EEN 1043/EE452 Wireless and Mobile Communication

The Wireless Channel

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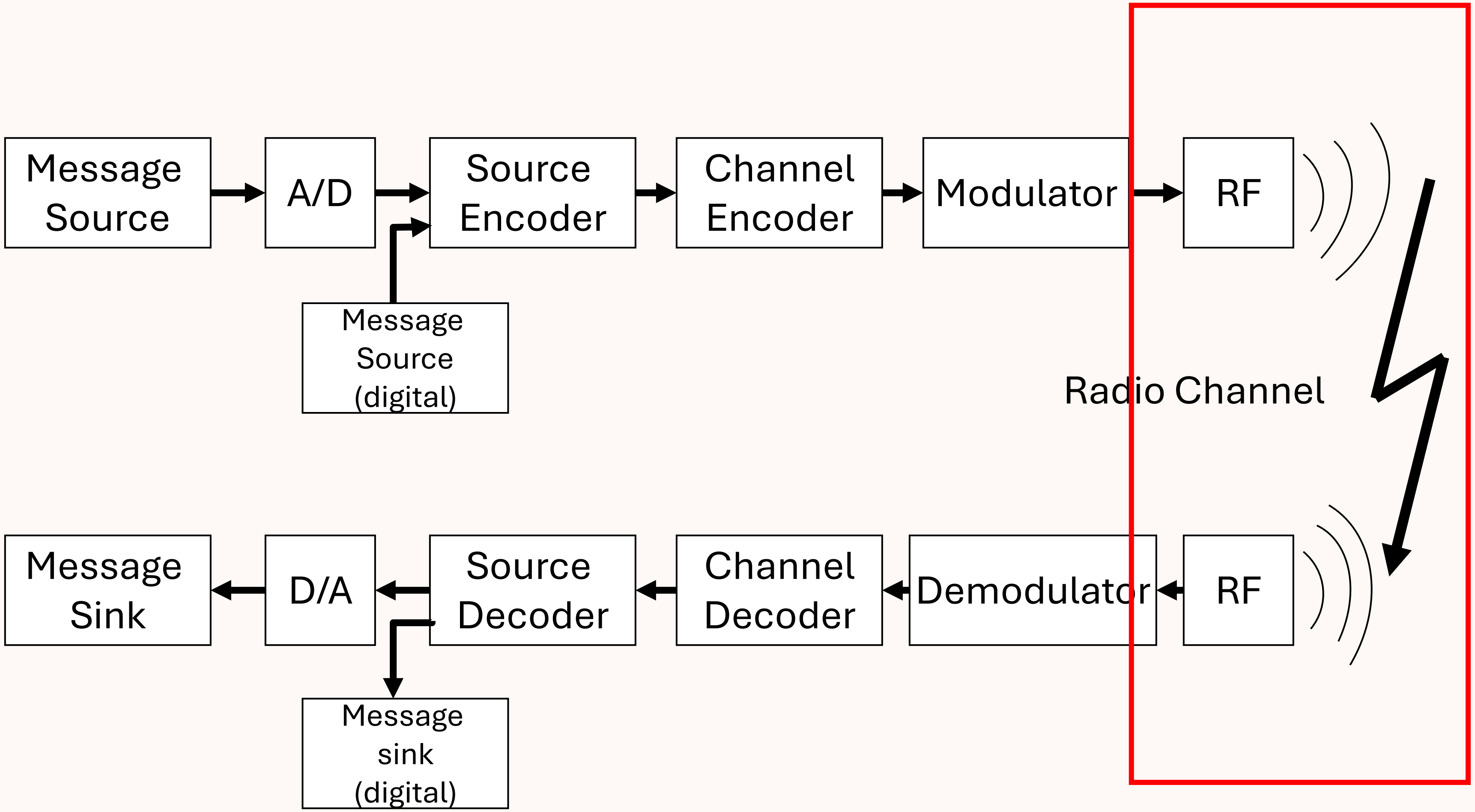
Radio Link


Message Source
A/D
Source Encoder
Channel Encoder
Modulator
RF
Message Source (digital)
Radio Channel
Message Sink
D/A
Source Decoder
Channel Decoder
Demodulator
RF
Message sink (digital)

Outline

- Antennas
  - Types
  - Directionality
- Propagation
  - Large-scale fading
    - Free space loss
    - Noise
    - Multipath
    - Loss Models
  - Small scale fading
    - Multipath
    - Mobility

Components of Wireless Channel

- Transmit Antenna
- Wireless Signal Propagation
- Receive Antenna

The three of them determine the signal quality

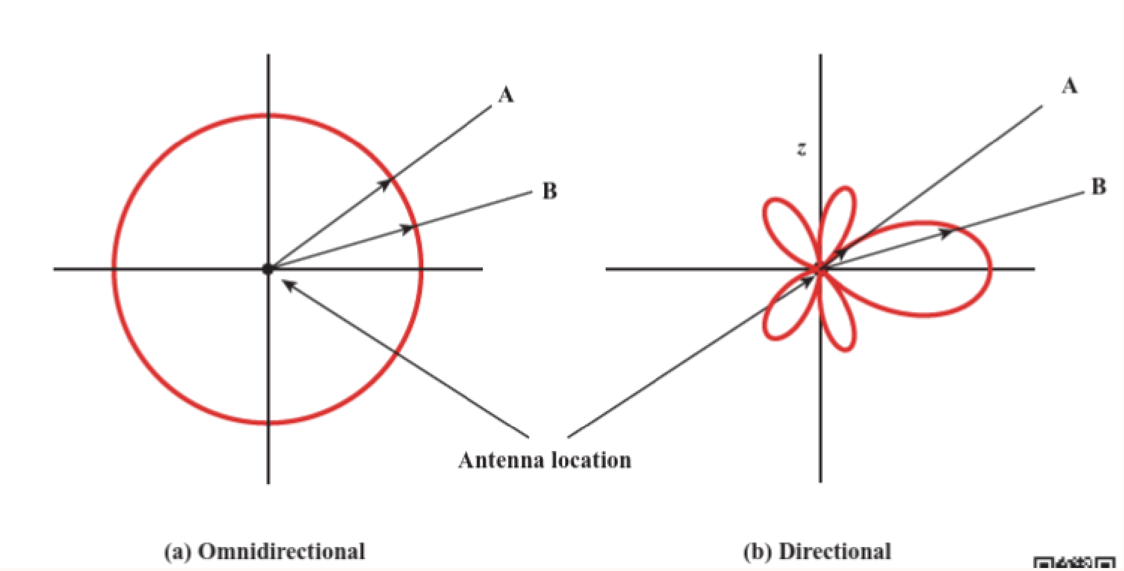
Antennas

- An antenna is an electrical conductor or system of conductors, used for
  - Transmission: radio-frequency electrical energy from the transmitter is converted into electromagnetic energy and radiated into the surrounding environment (atmosphere, space, water)
  - Reception: electromagnetic energy from environment is collected and converted into radio-frequency electrical energy which is fed to the receiver

- In two-way communication, the same antenna can be used for transmission and reception
  - Antenna characteristics are essentially the same for TX and RX

Antennas: Radiation Patterns

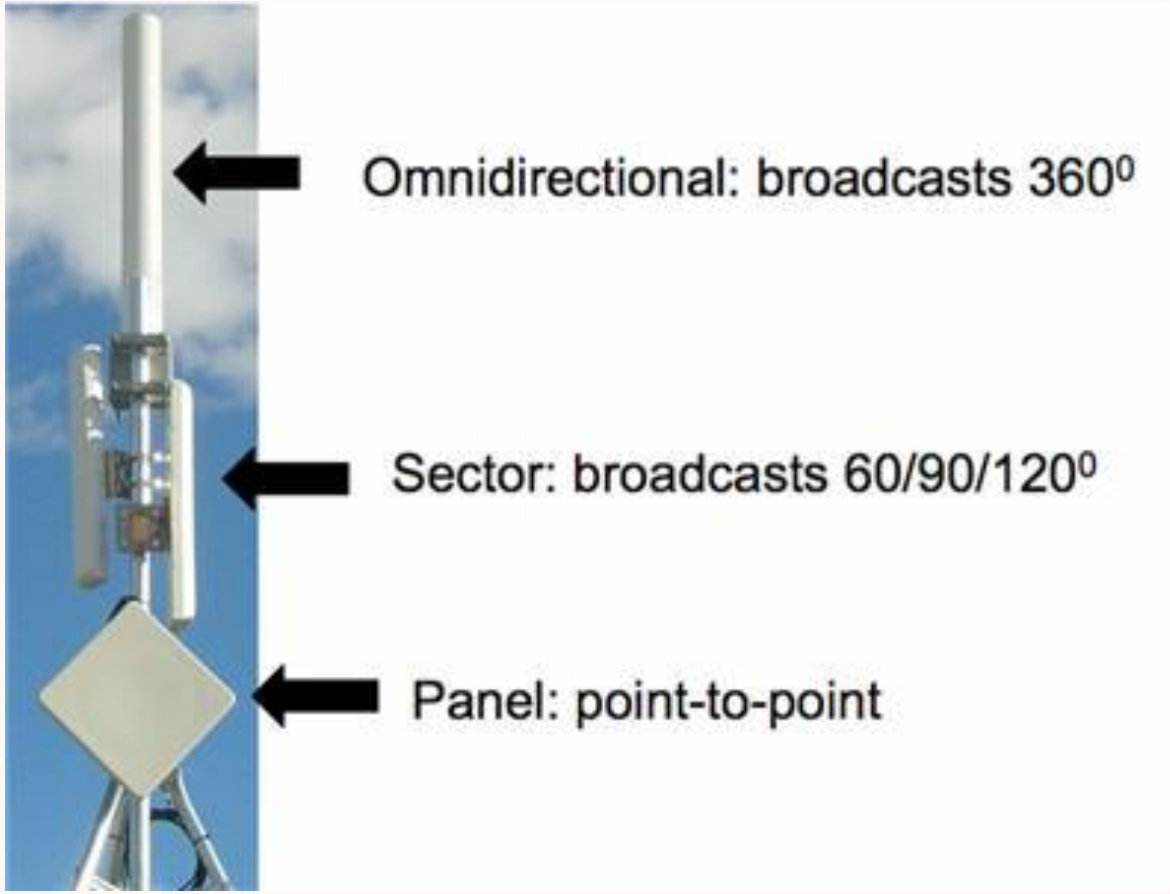
- Radiation pattern
  - Graphical representation of radiation properties of an antenna as a function of space coordinates
  - Depicted as a 2-D cross section of actual 3-D pattern



Antennas: Radiation Patterns

- Beam width (or half-power beam width)
  - Measure of ***directivity*** of an antenna
  - The angle within which the power radiated by the antenna is at least half of what it is in the most preferred direction
- Reception pattern
  - Receiving antenna's equivalent to radiation pattern

Antenna Types



Microstrip patch antenna

Iphone internal antennas

Antennas: Gain

- Antenna gain: a measure of the **directionality** of an antenna
  - Power output ***in a particular direction*** compared to that produced in any direction by a perfect omnidirectional antenna (i.e. isotropic antenna)
  - e.g. 3dB gain means the antenna improves on the isotropic antenna in that direction by 3dB (factor of 2 improvement)
  - Increased power radiated in one direction means reduced power radiated in other directions

