2016 2Q

Wireless Communication Engineering

#2 Link Budget Design for Wireless Access

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Course Schedule (1)

	Date	Text	Contents
#1	June 17	1, 7	Introduction to wireless communication systems
#2	June 17	2, 5, etc	Link budget design of wireless access
#3	June 24		Up/down conversion and equivalent baseband system
#4	June 24	3.3, 3.4	Digital modulation and pulse shaping
	July 1		No class
#5	July 8	3.5	Demodulation and detection error due to noise
#6	July 8	4.4	Channel fading and diversity combining

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

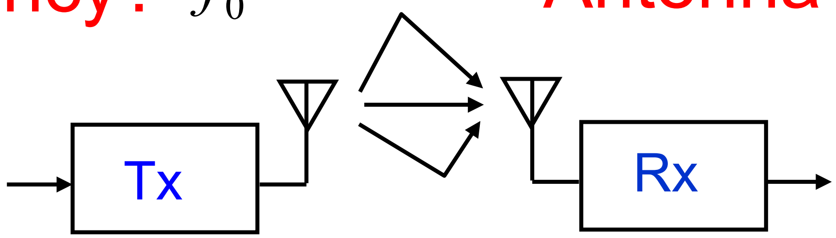
Design of Wireless Communication Systems

How to design wireless communication systems?

