MSIT 413: Wireless Technologies

Week 3

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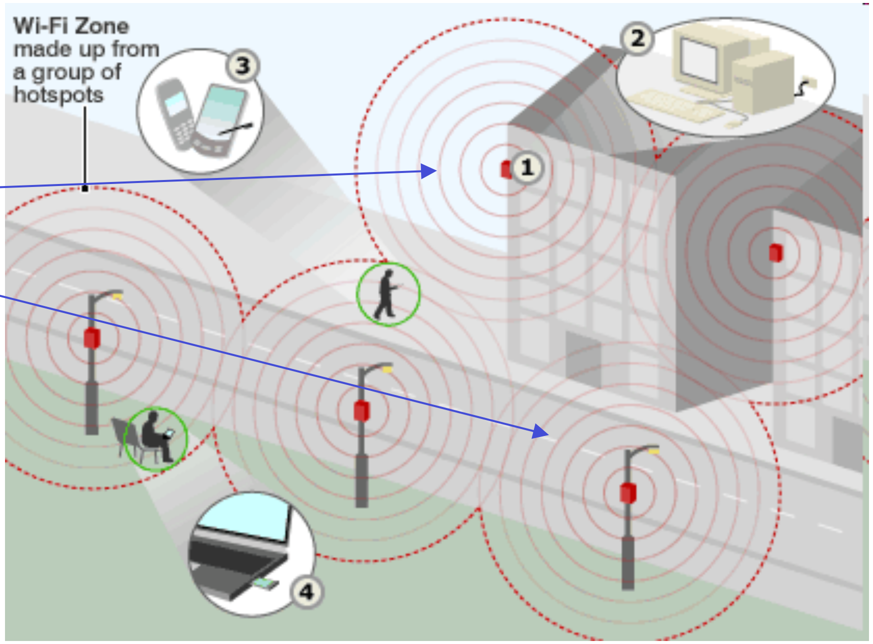
Why Study Radio Propagation?

- To determine coverage

Can we use the same channels?



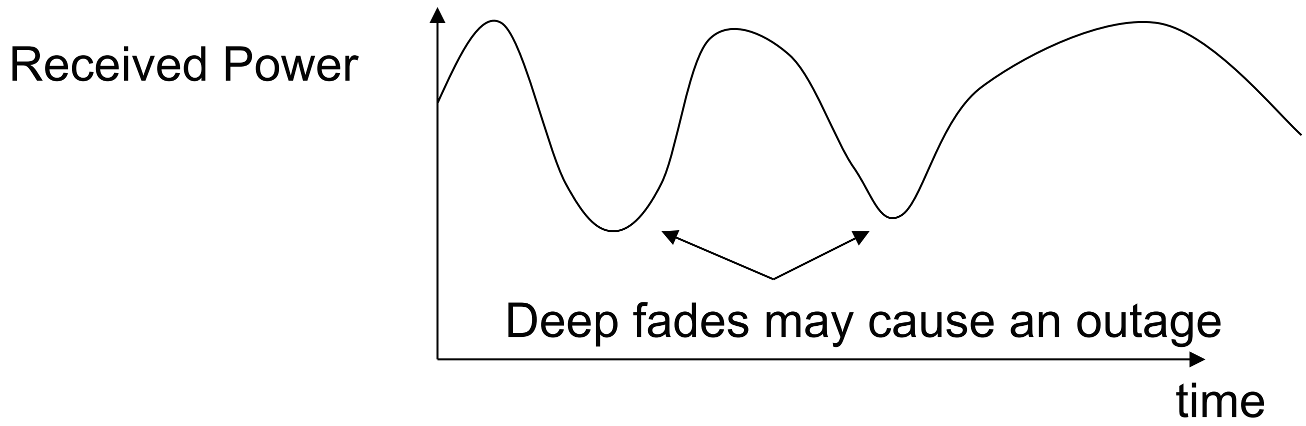
- Must determine path loss
  - Function of
    - Frequency
    - Distance
    - Terrain (office building, urban, hilly, rural, etc.)

Need "large-scale" models

Why Study Radio Propagation?

Why Study Radio Propagation?

- To enable robust communications



- How can we guarantee reliable communications?
- What data rate can we provide?
- Must determine signal statistics:
  - Probability of outage
  - Duration of outage

Need "small-scale" models

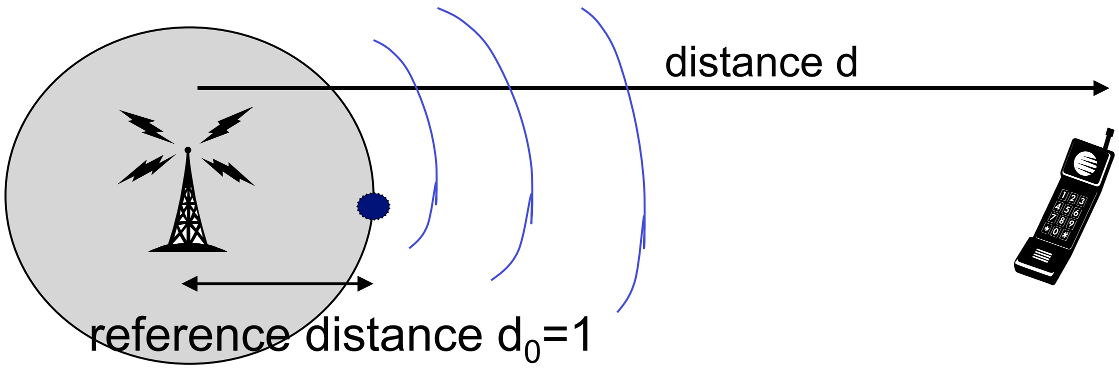
Will provide answers to…

- What are the major causes of attenuation and fading?
- Why does the achievable data rate decrease with mobility?
- Why are wireless systems evolving to wider bandwidths (spread spectrum and OFDM)?
- Why does the accuracy of location tracking methods increase with wider bandwidths?

Propagation Key Words

- Large-scale effects
  - Path-loss exponent
  - Shadow fading
- Small-scale effects
  - Rayleigh fading
  - Doppler shift and Doppler spectrum
  - Coherence time / fast vs slow fading
- Narrowband vs wideband signals
- Multipath delay spread and coherence bandwidth
- Frequency-selective fading and frequency diversity

Propagation Mechanisms: 1. Free Space

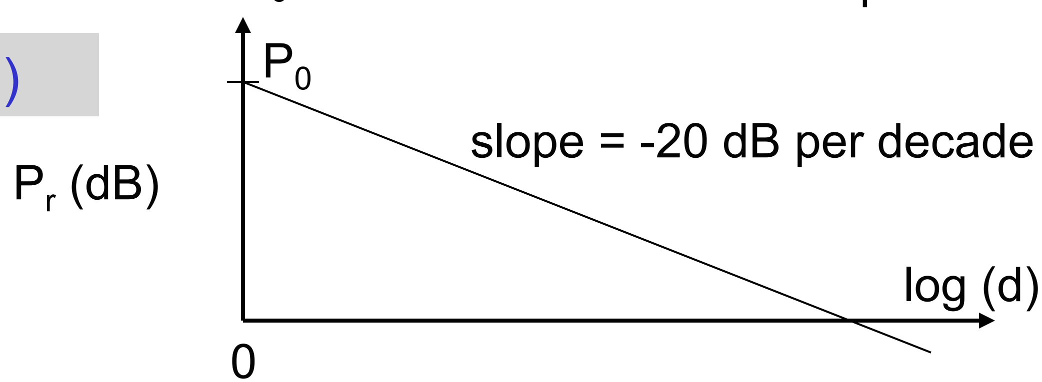


Received power $P_r \approx P_0 \left(\frac{d}{d_0}\right)^{-n}$

Reference power at reference distance d_0

Path loss exponent=2

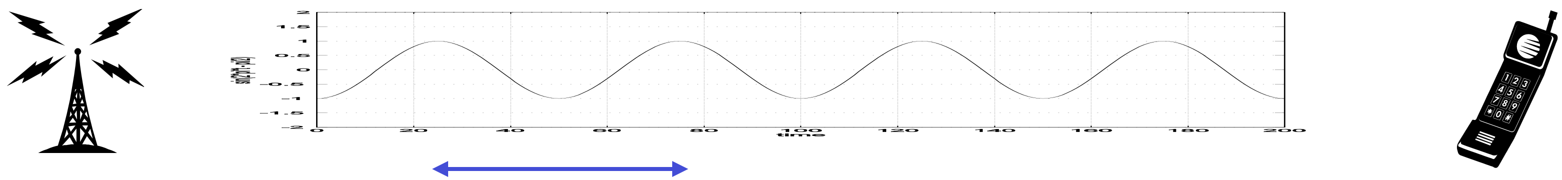
In dB: $P_r = P_0$ (dB) – 20 log (d)



$P_0 = G_t \, G_r \, (\lambda/4\pi)^2$

antenna gains   wavelength

Wavelength

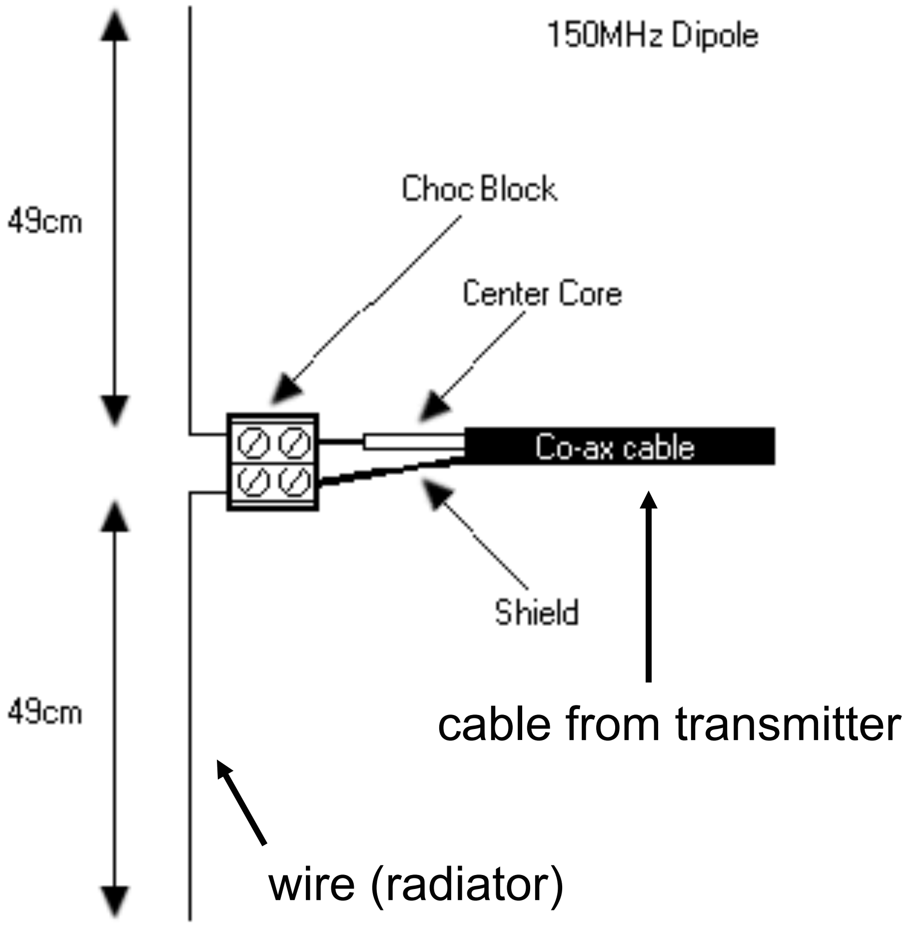


λ (meters) = c (speed of light) / frequency

- Wavelength >> size of object ➔ signal penetrates object.
- Wavelength << size of object ➔ signal is absorbed and/or reflected by object.
- Large-scale effects refers to propagation over distances of many wavelengths.

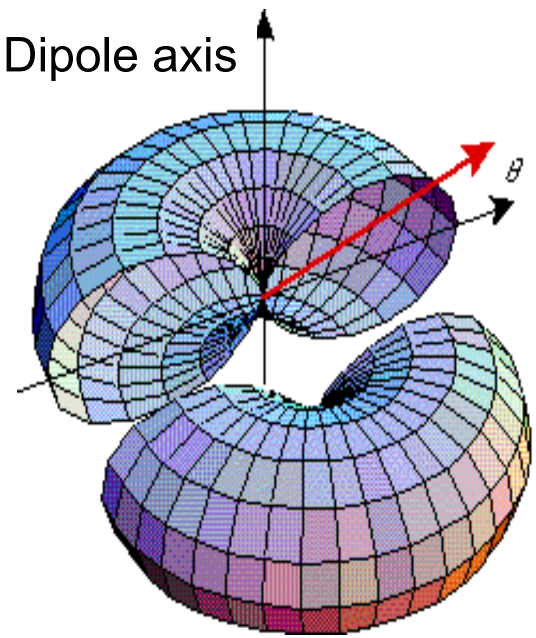
  Small-scale effects refers to propagation over a distances of a fraction of a wavelength.

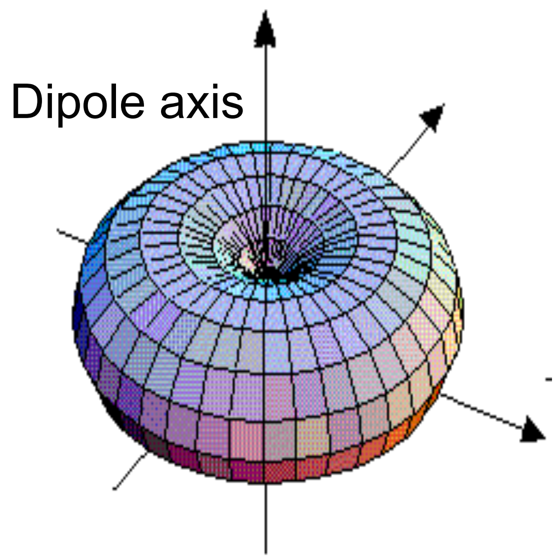
Dipole Antenna

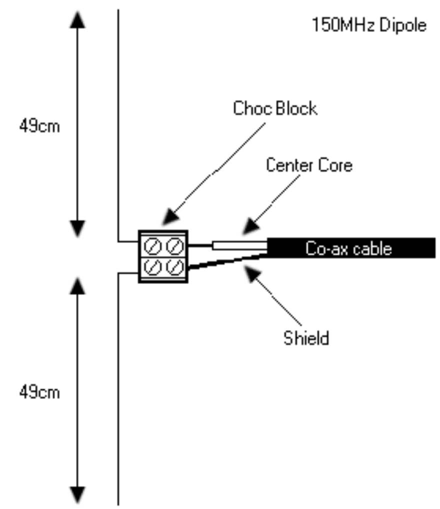


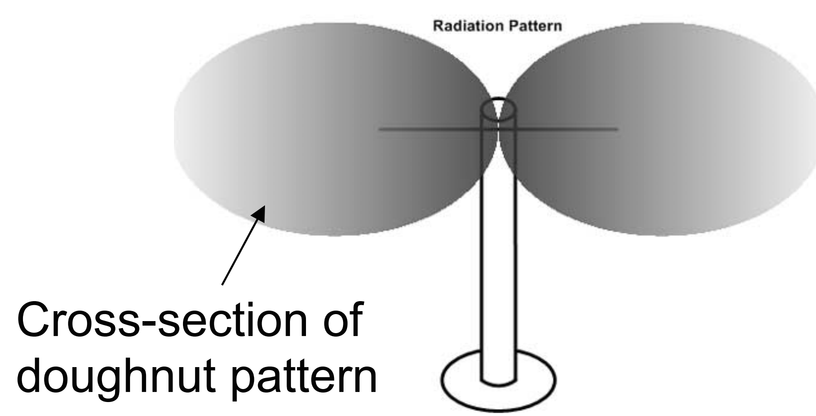
802.11 dipole antenna

Radiation Pattern: Dipole Antenna









Electromagnetic wave radiates out from the dipole axis.

Attenuation: Wireless vs. Wired

Unshielded Twisted Pair

- Path loss ~ 13 dB / 100 m or 130 dB / 1 km
  - Increases linearly with distance
- Requires repeaters for long distances

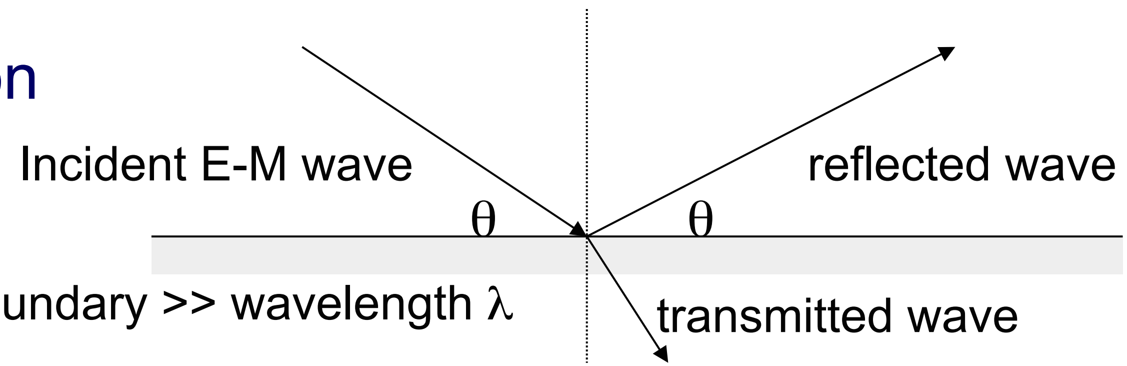
1 GHz Radio (free space)

- Path loss ~ 30 dB for the first meter + 20 dB / decade
  - 70 dB / 100 meters (2 decades)
  - 90 dB / 1 km (3 decades)
  - 130 dB / 100 km!
  - Increases as log (distance)
- Repeaters are infeasible for satellites

Short distance → Wired has less path loss.
Large distance → Wireless has less path loss.

Propagation Mechanisms

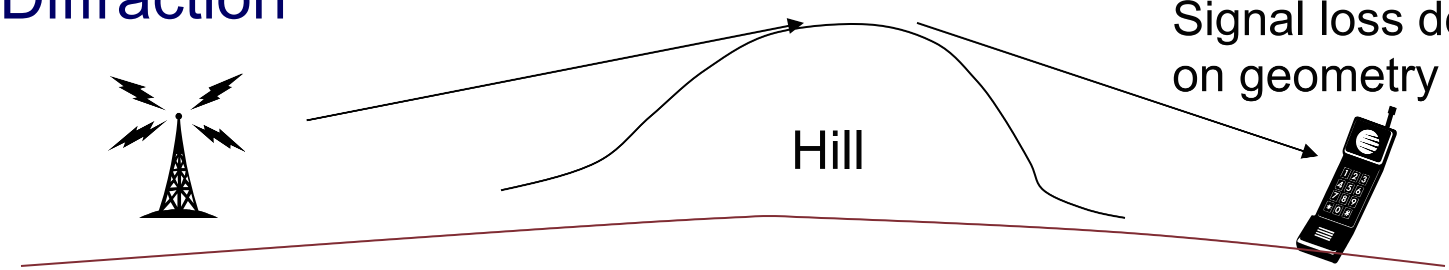
2. Reflection



Length of boundary >> wavelength λ

3. Diffraction

Signal loss depends on geometry



4. Scattering

Why Use > 500 MHz?

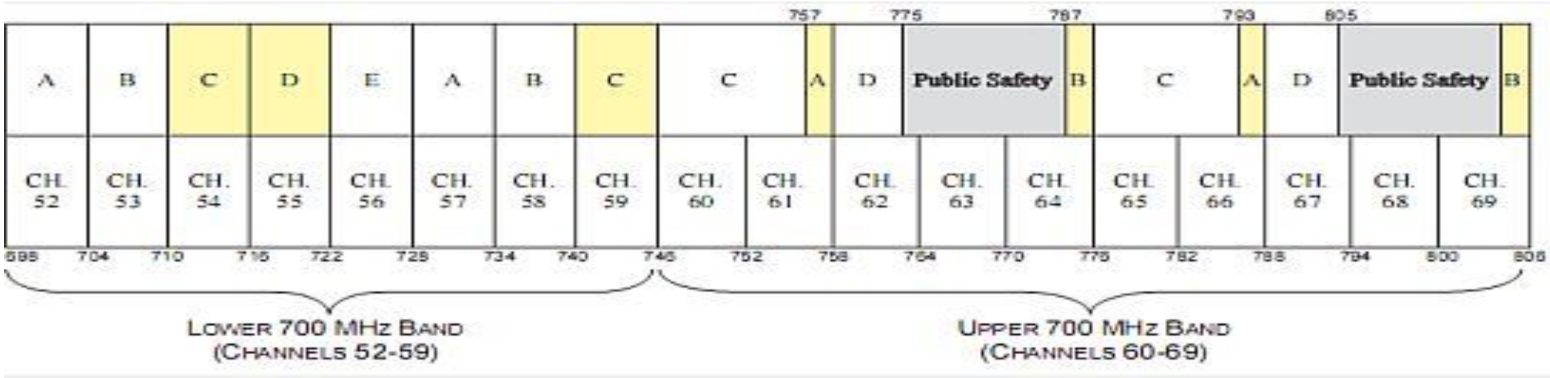
Why Use > 500 MHz?

- There is more spectrum available above 500 MHz.
- Lower frequencies require larger antennas
  – Antenna dimension is on the order of a wavelength = (speed of light/frequency)
  = 0.6 M @ 500 MHz

- Path loss increases with frequency for the first meter
  – 10’s of GHz: signals are confined locally
  – More than 60 GHz: attenuation is too large (oxygen absorbs signal)

700 MHz Auction

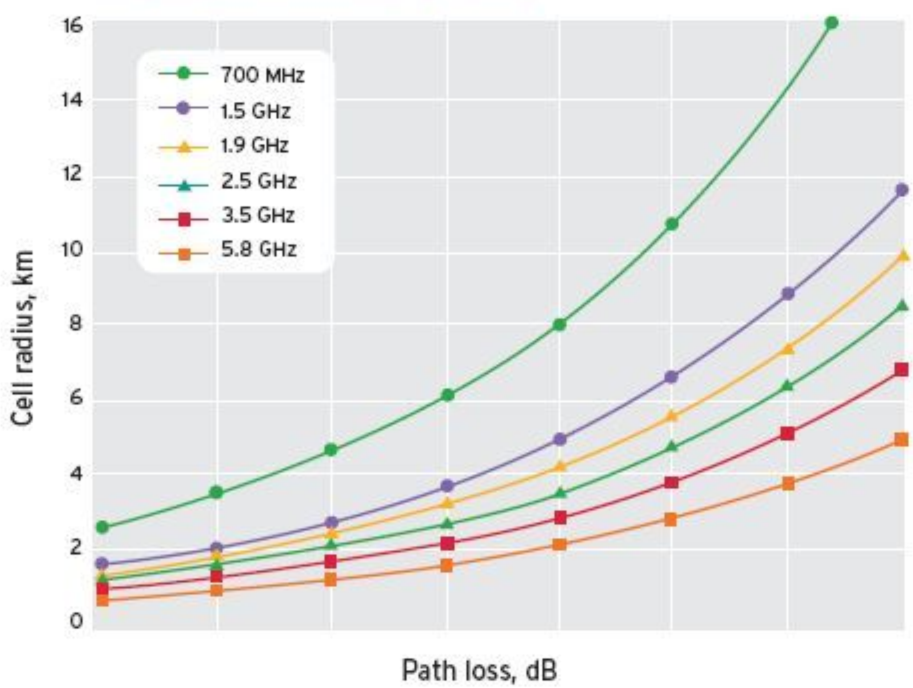
- Broadcast TV channels 52-69 relocated in Feb. 2009.
  - 6 MHz channels occupying 698 – 806 MHz
- Different bands were auctioned separately:
  - “A” and “B” bands: for exclusive use (like cellular bands)
  - “C” band (11 MHz): must support open handsets, software apps
  - “D” band (5 MHz): shared with public safety (has priority)
- Commenced January 24, 2008, ended in March



Why all the Hubbub?

