Objectives:

1) basic channel models
2) factors that determines throughput/bit error rate in wireless communication

Readings:

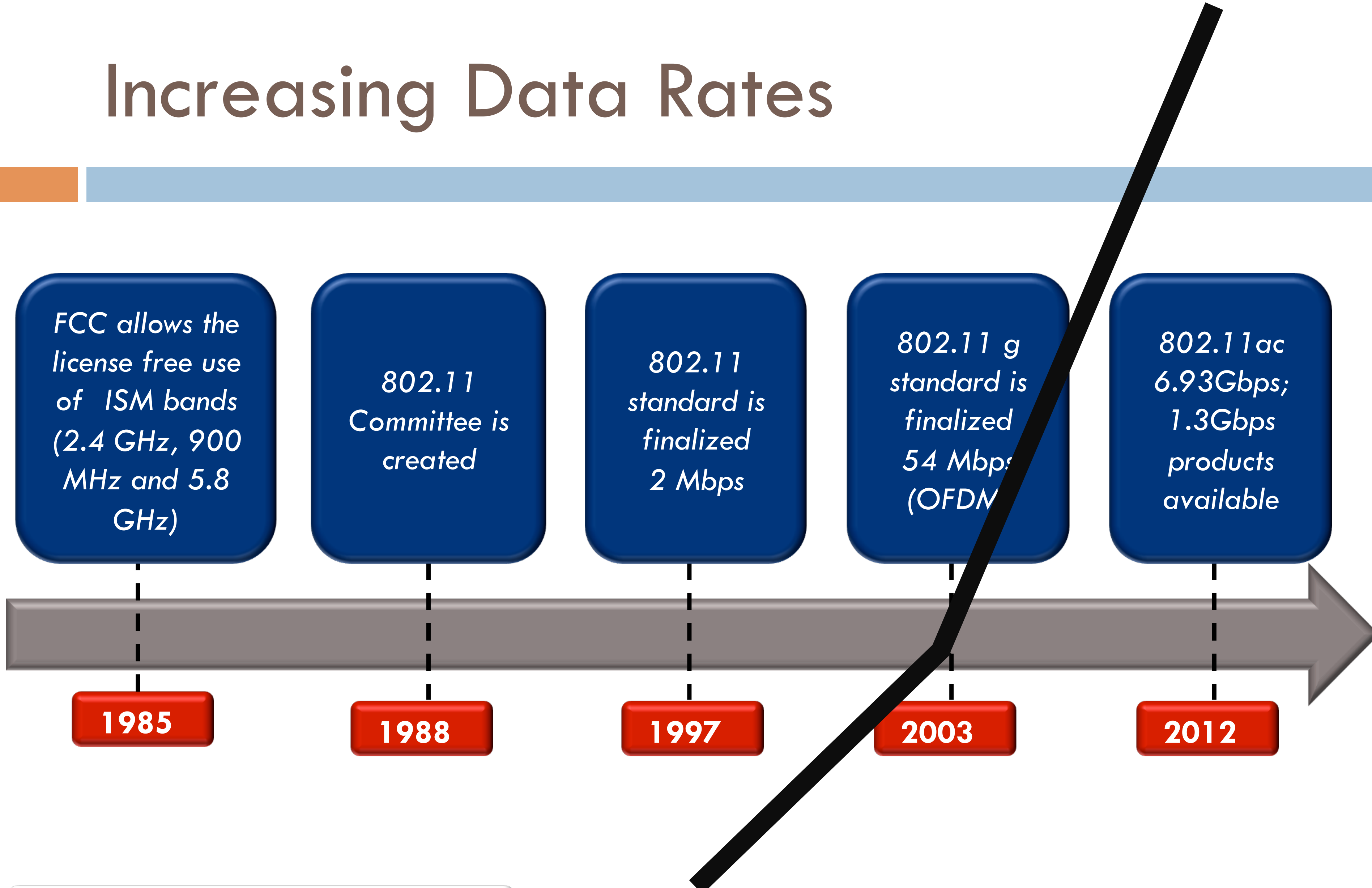
1. Rappaport, Wireless Communications: Principles and Practice, Pearson (chap 4,5)

FUNDAMENTALS OF WIRELESS COMMUNICATIONS

It's a Wireless World!

- Wireless, Mobile everywhere
  - WiFi @ 1+ Gbps standards being defined
  - LTE/4G @ 100Mbps over wide-area
  - Billion+ devices with wireless access

Increasing Data Rates



Evolution of WiFi

Increasing Data Rates

FCC allows the license free use of ISM bands (2.4 GHz, 900 MHz and 5.8 GHz)

1000+x increase in data rates over past 15 years

802.11ac 6.93Gbps; 1.3Gbps products available

1985

1988

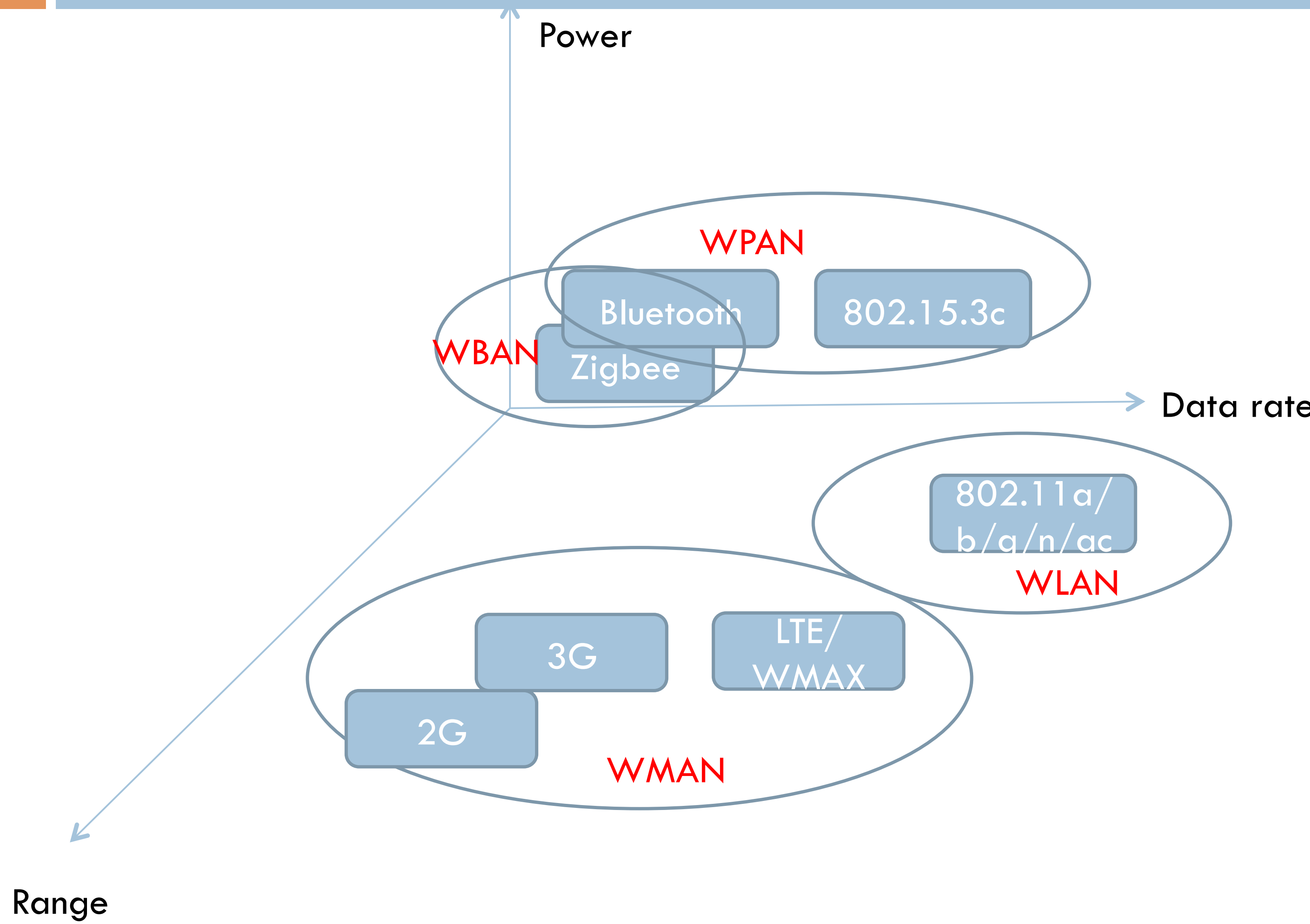
1997

2003

2012

Evolution of WiFi

Diverse Range and Power consumption



UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL AIDS
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- GOVERNMENT EXCLUSIVE
- GOVERNMENT/ NON-GOVERNMENT SHARED
- NON-GOVERNMENT EXCLUSIVE

