ECS 455 Chapter 1

Introduction & Review

1.3 Wireless Channel (Part 1)

↙ Radio

Severe challange for reliable high speed communication.

- noise
- interference

> time-varying

Office Hours:
BKD 3601-7
Wednesday 15:30-16:30
Friday 9:30-10:30

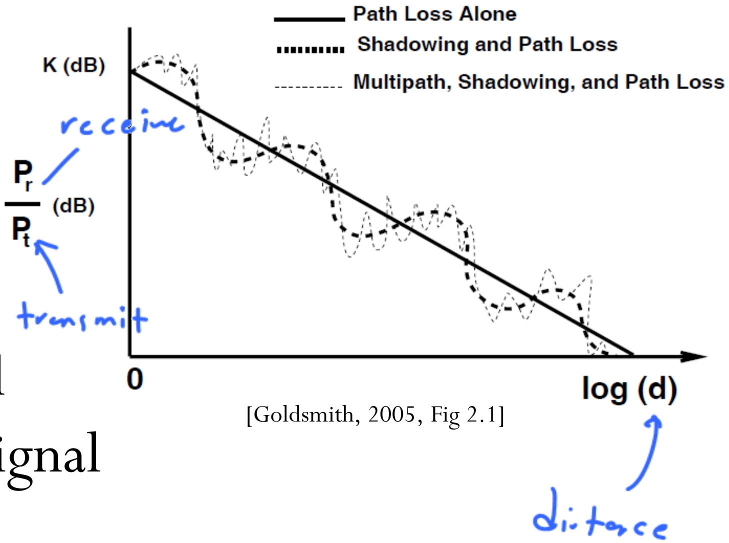
m

Wireless Channel

Section 1.3 focuses on

- ① **Large-scale** propagation effects
  - (1.1) Path loss
  - (1.2) Shadowing
  - Typically frequency independent
- ② **Small-scale** propagation effects
  - Variation due to the constructive and destructive addition of **multipath** signal components.
  - Occur over very short distances, on the order of the signal wavelength.

will be discussed after midterm



[Goldsmith, 2005, Fig 2.1]

$$\boxed{\lambda = \frac{c}{f}} \qquad c \approx 3\times10^8 \text{ [m/s]}$$

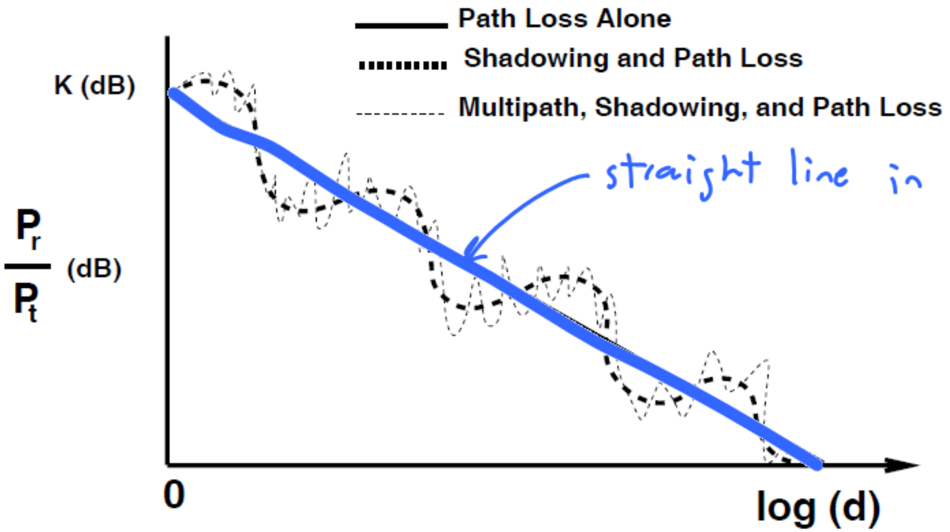
f = 3 GHz → $\lambda = 0.1$ m

(1.1) Path loss

- Caused by
  - dissipation of the power radiated by the transmitter
  - effects of the propagation channel
- Models generally assume that it is the same at a given transmit-receive distance.

(Need to move over large distance to observe its effect.)

