The Radio Channel

COS 463: Wireless Networks

Lecture 14

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

Motivation

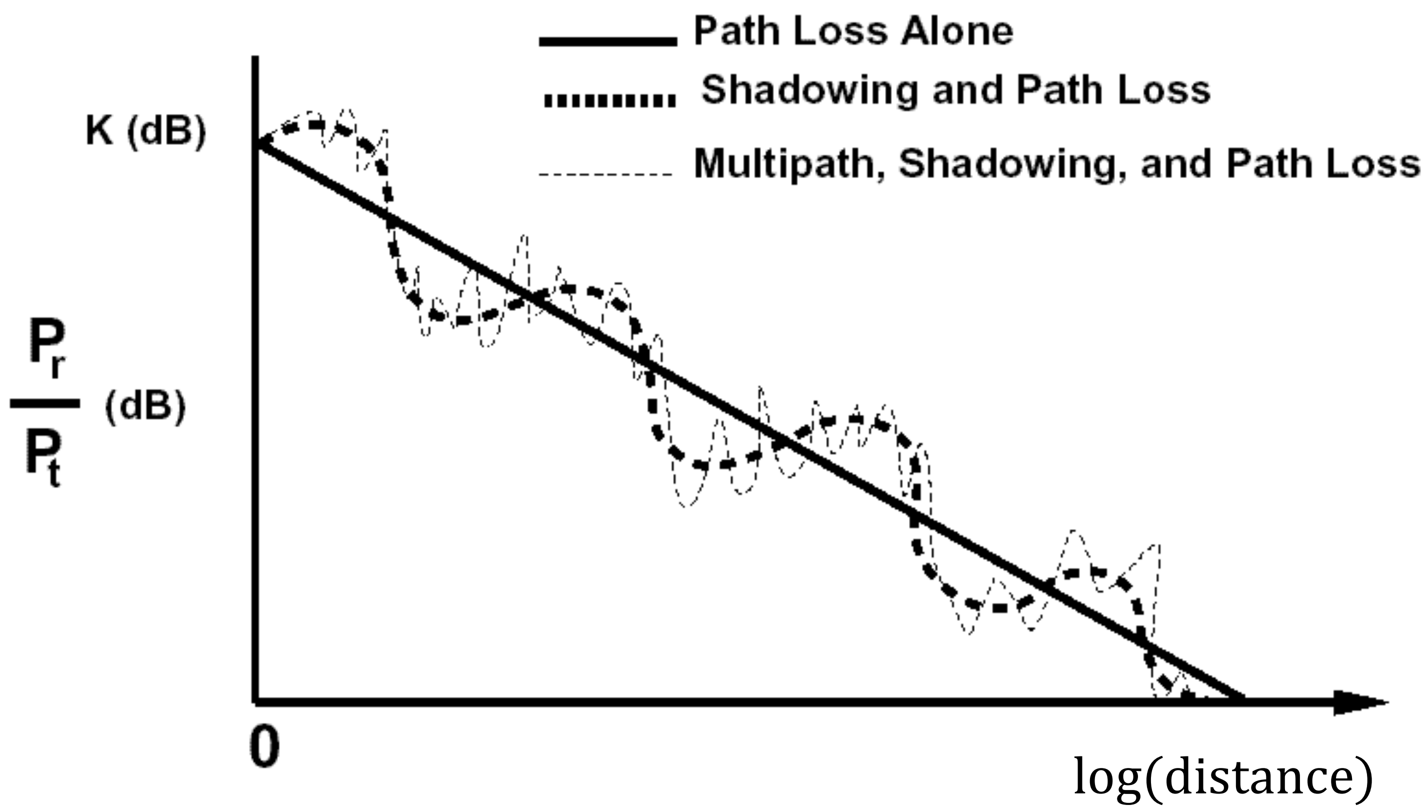
- The **radio channel** is what **limits** most radio systems – the main challenge!
  - Understanding its **properties** is therefore key to understanding radio systems' **design**
- There is **no single radio channel,** but instead **variation in many different properties**
  - Carrier frequency, environment (*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

Modeling (from a high-level perspective)



Today

1. **Large scale channel models**
   – Free space model
   – Two-ray ground model

2. Small-scale channel models

3. Equalization: Coping with the channel

The dBm unit

- If we take one milliwatt as a reference then we have a unit of absolute power called ***dBm***:

$$P_{dBm} = 10\log_{10}\left(\frac{P_1}{10^{-3}}\right)$$

- Where P_1 is the power we want to express in dBm, **in Watts**

Power (linear)	Power (dBm)
10 W	40 dBm
1 W	30 dBm
100 mW	20 dBm
10 mW	10 dBm
1 mW	0 dBm
10 µW	-20 dBm
1 µW	-30 dBm
1 nW	-60 dBm
1 pW	-90 dBm

Goal: Power Budget

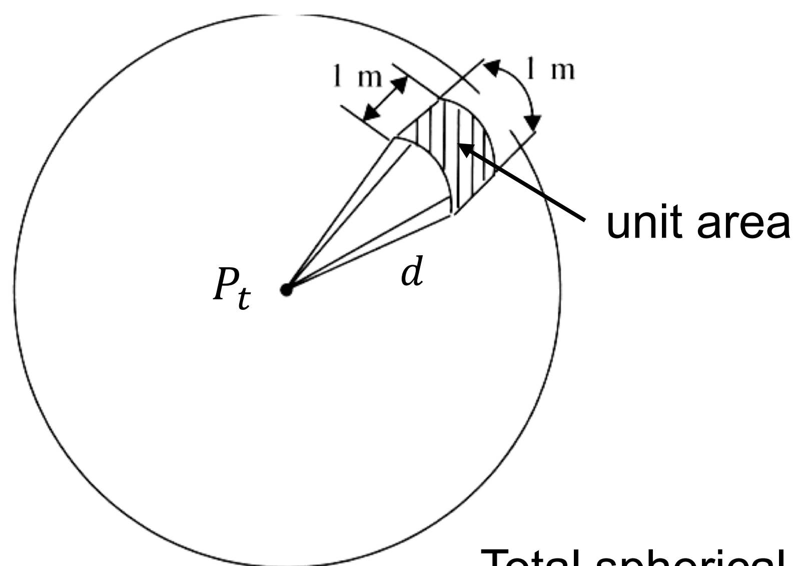
$$P_{RX}\ (\text{dBm}) = P_{TX}\ (\text{dBm}) + \text{Gains (dB)} - \text{Losses (dB)}$$

- Receiver needs a certain SINR to be able to decode the signal
- **Factors reducing power budget:**
  - Noise, attenuation (multiple sources), longer range, fading
- **Factors improving power budget:**
  - Antenna gain, transmit power

Goal: Predict **average** received signal strength given a transmitter-receiver separation distance

LARGE-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/m²
  - 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**

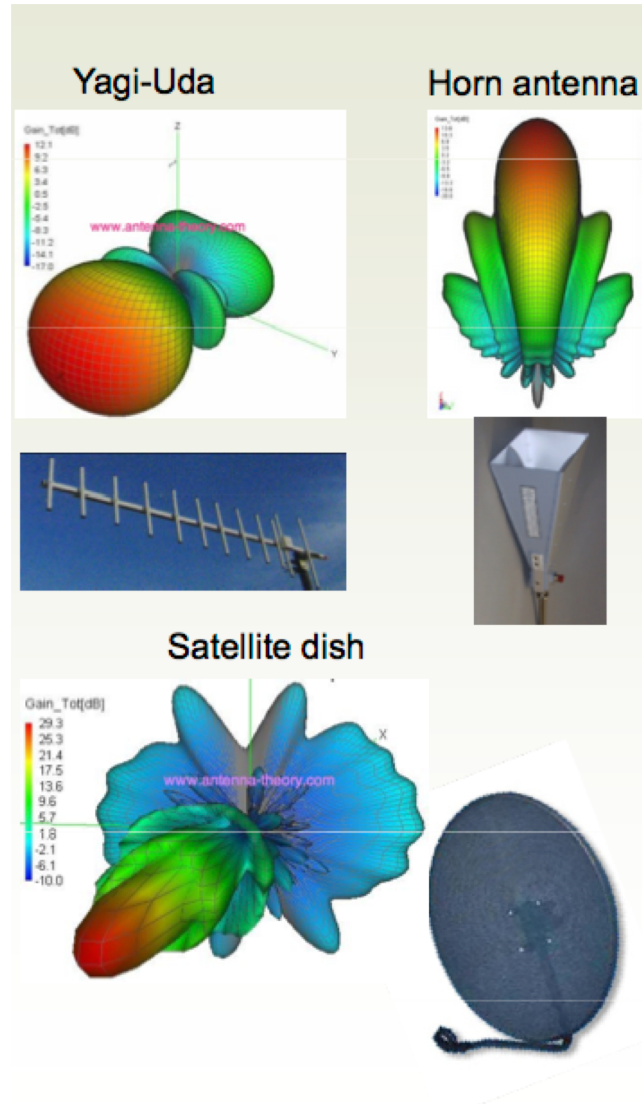
- So **power received** P_r is the product of the power density and effective aperture:

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

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

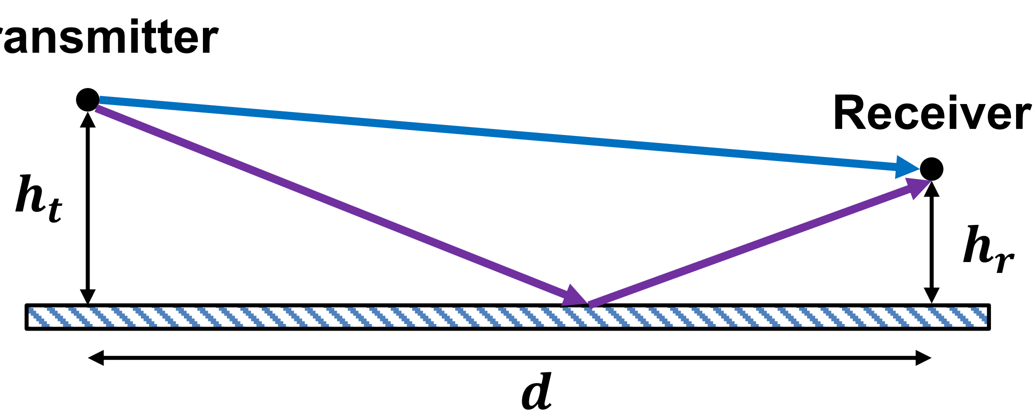


Friis Free Space Channel Model

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

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

Ground Reflection (Two-Ray) Propagation Model



- Commonly occurs in mobile cellular environments
- Near transmitter: multipath oscillation due to constructive and destructive interference
- Far from transmitter ($d \gg h_t, h_r$), reflection always approximately out of phase with line of sight path: rapid attenuation