Frequency? f_0

Antenna? G_t

Bandwidth? B



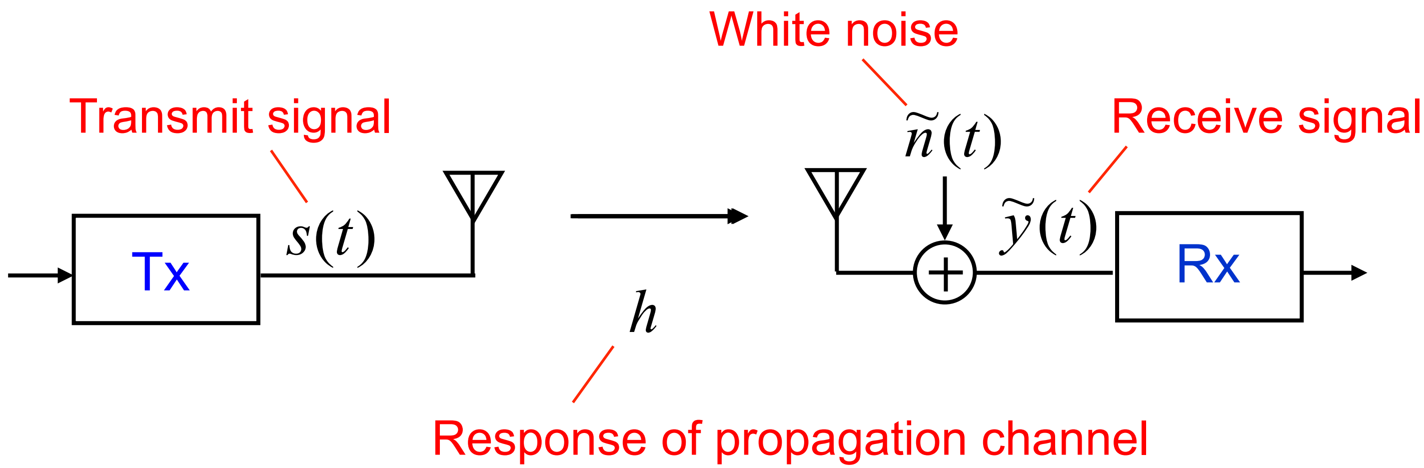
PHY layer? R

Transmit power? P_t

MAC layer? N_UE

System Model

- System model of wireless communications



- Receive signal

$$\tilde{y}(t) = hs(t) + \tilde{n}(t)$$

Transmit power

$$P_{\mathrm{t}} = \mathrm{E}\left[|s(t)|^2\right]$$

Channel gain

$$g = h^2$$

Noise power

$$P_{\mathrm{n}} = \mathrm{E}\left[|\tilde{n}(t)|^2\right]$$

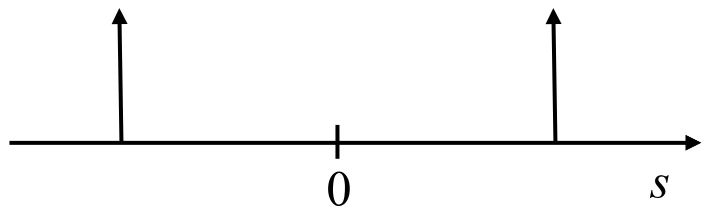
Information & Entropy

- Information of transmit symbol

$P(s)$: Probability of transmission

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

Binary probability

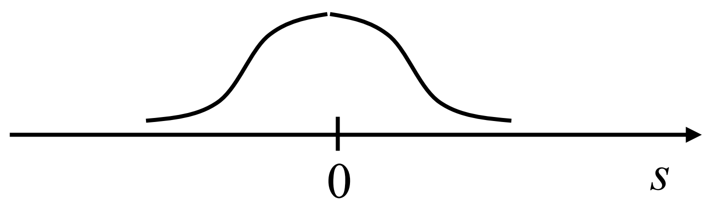


- Entropy of transmit signal

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

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

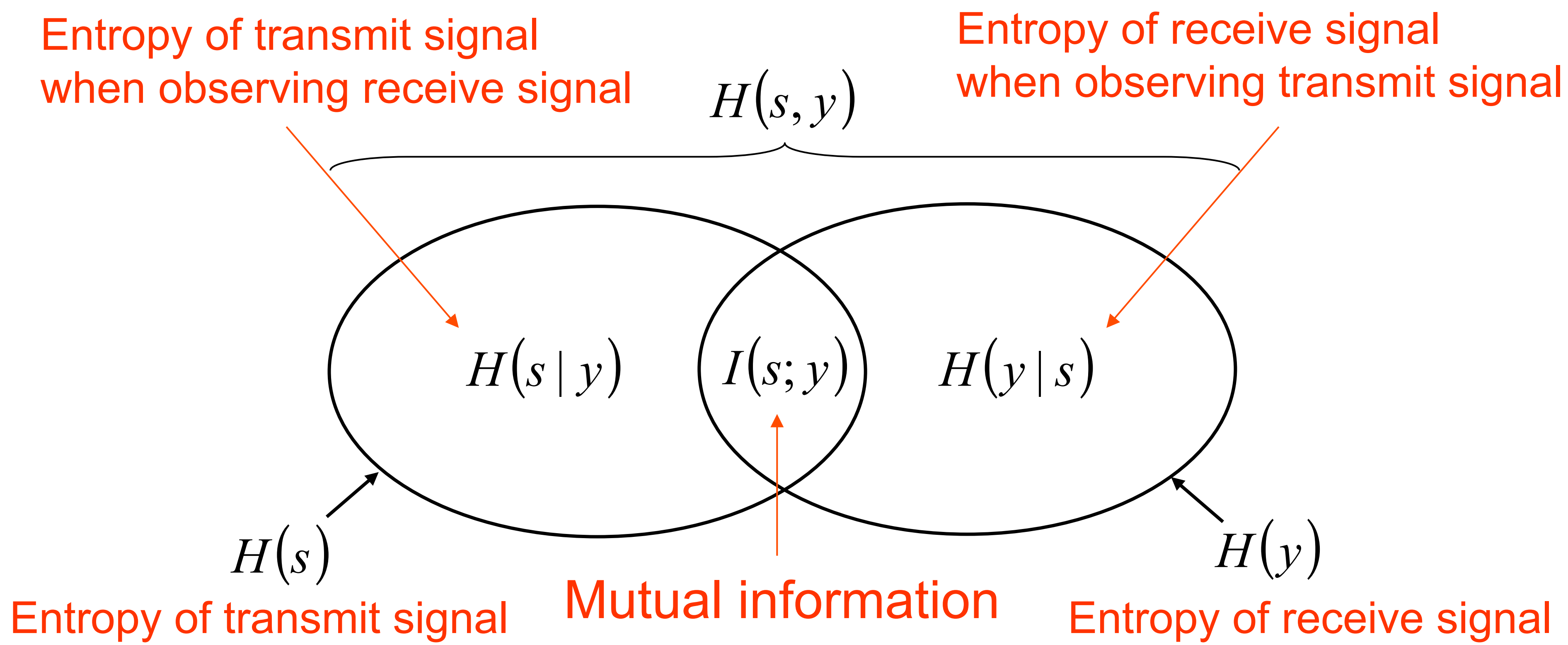
Gaussian probability



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

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

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

Signal−to-Noise Ratio (SNR)

Channel Capacity (Complex)

- Complex system model

$$s(t) = s_{\mathrm{R}}(t) + j s_{\mathrm{I}}(t), \qquad P_{\mathrm{t}} = \mathrm{E}\left[|s(t)|^2 \right]$$

$$\tilde{n}(t) = \tilde{n}_{\mathrm{R}}(t) + j \tilde{n}_{\mathrm{I}}(t), \qquad P_{\mathrm{n}} = \mathrm{E}\left[|\tilde{n}(t)|^2 \right]$$

