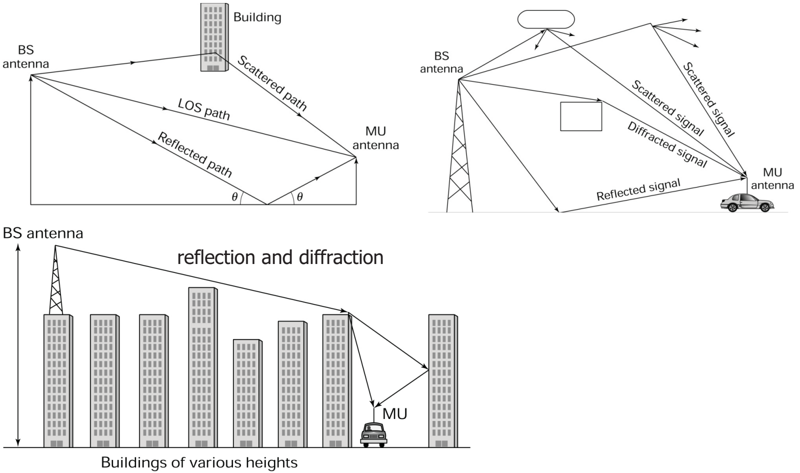
Chapter 2: Wireless Channel models

Multipath wireless propagation



Extracted from Digital Communication lecture notes, McGill Uni.

Path loss, shadowing and fading

- The characteristic of (mobile) wireless channel is the variations of the channel strength over time and frequency.
- The variations can be divided into two types:
    - **Large-scale** fading is yielded by:
        - **path loss** of signal as a function of distance and
        - **shadowing** by large objects such as buildings and hills.
    - **Small-scale** fading is yielded by the *constructive* and *destructive* interference of the multiple signal paths between transmitter and receiver.

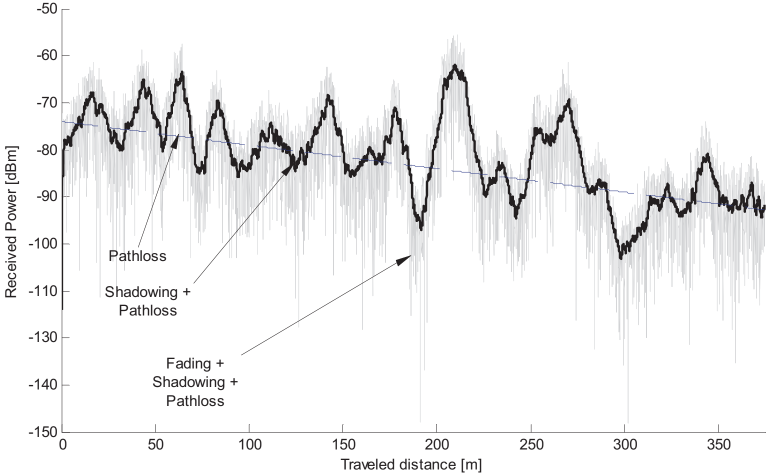
      Question: Why do both constructive and destructive intereference happen?

Path loss, shadowing and fading

- For Large-scale fading :
  - **path loss**: Received power variation due to path loss occurs over long distances (100-1000 m)
  - **shadowing**: Variation due to shadowing occurs over distances that are proportional to the length of the obstructing object (10-100 m in outdoor environments and less in indoor environments)

$\rightarrow$ Since variations in received power due to path loss and shadowing occur over relatively large distances, these variations are referred to as large-scale propagation effects.

An example of path loss, shadowing and fading



An example of path loss, shadowing and fading (cont.)

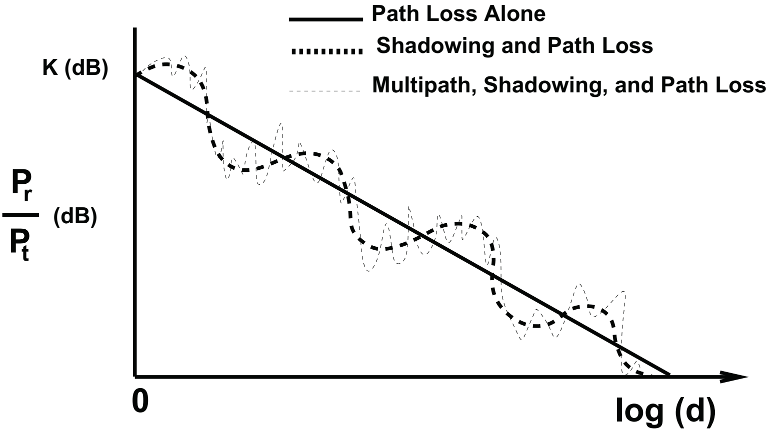


Figure 1: Effects of path loss, shadowing, and multipath on received power as a function of distance.