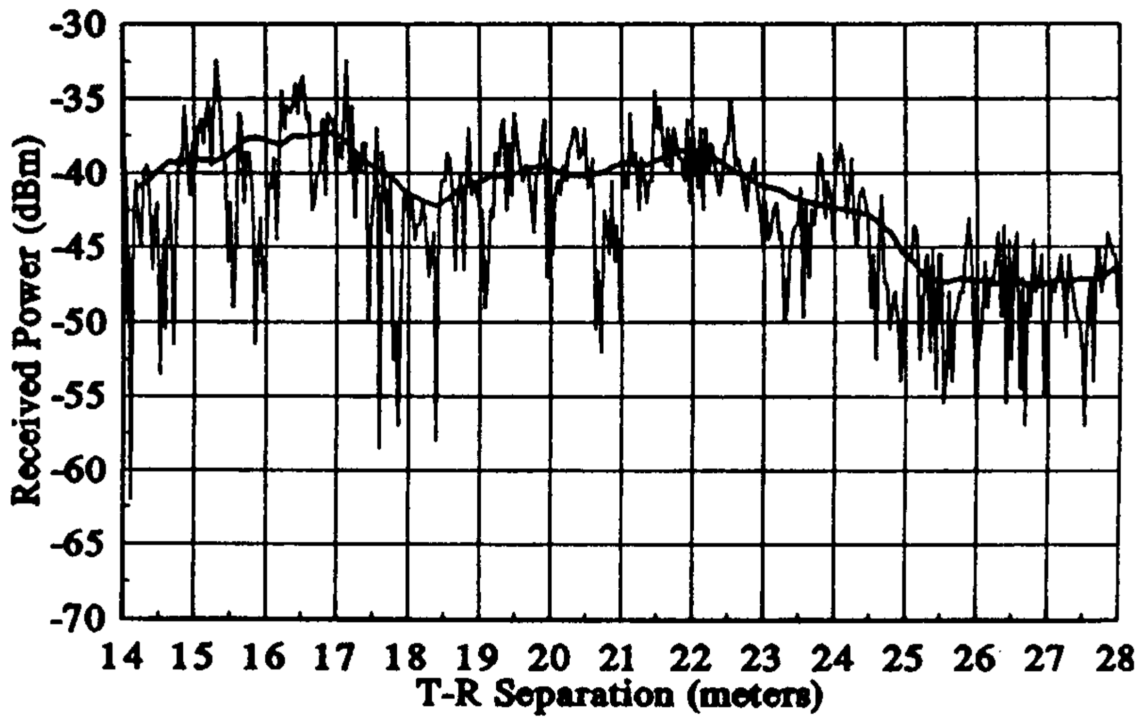
Today

1. Large scale channel models

2. **Small-scale channel models**

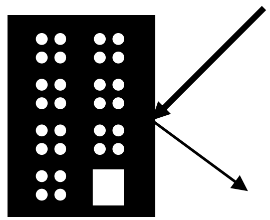
3. Equalization: Coping with the channel

Small-scale versus large-scale modeling

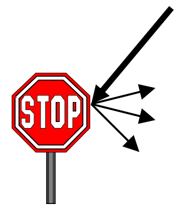


- ***Small-scale models:*** Characterize the channel over **at most** a few **wavelengths** or a few **seconds**

Radio Propagation Mechanisms



reflection



scattering

diffraction

- <u>Reflection</u>
  - Propagation wave impinges on object large compared to λ
    - e.g. the surface of the Earth, buildings, walls, etc.
- <u>Diffraction</u>
  - Path from transmitter to receiver obstructed by surface with sharp irregular edges
  - Waves bend around obstacle, even when LOS (line of sight) does not exist
- <u>Scattering</u>
  - Objects smaller than radio wavelength (i.e. foliage, street signs etc.)

Multipath Radio Propagation

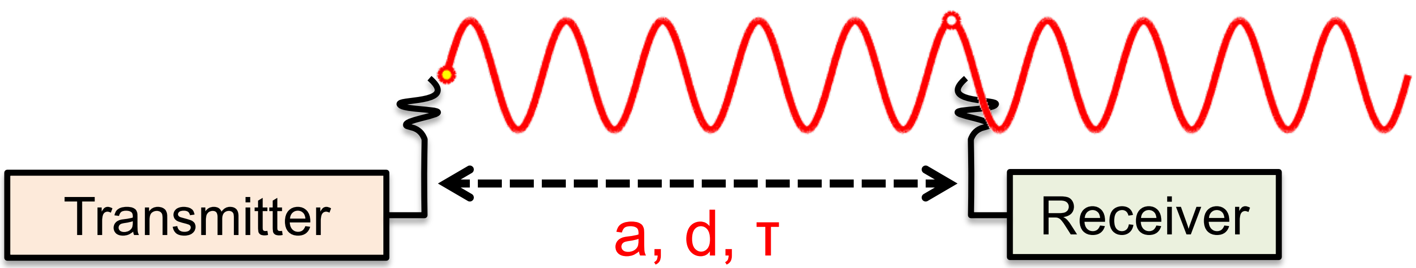
- Receiver gets **multiple copies** of signal
  - Each copy follows **different path**, with **different path length**
  - Copies can **either strengthen or weaken** each other
    - Depends on whether they are **in or out of phase**

- 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

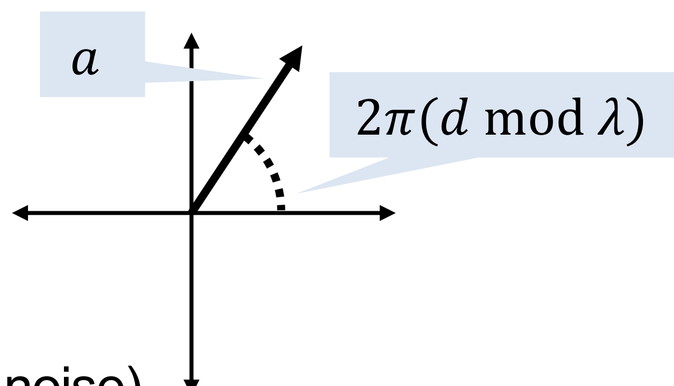
- Transmitter, receiver, or environment object **movement** on the order of λ significantly affects the outcome
  - *e.g.* 2.4 GHz → λ = 12 cm, 900 MHz → ≈ 1 ft

Sinusoidal carrier, line of sight only

- Baseband transmitted signal: $x(t) = 1 + 0j$
  - Transmitted signal: $\cos(2\pi f_c t)$

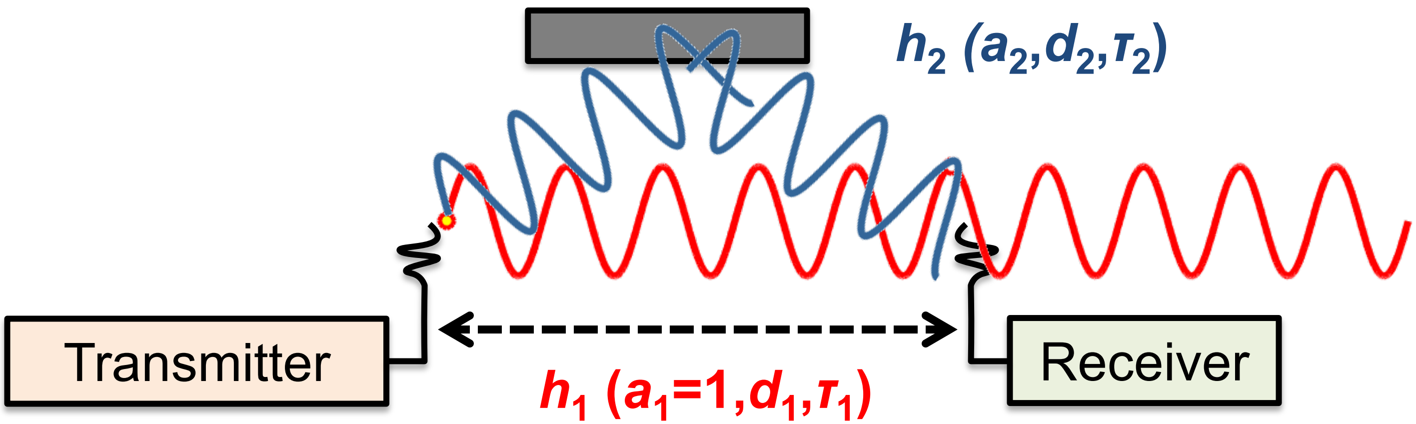


- Represent path ***attenuation*** *a*, **length** *d* with a complex number:
  - ***Complex channel*** $h = ae^{j2\pi d/\lambda}$

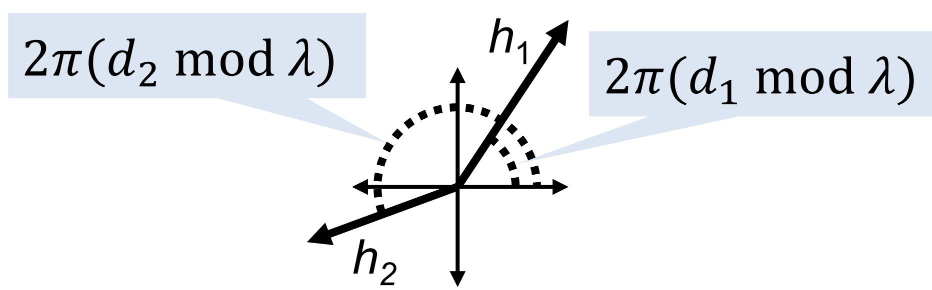


- **Received signal:** $y(t) = h \cdot x(t)$ (no noise)

Adding a reflecting path



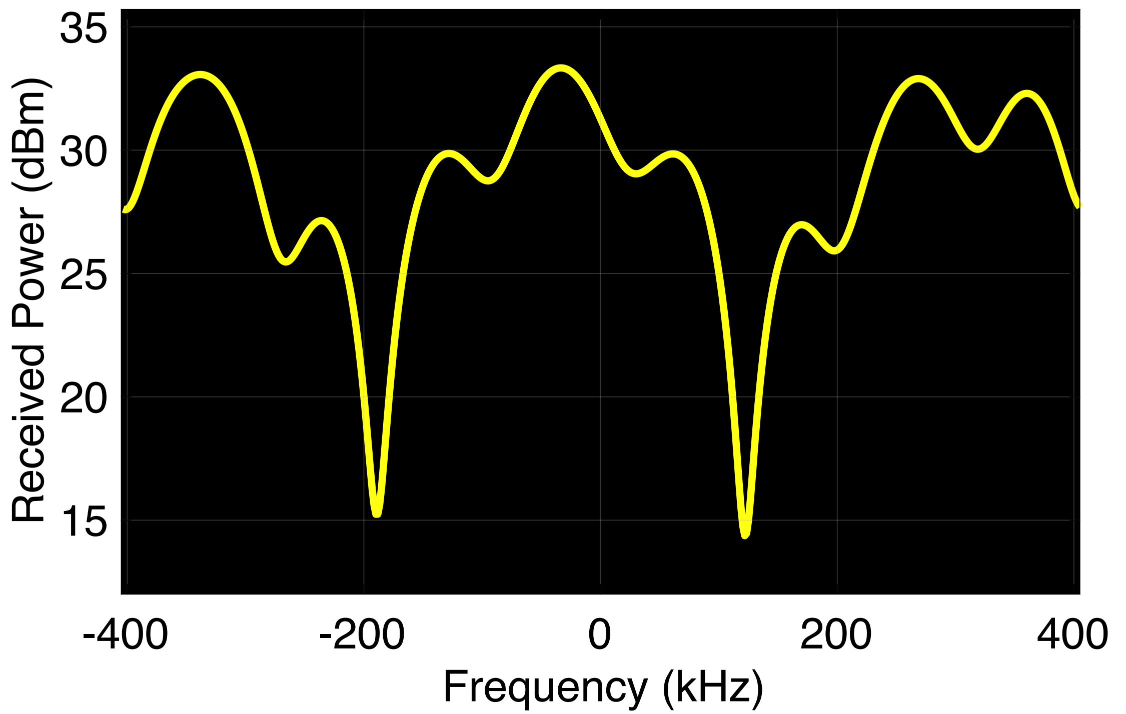
- Channel is now $h = h_1 + h_2 = a_1\, e^{j2\pi d_1/\lambda} + a_2 e^{j2\pi d_2/\lambda}$