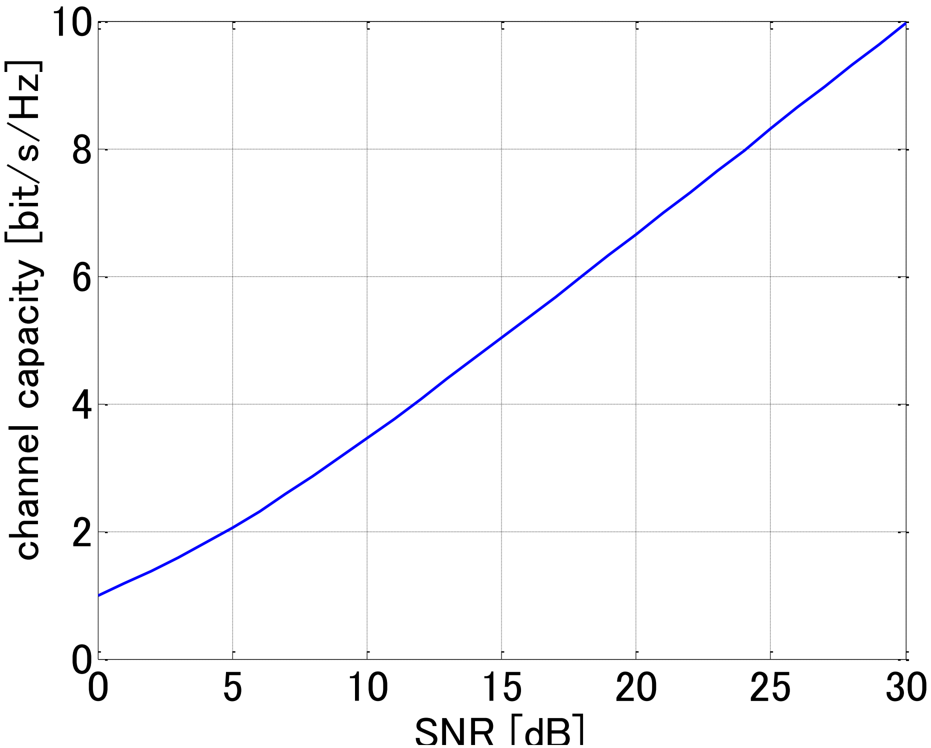
- Channel capacity of complex system

$$C_{\mathrm{R}} = \frac{1}{2T} \log_2 \left(1 + \frac{G_{\mathrm{h}} P_{\mathrm{t}}/2}{P_{\mathrm{n}}/2} \right) \qquad C_{\mathrm{I}} = \frac{1}{2T} \log_2 \left(1 + \frac{G_{\mathrm{h}} P_{\mathrm{t}}/2}{P_{\mathrm{n}}/2} \right)$$

$$C = \frac{2}{2T} \log_2 \left(1 + \frac{G_{\mathrm{h}} P_{\mathrm{t}}/2}{P_{\mathrm{n}}/2} \right) = B \log_2 (1 + \underbrace{\gamma}_{\text{SNR}}) = \underbrace{B}_{\text{Bandwidth}} \times \underbrace{R}_{\text{Bit rate}} \ \text{[bps]}$$

Channel Capacity

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



Bandwidth & Frequency

■ Frequency & bandwidth

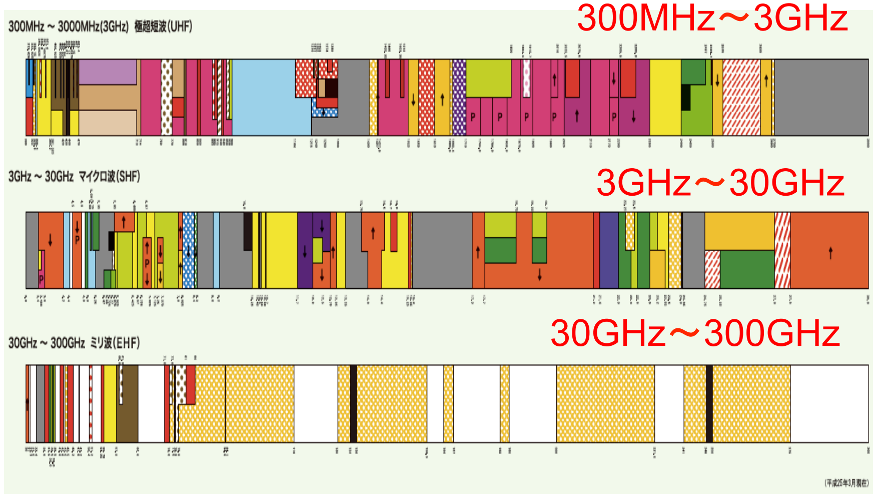
Bandwidth is proportional to center frequency due to available spectrum resource and limitation of RF circuit

$$B = \alpha f_0$$

f_0 : Center frequency [Hz]