Path loss models

- It is well known that the received signal power decays with the square of the path length in **free space**.
- More specifically, the received envelope power is introduced by Friis:

$$\boxed{P_r = P_t G_t G_r \left(\frac{\lambda_c}{4\pi d}\right)^2}, \tag{1}$$

where:

- P_t is the transmitted power,
- G_t and G_r are the transmitter and receiver antenna gains, respectively
- d is the radio path length.

Path loss models (cont.)

- The signals in land mobile radio applications, however, do not experience free space propagation. A more appropriate theoretical model assumes propagation over a flat reflecting surface (the earth).

$$P_r = 4P_t \left(\frac{\lambda_c}{4\pi d}\right)^2 G_t G_r \sin^2\left(\frac{2\pi h_b h_m}{\lambda_c d}\right), \tag{3}$$

where h_b and h_m are the heights of the BS and MS antennas, respectively.

- Under the condition that $d \gg h_b h_m$, (3) reduces to

$$P_r = P_t G_t G_r \left(\frac{\lambda_c}{4\pi d}\right)^2, \tag{4}$$

where we have used the approximation $\sin x \approx x$ for small x.

Path loss models (cont.)

- The path loss is defined by

$$\begin{aligned} L_{p\ (dB)} &= 10\log_{10}\left(\frac{P_t G_t G_r}{P_r}\right) \\ &= -10\log_{10}\left\{4\left(\frac{\lambda_c}{4\pi d}\right)^2 \sin^2\left(\frac{2\pi h_b h_m}{\lambda_c d}\right)\right\} \end{aligned} \qquad (5)$$

- Several useful empirical models for macrocellular systems have been obtained by curve fitting experimental data.
- Two of the useful models for 900 MHz cellular systems are:
  - Hata's model based on Okumura's prediction method and
  - Lee's model.
- Hata's empirical model is probably the simplest to use. The empirical data for this model was collected by Okumura in the city of Tokyo.

Okumura-Hata models

- With Okumura-Hata's model, the path loss between two isotropic BS and MS antennas is

$$L_{p\ (dB)} = \begin{cases} A + B\log_{10}(d) & \text{for urban area} \\ A + B\log_{10}(d) - C & \text{for suburban area} \\ A + B\log_{10}(d) - D & \text{for open area} \end{cases} \quad (6)$$

where

$$\begin{aligned} A &= 69.55 + 26.16\log_{10}(f_c) - 13.82\log_{10}(h_b) - a(h_m) \\ B &= 49.9 - 6.55\log_{10}(h_b) \\ C &= 5.4 + 2\left(\log_{10}(f_c/28)\right)^2 \\ D &= 40.94 + 4.78\left(\log_{10}(f_c)\right)^2 - 18.33\log_{10}(f_c) \end{aligned}$$

Okumura-Hata models (cont.)

and

$$a_{h_m} = \begin{cases} [1.1\log_{10}(f_c) - 0.7]\, h_m - 1.56\log_{10}(f_c) + 0.8 & \text{for medium or small city} \\ \begin{cases} 8.28\,[\log_{10}(1.54 h_m)]^2 - 1.1 & \text{for } f_c \le 200\text{MHz} \\ 3.2\,[\log_{10}(11.75 h_m)]^2 - 4.97 & \text{for } f_c \ge 400\text{MHz} \end{cases} & \text{for large city} \end{cases} \tag{7}$$

Okumura-Hata's model is expressed in terms of:

- the carrier frequency: $150 \le f_c \le 1000$(MHz),
- BS antenna height: $30 \le h_b \le 200$(m),
- the mobile station (MS) height: $1 \le h_m \le 10$(m),
- the distance: $1 \le d \le 20$(km).