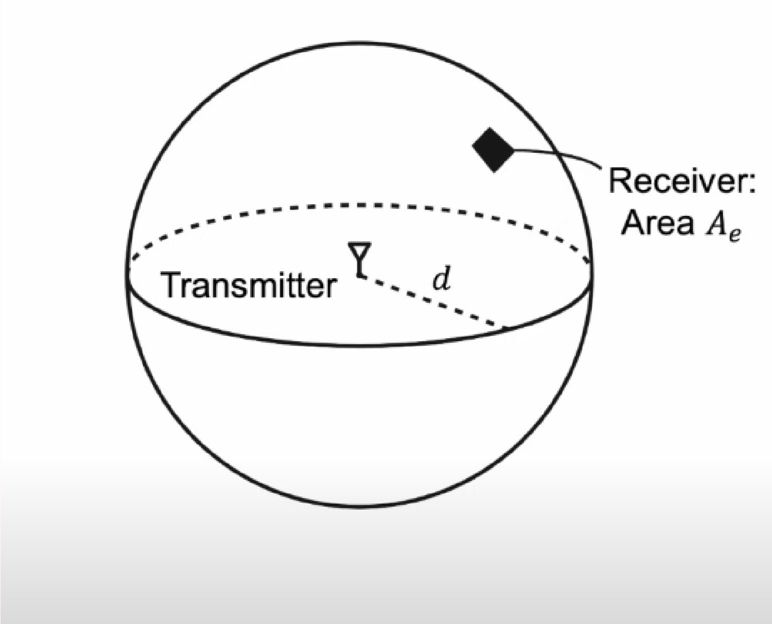
- Effective area
  - Related to physical size and shape of antenna

Antennas: Gain and effective area

- Relationship between antenna gain and effective area:

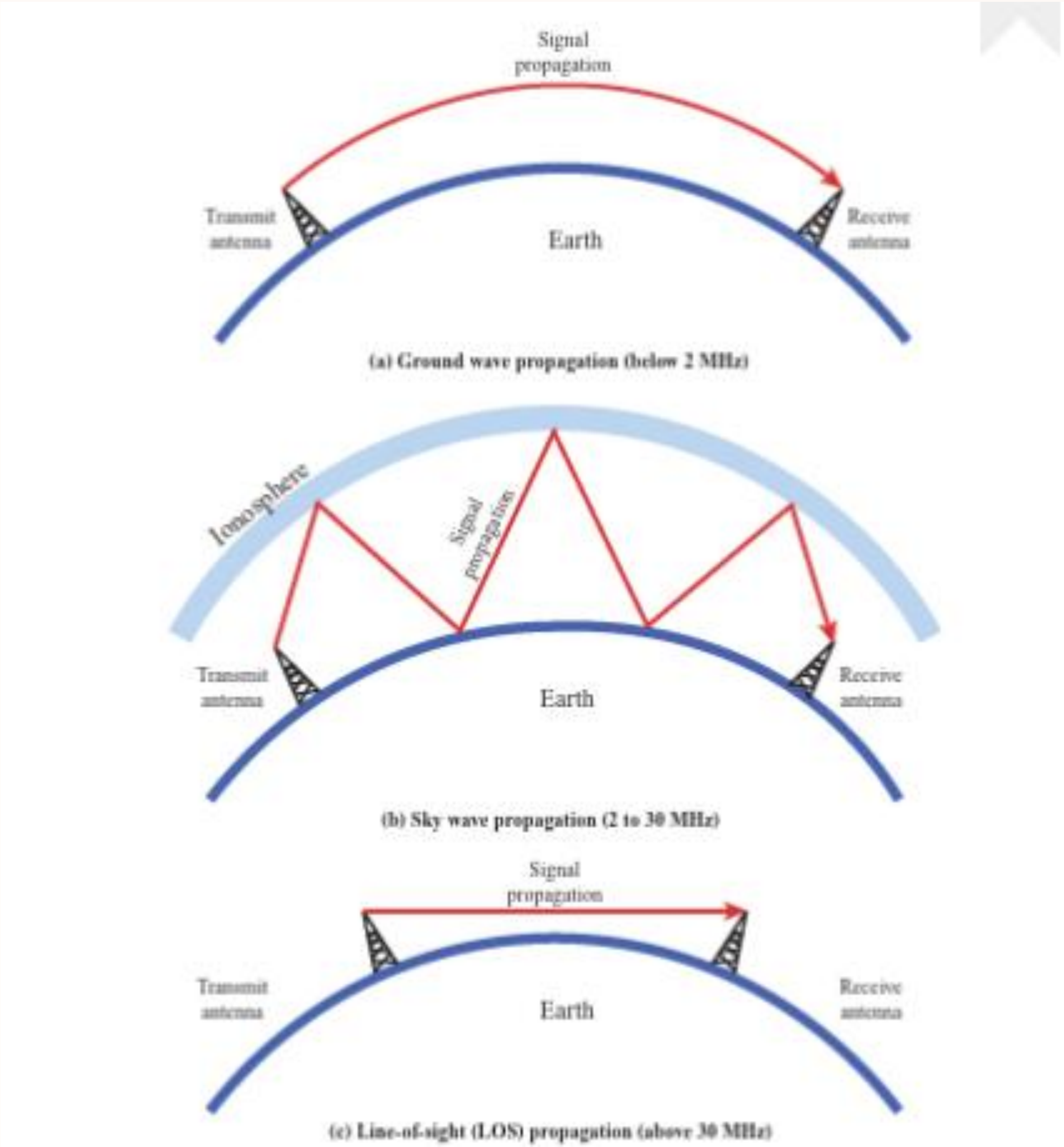
$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$

  - G = antenna gain
  - A_e = effective area
  - f = carrier frequency
  - c = speed of light ($\approx 3 \times 10^8$ m/s)
  - λ = carrier wavelength



Propagation Modes

- Signals travel along one of three routes
  - Ground wave: follows the contour of the earth.
    - Frequency <2MHz.
    - E.g. AM radio
    - Main advantage is distance.
  - Sky wave: bounces between earth's surface and ionosphere.
    - Amateur radios, CB radios, international broadcasts.
    - Potentially very large range
  - Line-of-Sight (LOS)
    - Only mode above 30MHz.
    - Factors such as refraction affect the actual Line of Sight.



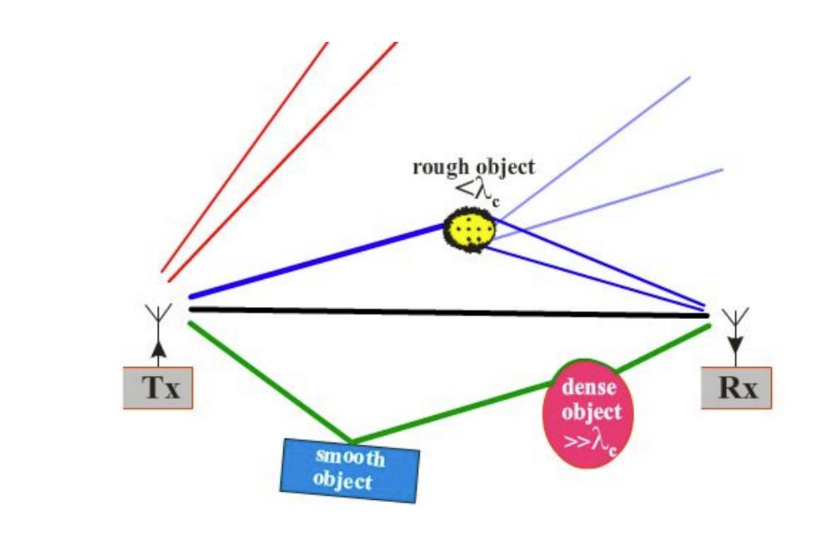
Signal
propagation
Transmit
antenna
Earth
Receive
antenna
(a) Ground wave propagation (below 2 MHz)
Ionosphere
Signal
propagation
Transmit
antenna
Earth
Receive
antenna
(b) Sky wave propagation (2 to 30 MHz)
Signal
propagation
Transmit
antenna
Earth
Receive
antenna
(c) Line-of-sight (LOS) propagation (above 30 MHz)

Line-of-Sight Transmission

- Various factors affect the signal in LOS wireless transmission, including:
  - Free space loss
  - Atmospheric absorption
  - Multipath
  - Mobility
- These factors will affect the power needed to send a signal and the amount of data which can be transmitted.
- Prediction of channel behavior requires relatively complex models, often based on empirical data.

Wireless Channels

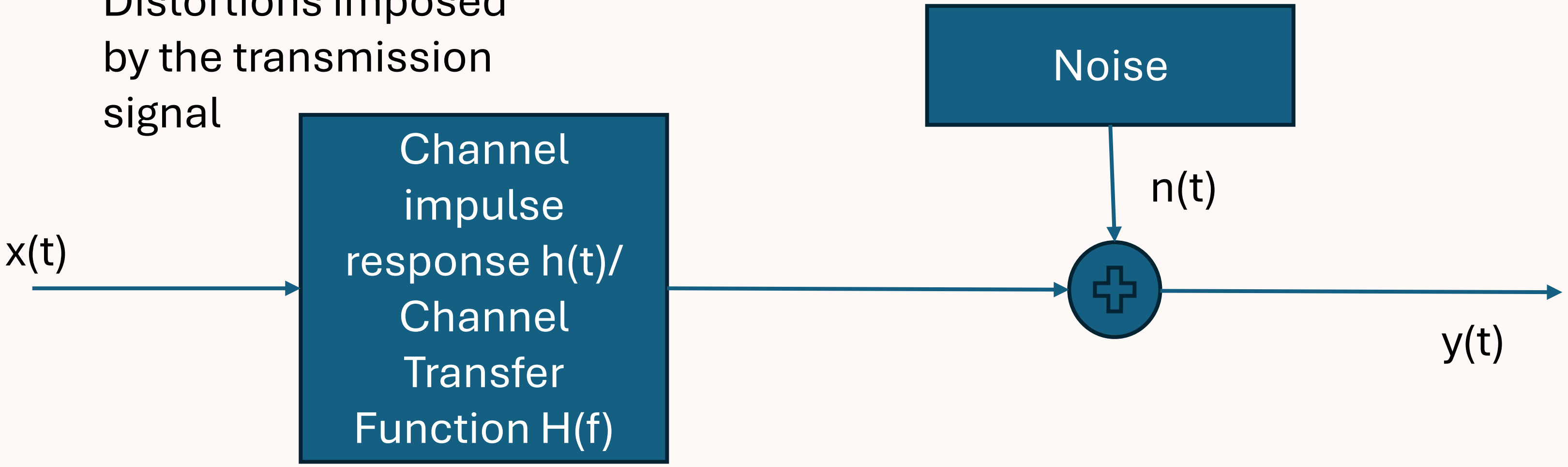
- Noise (thermal, sky, etc..)
- Unintentional interference from other Tx (multiple access interference)
- Intentional (hostile) interference (from Jammers)
- Multipaths
  - Reflection
  - Diffraction
  - Refraction
  - Scattering



Wireless Channel Model

The unwanted signal that is inserted somewhere between transmission and reception

Distortions imposed by the transmission signal



$$y(t) = h(t) * x(t) + n(t)$$

Noise

Noise

- The unwanted signal inserted somewhere between transmitter and receiver
- Noise is the major limiting factor in communications systems
- Divided into 4 categories
  - Thermal noise; white noise $N_o = kT\ (\frac{W}{Hz})$ (in a bandwidth of 1 Hz)
  - Intermodulation noise: signal with different frequencies share the same transmission medium
  - Cross talk: unwanted coupling between signal paths
  - Impulse noise: non continuous irregular pulses

Thermal Noise (white noise)

- It is due to thermal agitation of Electrons and present in all electronic devices and transmission media.
- It is a function of temperature.
- Thermal noise cannot be eliminated and places an upper bound on the performance of the communication system.
- The amount of thermal noise in a Bandwidth of 1 Hz I any device or conductor is $N_0 = kT\ \left(\frac{W}{Hz}\right)$
- k= Boltzmanns constant = $1.38 * 10^{-23}\ J/K$, Temperature in Kelvin
- Thermal Noise in watts in a bandwidth of B Hz $N_0 = kTB$

Intermodulation Noise

- When signals at different frequencies share the same transmission medium, the result may be intermodulation noise
- Produces signals at a frequency that is the sum or difference of the two original frequencies
- Consider two signal at $f_1$and f_2, might produce energy at the frequency $f_1 + f_2$, and interfere with an intended signal at the frequency $f_1 + f_2$.
- It is produced when there is some non linearity in the transmitter, receiver, or intervening transmission system.

