Modern Wireless Networks

Wireless Channel

UNIVERSITY AT ALBANY
State University of New York

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Why Channel Modeling?

- Performance of a radio system is determined by the radio channel
- The channel models basis for
  - System design
  - Algorithm design
  - Antenna design
- Trend towards more interactive system
  - MIMO, UWB

Without reliable channel models, it is hard to design radio systems that work well in ***real*** environments.

The Radio Channel

- More complex than just a loss
- Some examples:
  - Behavior in time/place?
  - Behavior in frequency?
  - Directional properties?
  - Bandwidth dependency?
  - Behavior in delay?

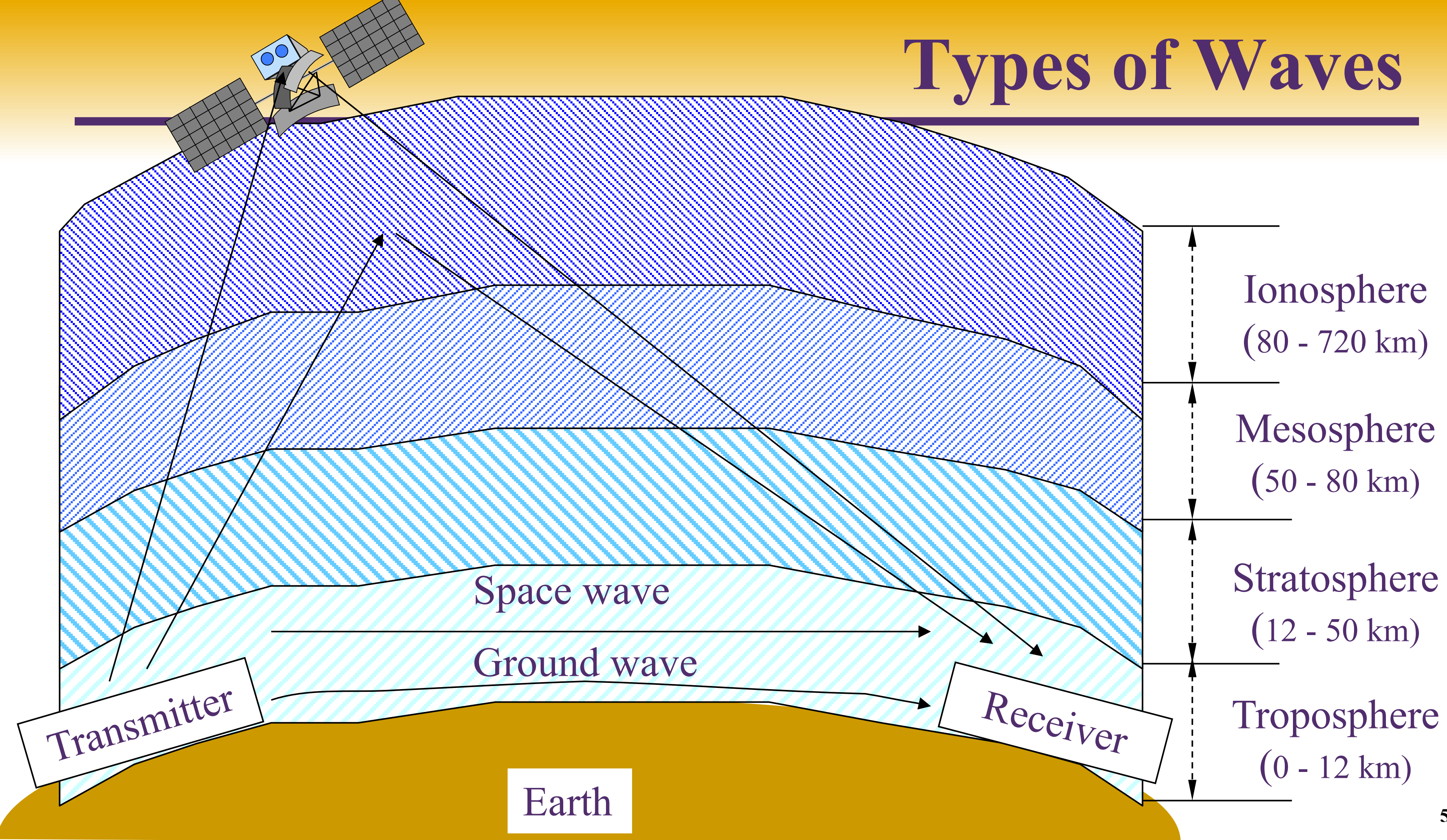
Speed, Wavelength and Frequency

Light speed = Wavelength x Frequency

$= 3 \times 10^8$ m/s = 300,000 km/s

System	Frequency	Wavelength
AC current	60 Hz	5,000 km
FM radio	100 MHz	3 m
Cellular	800 MHz	37.5 cm
Ka band satellite	20 GHz	15 mm
Ultraviolet light	10^{15} Hz	10^{-7} m