Numerical results of Okumura-Hata models: Lab assignment

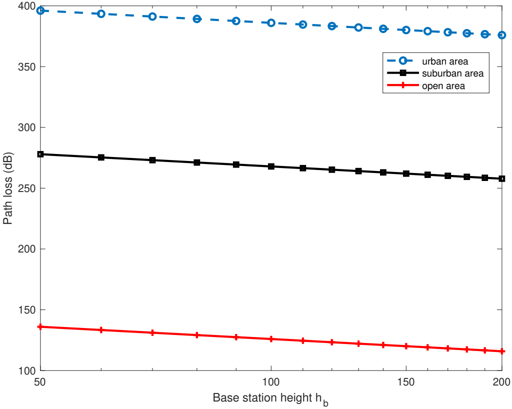


Figure 2: Path loss as a function of BS height for $h_m = 1.5\text{m}$, $d = 1(\text{km})$, $f_c = 900\text{MHz}$.

Numerical results of Okumura-Hata models

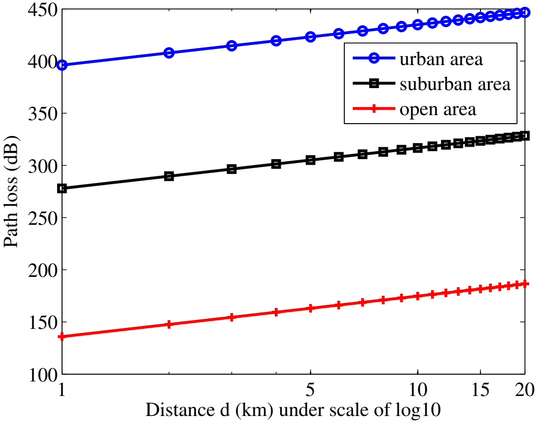


Figure 3: Path loss as a function of distance between BS and MS for $h_m = 1.5\text{m}, h_b = 50\text{m}, f_c = 900\text{MHz}$.

Path loss models: The COST231- model for $1500-2000$MHz frequency range

The COST231-Hata model is based on the proposal by Mogensen et al. [Gordon17] to extend the Okumura–Hata model for use in the $1500-2000$MHz frequency range, where it is known that the Okumura-Hata model underestimates the path loss. Note again that the parameters must be used in the model with their specified units.

Pathloss computing Parameters for the Okumura-Hata's model:

- the carrier frequency: $1500 \leq f_c \leq 2000$(MHz),
- BS antenna height ranging from $30 \leq h_b \leq 200$(m),
- the mobile station (MS) height: $1 \leq h_m \leq 10$(m),
- the distance: $1 \leq d \leq 20$(km).

Path loss models: The COST231-HATA model for $1500 - 2000$MHz frequency range

The path loss as predicted by the COST231-Hata model is

$$L_{p\ (dB)} = A + B\log_{10}(d) + C \tag{8}$$

where

$$\begin{aligned} A &= 46.3 + 33.9\log_{10}(f_c) - 13.82\log_{10}(h_b) - a(h_m) \\ B &= 44.9 - 6.55\log_{10}(h_b) \end{aligned} \tag{9}$$

$$C = \begin{cases} 0 \text{ for medium city and suburban areas} \\ 3 \text{ for metropolitan centers} \end{cases} \tag{10}$$

Shadowing

- A signal transmitted through a wireless channel will typically experience random variation due to blockage from objects in the signal path, giving rise to random variations of the received power at a **given distance**.
- Such variations are also caused by changes in reflecting surfaces and scattering objects.
- Thus, a model for the random attenuation due to these effects is also needed. Since the location, size, and dielectric properties of the blocking objects as well as the changes in reflecting surfaces and scattering objects that cause the random attenuation are generally unknown, statistical models must be used to characterize this attenuation.
- The most common model for this additional attenuation is log-normal shadowing.

Shadowing (cont.)

- Empirical studies have shown that X_m has the following log-normal distribution:

$$p_{X_m}(x) = \frac{2}{x\sigma_X \xi\sqrt{2\pi}} \exp\left\{-\frac{\left(10\log_{10} x^2 - \mu_{X_m\ (\text{dBm})}\right)}{2\sigma_X^2}\right\}$$

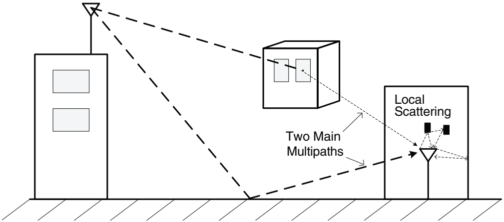
$$p_{X_s}(x) = \frac{2}{x\sigma_X \xi\sqrt{2\pi}} \exp\left\{-\frac{\left(10\log_{10} x - \mu_{X_s\ (\text{dBm})}\right)}{2\sigma_X^2}\right\}$$

