2018 2Q

Wireless Communication Engineering

#2 Link Budget Design for Wireless Access

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Course Schedule (1)

	Date	Text	Contents
#1	June 11	1, 7	Introduction to wireless communication systems
#2	June 14	2, 5, etc	Link budget design of wireless access
#3	June 18		Up/down conversion and equivalent baseband system
#4	June 21	3.3, 3.4	Digital modulation and pulse shaping
#5	June 25	3.5	Demodulation and matched filter
#6	June 28		Collaborative exercise for better understanding 1
#7	July 2	3.5	Detection and error due to noise
#8	July 5	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

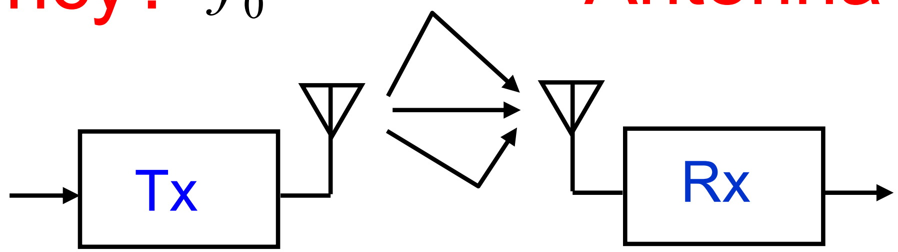
Design of Wireless Communication Systems

How to design wireless communication systems?

Frequency? f_0

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

Bandwidth? B



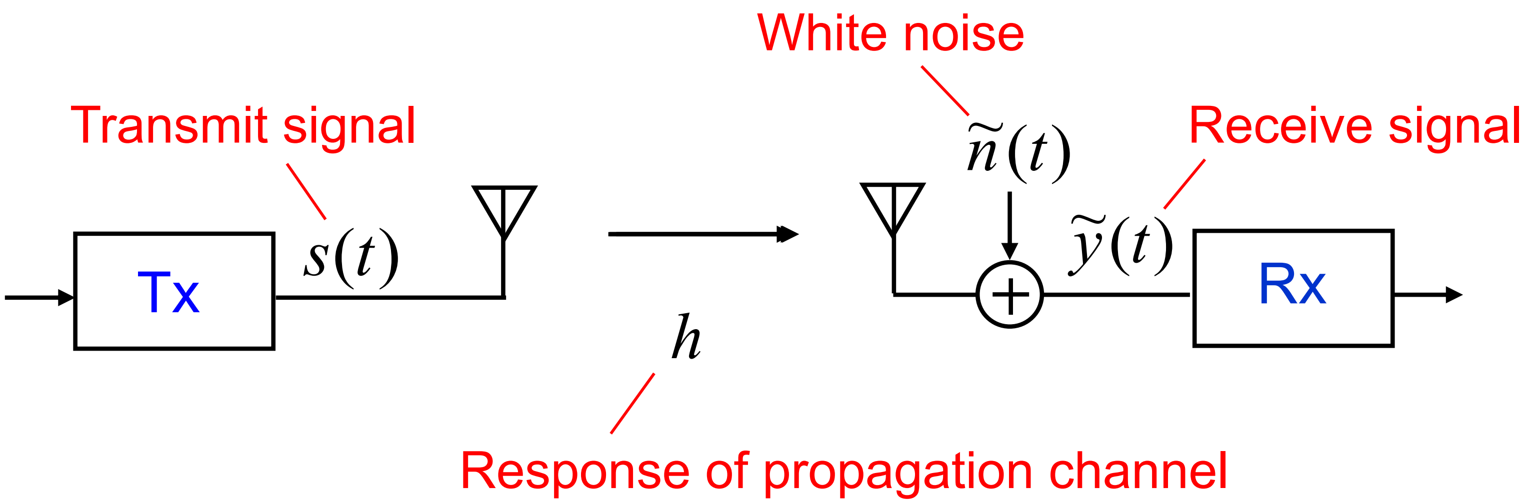
PHY layer? R

Transmit power? P_t

MAC layer? N_UE

System Model

- System model of wireless communications



- Receive signal

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

Signal-to-Noise Ratio

- Complex system model

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

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

$$h = h_R + jh_I \longrightarrow$$ 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