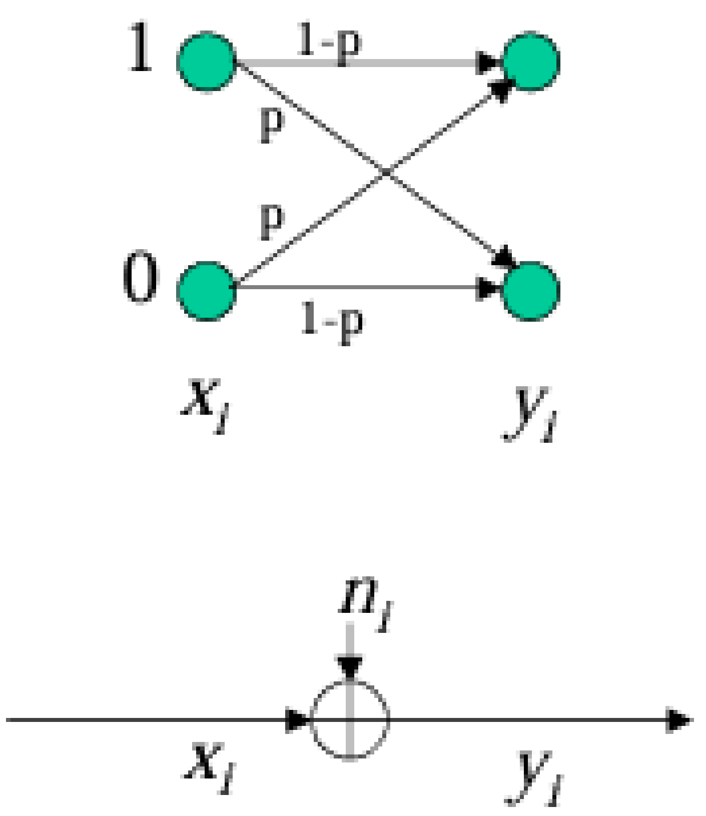
Cross Talk

- Unwanted coupling between signals

Impulse Noise

- It is non continuous, consisting of irregular pulses or noise spikes of short duration and of relatively higher amplitude

Binary Symmetric Channel



Noise Model

$$\mu = \frac{\sum_{n=0}^{N-1} noise[n]}{N}.$$

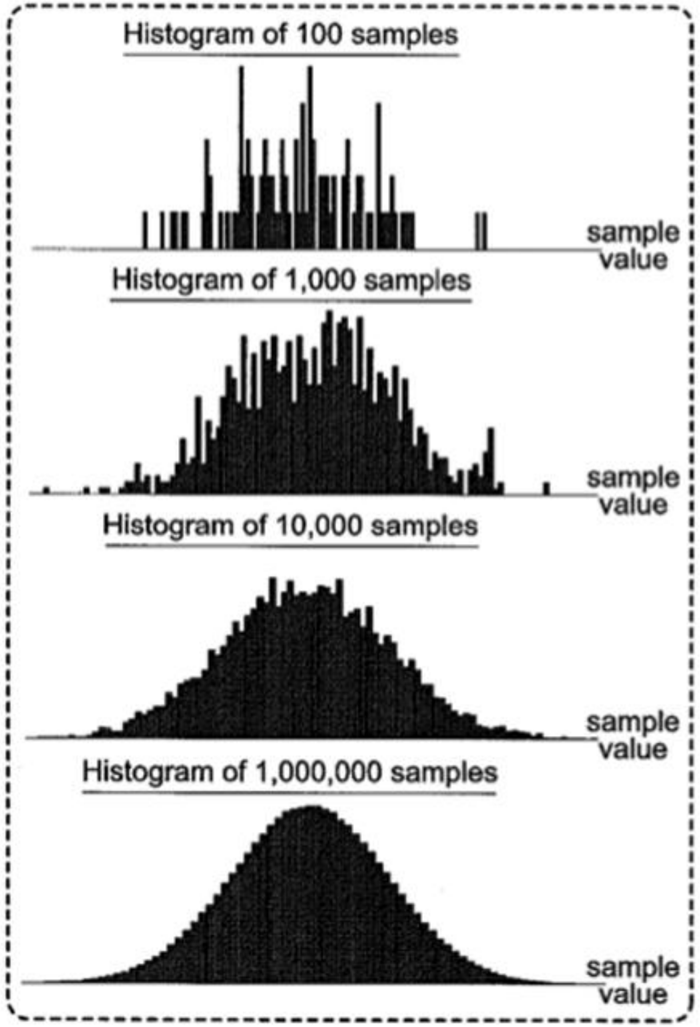
Mean

$$\sigma^2 = \frac{\sum_{n=0}^{N-1}(noise[n] - \mu)^2}{N}.$$

Variance

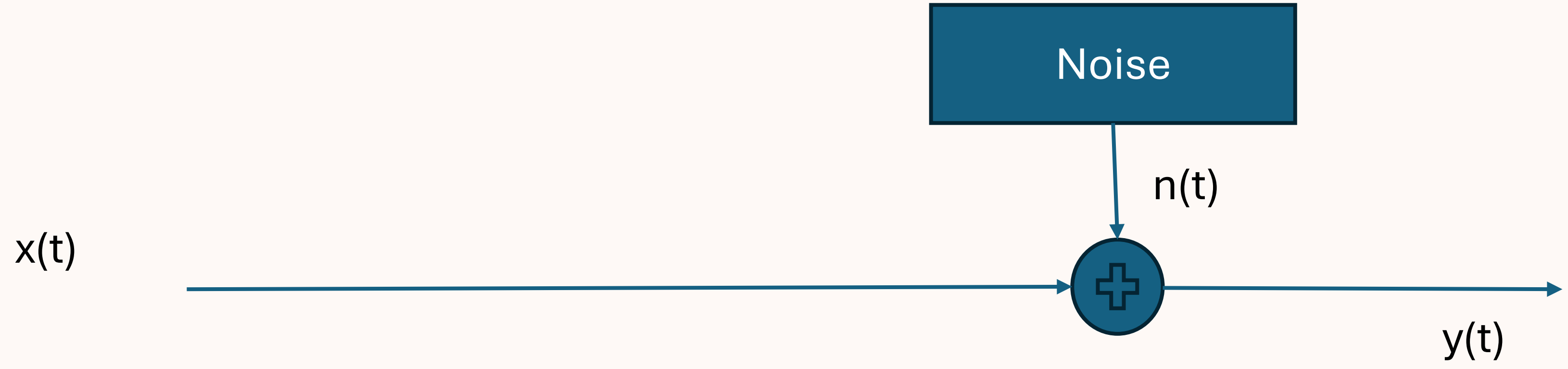
$$f_X(x) = \frac{e^{-(x-\mu)^2/2\sigma^2}}{\sqrt{2\pi\sigma^2}}.$$

Probability Density Function


Histogram of 100 samples
sample value
Histogram of 1,000 samples
sample value
Histogram of 10,000 samples
sample value
Histogram of 1,000,000 samples
sample value

Wireless Channel Model

The unwanted signal that is inserted somewhere between transmission and reception



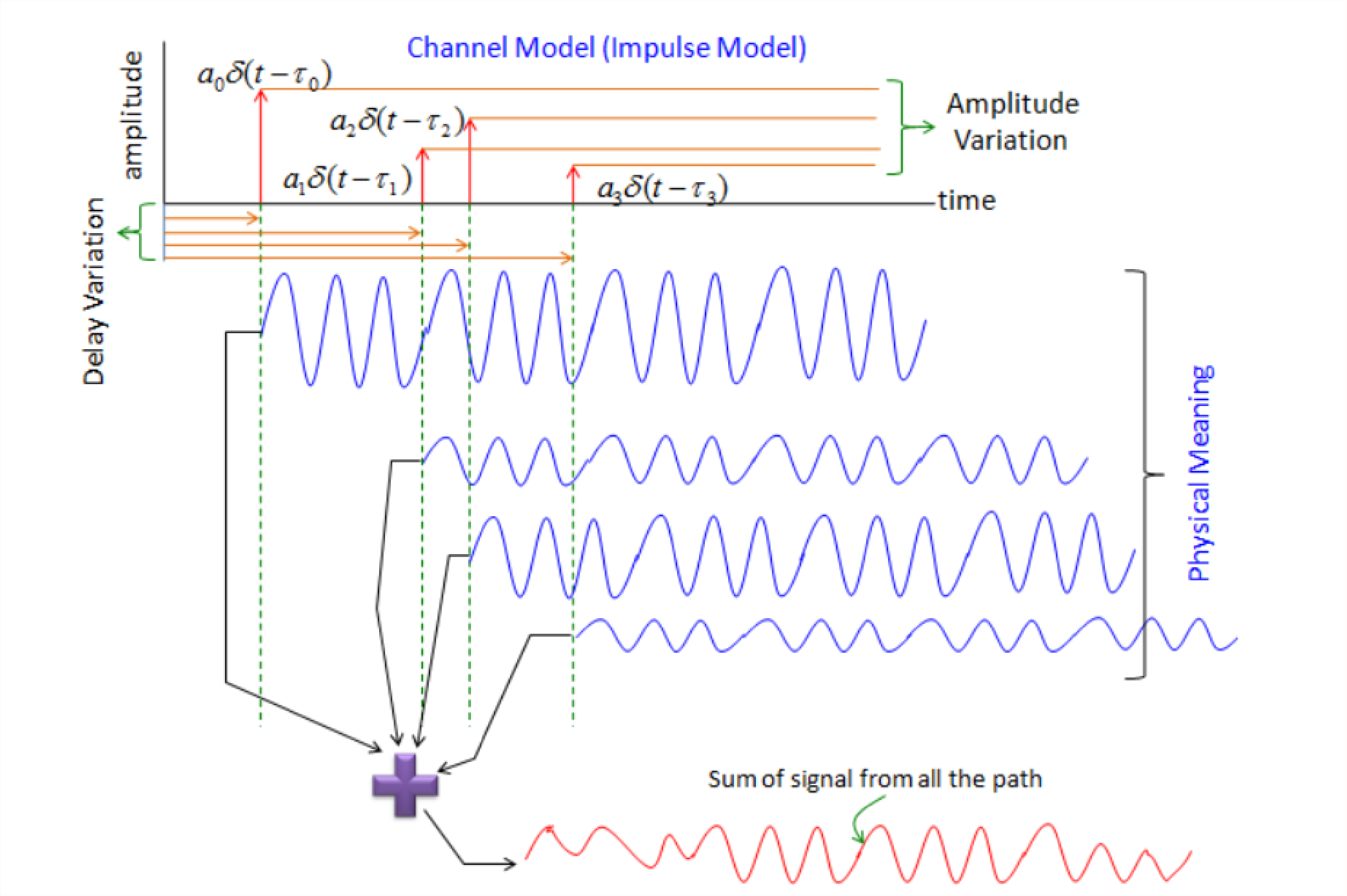
$$y(t) = h(t)*x(t) \ + n(t)$$

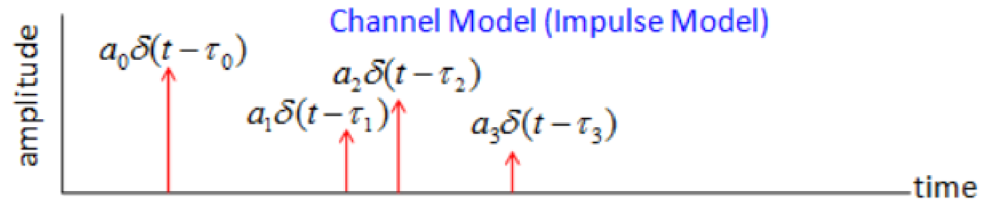
Effect of Channel

Channel Impulse Response

- The channel impulse response(CIR) shows the output of a communications channel when the input is an impulse or spike. It basically captures the effect of the channel on the signal. In wireless communication, where signals take multiple paths from transmitter to receiver, the CIR provides information about these different multipath components.