- where:
  - X_m and X_s denote the mean envelop and mean squared levels of received signal (where the expectation is taken over the pdf of the received envelope).
  - σ_X stands for standard deviation; ξ is a constant.
  - $\mu_{X_m\ (\text{dBm})} = 30 + 10\mathbb{E}[\log_{10} X_m^2]$
  - $\mu_{X_s\ (\text{dBm})} = 30 + 10\mathbb{E}[\log_{10} X_s]$

Shadowing (cont.)

- Sometimes X_m is called the local mean because it represents the mean envelope level where the averaging is performed over a distance of a few wavelengths that represents a locality.
- This model has been confirmed empirically to accurately model the variation in received power in both outdoor and indoor radio propagation environments.

Fading channel model



- The real transmitted signal can be expressed from the complex baseband signal $x(t)$ by [1]

$$s(t) = \text{Re}\left[x(t)e^{j2\pi f_c t}\right]. \tag{11}$$

- Over a multipath (L physical paths) propagation channel, the received signal can be obtained by

$$y_{RF}(t) = \sum_i \alpha_i(t) s(t - \tau_i(t)) + w(t). \tag{12}$$

[1] Source: David Tse - Fundamentals of Wireless Communication

Fading channel model (cont.)

- Substituting (11) into (12) yields the following

$$\begin{aligned} y_{RF}(t) &= \text{Re}\left[\sum_i \alpha_i(t) x\left(t-\tau_i(t)\right) e^{j2\pi f_c(t-\tau_i(t))}\right] + w(t) \\ &= \text{Re}\left[\left(\sum_i \alpha_i(t) e^{-j2\pi f_c(\tau_i(t))} x\left(t-\tau_i(t)\right)\right) e^{j2\pi f_c t}\right] + w(t) \\ &= \text{Re}\left[y(t) e^{j2\pi f_c t}\right] + w(t) \end{aligned}$$

- As a result, the received baseband signal can be determined by

$$y(t) = \sum_i \alpha_i^b(t) x(t-\tau_i(t)) + w_b(t). \tag{13}$$

where $\alpha_i^b(t) = \alpha_i(t) e^{-j2\pi f_c \tau_i(t)}$ and $w_b(t)$ is the receiver (thermal) noise signal.

Fading channel model: A discrete-time Baseband model

- The next step in creating a useful channel model is to convert the **continuous**-time channel to a **discrete**-time channel.
- We take the usual approach of sampling theorem.
- Assuming that the input waveform is band-limited to W, the baseband equivalent can be represented by

$$x(t) = \sum_n x_n \text{sinc}(Wt - n), \tag{14}$$

where $x_n = x(n/W)$ and $\text{sinc}(t) \triangleq \frac{\sin(\pi t)}{\pi t}$.
- This representation follows from the sampling theorem, which says that any waveform band-limited to $W/2$ can be expanded in terms of the orthogonal basis functions $\text{sinc}(Wt - n)$ with coefficients by samples (taken uniformly at integer multiples of $1/W$)

Fading channel model: A discrete-time Baseband model

- As a result, the baseband received signal can be determined by

$$\begin{aligned} y(t) &= \sum_i \alpha_i^b(t) \sum_n x_n \mathrm{sinc}\left(W(t-\tau_i(t))-n\right) + w_b(t) \\ &= \sum_n x_n \sum_i \alpha_i^b(t) \mathrm{sinc}\left(W(t-\tau_i(t))-n\right) + w_b(t). \end{aligned}$$

- The sampled outputs at multiples of $1/W$ is $y_m \triangleq y(m/W)$ then

$$y_m = \sum_n x_n \sum_i \alpha_i^b(m/W) \mathrm{sinc}\left(m-n-\tau_i(m/W)W\right) + w_b(m/W). \tag{15}$$

Fading channel model: A discrete-time Baseband model

- Let $l \triangleq m - n$ then one can have

$$y_m = \sum_l x_{m-l} \sum_i \alpha_i^b(m/W) \text{sinc}\,(l - \tau_i(m/W)W) + w_b(m/W)$$

