The Radio Channel

COS 463: Wireless Networks

Lecture 14

Kyle Jamieson

[Parts adapted from I. Darwazeh, A. Goldsmith, T. Rappaport, P. Steenkiste]

Radio Channel: Motivation

- The **radio channel** is what **limits** most communications systems – the main challenge!
  - Understanding its **properties** is therefore key to understanding radio systems' **design**

- There is **variation in many different properties**
  - Carrier frequency, environment (*e.g.* indoors, outdoors, satellite, space)

- Many different **models** covering **many different scenarios**

Channel and Propagation Models

- A ***channel model*** describes **what happens**
  - Gives channel output power for a particular input power
  - “Black Box” – no explanation of mechanism
  - Requires appropriate statistical parameters (*e.g.* loss, fading)

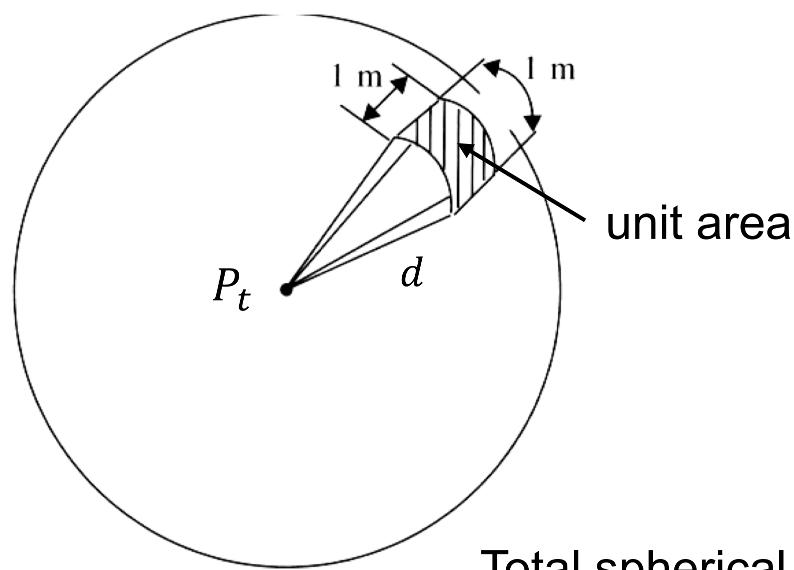
- A ***propagation model*** describes **how it happens**
  - How signal gets from transmitter to receiver
  - How energy is redistributed in time and frequency
  - Can **inform** **channel model** parameters

Today

1. **Large scale channel model**
   - ***Friis* Free space model**
     - How much power delivered from omnidirectional transmitter to omnidirectional receiver, in free space?

2. Small-scale channel models

Transmitting in Free Space



Total spherical surface area: $4\pi d^2$

- Deliver P_t Watts to an omnidirectional transmitting antenna
- So then ***power density*** (Watts per unit area) at ***range d*** is $p = \frac{P_t}{4\pi d^2}$ W/m^2
  - Independent of wavelength (frequency)

Idealized Receive Antenna

- ***Effective aperture A_e:*** fraction of incident power density p captured and received: $A_e = \frac{\lambda^2}{4\pi}$
  - Larger antennas at greater λ **capture more power**

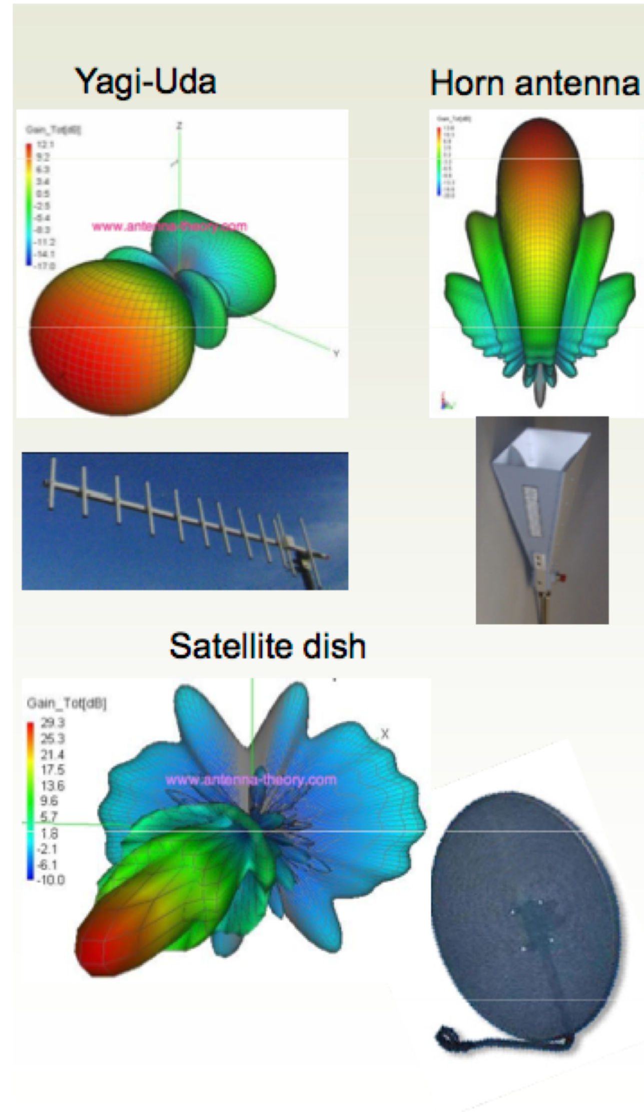
- Therefore, **power received** P_r is the product of the power density and effective aperture:

$$P_r = p \cdot A_e = \frac{P_t \lambda^2}{(4\pi)^2 d^2}$$

Antenna Gain

- Antennas **don't radiate power equally in all directions**
  - Specific to the antenna design

- Model these gains in the directions of interest between transmitter, receiver:
  - ***Transmit antenna gain*** G_t
  - **Receive antenna gain** G_r



Friis Free Space Channel Model

- **Power received** P_r is the product of the power received by idealized antennas, times transmit and receive antenna gains:

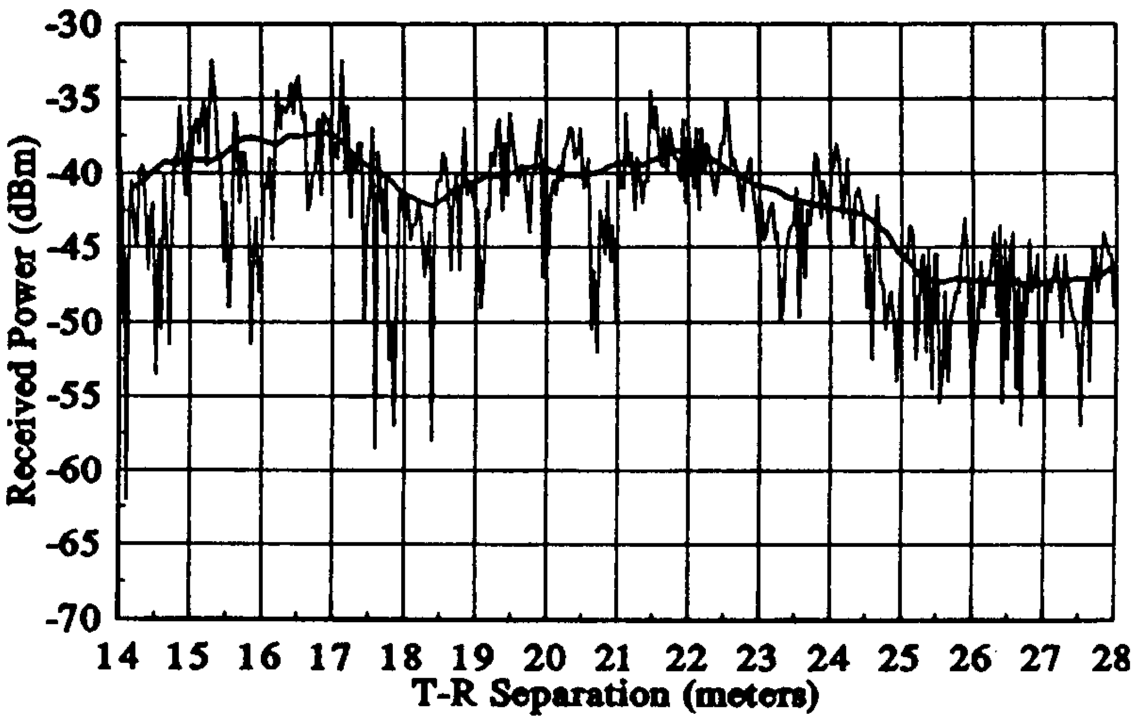
$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2}$$

Today

1. Large scale channel models

2. **Small-scale channel models**
   - **Multi-path propagation**
   - Motion and channel coherence time

Small-scale versus large-scale modeling



- ***Small-scale models:*** Characterize the channel over **at most** a few **wavelengths** or a few **seconds**

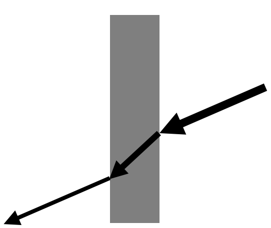
Multipath Radio Propagation

- Receiver gets **multiple copies** of signal
  - Each copy follows **different path**, with **different path length**
  - Copies can **either strengthen or weaken** each other
    - Depends on whether they are **in or out of phase**

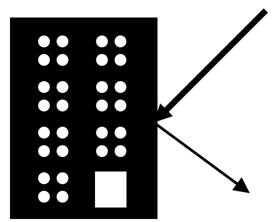
- Enables communication even when transmitter and receiver are not in "line of sight"
  - Allows radio waves effectively to propagate around obstacles, thereby increasing the radio coverage area