α : Relative bandwidth
1% is normal

Spectrum allocation in Japan



■ Capacity & frequency

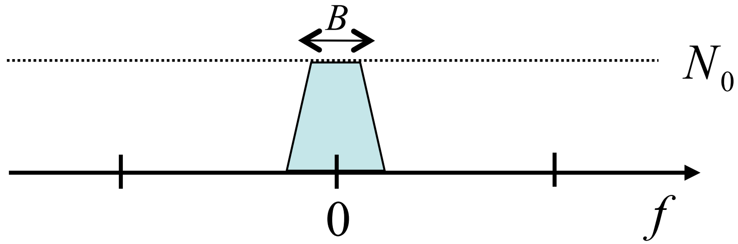
$$C = B\log_2(1+\gamma) = \alpha f_0 \log_2(1+\gamma)$$

Noise Power

- Power of thermal noise

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

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



- Example of noise power

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

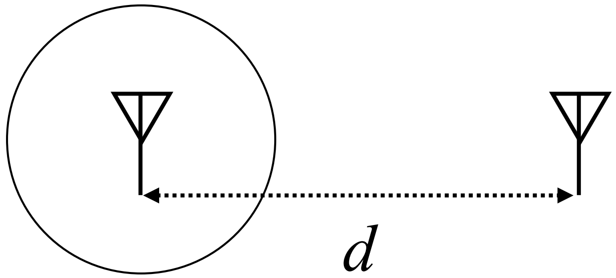
$$kT_{\mathrm{emp}} = -174 \text{ [dBm/Hz]}$$

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

Propagation Loss

- Friis propagation model

$$P_r = A_r \frac{G_t P_t}{4\pi d^2} = \left(\frac{\lambda_0}{4\pi d}\right)^2 G_r G_t P_t$$



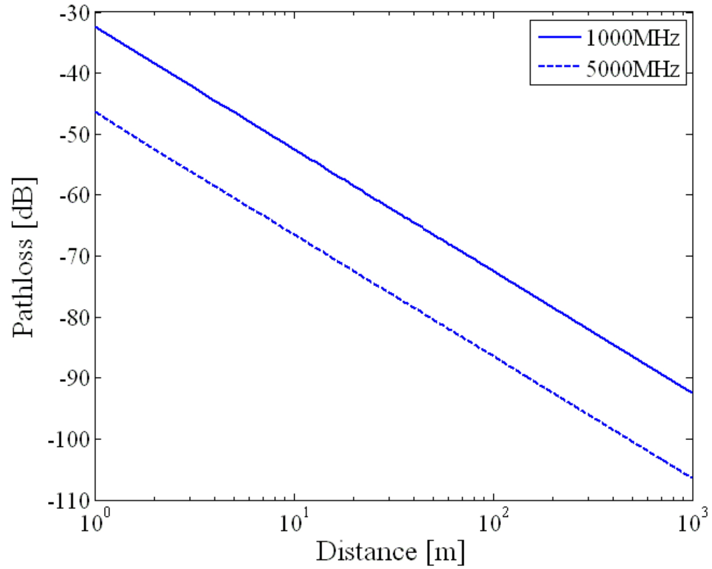
$$A_r = G_r \frac{\lambda_0^2}{4\pi}$$ Effective aperture of antenna

- Free space path loss

$$G_h = 10\log_{10}\left(\frac{\lambda_0}{4\pi d}\right)^2$$

$$= 10\log_{10}\left(\frac{c}{4\pi f_0 d}\right)^2$$

Free space path loss



Coverage

- SNR & coverage

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

$$\gamma = \frac{G_\mathrm{h} P_\mathrm{t}}{P_\mathrm{n}} = \frac{P_\mathrm{t}}{\alpha f_0 B} \cdot \left(\frac{c}{4\pi f_0 d} \right)^2$$

Example of SNR

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

$$G_\mathrm{h} \cong -85\,[\mathrm{dB}]\,@\,5\,[\mathrm{GHz}], 100\,[\mathrm{m}]$$