Channel Impulse Response

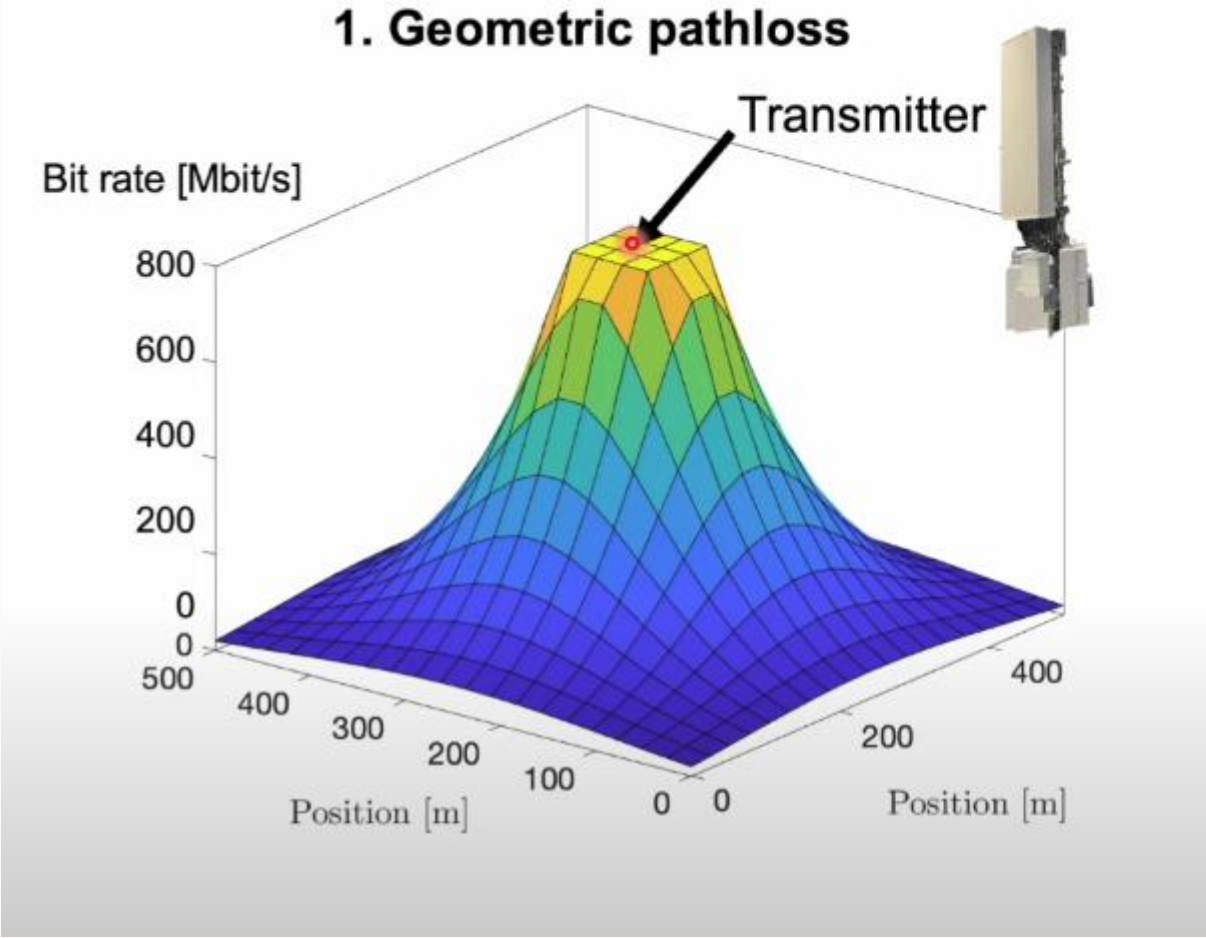




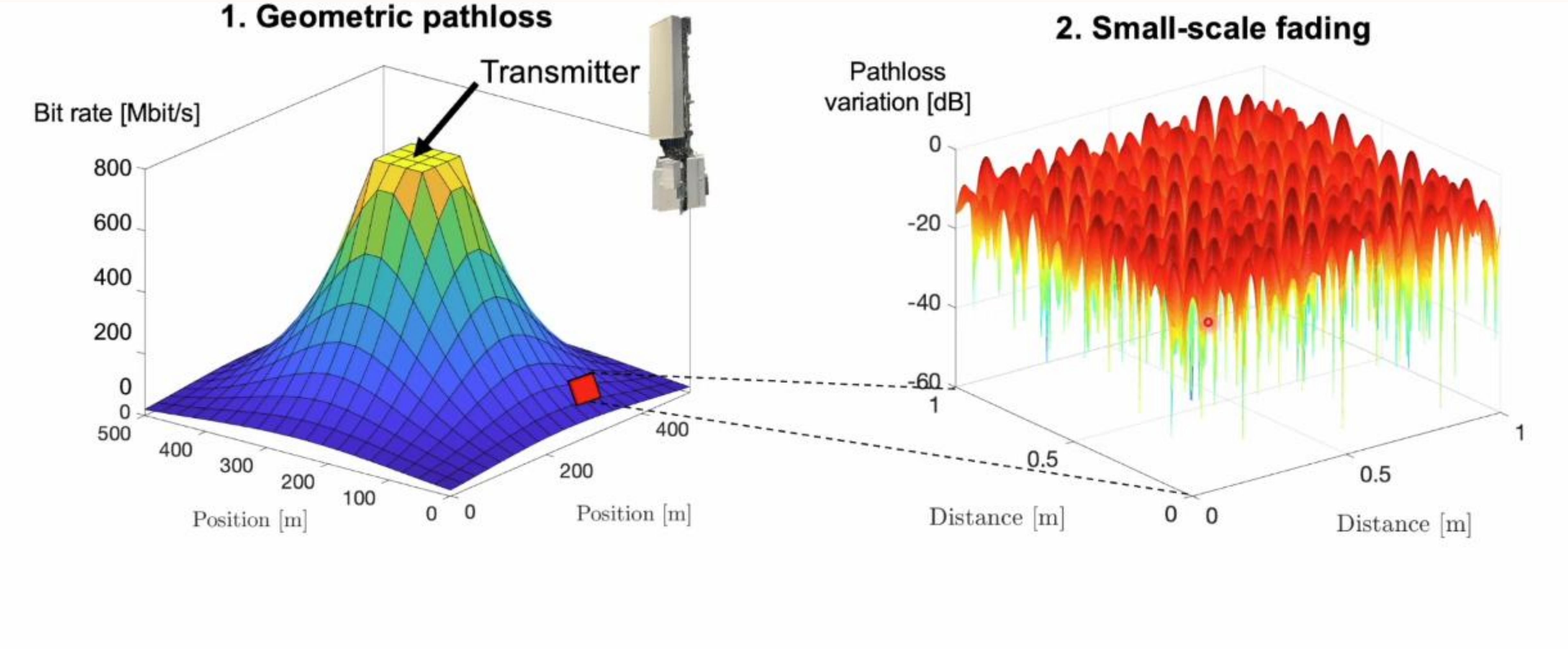
$$h(t) = a_0\delta(t-\tau_0) + a_1\delta(t-\tau_1) + a_2\delta(t-\tau_2) + a_3\delta(t-\tau_3)$$
$$= \sum_{i=0}^{3} a_i\delta(t-\tau_i)$$

Function representing the channel impulse

Three Wireless Propagation Phenomena



Three Wireless Propagation Phenomena

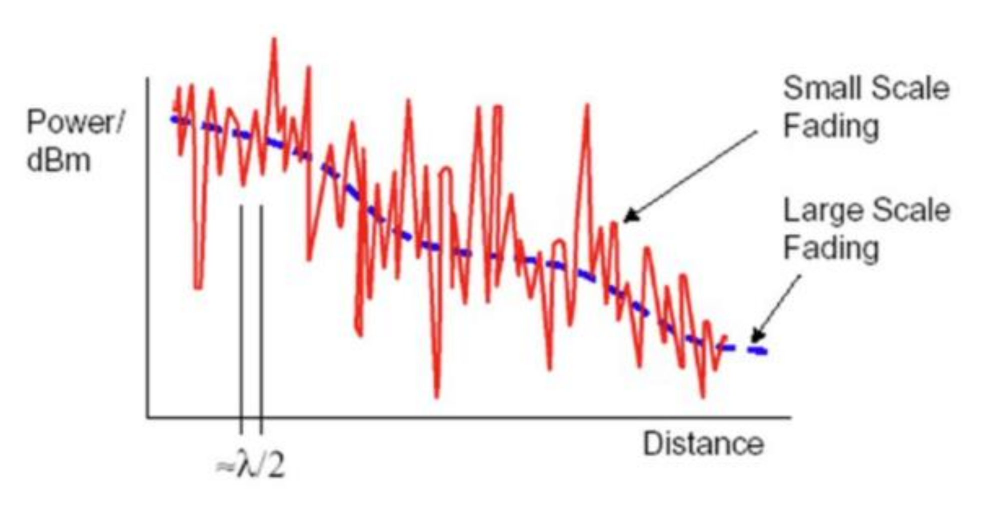


Wireless Propagation: Impact on Signal

- *Signal Attenuation* is the phenomenon whereby the *Amplitude* of a signal decreases as it propagates.
    - Attenuation is a function of distance and frequency of signal
    - Transmitter signal strength must be large enough that the received signal may be distinguished from noise,
        - but not so large as to overwhelm the receiver circuitry.
    - May be overcome using amplifiers or repeaters.
- *Signal Distortion* involves the shape of the signal becoming altered as it propagates.
    - One cause of distortion is that attenuation is greater for higher frequencies.
    - Also small scale fading.
        - Equalisers can be used to amplify specific frequency components.