- Transmitter, receiver, or environment object **movement** on the order of λ significantly affects the outcome
  - *e.g.* 2.4 GHz → λ = 12 cm, 900 MHz → ≈ 1 ft

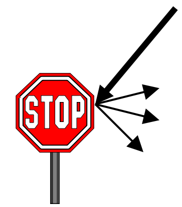
Radio Propagation Mechanisms



Refraction



Reflection



Scattering

Diffraction

- **Refraction**
  - Propagation wave changes direction when impinging on different medium
- **Reflection**
  - Propagation wave impinges on **large object (compared to λ)**
- **Scattering**
  - Objects **smaller than λ** (i.e. foliage, street signs etc.)
- **Diffraction**
  - Transmission path obstructed by surface with **sharp irregular edges**
  - Waves **bend around obstacle**, even when line of sight does not exist

Today

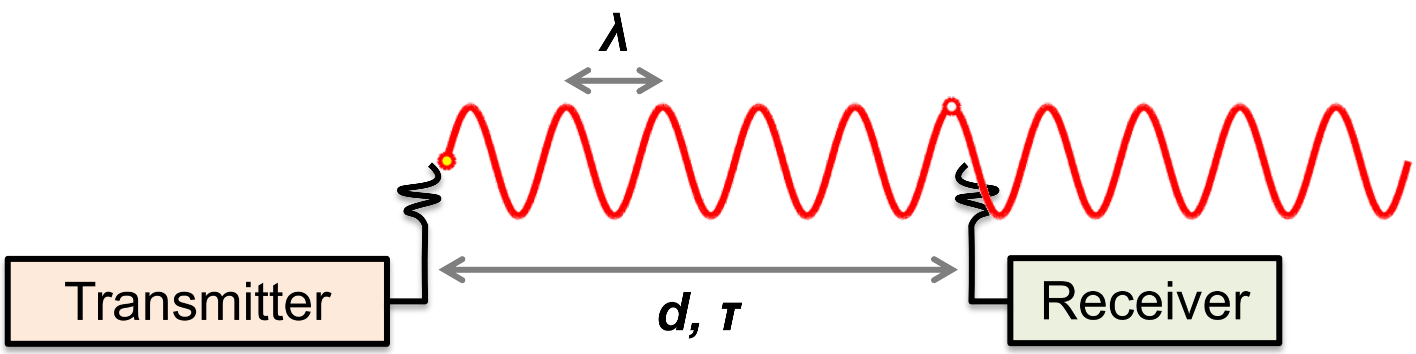
1. Large scale channel models

2. **Small-scale channel models**
   - **Multi-path propagation**
     - **Frequency-domain view**
     - Time-domain view

   - Motion and channel coherence time

Sinusoidal carrier, line of sight only

- Suppose **transmitter** is **distance *d*** (**propagation time delay *τ* = *d* / *c***) away from **receiver** (where *c* is the speed of light)

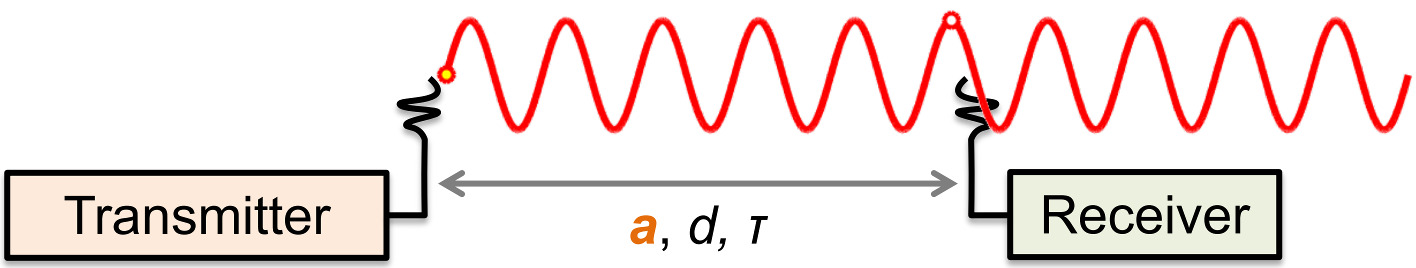


- Radio frequency transmitted signal: $\cos(2\pi f_c t) = \cos(2\pi c/\lambda \cdot t)$
  - Carrier frequency f_c corresponds to ***radio wavelength λ***
  - **Baseband** transmitted signal **in one symbol period:** $x = 1 + 0j$

How to model the effect of the channel?

Sinusoidal carrier, line of sight only: Signal Attenuation

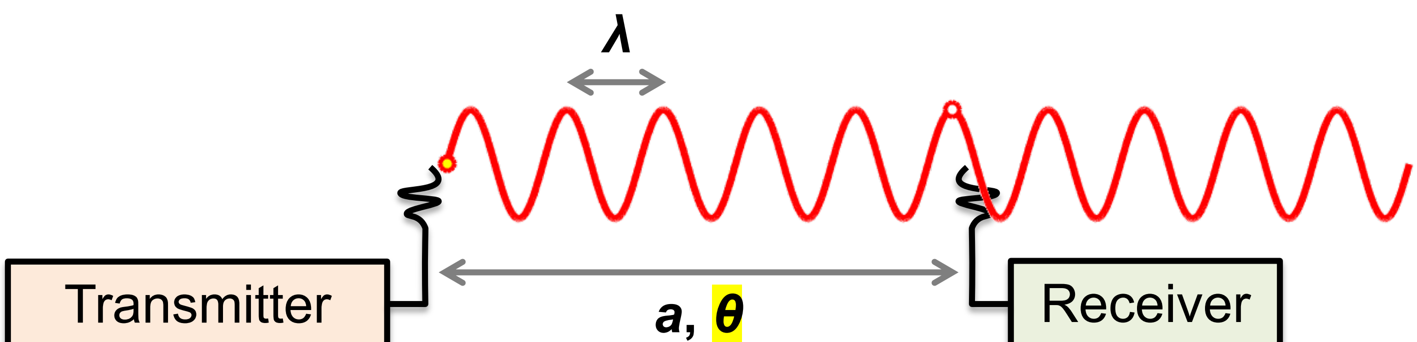
- Represent channel's amplitude ***attenuation*** with a real number ***a***



- Models, *e.g.* attenuation due to two refractions and partial reflection as the signal passes through an indoor wall

Sinusoidal carrier, line of sight only: Signal Phase Shift

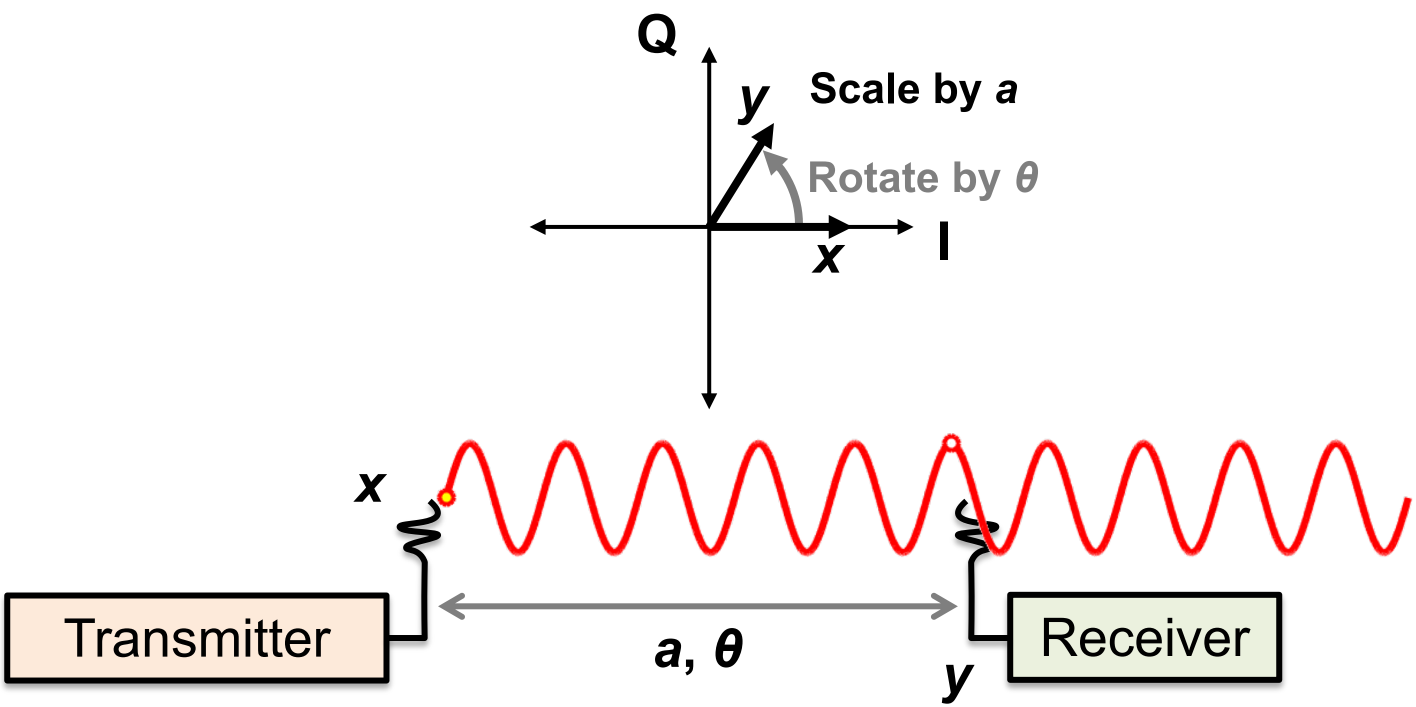
- Received signal travels distance *d*
- **One wavelength** corresponds to a 360˚ (**2π radian**) **phase shift**
- Represent path's **phase shift** with an **angle** (real number) $\boldsymbol{\theta = 2\pi \cdot d / \lambda}$
  - "Abstract away" distance and wavelength into (one) phase shift θ