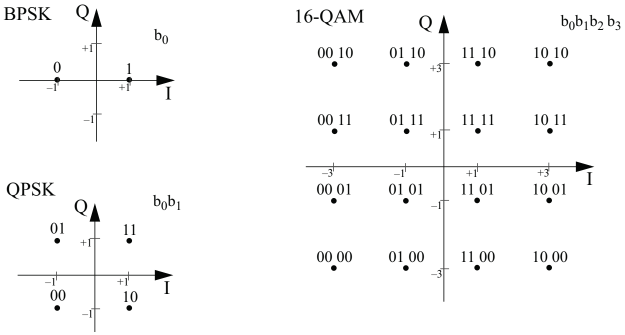
- Then, the **discrete-time** channel model can be given by

$$\boxed{y_m = \sum_l x_{m-l} h_{l,m} + w_b(m/W)} \qquad (16)$$

where $h_{l,m} = \sum_i \alpha_i^b(m/W) \text{sinc}\,(l - \tau_i(m/W)W)$

- This simple discrete-time signal model is widely used in physical-layer transmission techniques in OFDM systems (e.g., WiFi, LTE)

Examples of transmitted baseband signal x_m

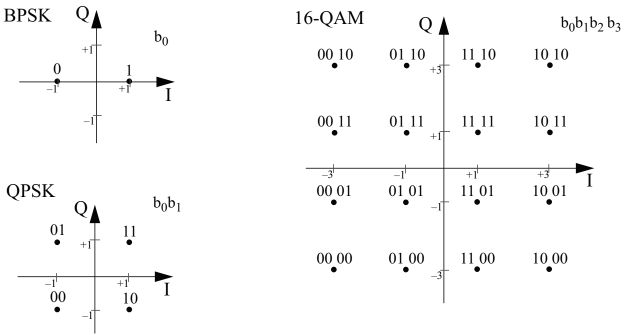


- Number of bits to be conveyed by one M-QAM ($M \in \{2, 4, 8, 16, 64\}$) complex symbol:

$$\boxed{b = \log_2(M)} \tag{17}$$

- It is noted that multipath fading gains $h_{l,m}$ (channel impulse response) is time-variant (depend on time index m).

Examples of transmitted baseband signal x_m

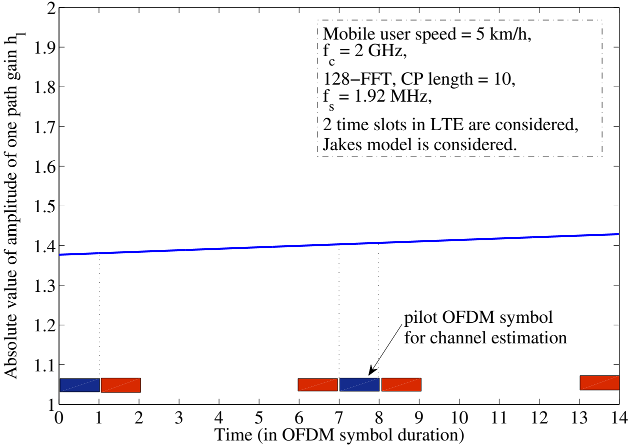


- Over multipath channels, the received signal at MS is:

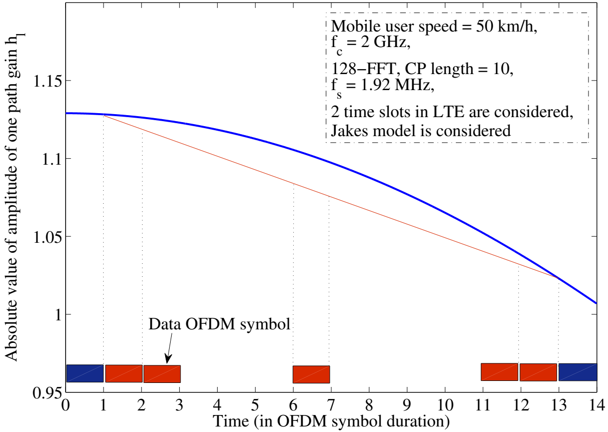
$$\boxed{y_m = \sum_l x_{m-l} h_{l,m} + w_b(m/W)} \quad (18)$$

- It is noted that multipath fading gains $h_{l,m}$ (channel impulse response) is time-variant (depend on time index m).