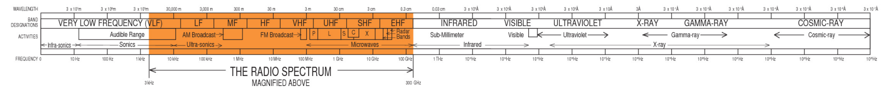
ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it does not completely reflect all aspects, i.e., footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

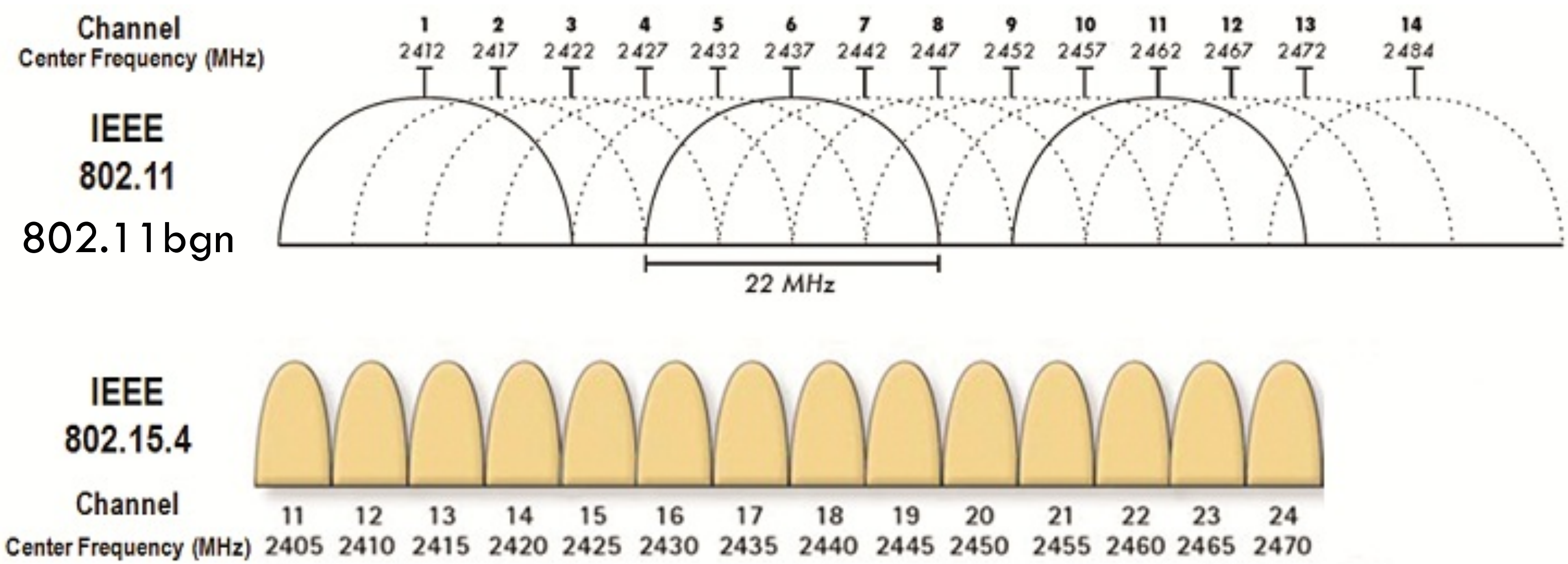
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management

October 2003

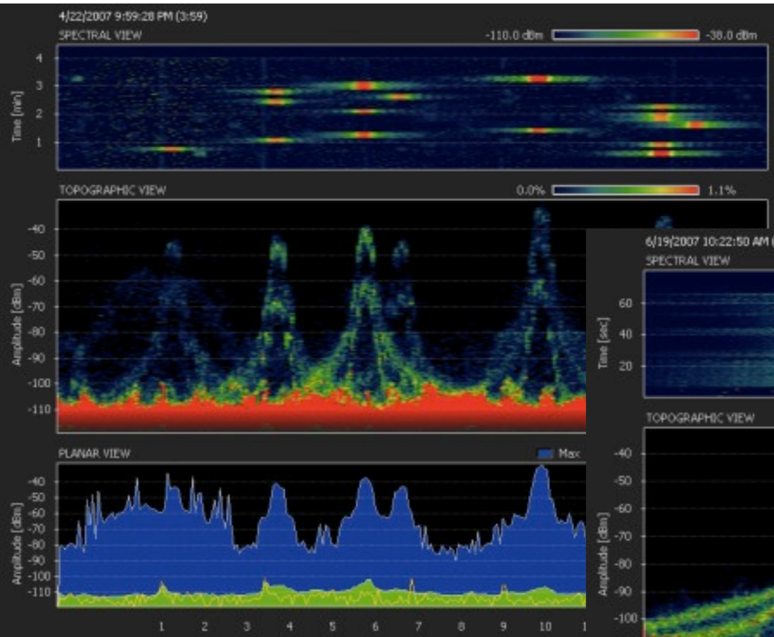


PLEASE NOTE: THE SPACING ALLOTTED THE SERVICES IN THE SPECTRUM SEGMENTS SHOWN IS NOT PROPORTIONAL TO THE ACTUAL AMOUNT OF SPECTRUM OCCUPIED.