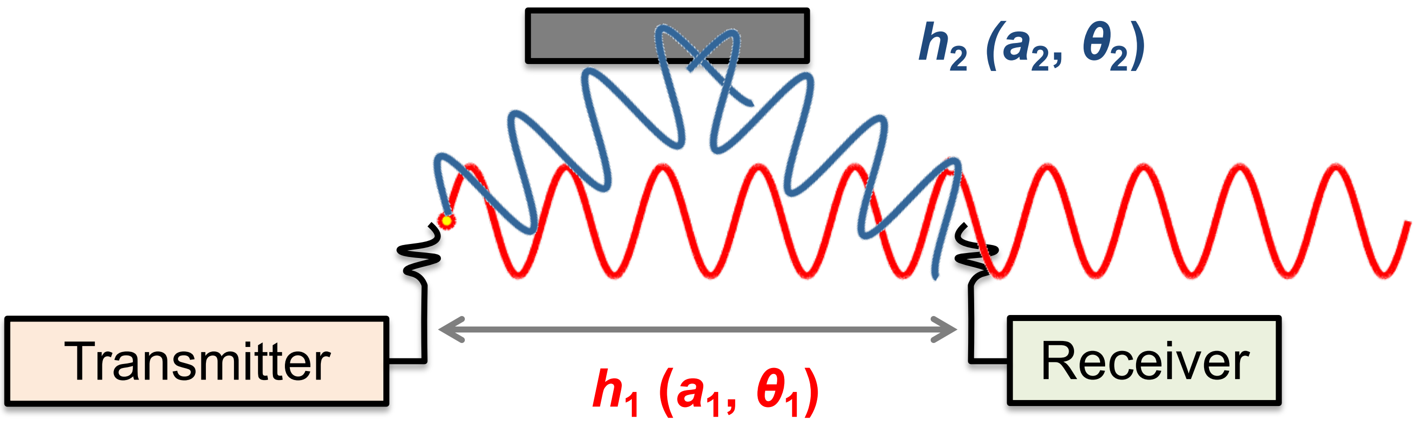
Sinusoidal carrier, line of sight only: Channel Model

- *Wireless channel h* **attenuates by *a*, phase-shifts by *θ***
  - Therefore, $h = ae^{j\theta}$

- **Received baseband signal:** $y = h \cdot x$ (no noise)



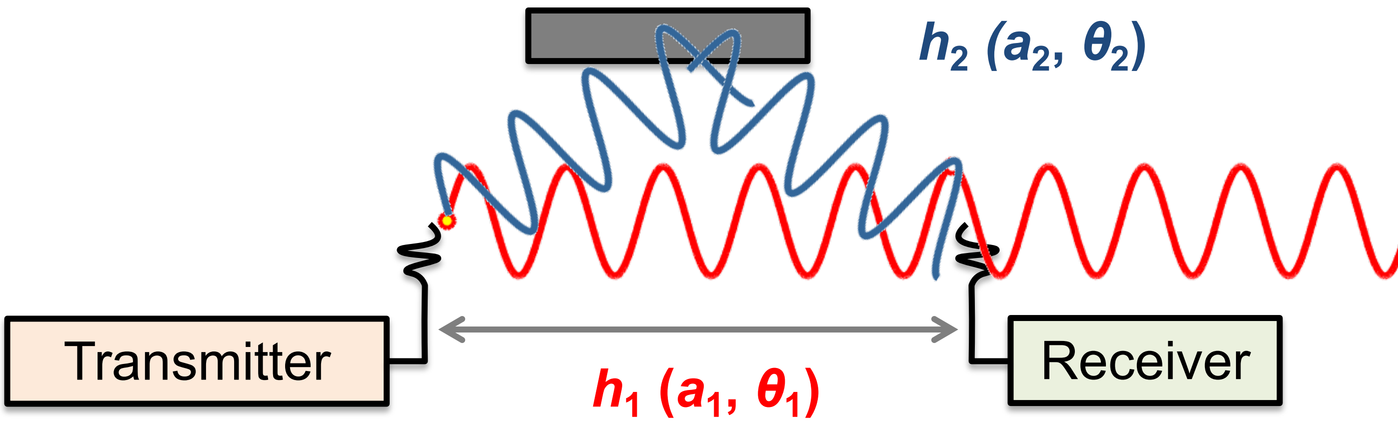
Line-of-sight plus reflecting path: Motivation



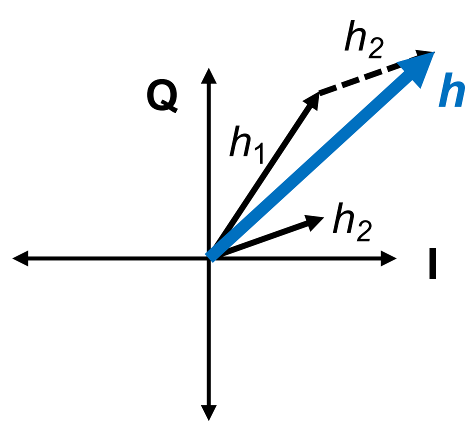
- What if reflections (*e.g.*, indoor walls) introduce a second path?

- Wireless channel becomes the **superposition** of the ***direct path's channel*** $\boldsymbol{h_1}$ and the ***reflection path's channel*** $\boldsymbol{h_2}$

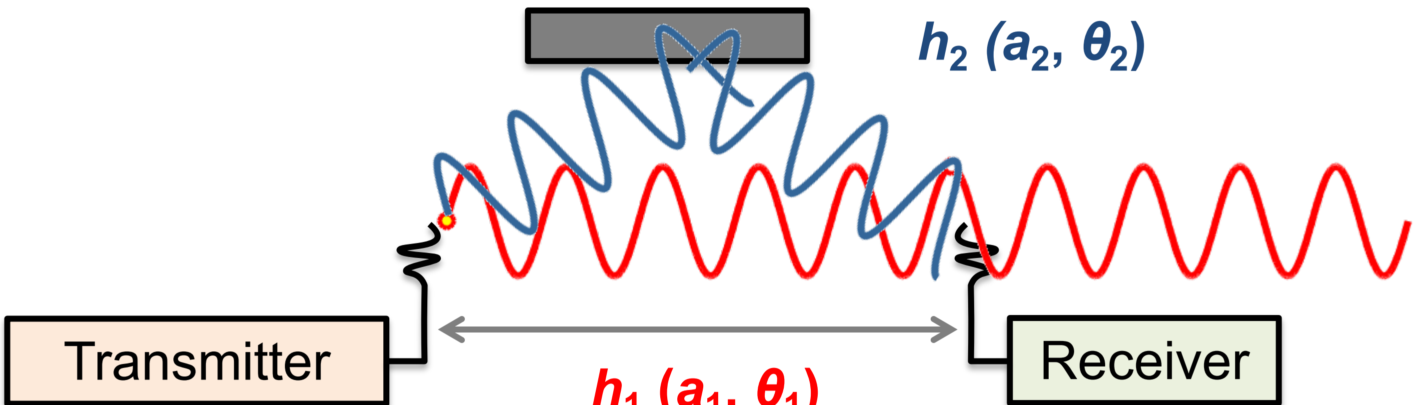
Line-of-sight plus reflecting path: Channel Model

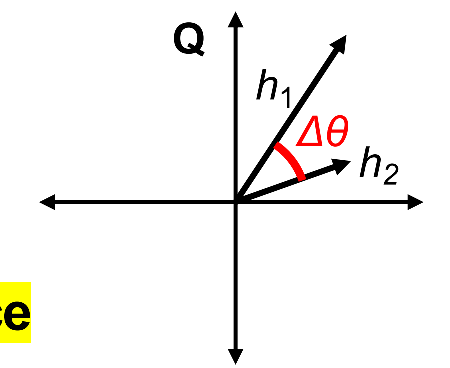


- Channel is now $h = h_1 + h_2 = a_1\ e^{j\theta_1} + a_2 e^{j\theta_2}$



Line-of-sight plus reflecting path: Channel Model



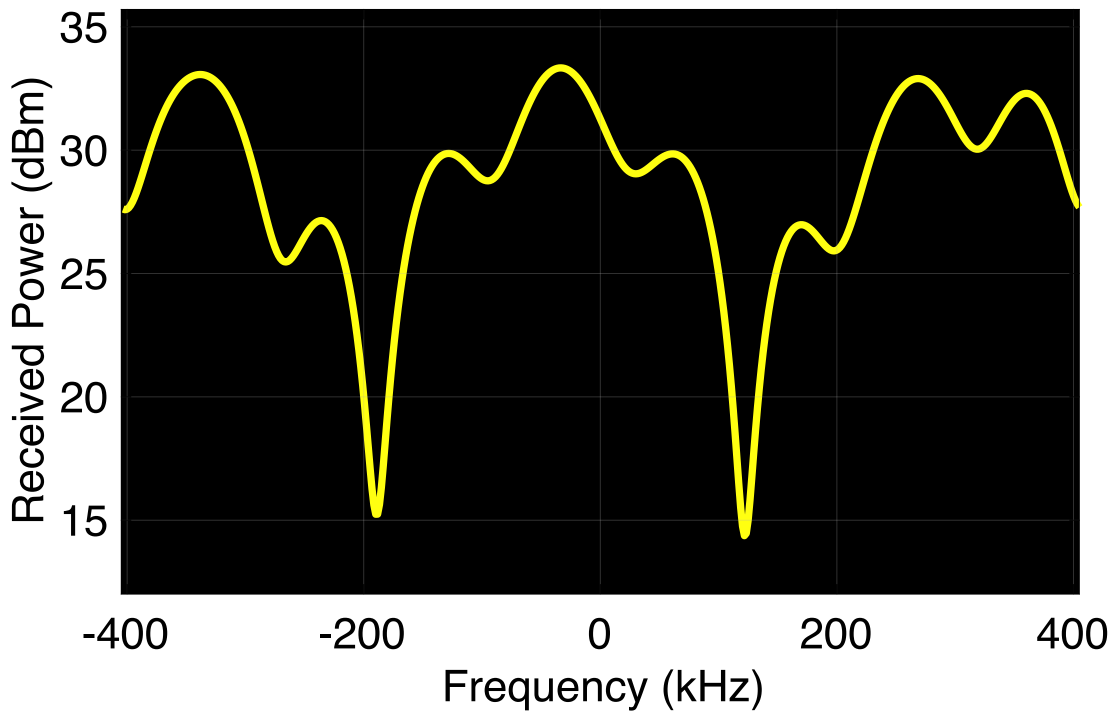


- ***Phase difference between paths*** $\Delta\theta = 2\pi/\lambda(d_1 - d_2)$
  - Depends on **wavelength** and **path length difference**