- **Conclusion:** At **different** λ, fading is **different** in frequency

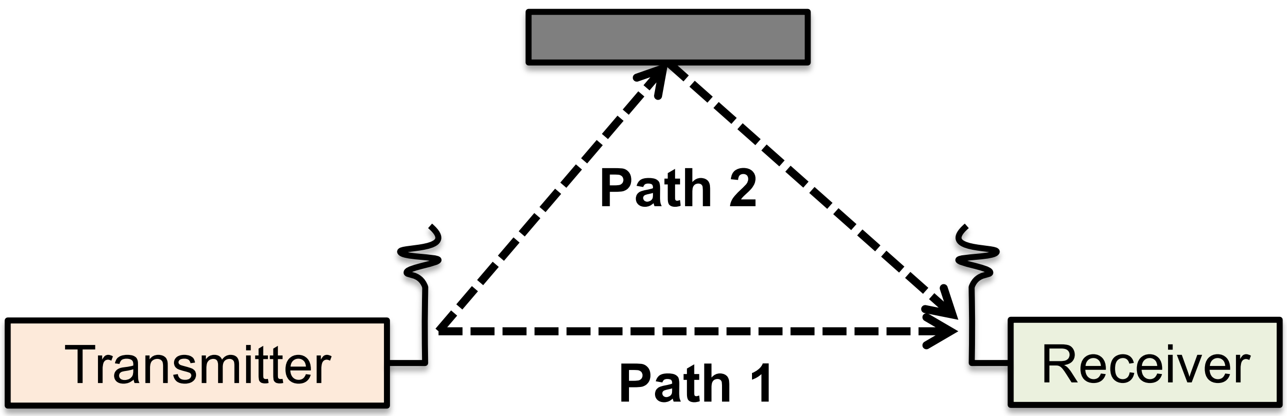
Reflections cause frequency *selectivity*

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

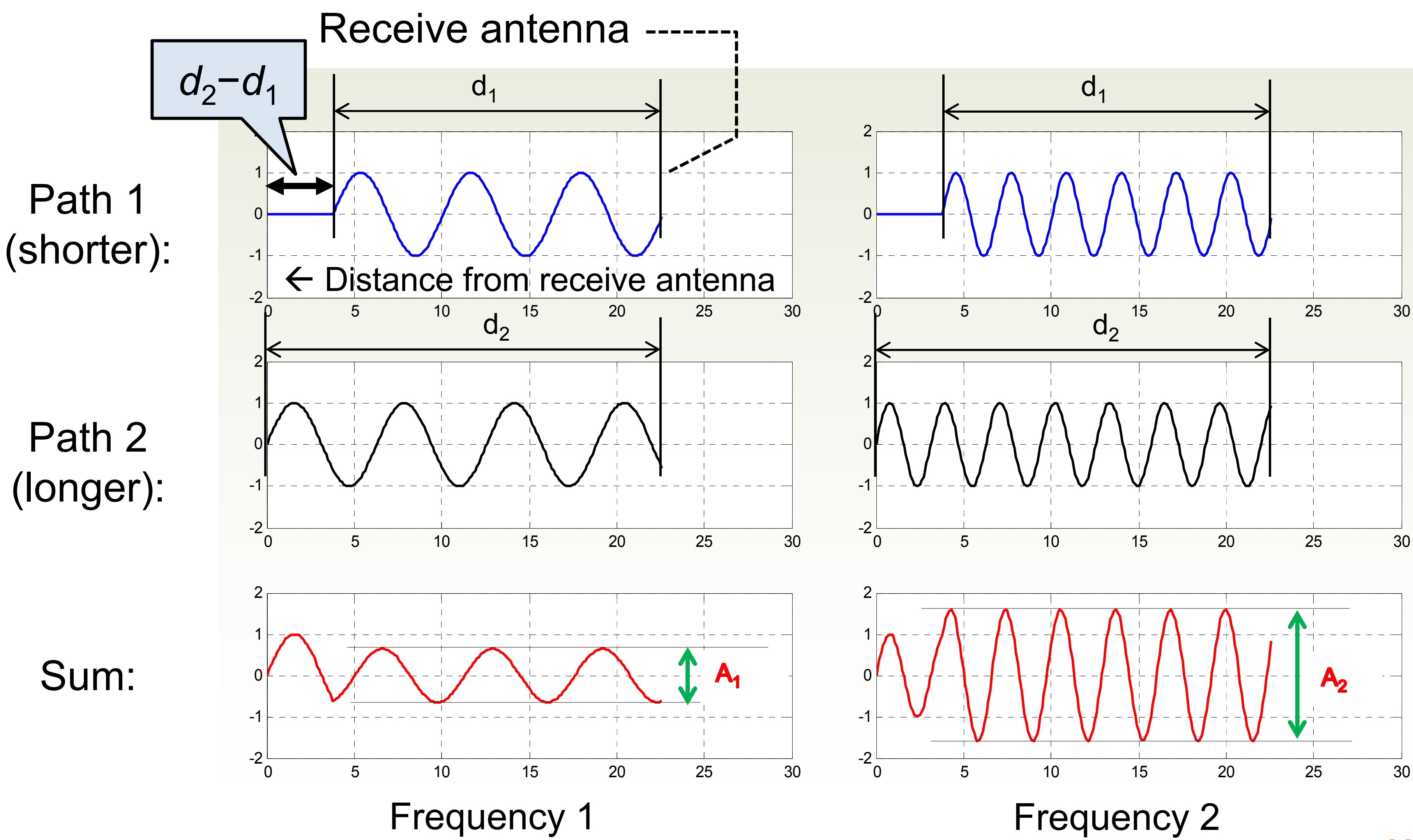


- ***Coherence bandwidth*** B_c: **Frequency range** over which the channel is roughly the **same** ("flat")

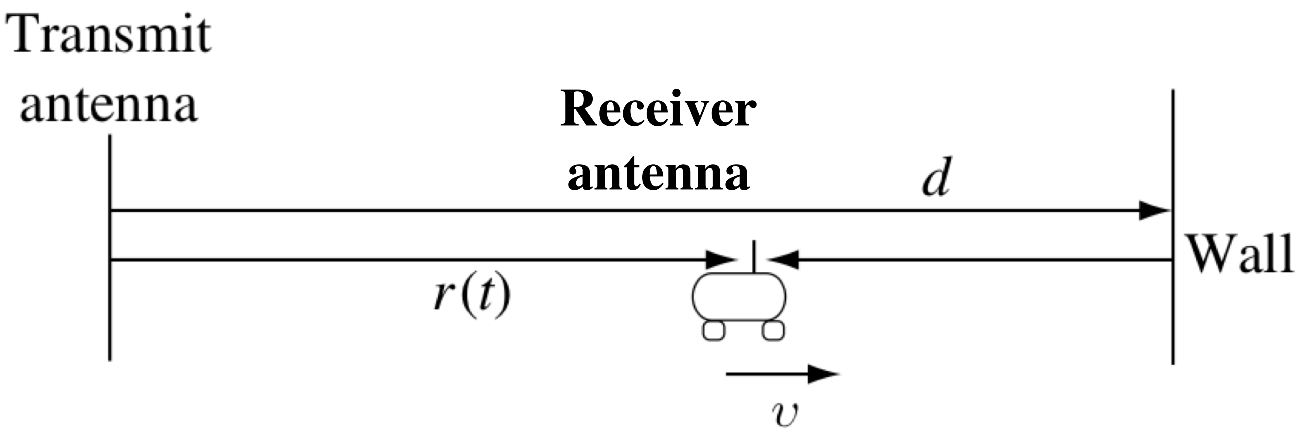
How does frequency selectivity arise? (Another look)



How does frequency selectivity arise? (Another look)



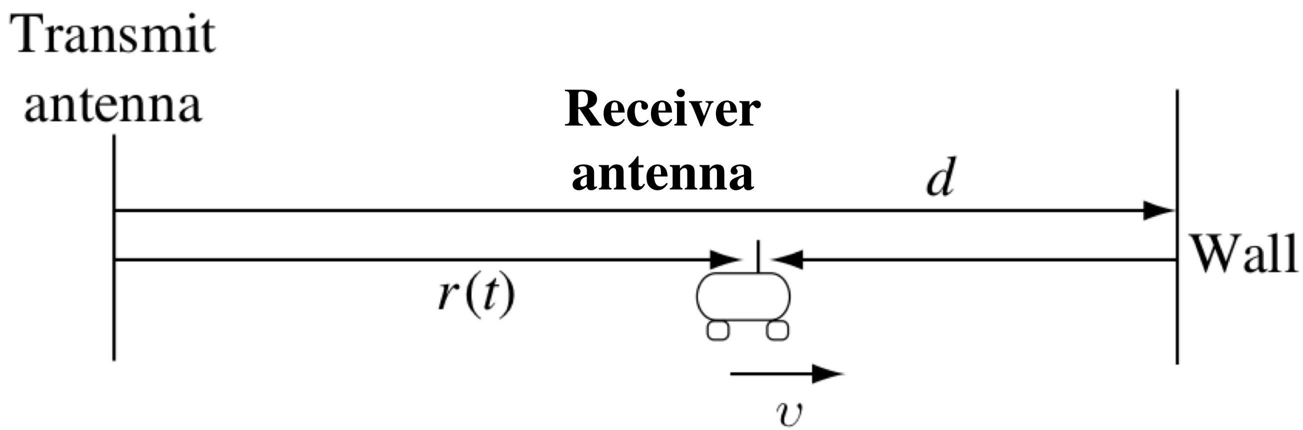
Stationary transmitter, moving receiver



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

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

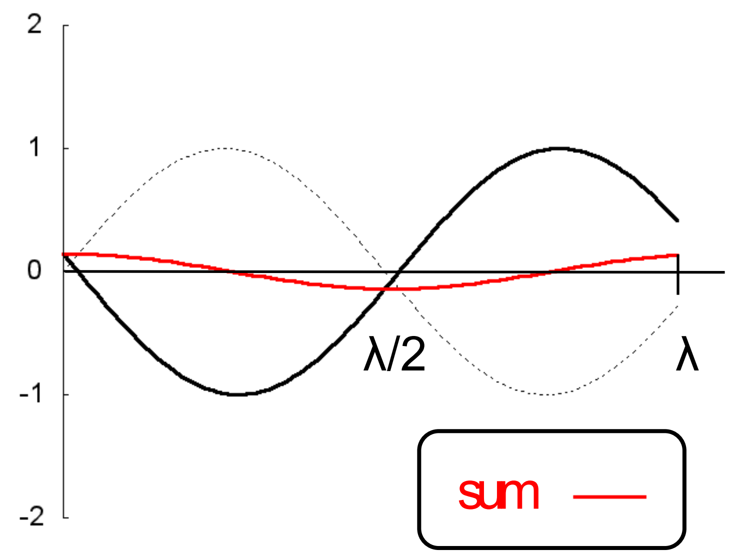
How does fading in time arise?