- Variation occurs over **large distances** (100-1000 m)



straight line in log-log plot.

[Goldsmith, 2005, Fig 2.1]

① 1.1 Path Loss

To find Power P in dB,
take $10 \log_{10} P$

$$P_L = \frac{\text{Transmitted power}}{\text{Average received power}} = \frac{P_t}{P_r}$$

$P_L[dB] = P_t[dB] - P_r[dB]$

Path Gain

$P_G = \frac{1}{P_L}$

$P_G[dB] = -P_L[dB]$

Averaged over any random variations due to shadowing

- **Free-Space Path Loss:**

$$\frac{P_r}{P_t} \propto \frac{1}{d^{2}}$$

$P_r = \text{some constant} \times \frac{1}{d^2} \times P_t$

  - P_r falls off inversely proportional to the square of the distance d between the Tx and Rx antennas.
  - For other signal propagation models, P_r falls off more quickly relative to d.

- **Simplified** Path Loss Model:

$$\frac{P_r}{P_t} = K\left(\frac{d_0}{d}\right)^{\gamma} = \frac{K(d_0)^{\gamma}}{d^{\gamma}}$$

Loss [dB]

$$10 \log_{10} \frac{P_r}{P_t} = \overset{\text{constant}}{\boxed{10 \log_{10}(K d_0^{\gamma})}} \overset{\text{slope}}{\boxed{-10\gamma}} \log_{10} d$$

Friss Equation

1 for non-directional antennas

- One of the most fundamental equations in antenna theory

$$\frac{P_r}{P_t} = \left(\frac{\sqrt{\overset{1}{G_{Tx}G_{Rx}}}\,\lambda}{4\pi d}\right)^2 = \left(\frac{\sqrt{G_{Tx}G_{Rx}}\,c}{4\pi df}\right)^2 \propto \frac{1}{d^2 f^2} = \frac{\lambda^2}{d^2}$$

- More power is lost at higher frequencies.

$$2.4\text{ GH} \longrightarrow 5\text{ GHz} \longrightarrow 60\text{ GHz}$$

6.4 dB loss $20\log_{10}\frac{5}{2.4}$

21.6 dB loss $20\log_{10}\frac{60}{5}$

- Some of these losses can be offset by reducing the maximum operating range. The remaining loss must be compensated for by increasing the antenna gain.

Path Loss Models

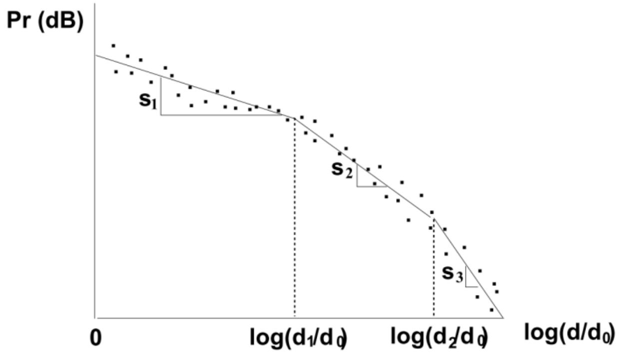
- Analytical models
  - Maxwell's equations
  - Ray tracing

} prohibitive

complex, impractical
Need to know/specify
"almost everything"
about the environment

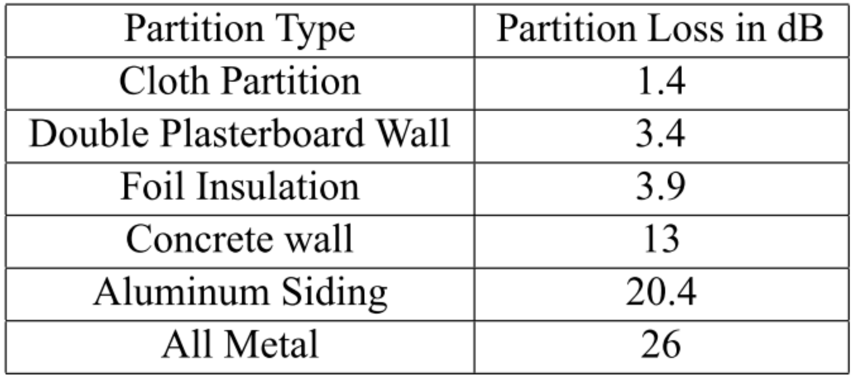
- Empirical models
  - Okumura
  - Hata
  - COST 231
    - by EURO-COST (EUROpean Cooperative for Scientific and Technical research)
  - Piecewise Linear (Multi-Slope) Model
- Tradeoff: Simplified Path Loss Model

Developed
to predict
path loss
in typical
environment.