- **So,** $|h|$ **depends on wavelength (frequency)** as well as channel attenuation

Reflections cause frequency *selectivity*

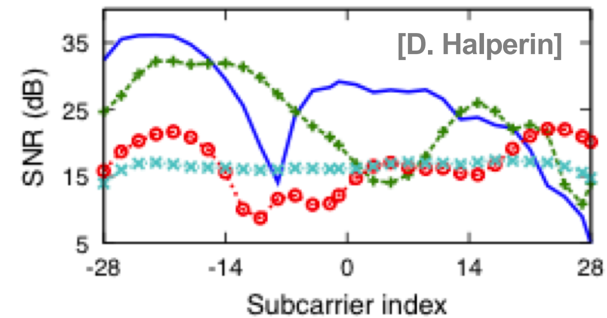
- Interference between reflected and line-of-sight radio waves results in **frequency dependent fading**



- ***Coherence bandwidth*** B_c: **Frequency range** over which the channel is roughly the **same** (“flat”)

Practical Frequency-Selective Fading

- One 2.4 GHz Wi-Fi channel is centered at **2412 MHz** and spans a **20 MHz** bandwidth



- **Observe:** Frequency-selective fading

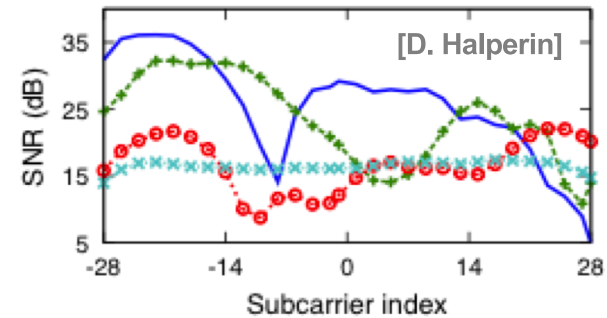
- **Recall, phase shift for *k*th path** $\theta_k = 2\pi d_k/\lambda$
  - Received phase difference between paths **depends on wavelength**

- Channel spans 2402–2422 MHz
  - Lowest wavelength (2402 MHz): **12.49 cm**
  - Highest wavelength (2422 MHz): **12.39 cm**

    - **Just one millimeter wavelength difference**
      - Almost the same. **Contradiction?**

Practical Frequency-Selective Fading

- Channel spans 2402–2422 MHz
  - Lowest wavelength (2402 MHz): **12.49 cm**
  - Highest wavelength (2422 MHz): **12.39 cm**

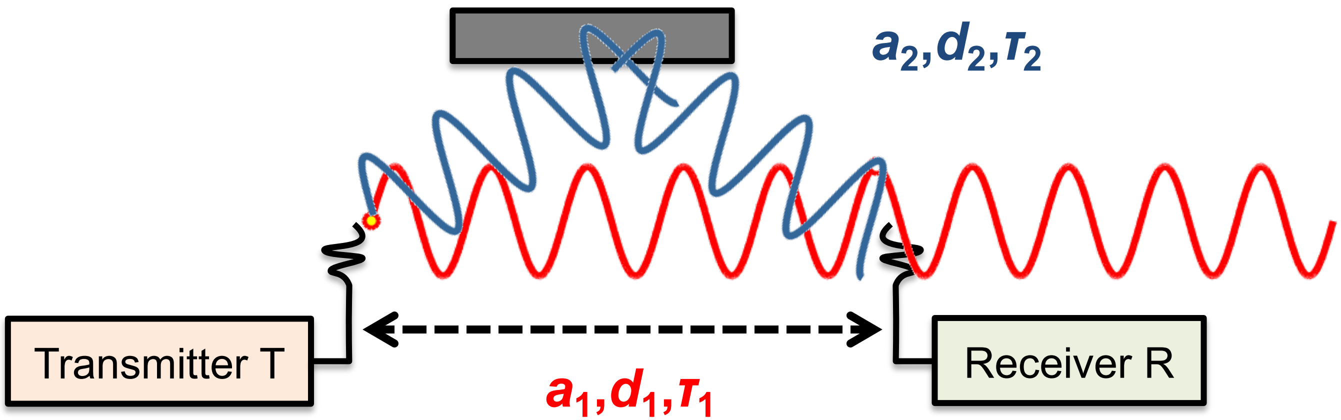


1. Recall, $\Delta\theta = 2\pi/\lambda(d_1 - d_2)$ causes additive vs. destructive fading

2. For Wi-Fi, $d_k < 50\text{ m}$ so, e.g., $d_2 - d_1 \approx 20\text{ m}$, equals:
   - 160 × 12.49 cm wavelengths
   - **161** × 12.39 cm wavelengths

- So we move from *e.g.* **constructive to destructive, to constructive** fading **from lowest to highest** wavelength

Radio Channels are "Reciprocal"



- ***Forward channel*** (T to R) is $h_{TR} = a_1\ e^{j2\pi d_1/\lambda} + a_2 e^{j2\pi d_2/\lambda}$

- Switch T and R roles, changing nothing else:
  - ***Reverse channel*** (R to T) is $h_{RT} = a_1\ e^{j2\pi d_1/\lambda} + a_2 e^{j2\pi d_2/\lambda} = h_{TR}$
  - The reverse radio channel is ***"reciprocal"***

- Practical radio **receiver** circuitry induces differences between h_{TR}, h_{RT}

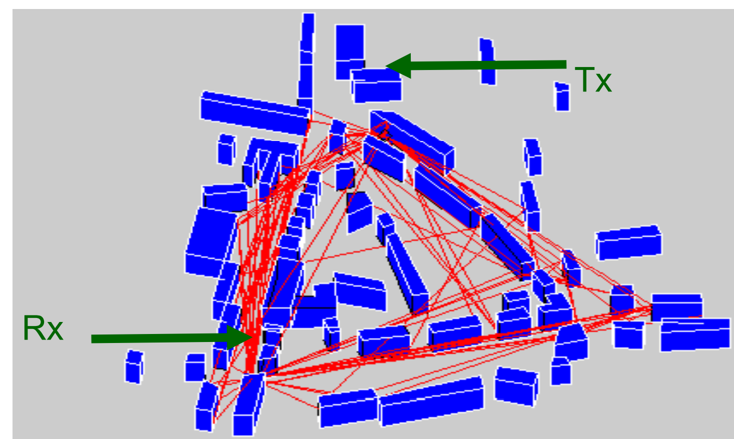
Putting it all Together: Ray Tracing

- Approximate solutions to Maxwell's electromagnetic equations by instead **representing wavefronts as particles, traveling along rays**
  - Apply geometric reflection, diffraction, scattering rules
    - Compute angle of reflection, angle of diffraction

- Error is smallest when **receiver is many λ from nearest scatterer,** and all **scatterers are large relative to λ**

- Good match to empirical data in rural areas, along city streets (radios close to ground), and indoors

- **Completely site-specific**
  - Changes to site may **invalidate model**



Today

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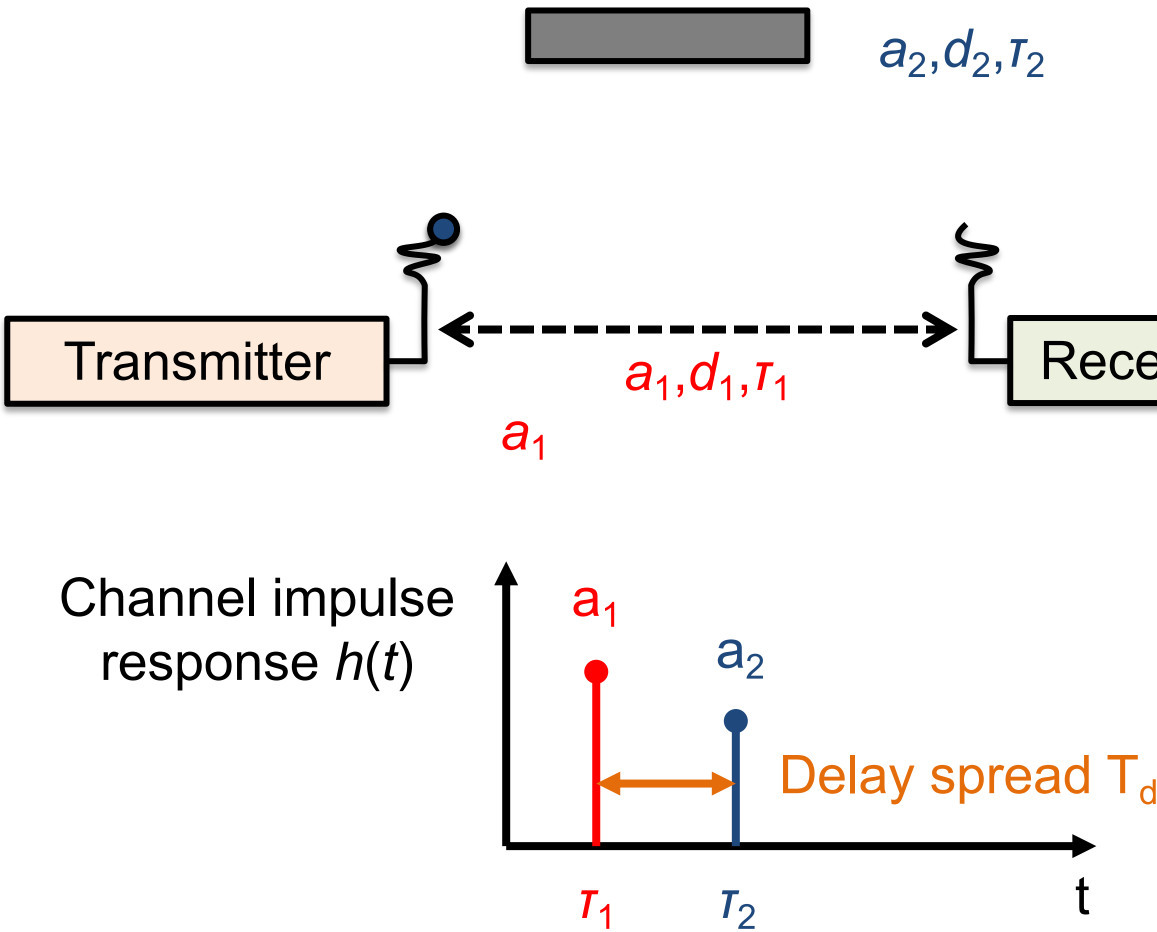
2. **Small-scale channel models**
   - **Multi-path propagation**
     - Frequency-domain view
     - **Time-domain view**
   - Motion and channel coherence time

