Wireless Communications SSY135 – Lecture 2

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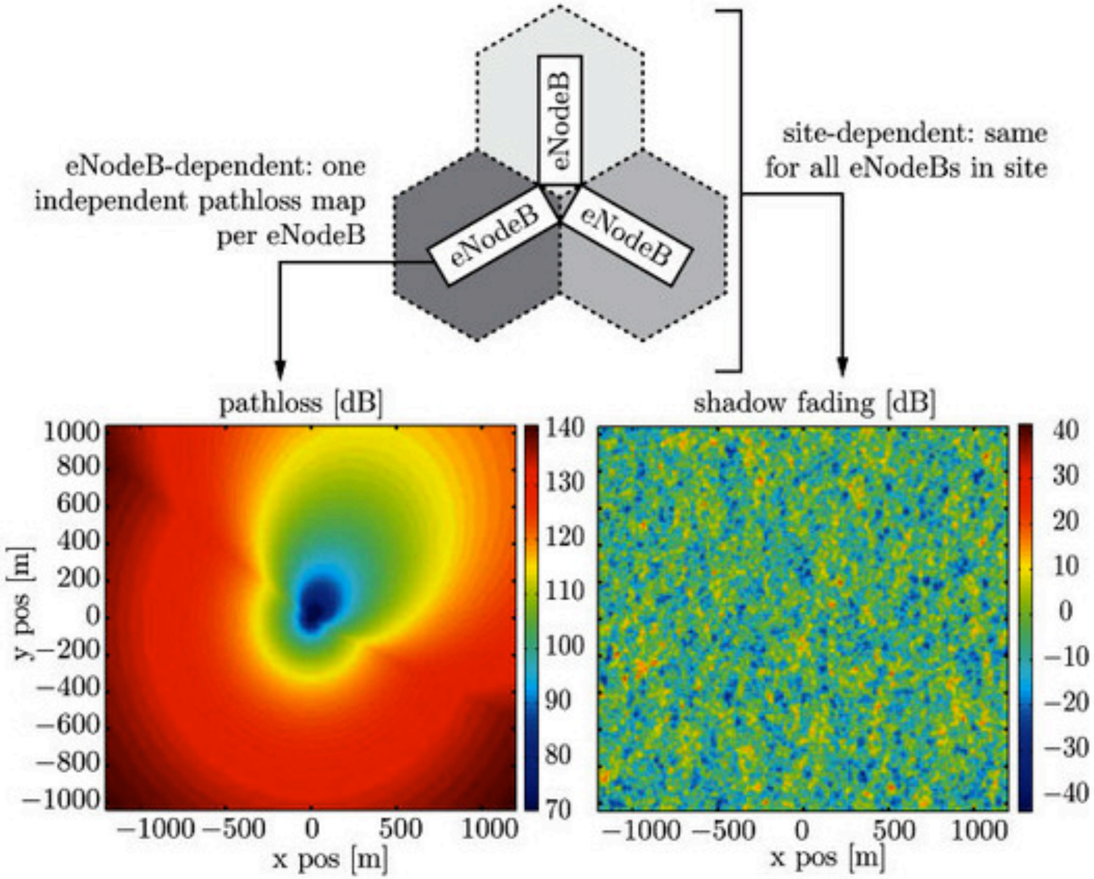
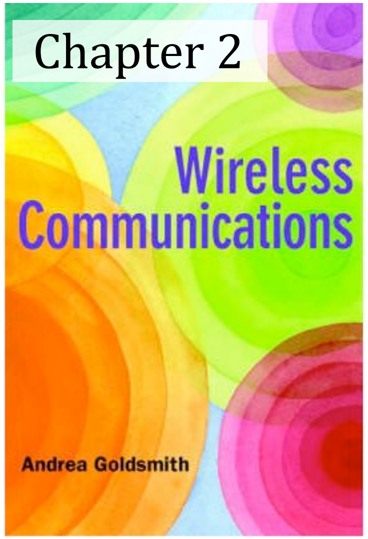


Topics for today

- Lecture learning outcomes
- Antenna basics
- Path loss, shadowing, multipath fading
- Path loss models
- Shadowing models, outage computation
- Small-scale fading introduction



Suggested reading:
- Every section from Chapter 2
- No derivations from sections 2.4, 2.5, 2.10