- **Path length difference** $\Delta = 2(d - r(t))$

- If $\Delta \pmod{\lambda} = \frac{\lambda}{2}$ → receive ≈ 0
  - ***Destructive interference***

- If $\Delta \pmod{\lambda} = 0$ → receive ≈ 2
  - ***Constructive interference***



Channel Coherence Time

- Radio carrier frequency $f = c/\lambda$
  - Speed of light: c; Wavelength of the signal: λ

- Change in path length difference of λ/2 moves from constructive to destructive interference

  - Receiver movement of **λ/4:** ***coherence distance***

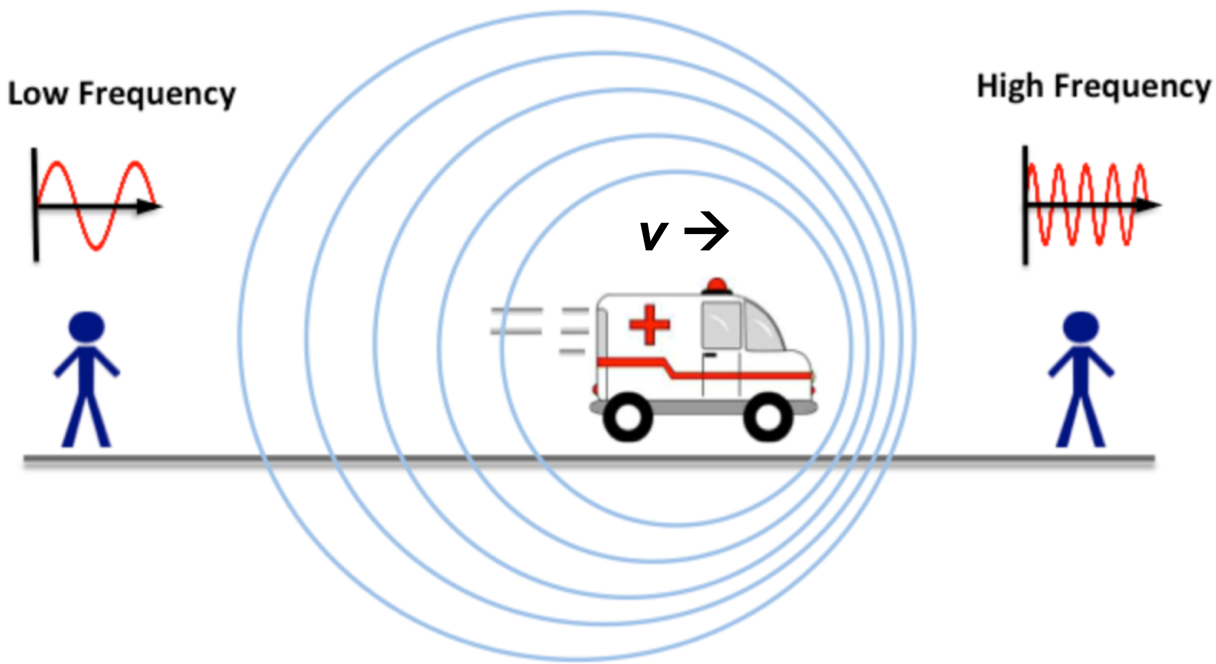
  - **Time** transmitter, receiver, or objects in environment take to move a coherence distance: ***channel coherence time T_c***

    - 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

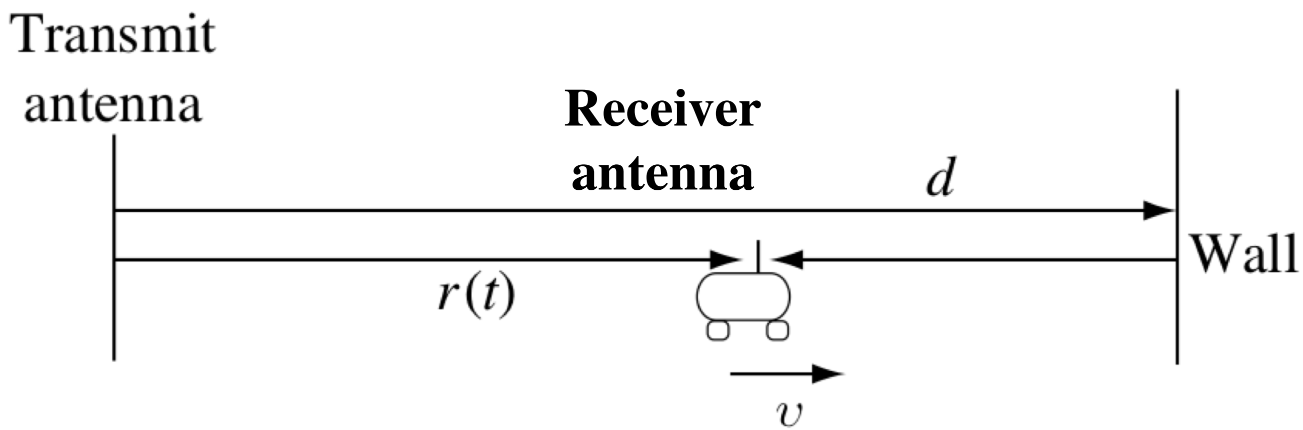
Another perspective: Doppler Effect

- 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 the **radial** component of the receiver's velocity vector **along the path**
    - **Positive Δf** with **decreasing path length**, **negative Δf with increasing** path length

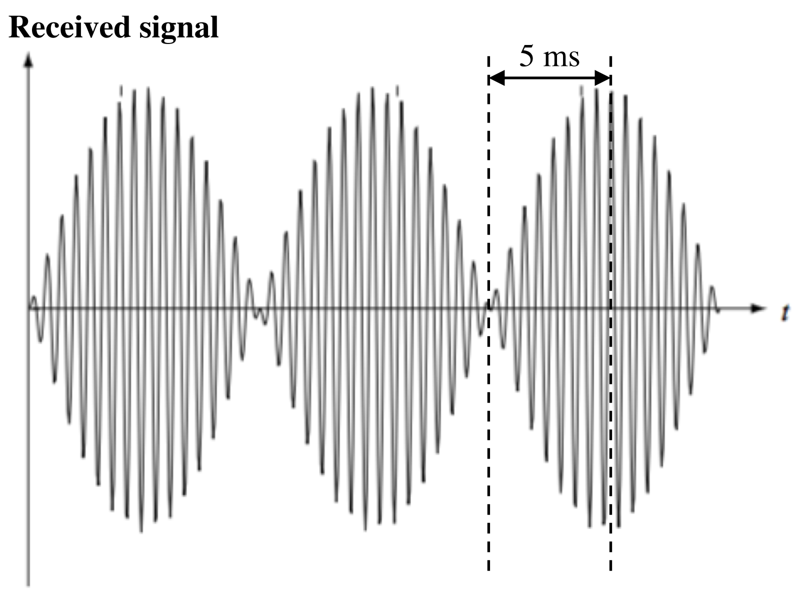
- Suppose v = 60 km/h, f_c = 900 MHz
  - Direct path $\Delta f = -50\ Hz$, reflection path $\Delta f = +50\ Hz$

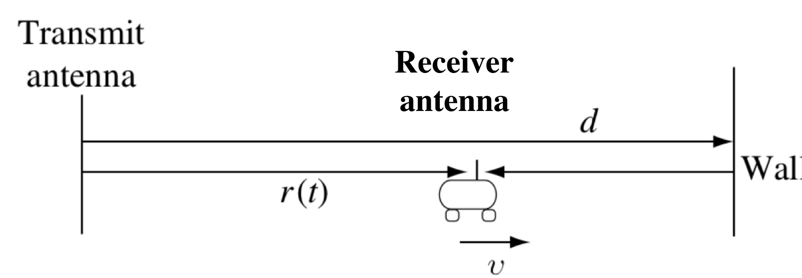
Stationary transmitter, moving receiver: From a Doppler Perspective

- ***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**

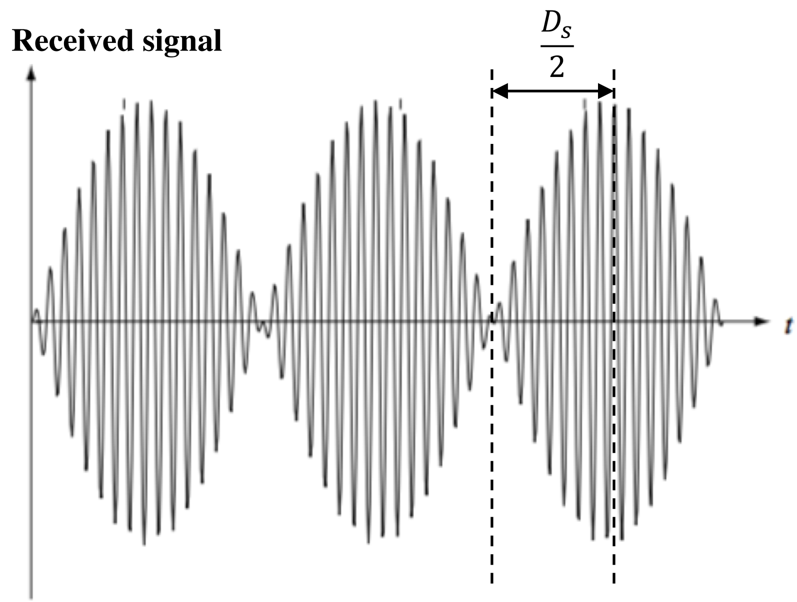
- Results in sinusoidal "envelope" at frequency D_s / 2:





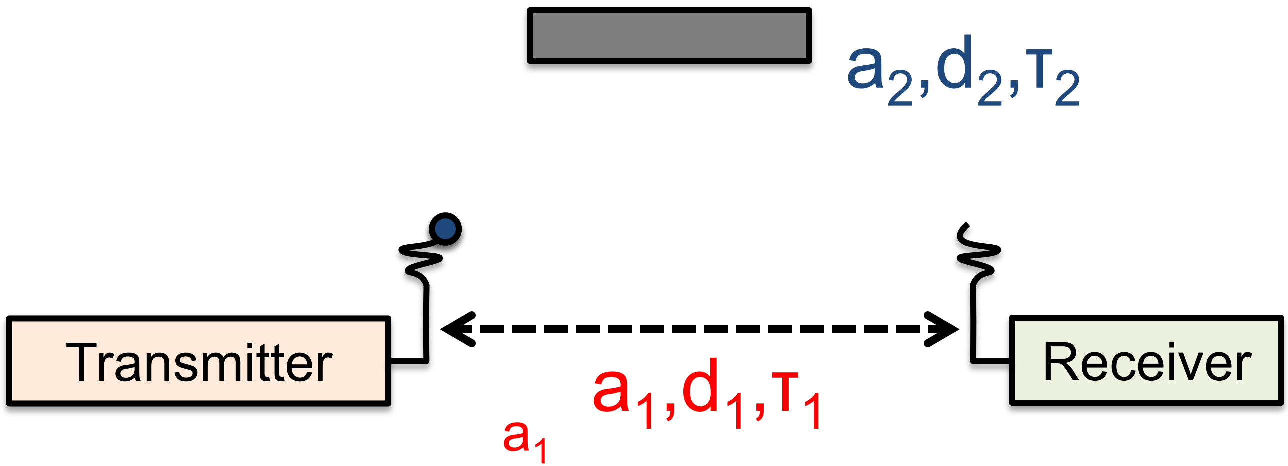
Channel Coherence Time: From a Doppler Perspective

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

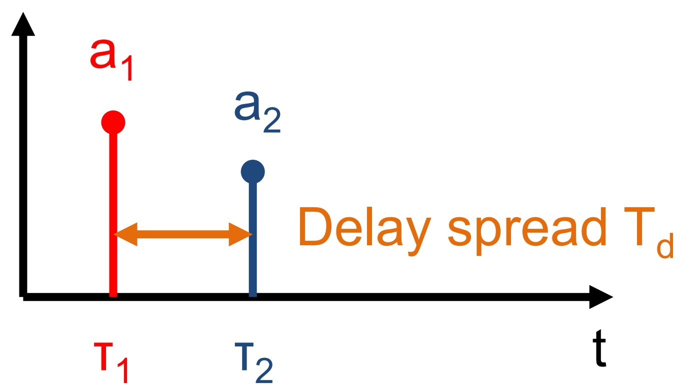


- Transition from 0 to peak in $\frac{1}{2D_s}$
  - So **qualitatively significant** change in time $T_c = \frac{1}{4D_s}$
    - Alternate definition of ***channel coherence time***

What does the channel look like in time?



