2017 2Q

Wireless Communication Engineering

#2 Link Budget Design for Wireless Access

Kei Sakaguchi

sakaguchi@mobile.ee.

June 15, 2017

Course Schedule (1)

	Date	Text	Contents
#1	June 12	1, 7	Introduction to wireless communication systems
#2	June 15	2, 5, etc	Link budget design of wireless access
#3	June 19		Up/down conversion and equivalent baseband system
#4	June 22	3.3, 3.4	Digital modulation and pulse shaping
#5	June 26	3.5	Demodulation and detection error due to noise
#6	June 29		Collaborative exercise for better understanding 1
#7	July 3	4.4	Channel fading and diversity combining
#8	July 6	4.6	Error correction coding

From Previous Lecture

- Introduction to wireless communication systems
  BAN, PAN, LAN, MAN, ITU, PHY, MAC

- Design of wireless communication systems
  Frequency, Bandwidth, Tx power, Antenna, PHY scheme

- Factor of performance degradation
  Fading, Inter symbol interference, Inter system interference

- IEEE802.11a WLAN
  WLAN using OFDM and adaptive modulation coding

Contents

- Channel capacity
- Bandwidth & frequency
- Signal-to-Noise Ratio (SNR)
- Antenna & coverage
- Multiple access
- Design of wireless access

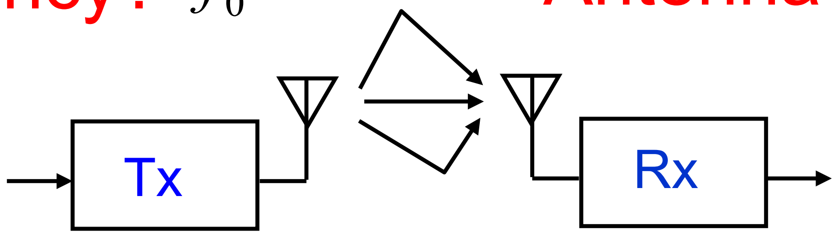
Design of Wireless Communication Systems

How to design wireless communication systems?