Wireless Propagation: Fading

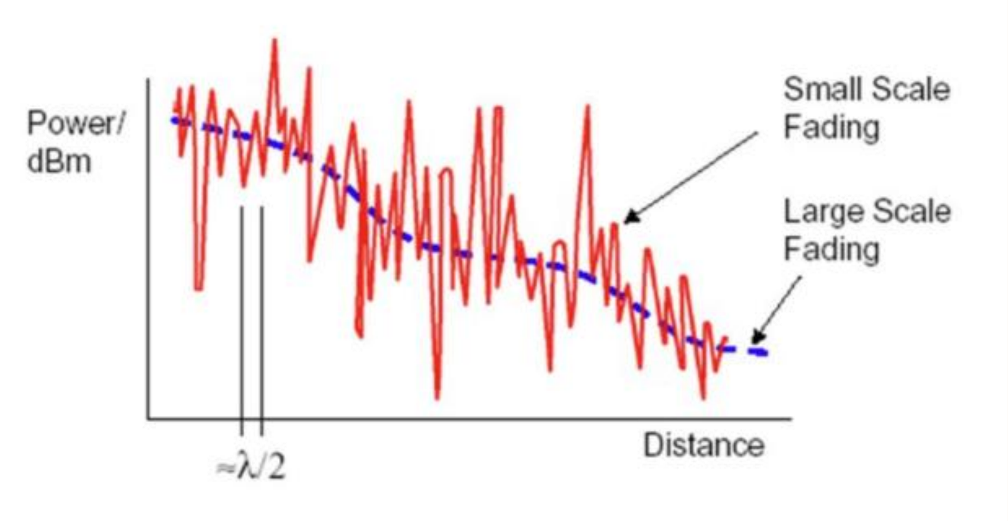
- *Fading* is the reduction of power in a transmitted signal is determined by the positioning of the receiver relative to the transmitter.
  - Effects related to distance from transmitter
  - Interference with signal caused by interaction with the atmosphere and terrain.
  - Effects typically classified as either
    - *Large scale fading*—effects due to relatively large distances between transmitter and receiver. Average path loss and Shadowing
    - *Small scale fading*—effects observed with small changes in the position of the mobile unit relative to the base station/access point.



Large Scale Fading

Large Scale Fading

- Macroscopic or large scale variation of Received signal strength (RSS)
- Path Loss models are commonly used
- $L_{dB} = P_t(dB) - P_r(dB)$



Large Scale fading

- Free space loss, ideal **isotropic antenna**:

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}$$

- P_t = signal power at transmitting antenna
- P_r = signal power at receiving antenna
- λ = carrier wavelength=c/f
- d = propagation distance between antennas
- c = speed of light ($\approx 3 \times 10^8$ m/s)

where d and λ are in the same units (e.g. meters)

Large Scale fading: Isotropic antenna Path Loss

Free space path loss equation can be recast (in dB):

$$L_{dB} = 10\log\frac{P_t}{P_r} = 20\log\left(\frac{4\pi d}{\lambda}\right)$$

$$= -20\log(\lambda) + 20\log(d) + 21.98\text{ dB}$$

$$= 20\log\left(\frac{4\pi f d}{c}\right) = 20\log(f) + 20\log(d) - 147.56\text{ dB}$$

As the frequency increases, the loss also increases...

$\lambda = 0.1\ (3GHz)$,
d=1 m, L=42dB...........0.006% of the power is received
d=10m, L= 62dB.........0.00006% of the power

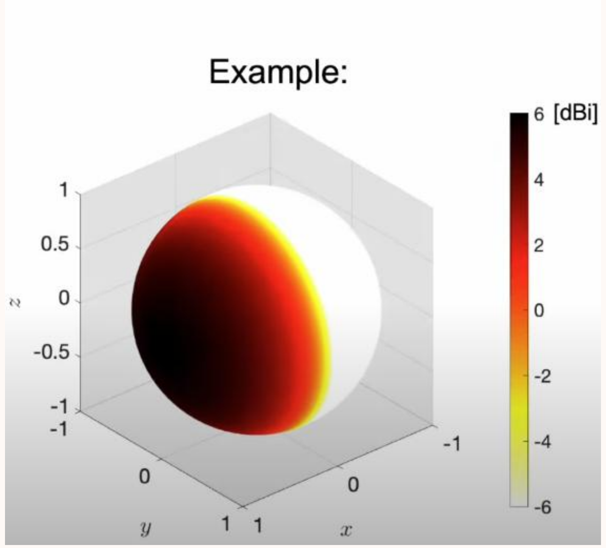
Even at short distances only a tiny fraction of the power is received

Large Scale fading: Directive Antennas

- Accounting for gains of non-ideal antennas:

$$\frac{P_t}{P_r} = \frac{(4\pi)^2 (d)^2}{G_r G_t \lambda^2} = \frac{(\lambda d)^2}{A_r A_t} = \frac{(cd)^2}{f^2 A_r A_t}$$

- G_t = gain of transmitting antenna
- G_r = gain of receiving antenna
- A_t = effective area of transmitting antenna
- A_r = effective area of receiving antenna



Large Scale fading: Directive Antennas

- Free space loss accounting for gains of non-ideal antennas can be recast (in dB) as:

$$L_{dB} = 20\log(\lambda) + 20\log(d) - 10\log(A_t A_r)$$

$$= -20\log(f) + 20\log(d) - 10\log(A_t A_r) + 169.54\text{dB}$$

As the frequency increases, the loss also increases...
but these increased losses can be compensated for with antenna gains, leading to a net gain instead of a loss

Adaptive Directivity

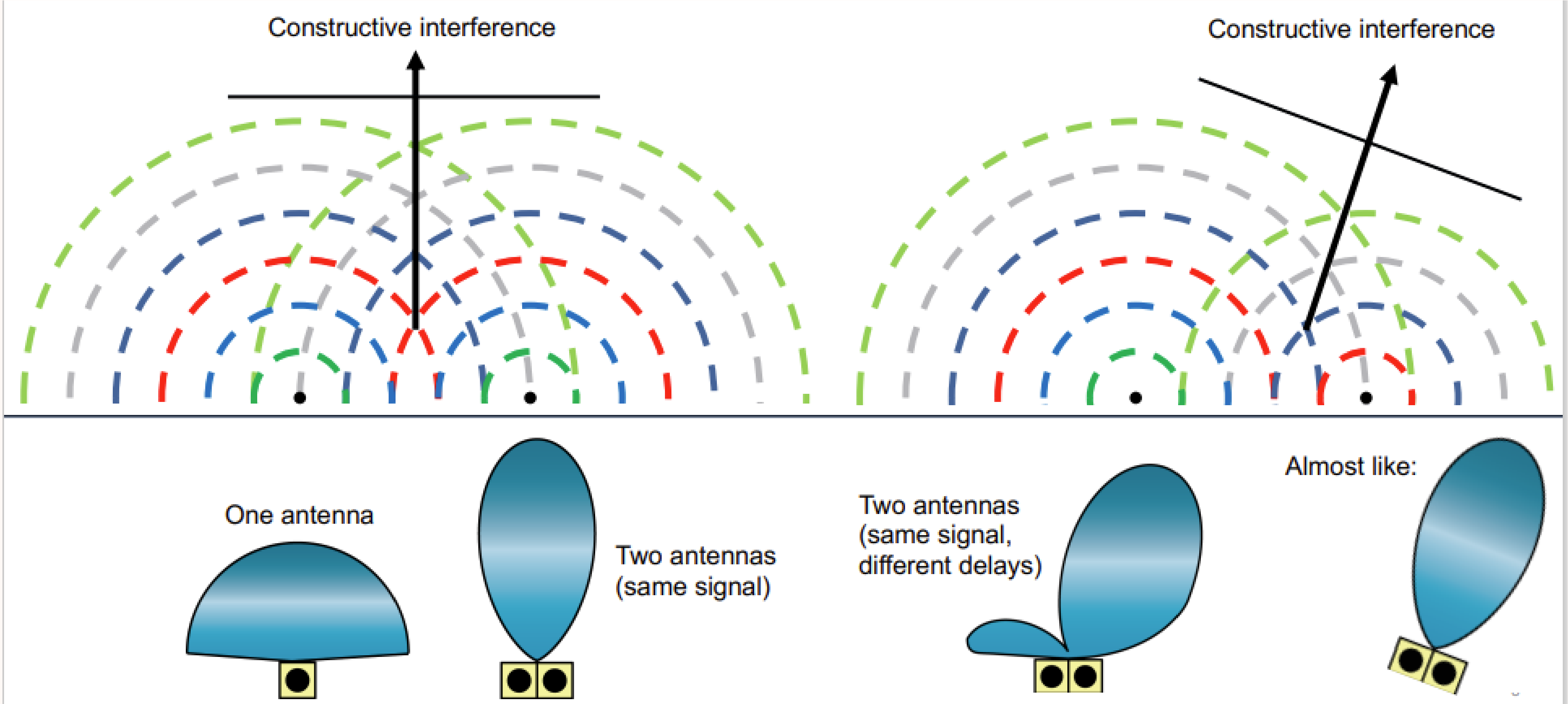


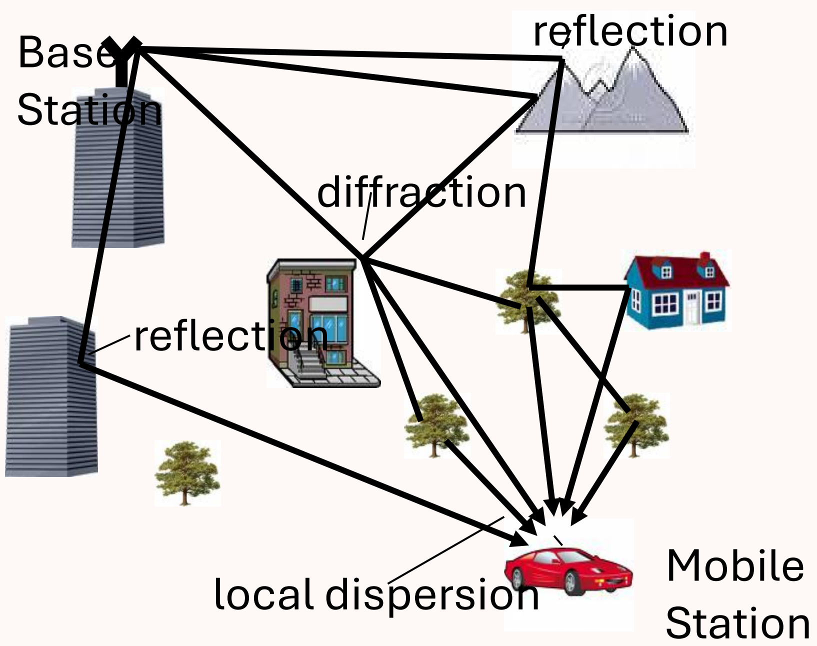
Image courtesy: https://github.com/emilbjornson/presentation_slides/blob/master/IK2560_video3.pdf