Today's learning outcomes

At the end of this lecture, you must be able to

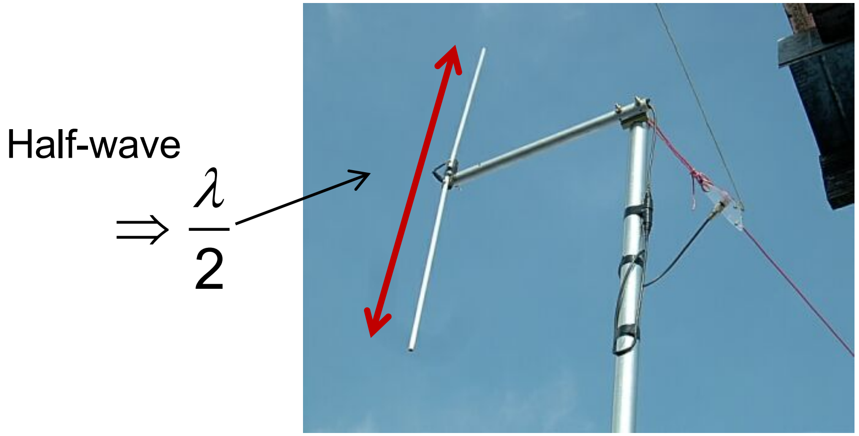
- state and interpret Friis' law
- state the differences between path loss, shadowing, and multipath fading
- mathematically describe at least two path loss models
- compute outage probabilities due to shadowing and path loss

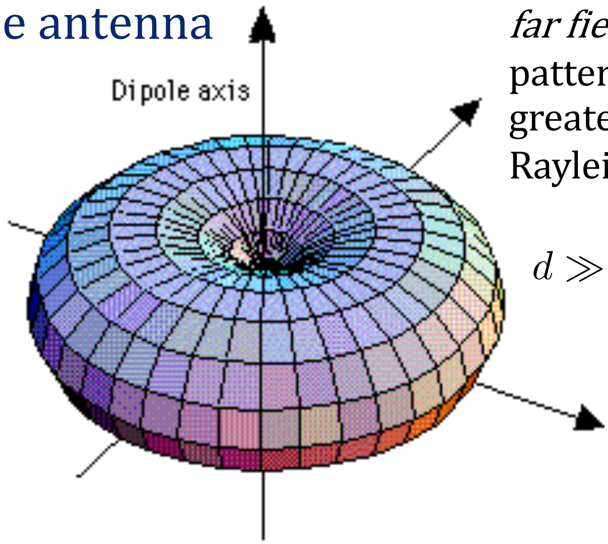
Radio wave propagation

- In principle: Maxwell's equations
- We will work with simple models in far field (plane waves)

Point Form	Integral Form
$\nabla \times \mathbf{H} = \mathbf{J}_c + \frac{\partial \mathbf{D}}{\partial t}$	$\oint \mathbf{H} \cdot d\mathbf{l} = \int_S \left(\mathbf{J}_c + \frac{\partial \mathbf{D}}{\partial t}\right) \cdot d\mathbf{S}$ (Ampère's law)
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint \mathbf{E} \cdot d\mathbf{l} = \int_S \left(-\frac{\partial \mathbf{B}}{\partial t}\right) \cdot d\mathbf{S}$ (Faraday's law; S fixed)
$\nabla \cdot \mathbf{D} = \rho$	$\oint_S \mathbf{D} \cdot d\mathbf{S} = \int_v \rho \, dv$ (Gauss' law)
$\nabla \cdot \mathbf{B} = 0$	$\oint_S \mathbf{B} \cdot d\mathbf{S} = 0$ (nonexistence of monopole)

- Antenna example: half-wave linear dipole antenna





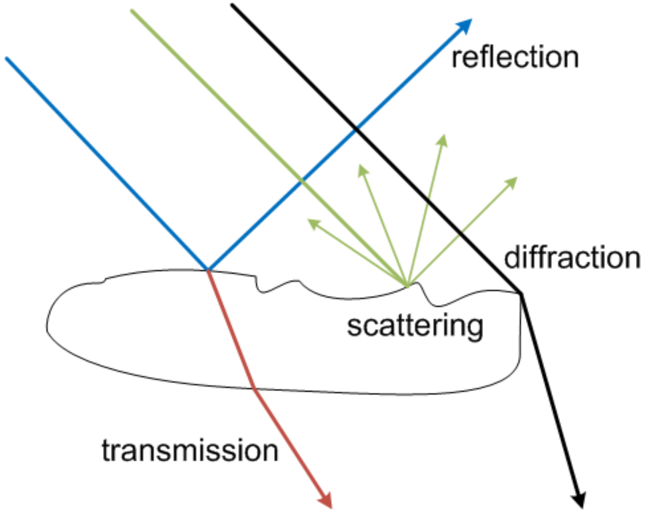
far field radiation pattern: distance greater than Rayleigh distance