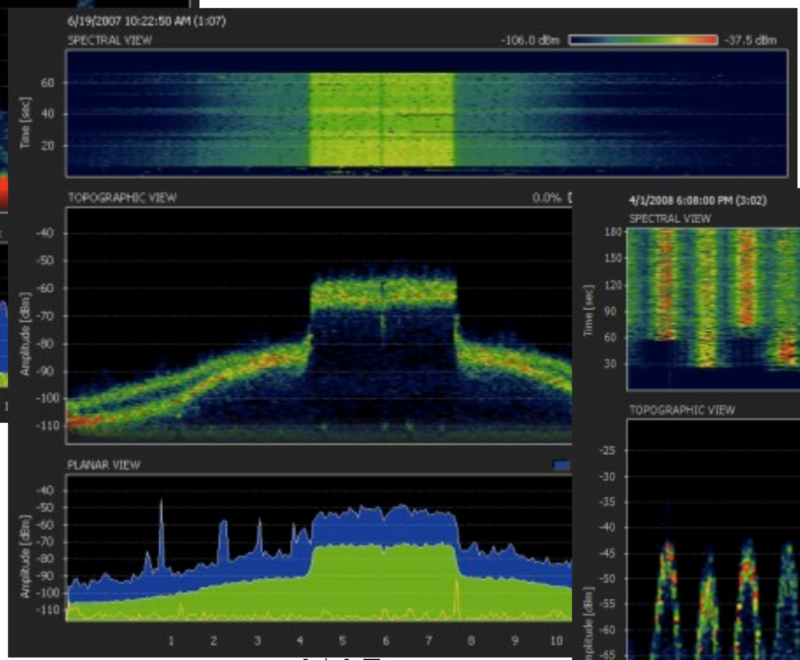
Spectrum Allocation



Spectrum Usage

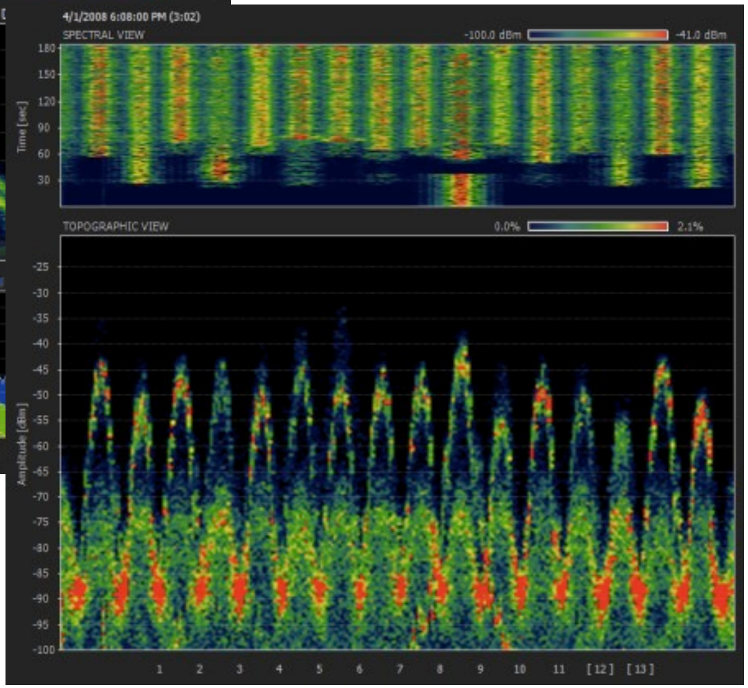


Cellphone



WiFi

Zigbee

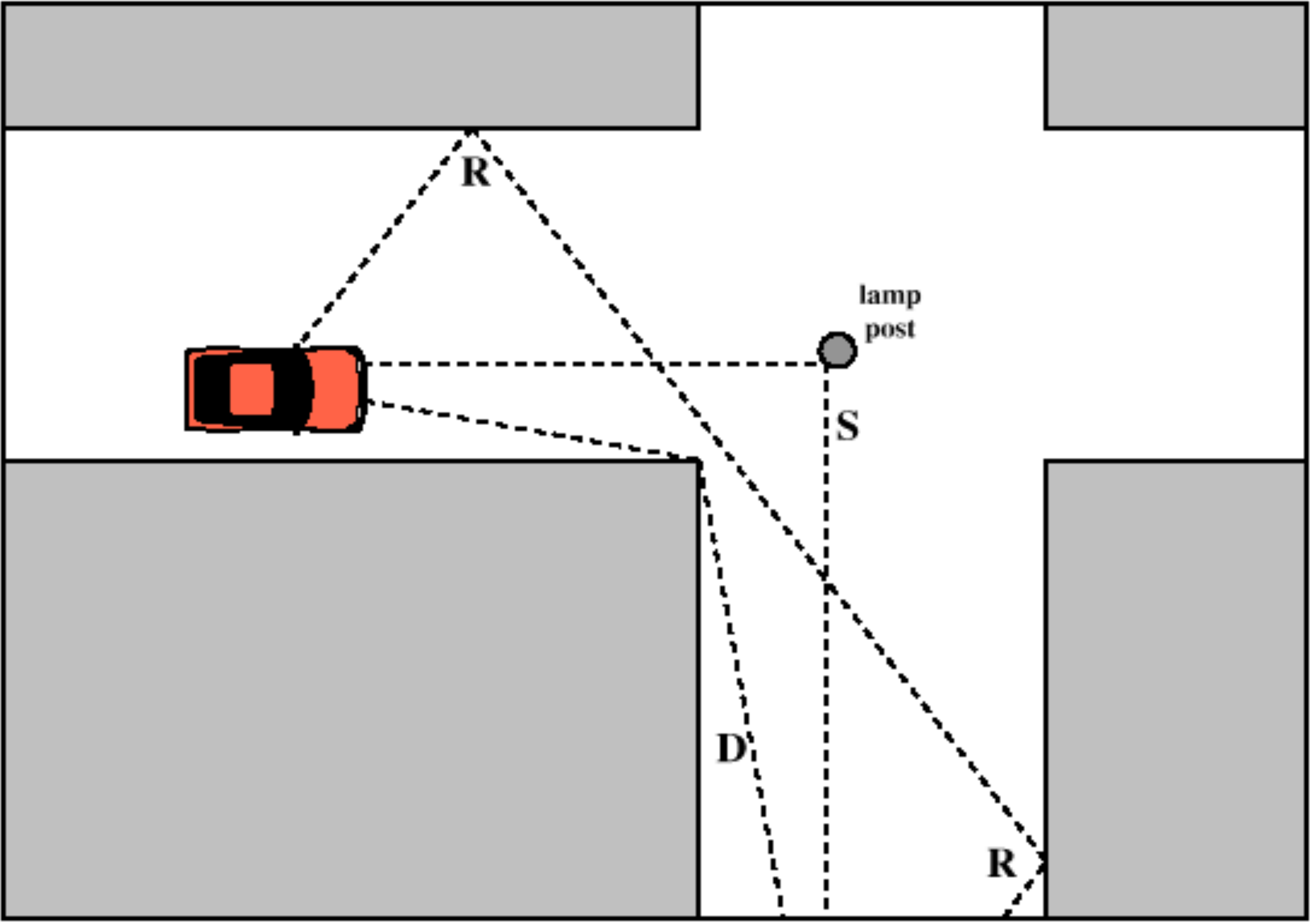


Wireless Link Characteristics

Differences from wired link ….

- decreased signal strength: radio signal attenuates as it propagates through matter (path loss)
- interference from other sources: standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors) interfere as well
- multipath propagation: radio signal reflects off objects ground, arriving ad destination at slightly different times

… make communication across (even a point to point) wireless link much more "difficult"



$$\lambda = C / f$$

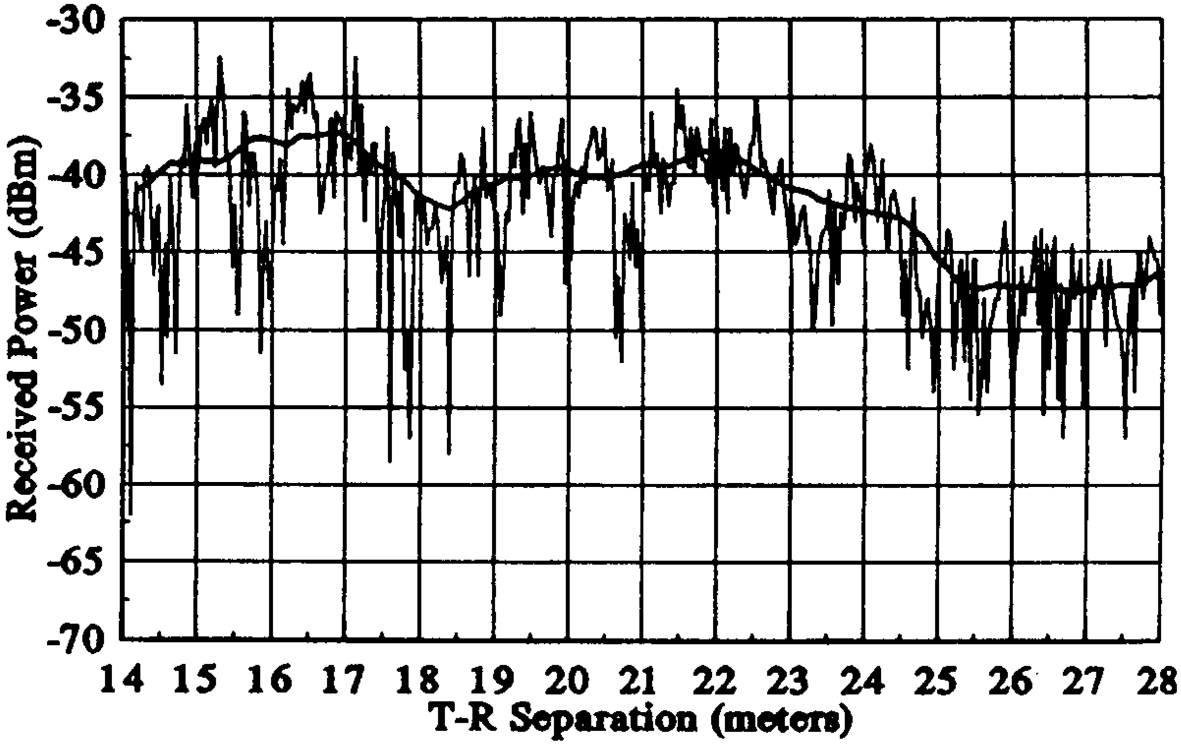
Ex: 3e8/2.4e9 = 12.5cm

R: reflection

D: diffraction -- a modification which light undergoes especially in passing by the edges of opaque bodies or through narrow openings

S: scattering -- obstacle << wave length

Radio Propagation Models



How to characterize the signal at the receiver?

-Transmitter, receiver, environment, time

- Large scale, small scale

Large scale Propagation

- Large scale models predict behavior averaged over distances >> λ
  - Function of distance & significant environmental features, roughly frequency independent
  - Breaks down as distance decreases
  - Useful for modeling the range of a radio system and rough capacity planning

Small Scale Propagation Model

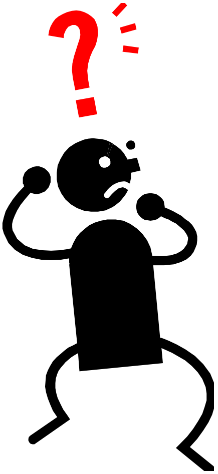
- Small scale (fading) models describe signal variability on a scale of λ
  - Multipath effects (phase cancellation) dominate, path attenuation considered constant
  - Frequency and bandwidth dependent
  - Focus is on modeling "Fading": rapid change in signal over a short distance or length of time.