Frequency? f_0

Antenna? $G_\mathrm{t}, G_\mathrm{r}$

Bandwidth? B



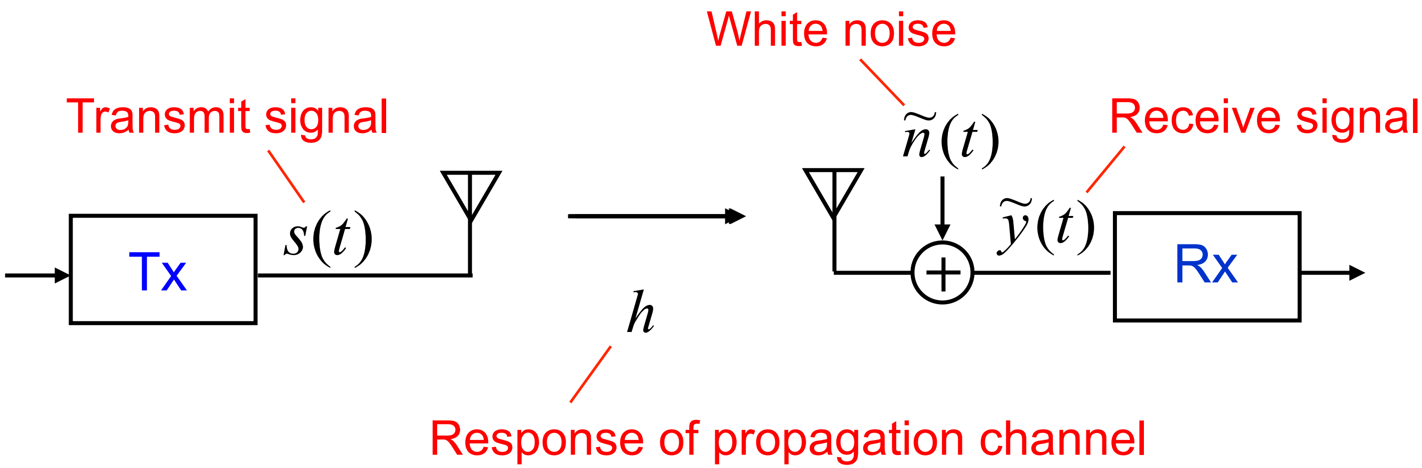
PHY layer? R

Transmit power? P_t

MAC layer? N_UE

System Model

- System model of wireless communications



- Receive signal

Linear time invariant system: $$\tilde{y}(t) = hs(t) + \tilde{n}(t)$$

Signal-to-Noise Ratio

- Complex system model

$s(t) = s_R(t) + js_I(t)$ ⟶ Transmit power $P_t = \mathrm{E}\left[|s(t)|^2\right]$

$\tilde{n}(t) = \tilde{n}_R(t) + j\tilde{n}_I(t)$ ⟶ Noise power $P_n = \mathrm{E}\left[|\tilde{n}(t)|^2\right]$

$h = h_R + jh_I$ ⟶ Channel gain $G_h = |h|^2$

- Signal-to-Noise Ratio

Most important parameter to qualify the system

$$\gamma = \frac{G_h P_t}{P_n} = \frac{P_r}{P_n}$$

Channel Capacity

- Channel capacity of complex system

Theoretical upper bound of achievable data rate

$$C = C_R + C_I = B\log_2\left(1 + \frac{G_h P_t}{P_n}\right) = B\log_2(1+\gamma) \quad \text{[bps]}$$

Bandwidth (B), SNR (γ)

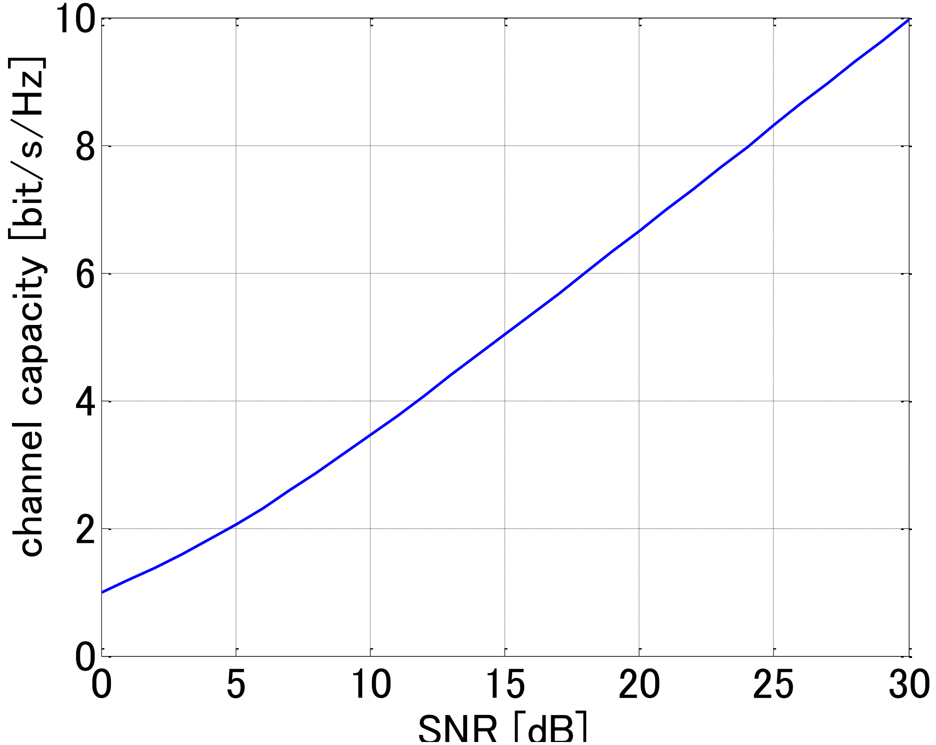
$$= B \times R$$

Bit rate (spectrum efficiency) [bps/Hz] (R)

$$C_R = C_I = \frac{B}{2}\log_2\left(1 + \frac{G_h P_t/2}{P_n/2}\right) = \frac{B}{2}\log_2(1+\gamma)$$