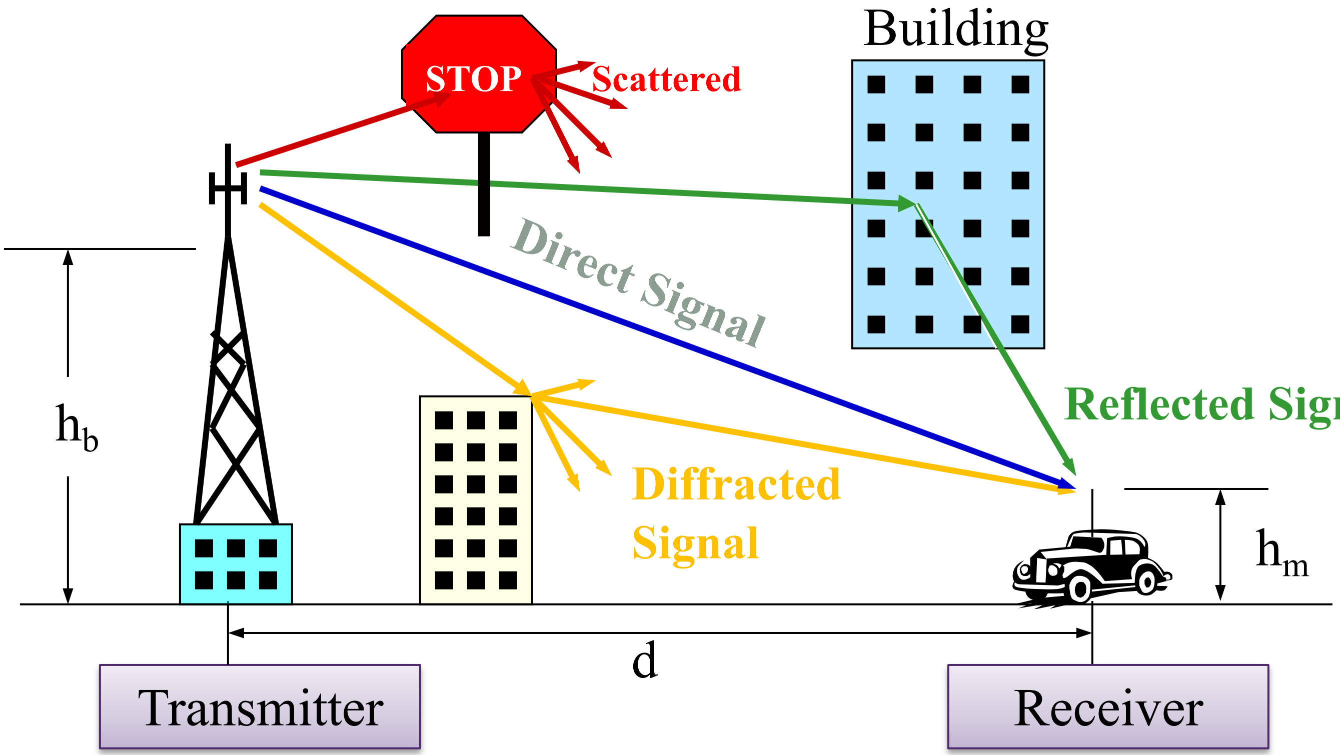
Types of Waves



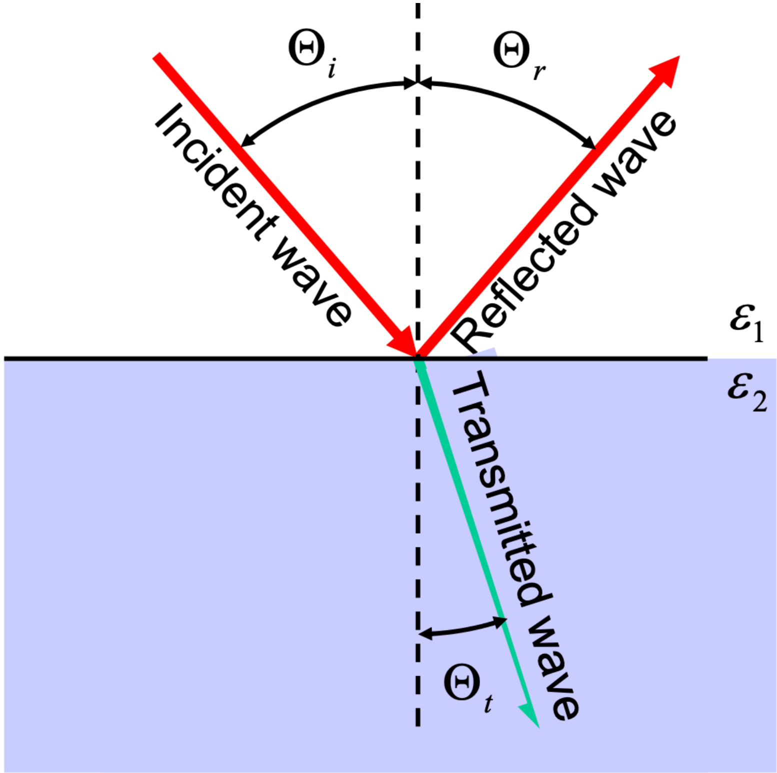
Propagation Mechanisms

- Reflection
  - Propagation wave impinges on an object which is large as compared to wavelength
    - e.g., the surface of the Earth, buildings, walls, etc.
- Diffraction
  - Radio path between transmitter and receiver obstructed by surface with sharp irregular edges
  - Waves bend around the obstacle, even when LOS (line of sight) does not exist
- Scattering
  - Objects smaller than the wavelength of the propagation wave
    - e.g. foliage, street signs, lamp posts

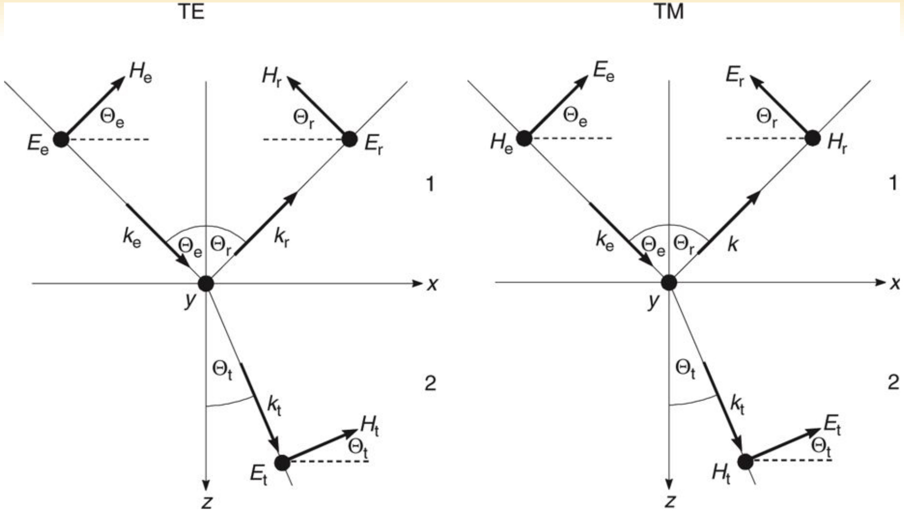
Radio Propagation Effects



Reflection and Transmission



Reflection and Transmission



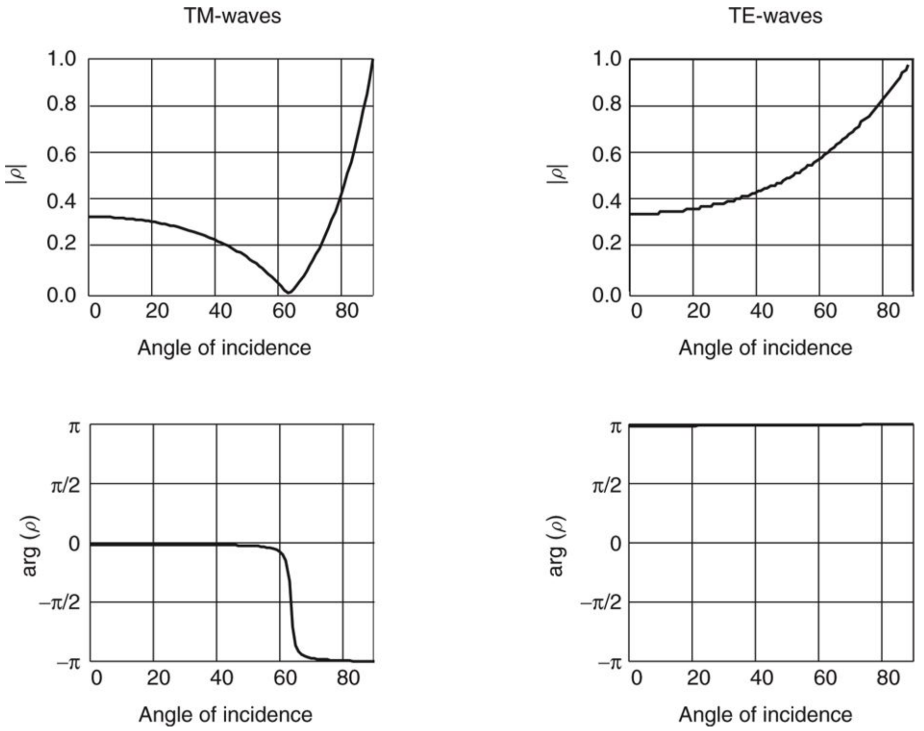
- Snell's Law
  - Reflection Angle ($\theta_r = \theta_e$)
  - Transmission Angle ($\frac{\sin \theta_t}{\sin \theta_e} = \frac{\sqrt{\epsilon_1}}{\sqrt{\epsilon_2}}$)
- TE and TM waves
  - Traversal Magnetic (TM)
    - magnetic field component is parallel to the boundary between the two dielectrics
  - Traversal Electric (TE)
    - electric field component is parallel to the boundary between the two dielectrics

Reflection Coefficient for Polarization

$$\rho_{TM} = \frac{\sqrt{\varepsilon_2}\cos\Theta_e - \sqrt{\varepsilon_1}\cos(\Theta_t)}{\sqrt{\varepsilon_2}\cos\Theta_e + \sqrt{\varepsilon_1}\cos(\Theta_t)}$$

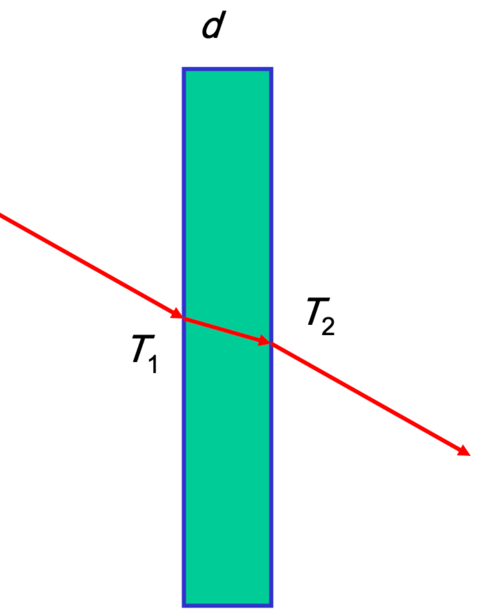
$$\rho_{TE} = \frac{\sqrt{\varepsilon_1}\cos(\Theta_e) - \sqrt{\varepsilon_2}\cos(\Theta_t)}{\sqrt{\varepsilon_1}\cos(\Theta_e) + \sqrt{\varepsilon_2}\cos(\Theta_t)}$$

- Has both Amplitude & Phase
- reflection coefficient becomes −1 (magnitude 1, phase shift of 180°) at grazing incidence (Θe → 90°)



Case for dielectric halfspace: ground reflections and reflections by terrain features, like mountains

Transmission through Dielectric Layer



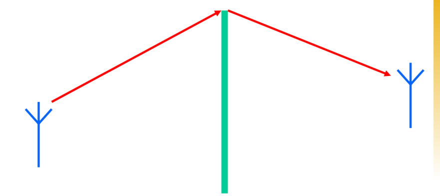
- Results in Attenuation and Phase Shift
- The reflection and transmission coefficients can be determined by summation of the partial waves
- Total Transmission Coefficient $T = \dfrac{T_1 T_2 e^{-j\alpha}}{1 + \rho_1 \rho_2 e^{-2j\alpha}}$
- Total Reflection Coefficient

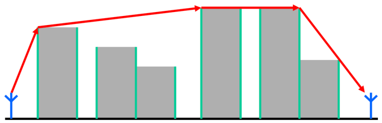
$$\rho = \frac{\rho_1 + \rho_2 e^{-j2\alpha}}{1 + \rho_1 \rho_2 e^{-2j\alpha}}$$

- Electrical length of the dielectric

$$\alpha = \frac{2\pi}{\lambda} \sqrt{\varepsilon_{r,2}}\, d_{\text{layer}} \cos(\Theta_t)$$