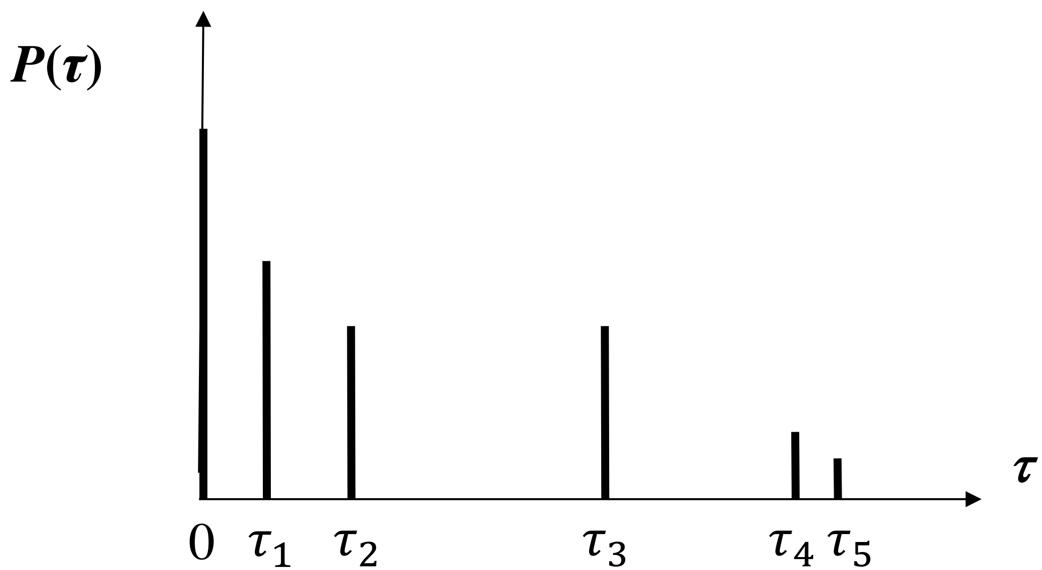
Channel impulse response *h*(*t*)



Power delay profile (PDP)

- **Power** received via the path with **excess time delay τ_i** is the value (height) of the discrete PDP component at τ_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 $P(\tau_k)$:

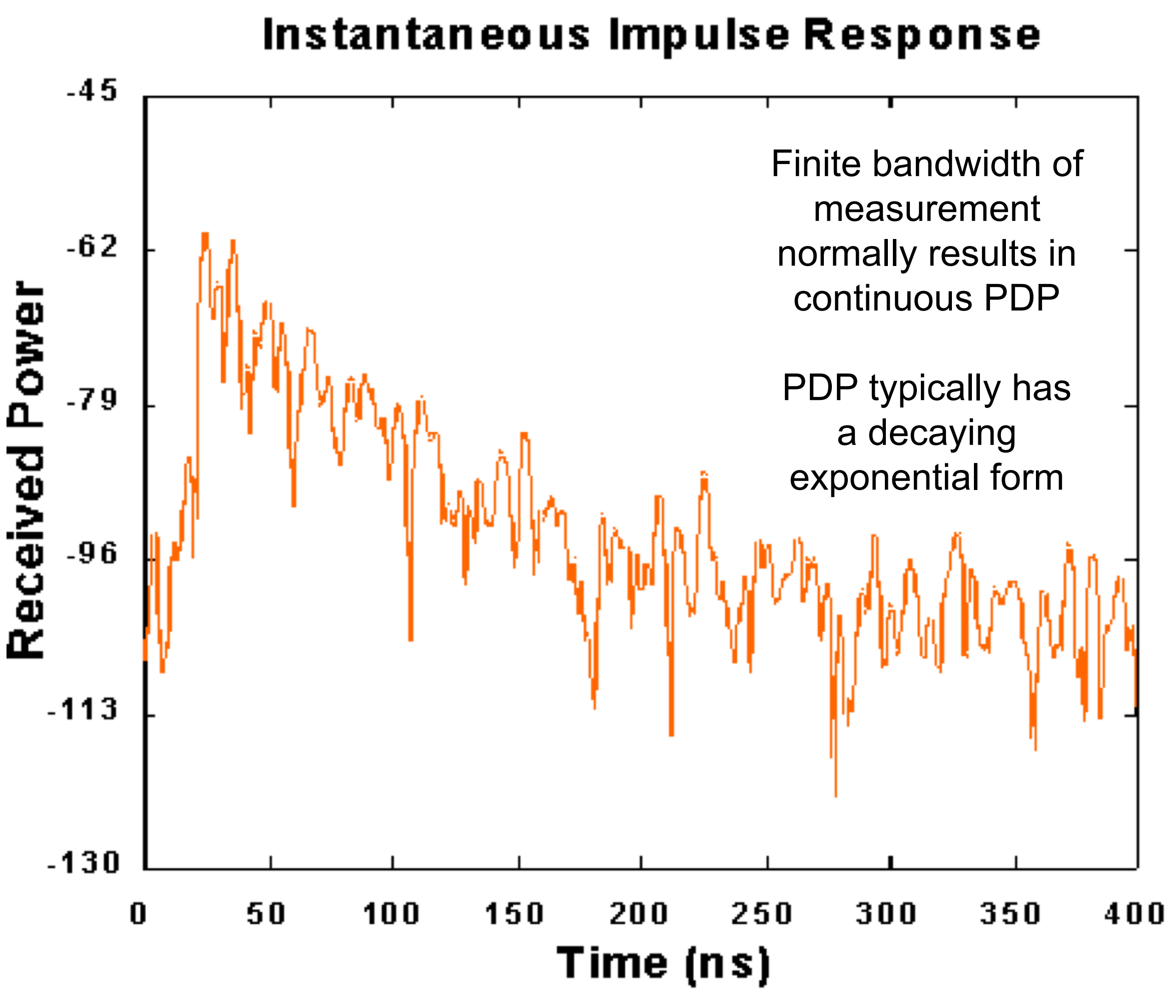
$$\bar{\tau} = \frac{\sum_k P(\tau_k)\,\tau_k}{\sum_k P(\tau_k)}$$