Indoor Attenuation Factors

- Building penetration loss: 8-20 dB (better if behind windows)
- Attenuation between floors
  - @ 900 MHz
    - 10-20 dB when the Tx and Rx are separated by a single floor
    - 6-10 dB per floor for the next three subsequent floors
    - A few dB per floor for more than four floors
  - Typically worse at higher frequency.
- Attenuation across floors



Partition Type	Partition Loss in dB
Cloth Partition	1.4
Double Plasterboard Wall	3.4
Foil Insulation	3.9
Concrete wall	13
Aluminum Siding	20.4
All Metal	26

[Goldsmith, 2005, Sec. 2.5.5]

Simplified Path Loss Model

$$\frac{P_r}{P_t} = K\left(\frac{d_0}{d}\right)^{\gamma}$$

Captures the essence of signal propagation without resorting to complicated path loss models, which are only approximations to the real channel anyway!

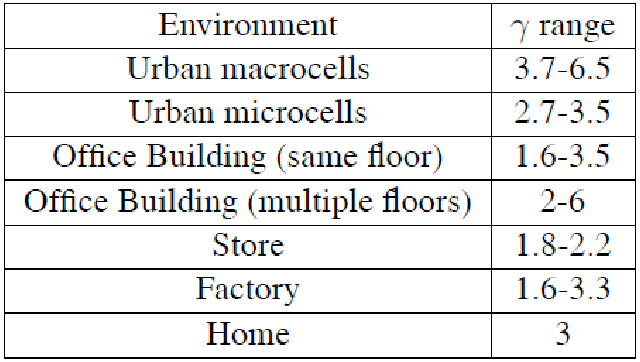
- K is a unitless constant which depends on the antenna characteristics and the average channel attenuation
  - $\left(\frac{\lambda}{4\pi d_0}\right)^2$ for free-space path gain at distance d_0 assuming omnidirectional antennas
- d_0 is a reference distance for the antenna far-field
  - Typically 1-10 m indoors and 10-100 m outdoors.
- γ is the **path loss exponent**.

(Near-field has scattering phenomena.)

[Goldsmith, 2005, Table 2.2]

Path Loss Exponent γ

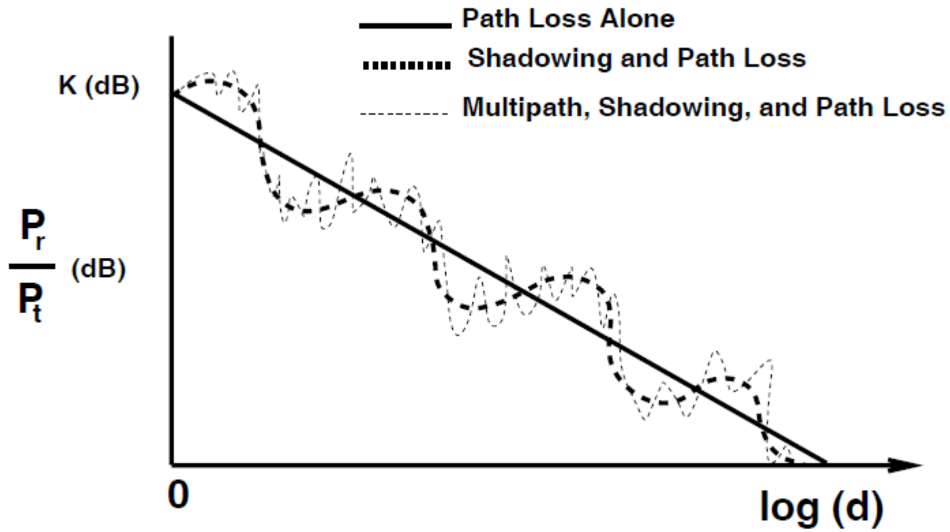
- 2 in free-space model
- 4 in two-ray model
  [Goldsmith, 2005, eq. 2.17]
- Cellular: 3.5 – 4.5
  [Myung and Goodman, 2008 , p 17]
- Larger @ higher freq.
- Lower @ higher antenna heights