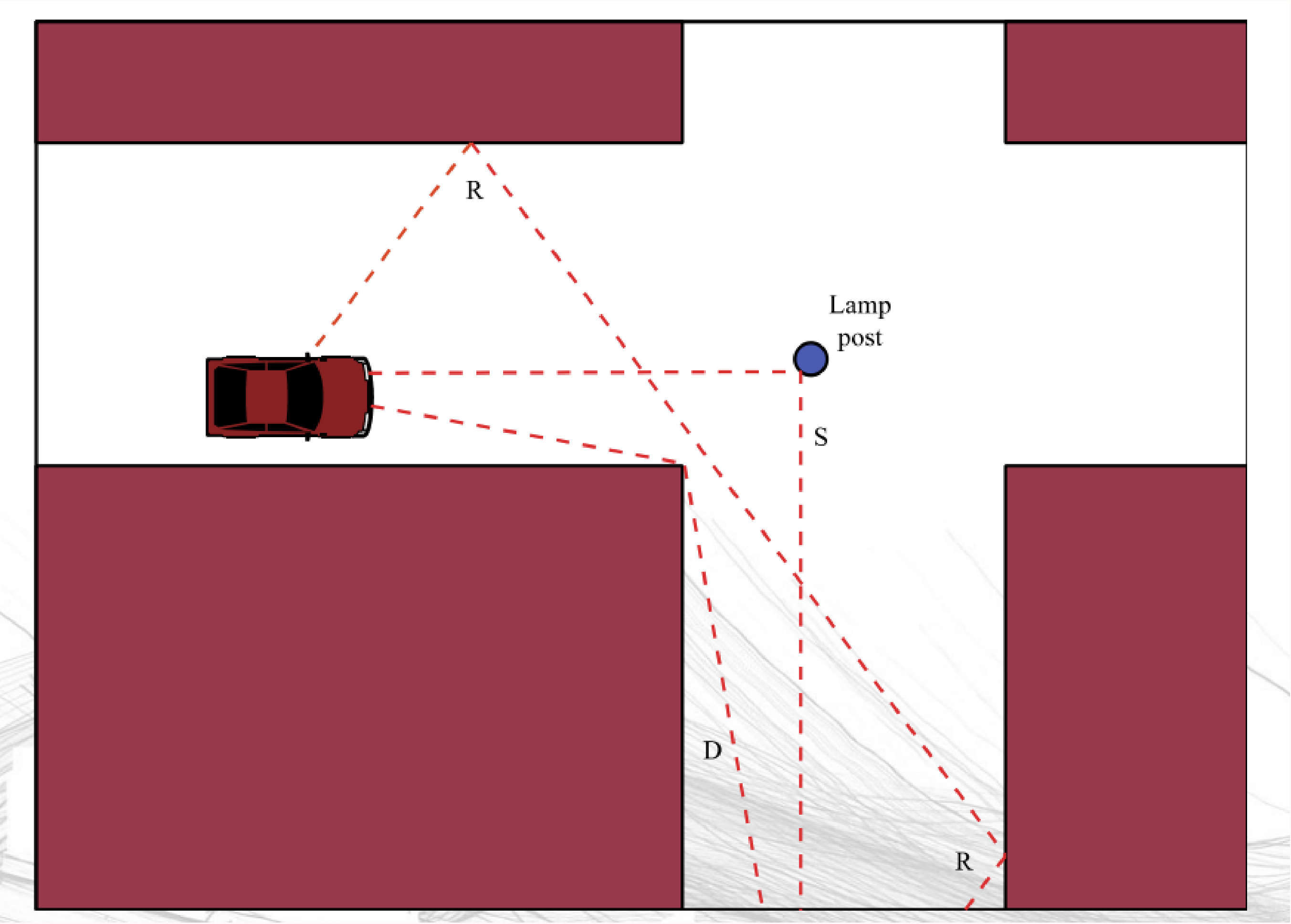
General Formulation of Path Loss

- Path Loss varies as some power of distance from the transmitter
- $P_r \propto \frac{P_t}{d^n}$
- $P_r = \frac{P_t}{L_p}$
- $L_p(dB) = L_o(dB) + 10nLog_{10}\, d$
- n= path loss exponent. n= 2.5 (rural areas) and n=4.8(dense urban areas)
- L_0 = Path loss at a reference distance

Large-scale fading-Shadowing

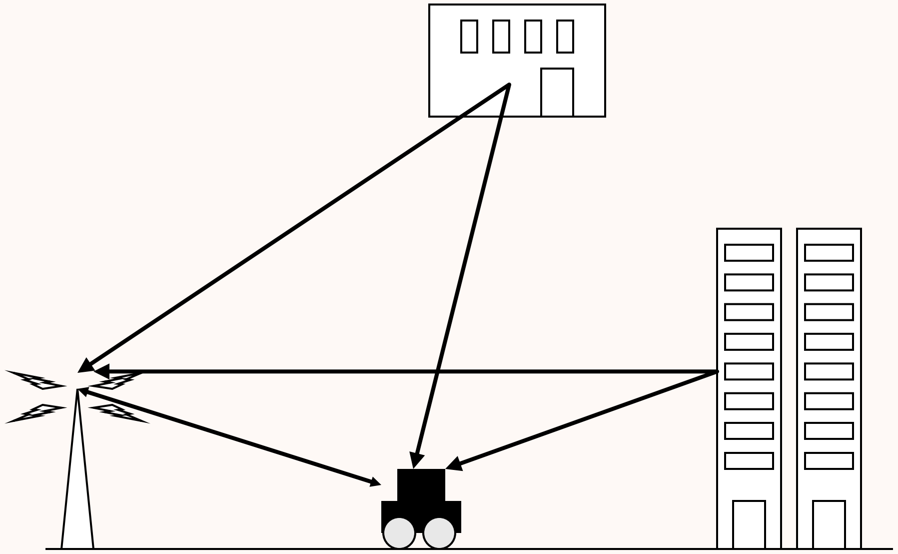
- Shadowing is the effect that the received signal power fluctuates due to objects obstructing the propagation path between transmitter and receiver.
- physical obstacles (hills, buildings etc.) decrease the received signal strength and MS mobility causes its fluctuation
    - Reflection: wave reflects off object that is large relative to wavelength.
    - Diffraction: radio path is obstructed by object that has sharp edges. Wave bends around corners.
    - Scattering: wave travels through a large number of objects small in comparison with wavelength such as trees, lamp posts, street signs, etc.
- $P_r = P_t - L_p + X_\sigma$
- X_σ is a random signal




R
Lamp
post
S
D
R

Wireless Propagation: Multipath

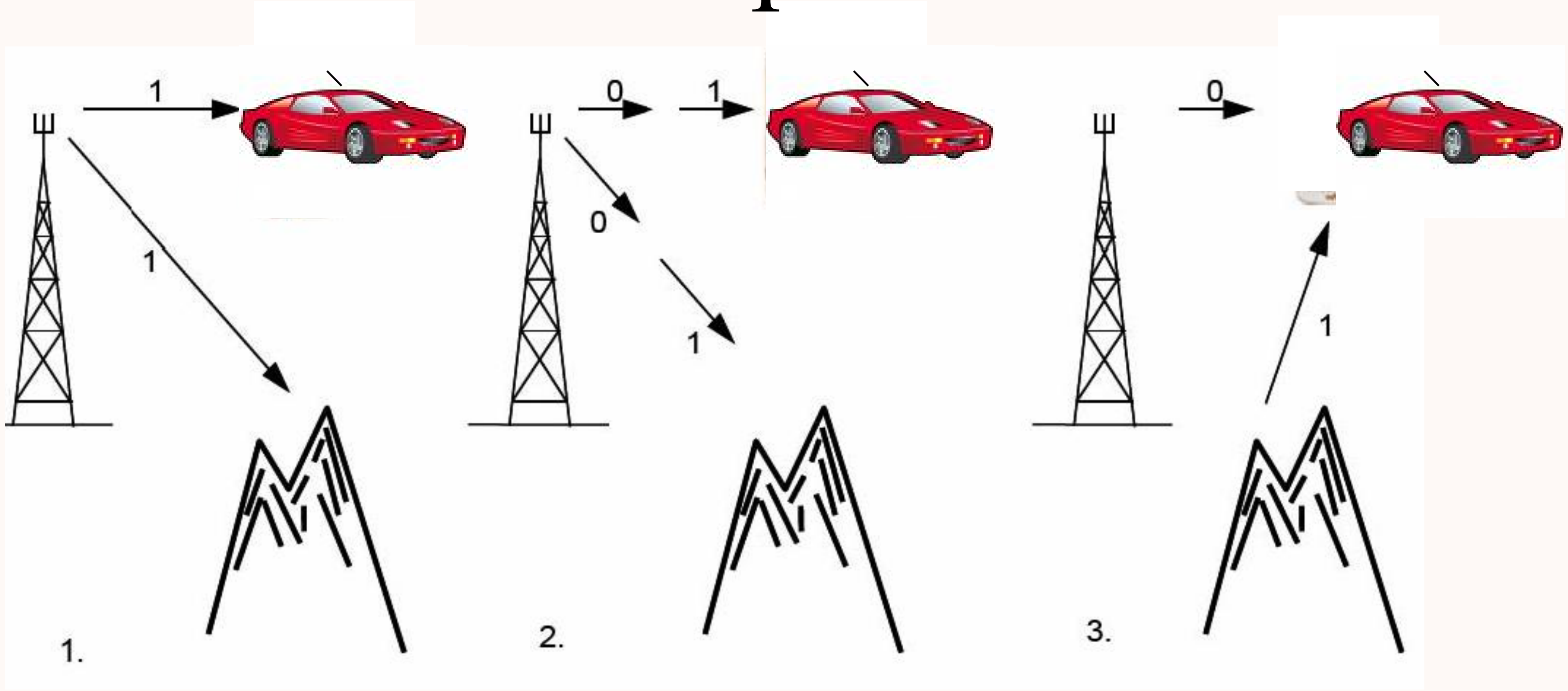
- Multipath
  - The effects mentioned mean that multiple copies of the signal may arrive at the receiver via different paths.
  - This can lead to either reinforcement or cancellation of the original signal.



Multi Path and Time Dispersion

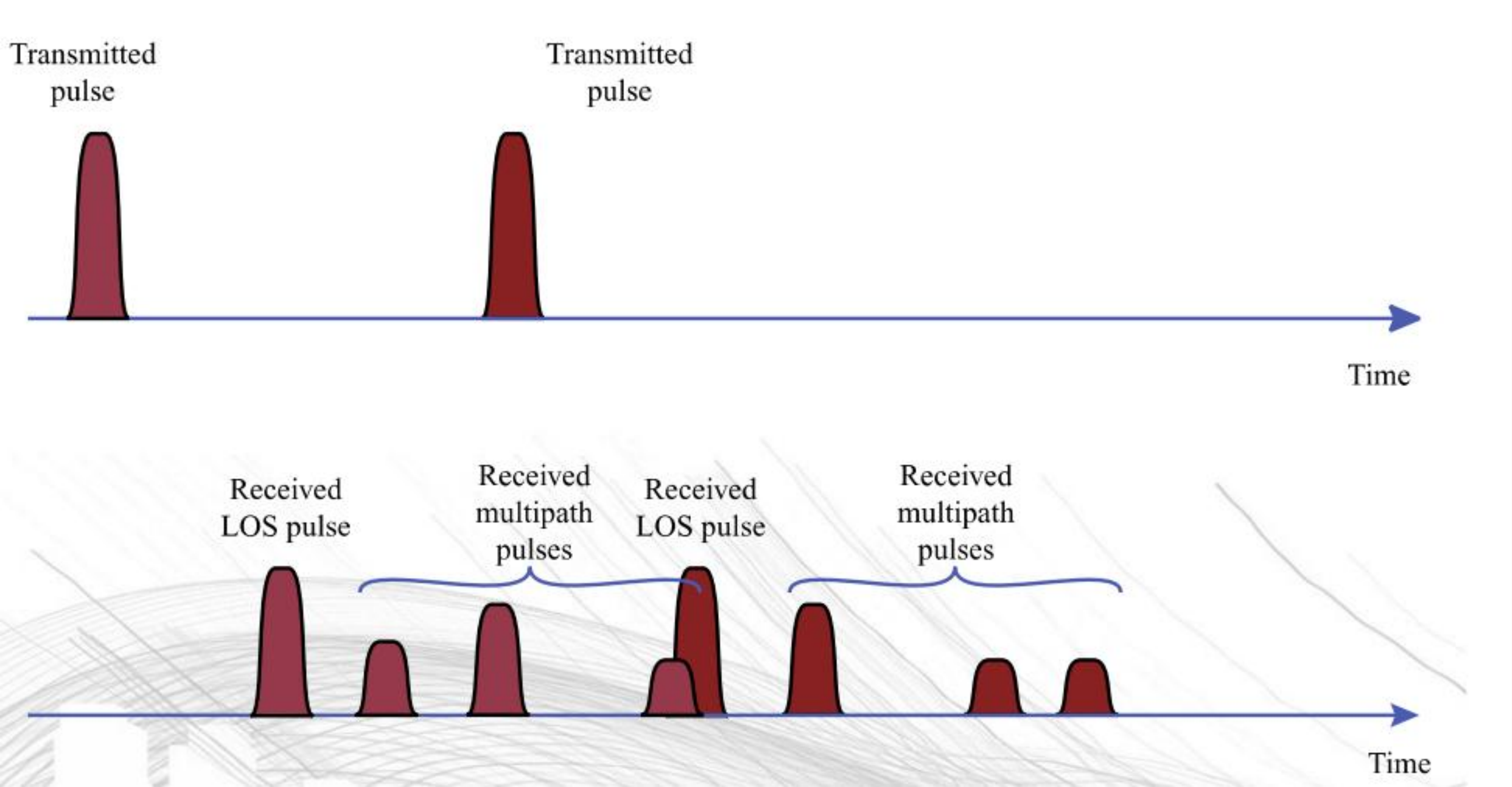
- *Time dispersion* occurs, when the reflected signal comes from an object far away from the receiving antenna
  - The lengths of the paths over which the signal travels differ significantly
- Time dispersion causes Inter-Symbol Interference (ISI) where consecutive symbols (bits) interfere with each other making it difficult for the receiver to determine which symbol is the correct one.
- An example of this is shown in the next slide where the sequence 1,0 is sent from the base station

Multi Path and Time Dispersion



If the reflected signal arrives one bit time after the direct signal, then the receiver detects a 1 from the reflected wave at the same time it detects a 0 from the direct wave.