Channel Capacity

$$C = B\log_2(1+\gamma)\ [\text{bps}]$$



Bandwidth & Frequency

- Frequency & bandwidth

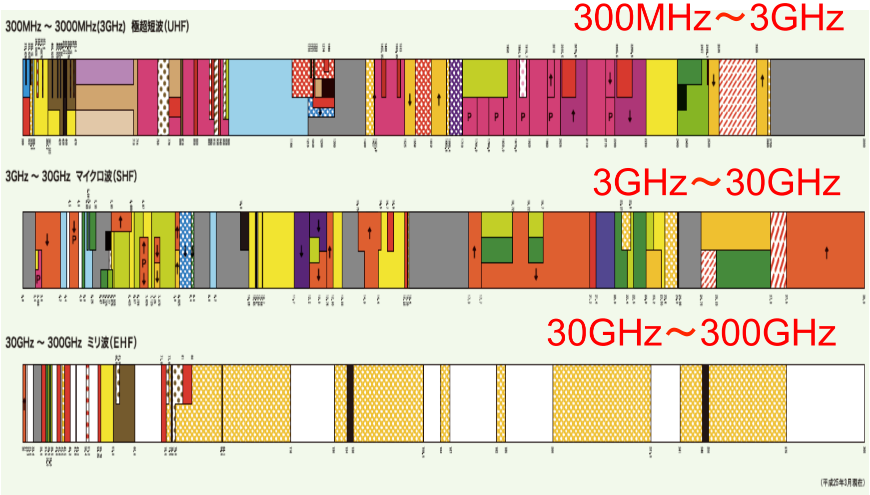
Bandwidth is proportional to center frequency due to available spectrum resource and limitation of RF circuit

$$B = \alpha f_0$$

f_0 : Center frequency [Hz]