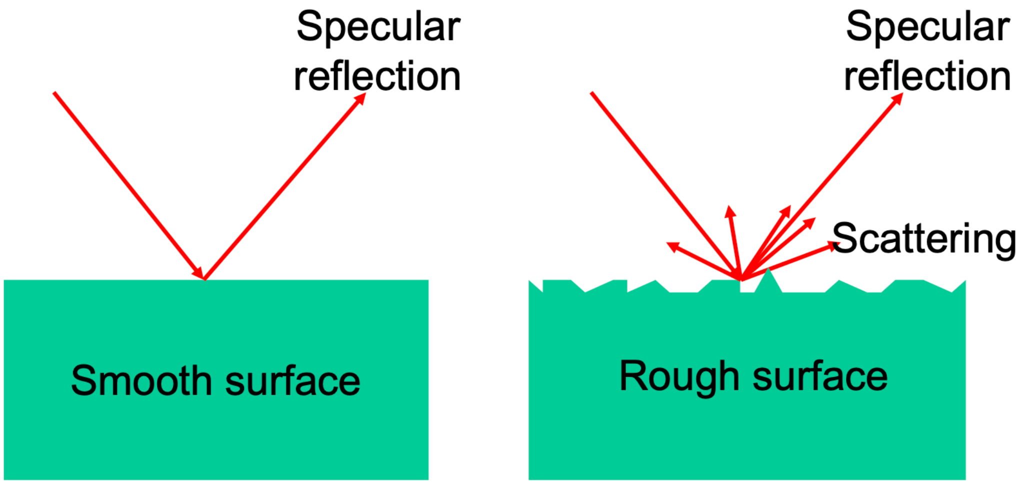
Diffraction





- Only in the limit of very small wavelength (large frequency) does geometrical optics become exact
- Behavior of homogeneous wave by a semi-infinite screen
- Single or multiple edges
- Makes it possible to go behind corners
- Less pronounced when the wavelength is small compared to objects

Scattering



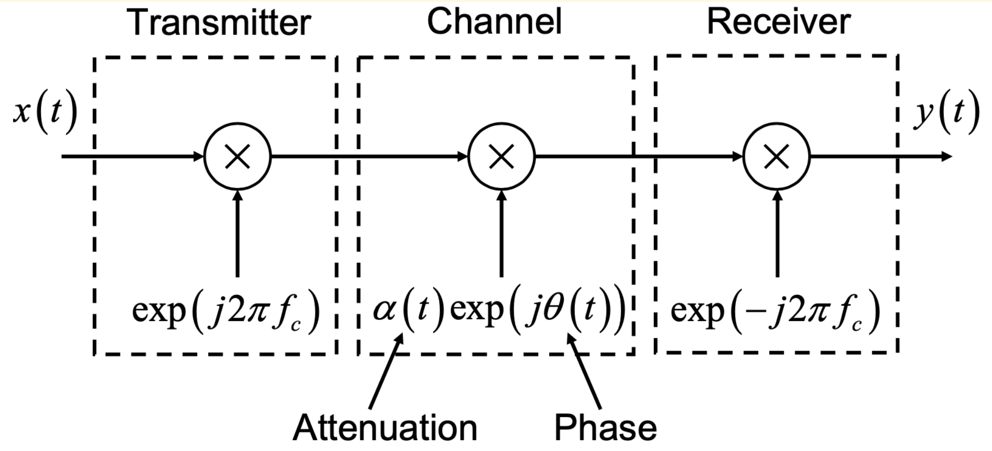
for Gaussian surface distribution

$$\rho_{\text{rough}} = \rho_{\text{smooth}} \exp\left[-2\left(k_0 \sigma_{\text{h}} \sin\psi\right)^2\right]$$

angle of incidence

standard deviation of height

Narrowband System (Noise free)



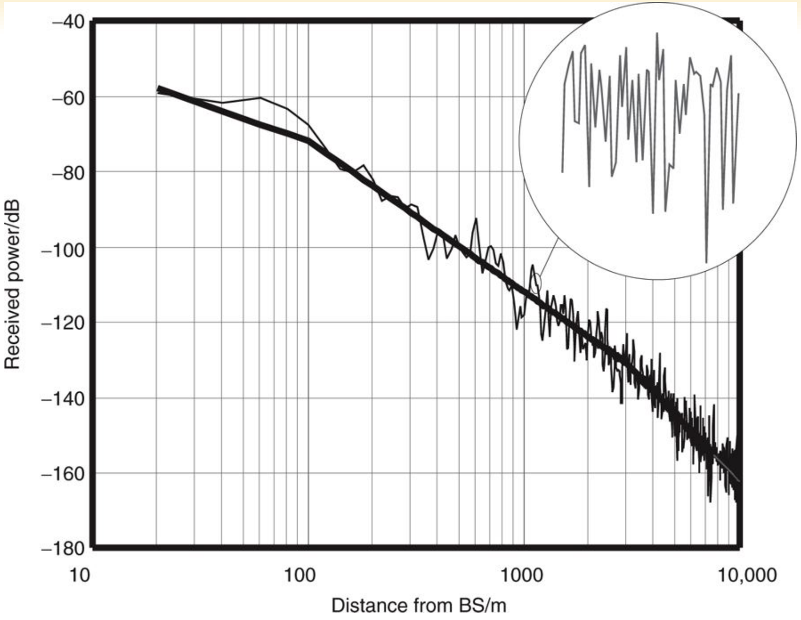
In: $x(t) = A(t)\exp(j\phi(t))$

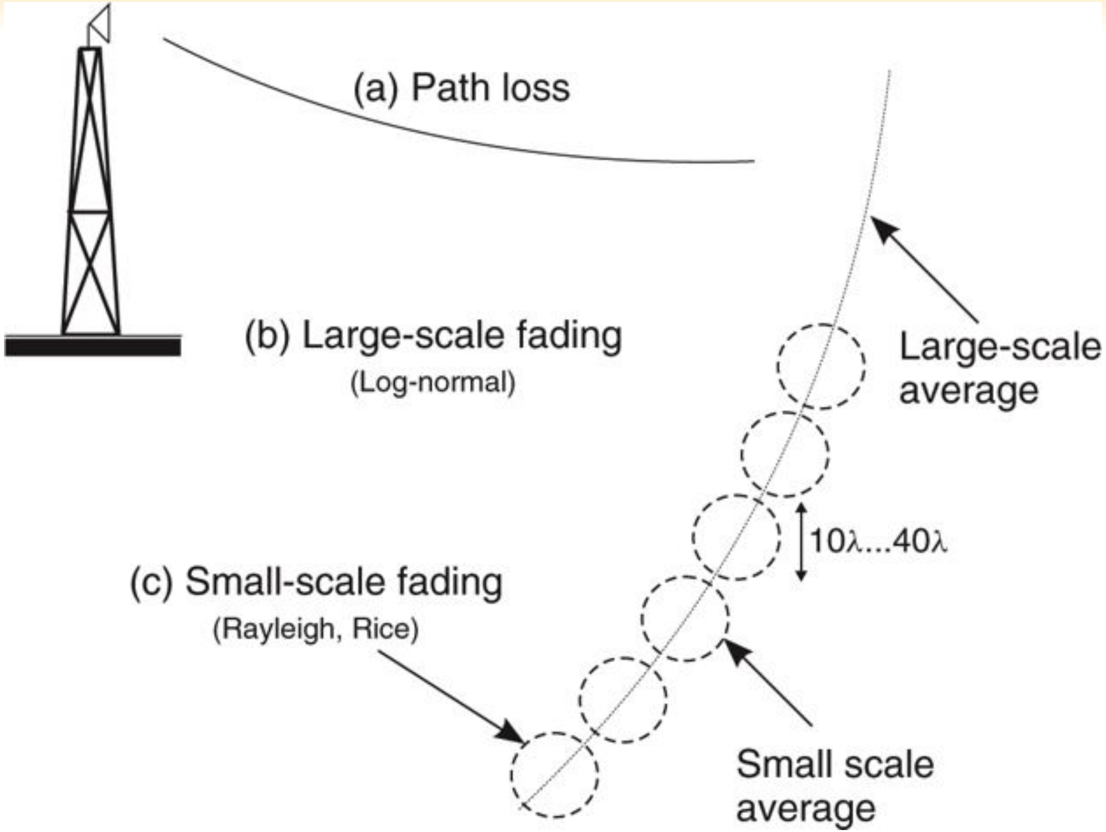
Out: $y(t) = A(t)\exp(j\phi(t))\cancel{\exp(j2\pi f_c t)}\alpha(t)\exp(j\theta(t))\cancel{\exp(-j2\pi f_c t)}$