- This band has excellent propagation characteristics for cellular types of services (“beach-front property”).
- Rules for spectrum sharing can be redefined…

Figure 2. Cell radius vs. path loss



700 MHz Offers the Only Affordable Network Solution in Sparsely Populated Areas

	700 MHz Propagation	1900 MHz Propagation	2400 MHz Propagation
Total Network cost @$150k/cell	**$150,000**	**$600,000**	**$1,500,000**
Network Cost per Customer	$180	$725	$1820
# Mos. to Network Cost Breakeven	**9 Months**	**36 Months**	**91 Months**

Cell Site Coverage per thousand square miles

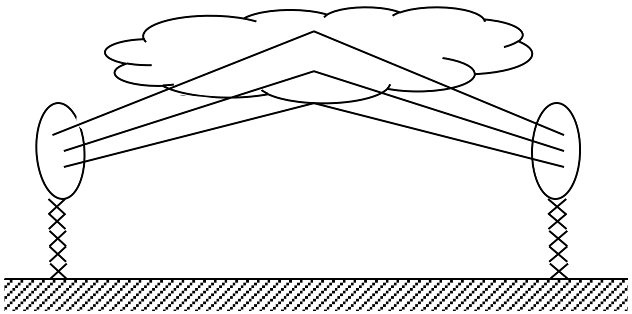
C Band Debate

- Service providers in the U.S. did not allow any services, applications, or handsets from unauthorized 3rd party vendors.
- Google asked the FCC to stipulate that whoever wins the spectrum must support open applications, open devices, open services, open networks (net neutrality for wireless).
- Verizon wants to maintain "walled-garden".
- FCC stipulated open applications and devices, but not open services and networks:
  spectrum owner must allow devices or applications to connect to the network as long as they do not cause harm to the network
- Aggressive build-out requirements:
  - *Significant coverage requirement in four years, which continues to grow throughout the 10-year term of the license.*

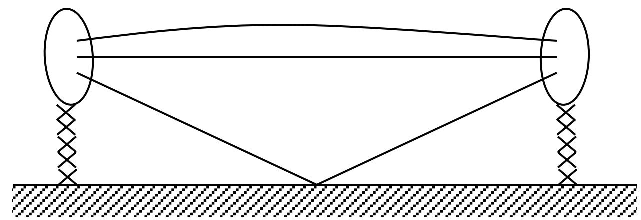
Sold to…

- Verizon
- Other winners: AT&T (B block), Qualcomm (B, E blocks)
- Total revenue: $19.6 B
  - $9.6 B from Verizon, $6.6 B from AT&T
- Implications for open access, competition?

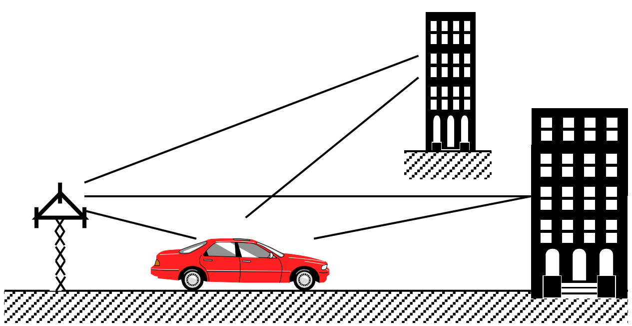
Radio Channels



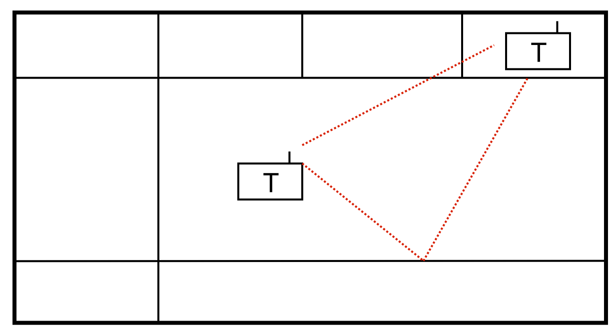
Troposcatter



Microwave LOS



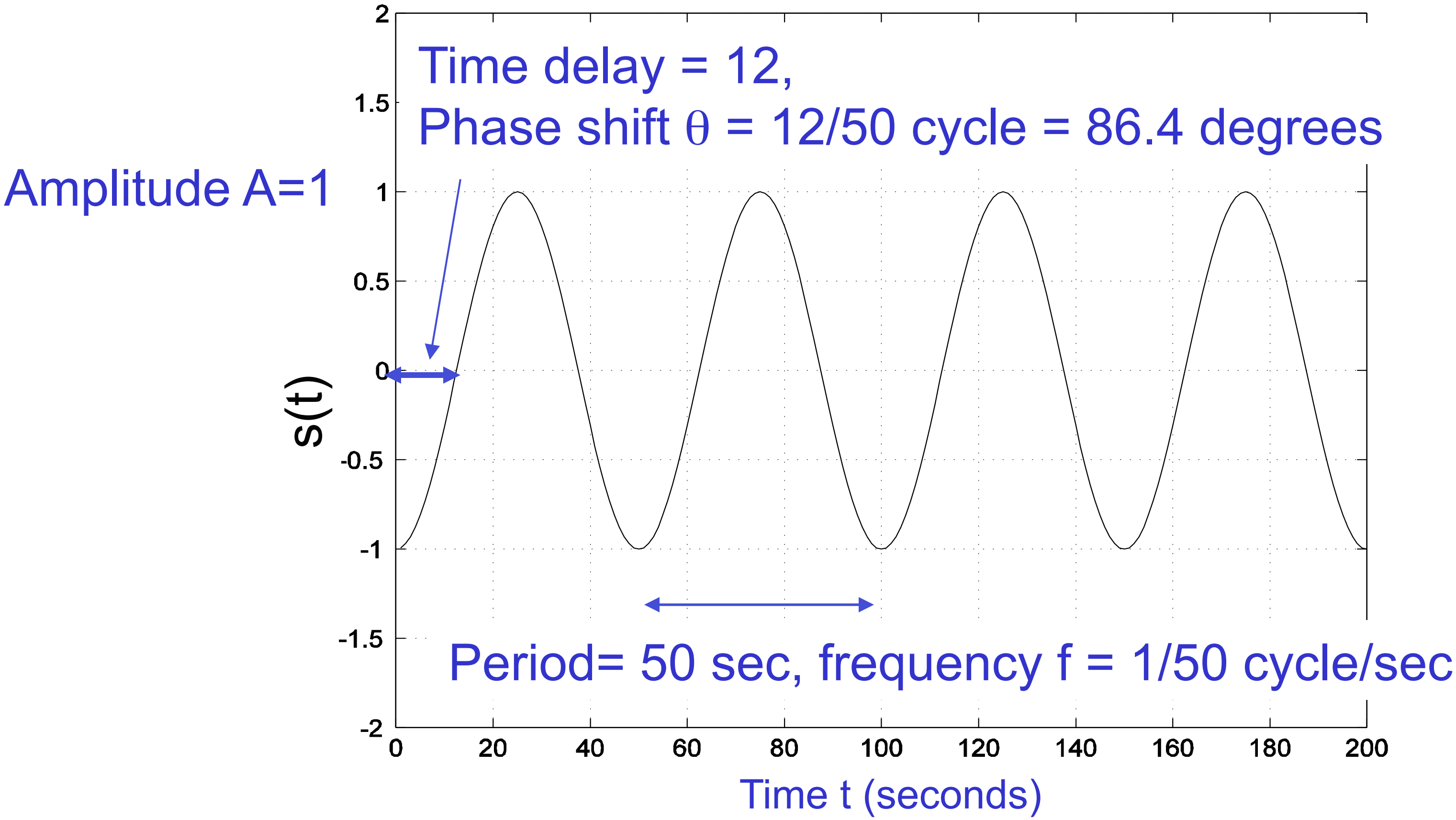
Mobile radio



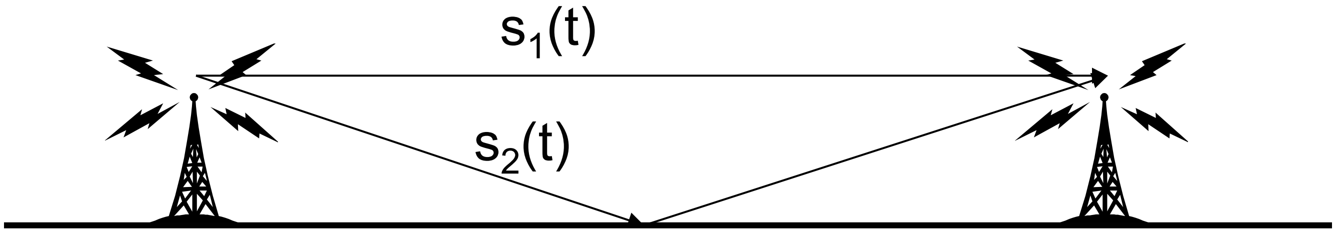
Indoor radio

Sinusoidal Signal

Electromagnetic wave $s(t) = A \sin(2 \pi f t + \theta)$



Two Signal Paths



Received signal $r(t) = s_1(t) + s_2(t)$

Suppose $s_1(t) = \sin 2\pi f\, t$.

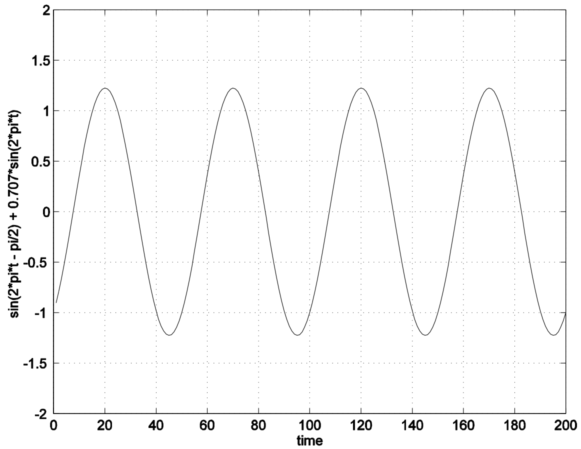
Then $s_2(t) = h\, s_1(t - \tau) = h \sin 2\pi f\,(t - \tau)$

attenuation (e.g., h could be ½)

delay (e.g., τ could be 1 microsec.)

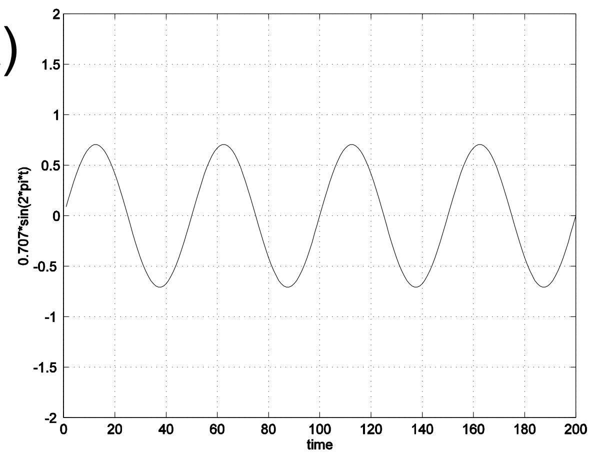
Sinusoid Addition (Constructive)

$s_1(t)$



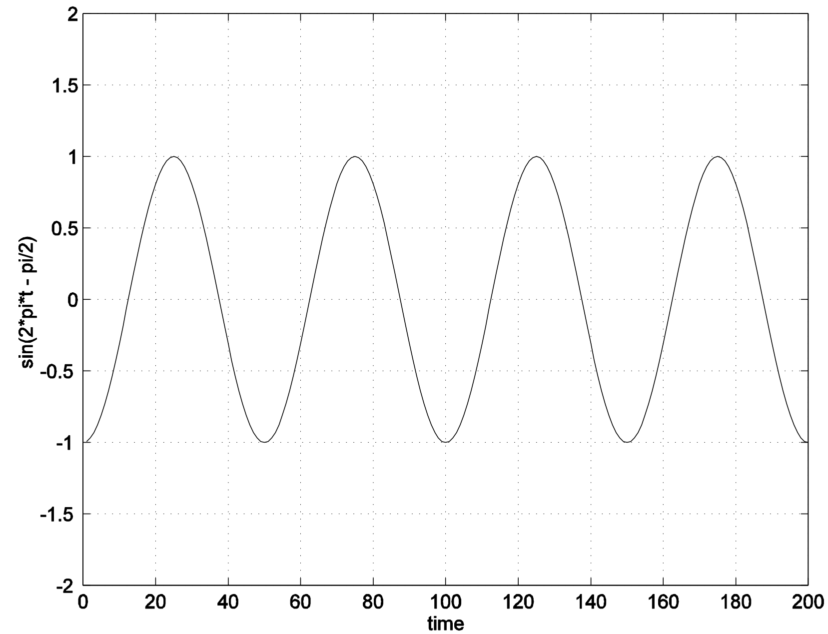
+

$s_2(t)$



=

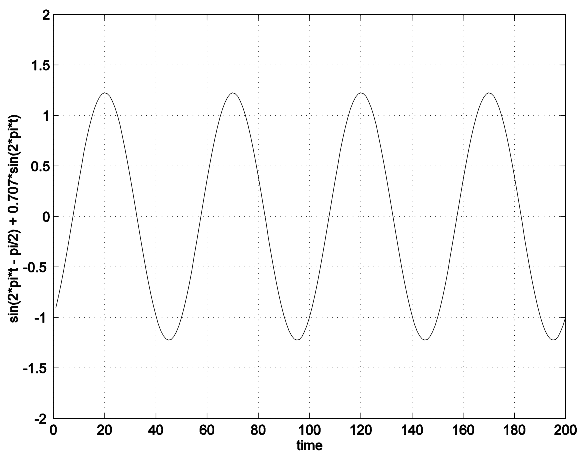
$r(t)$



Adding two sinusoids with the same frequency gives another sinusoid with the same frequency!

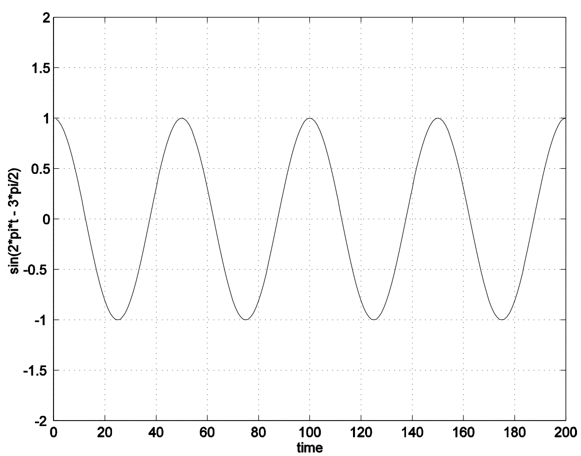
Sinusoid Addition (Destructive)

$s_1(t)$



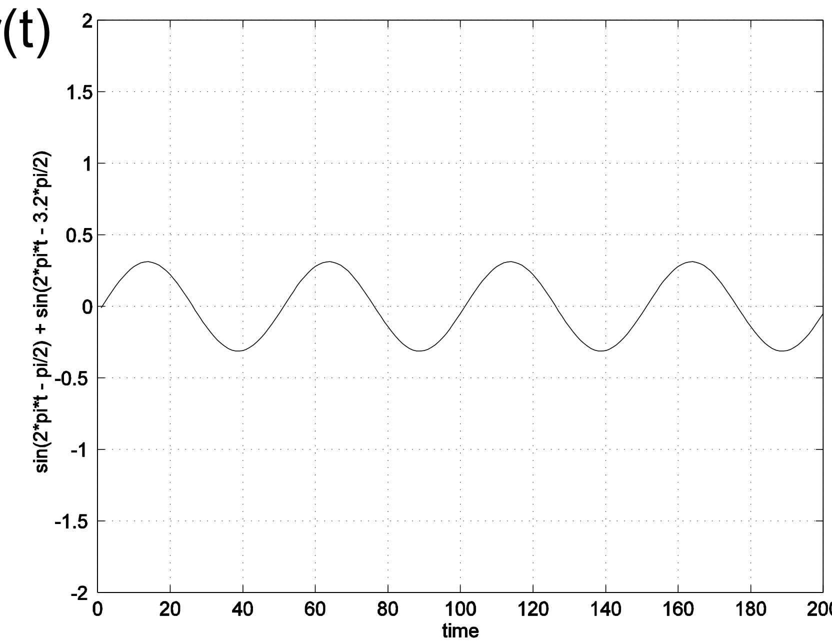
+

$s_2(t)$



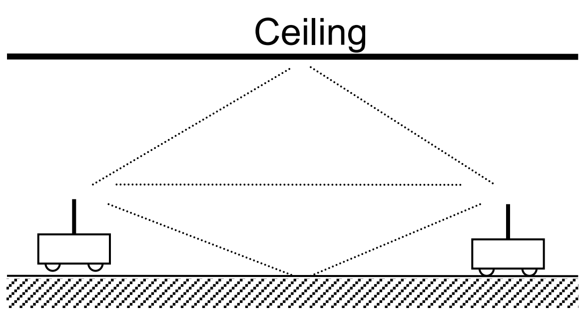
=

$r(t)$

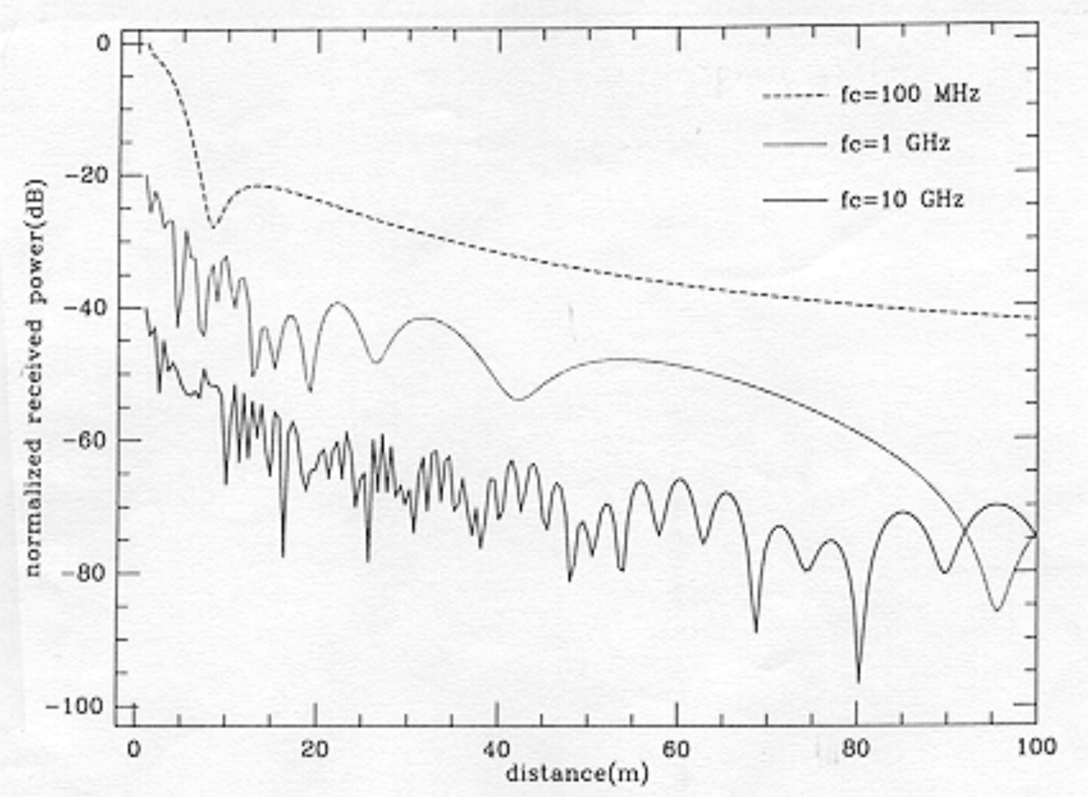


Signal is faded.