α : Relative bandwidth
1% is normal

Spectrum allocation in Japan



- Capacity & frequency

$$C = B \log_2(1+\gamma) = \alpha f_0 \log_2(1+\gamma)$$

Noise Power & Frequency

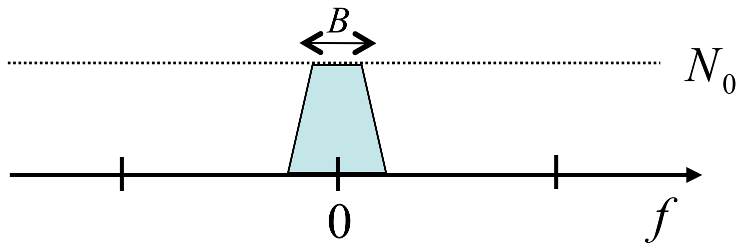
- Power of thermal noise

Noise power is proportional to center frequency

$$P_{\mathrm{n}} = N_0 B = \alpha N_0 f_0$$

$$N_0 = kT_{\mathrm{emp}}$$

$$k = 1.38\times 10^{-23}\ \text{[Joules/K]}$$



- Example of noise power

$$T_{\mathrm{emp}} = 290\ \text{[K]}$$

$$kT_{\mathrm{emp}} = -174\ \text{[dBm/Hz]}$$

$$B = 10\ \text{[MHz]} \rightarrow P_{\mathrm{n}} = -104\ \text{[dBm]}$$

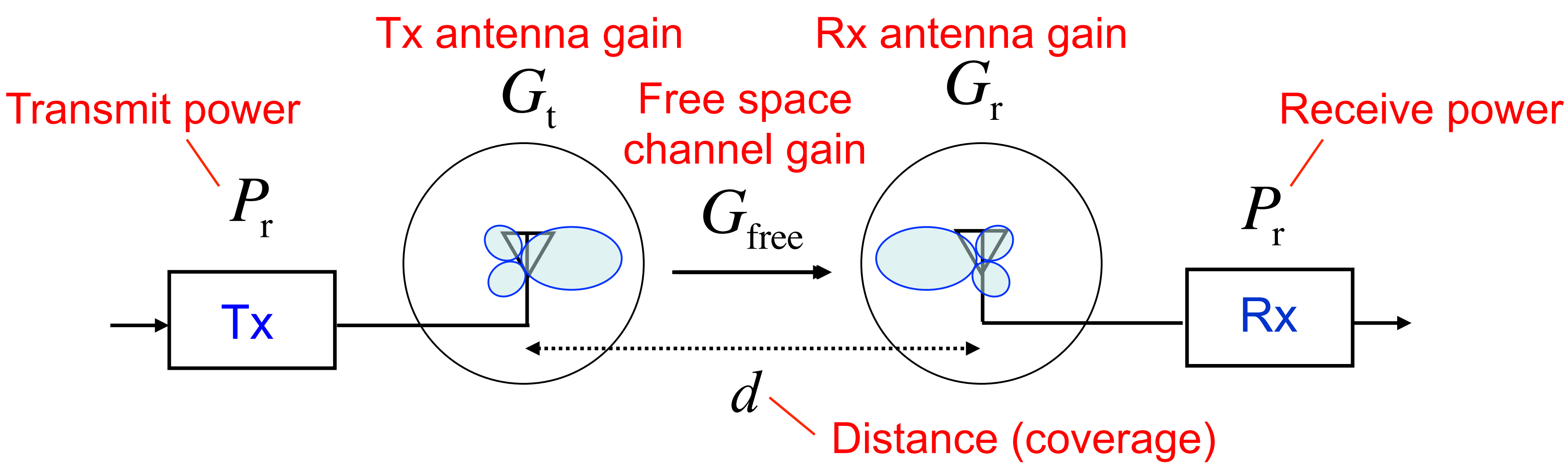
Friis Propagation Model

- Friis propagation model

$$P_{\mathrm{r}} = A_{\mathrm{r}} \frac{G_{\mathrm{t}} P_{\mathrm{t}}}{4\pi d^2} = \left(\frac{\lambda_0}{4\pi d} \right)^2 G_{\mathrm{r}} G_{\mathrm{t}} P_{\mathrm{t}} = G_{\mathrm{free}} G_{\mathrm{r}} G_{\mathrm{t}} P_{\mathrm{t}} = G_{\mathrm{h}} P_{\mathrm{t}}$$

$$A_{\mathrm{r}} = G_{\mathrm{r}} \frac{\lambda_0^2}{4\pi}$$

Effective aperture of antenna is squarely proportional to wavelength



Channel Gain & Frequency

- Channel gain in free space

Channel gain is inversely proportional to square of distance & center frequency

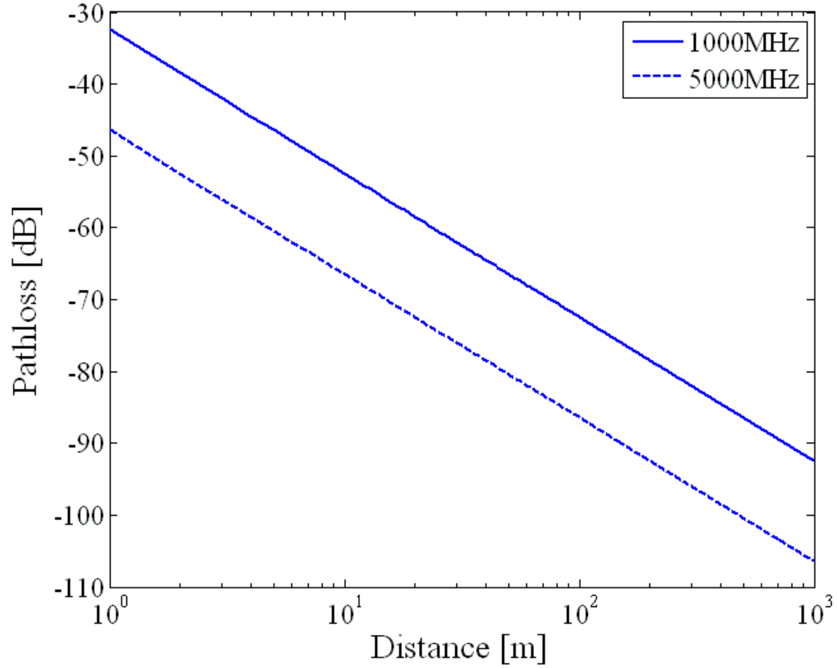
$$G_{\text{free}} = \left(\frac{\lambda_0}{4\pi d}\right)^2 = \left(\frac{c}{4\pi f_0 d}\right)^2$$