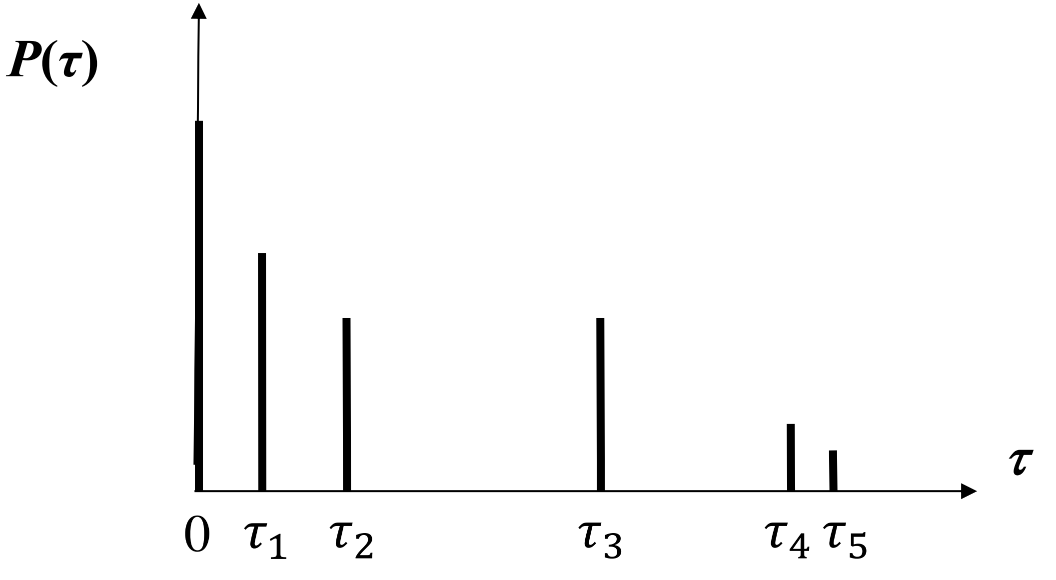
What does the channel look like in time?



Power delay profile (PDP)

- **Power** received via the path with **excess time delay $\boldsymbol{\tau_i}$** is the value (height) of the discrete PDP component $P(\tau_i)$ at $\boldsymbol{\tau_i}$

$P(\tau)$ corresponds to $|h(\tau)|^2$



Characterizing a power delay profile

- Given a PDP $P(\tau_k)$ sampled at time steps τ_k:

- ***Mean excess delay*** $\bar{\tau}$: Expected value of $P(\tau_k)$:

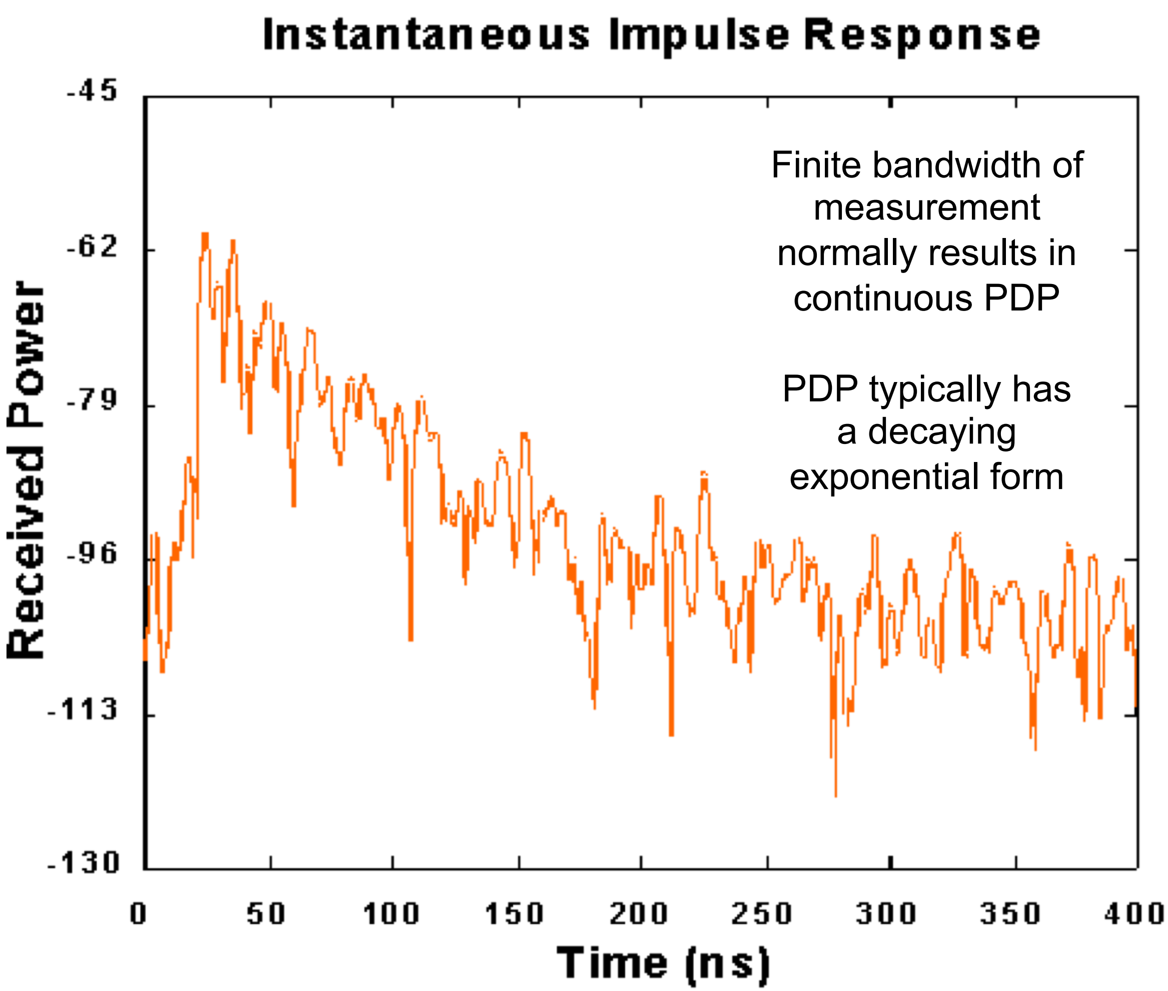
$$\bar{\tau} = \frac{\sum_k P(\tau_k)\,\tau_k}{\sum_k P(\tau_k)}$$

- ***Root mean squared (RMS) delay spread*** σ_τ measures the spread of the power's arrival in time
  - RMS delay spread is the variance of $P(\tau_k)$:

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2}, \text{ where } \overline{\tau^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)}$$

- ***Maximum excess delay < X dB*** $\tau_{<X}$ is the **greatest** delay at which the PDP is **greater than *X* dB below** the strongest arrival in the PDP