- ***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

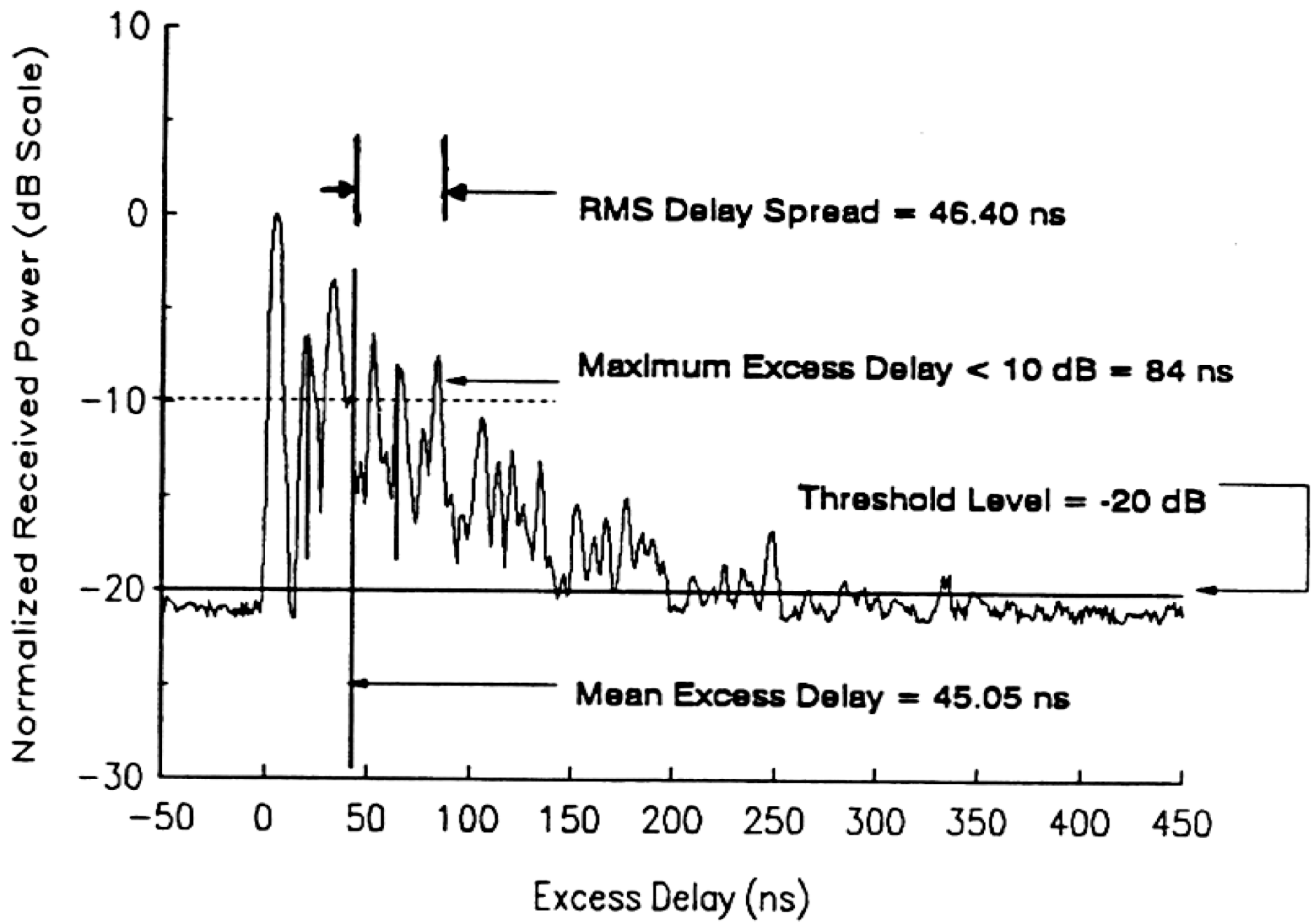
Example Indoor PDP Estimation



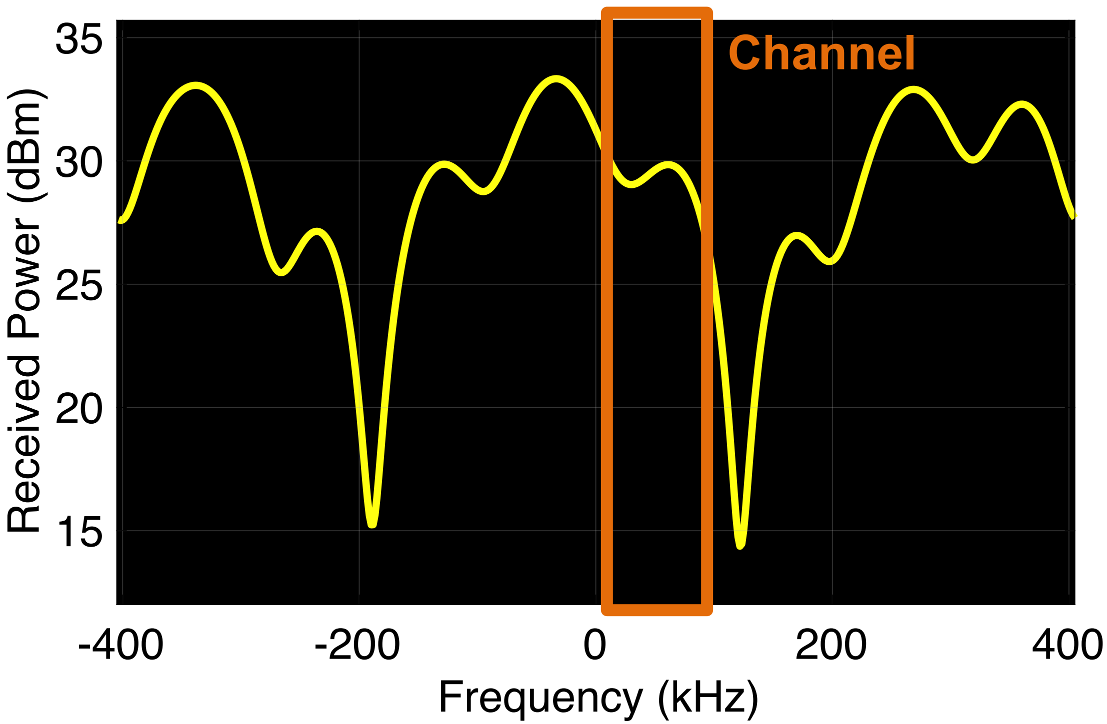
Typical RMS delay spreads

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



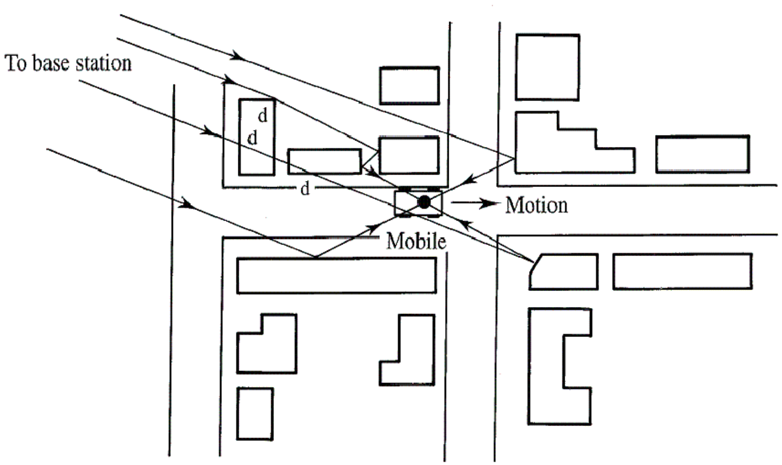
Flat Fading

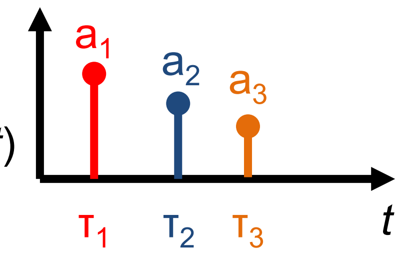


- Slow down → sending data over a **narrow bandwidth** channel
  - Channel is **constant** over its bandwidth
  - **Multipath is still present,** so channel strength fluctuates **over time**
    - **How to model this fluctuation?**

Not shown above!

Rayleigh Fading Model



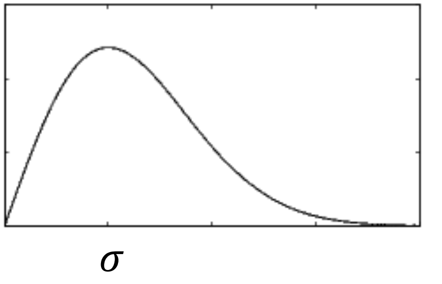


- Random gain of k^{th} arriving path: $a_k = a_k^I + ja_k^Q$

- 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

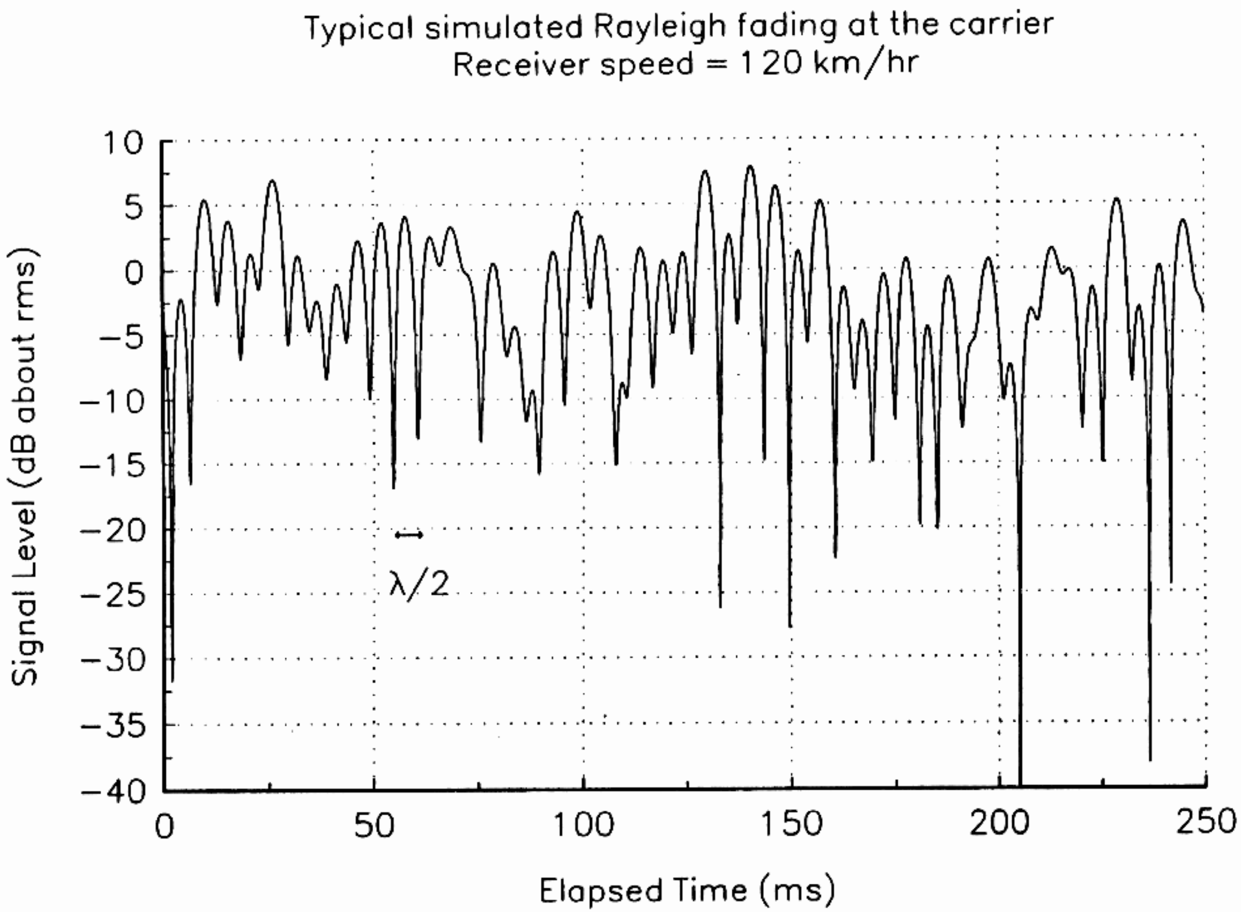


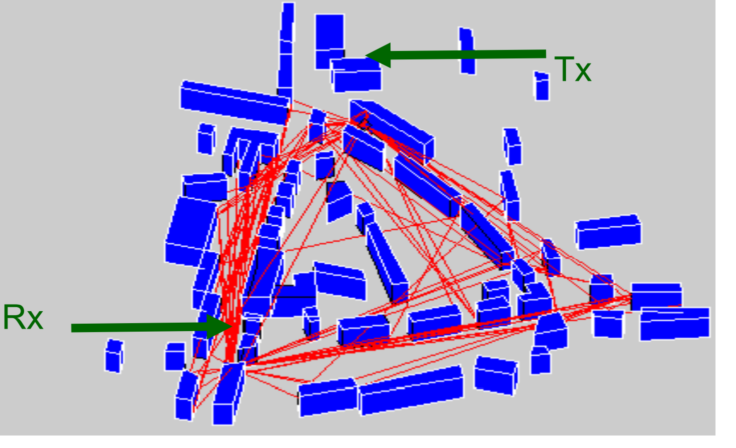
Figure 5.15 A typical Rayleigh fading envelope at 900 MHz [from [Fun93] © IEEE].

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**

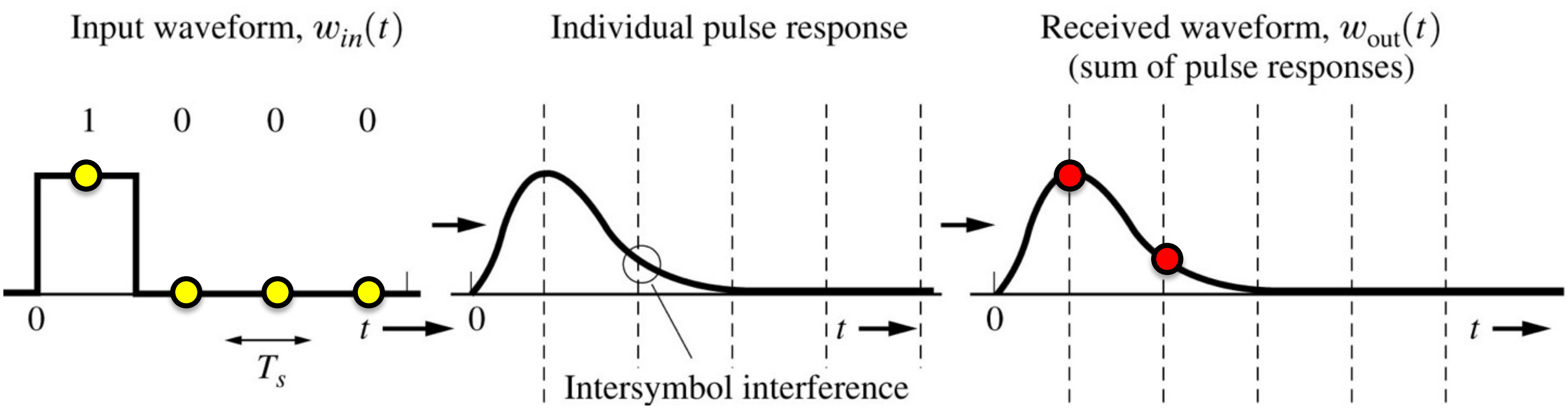
Today

1. Large scale channel models

2. Small-scale channel models

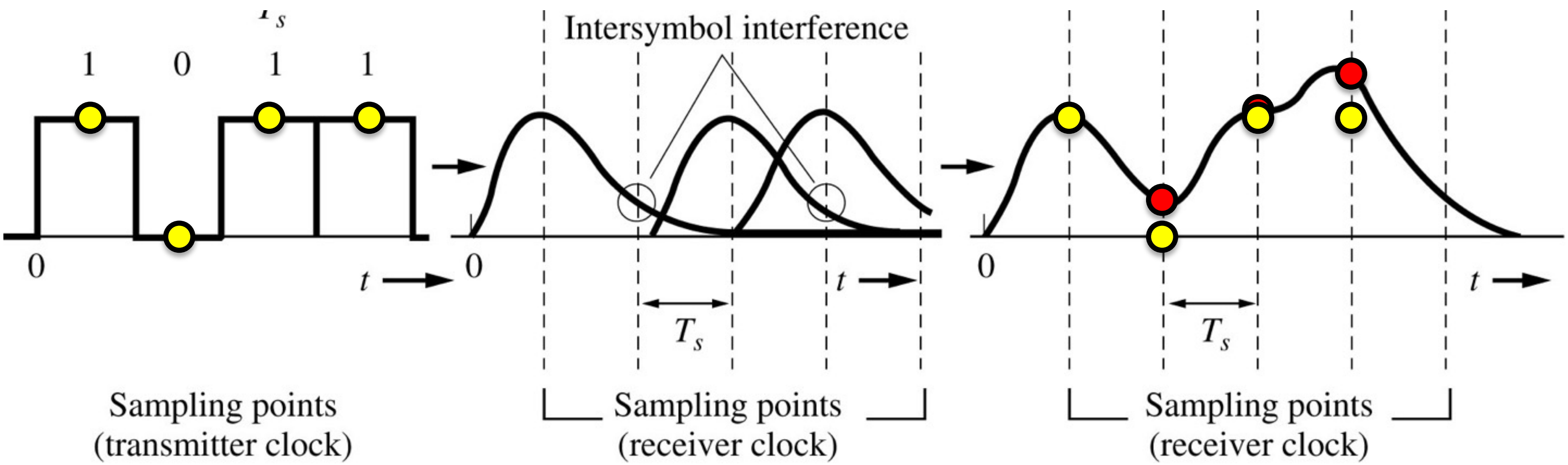
3. **Equalization: Coping with the channel**