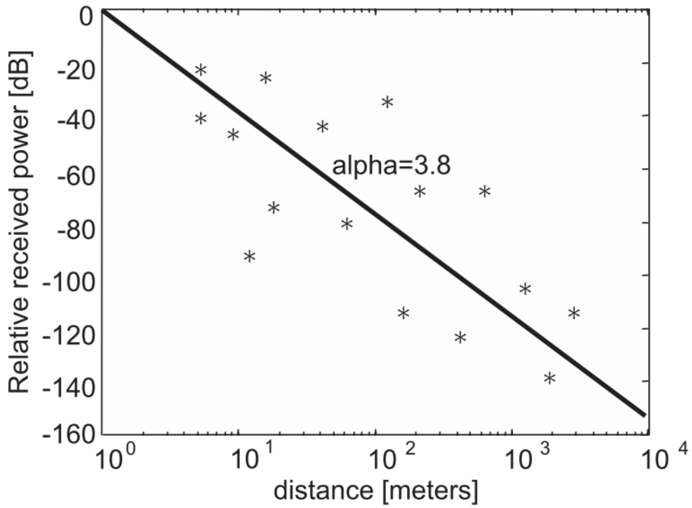
Environment	γ range
Urban macrocells	3.7-6.5
Urban microcells	2.7-3.5
Office Building (same floor)	1.6-3.5
Office Building (multiple floors)	2-6
Store	1.8-2.2
Factory	1.6-3.3
Home	3

(1.2) Shadowing (or Shadow Fading)

- Caused by **obstacles** (**large objects** such as buildings and hills) between the transmitter and receiver.
  - Think: cloud blocking sunlight
- Attenuate signal power through absorption, reflection, scattering, and diffraction.
- Variation occurs over distances proportional to the length of the obstructing object (**10-100 m** in outdoor environments and less in indoor environments).