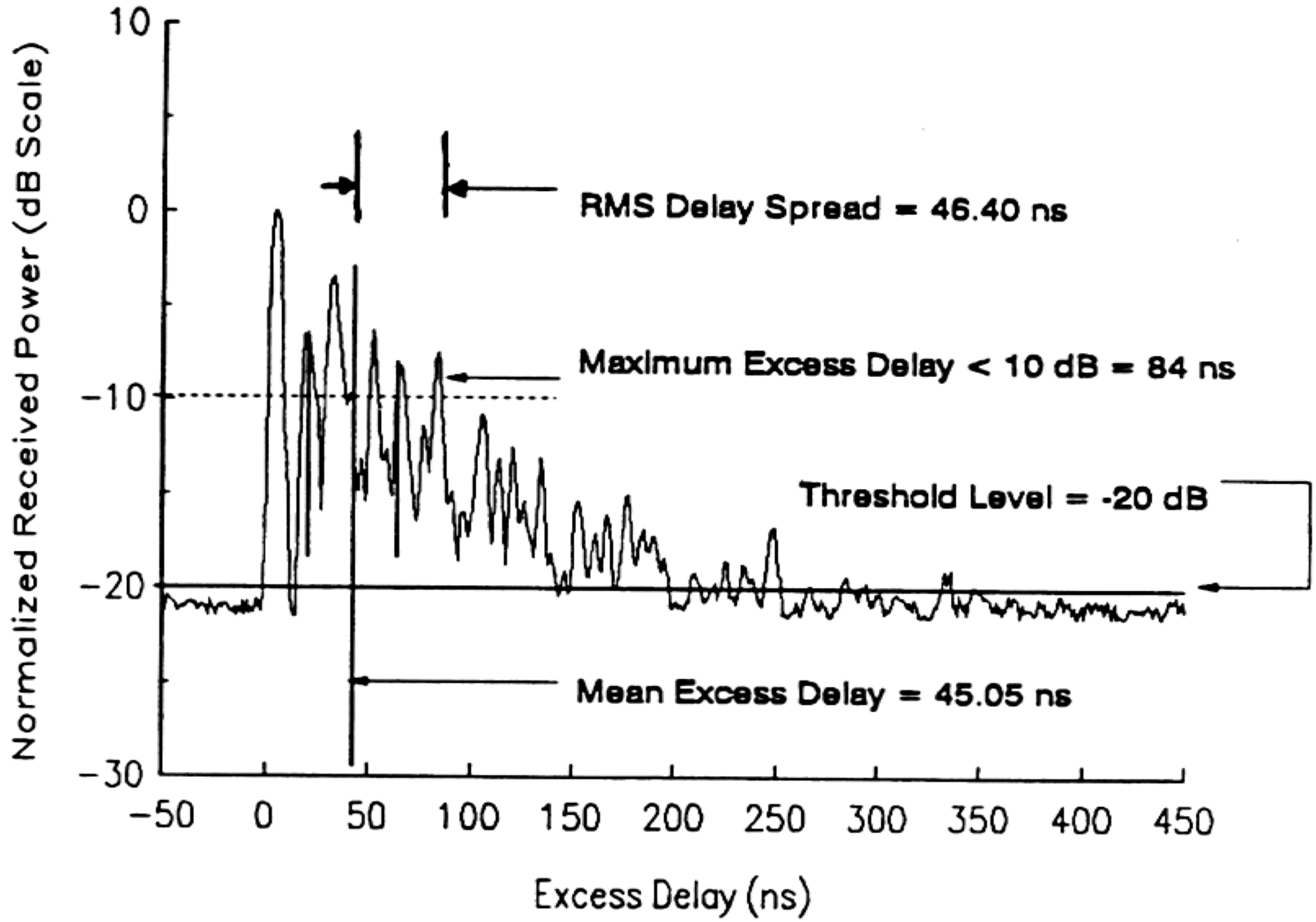
Example Indoor PDP Estimation



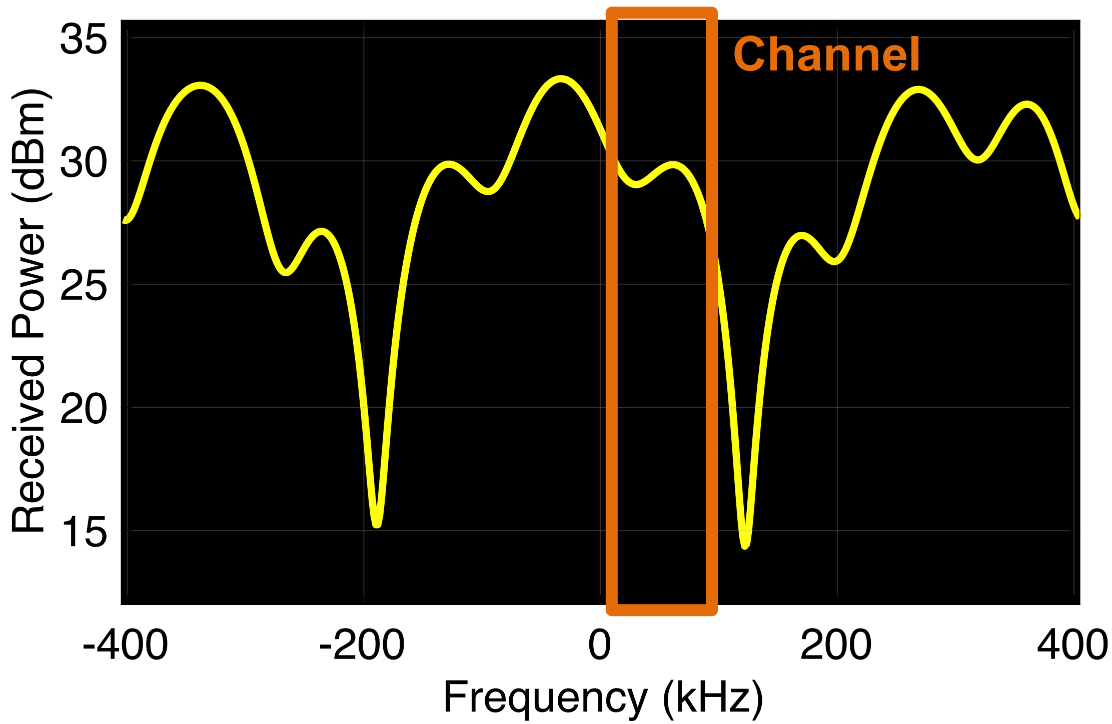
Typical RMS delay spreads

Environment	RMS delay spread
Indoor cell	10 – 50 ns
Satellite mobile	40 – 50 ns
Open area (rural)	< 0.2 μs
Suburban macrocell	< 1 μs
Urban macrocell	1 – 3 μs
Hilly macrocell	3 – 10 μs

Indoor power delay profile

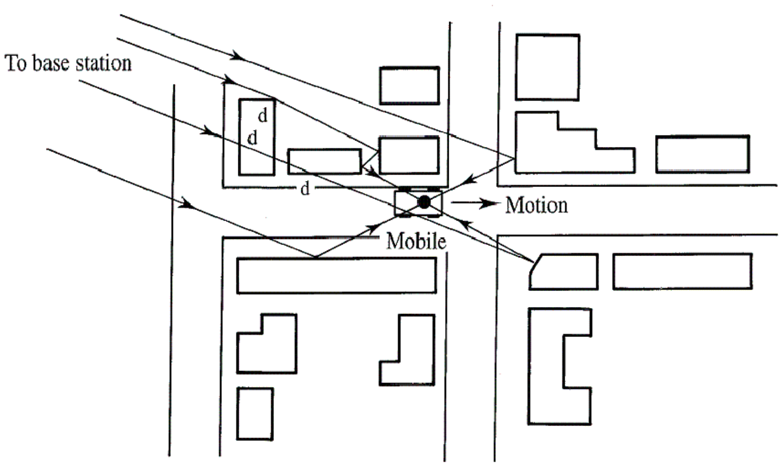


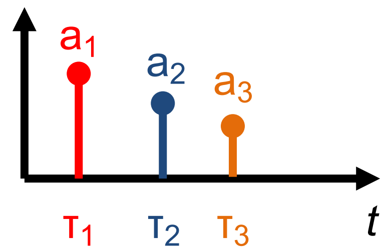
Flat Fading



- Slow down → sending data over a **narrow bandwidth** channel
  - Channel is **constant** over its bandwidth
  - **Multipath is still present,** so channel strength fluctuates **over time**
    - **How to model this fluctuation?**

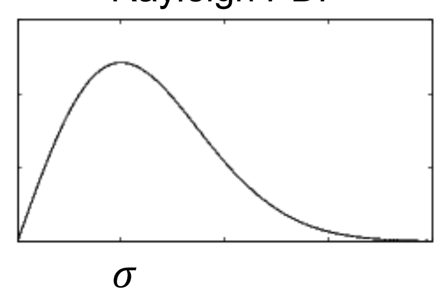
Rayleigh Fading Model





- Random gain of k^{th} arriving path: $a_k = a_k^I + ja_k^Q$
- Therefore, the I and Q **channel components** h_I, h_Q are **zero-mean Gaussian distributed**
- So $|h| = \sqrt{h_I^2 + h_Q^2}$ is ***Rayleigh-distributed***