Multipath and Time Dispersion



Propagation: Large-scale fading

Loss Models

- Clearly, calculating path loss is complicated.
  - Very difficult to determine analytically.
- Models have been developed for specific wireless scenarios based on empirical data.
  - Lee model
    - Relatively simple model
    - Based on LA data
  - Okomura model
    - Large urban macrocell
    - Based on Tokyo data
      - Lots of buildings, not that high
  - Hata model
    - Extension of Okomura model

Small Scale Fading

Small Scale Fading

- Large scale fading is characterised by the drop in received power with distance.
- However, power can fluctuate rapidly over small changes in distance or short periods of time.
  - These effects are referred to as small scale fading.

Propagation: Small-scale fading
Main Factors

- **The main factors influencing small-scale fading are**
  - **Multipath propagation:**
    - Presence of reflecting objects and scatterers in the channel constantly create a changing environment that dissipates signal energy in amplitude, phase and time.
  - **Speed of Mobile:**
    - Relative motion between BS and mobile results in random frequency modulation.
  - Speed of Surrounding Objects:
    - If surrounding objects move at a rate greater than mobile, it will dominate small-scale fading, otherwise could be neglected.
  - Transmission BW of signal:
    - If Tx radio signal BW is greater than the "bandwidth" of the multipath channel, the received signal will be distorted.

Types of Small Scale fading Effects

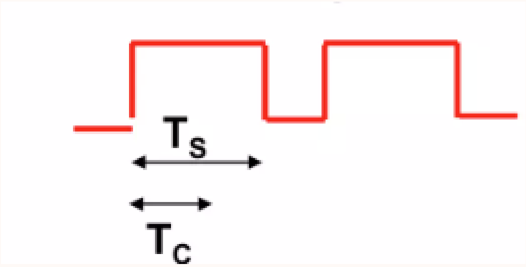
- Doppler Spread and Coherence time are parameters which describe the time varying nature of the channel caused either by relative motion between BS and mobile or by motion of objects in channel.
- Delay Spread and Coherence Bandwidth are parameter which describe the time dispersive nature of the channel caused due to the combination of delayed multipath signal arrivals

Doppler Spread

- ***Doppler spread*** B_d is a measure of spectral broadening caused by the time rate of change of the mobile radio channel
- Defined as the range of frequencies over which the received Doppler spectrum is essentially nonzero.
- Doppler Shift: Change in apparent frequency of a signal as Transmitter and Receiver mover towards ($f_c + f_d$) or away ($f_c - f_d$) from each other
- Doppler Spread is defined as the maximum doppler shift $f_d^m = v/\lambda$
- If the transmit signal bandwidth(B_s) is more than the B_d, then effect of doppler spread is not important

Coherence time

- ***Coherence time*** T_c is a statistical measure of the time duration over which the channel impulse response essentially remains unchanged (i.e., highly correlated).
- If the symbol period of the baseband signal is more than the coherence time ($T_s > T_c$) then the signal will distort since the channel will change during the transmission of the signal



Slow Fading and Fast Fading

- **Slow Fading:** The channel changes very slowly during the time to transmit each bit.

$$T_s \ll T_c \text{ usually 10 times greater}$$

- **Fast Fading**: If the above is not true

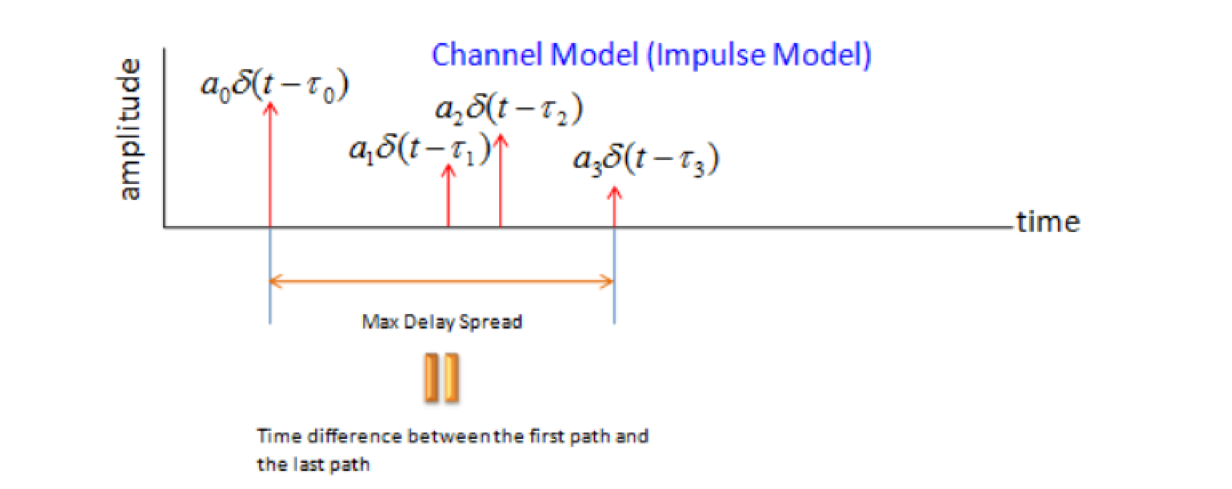
$$T_s \geq T_c$$

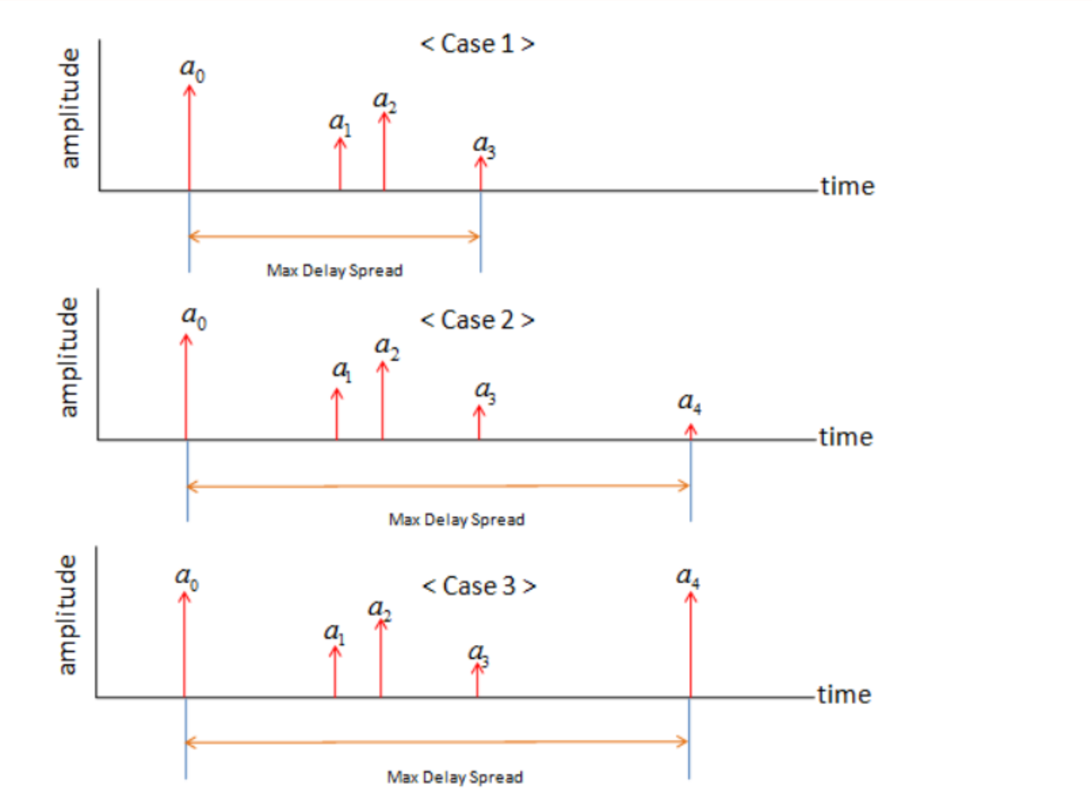
Delay Spread

- Delay Spread: It is generally defined as the difference between the time of arrival of the earliest component (e.g., the line-of-sight wave if there exists) and the time of arrival of the latest multipath component.

Multipath Fading: Delay Spread

- Max delay spread



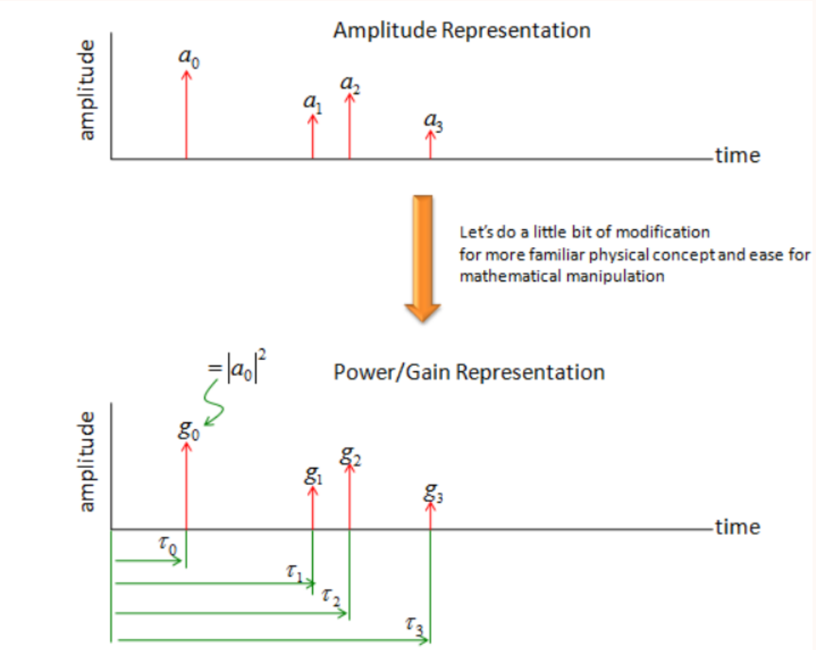


Even though Cases 2 and 3 might have a similar max delay spread, their channel characteristics could be quite different due to amplitude variations.

Acknowledgement: https://www.sharetechnote.com/html/Handbook_Communication_DelaySpread.html#:~:text=Mathematically%2C%20RMS%20delay%20spread%20is,the%20power%20in%20each%20path.