Indoor Propagation Measurements

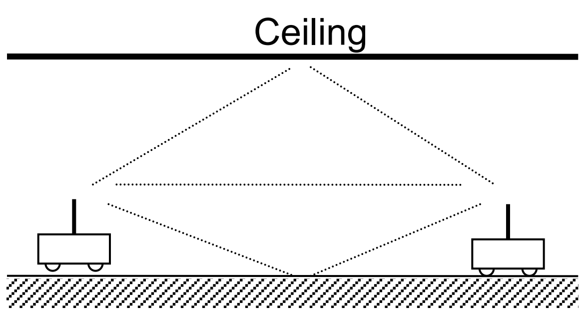


Hypothetical large indoor environment

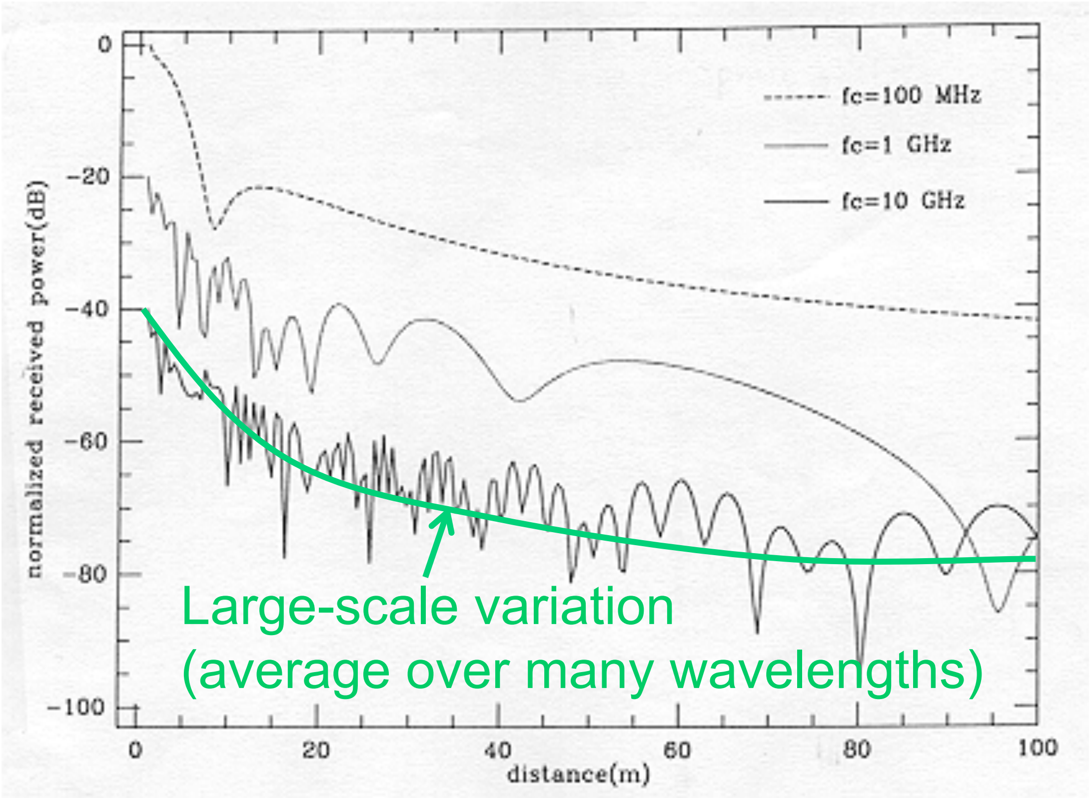


Normalized received power vs. distance

Indoor Propagation Measurements

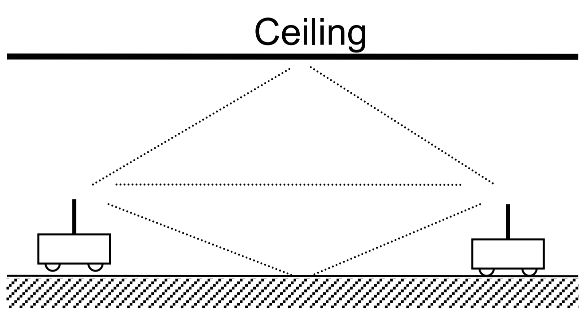


Hypothetical large indoor environment

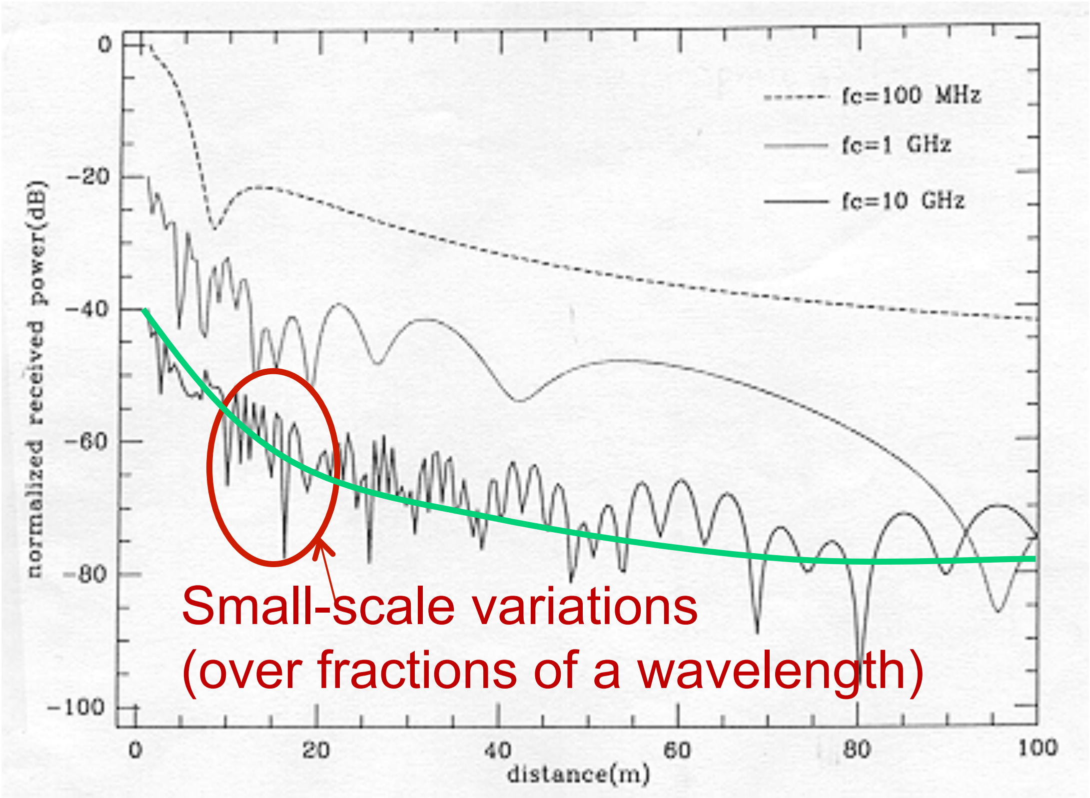


Normalized received power vs. distance

Indoor Propagation Measurements

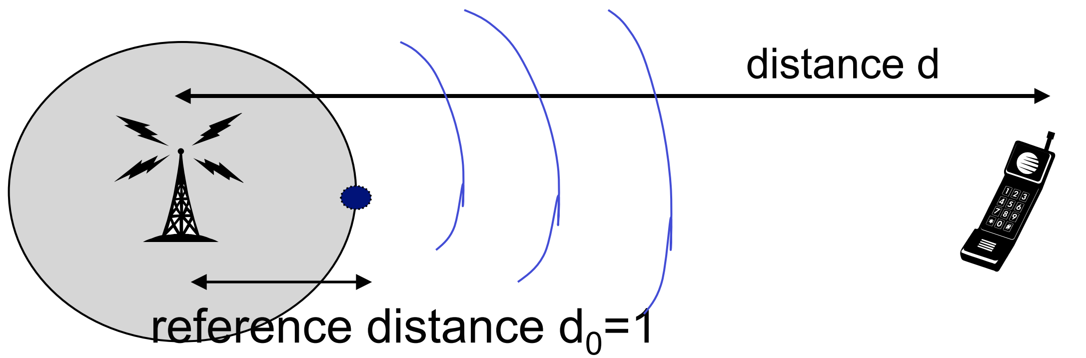


Hypothetical large indoor environment



Normalized received power vs. distance

Power Attenuation

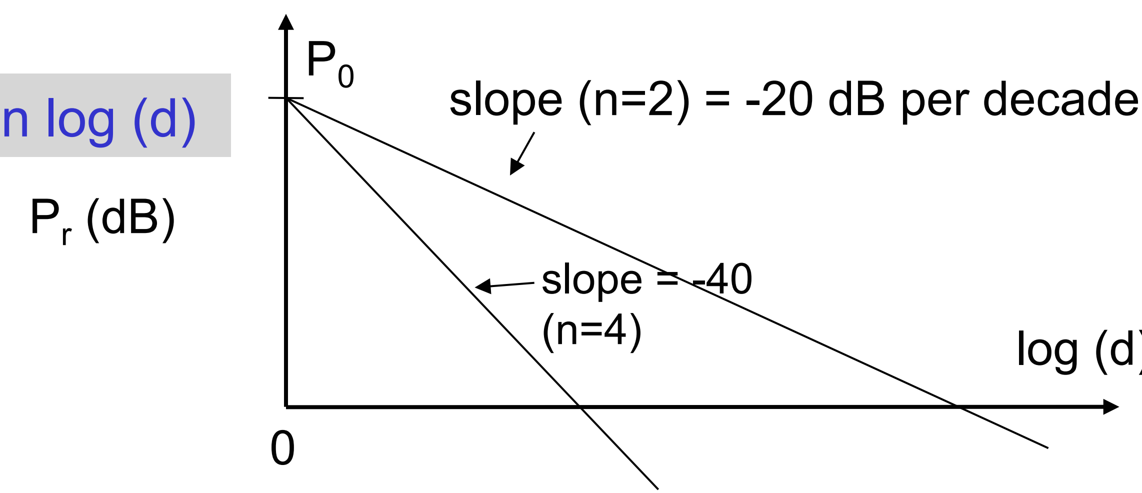


Received power $P_r \approx P_0 \left(\frac{d}{d_0}\right)^{-n}$

Reference power at reference distance d_0

Path loss exponent

In dB: $P_r = P_0$ (dB) – 10 n log (d)

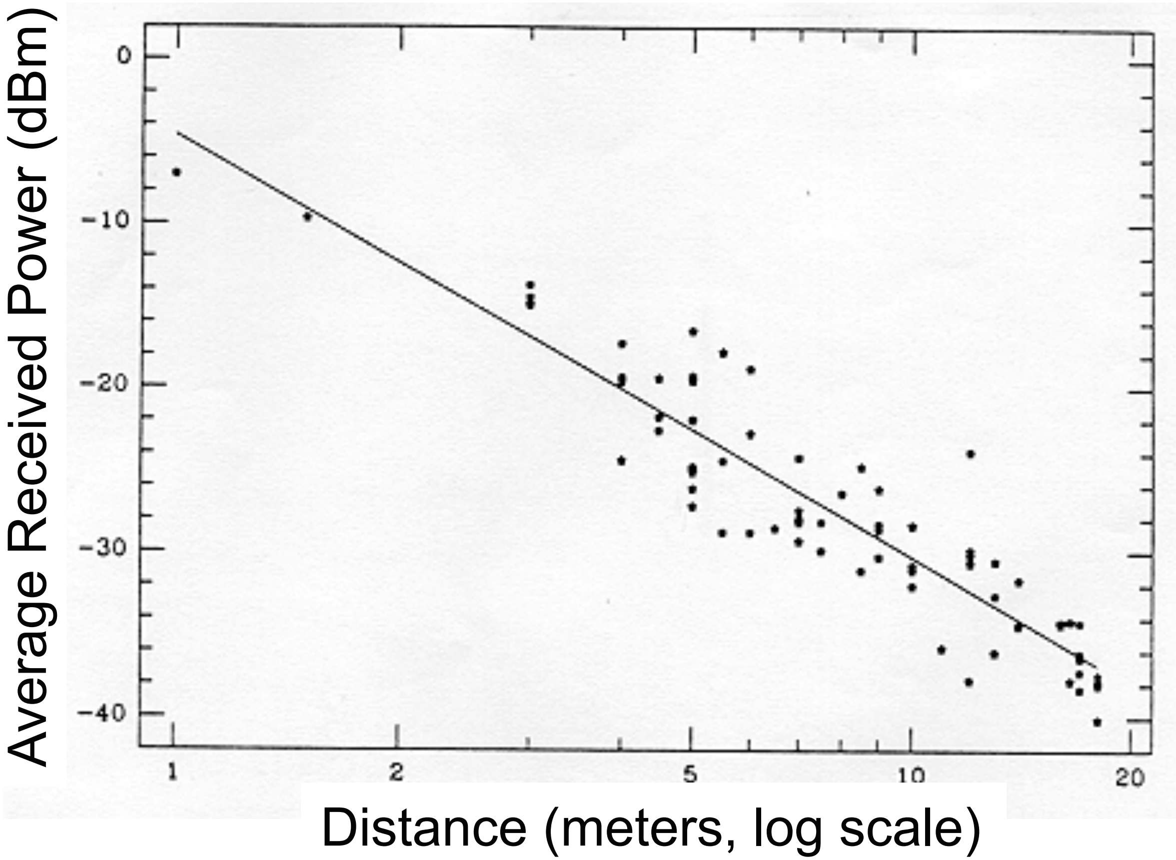


Path Loss Exponents

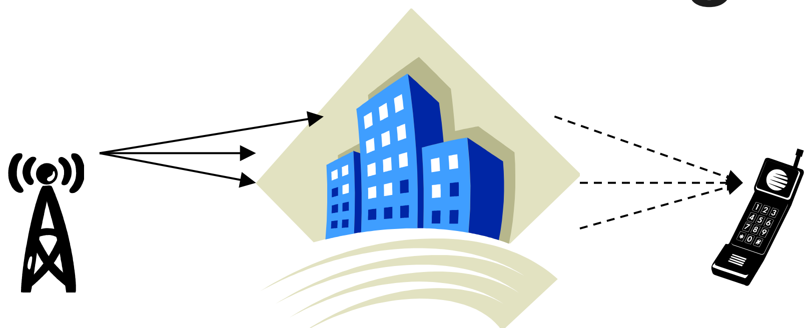
ENVIRONMENT	PATH LOSS EXPONENT, n
Free space	2
Urban cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-site	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Large-Scale Path Loss

(Scatter Plot)



Shadow Fading

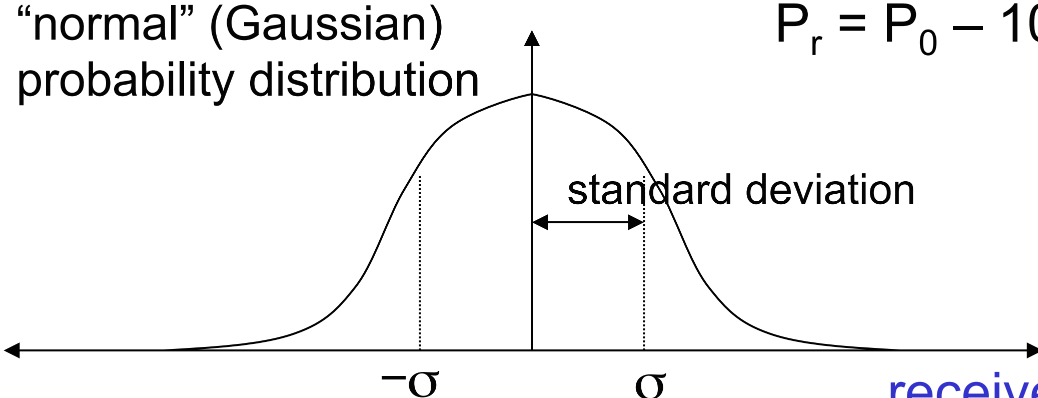


- Random variations in path loss as mobile moves around buildings, trees, etc.
- Modeled as an additional random variable:

"normal" (Gaussian) probability distribution

$$P_r = P_0 - 10\, n \log d + X$$

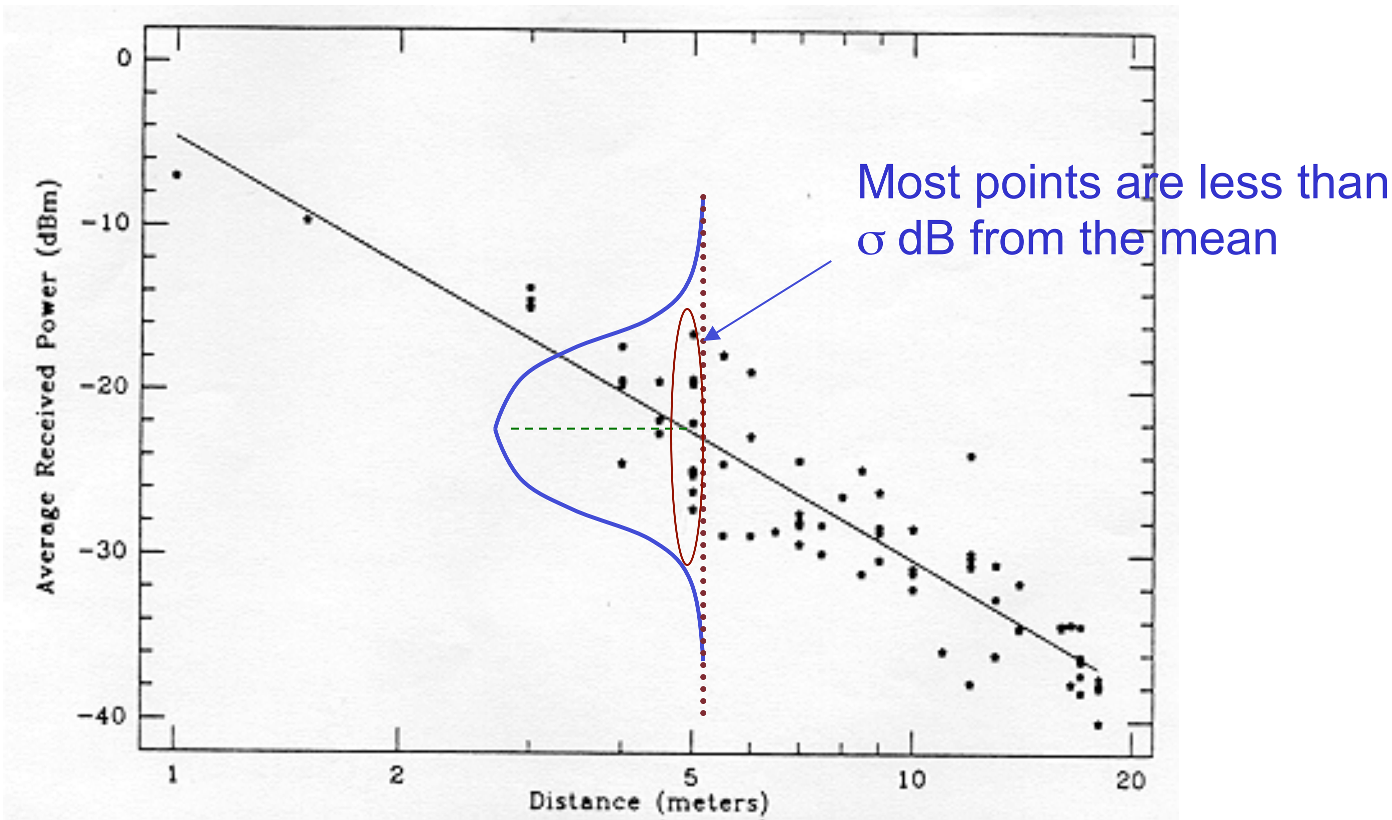
"log-normal" random variable



received power in dB

For cellular: σ is about 8 dB

Large-Scale Path Loss
(Scatter Plot)



Empirical Path Loss Models

- Propagation studies must take into account:
  - Environment (rural, suburban, urban)
  - Building characteristics (high-rise, houses, shopping malls)
  - Vegetation density
  - Terrain (mountainous, hilly, flat)
- Okumura's model
  (based on measurements in and around Tokyo)
  - Median path loss =
    free-space loss + urban loss + antenna gains + corrections
  - Obtained from graphs
  - Additional corrections for street orientation, irregular terrain
- Numerous indoor propagation studies for 802.11

SINR Measurements: 1xEV-DO

drive test plots

dB and dBm

- dB is a ratio of two powers:

  We say that power P_1 is x dB stronger than power P_2 if $x = 10 \log (P_1/P_2)$, where log is base 10.
  - Example: P_1 is 3 dB more than P_2 if $P_1/P_2 \approx 2$.

- dBm is power relative to a milliwatt (1 mW = 0.001 W):

  P in dBm = 10 log (P/0.001)
  - Example: 1 mW = 10 log 1 = 0 dBm

Link Budget

How much transmit power is required to achieve a target received power?

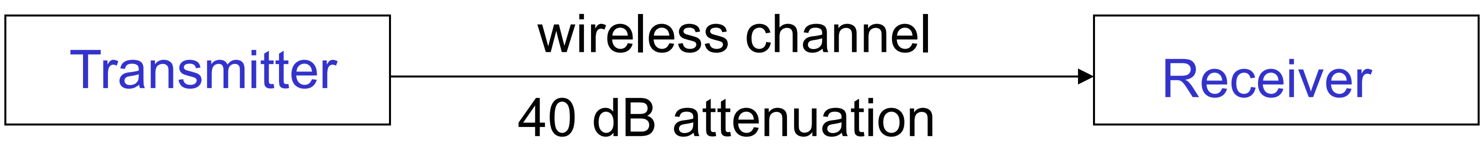
- dBs add:

Target received power (dBm)

+ path loss (dB)
+ other losses (components) (dB)
- antenna gains (dB)

Total power needed at transmitter (dBm)

Example

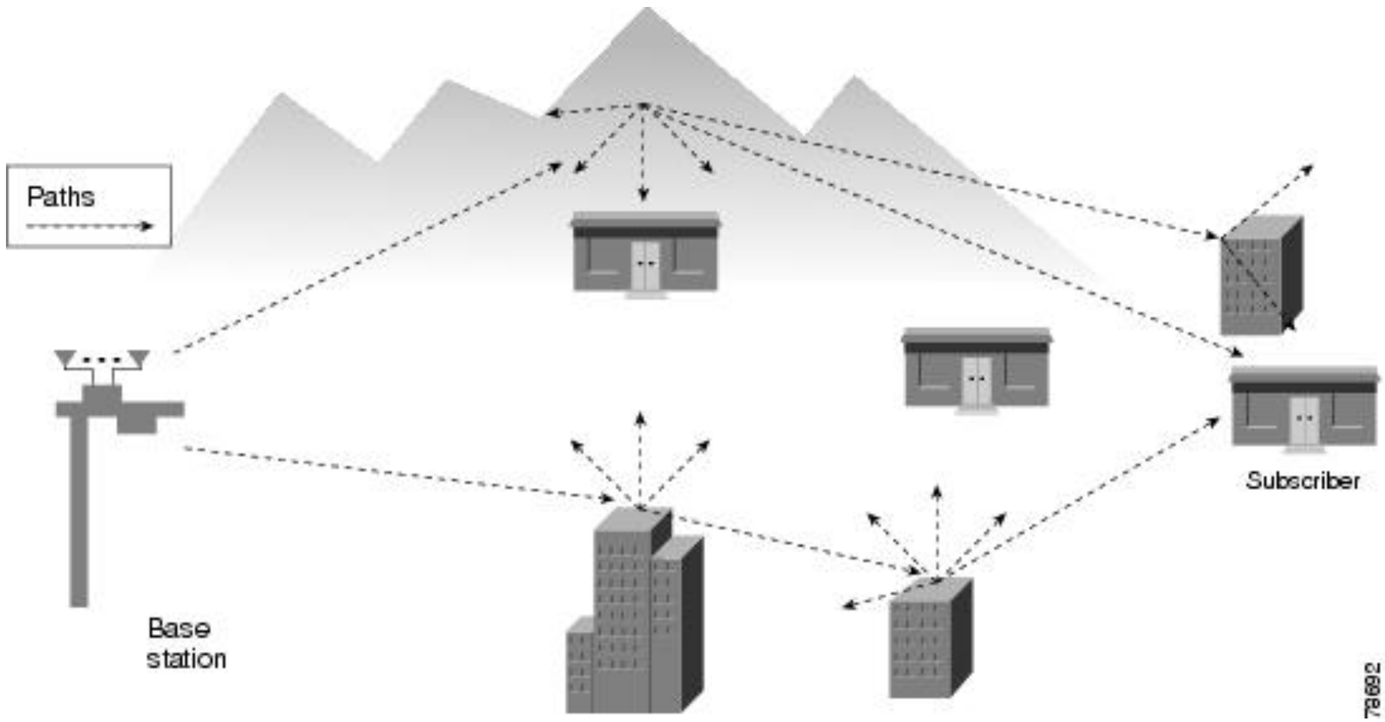


What is the required Transmit power?

Received power must be > -30 dBm

- Recall that dBm measures the signal power relative to 1 mW (milliwatt) = 0.001 Watt. To convert from S Watts to dBm, use S (dBm) = 10 log (S / 0.001)
- Transmitted power (dBm) = -30 + 40 = 10 dBm = 10 mW
- What if the received signal-to-noise ratio must be 5 dB, and the noise power is -45 dBm?

Urban Multipath



- No direct Line of Sight between mobile and base
- Radio wave scatters off of buildings, cars, etc.
- Severe multipath

Narrowband vs. Wideband

- Narrowband means that the bandwidth of the transmitted signal is small (e.g., < 100 kHz for cellular). It therefore looks “almost” like a sinusoid.
  - Multipath changes the amplitude and phase.
- Wideband means that the transmitted signal has a large bandwidth (e.g., > 1 MHz for cellular).
  - Multipath causes “self-interference”.