$$d \gg \frac{2L_a^2}{\lambda}$$

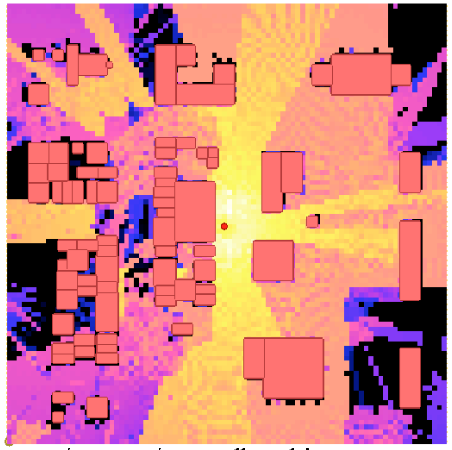
- Antennas have a far field pattern: directional or non-directional
- Simplified model: ray-based model

Radio wave propagation

- In practice: obstacles

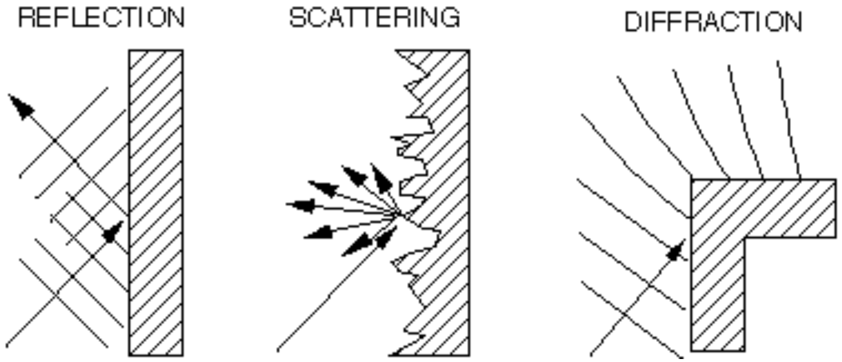


- Models based on ray tracing



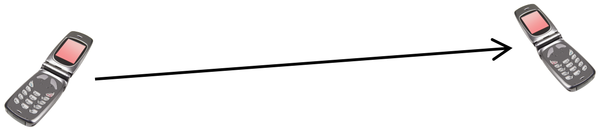
http://www.emagtech.com/content/groundbreaking-em-ray-tracer-wireless-propagation-modeling

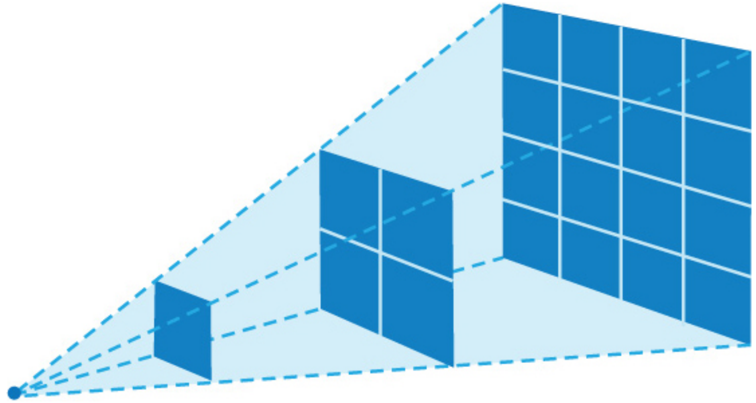
- **Reflection** on smooth surfaces
- **Transmission** through objects
- **Scattering** on rough surfaces
- **Diffraction** around sharp edges
- Smooth/rough, large/small are relative the wavelength
- Line-of-sight is not necessarily needed for communication
- Increasing frequency gives
  - more "optical" propagation
  - smaller antennas
  - higher path loss



http://interface.cipic.ucdavis.edu/images/research/waves2.gif

Ray tracing: 1 path





Model

$$r(t) = \mathrm{Re}\left\{ \frac{\lambda \sqrt{G_l} e^{-j2\pi d/\lambda}}{4\pi d} u(t) e^{j2\pi f_c t} \right\}$$

- Distance-dependent rotation
- Distance-dependent power decay
- Wavelength plays a role as does TX and RX antenna pattern