Large-scale Models

- Path loss models
  - Free space
  - Log-distance
  - Log-normal shadowing
- Outdoor models
  - “2-Ray” Ground Reflection model
  - Diffraction model for hilly terrain
- Indoor models

Free-space Path Loss Model

- Friis free space equation:
  - G_t, G_r are the antenna gains at the transmitter and receiver
  - λ is the wavelength
  - d is the distance
  - L is a loss factor not related to propagation
  - Transmission power Pt
  - Received power



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

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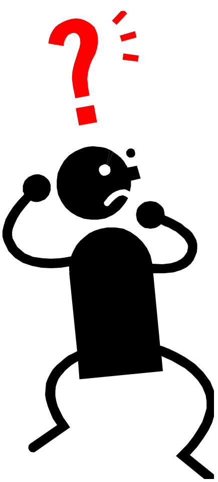
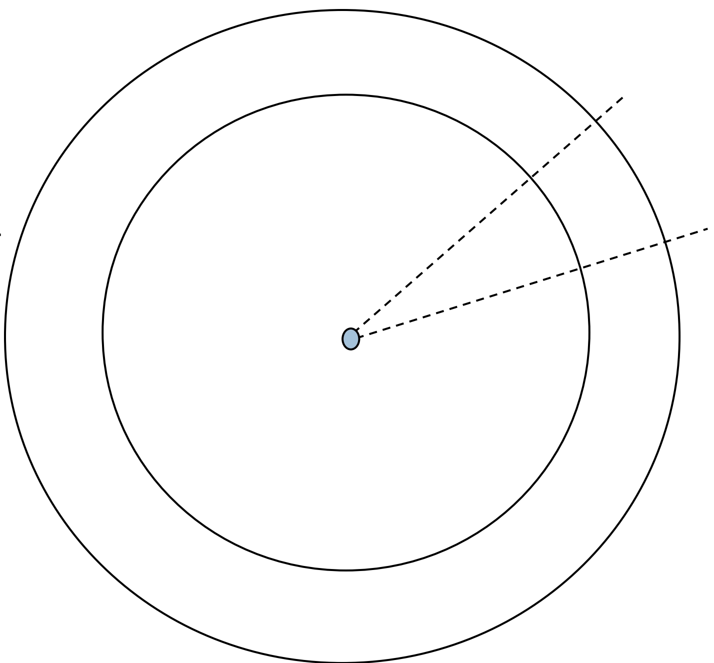


$$E_r(f,t) = \frac{\alpha \cos 2\pi f(t - d/c)}{d}$$

$$P_r(d) \propto E_r^2(f,t)$$



Free Space Model

- Path loss $$P_r(d) = P_r(d_0)(\frac{d_0}{d})^2, d \geq d_0 \geq d_f$$

$$PL(dB) = 10\log\frac{P_t}{P_r} = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right]$$

- Only valid beyond far-field distance

$$d_f = \frac{2D^2}{\lambda}$$, where D is the transmit antenna aperture

$$d_f >> D, d_f >> \lambda$$

dB = 10 log(P2/P1), use to represent power ratio; P1 is called the power reference.

dBm indicates dB refers to P1 = 1mW

dBW indicated dB refers to P1 = 1W

Example: 0dBW = 1W = 30dBmW = 1000mW

Example

- Far field distance for an antenna with maximum dimension of 1m and operating freq of 900MHz
- Consider a transmitter producing 50w of power and with a unity gain antenna at 900MHz. What is the received power in dBm at a free space distance of 100? What about 10Km?

Example

- Far field distance for an antenna with maximum dimension of 1m and operating freq of 900MHz

$$d_f = \frac{2D^2}{\lambda} = \frac{2}{3\times10^8/900\times10^6} = 6m$$

- Consider a transmitter producing 50w of power and with a unity gain antenna at 900MHz. What is the received power in dBm at a free space distance of 100? What about 10Km? (assume L =1)

$$P_t = 10\log(50\times10^3) = 47dBm$$

$$P_r(100) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} = 3.5\times10^{-3} mW = -24.5dBm$$

$$P_r(10km) = -24.5 - 20\log(100) = -64.5dBm$$

Log-distance Path Loss Model

- Log-distance generalizes path loss to account for other environmental factors

$$PL(d)[dB] = PL(d_0) + 10\beta \log(d / d_0)$$

  - Choose a d_0 in the far field.
  - Measure $PL(d_0)$
  - Take measurements and derive β empirically

Table 4.2 Path Loss Exponents for Different Environments

Environment	Path Loss Exponent, *n*
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Log-normal Shadowing

- Shadowing occurs when objects block light of sight (LOS) between transmitter and receiver

$$PL(d)[dB] = \overline{PL}(d) + X_\sigma = \overline{PL}(d_0) + 10\beta \log(\frac{d}{d_0}) + X_\sigma$$

X_σ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (also in dB)

Building Type	Frequency of Transmission	γ	σ [dB]
Vacuum, infinite space		2.0	0
Retail store	914 MHz	2.2	8.7
Grocery store	914 MHz	1.8	5.2
Office with hard partition	1.5 GHz	3.0	7
Office with soft partition	900 MHz	2.4	9.6
Office with soft partition	1.9 GHz	2.6	14.1
Textile or chemical	1.3 GHz	2.0	3.0
Textile or chemical	4 GHz	2.1	7.0, 9.7
Metalworking	1.3 GHz	1.6	5.8
Metalworking	1.3 GHz	3.3	6.8

Ground Reflection (Two-Ray) Model

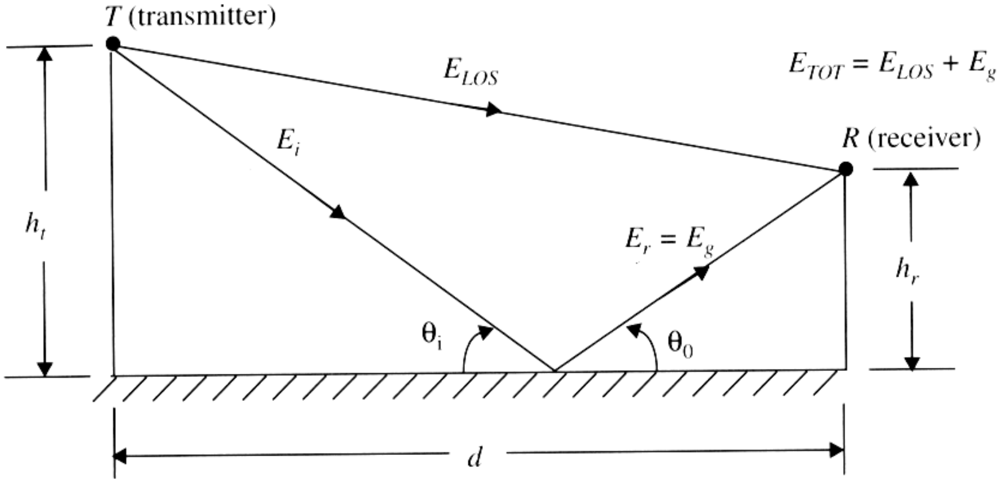


Figure 4.7 Two-ray ground reflection model.

$$E_r(f,t) = \frac{\alpha \cos 2\pi f (t - d'/c)}{d'} - \frac{\alpha \cos 2\pi f (t - d''/c)}{d''}$$

$$\Delta = d'' - d' = \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2} \approx \frac{2 h_t h_r}{d},$$

when d is large compared to $h_t + h_r$

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}, \text{ for d} > \frac{20\pi h_t h_r}{3\lambda}$$

Example

- A mobile is located at 10Km away from a base-station transmitting 50W. Both antennas are unit gain at height 50m and 1.5m respectively. By the ground reflection model, what is the received signal power at the mobile?