Narrowband Fading

Received signal $r(t) = h_1\, s(t - \tau_1) + h_2\, s(t - \tau_2) + h_3\, s(t - \tau_3) + \ldots$

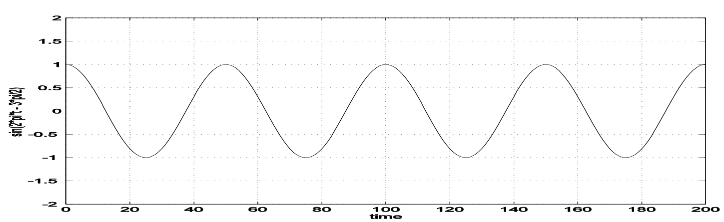
attenuation for path 1 (random) (h_1)

delay for path 1 (random) (τ_1)

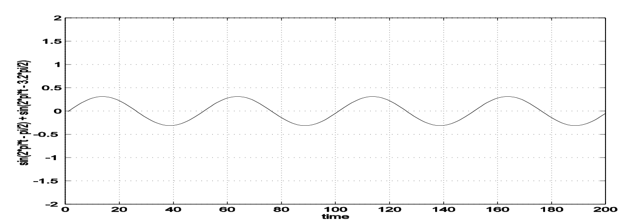
If the transmitted signal is sinusoidal (narrowband), $s(t) = \sin 2\pi f\, t$,

then the received signal is also sinusoidal, but with a different (random) amplitude and (random) phase:

$$r(t) = A \sin (2\pi f\, t + \theta)$$



Transmitted s(t)



Received r(t)

A, θ depend on environment, location of transmitter/receiver

Rayleigh Fading

Can show:

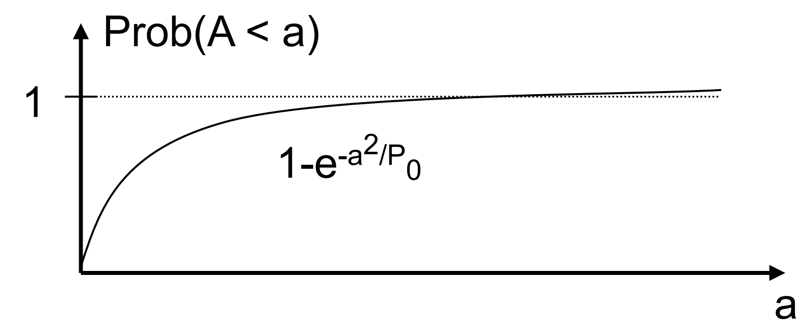
A has a "Rayleigh" distribution

θ has a "uniform" distribution

(all phase shifts are equally likely)

Probability $(A < a) = 1 - e^{-a^2/P_0}$

where P_0 is the reference power (averaged over different locations)

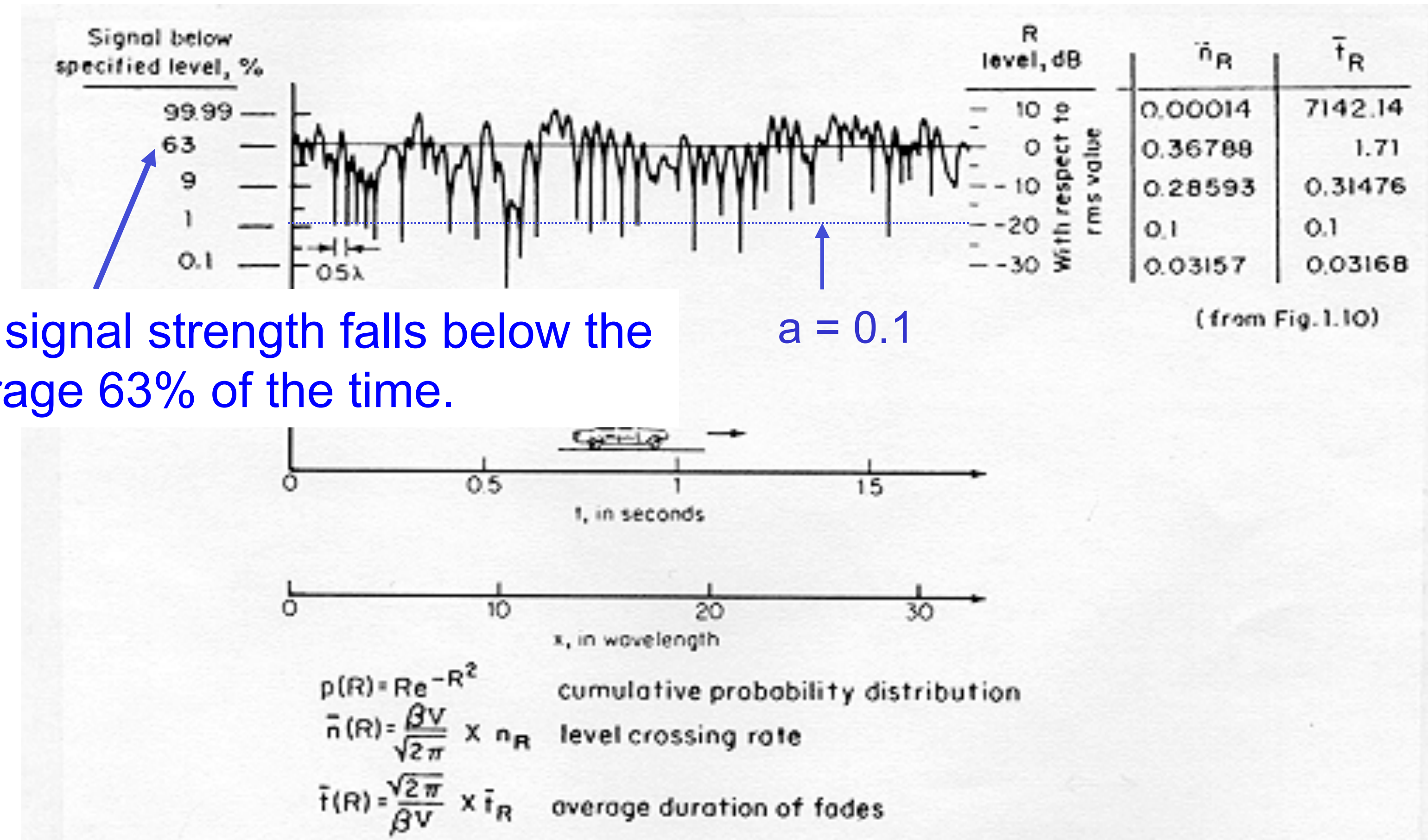


Ex: $P_0 = 1$, $a=1$: $Pr(A<1) = 1 - e^{-1} = 0.63$ (probability that signal is faded)

$P_0 = 1$, $a=0.1$: $Pr(A<0.1) = 1 - e^{-1/100} \approx 0.01$

(prob that signal is severely faded)

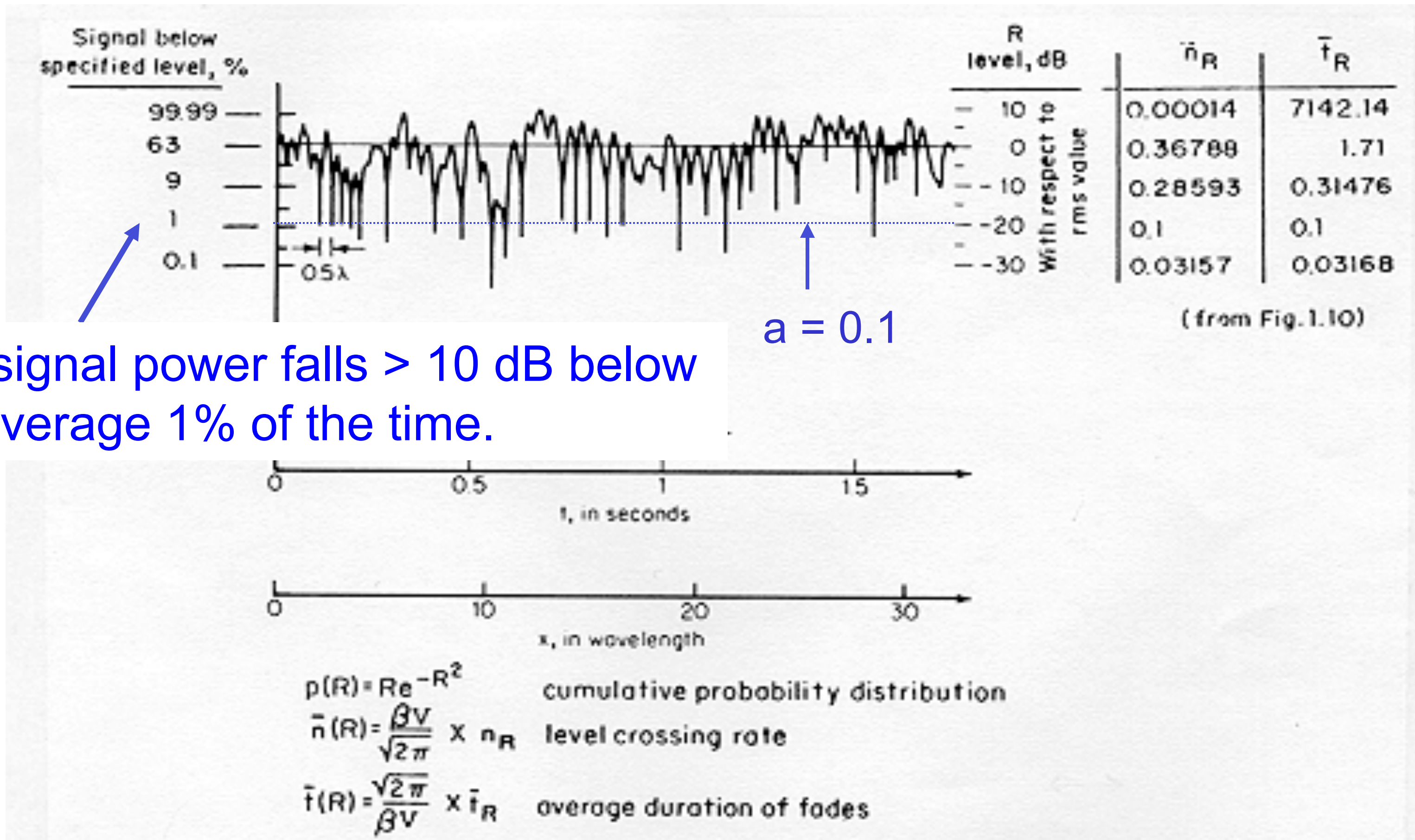
Small-Scale (Rayleigh) Fading



The signal strength falls below the average 63% of the time.

a = 0.1

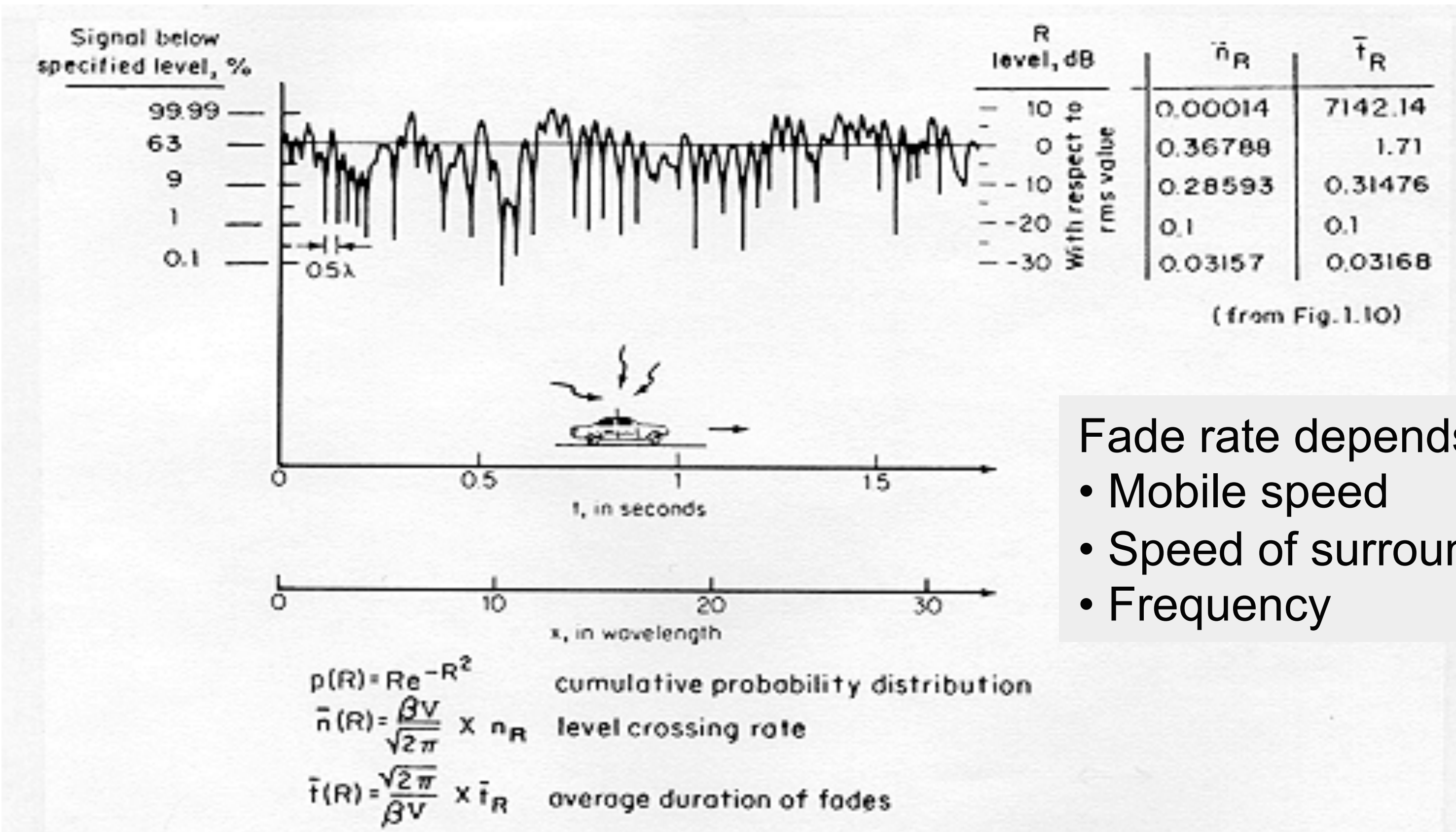
Small-Scale (Rayleigh) Fading



a = 0.1

The signal power falls > 10 dB below the average 1% of the time.

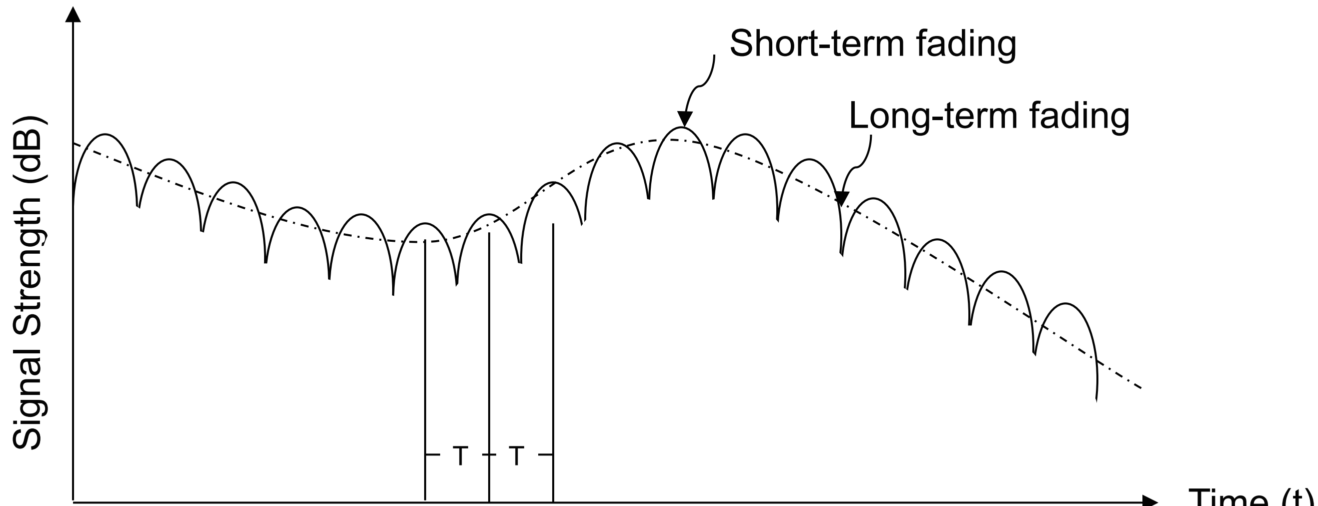
Small-Scale Fading



Fade rate depends on

- Mobile speed
- Speed of surrounding objects
- Frequency

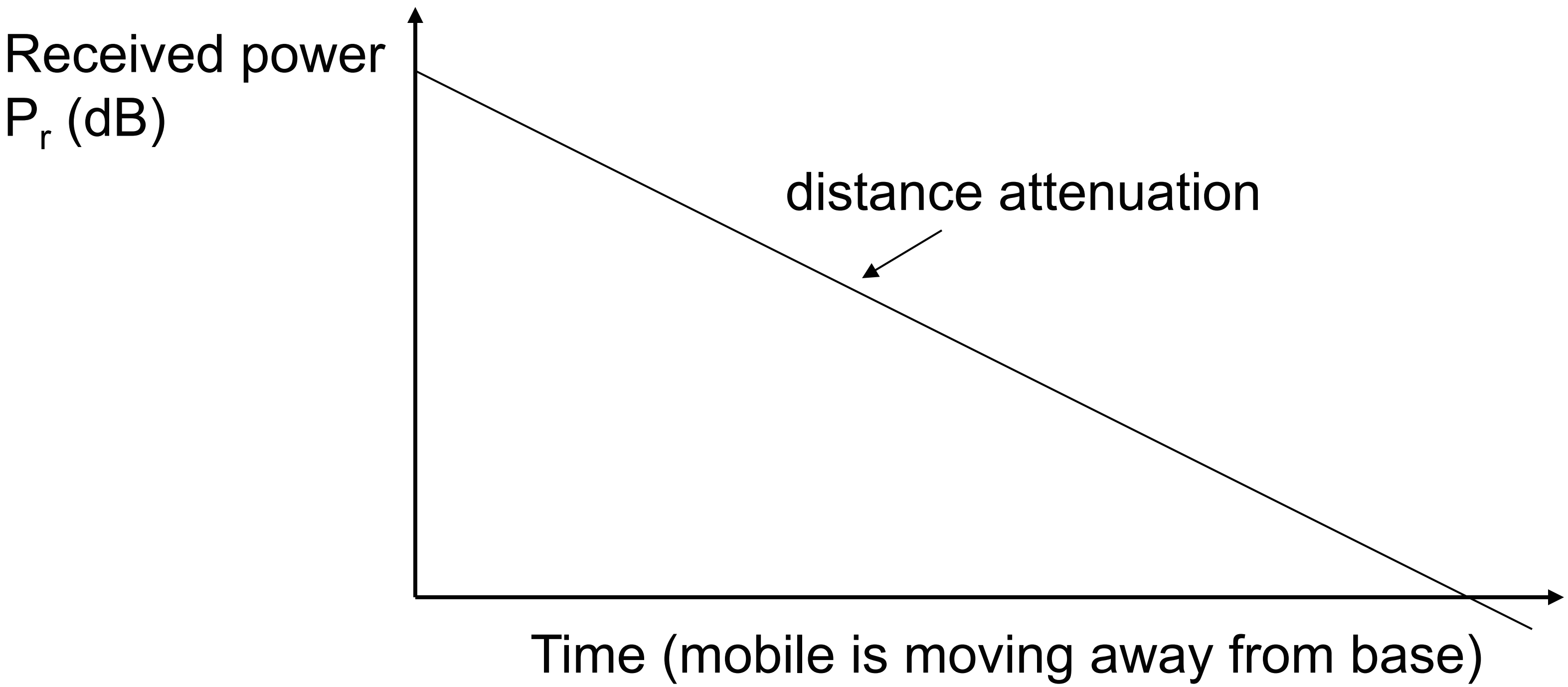
Short- vs. Long-Term Fading



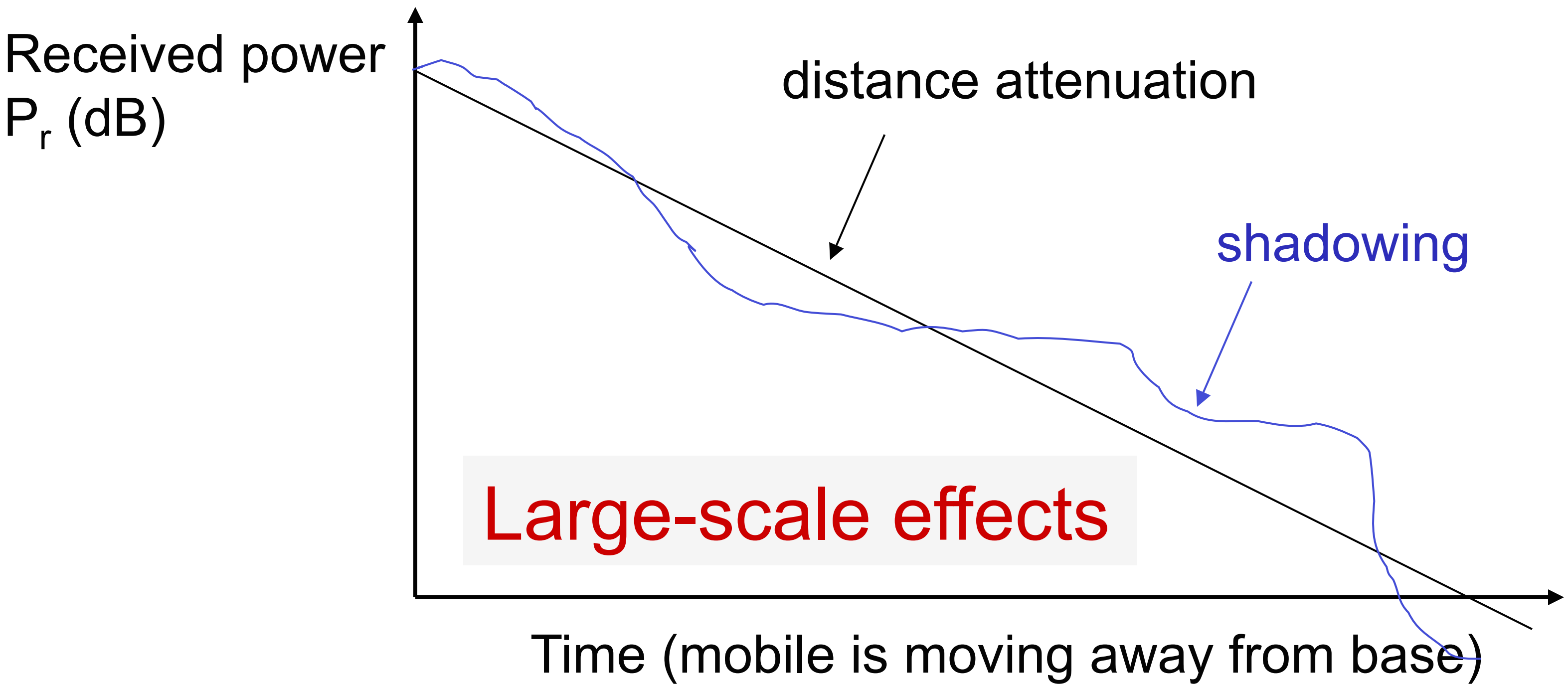
Long-term (large-scale) fading:

- Distance attenuation
- Shadowing (blocked Line of Sight (LOS))
- Variations of signal strength over distances on the order of many wavelengths