$= A(t)\alpha(t)\exp(j(\phi(t)+\theta(t)))$

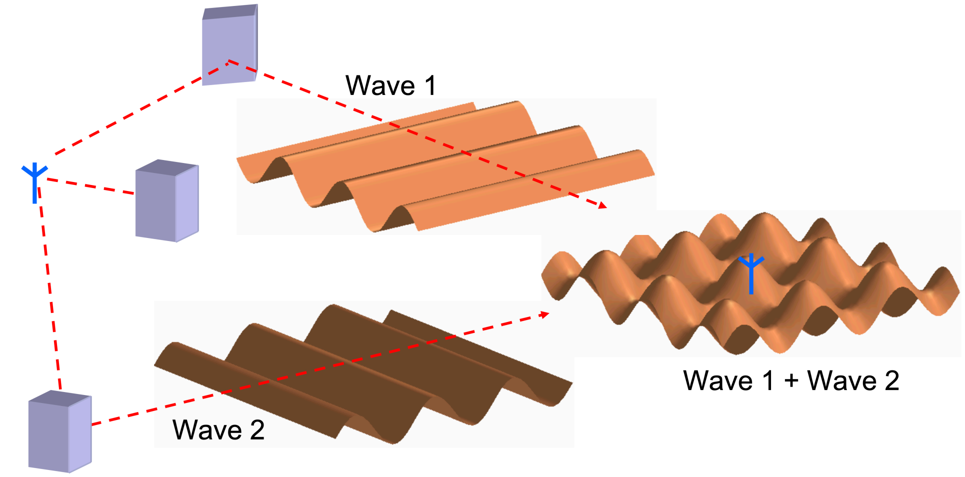
- Model the channel attenuation & phase

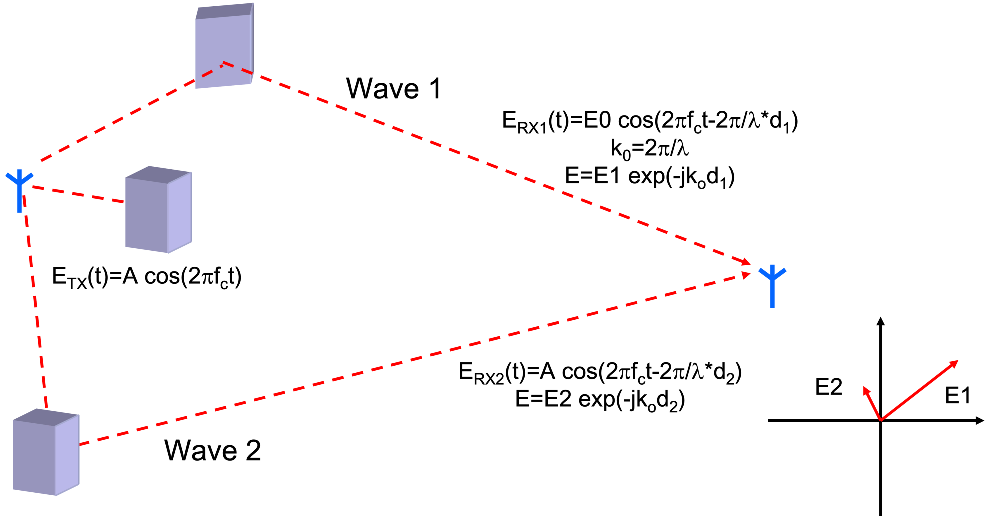
Wireless Channel





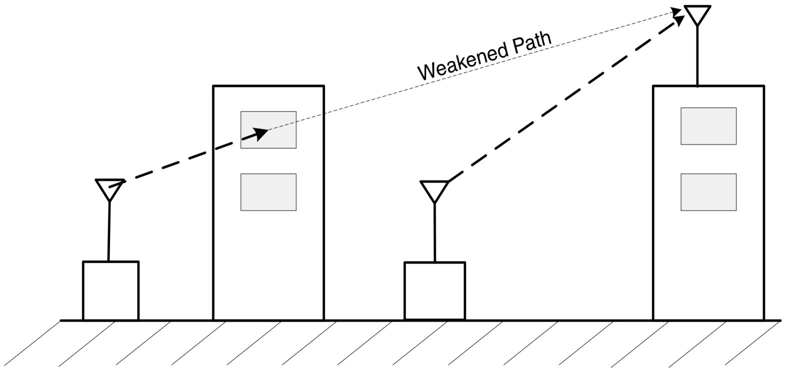
Small Scale Fading





Shadowing

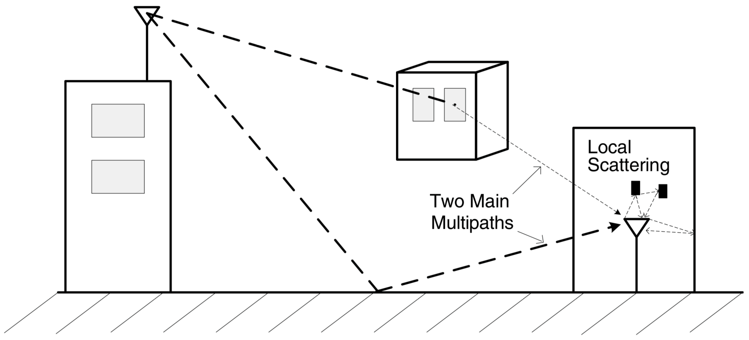
- Trees and buildings may be located between the transmitter and the receiver and cause degradation in received signal strength
- Shadowing is a random pro

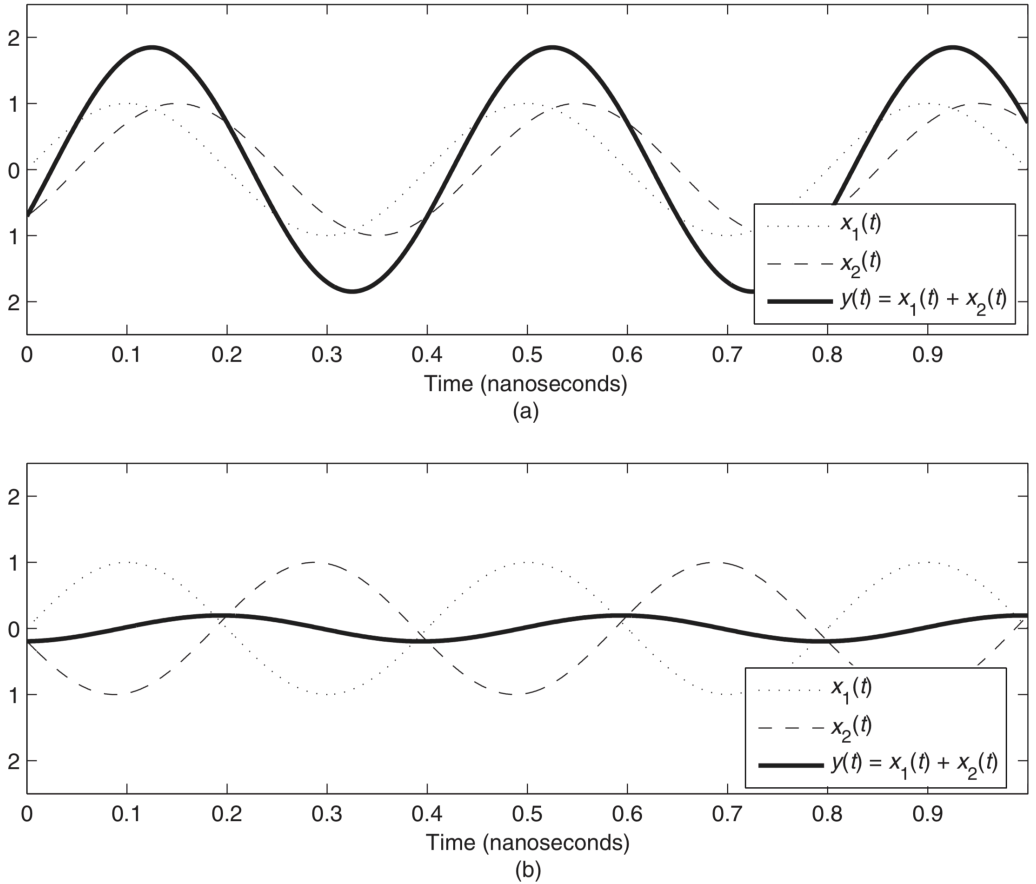


$$P_r = P_t P_o \chi \left(\frac{d_o}{d} \right)^{\alpha}$$

$$\chi = 10^{x/10}, \text{where } x \sim N(0, \sigma_s^2).$$

Fading





- Multipath
- Local Scattering
- Constructive & Destructive Interference

Doppler

- **Doppler Effect**:
  - When a wave source and a receiver are moving towards each other, the frequency of the received signal will not be the same as the source.
  - When they are moving toward each other, the frequency of the received signal is higher than the source.
  - When they are opposing each other, the frequency decreases.
  - Thus, the frequency of the received signal is

$$f_R = f_C - f_D$$

where f_C is the frequency of source carrier, f_D is the Doppler frequency.