- Example of channel gain

$$f_0 = 5 \ \ [\text{GHz}], d = 100 \ [\text{m}]$$

$$G_{\text{free}} \cong -85 \ [\text{dB}]$$

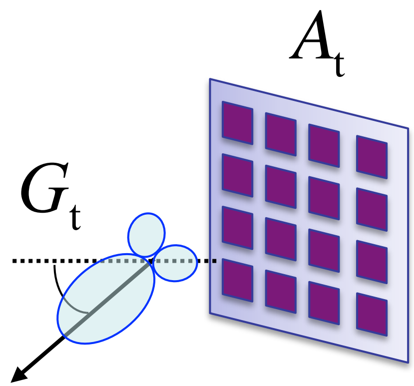
Free space channel gain



Antenna Gain & Frequency

- Antenna gain

If the size of antenna aperture is fixed,
antenna gain is squarely proportional to center frequency



$$A_t = G_t \frac{\lambda_0^2}{4\pi} \longrightarrow G_t = A_t \frac{4\pi}{\lambda_0^2} = A_t \frac{4\pi f_0^2}{c^2}$$

- Example of antenna gain

$$f_0 = 1 \ \text{[GHz]}, \lambda_0 = 30 \ \text{[cm]} \longrightarrow G_t = 1$$

$$f_0 = 30 \ \text{[GHz]}, \lambda_0 = 1 \ \text{[cm]} \longrightarrow G_t = 900$$

SNR & Frequency

- SNR

Assuming antenna gain of user terminal is small,
SNR is inversely proportional to
center frequency and square of distance

Assuming $G_{\mathrm{r}} = 1$

$$\gamma = \frac{G_{\mathrm{free}} G_{\mathrm{t}} P_{\mathrm{t}}}{P_{\mathrm{n}}} = \frac{A_{\mathrm{t}} P_{\mathrm{t}}}{4\pi\alpha N_0 f_0 d^2}$$

- Example of SNR

$$P_{\mathrm{t}} = 1\,[\mathrm{mW}] = 0\,[\mathrm{dBm}]$$

$$G_{\mathrm{free}} = -85\ [\mathrm{dB}]$$

$$G_{\mathrm{t}} = 11\ [\mathrm{dB}]$$

$$P_{\mathrm{n}} = -104\ [\mathrm{dBm}]$$

$$\gamma = 30\ [\mathrm{dB}]$$

$$R \cong 10\ [\mathrm{bps/Hz}]$$

Free space channel gain:

$$G_{\mathrm{free}} = \left(\frac{c}{4\pi f_0 d} \right)^2$$

Tx antenna gain:

$$G_{\mathrm{t}} = A_{\mathrm{t}} \frac{4\pi f_0^2}{c^2}$$

Noise power:

$$P_{\mathrm{n}} = \alpha N_0 f_0$$

Coverage

- Coverage

Coverage is the maximum distance satisfying minimum required SNR

$$d_0 = \max d \ \text{ s.t. } \gamma \geq \gamma_0$$

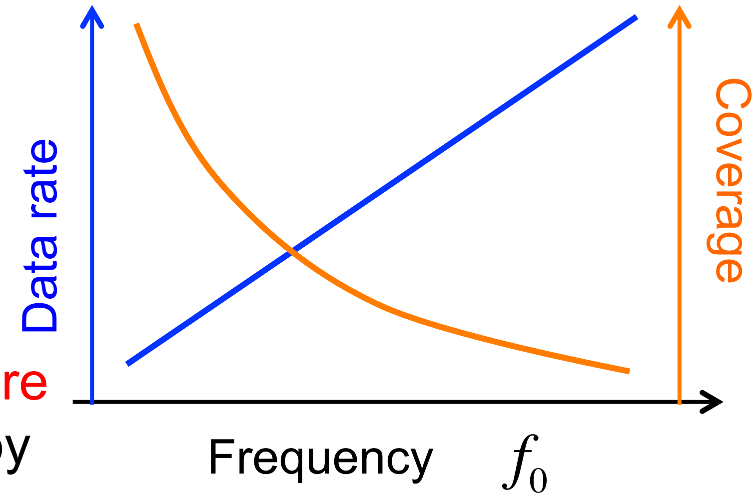
$$\gamma = \frac{G_{\mathrm{free}} G_{\mathrm{t}} P_{\mathrm{t}}}{P_{\mathrm{n}}} = \frac{A_{\mathrm{t}} P_{\mathrm{t}}}{4\pi\alpha N_0 f_0 d^2}$$

⇩

Coverage is inversely proportional to square root of center frequency and controllable by transmit power & antenna aperture

$$d_0 = \sqrt{\frac{A_{\mathrm{t}} P_{\mathrm{t}}}{4\pi\alpha N_0 f_0 \gamma_0}} = \beta f_0^{-\frac{1}{2}}$$

Data rate & coverage



Multiple Access

■ User rate

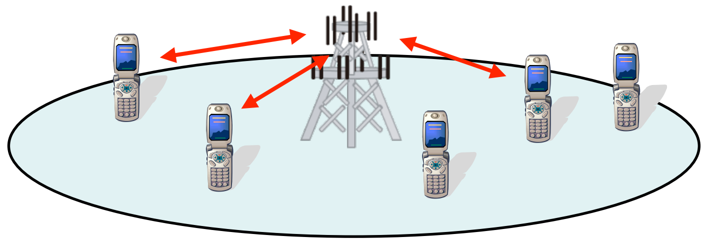
Radio resources are equally divided into multiple users

$$C_{\mathrm{UE}} = \frac{B \log_2 (1+\gamma)}{N_{\mathrm{UE}}} \quad \text{[bps/user]}$$

$N_{\mathrm{UE}} = \pi d_0^2 \eta$: # of users in the coverage

η : Density of users [users/m^2]

Multiple access



■ Cell (coverage) edge user rate

Cell edge user rate is squarely proportional to center frequency

$$C_{\mathrm{UE0}} = \frac{\alpha f_0 \log_2 (1+\gamma_0)}{\pi d_0^2 \eta} \longrightarrow C_{\mathrm{UE0}} = \frac{\alpha f_0 \log_2 (1+\gamma_0)}{\pi \beta^2 f_0^{-1} \eta} = \delta f_0^2$$

Design of Wireless Access

- Passive type

  Conventional design of wireless systems:

$$f_0, B, P_\mathrm{t} \longrightarrow d_0^\mathrm{req} \longrightarrow G_\mathrm{t} \longrightarrow C_\mathrm{UE0}$$

- Active type

  System design for higher frequency & small cells:

$$C_\mathrm{UE0}^\mathrm{req} \longrightarrow N_\mathrm{UE}, C \longrightarrow d_0, B, R \longrightarrow f_0, P_\mathrm{t}, G_\mathrm{t}$$

- P2P type

  Satellite communication, etc.:

$$d_0^\mathrm{req}, C_0^\mathrm{req} \longrightarrow f_0, B, P_\mathrm{t} \longrightarrow R \longrightarrow G_\mathrm{t}$$