Problem: Inter-symbol interference (ISI)



- **Transmitted signal** 🟡
- **Received signal with ISI** 🔴

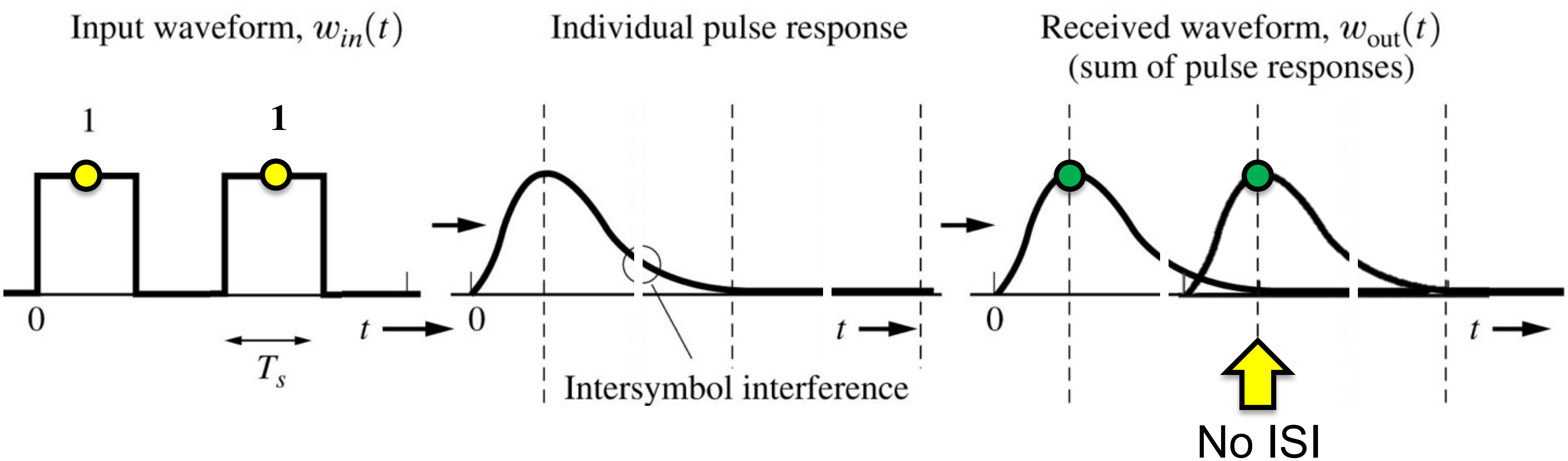
Problem: Inter-symbol interference (ISI)



- Transmitted signal
- Received signal with ISI

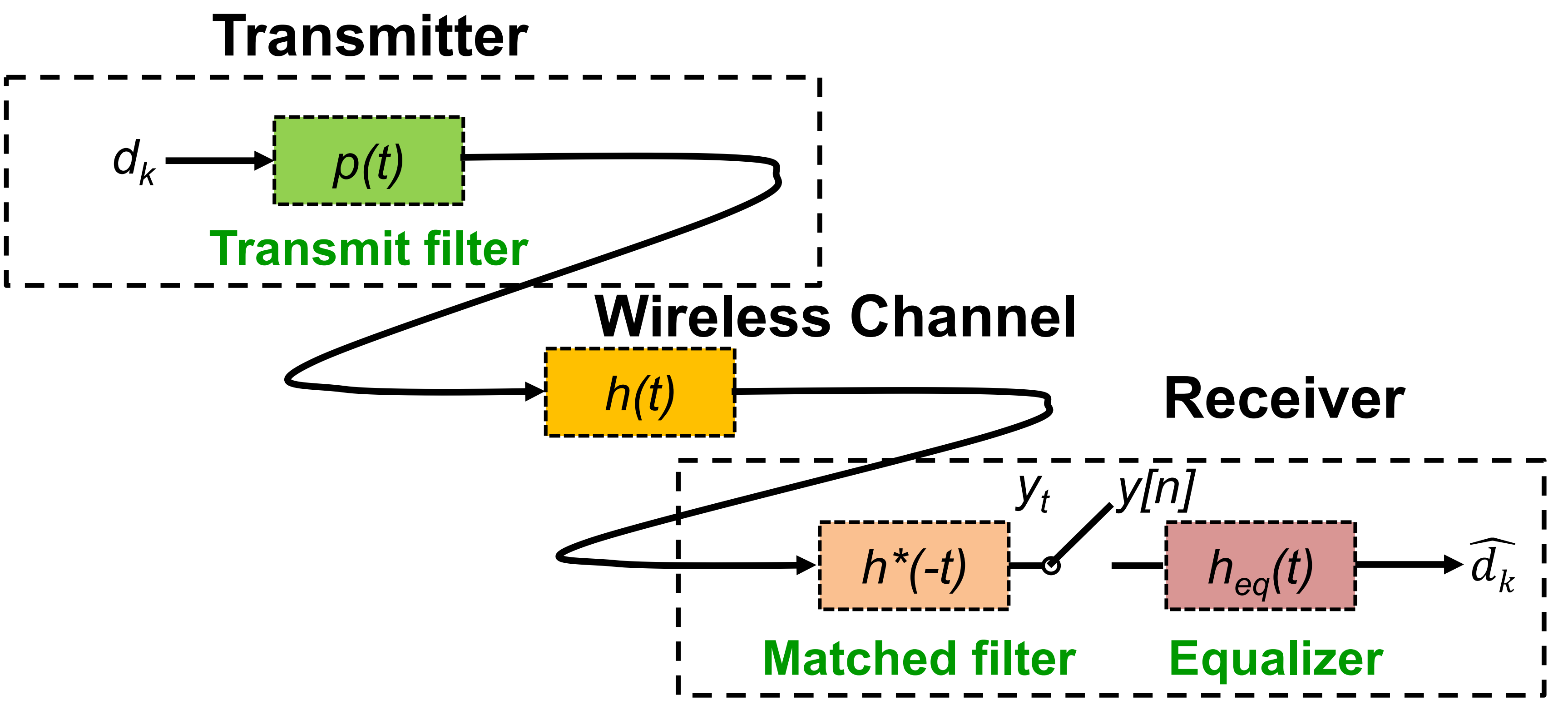
- ISI at one symbol **depends on** the value of **other** symbols

One Solution: Slow down



- **Transmitted signal**
- **Received signal**

Channel Model

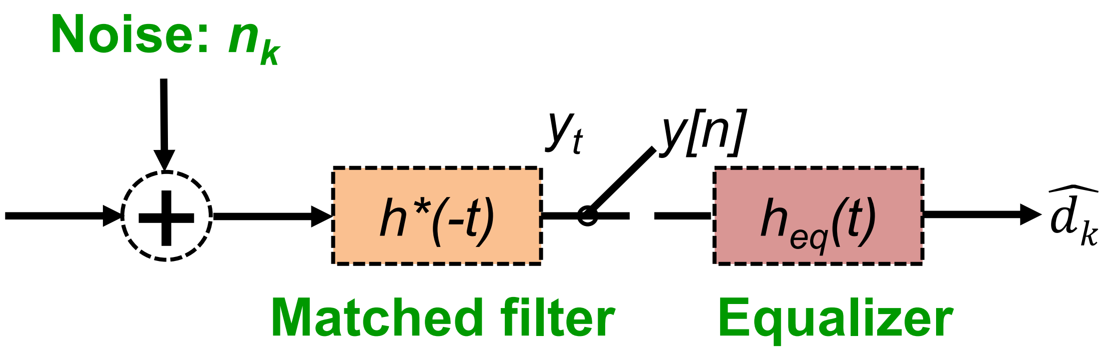


$$f(t) = (p * h)(t) * h^*(-t)$$

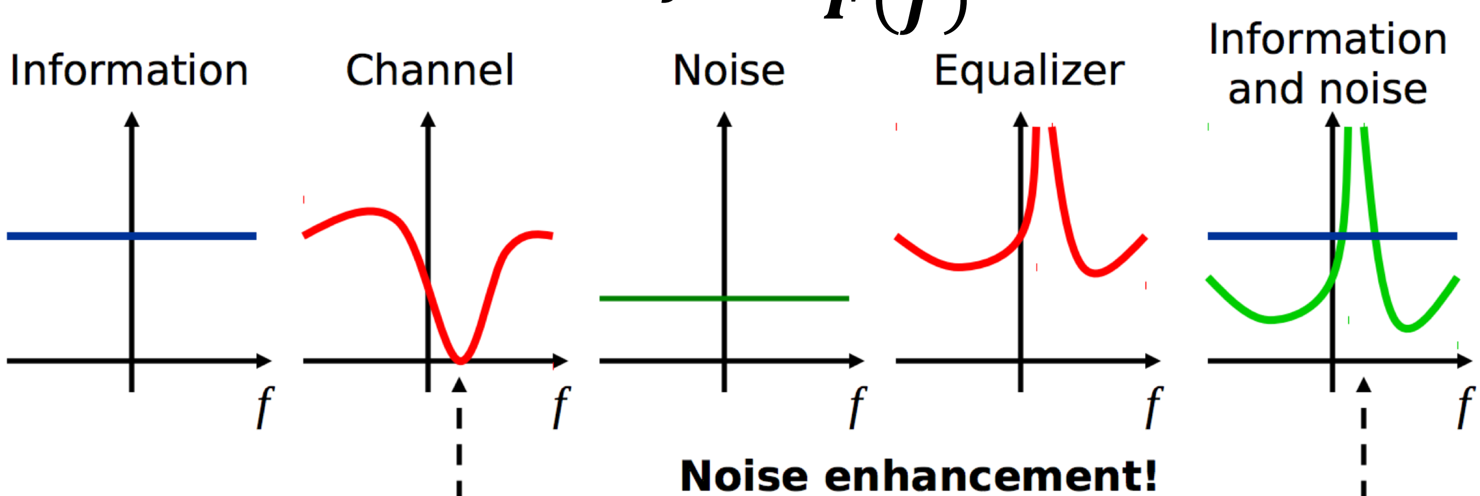
- **Composite channel** (made up of pulse shape, radio channel, and matched filter)