Multipath Fading: Avg. Delay Spread

- To overcome the limitation of the Max Delay Spread (i.e, the distortion by outlier, no consideration of power), a new terms was introduced.



$$Total\ Power = g_0 + g_1 + g_2 + g_3 = \sum_{i=1}^{3} g_i$$

$$Fraction\ power\ for\ path\ 0 = \frac{g_0}{\sum_{i=1}^{3} g_i} = b_0$$

$$Fraction\ power\ for\ path\ 1 = \frac{g_1}{\sum_{i=1}^{3} g_i} = b_1$$

$$Fraction\ power\ for\ path\ 2 = \frac{g_2}{\sum_{i=1}^{3} g_i} = b_2$$

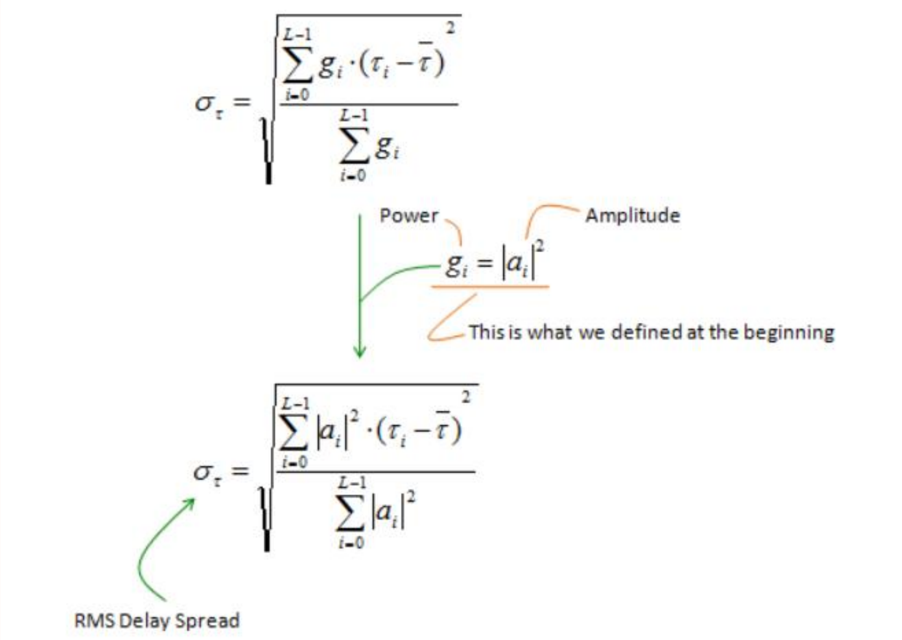
$$Fraction\ power\ for\ path\ 3 = \frac{g_3}{\sum_{i=1}^{3} g_i} = b_3$$

$$average\ delay = \bar{\tau} = b_0\tau_0 + b_1\tau_1 + b_2\tau_2 + b_3\tau_3 = \sum_{i=0}^{3} b_i\tau_i$$

$$\bar{\tau} = \sum_{i=0}^{L-1} b_i\tau_i = \frac{\sum_{i=0}^{L-1} g_i\tau_i}{\sum_{i=0}^{L-1} g_i}$$

Multipath Fading: Variance of Delay

- Variance of delay = $\sigma_\tau^2 = \sum_{i=0}^{L-1} b_i(\tau_i - \bar{\tau})^\wedge 2 = \frac{\sum_{i=0}^{L-1} g_i(\tau_i - \bar{\tau})^\wedge 2}{\sum_{i=0}^{L-1} g_i}$
- RMS delay spread



Example

- Let a wireless channel be described by the following path gain and path delay vectors:

$$\alpha_i = \{0.75\ 0.25\ 0.5\ 0.11\}, \tau_i = \{0.2\ 0.34\ 0.78\ 0.98\}$$

Find the RMS delay spread of this channel

Multipath Fading: Coherence Bandwidth

- *Coherence bandwidth* B_c is a statistical measure of the range of frequencies over which the channel can be considered flat (i.e., it passes all spectral components with approximately equal gain and linear phase). All frequency components of the transmitted signal within the coherence bandwidth will fade simultaneously.
- The coherence bandwidth is inversely proportional to the delay spread

$$B_c = \frac{1}{\sigma_\tau}$$

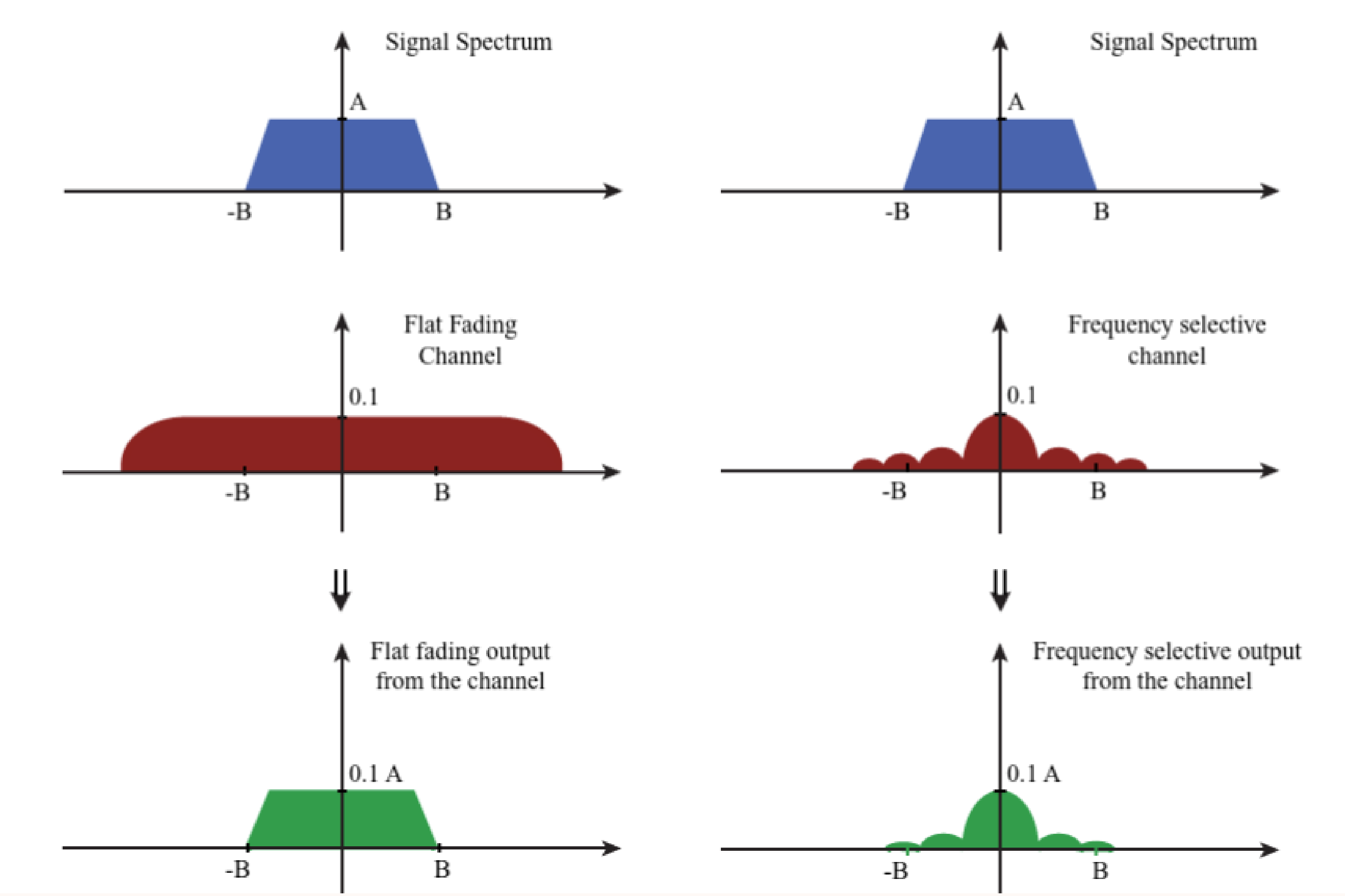
Flat Fading and Frequency Selective Fading

- **Flat Fading:** In this all-frequency components of the received signal fluctuate in the same proportions simultaneously

$$B_c \gg B_s$$

- **Frequency Selective Fading:** In this the different spectral components of the signals are affected unequally

Flat Fading and Frequency Selective Fading



Small-Scale Fading
(Based on multipath time delay spread)

Flat Fading
1. BW of signal < BW of channel
2. Delay spread < Symbol period

Frequency Selective Fading
1. BW of signal > BW of channel
2. Delay spread > Symbol period

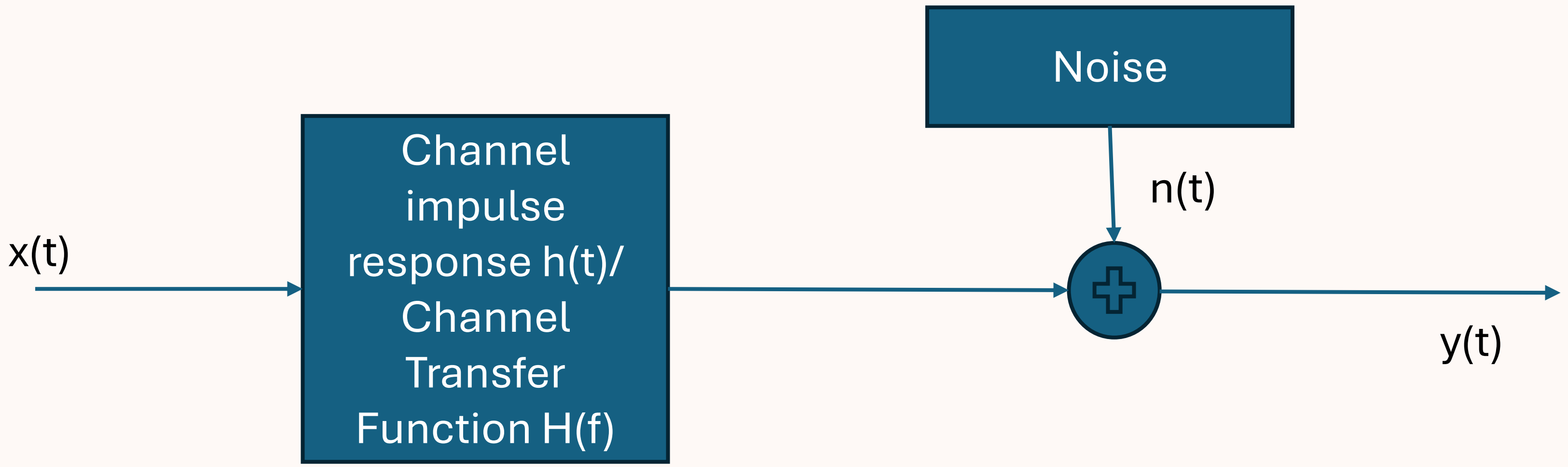
Small-Scale Fading
(Based on Doppler spread)

Fast Fading
1. High Doppler spread
2. Coherence time < Symbol period
3. Channel variations faster than baseband signal variations

Slow Fading
1. Low Doppler spread
2. Coherence time > Symbol period
3. Channel variations slower than baseband signal variations

The fading Channel

- Additive White Gaussian Noise
- Rayleigh Fading
- Rician fading



Wrap-up

- Radio signals change with distance from sender to receiver
- Large scale fading
  - Signal strength decreases exponentially with distance from sender to receiver
  - Free space loss
- Small scale fading
  - Signal strength fluctuates over small changes in distance between sender and receiver

Question

- We have seen that channel conditions can be quite unpredictable. Thus, degree of loss will vary.
- What can be done to deal with this?