Example

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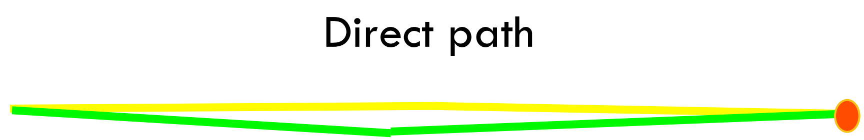
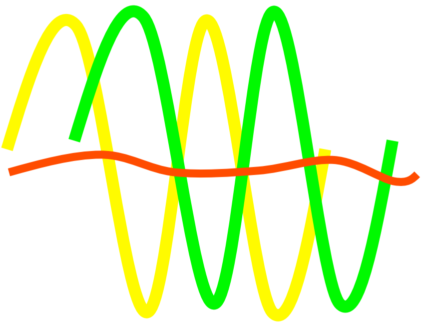
$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} = 50 \times \frac{(1.5 \times 50)^2}{10000^4} = 2.8 \times 10^{-11} W = -100.55 dBW = -74.55 dBm$$

Small-scale Fading

- Factors that contribute to small-scale fading
  - Multi-path propagation -- phase cancellation etc.
  - Speed of the mobile -- Dopler effect
  - Speed of surrounding objects
  - The transmission bandwidth of the signal wrt bw of the channel

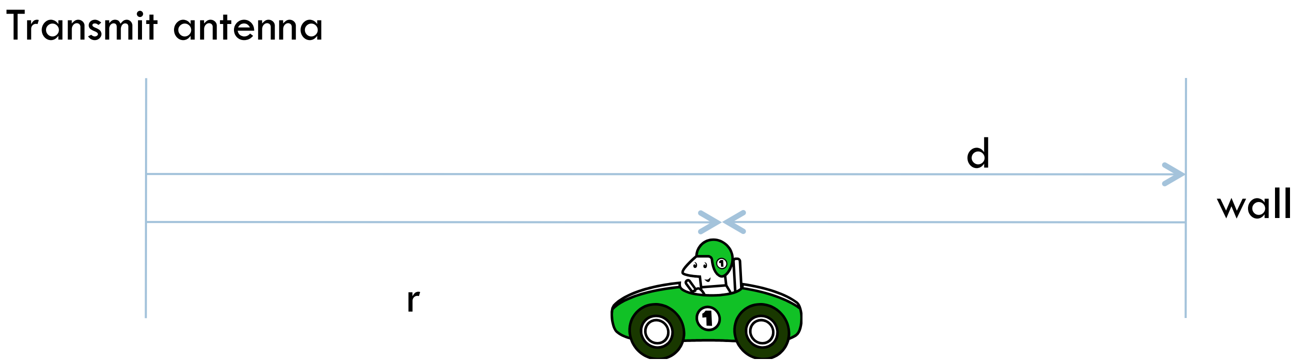
Multipath Causes Phase Difference





Green signal travels $1/2\lambda$ farther than Yellow to reach receiver, who sees Red. For 2.4 GHz, λ (wavelength) =12.5cm.

Reflecting wall, fixed antenna



$$E_r(f,t) = \frac{\alpha \cos 2\pi f(t - r/c)}{r} - \frac{\alpha \cos 2\pi f(t-(2d-r)/c)}{2d-r}$$

$$\text{Phase difference: } \Delta\theta = \frac{4\pi f}{c}(d-r) + \pi$$

Doppler Shift

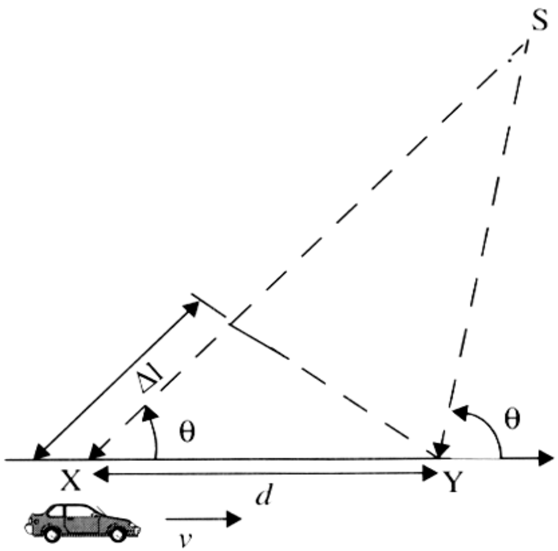
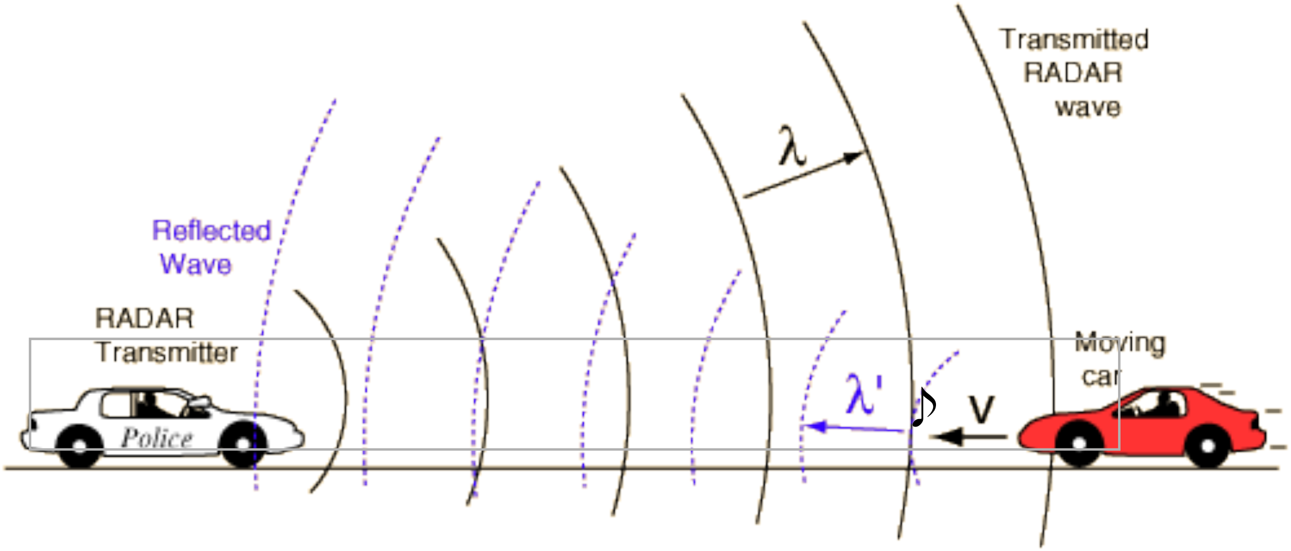


Figure 5.1 Illustration of Doppler effect.

$$E_r(f,t) = \frac{\alpha \cos 2\pi f\left(t + \frac{v\cos\theta}{c}t + t_0\right)}{r}$$

$$f' = \frac{1}{2\pi}\frac{\Delta\phi}{\Delta t} = f + \frac{v}{\lambda}\cos\theta, f_d = \frac{v}{\lambda}\cos\theta$$

Example: Police Radar



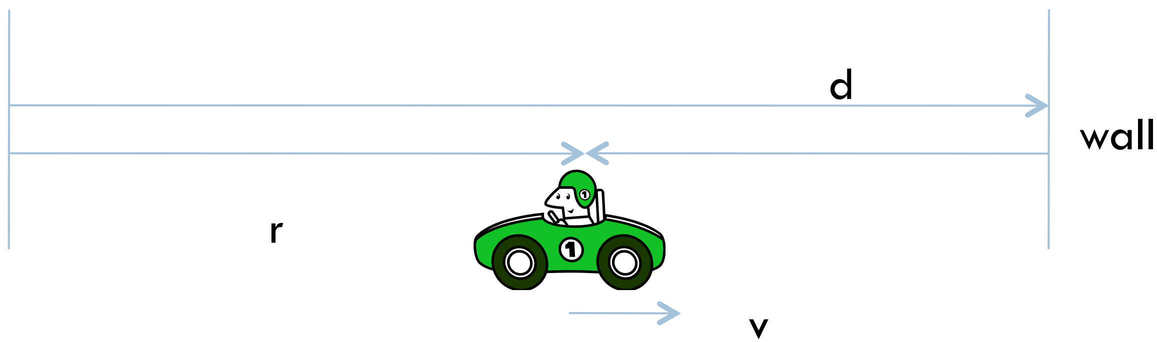
$$f_{reflected} - f_{transmitted} = \Delta f = \frac{2v_{target}}{\lambda}$$

$$f = 900\,MHz, \lambda = 0.333m, v = 60\,Km/hr$$

$$\Delta f = 100\,Hz$$

Reflecting wall, moving antenna

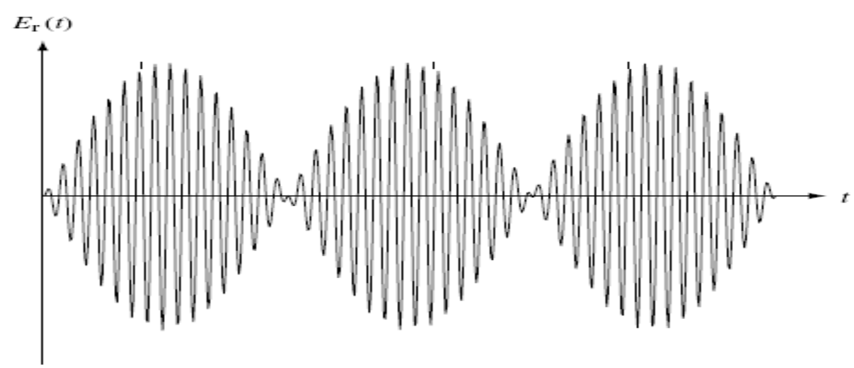
Transmit antenna



$$E_r(f,t) = \frac{\alpha \cos 2\pi f(t - r/c - vt/c)}{r + vt} - \frac{\alpha \cos 2\pi f(t - (2d - r - vt)/c)}{2d - r - vt}$$

$$\approx \frac{2\alpha \sin 2\pi f[vt/c + (r-d)/c] \sin 2\pi f[t - d/c]}{\mathrm{r} + \mathrm{vt}}$$