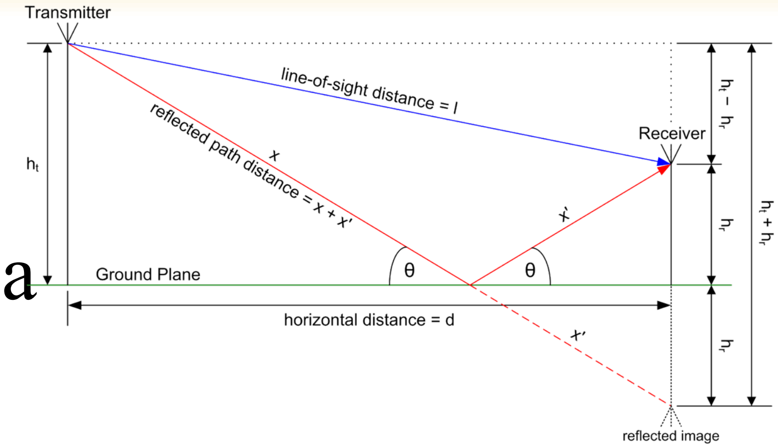
- **Doppler Shift** in frequency:

$$f_D = \frac{v}{\lambda} \cos\theta$$

where v is the moving speed, λ is the wavelength of carrier.

Two Ray Ground Reflection

$$P_r = P_t \frac{G_t G_r h_t^2 h_r^2}{d^4}$$



- Empirical Pathloss Formula

$$P_r = P_t P_o \left(\frac{d_o}{d}\right)^{\alpha}$$

$\alpha = Pathloss\ exponent$

$d_0 = 1m$

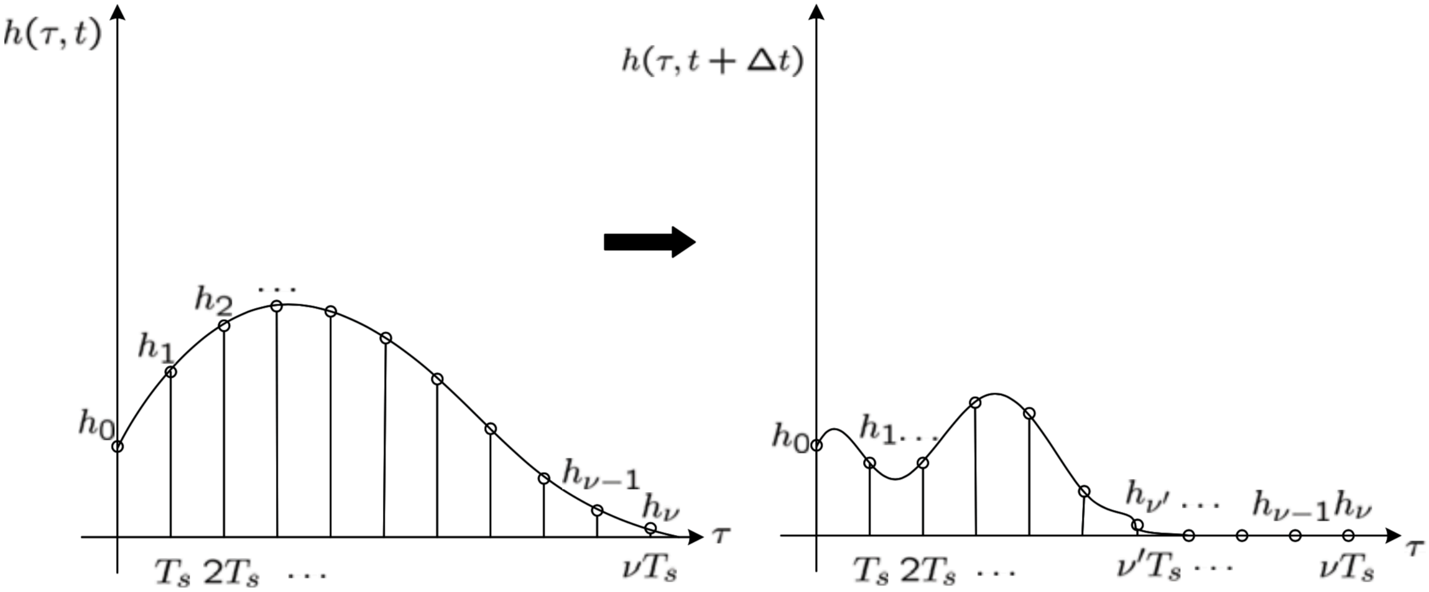
$P_0 = Received\ power\ at\ d_0$

Delay Spread

- When a signal propagates from a transmitter to a receiver, signal suffers one or more reflections.
- This forces signal to follow different paths.
- Each path has different path length, so the time of arrival for each path is different.
- This effect which spreads out the signal is called "Delay Spread".

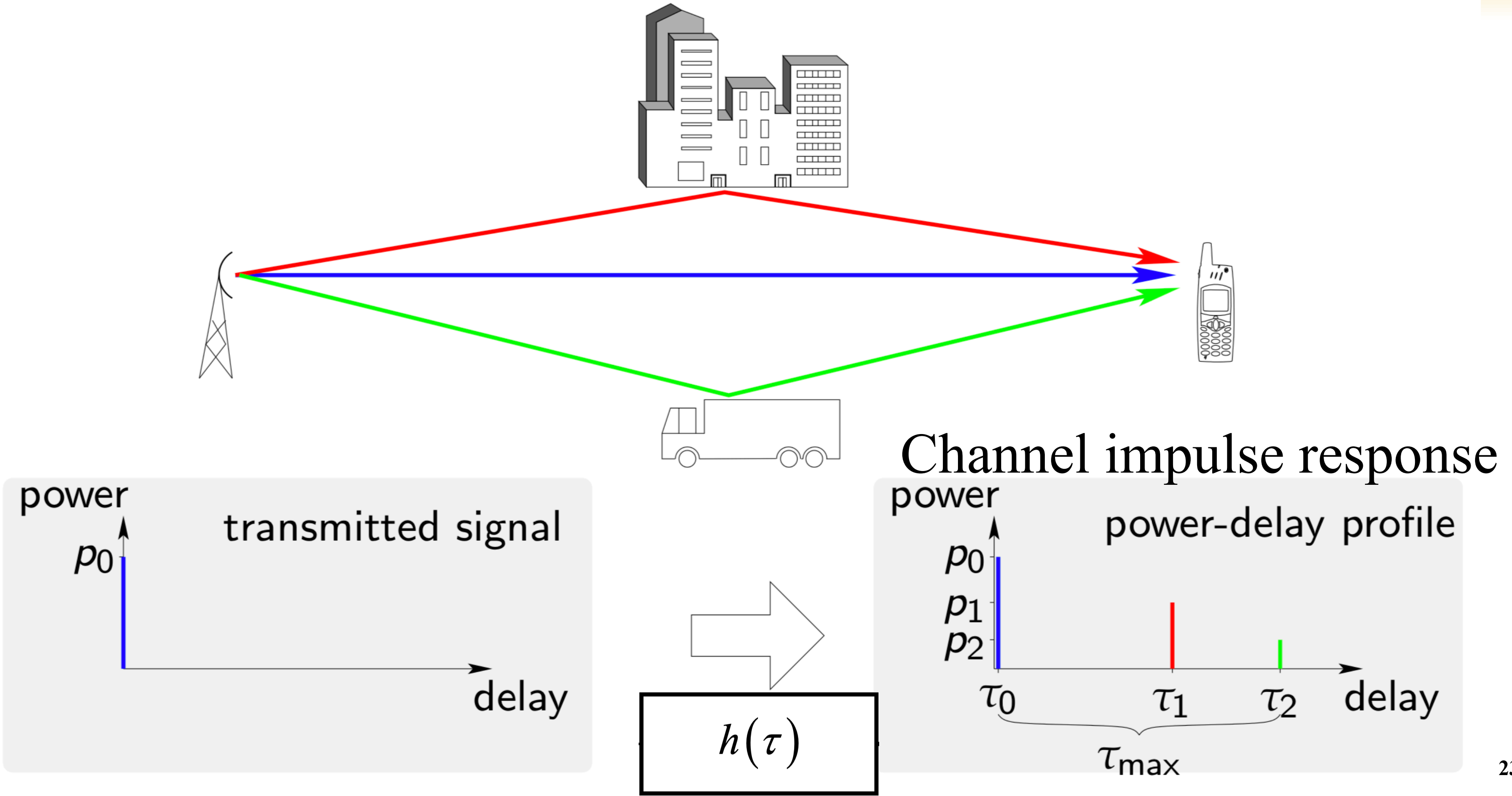
Channel Impulse Response

- The channel is time varying, so the channel impulse response is also a function of time and can be quite different at time $t + \Delta t$ than it was at time t