Bandwidth

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

SNR

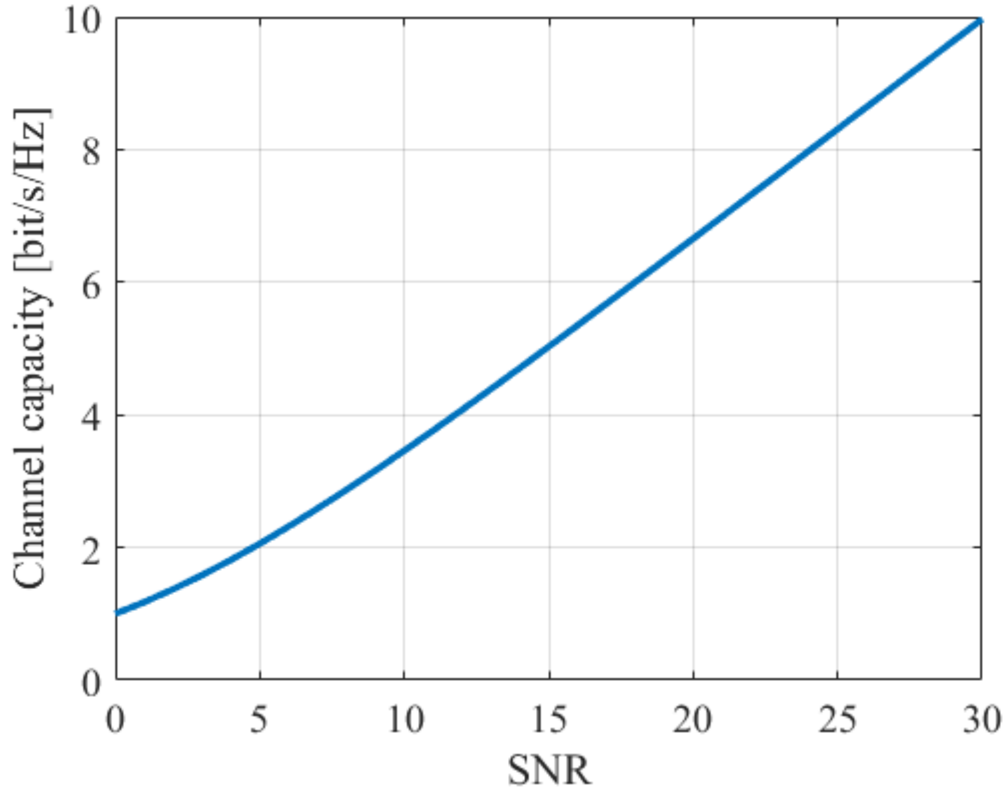
$$= B \times R$$

Bit rate (spectrum efficiency) [bps/Hz]

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

Channel Capacity

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



Bandwidth & Frequency

- Frequency & bandwidth

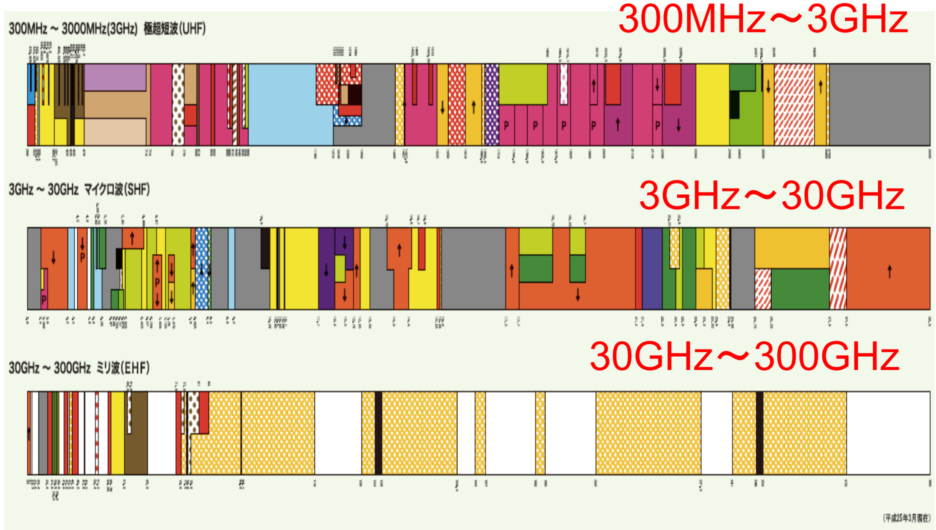
Bandwidth is proportional to center frequency due to available spectrum resource and limitation of RF circuit