Dopler spread: $D_s = 2fv/c$



Statistical Fading Models

- Fading models model the probability of a fade occurring at a particular location
  - Used to generate an impulse response
  - In fixed receivers, channel is *slowly* time-varying; the fading model is reevaluated at a rate related to motion

Common Distributions

- Rayleigh fading distribution
  - Models a flat fading signal
  - Used for individual multipath components
- Ricean fading distribution
  - Used when there is a dominant signal component, e.g. LOS + weaker multipaths
  - parameter K (dB) defines strength of dominant component; for $K=-\infty$, equivalent to Rayleigh

Rayleigh fading

- Models a flat fading channel or an individual multipath component

$$p(r) = \frac{r}{\sigma^2}\exp(-\frac{r^2}{2\sigma^2})$$

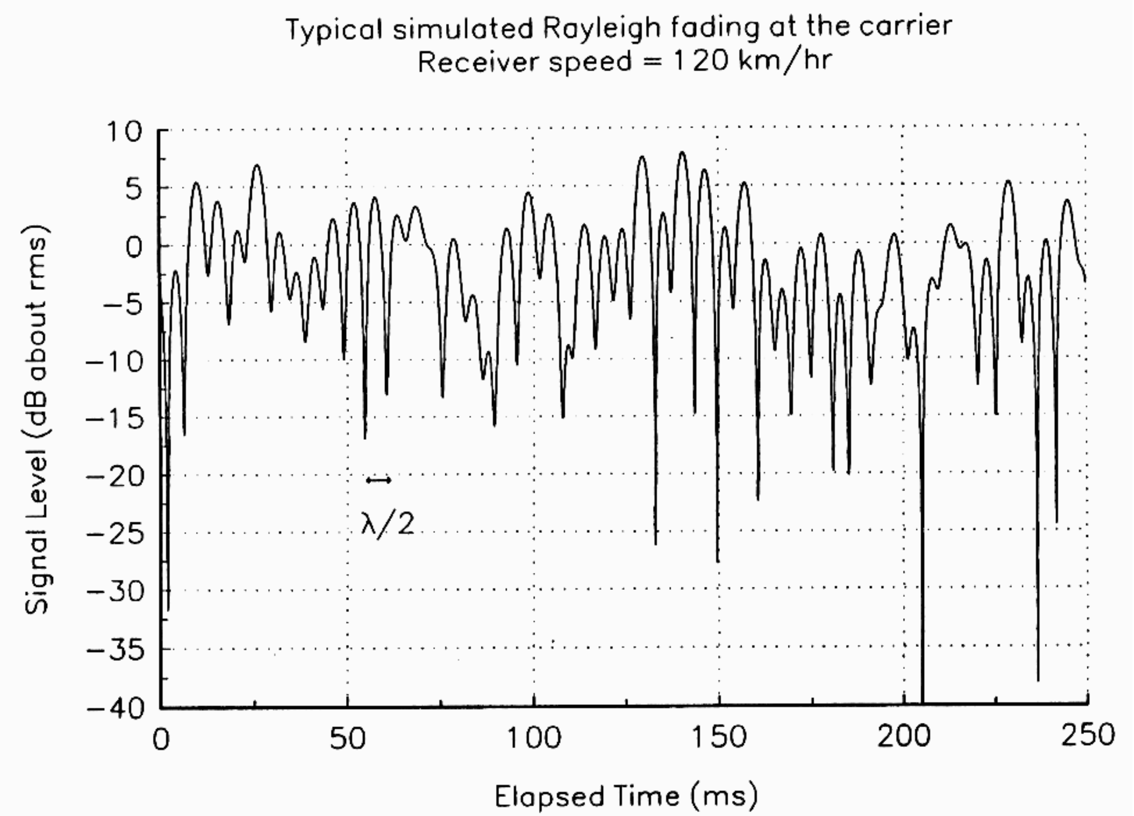
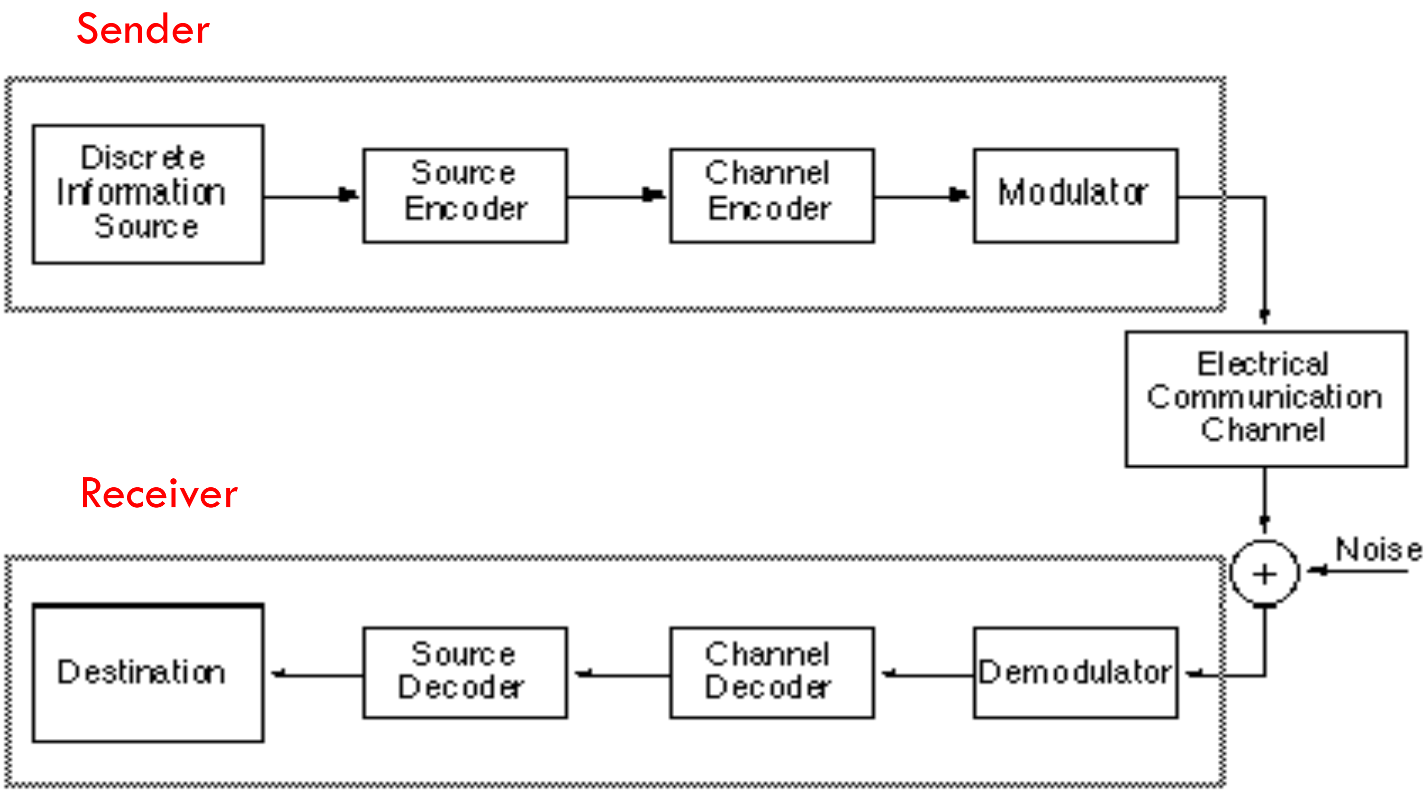
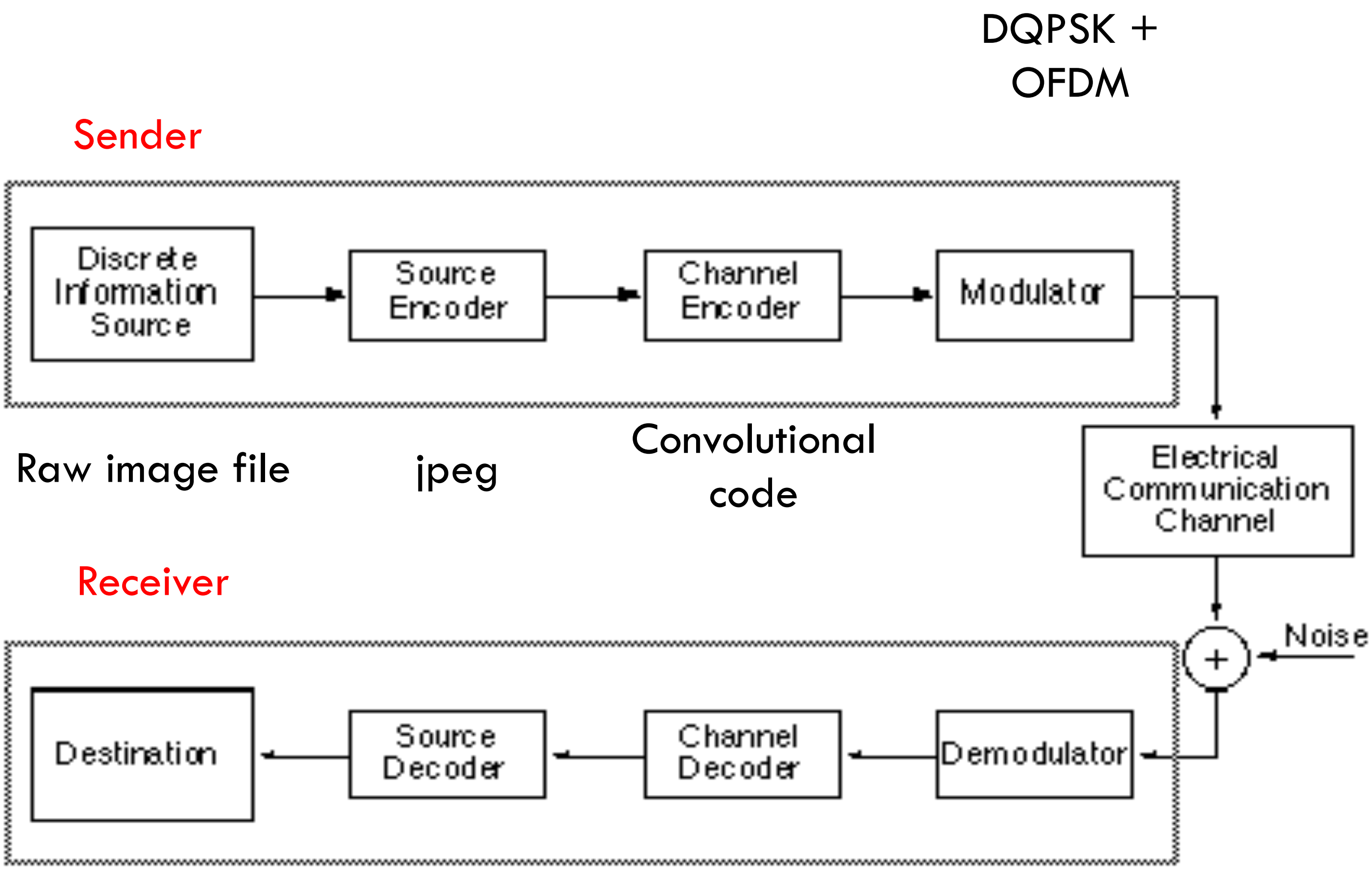