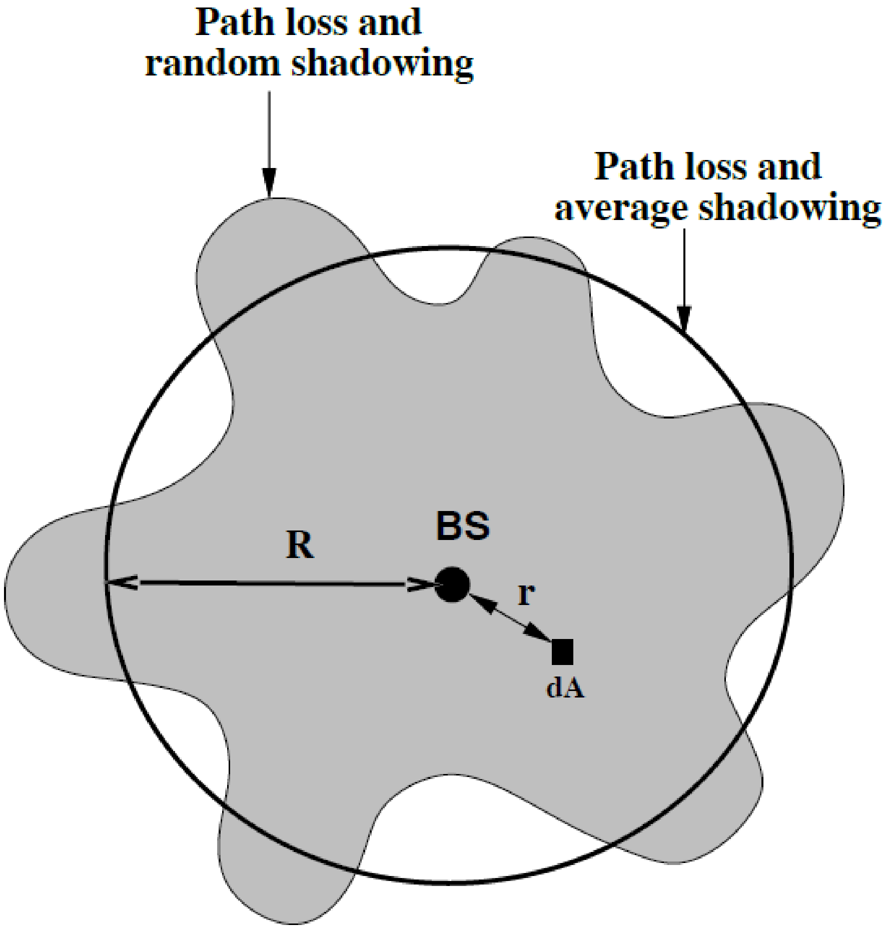


[Goldsmith, 2005, Fig 2.1]



[Myung and Goodman, 2008, Fig 2.1]

Contours of Constant Received Power



[Goldsmith, 2005, Fig 2.10]

$$X \longrightarrow \Box \xrightarrow{F_1 X} \Box \xrightarrow{F_2 F_1 X} \Box \xrightarrow{F_3 F_2 F_1 X} \Box \longrightarrow \cdots Y = F_1 \times F_2 \times F_3 \times \cdots \times F_N \times X$$

Log-normal shadowing

$$Y[dB] = \underbrace{\sum_i F_i[dB]}_{\sim \mathcal{N}} + X[dB]$$

- Random variation due to blockage from objects in the signal path and changes in reflecting surfaces and scattering objects → random variations of the received power at a given distance

$$10\log_{10}\frac{P_t}{P_r} \sim \mathcal{N}\left(\mu,\sigma^2\right)$$

4 – 13 dB with higher values in urban areas and lower ones in flat rural environments.

in dB

- This model has been confirmed empirically to accurately model the variation in received power in both outdoor and indoor radio propagation environments.