$$B = \alpha f_0$$

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

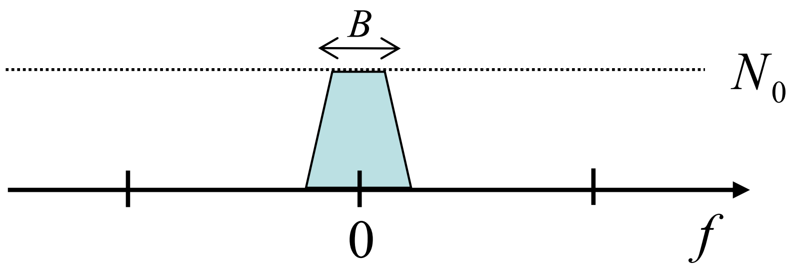
- Power of thermal noise

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

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

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

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

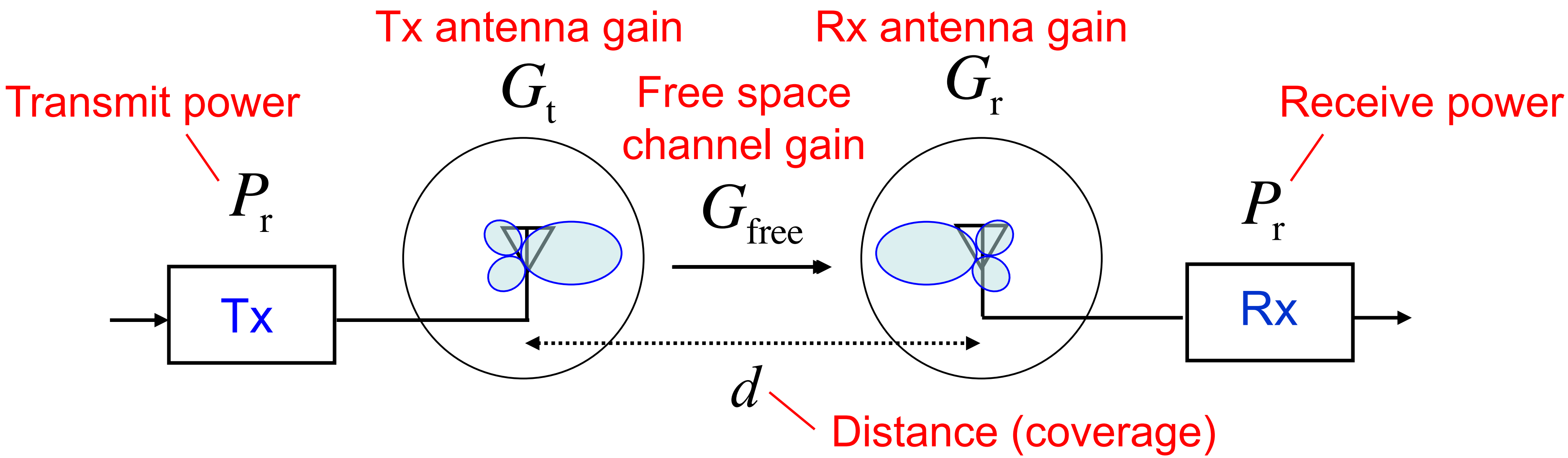
Friis Propagation Model

- 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

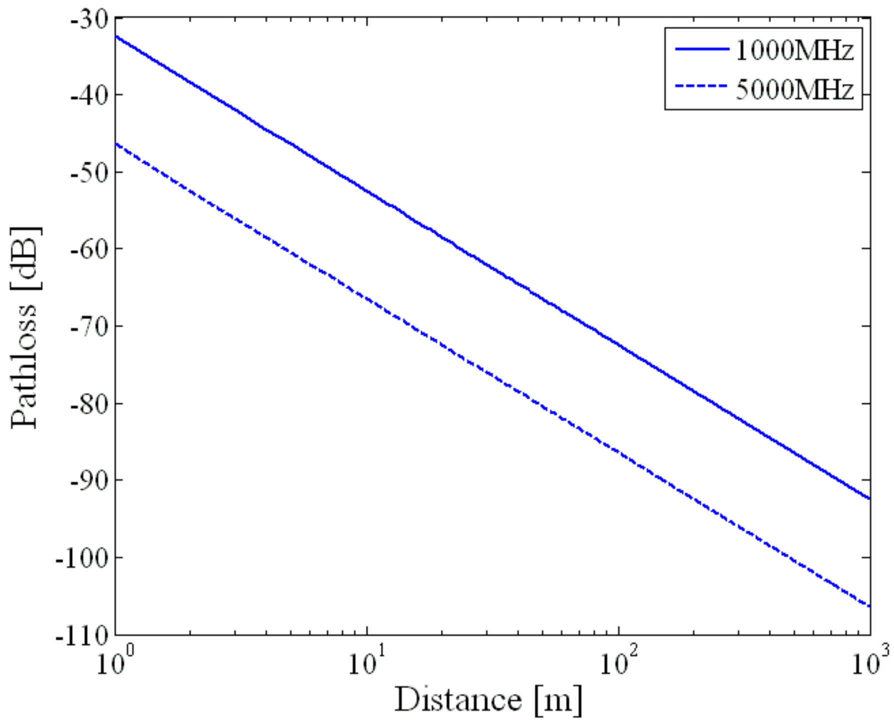
$$G_{\text{free}} = \left(\frac{\lambda_0}{4\pi d}\right)^2 = \left(\frac{c}{4\pi f_0 d}\right)^2$$