Rayleigh PDF



Rayleigh fading example

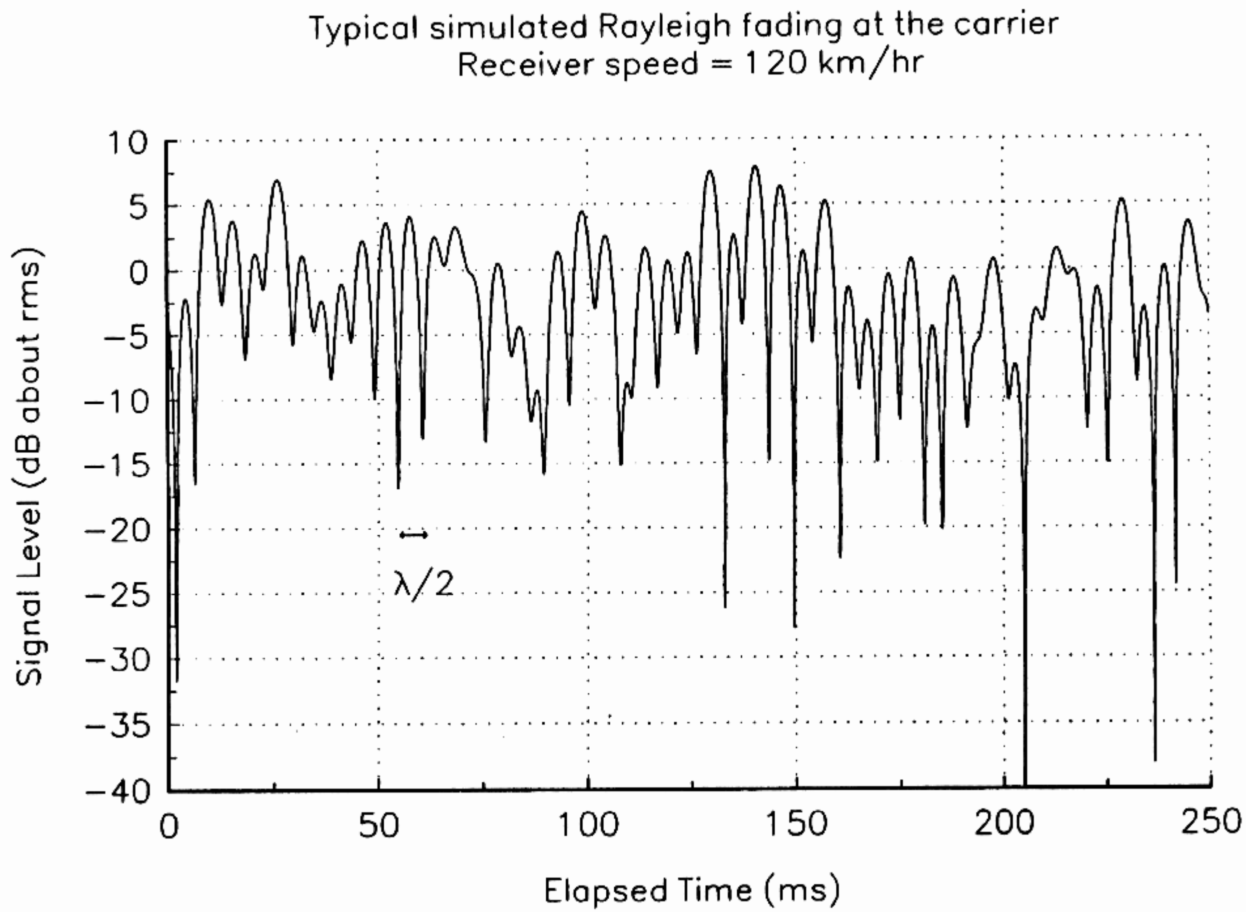


Figure 5.15 A typical Rayleigh fading envelope at 900 MHz [from [Fun93] © IEEE].

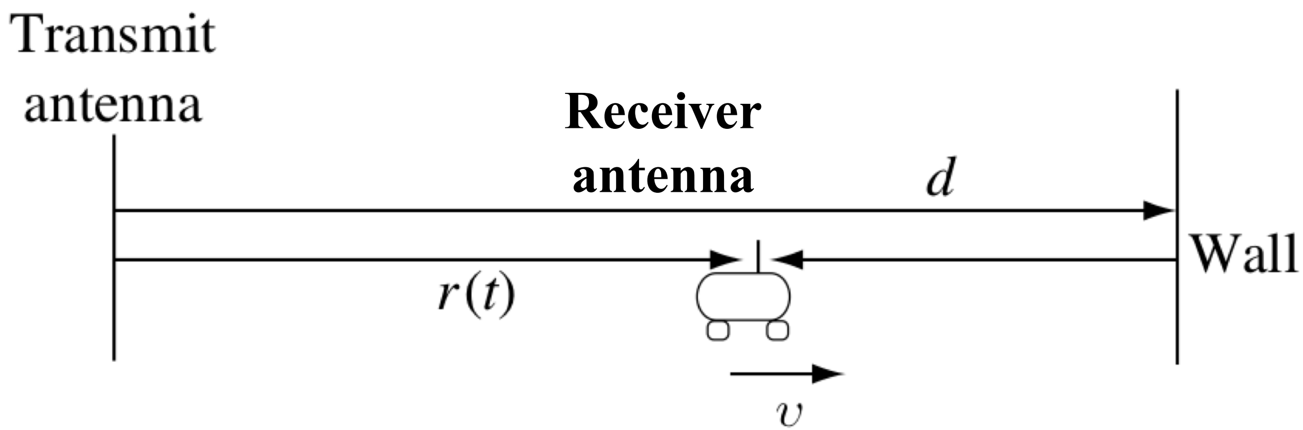
Today

1. Large scale channel models

2. **Small-scale channel models**
   - Multi-path propagation

   - **Motion and channel coherence time**

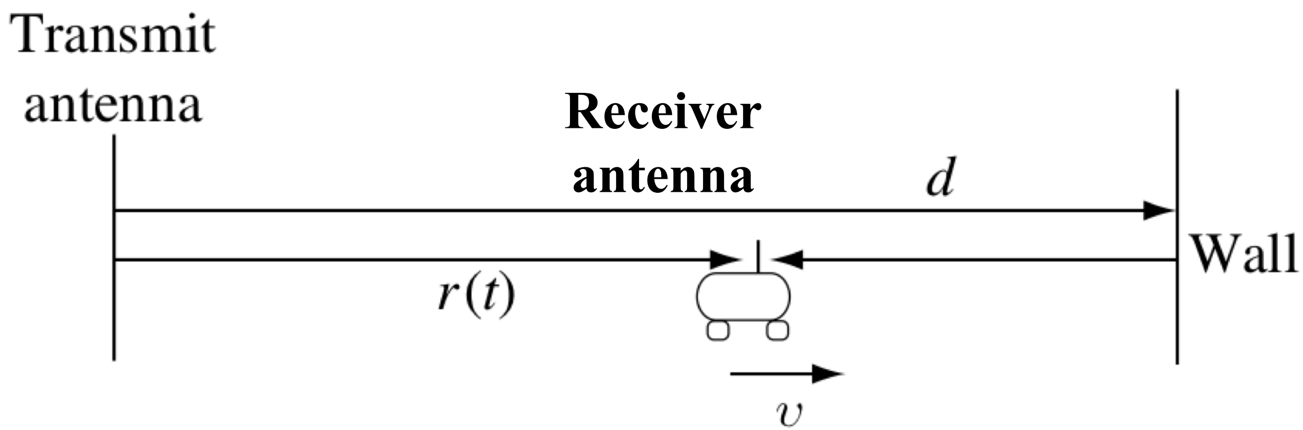
Stationary transmitter, moving receiver



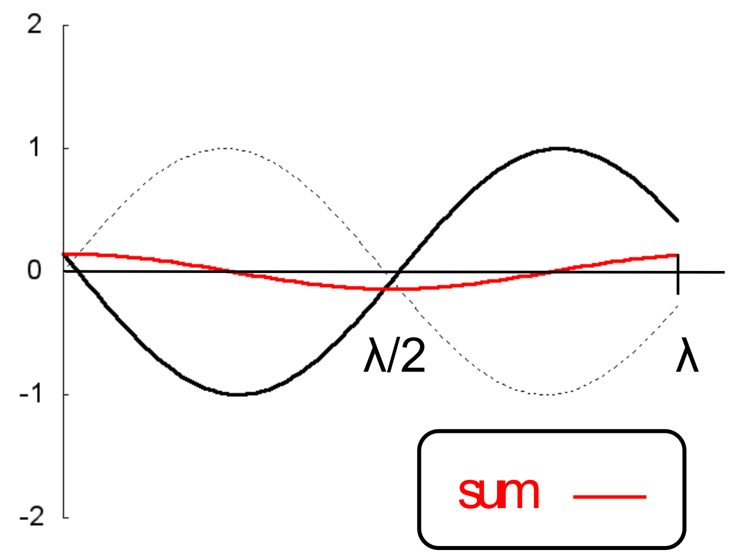
- Suppose **reflecting wall**, fixed transmit antenna, no other objects
  - Receive antenna moving rightwards at velocity *v*

- **Two arriving signals** at receiver antenna with a **path length difference of** $2(d - r(t))$

How does fading in time arise?

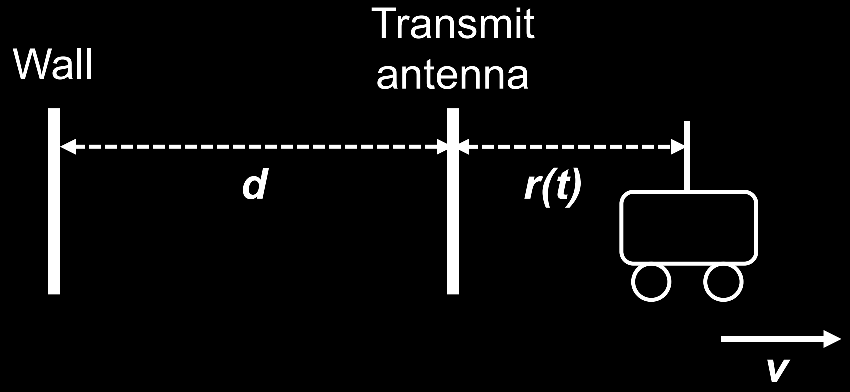


- **Path length difference** $\Delta = 2(d - r(t))$
- If $\Delta \,(\mathrm{mod}\, \lambda) = \frac{\lambda}{2}$ → receive ≈ 0
  - ***Destructive interference***
- If $\Delta \,(\mathrm{mod}\, \lambda) = 0$ → receive ≈ 2
  - ***Constructive interference***



Stretch Break and In-Class Question

- In the preceding example, the reflected wave and direct wave travel in opposite directions
  - *What happens if we move the reflecting wall to the left side of the transmitter?*



- *What is the nature of the multipath fading, both over time and over frequency?*