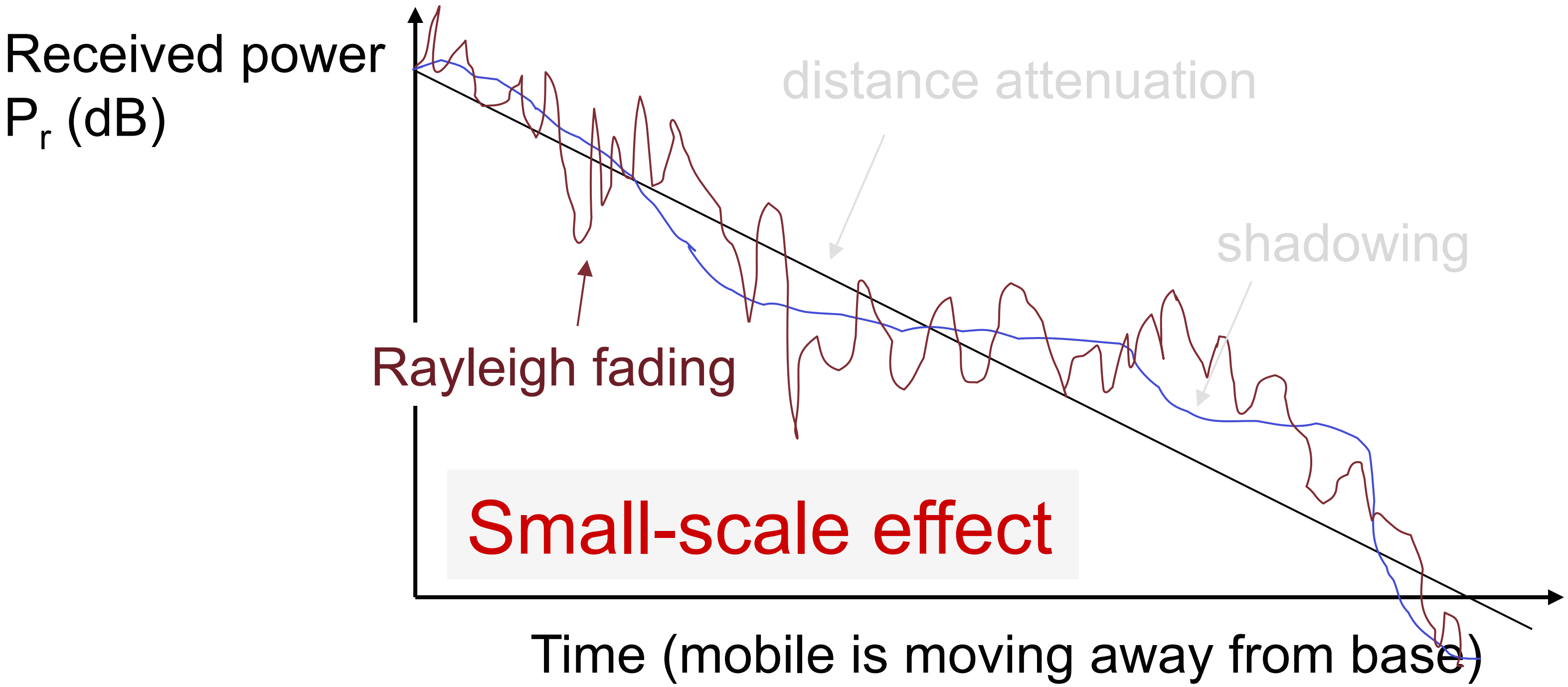
Combined Fading and Attenuation



Combined Fading and Attenuation



Combined Fading and Attenuation

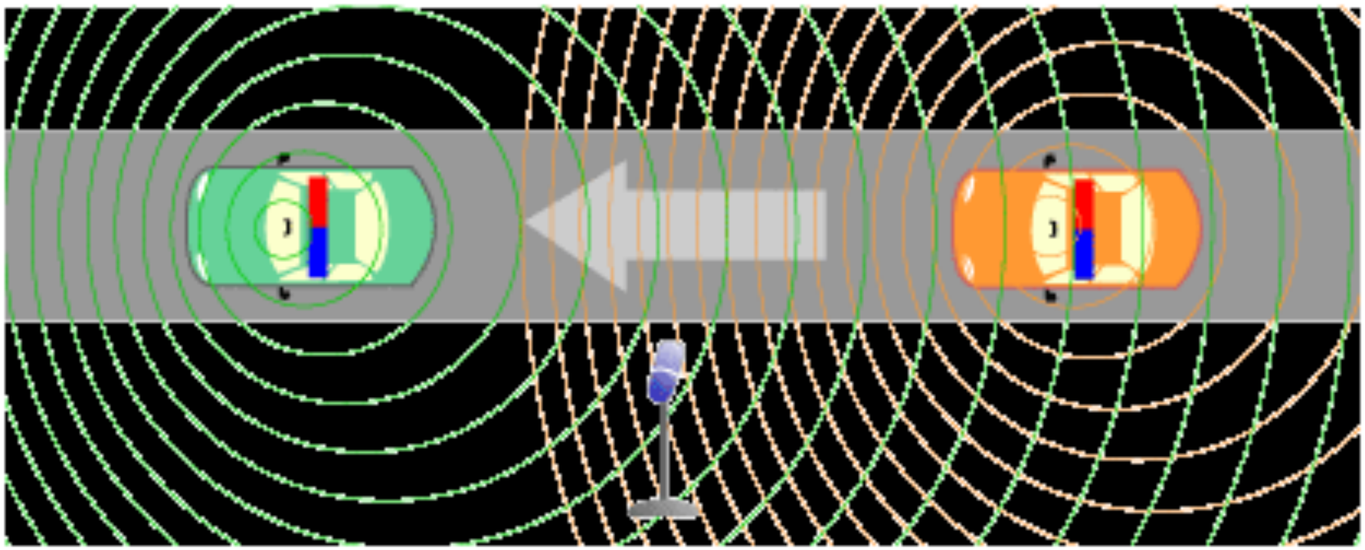


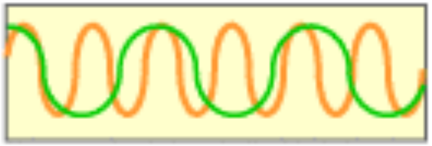
Example Diagnostic Measurements: 1XEV-DO

drive test measurements

drive path

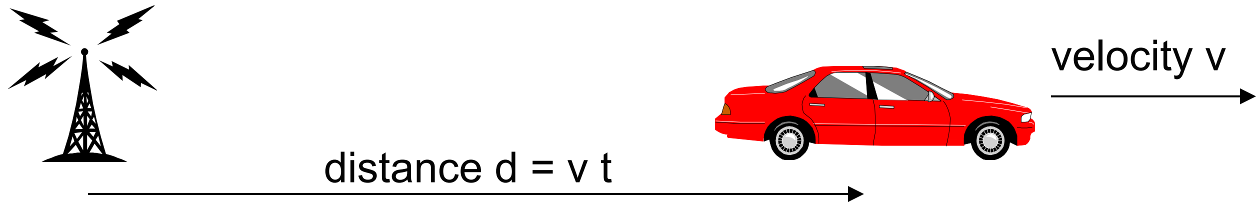
Time Variations: Doppler Shift





Audio clip (train station)

Time Variations: Doppler Shift

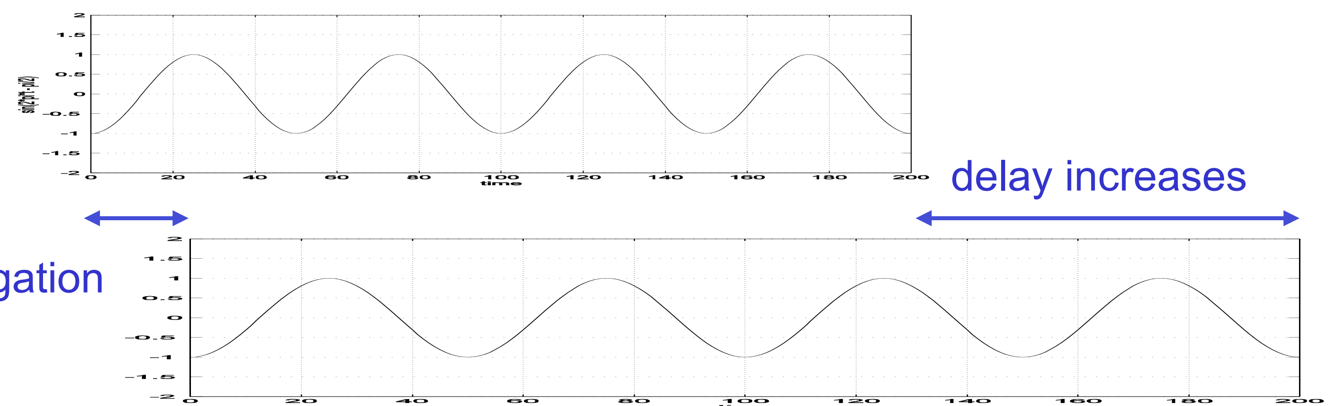


Propagation delay = distance d / speed of light c = vt/c

transmitted signal s(t)

received signal r(t)

propagation delay



Received signal r(t) = sin $2\pi f$ (t- vt/c) = sin $2\pi(f - fv/c)$ t

received frequency

Doppler shift $f_d = -fv/c$

Doppler Shift (Ex)

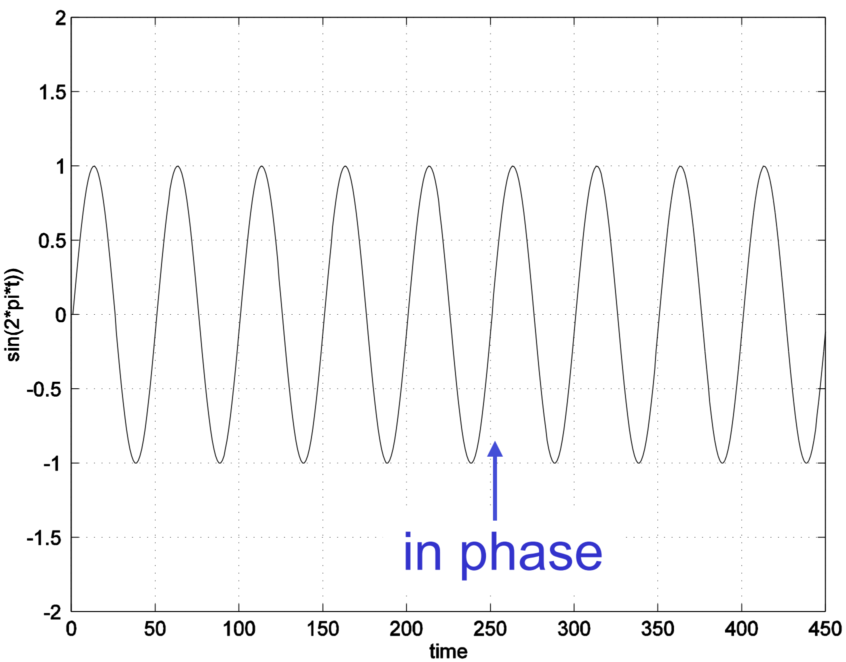
Mobile moving away from base → $v > 0$, Doppler shift < 0
Mobile moving towards base → $v < 0$, Doppler shift > 0

Carrier frequency f = 900 MHz, v = 60 miles/hour = 26.82 meters/sec

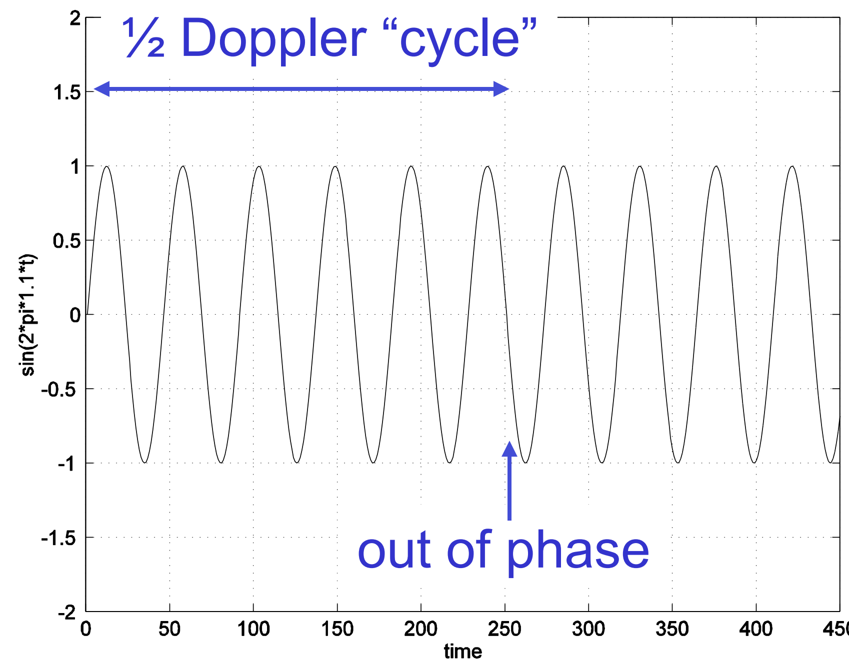
Mobile → Base: $f_d = fv/c = (900 \times 10^6) \times 26.82 \,/\, (3 \times 10^8) \approx 80$ Hz

meters/sec

Doppler (Frequency) Shift



Frequency= 1/50



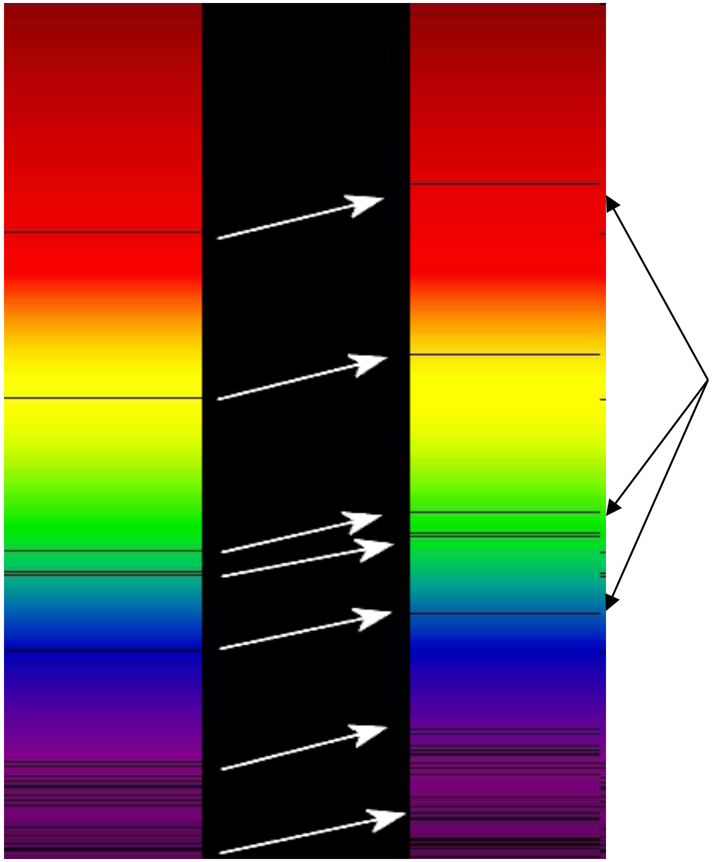
Frequency= 1/45

Application of Doppler Shift: Astronomy

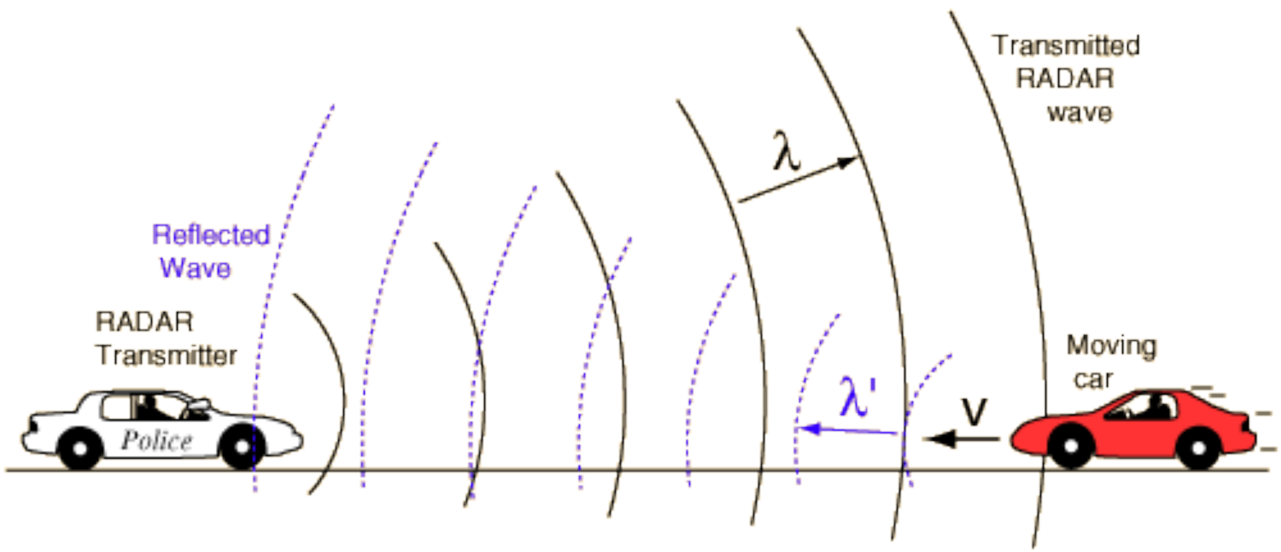
Doppler shift determines relative velocity of distant objects (e.g., stars, galaxies…)

"red shift": object is moving away

"blue shift" object is moving closer

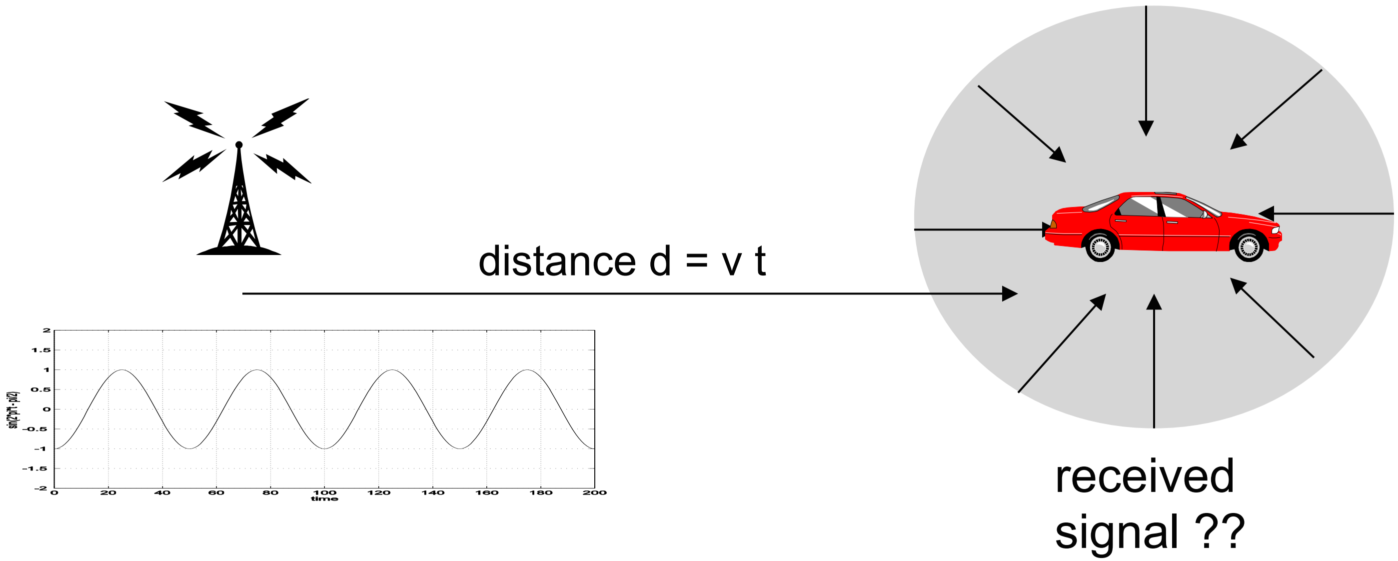


Application of Doppler Shift: Police Radar

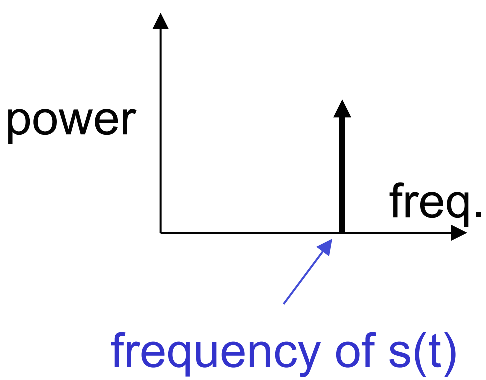


Doppler shift can be used to compute relative speed.