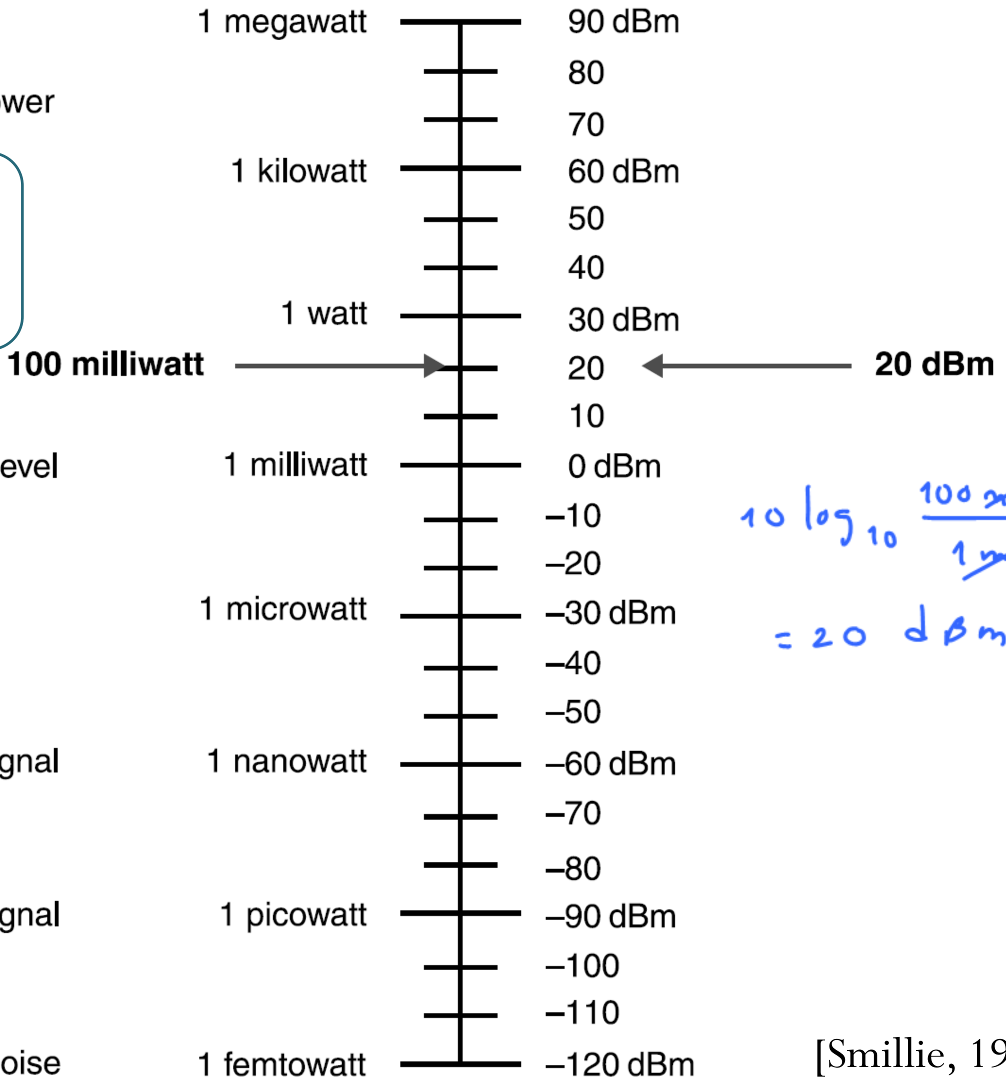
dBm

- The range of RF power that must be measured in cellular phones and wireless data transmission equipment varies from
  - hundreds of watts in base station transmitters to
  - picowatts in receivers.
- For calculations to be made, all powers must be expressed in the same power units, which is usually **milliwatts**.
  - A transmitter power of 100 W is therefore expressed as 100,000mW. A received power level of 1 pW is therefore expressed as 0.000000001mW.
- Making power calculations using decimal arithmetic is therefore complicated.
- To solve this problem, the dBm system is used

[Scott and Frobenius, 2008, Fig 1.1]

Range of RF Power in Watts and dBm

$$P\ [W] = 10\log_{10}\frac{P}{1mW}\ [dBm]$$



	1 megawatt	90 dBm	
		80	
Transmitter Power			
		70	
	1 kilowatt	60 dBm	
		50	
		40	
	1 watt	30 dBm	
	100 milliwatt →	20	← **20 dBm**
		10	
Reference Level	1 milliwatt	0 dBm	
		–10	
		–20	
	1 microwatt	–30 dBm	
		–40	
		–50	
Lowest Measureable Signal	1 nanowatt	–60 dBm	
		–70	
		–80	
Received Signal	1 picowatt	–90 dBm	
		–100	
		–110	
Noise	1 femtowatt	–120 dBm	

$10\log_{10}\frac{100\ \cancel{mW}}{1\ \cancel{mW}}$

$= 20$ dBm

[Smillie, 1999, p 11]

Doppler Shift: 1D Move

- At distance $d = 0$, suppose we have

$$A_0 \cos\left(2\pi ft + \phi\right)$$

- At distance r, we have

$$A_r \cos\left(\overbrace{2\pi f\left(t - \frac{r}{c}\right)}^{\theta(t)} + \phi\right)$$

Time to travel a distance of *r*

Instantaneous freq.

$$f(t) = \frac{1}{2\pi}\theta'(t) = \underset{\uparrow}{f} - \frac{f}{c}r'(t)$$

$$= f - \frac{1}{\lambda}r'(t)$$

- If moving, r becomes $r(t)$.

$$A_r \cos\left(2\pi f\left(t - \frac{r(t)}{c}\right) + \phi\right)$$

- If moving ***away*** at a constant velocity v, then $r(t) = r_0 + vt$.