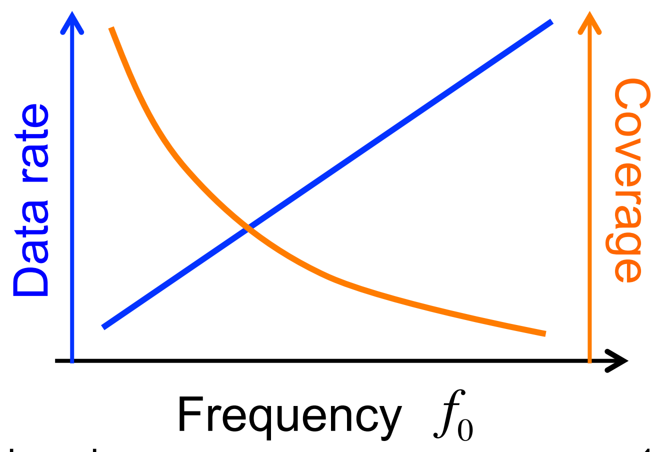
$$P_\mathrm{n} = -104\,[\mathrm{dBm}]\,@\,10\,[\mathrm{MHzBW}]$$

$$\gamma = 19\,[\mathrm{dB}] \quad R \cong 6\,[\mathrm{bps/Hz}]$$

- Coverage & frequency

$$d_0 = \frac{c}{4\pi f_0^{3/2}} \sqrt{\frac{P_\mathrm{t}}{\alpha N_0 \gamma_0}}$$

Data rate & coverage

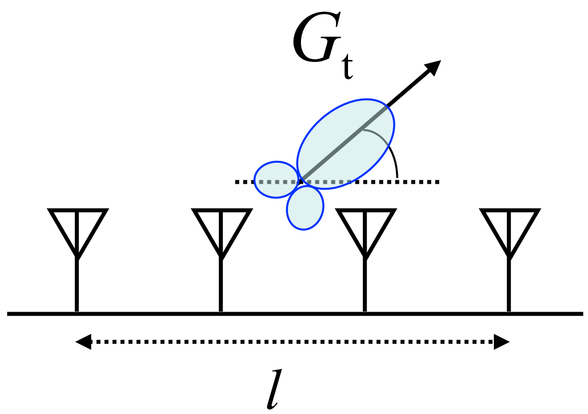


Antenna

- Antenna gain & receive power

$$P_{\mathrm{r}} = G_{\mathrm{h}} G_{\mathrm{r}} G_{\mathrm{t}} P_{\mathrm{t}}$$

$$\gamma = \frac{G_{\mathrm{h}} G_{\mathrm{r}} G_{\mathrm{t}} P_{\mathrm{t}}}{P_{\mathrm{n}}}$$



- Antenna gain & coverage

Omni: $G_{\mathrm{r}} = 1$

Linear: $G_{\mathrm{t}} = \frac{l}{\lambda_0} G_{\mathrm{t0}} = \frac{l}{c} f_0 G_{\mathrm{t0}} \longrightarrow d_0 = \frac{c}{4\pi f_0} \sqrt{\frac{l G_{\mathrm{t0}} P_{\mathrm{t}}}{\alpha c N_0 \gamma_0}}$

Multiple Access

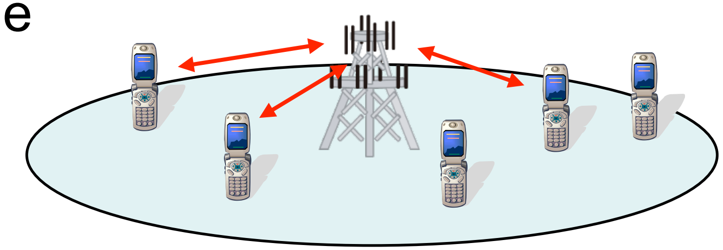
- User rate

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

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

η : Density of users [users/m^2]

Multiple access



- Cell (coverage) edge user rate

If $G_{\mathrm{t}} = \frac{l}{c} f_0 G_{\mathrm{t0}}$

$$C_{\mathrm{UE0}} = \frac{\alpha f_0 \log_2(1+\gamma_0)}{\pi d_0^2 \eta} \longrightarrow C_{\mathrm{UE0}} = \frac{16\pi\alpha^2 N_0 \gamma_0 \log_2(1+\gamma_0)}{c\eta l G_{\mathrm{t0}} P_{\mathrm{t}}} f_0^3$$

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

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