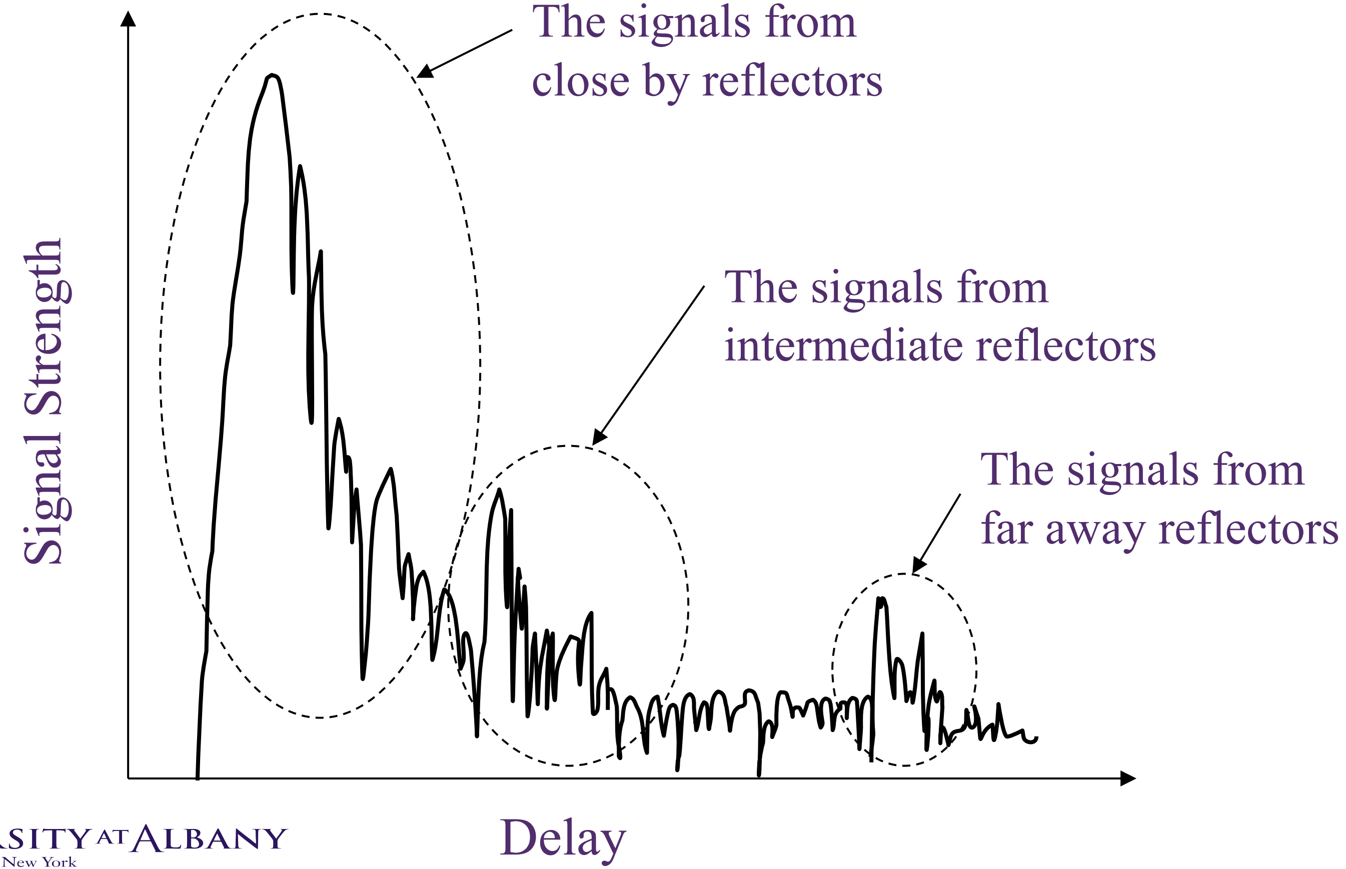


Multipath Channel Effects

➤



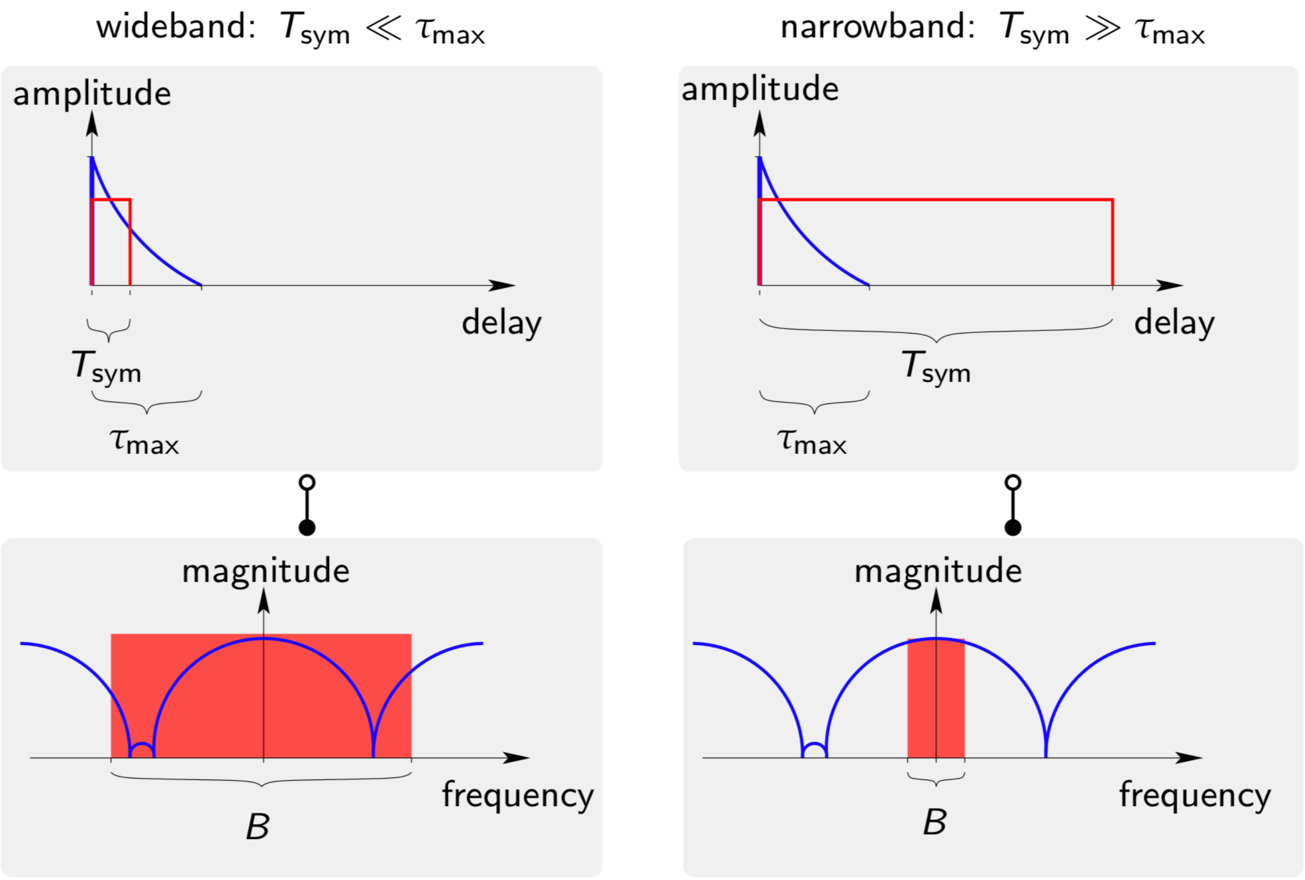
Delay Spread



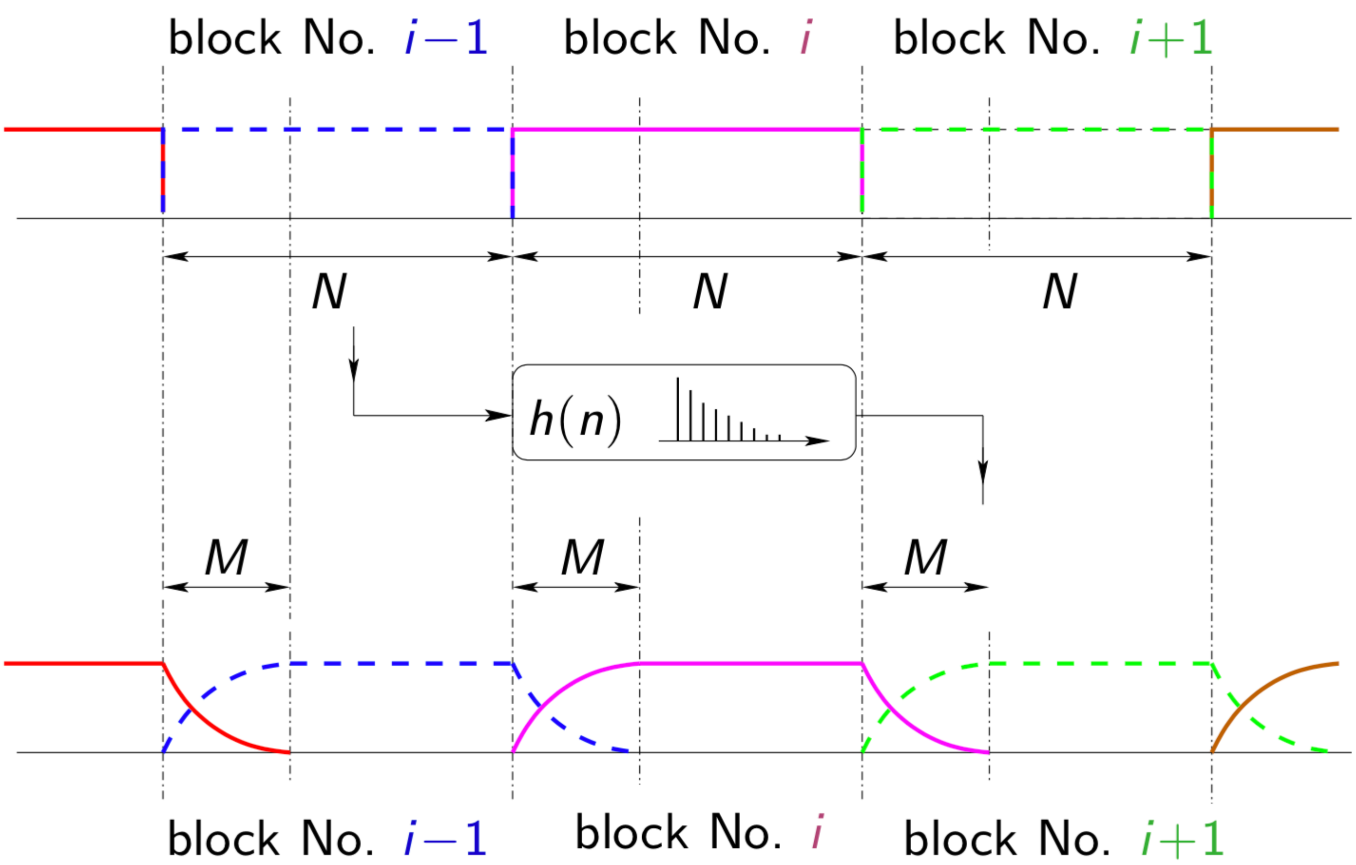
Wideband vs Narrowband

The *maximum excess delay* $\tau_{\max}$ is defined as the difference between minimum and maximum delay.

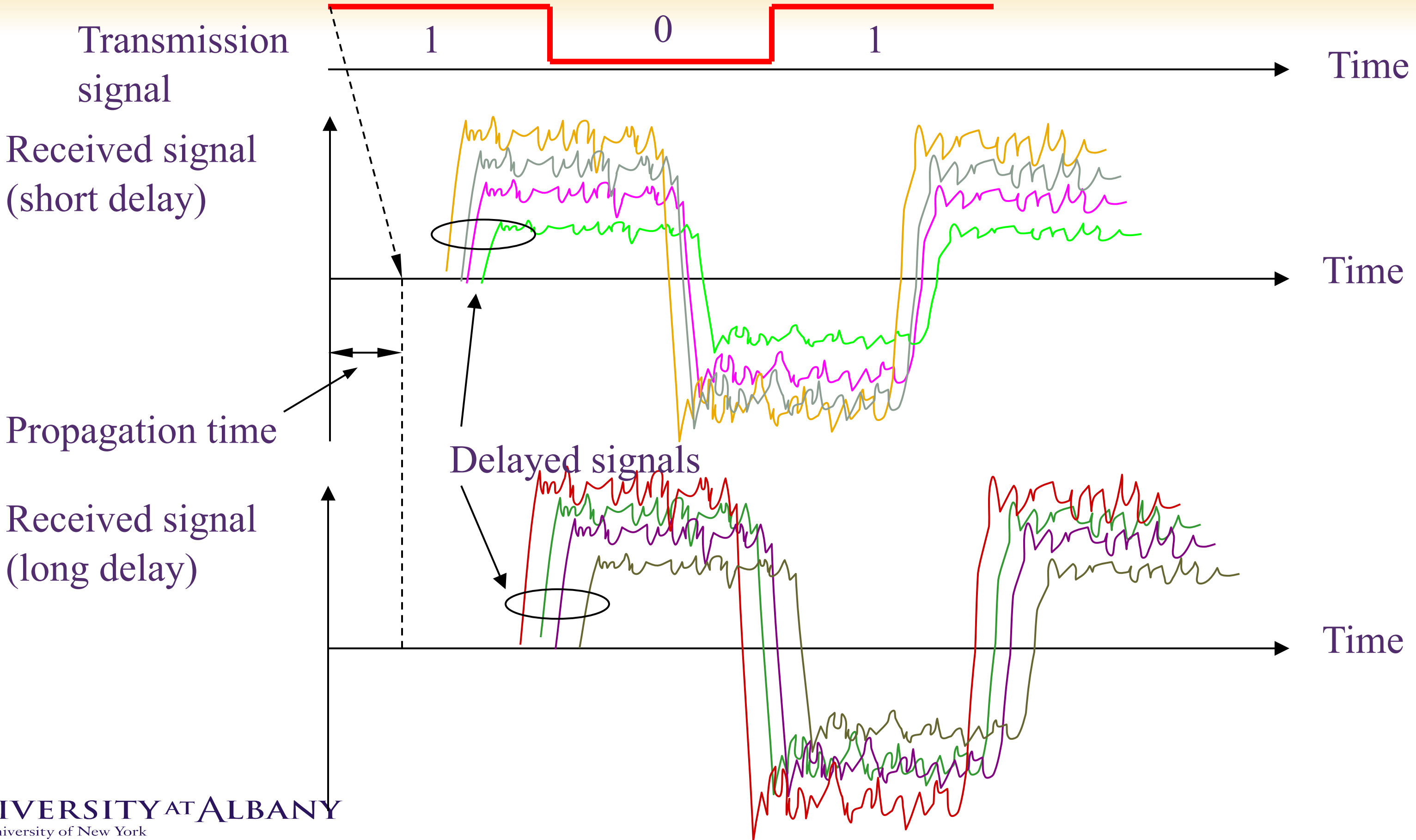
Delay dispersion results in *frequency selective* channel.



Effect of dispersion (ISI)

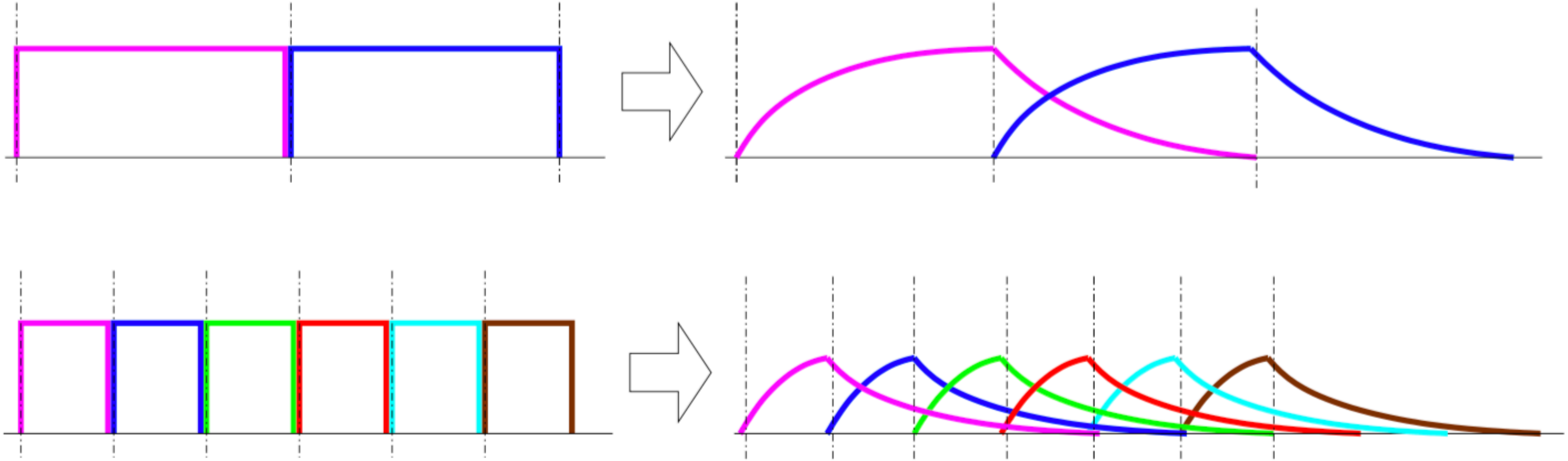


Intersymbol Interference (ISI)



ISI: impediment to increase data rate

- Need for higher data rate urges to transmit at higher symbol ➔ Higher ISI



Coherence Bandwidth

- Statistical measure of the range of frequencies over which the channel can be considered "flat"
  - a channel which passes all spectral components with approximately equal gain and linear phase
  - Two frequencies that are larger than the coherence bandwidth fade independently
  - Represents correlation between two fading signal envelopes at frequencies f_1 and f_2.

$$(\mathrm{B_C})\text{ in Hertz} = \frac{1}{2\pi \times (\text{Delay Spread})}$$

Coherence Bandwidth

The coherence bandwidth is defined relative to the Fourier transform of $A_c(\tau)$, given by $A_C(\Delta f) = \mathcal{F}[A_c(\tau)]$. Note that $A_C(\Delta f) = A_C(\Delta f, \Delta t = 0)$.

$$A_C(f_1, f_2; \Delta t) = \mathrm{E}[C^*(f_1; t) C(f_2; t + \Delta t)].$$

By the Fourier transform relationship, the bandwidth over which $A_C(\Delta f)$ is nonzero is roughly $B_c \approx 1/\sigma T_m$ or $B_c \approx 1/\sigma_{T_m}$ (can also add constants to these denominators).