Scattering: Doppler Spectrum

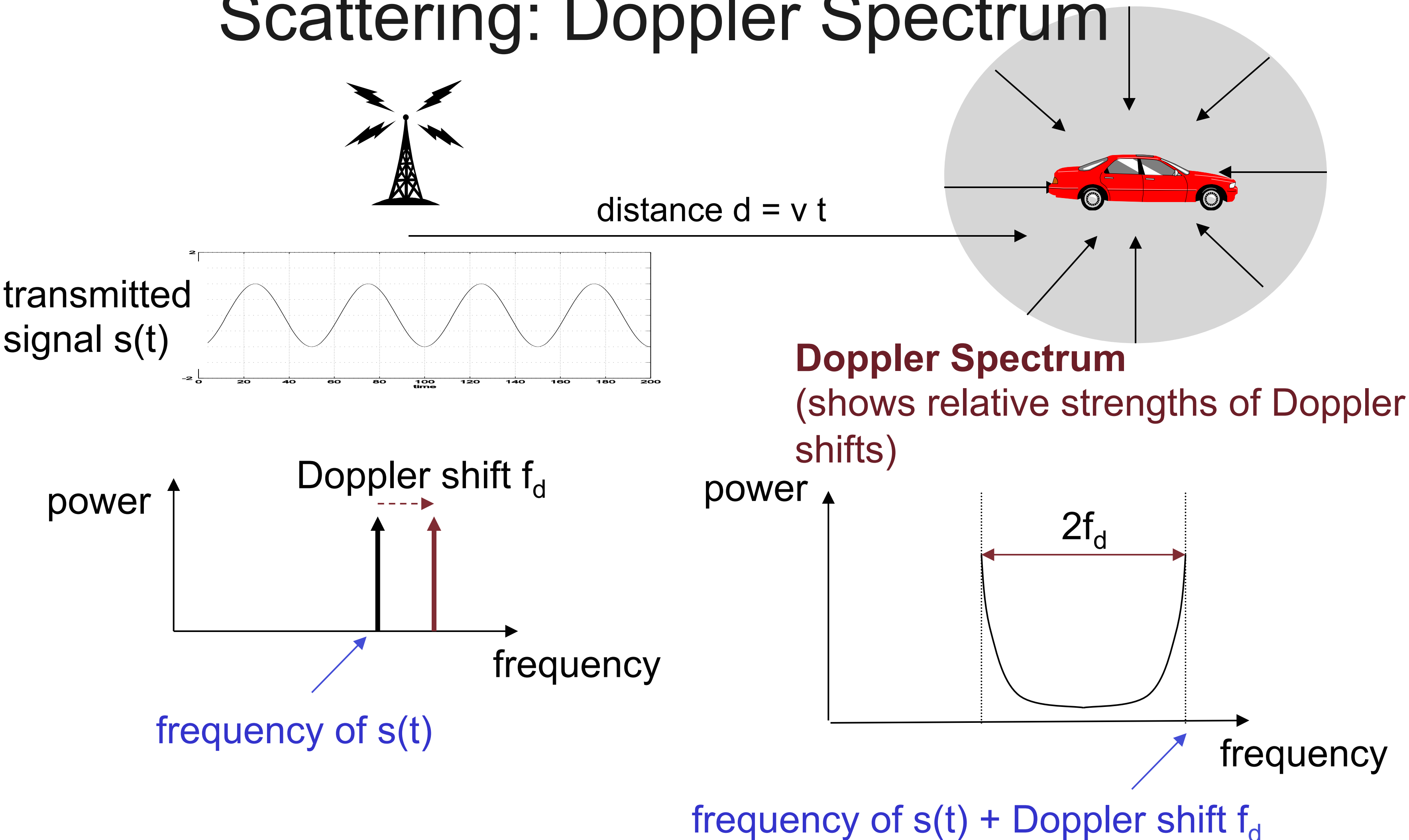


transmitted signal s(t)

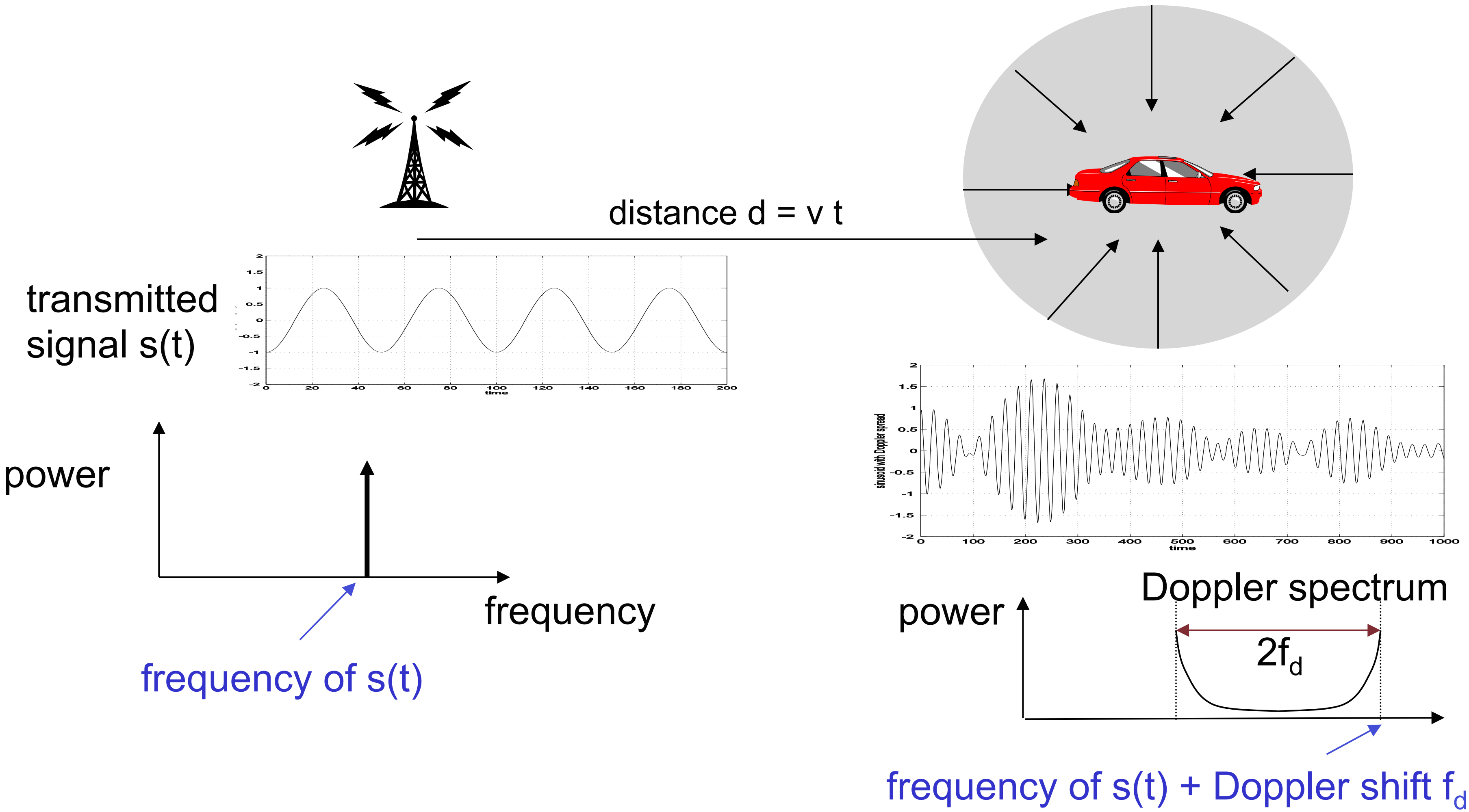


- Received signal is the sum of all scattered waves
- Doppler shift for each path depends on angle (vf cos θ/c)
- Typically assume that the received energy is the same from all directions (uniform scattering)

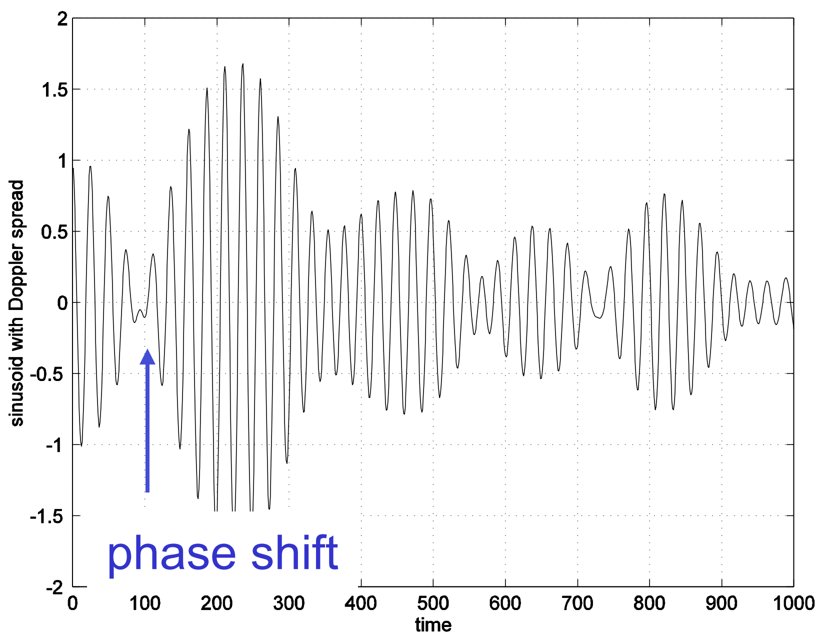
Scattering: Doppler Spectrum



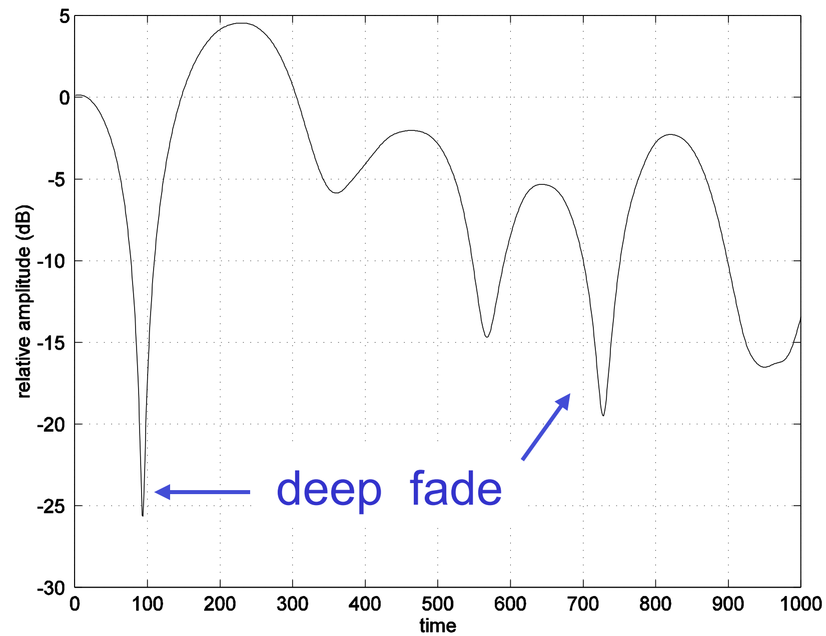
Scattering: Doppler Spectrum



Rayleigh Fading

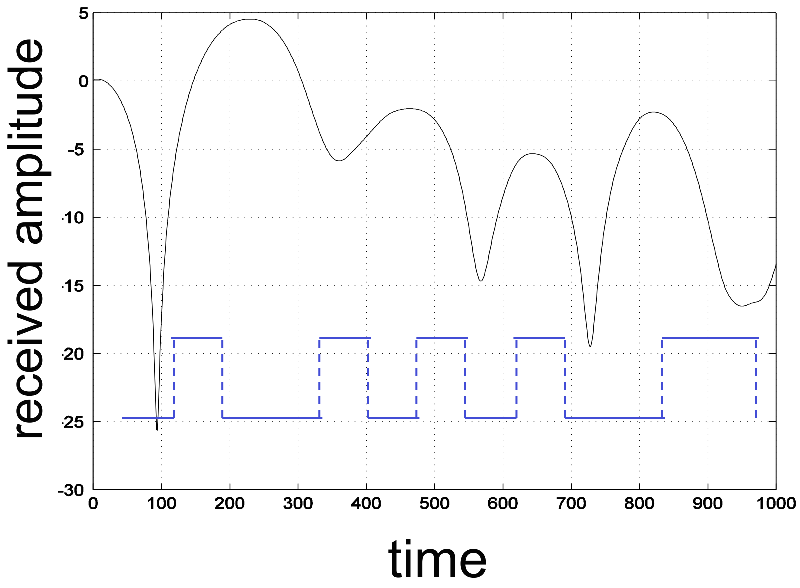


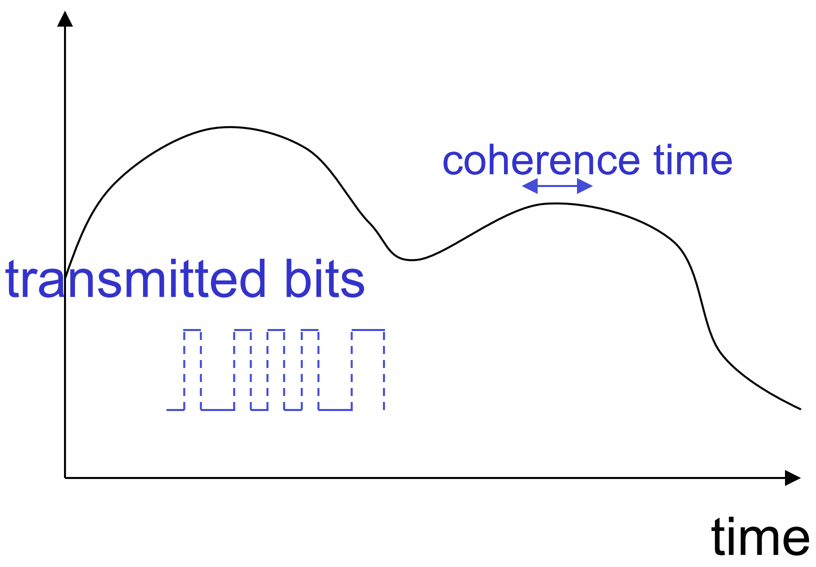
Received waveform



Amplitude (dB)

Fast vs. Slow Fading

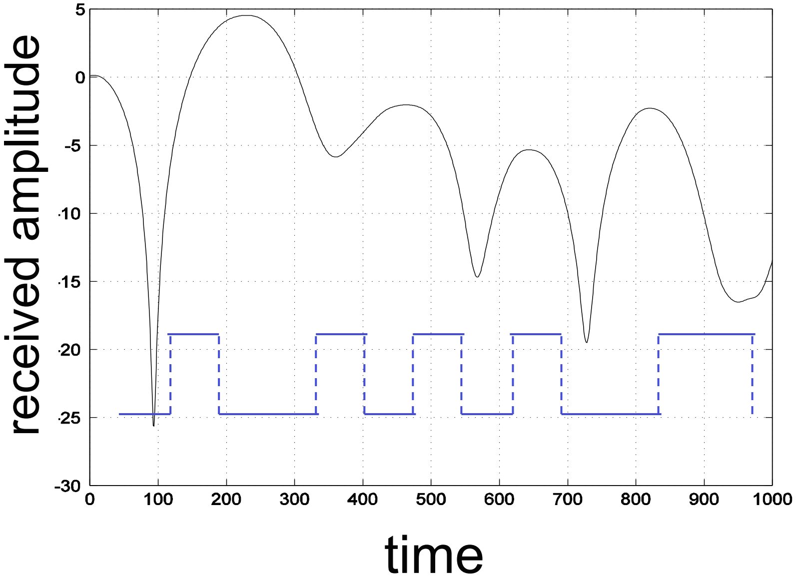


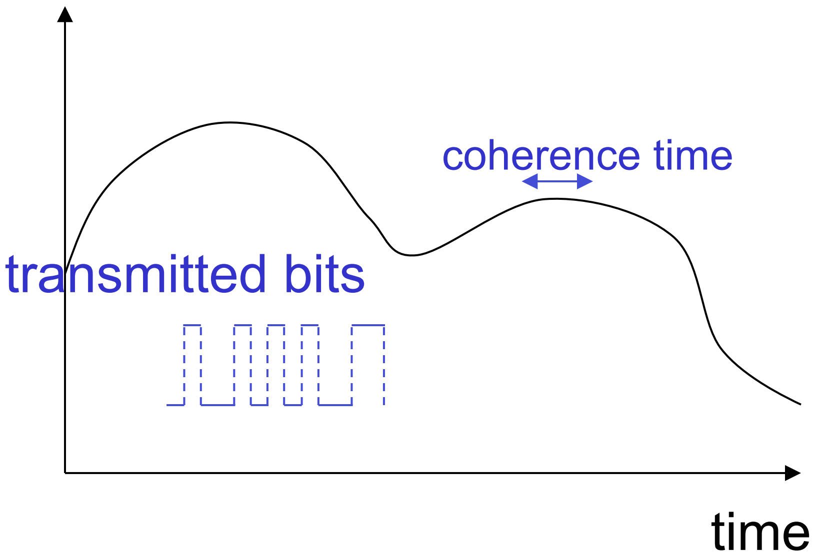


Fast fading: channel changes every few symbols. Coherence time is less than roughly 100 symbols.

Slow fading: Coherence time lasts more than a few 100 symbols.

Fast vs. Slow Fading

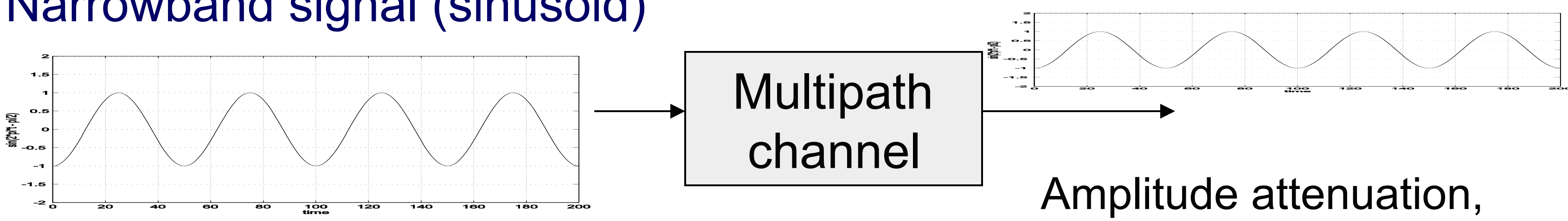




What is important is the coherence time (1/Doppler) relative to the Data rate.

Channel Characterizations: Narrowband vs. Wideband

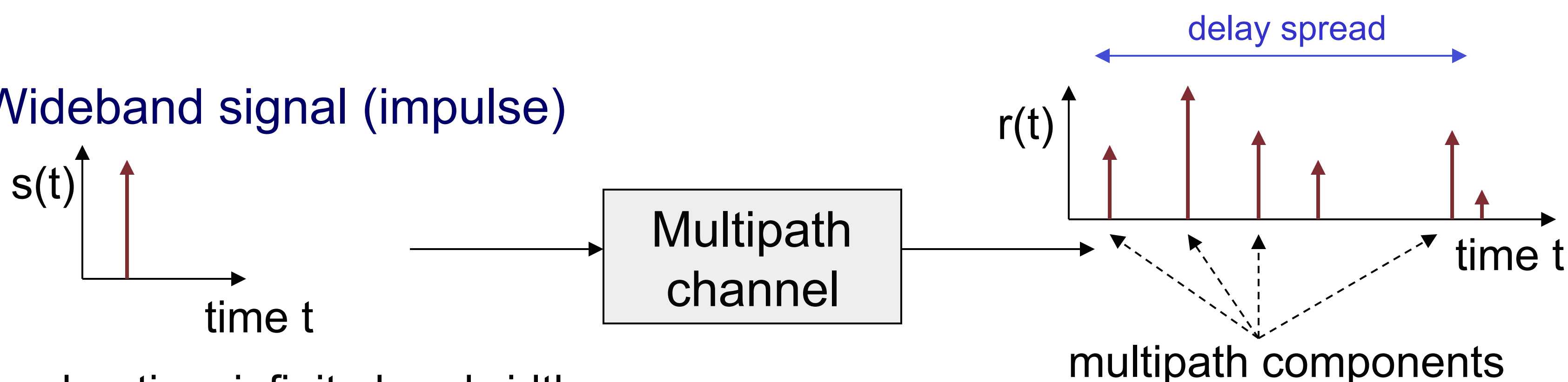
Narrowband signal (sinusoid)



Amplitude attenuation,
Delay (phase shift)

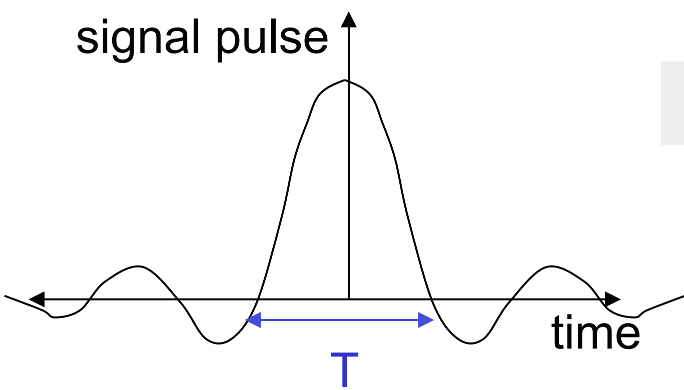
infinite duration, zero bandwidth

Wideband signal (impulse)