Another Solution I: Zero-forcing Equalizer

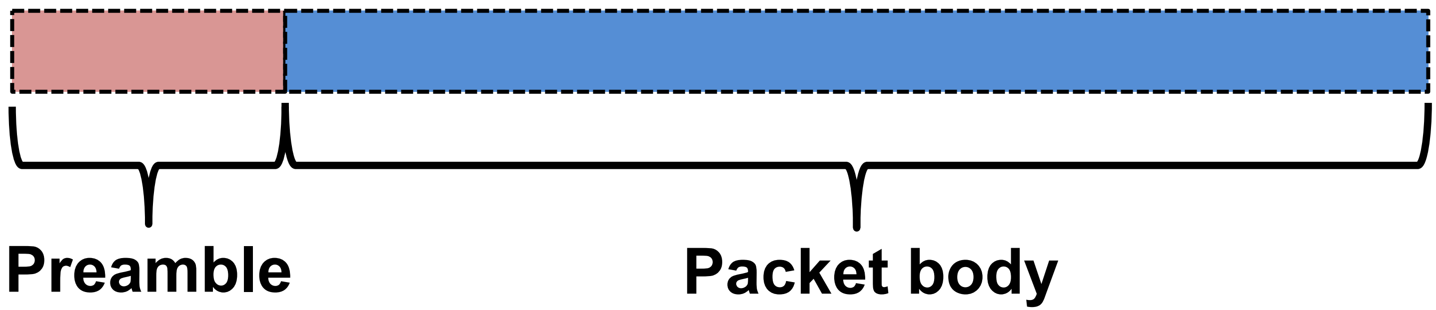
Receiver



$$H_{eq}(f) = \frac{1}{F(f)}$$



Preamble



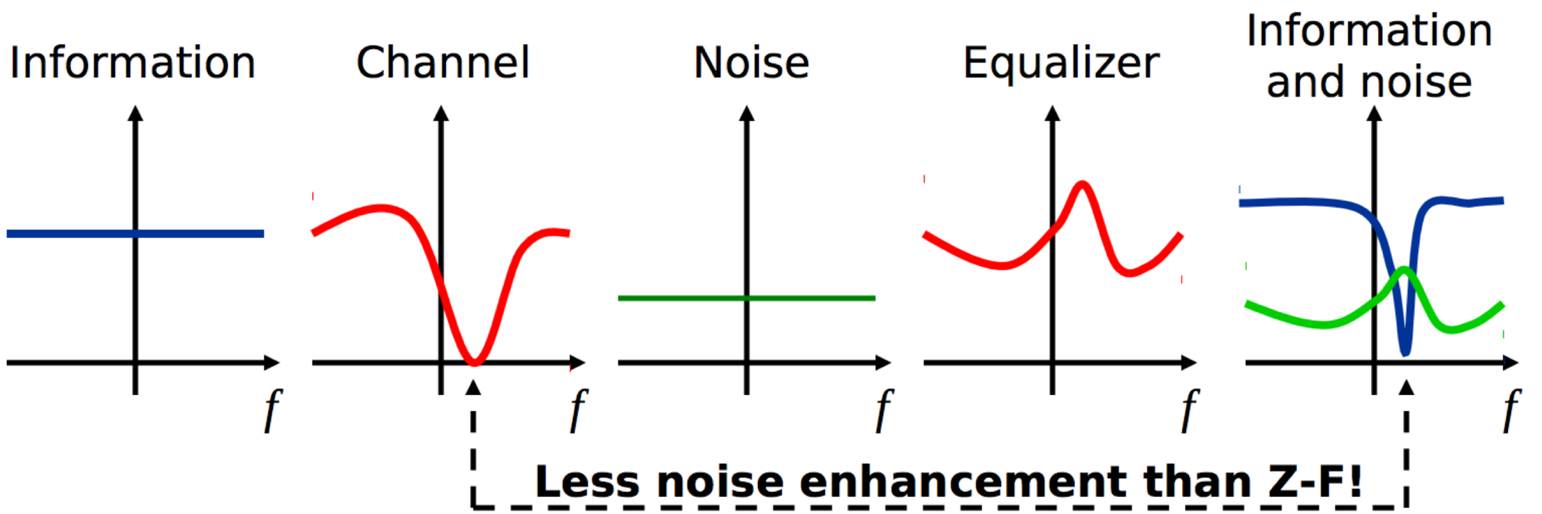
- Sequence of symbols known to both transmitter & receiver

Another Solution II: MSE Equalizer

- **Goal**: Minimizing mean-squared error (MSE) between **received symbols** & **transmitted symbols**

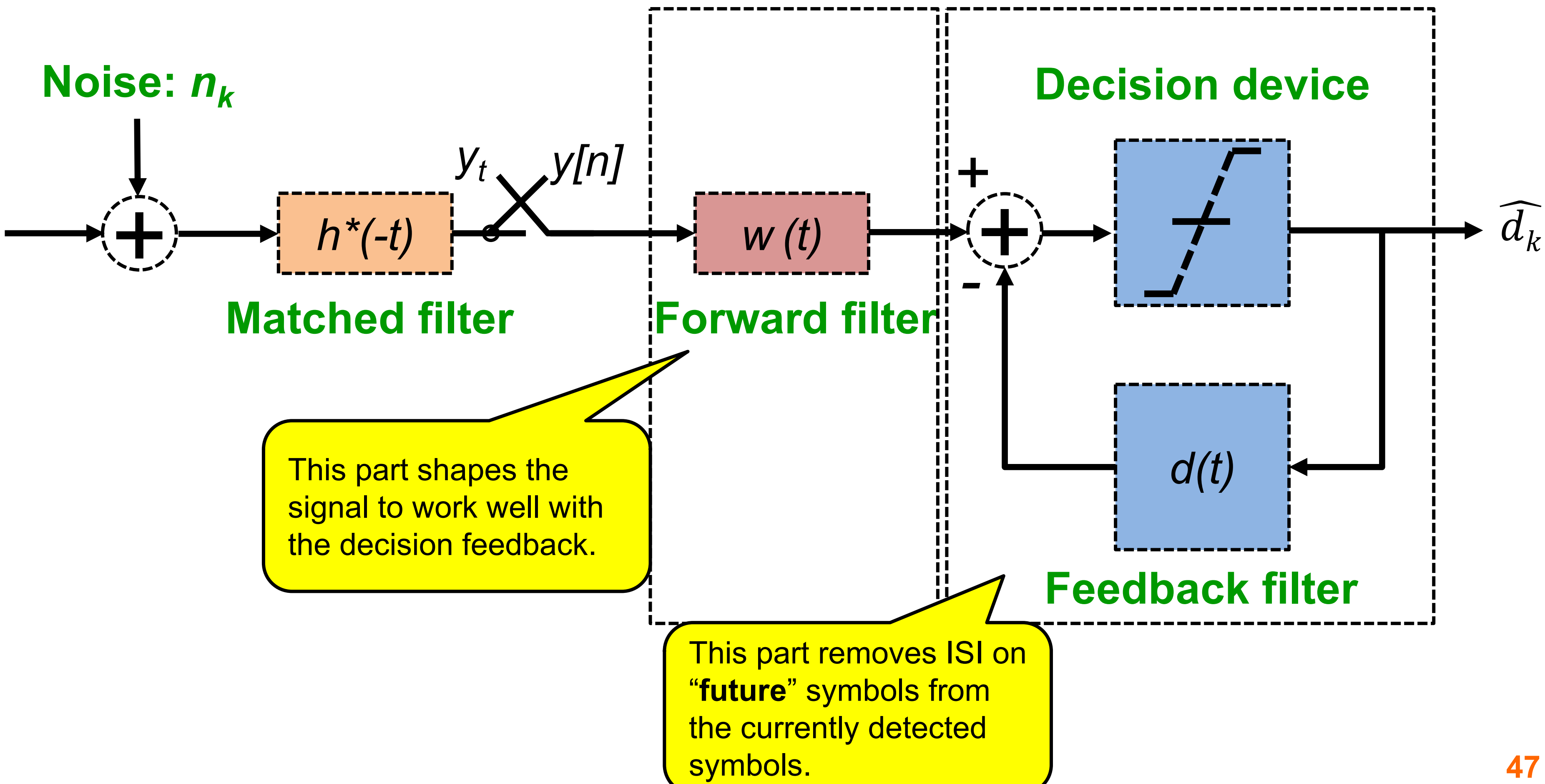
$$MSE = \sum_{k=0}^{K} |d_k - \widehat{d_k}|^2$$

- **Assumes Receiver has a preamble**



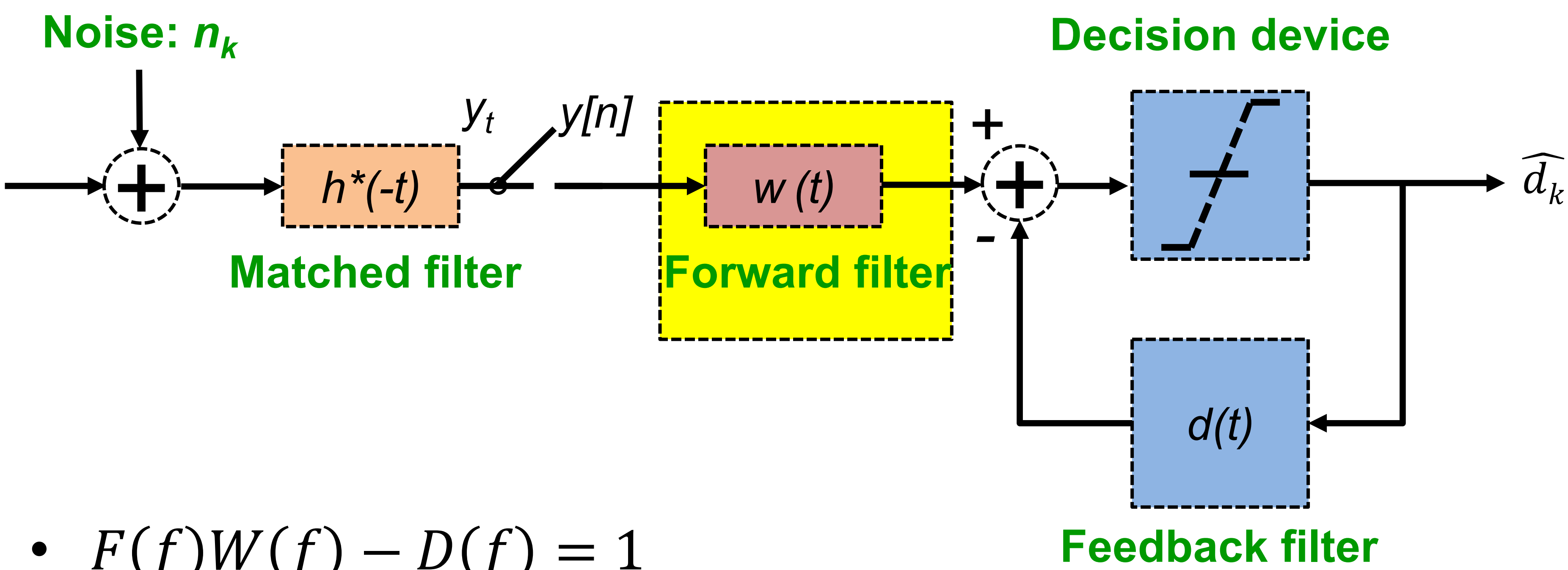
Another Solution III: Decision-feedback Equalizer

- **Idea:** Subtract the **interference** caused by already detected data (symbols)



Another Solution III: Decision-feedback Equalizer

- The forward filter *w(t)* here uses a **linear equalizer**
  - e.g., **zero-forcing**, **MSE**



- $F(f)W(f) - D(f) = 1$

- The DFE has access to the symbol decisions

Thursday Topic:
OFDM

Friday Precept:
Lab 4: BPSK Radio