Figure 5.15 A typical Rayleigh fading envelope at 900 MHz [from [Fun93] © IEEE].

Principle of digital communication



Principle of digital communication

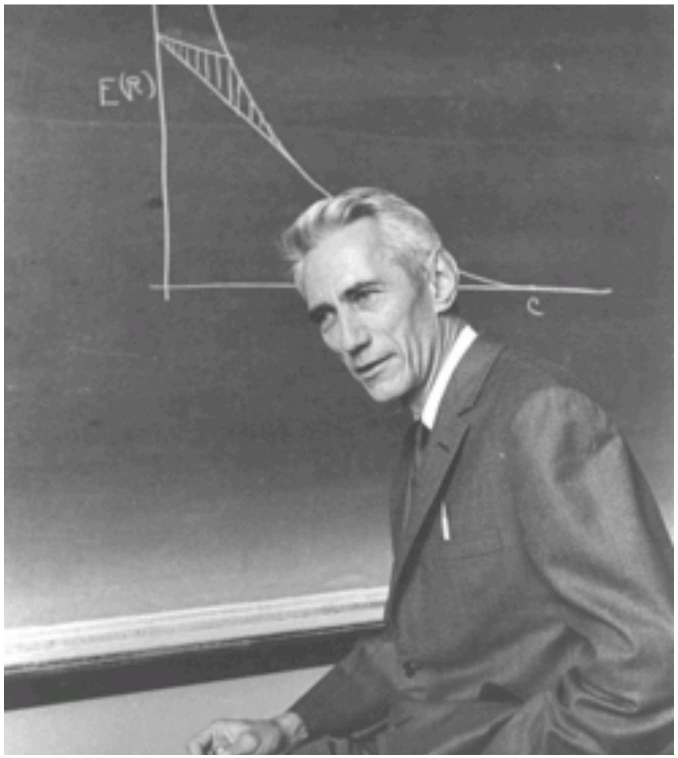


How 802.11ac can be so fast?

1985	1988	1997	2003	2012
FCC allows the license free use of ISM bands (2.4 GHz, 900 MHz and 5.8 GHz)	*802.11 Committee is created*	*802.11 standard is finalized 2 Mbps*	*802.11 g standard is finalized 54 Mbps (OFDM*	*802.11ac 6.93Gbps; 1.3Gbps products available*

Evolution of WiFi

Shannon capacity



$$C = B \log_2\left(1 + \frac{P_s}{N_o B}\right)$$

C is the capacity in bits per second, B is the bandwidth in Hertz, P_s is the signal power and N_0 is the noise spectral density.

Example

- B = 1MHz
- Pr= -94.26dBm, N_0= -160dBm, SNR = 5.74dB

- B = 1MHz
- Pr= -64.5dBm, N_0= -160dBm, SNR = 35.5dB

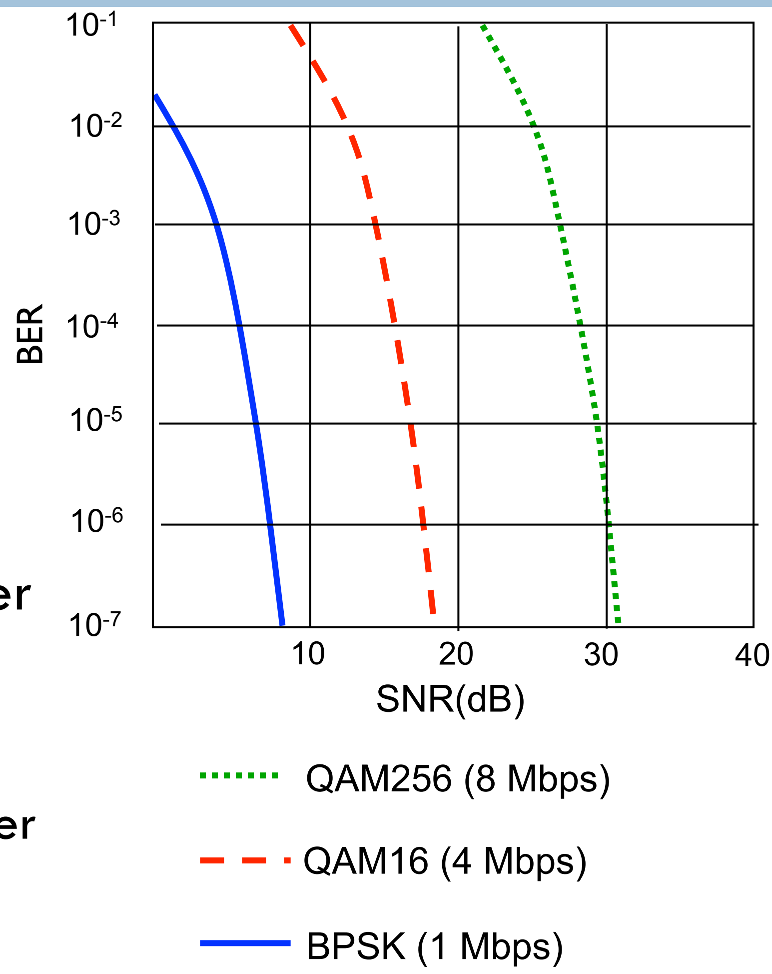
Example

- B = 1MHz
- Pr= -94.26dBm, N_0= -160dBm, SNR = 5.74dB
- C = 2.24Mbps

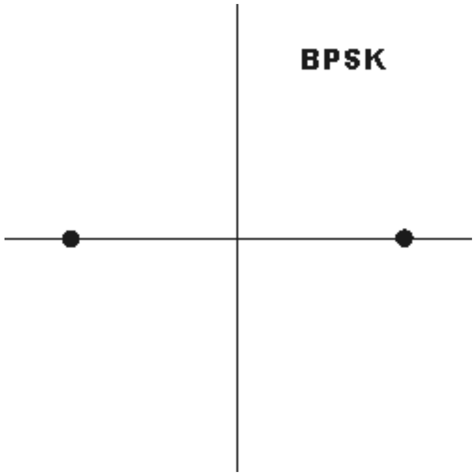
- B = 1MHz
- Pr= -64.5dBm, N_0= -160dBm, SNR = 35.5dB
- C =11.8Mbps