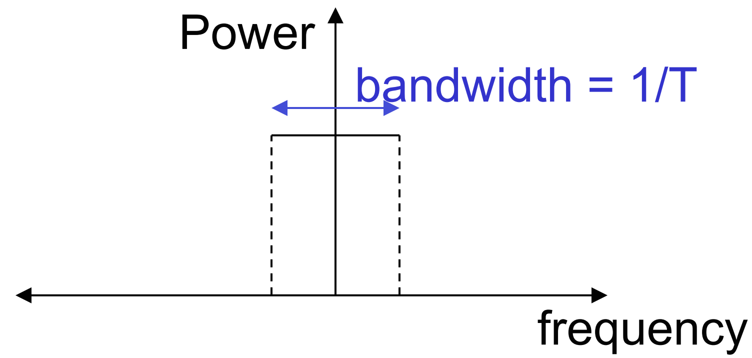


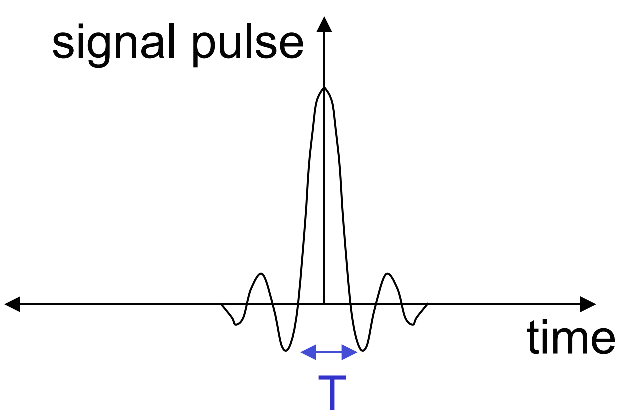
zero duration, infinite bandwidth

Pulse Width vs. Bandwidth

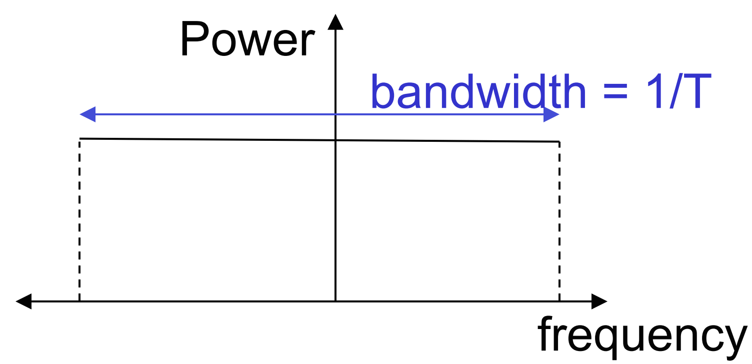


Narrowband

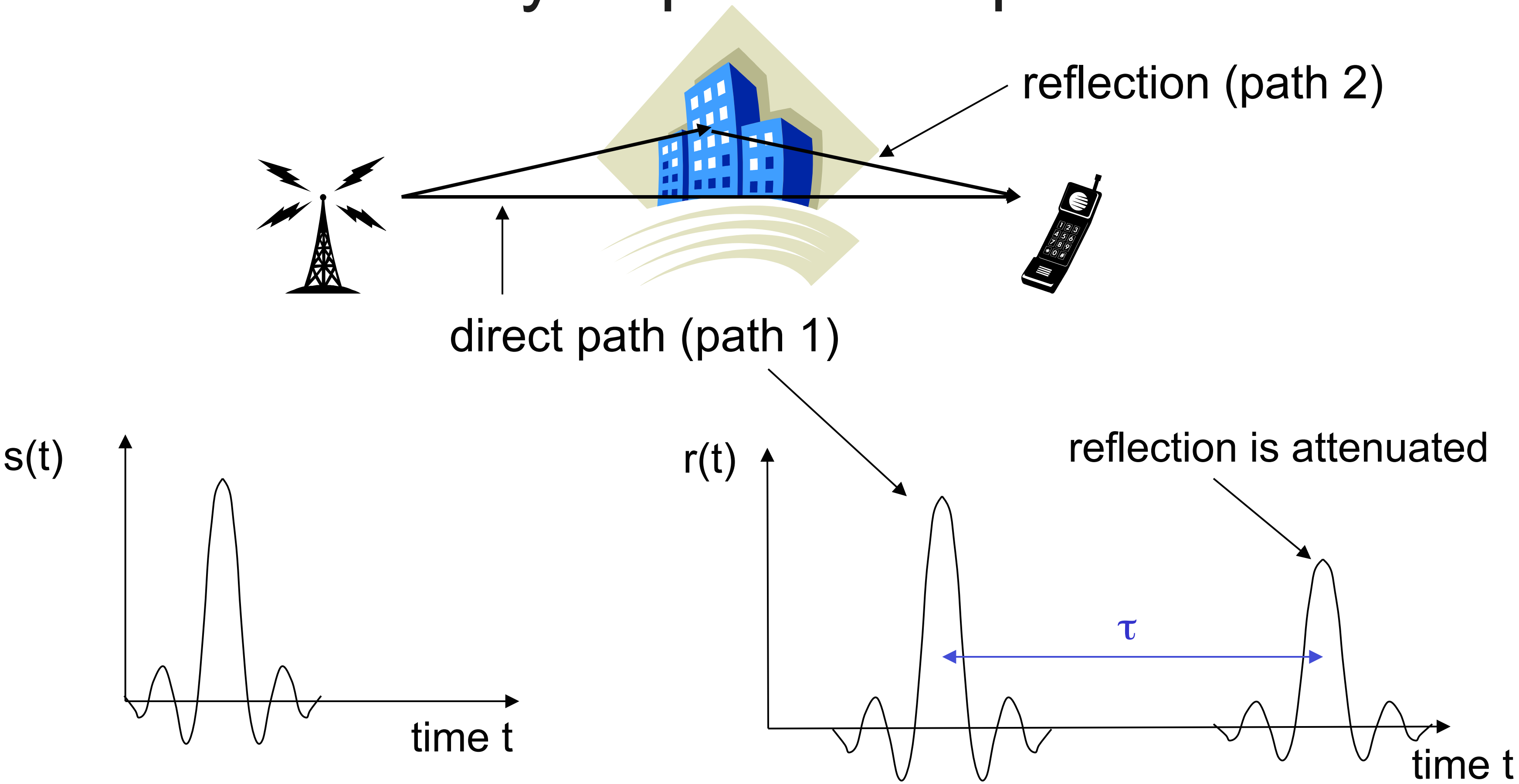




Wideband

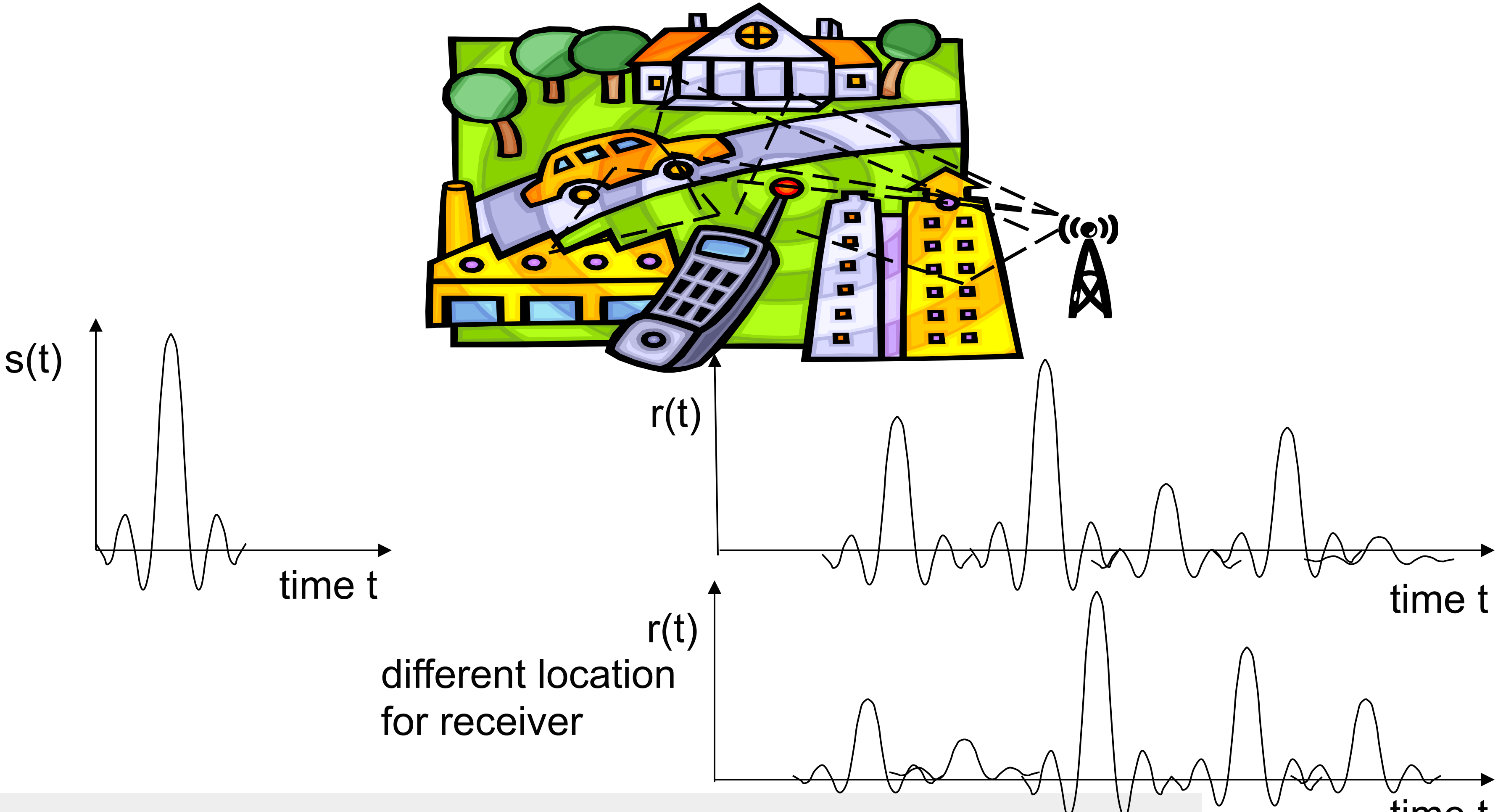


Two-Ray Impulse Response



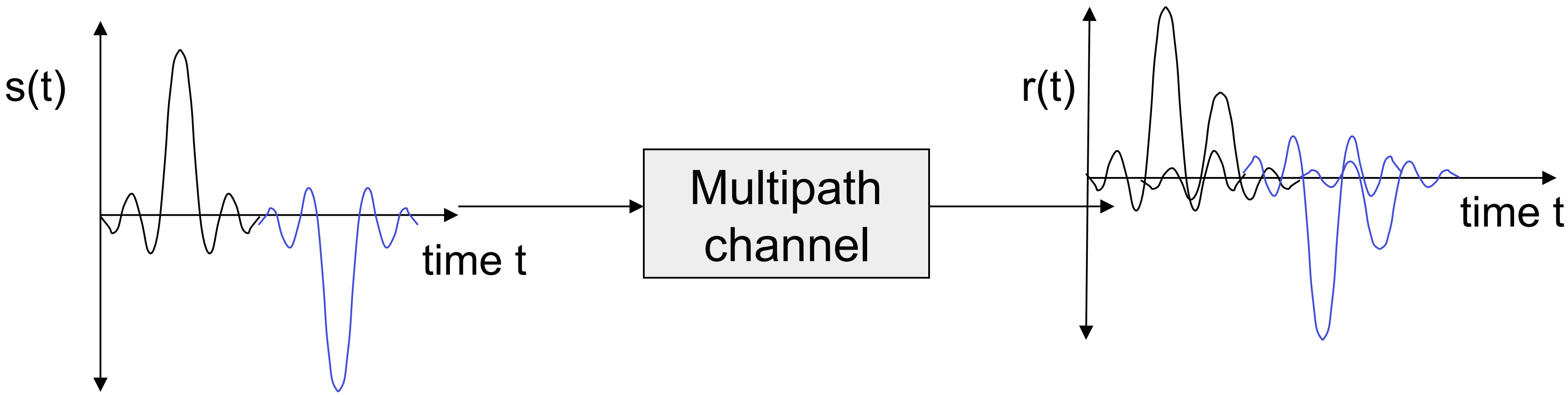
τ = [(length of path 2) – (length of path 1)]/c

Urban Multipath

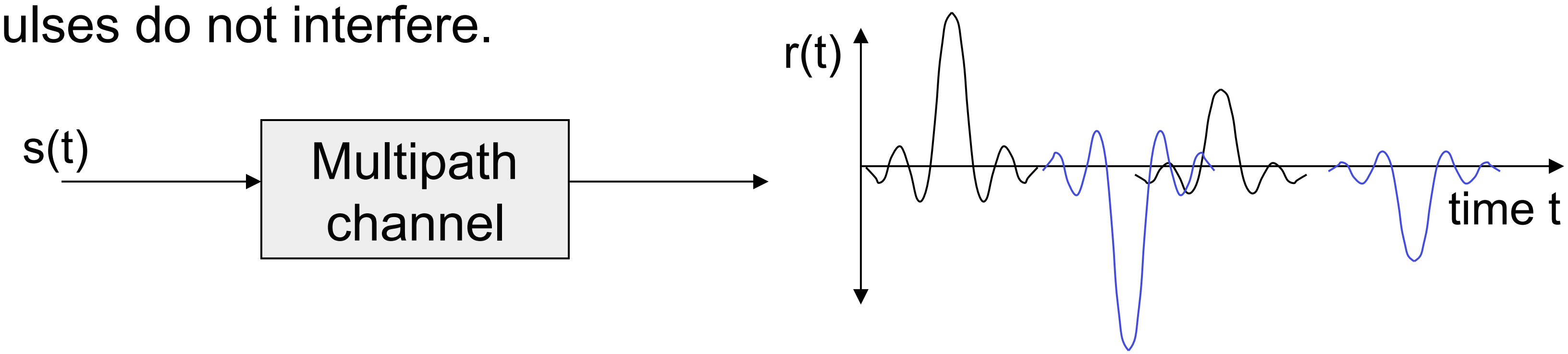


Spacing and attenuation of multipath components depend on location and environment.

Multipath and Intersymbol Interference

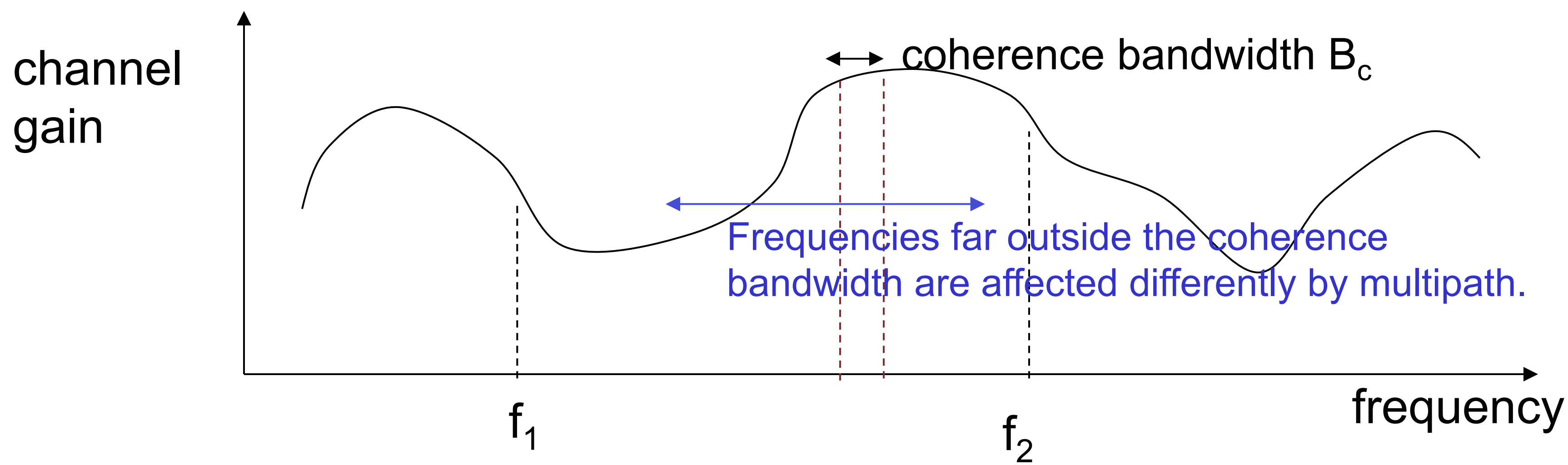


Time between pulses is >> delay spread, therefore the received pulses do not interfere.



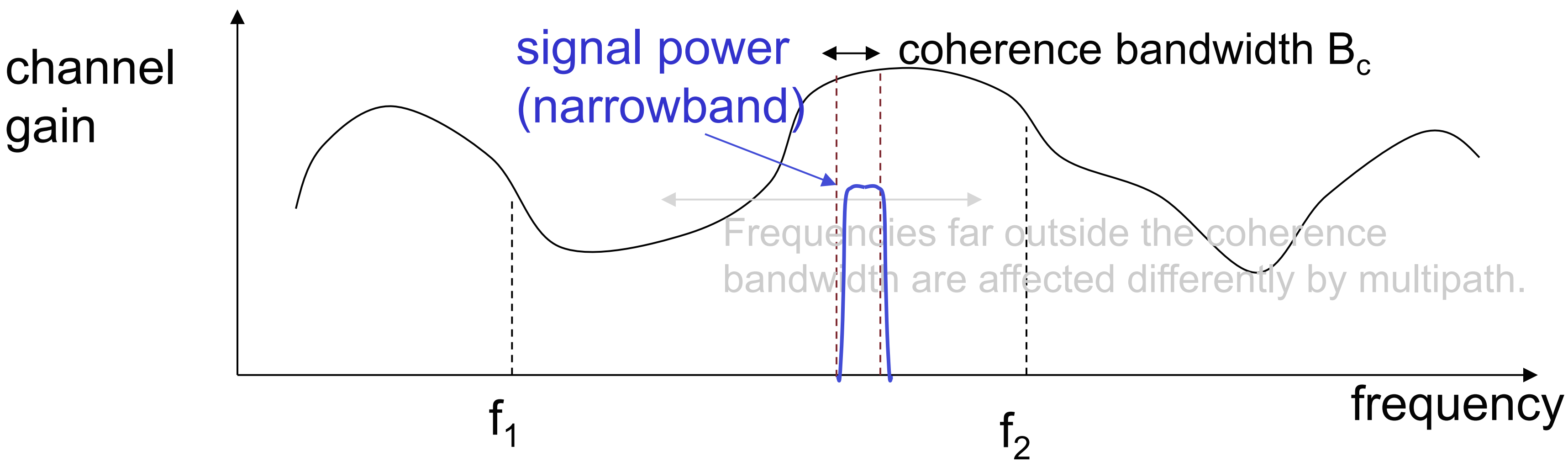
Time between pulses is < multipath delay, which causes intersymbol interference.

Coherence Bandwidth



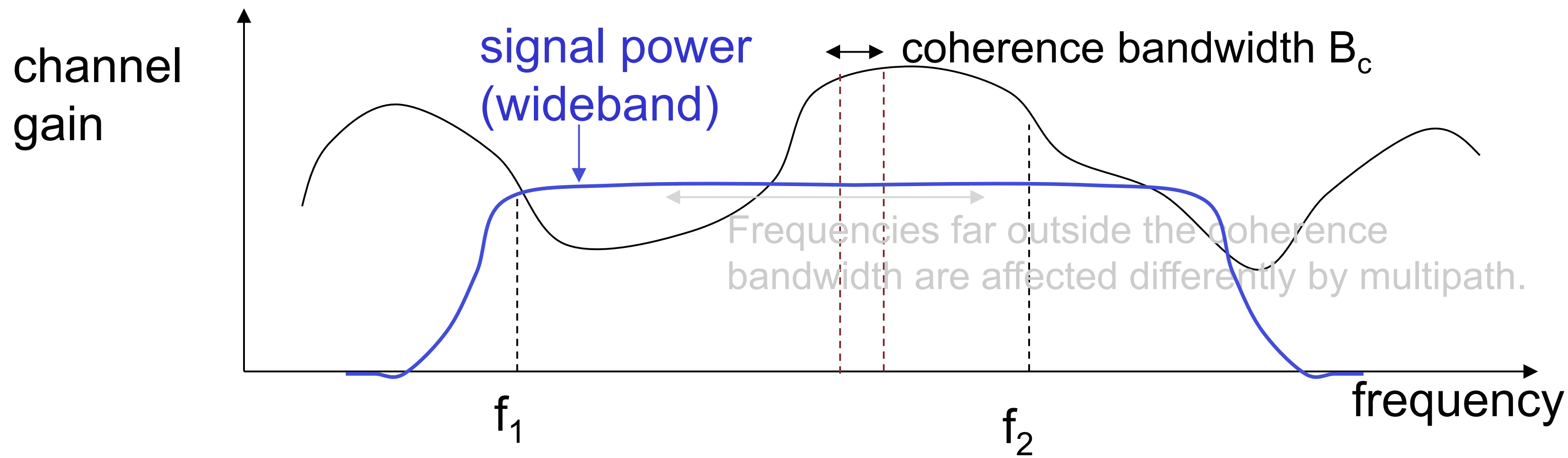
- The channel gain is approximately constant within a coherence bandwidth B_c.
- Frequencies f_1 and f_2 fade independently if $| f_1 – f_2 | >> B_c$.

Narrowband Signal



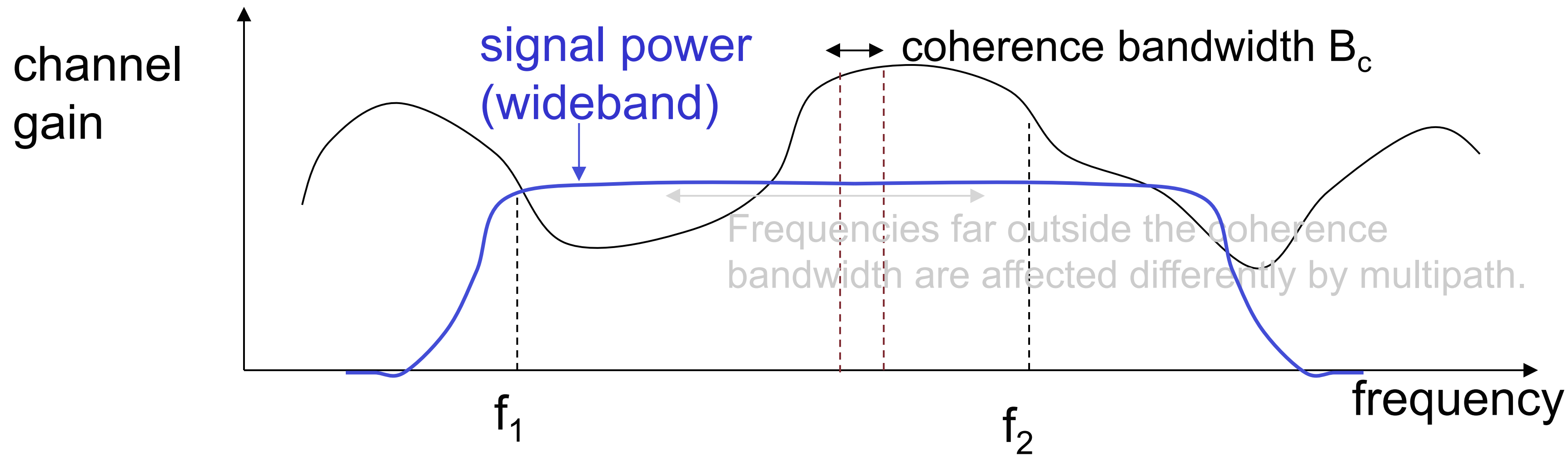
- The signal power is confined within a coherence band.
- Flat fading: all signal frequencies are affected the same way.

Wideband Signals



- A wideband signal spans many coherence bands.
- Frequency-selective fading: different parts of the signal (in frequency) are affected differently by the channel.

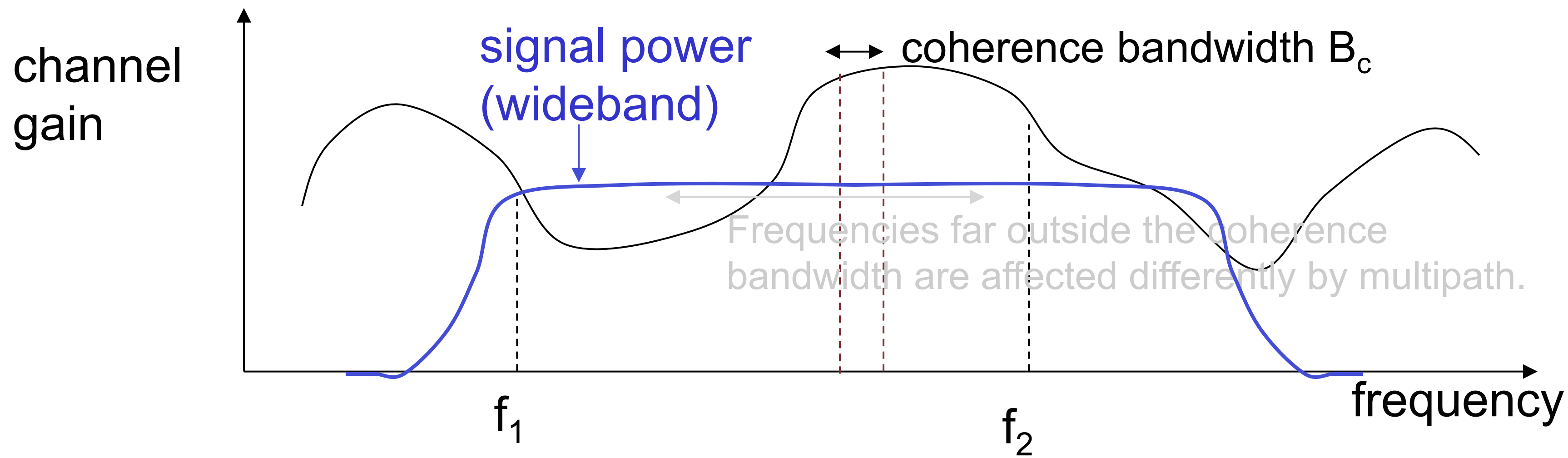
Frequency Diversity



Wideband signals exploit frequency diversity.
Spreading power across many coherence bands reduces the chances of severe fading.

Wideband signals are distorted by the channel fading (distortion causes intersymbol interference).