Summary

- Channel capacity

$$C = B\log_2(1+\gamma) = \alpha \times f_0 \times R \ \ \text{[bps]}$$

- Friis propagation model

$$P_\mathrm{r} = \left(\frac{\lambda_0}{4\pi d}\right)^2 G_\mathrm{r} G_\mathrm{t} P_\mathrm{t} \qquad \gamma = \left(\frac{\lambda_0}{4\pi \mathrm{d}}\right)^2 \cdot \frac{G_\mathrm{r} G_\mathrm{t} P_\mathrm{t}}{P_\mathrm{n}}$$

- User rate and multiple access

$$C_\mathrm{UE} = \frac{B\log_2(1+\gamma)}{N_\mathrm{UE}} = \frac{B\log_2(1+\gamma)}{\pi d_0^2 \eta}$$

- Design of wireless access systems

$$C_\mathrm{UE0}^\mathrm{req} \longrightarrow N_\mathrm{UE}, C \longrightarrow d_0, B, R \longrightarrow f_0, P_\mathrm{t}, G_\mathrm{t}$$

Information & Entropy

■ Information of transmit symbol

$P(s)$: Probability of transmission

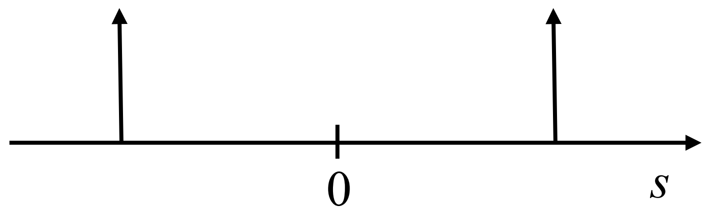
$$I(s) = \log_2 \frac{1}{P(s)} = -\log_2 P(s)$$

■ Entropy of transmit signal

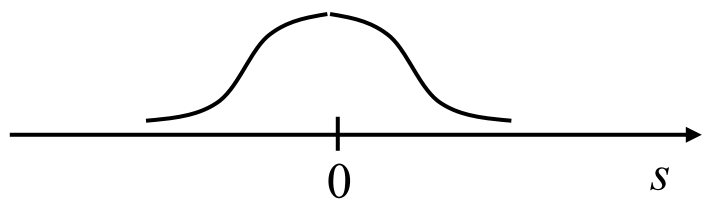
$$H(s) = \mathrm{E}[I(s)] = \int P(s) I(s) \, \mathrm{d}\,s$$