B_c defines the coherance bandwidth of the channel, i.e. the bandwidth over which fading is correlated.

The function $A_C(\Delta f;\Delta t)$ can be measured in practice by transmitting a pair of sinusoids through the channel that are separated in frequency by Δf and calculating their cross correlation at the receiver for the time separation Δt.

Coherence Time

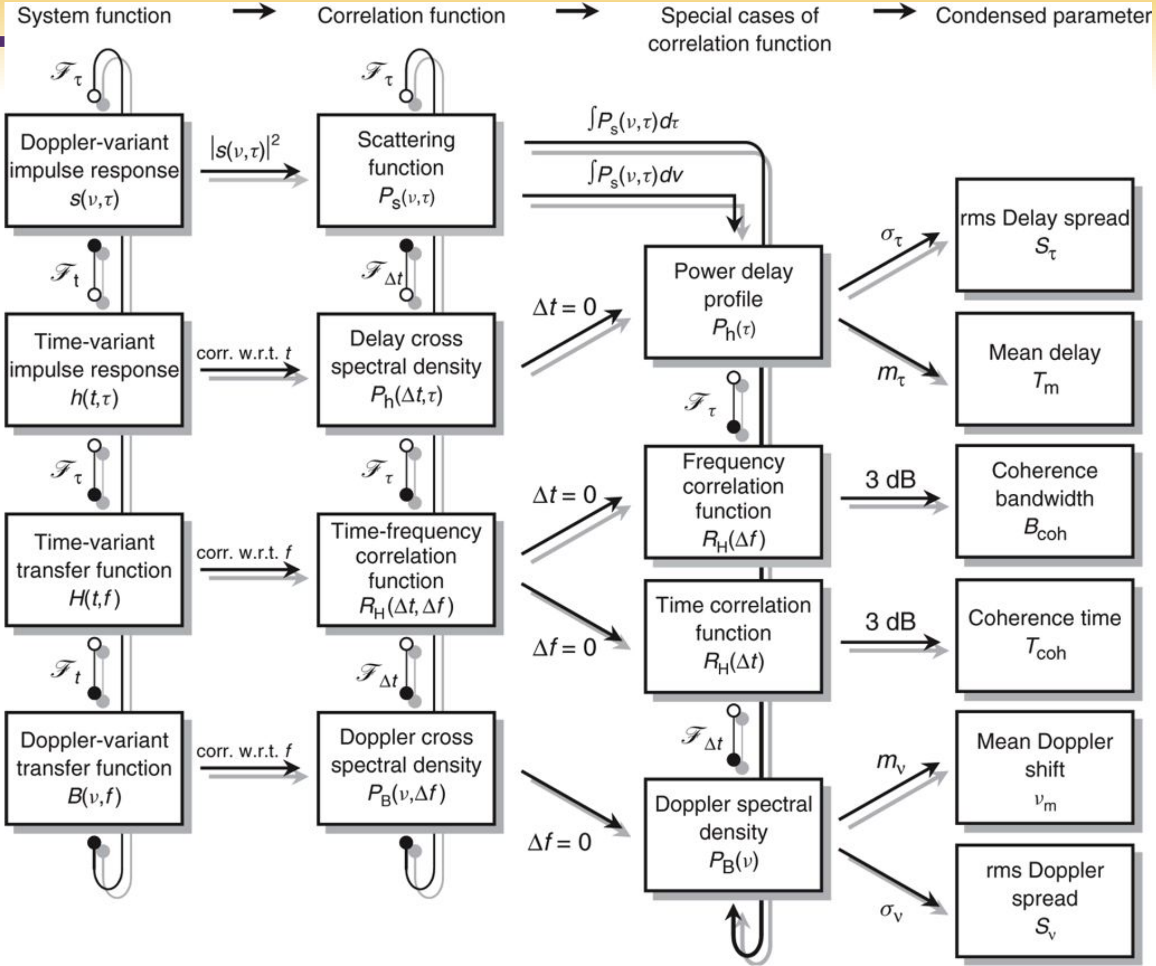
- Doppler effect can be characterized by taking the Fourier transform of $A_C(\Delta f;\Delta t)$ relative to Δt
- In order the characterize Doppler at a single frequency, we set Δf to zero

Doppler Power Spectrum $$S_C(\rho) = \int_{-\infty}^{\infty} A_C(\Delta t) e^{-j2\pi\rho\Delta t} d\Delta t$$

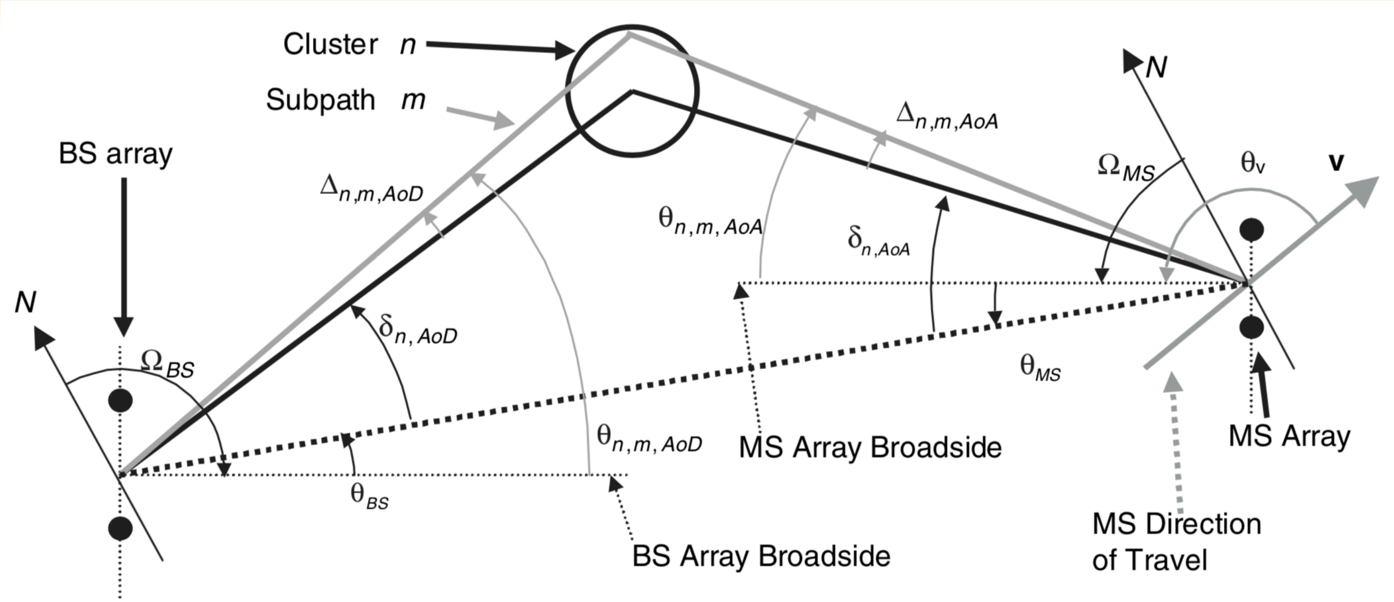
- $A_C(\Delta t = T) = 0$ indicates that observations of the channel impulse response at times separated by T are uncorrelated and therefore independent
- The channel coherence time T_c is the range of values over which $A_C\,(\Delta t)$ is approximately nonzero
- The maximum value of ρ for which $|S_c(\rho)| > 0$ is called the channel Doppler spread, which is denoted by B_d

Andrea Goldsmith book Sections 3.3.2 and 3.3.3

Relationships



3GPP Channel Model



$$h_{u,s,n}(t) = \sqrt{\frac{P_n \sigma_s}{M}} \sum_{m=1}^{M} \begin{pmatrix} \sqrt{G_{BS}\left(\theta_{n,m,AoD}\right)} \exp\left(j\left[kd_s \sin\left(\theta_{n,m,AoD} + \Phi_{n,m}\right)\right]\right) \times \\ \sqrt{G_{BS}\left(\theta_{n,m,AoA}\right)} \exp\left(jkd_u \sin\left(\theta_{n,m,AoA}\right)\right) \times \\ \exp\left(jk \|\mathbf{v}\| \cos\left(\theta_{n,m,AoA} - \theta_v\right) t\right) \end{pmatrix}$$