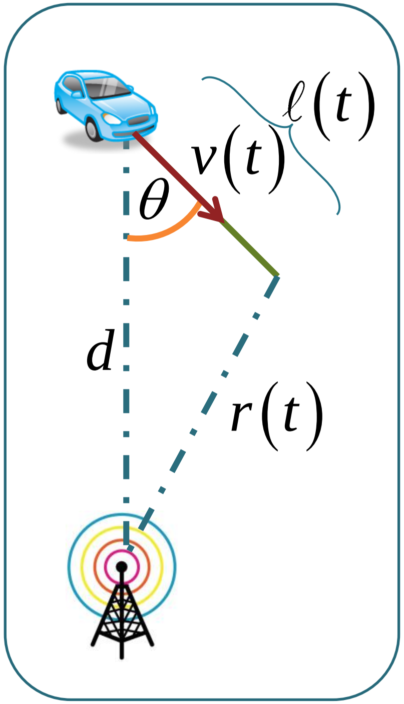
$$A_{r(t)} \cos\left(2\pi f\left(t - \frac{r_0 + vt}{c}\right) + \phi\right) = A_{r(t)} \cos\left(2\pi\left(f - f\frac{v}{c}\right)t - 2\pi f\frac{r_0}{c} + \phi\right)$$

Frequency shift

$$\Delta f = \frac{v}{\lambda}$$

Doppler Shift: With angle

Rx speed = $v(t)$. At time t, cover distance $\ell(t) = \int_0^t v(\tau)d\tau$



$$r(t) = \sqrt{d^2 + \ell^2(t) - 2d\ell(t)\cos\theta}$$

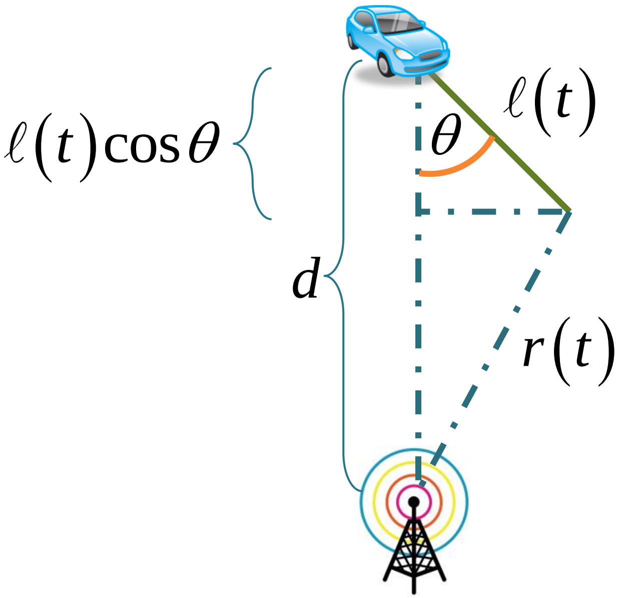
$$\frac{d}{dt}r(t) = \frac{2\ell(t) - 2d\cos\theta}{2\sqrt{d^2 + \ell^2(t) - 2d\ell(t)\cos\theta}}v(t)$$

$$\left.\frac{d}{dt}r(t)\right|_{t=0} = -\cos\theta v(0)$$

$$f_{\text{new}}(t) = f - \frac{1}{\lambda}\frac{d}{dt}r(t)$$

$$f_{\text{new}}(0) = f + \underbrace{\frac{1}{\lambda}\cos\theta v(0)}_{\textbf{Frequency shift}}$$

Doppler Shift: Approximation



$$r(t) \approx d - \ell(t)\cos\theta$$

$$\frac{d}{dt} r(t) \approx -v(t)\cos\theta$$

$$f_{\text{new}}(t) \approx f + \frac{v(t)\cos\theta}{\lambda}$$

$$\Delta f = \frac{v\cos\theta}{\lambda}$$

For typical vehicle speeds (75 Km/hr) and frequencies (around 1 GHz), it is on the order of 100 Hz 70 Hz

100 km/hr, 2GHz → 185 Hz.

[Goldsmith, 2005, Fig 2.2]

Big Picture

Transmission impairments in cellular systems

Physics of radio propagation	✓Attenuation (Path Loss) ✓Shadowing ✓Doppler shift Inter-symbol interference (ISI) Flat fading Frequency-selective fading
Extraneous signals	Co-channel interference Adjacent channel interference Impulse noise White noise
Transmitting and receiving equipment	White noise Nonlinear distortion Frequency and phase offset Timing errors

[Myung and Goodman, 2008, Table 2.1]