- Example of channel gain

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

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

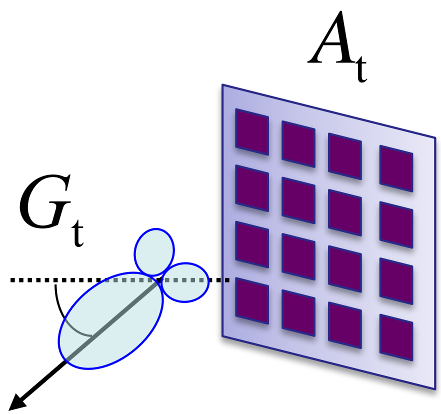
Free space channel gain



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 $G_r = 1$

$$\gamma = \frac{G_{\mathrm{free}} G_t P_t}{P_n} = \frac{A_t P_t}{4\pi\alpha N_0 f_0 d^2}$$

- Example of SNR

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

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

$$G_t = 11\ [\mathrm{dB}]$$

$$P_n = -104\ [\mathrm{dBm}]$$

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

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

Free space channel gain:

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

Tx antenna gain:

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

Noise power:

$$P_n = \alpha N_0 f_0$$

Coverage

- Coverage

Coverage is the maximum distance satisfying minimum required SNR

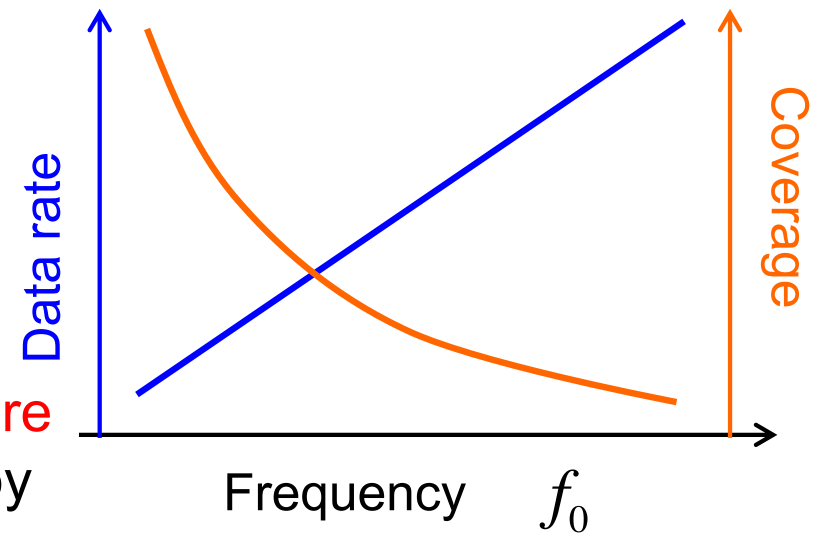
$$d_0 = \max d \;\; \text{s.t.} \;\; \gamma \geq \gamma_0$$

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

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

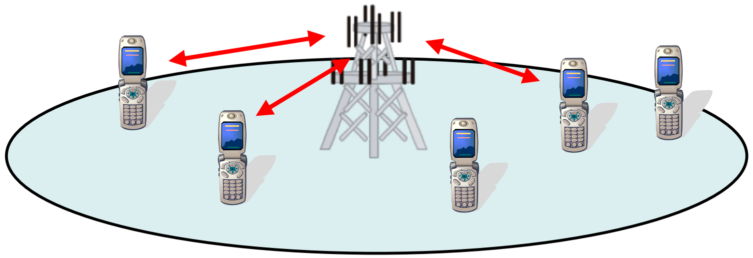
Radio resources are equally divided into multiple users

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

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

η : Density of users [users/m²]

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:

$$f_0, B, P_\mathrm{t} \longrightarrow d_0^\mathrm{req} \longrightarrow G_\mathrm{t} \longrightarrow C_{\mathrm{UE}0}$$

- Active type

  System design for higher frequency & small cells:

$$C_{\mathrm{UE}0}^\mathrm{req} \longrightarrow N_\mathrm{UE}, C \longrightarrow d_0, B, R \longrightarrow f_0, P_\mathrm{t}, G_\mathrm{t}$$

- 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

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

- 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

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

- Design of wireless access systems

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