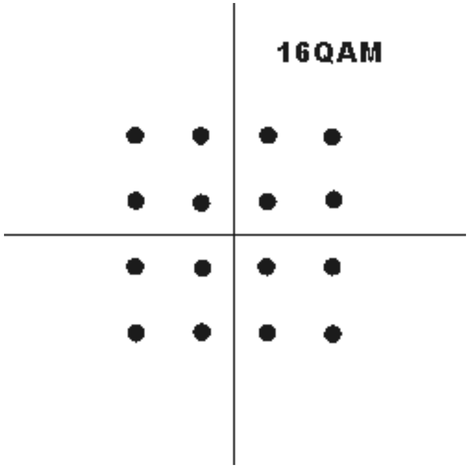
Link Bit Error Rate

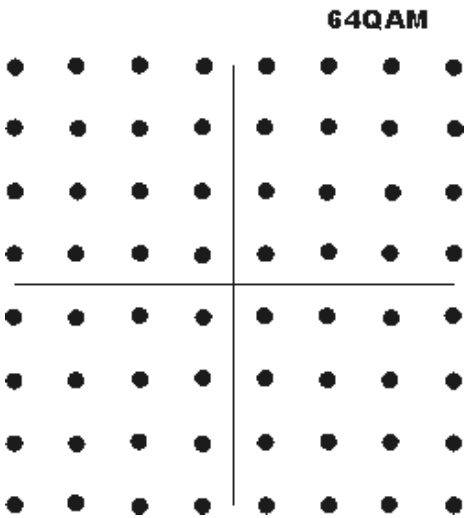
- SNR: signal-to-noise ratio
  - larger SNR – easier to extract signal from noise (a "good thing")
- SNR versus BER tradeoffs
  - given physical layer: increase power -> increase SNR->decrease BER
  - given SNR: choose physical layer that meets BER requirement, giving highest throughput
    - SNR may change with mobility: dynamically adapt physical layer (modulation technique, rate)



Packing More Bits per Symbol

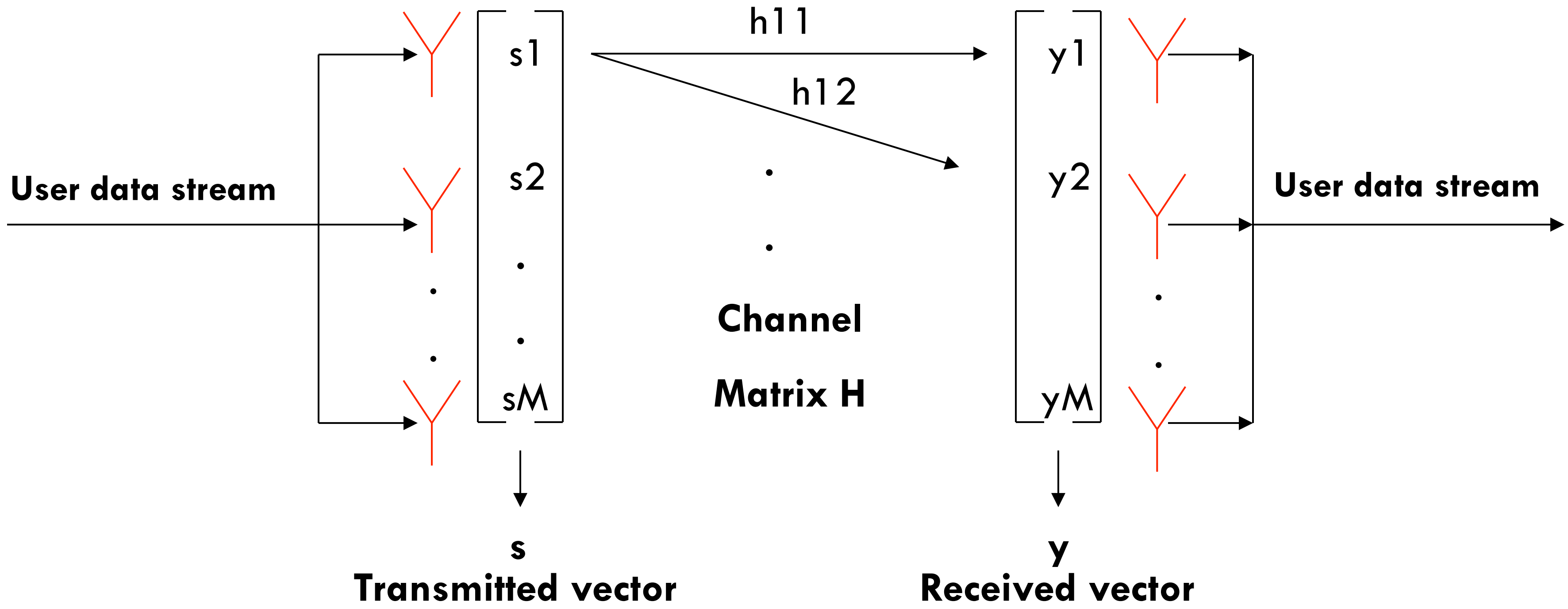






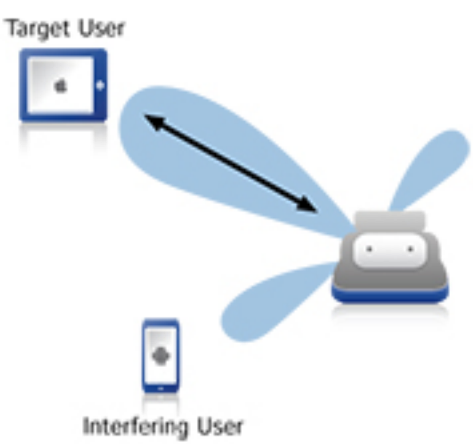
MODULATION	BITS PER SYMBOL	SYMBOL RATE
BPSK	1	1 x bit rate
QPSK	2	1/2 bit rate
8PSK	3	1/3 bit rate
16QAM	4	1/4 bit rate
32QAM	5	1/5 bit rate
64QAM	6	1/6 bit rate

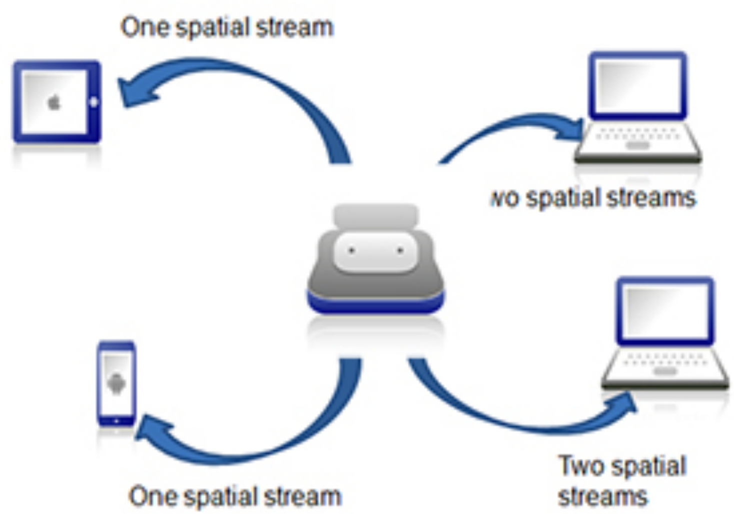
Spatial Diversity in MIMO



The Magic of 802.11ac

	Channel Width			
# Spatial Streams	20 MHz	40 MHz	80 MHz	160 MHz
1	86 Mbps	200 Mbps	433 Mbps	866 Mbps
2	173 Mbps	400 Mbps	866 Mbps	1.73 Gbps
3	288.9 Mbps	600 Mbps	1.3 Gbps	2.34 Gbps
4	346.7 Mbps	800 Mbps	1.73 Gbps	3.46 Gbps





http://www.merunetworks.com/products/technology/80211ac/index.html

Summary

- Efficiency of wireless communication (effective throughput) is determined by many factors including, the channel conditions, bandwidth, transmission power, modulation, number of antennas, etc.
- Though can be treated mostly as a black box from upper layers, it is important to understand the factors that contribute to the capacity of the wireless link