$$= -\int P(s) \log_2 P(s) \, \mathrm{d}\,s$$

Binary probability



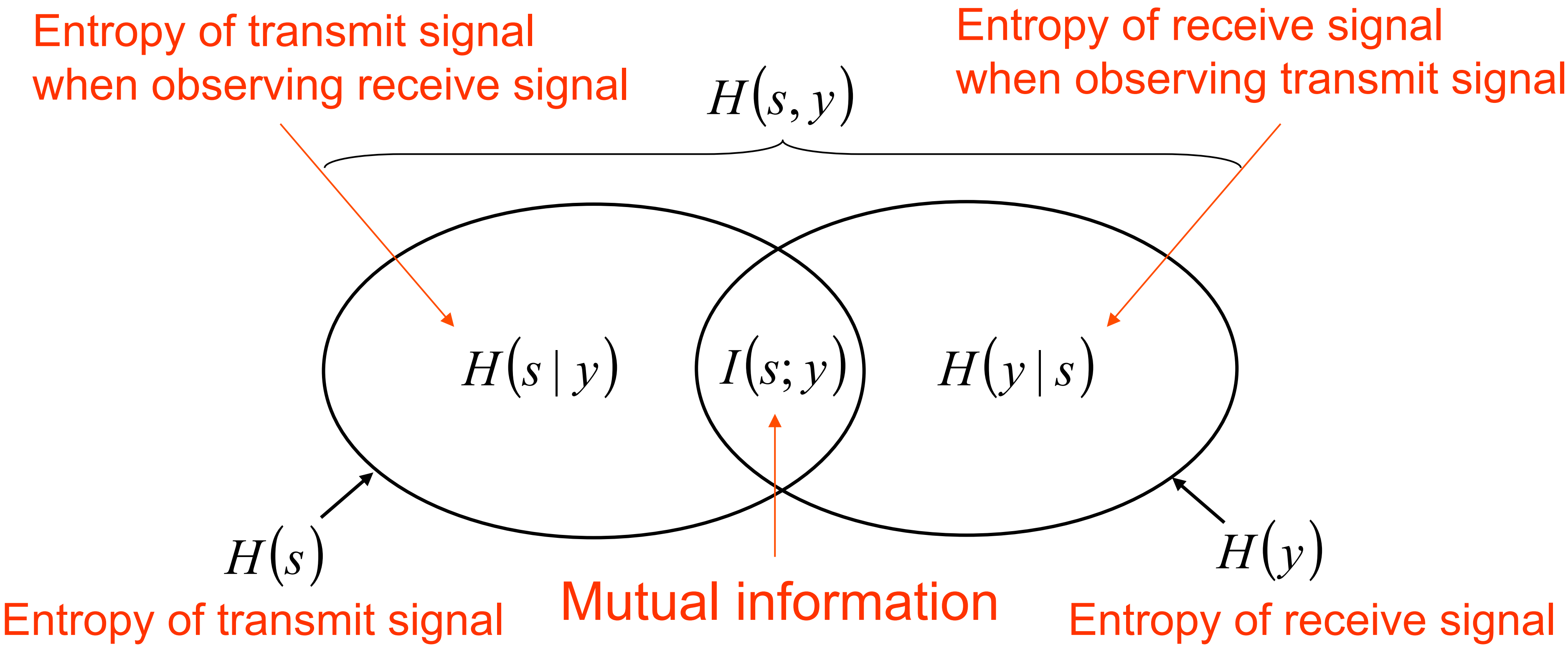
Gaussian probability



Mutual Information

$$y(t) = \frac{\tilde{y}(t)}{h} = s(t) + \frac{\tilde{n}(t)}{h} = s(t) + n(t)$$

$$I(s;y) = H(y) - H(y \mid s)$$



Entropy of Noise

- Conversion of conditional entropy

$$H(y \mid s) = H(s + n \mid s) = H(n)$$

- Entropy of Gaussian noise

$$P(n) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{n^2}{2\sigma^2}}$$

$$H(n) = -\int P(n) \log_2 P(n) \mathrm{d}\, n = \frac{1}{2} \log_2 2\pi e \sigma^2 = \frac{1}{2} \log_2 2\pi e \frac{P_{\mathrm{n}}}{h^2}$$

Channel Capacity (Real)

- Channel capacity

$$C_{\mathrm{R}} = \frac{1}{T} \max_{\mathrm{E}[s^2] \le P_{\mathrm{t}}} I(s;y) = \frac{1}{T} \max_{\mathrm{E}[s^2] \le P_{\mathrm{t}}} H(s+n) - H(n)$$

Time period needed to transmit a symbol

- Maximization of mutual entropy

Fano's inequality

$$H(s+n) \le \frac{1}{2}\log_2 2\pi e\left(P_{\mathrm{t}} + \frac{P_{\mathrm{n}}}{h^2}\right) = \frac{1}{2}\log_2 2\pi e\left(P_{\mathrm{t}} + \frac{P_{\mathrm{n}}}{G_{\mathrm{h}}}\right)$$

$$C_{\mathrm{R}} = \frac{1}{T}\left(\frac{1}{2}\log_2 2\pi e\left(P_{\mathrm{t}} + \frac{P_{\mathrm{n}}}{G_{\mathrm{h}}}\right) - \frac{1}{2}\log_2 2\pi e \frac{P_{\mathrm{n}}}{G_{\mathrm{h}}}\right) = \frac{1}{2T}\log_2\left(1 + \frac{G_{\mathrm{h}} P_{\mathrm{t}}}{P_{\mathrm{n}}}\right)$$

Signal−to-Noise Ratio (SNR)