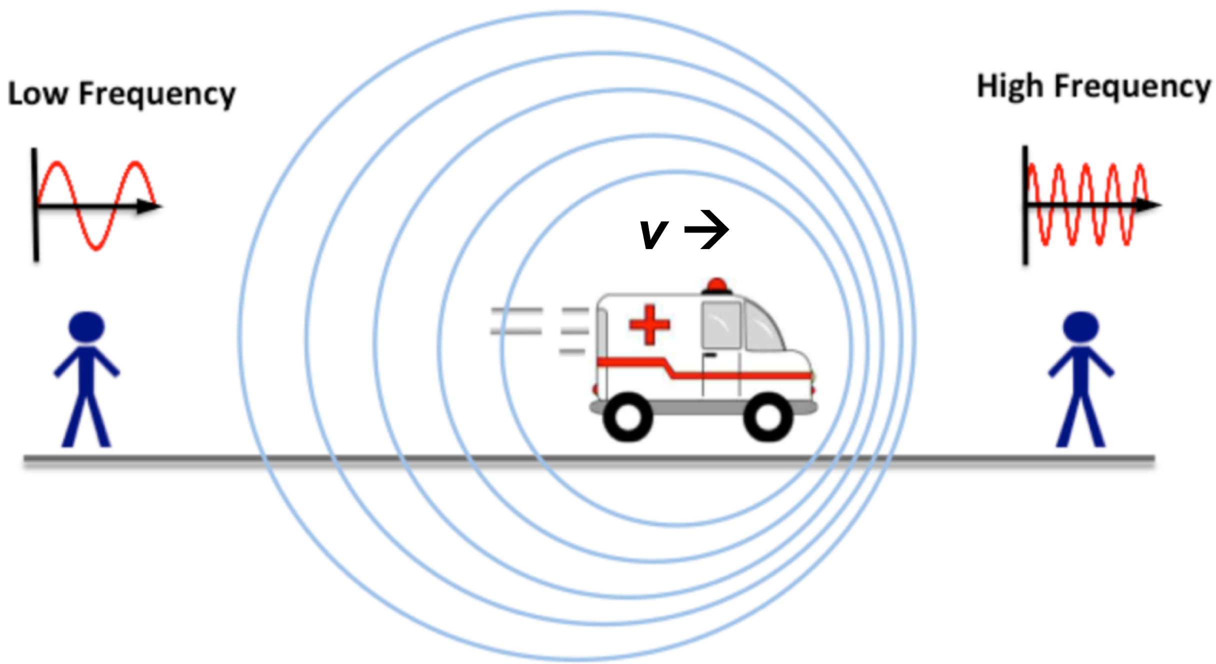
Channel Coherence Time

- **A change** in **path length difference** of λ / 2 transitions from constructive to destructive interference
  - Receiver movement of **λ/4:** ***coherence distance***
  - **Duration of time** that transmitter, receiver, or objects in environment take to move a coherence distance: ***channel coherence time*** T_c
    - Walking speed (2 mph) @ 2.4 GHz: ≈ 15 milliseconds
    - Driving speed (20 mph) @ 1.9 GHz: ≈ 2.5 milliseconds
    - Train/freeway speed (75 mph) @ 1.9 GHz: < 1 millisecond

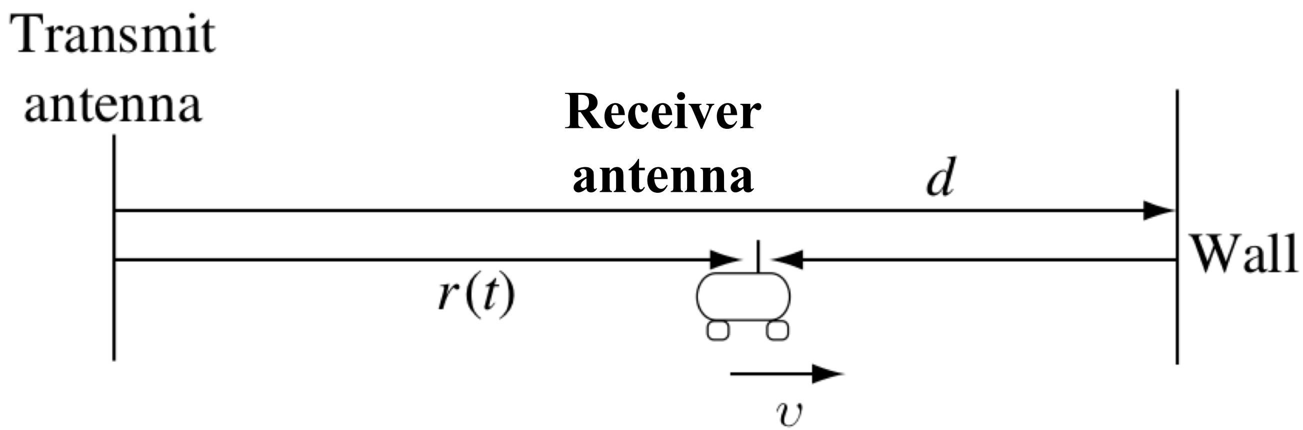
Another perspective: Doppler Effect

- Movement by the transmitter, receiver, or objects in the environment creates a ***Doppler Shift***

$$\Delta f = \left(\frac{v}{c}\right) f$$



Stationary transmitter, moving receiver: From a Doppler Perspective



- ***Doppler Shift of a path*** $\Delta f = \frac{f_c \cdot v_{radial}}{c}$
  - v_{radial} is **radial** component of receiver's velocity vector **along the path**
    - **Positive Δf** with **decreasing path length**, **negative Δf with increasing** path length

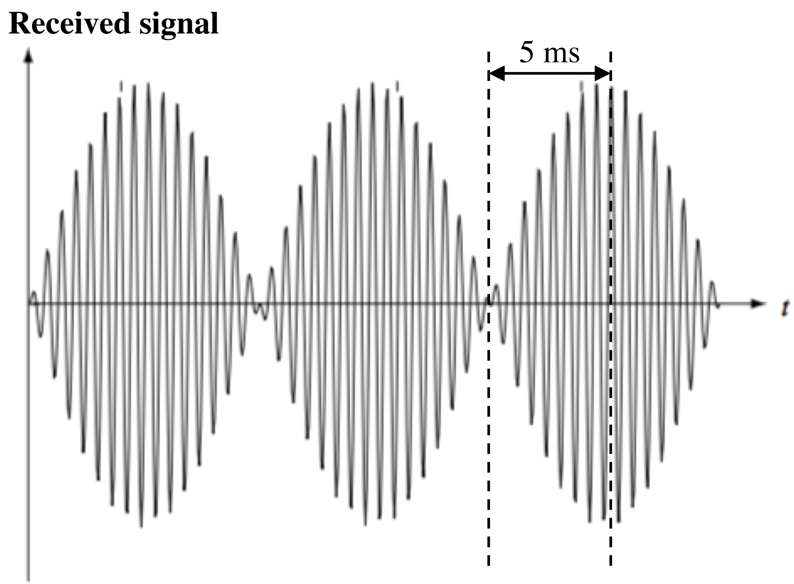
- Suppose v = 60 km/h, f_c = 900 MHz
  - Direct path $\Delta f = -50\ Hz$, reflection path $\Delta f = +50\ Hz$

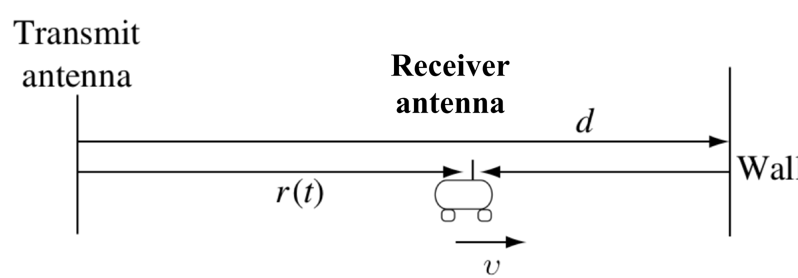
Stationary transmitter, moving receiver: From a Doppler Perspective

- ***Channel Doppler Spread D_s***: maximum path Doppler shift, minus minimum path Doppler shift

- Suppose v = 60 km/h, f_c = 900 MHz
  - Direct path $\Delta f = -50\,Hz$, reflection path $\Delta f = +50\,Hz$
  - Doppler Spread: **100 Hz**

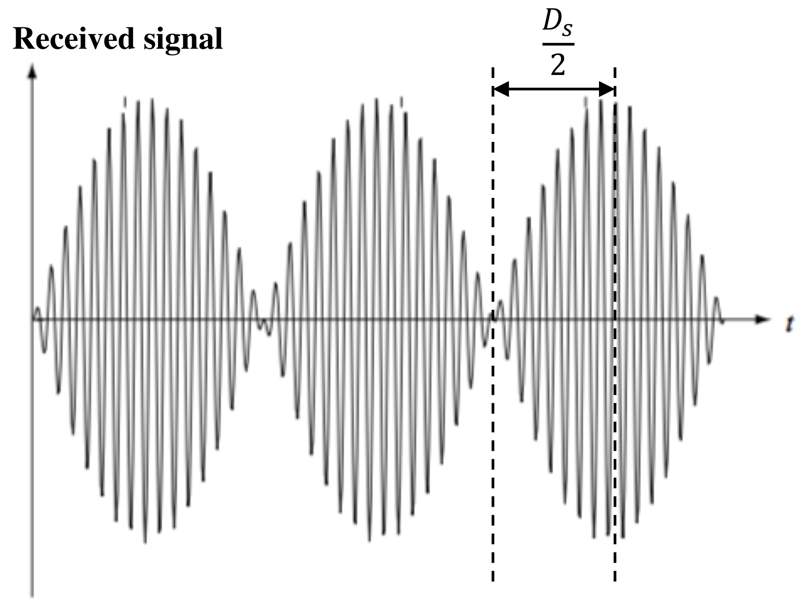
- Results in sinusoidal "envelope" at frequency D_s / 2:





Channel Coherence Time: From a Doppler Perspective

- Sinusoidal "envelope" at frequency $\frac{D_s}{2}$:



- Transition from 0 to peak in $\frac{1}{2D_s}$
  - So **qualitatively significant** change in time $T_c = \frac{1}{4D_s}$
    - Alternate definition of ***channel coherence time***

Thursday Topic:
Receiver Designs for the Wireless Channel