Coherence Bandwidth for Cellular

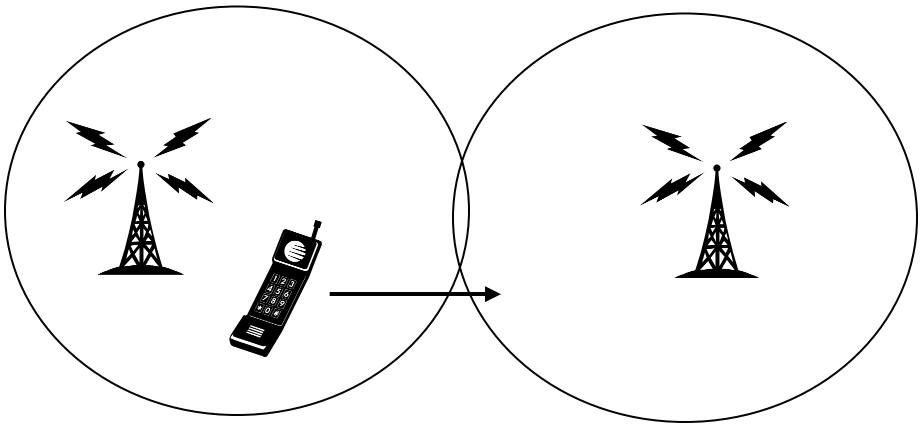


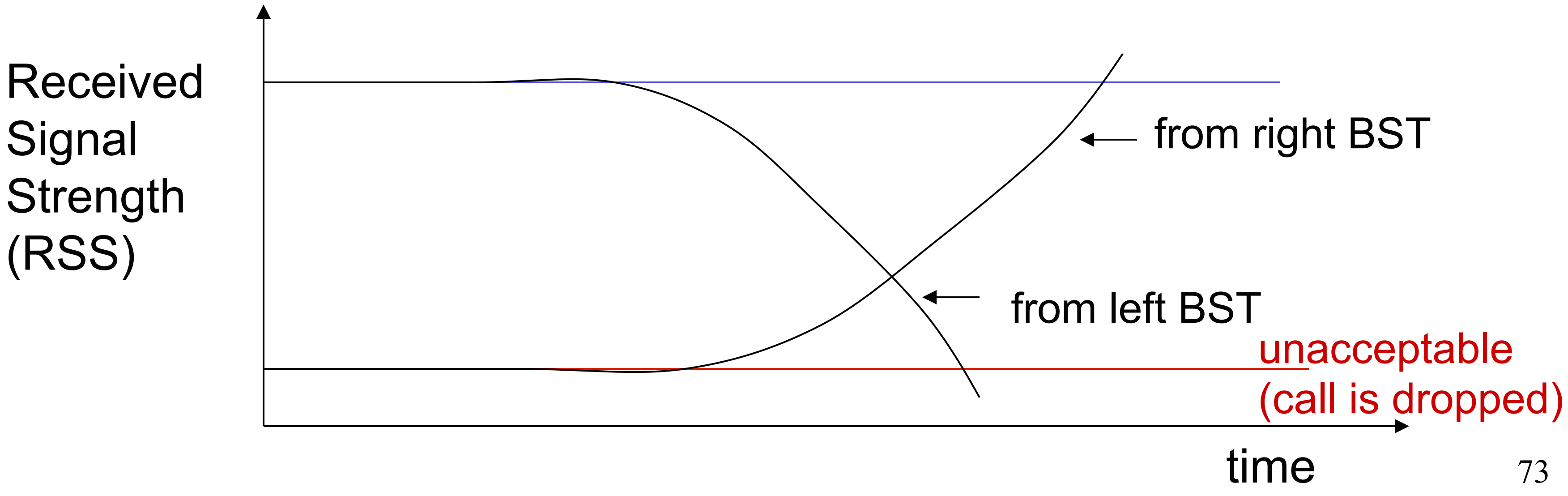
For the cellular band, B_c is around 100 to 300 kHz.
How does this compare with the bandwidth of cellular systems?

Fading Experienced by Wireless Systems

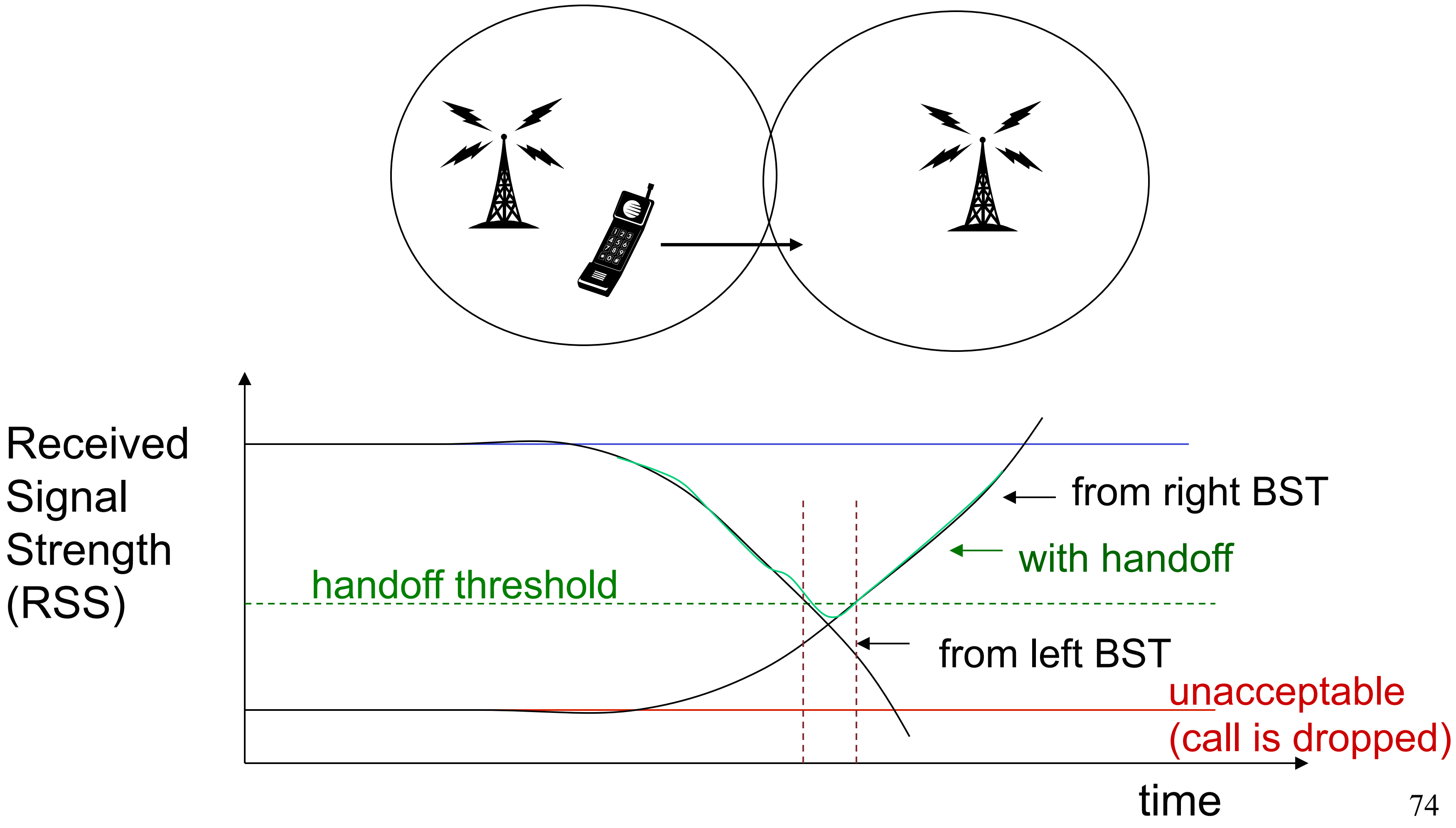
Standard	Bandwidth	Fade rate
AMPS	30 kHz (NB)	Fast
IS-136	30 kHz	Fast
GSM	200 kHz	Slow
IS-95 (CDMA)	1.25 MHz (WB)	Fast
3G	1.25-5 MHz	Slow to Fast (depends on rate)
LTE	up to 20 MHz	Slow
802.11	> 20 MHz	Slow
Bluetooth	> 5 MHz (?)	Slow

Propagation and Handoff





Propagation and Handoff



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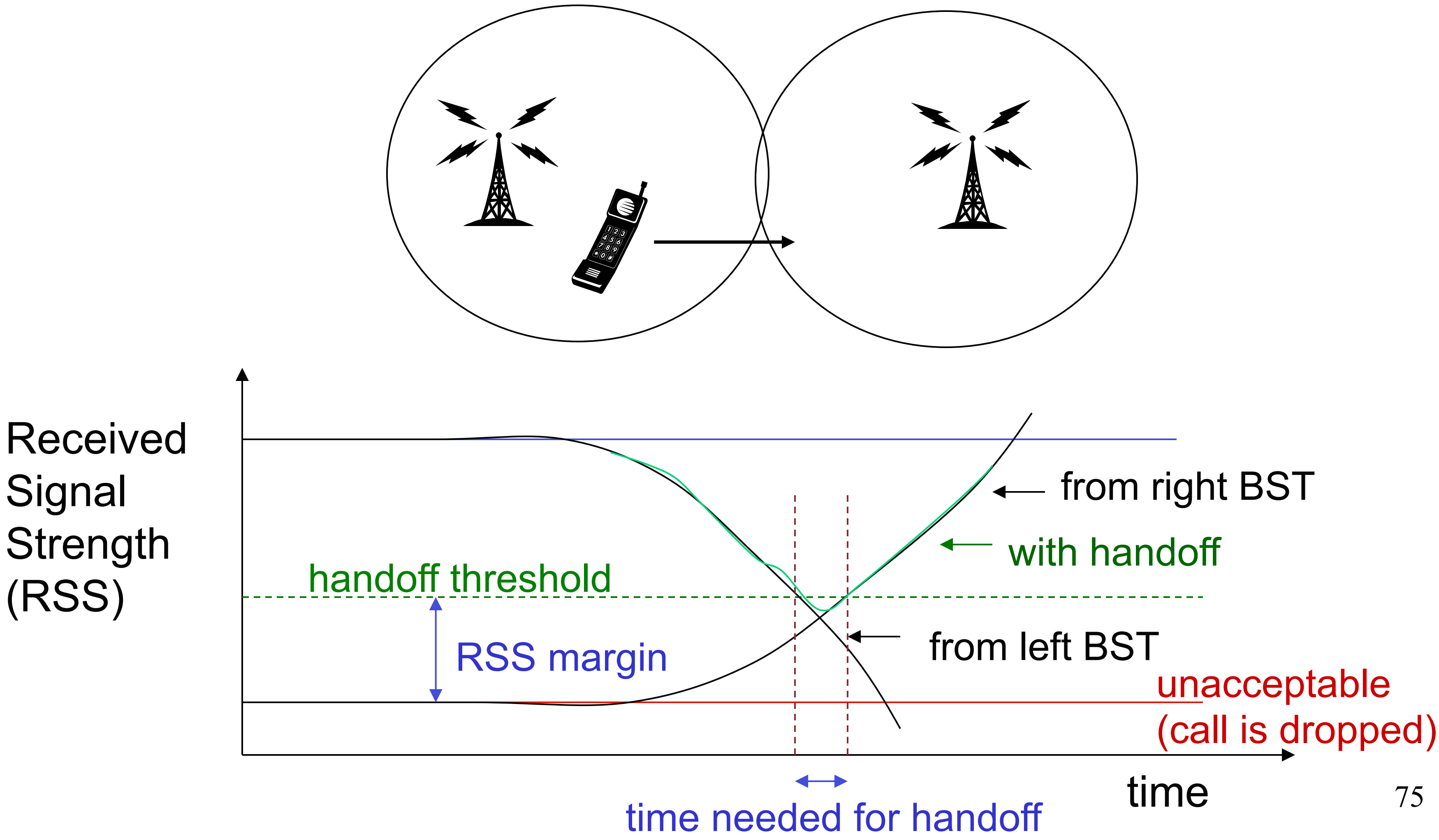

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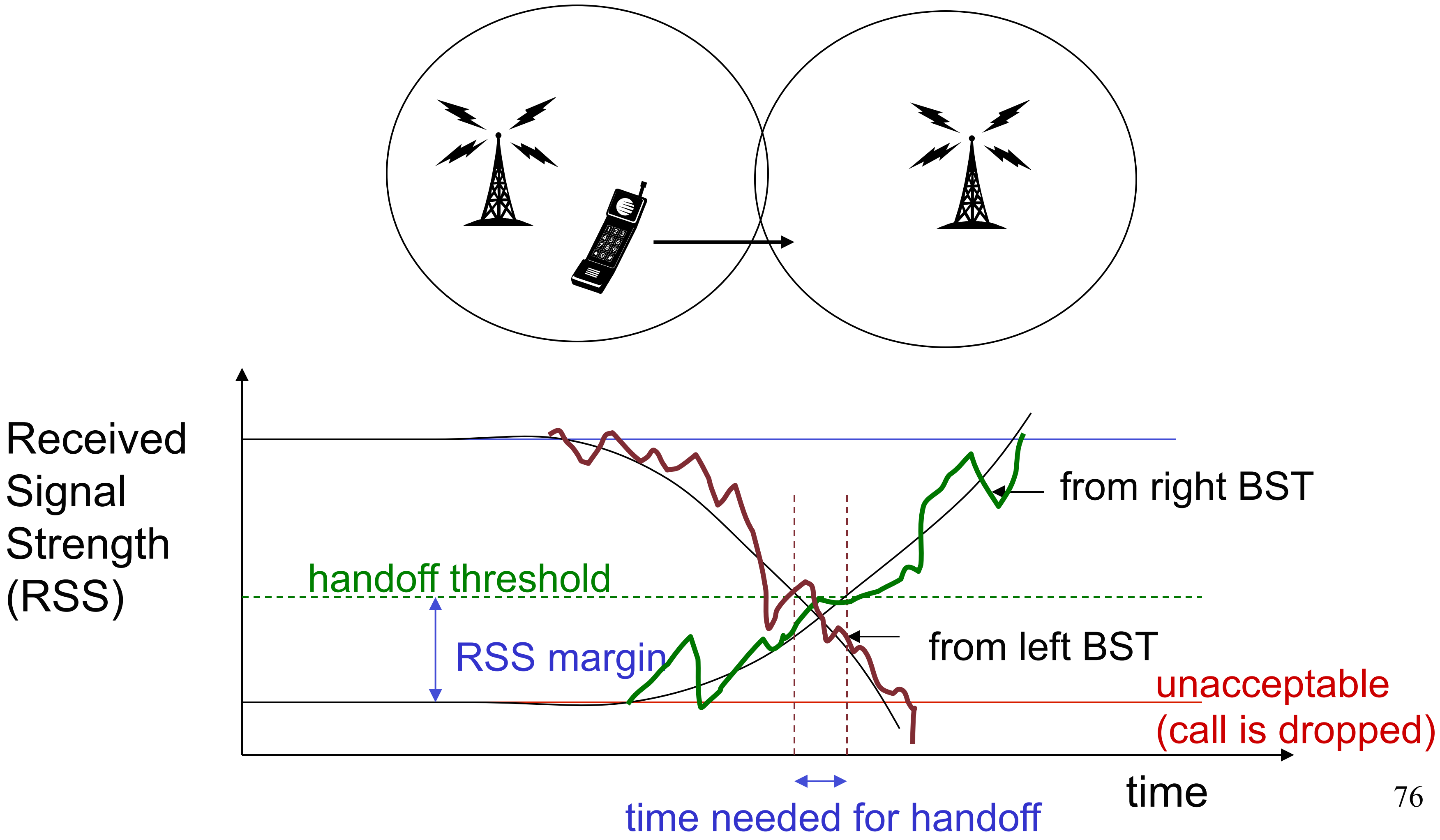
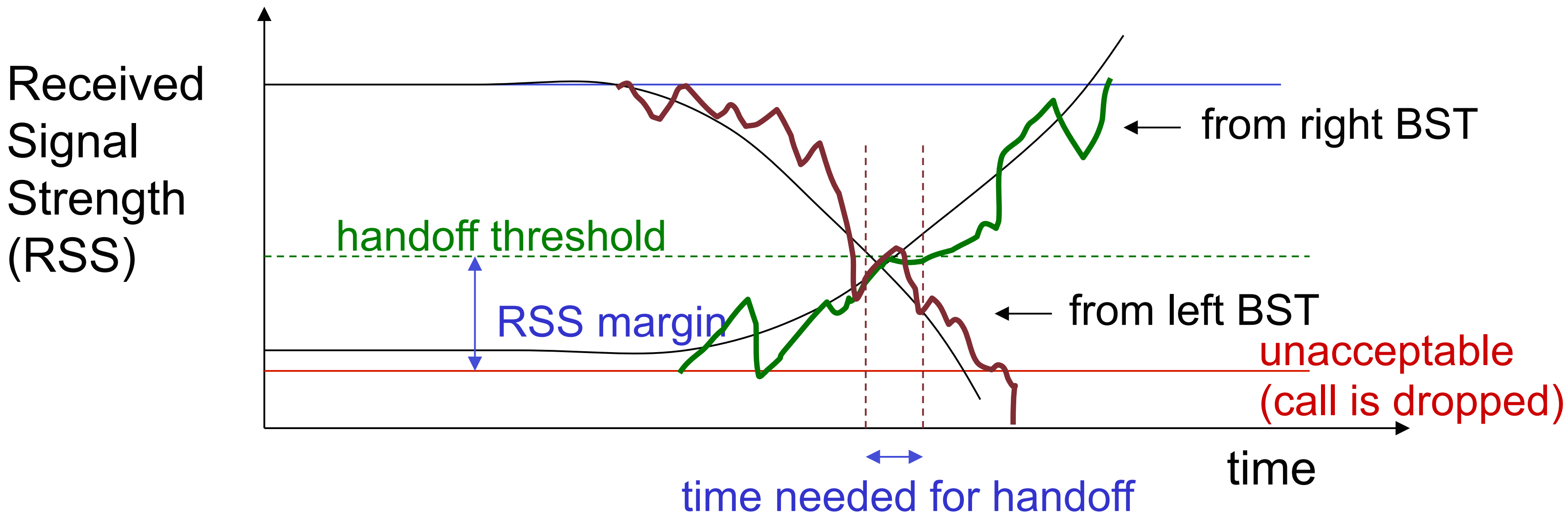


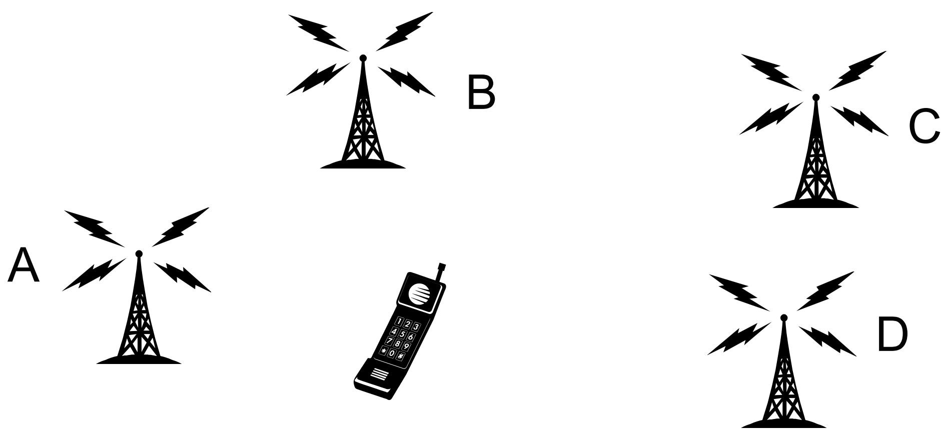
Handoff Threshold



- Handoff threshold too high ➔ too many handoffs (ping pong)
- Handoff threshold too low ➔ dropped calls are likely
- Threshold should depend on slope on vehicle speed (Doppler).

Handoff Measurements (3G)

- Mobile maintains a list of neighbor cells to monitor.
- Mobile periodically measures signal strength from BST pilot signals.
- Mobile sends measurements to network to request handoff.
- Handoff decision is made by network.



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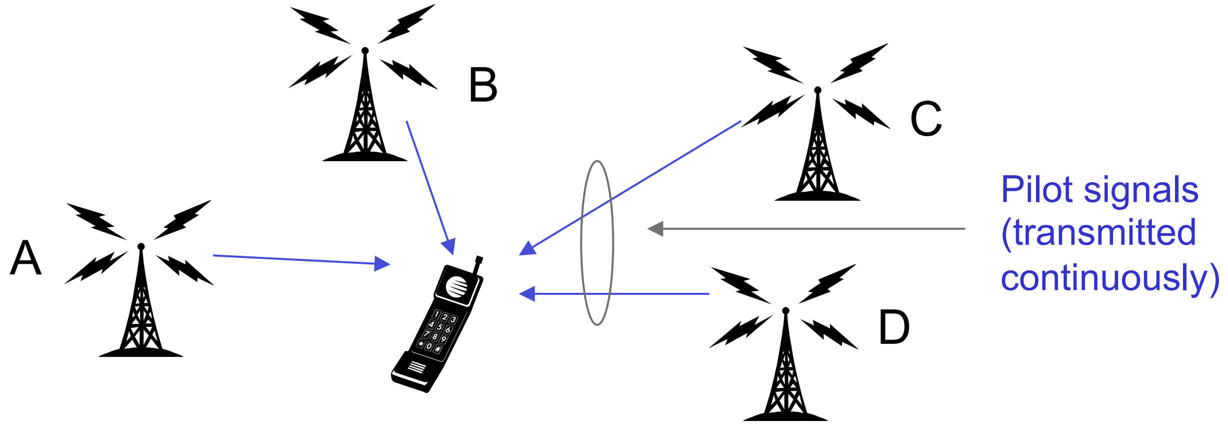

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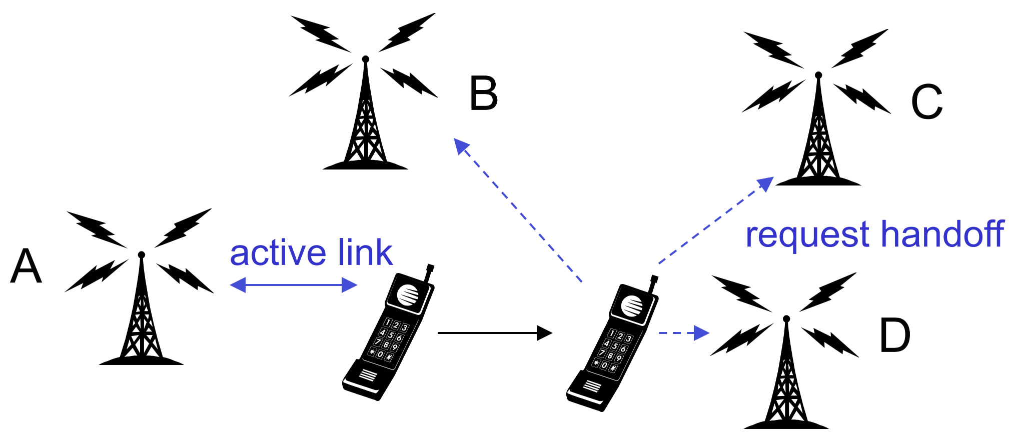

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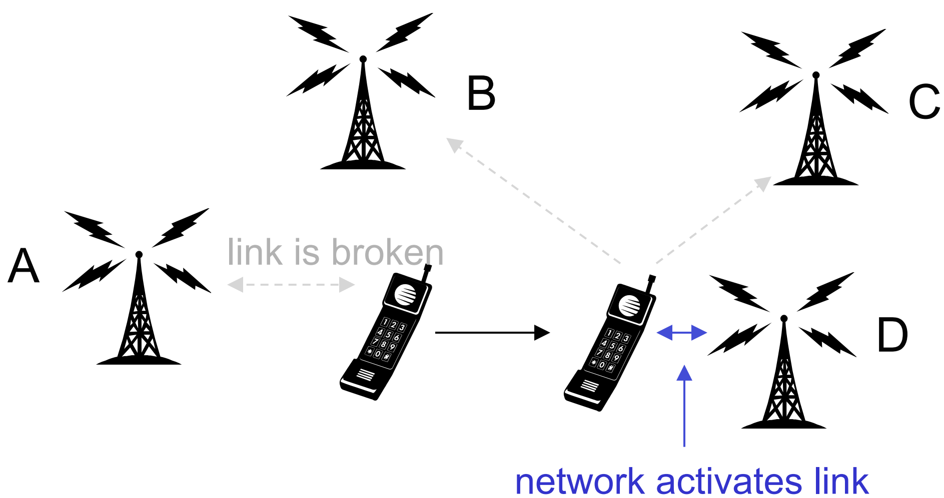

Handoff Measurements (3G)

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- Mobile periodically measures signal strength from BST pilot signals.
- Mobile sends measurements to network to request handoff.
- Handoff decision is made by network.
  - Depends on available resources (e.g., channels/time slots/codes). Handoffs take priority over new requests (why?).
  - Hysteresis needed to avoid handoffs due to rapid variations in signal strength.