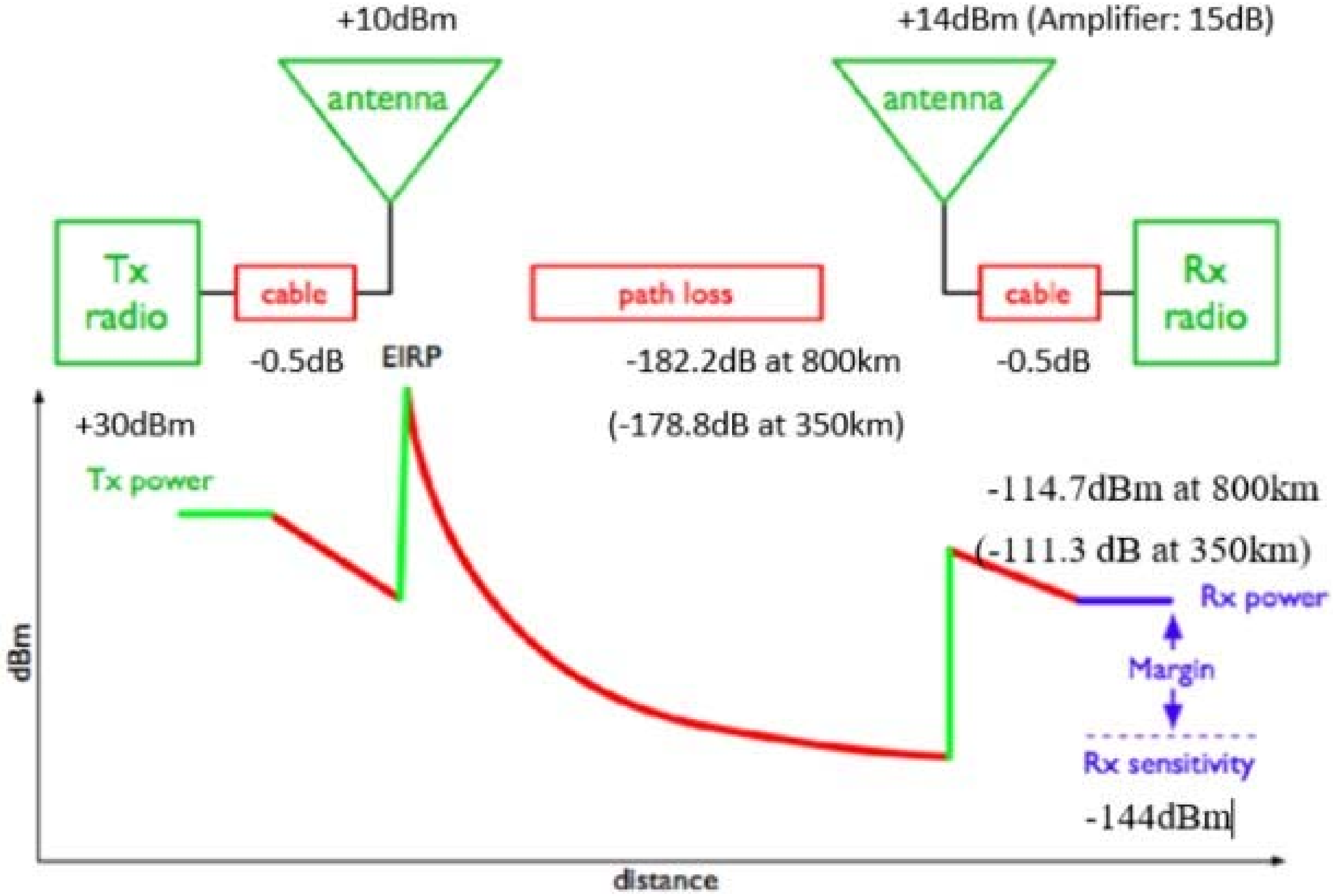
$$M = EIRP - FSL - L + \left[\frac{G_r}{T_S}\right]_{\mathrm{dB}} + 228.6 - 10\log(B) - \left[\frac{C}{N}\right]_{req,\mathrm{dB}}$$

A nice example link budget for a satellite system is taken from page 229 of Sklar, B., "Digital Communications: Fundamentals and Applications", Prentice-Hall, 1998, and is shown in Table 1. It is an uplink budget (from the earth terminal to the satellite) at 8 GHz, covering a distance of 40,721 km. The bandwidth of the satellite signal is 2 MHz.

4. Link Budget

	Description	Symbol	Value	Notes
1.	Transmit power	W_t	**20.0 dBW**	100.0 W
2.	Transmit circuit loss	$-L_t$	-2.0 dB	
3.	Transmitter antenna gain	G_t	51.6 dBi	20 ft dia. dish, 55.1% efficiency
4.	Terminal EIRP	$EIRP$	**69.6 dBW**	
5.	Free space path loss	$-FSL$	-202.7 dB	
6.	Fade allowance	$-L$	-4.0 dB	Rain fade allowance
7.	Other losses	$-L$	-6.0 dB	Other losses
8.	Received isotropic power	W_r/G_r	**-143.1 dBW**	Received power before gain
9.	Receiver antenna gain	G_r	35.1 dBi	3 ft dia. dish 55.1% efficiency
10.	Edge of coverage loss	$-L$	-2.0 dB	
11.	Received signal power	W_r	**-110.0 dBW**	
12.	Noise PSD	N_0	-192.5 dBW/Hz	$N_0 = kT_S$, $T_S = 4106$ K
13.	Received W_r/N_0	W_r/N_0	**82.5 dB-Hz**	
14.	Bandwidth	$-B$	-63.0 dB-Hz	$10\log(2$ MHz$)$
15.	Received CNR	CNR	**19.5 dB**	
16.	Implementation loss	$-L$	-1.5 dB	e.g. detector efficiency
17.	Required CNR	$-CNR_{req}$	-10.0 dB	
18.	Link margin	M	**8.0 dB**	

4. Link Budget



5. Coding Problems

1. Write a Python coded for the following problem.

Friis formula: EIRP, power density at receiver, receiving antenna effective aperture, received power

(Input)

f: frequency (Hz)

pt: tx power (dBm)

gt: tx antenna gain (dB)

gr: rx antenna gain (dB)

r: tx-rx distance (m)

(Output)

eirp: effective isotropically radiated power (W)

pd: power density at receiver (W/m^2)

fsL: free-space loss (dB)

ae: receiving antenna effective aperture (m^2)

pr: received power (W)

prdbm: received power in dBm

5. Coding Problems

2. Write a Python code for the following problem.

Link budget calculation

(Input)

pt: tx power (dBm)

gt: tx antenna gain (dB)

txL: tx side loss (dB)

gr: rx antenna gain (dB)

r: tx-rx distance (m)

rxL: rx side loss (dB)

ts: receiver noist temperature (K)

b: receiver bandwidth (Hz)

f: frequency (Hz)

(Output)

eirp: effective isotropically radiated power (dBm) with Tx-side loss included

pd: power density at receiver (dBm/m^2)

ae: receiving antenna effective aperture (m^2)

pr: received power (dBm) before the inclusion of Rx-side loss

sr: received signal power (dBm) after the inclusion of Rx-side loss

n: receiver noise power (dBm)

cnr: carrier-to-noise power ratio (dB)

Fin

(End)