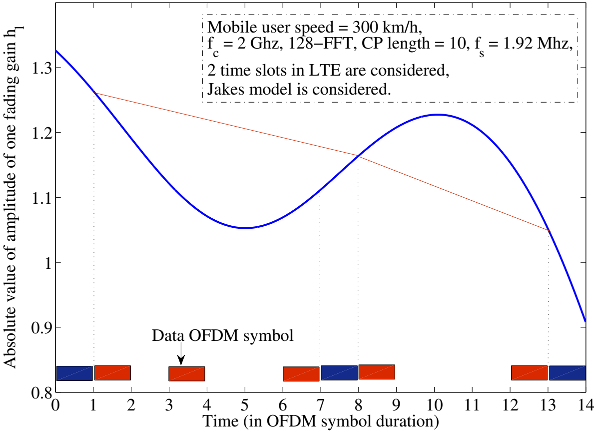
Time-variant path gain $h_{l,m}$ under mobile speed of 5 km/h



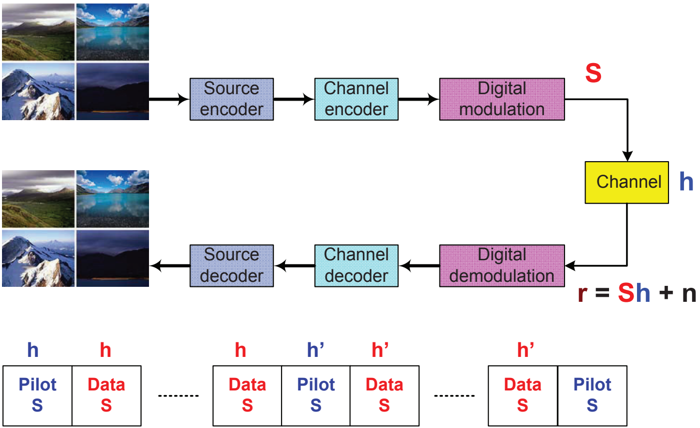
$h_{l,m}$ under mobile speed of 50 km/h



$h_{l,m}$ under mobile speed of 300 km/h

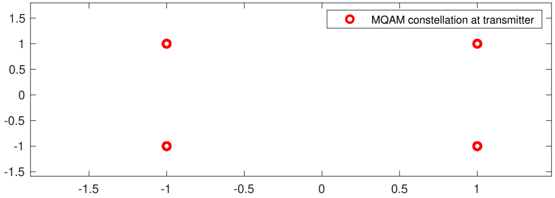


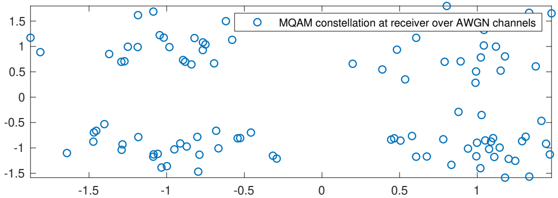
Channel estimation in mobile communications



Digital Modulation: Lab 4

Lab 4. Expected plots of MQAM constellation before (at TX) and after (at RX) transmitting via the AWGN channel





Introduction

- A communication link encompasses the entire path from the information source, through the channel, and terminating at the information sink.
- The link analysis and its output, the link budget, consist of the calculations and tabulation of the useful signal power and the interfering noise power available at the receiver.
- The link budget is a balance sheet of gains and losses.

Introduction (cont.)

- By examining the link budget, one can learn many things about overall system design and performance.
- For instance, from the link margin, one learns whether the system will meet many of its requirements comfortably, marginally, or not at all.
- The link budget may reveal if there are any hardware constraints, and whether such constraints can be compensated in other parts of the link.

Introduction (cont.)

- The link budget is often used as a "score sheet" in considering system trade-offs and configuration changes, and in understanding subsystem nuances and interdependencies.
- Based on a quick examination of the link budget and its supporting documentation, one can judge whether the analysis was done precisely or if it represents a rough estimate.
- Together with other modeling techniques, the link budget can help predict equipment weight, size, prime power requirements, technical risk, and cost.

The channel

- The propagating medium or electromagnetic path connecting the transmitter and receiver is called the channel.
- In general, a communication channel might consist of wires, coaxial cables, fiber optic cables, and in the case of radio-frequency links, waveguides, the atmosphere or empty space.
- Most of this part presents link analysis in the context of a wireless communication link.