Friis' Law

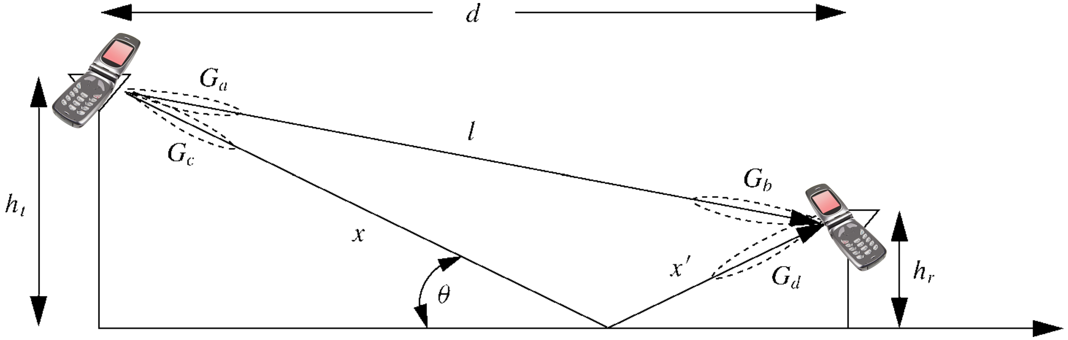
free space loss factor

$$P_{\mathrm{RX}}(d) = P_{\mathrm{TX}} G_{\mathrm{TX}} G_{\mathrm{RX}} \boxed{\left(\frac{\lambda}{4\pi d}\right)^2}$$

$$\begin{aligned} P_{\mathrm{RX}}(d)\ [\mathrm{dBm}] = {} & P_{\mathrm{TX}}\ [\mathrm{dBm}] + G_{\mathrm{TX}}\ [\mathrm{dB}] + G_{\mathrm{RX}}\ [\mathrm{dB}] \\ & + 20\log_{10}(\lambda) - 20\log_{10}(4\pi) - 20\log_{10}(d) \end{aligned}$$

Ray tracing: 2 paths

Model $$r_{\text{2-ray}}(t) = \mathrm{Re}\left\{\frac{\lambda}{4\pi}\left[\frac{\sqrt{G_l}u(t)e^{-j2\pi l/\lambda}}{l} + \frac{R\sqrt{G_r}u(t-\tau)e^{-j2\pi(x+x')/\lambda}}{x+x'}\right]e^{j2\pi f_c t}\right\},$$



- Each path has rotation, depending on path length
- Each path has gain, depending on distance, antenna pattern in LOS, NLOS direction, ground reflectivity

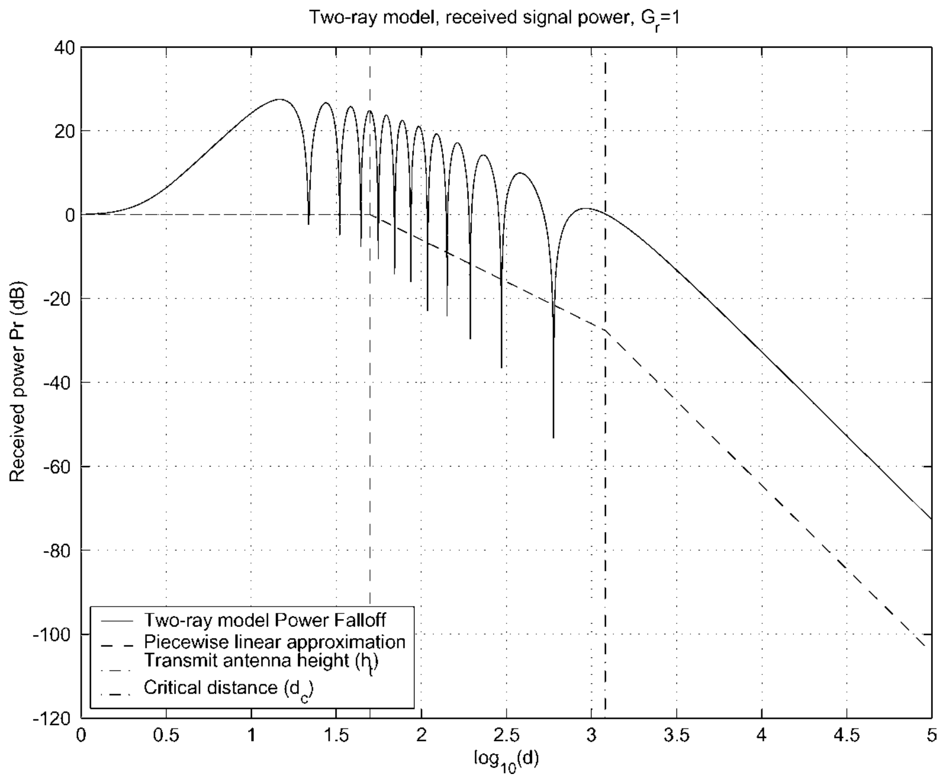
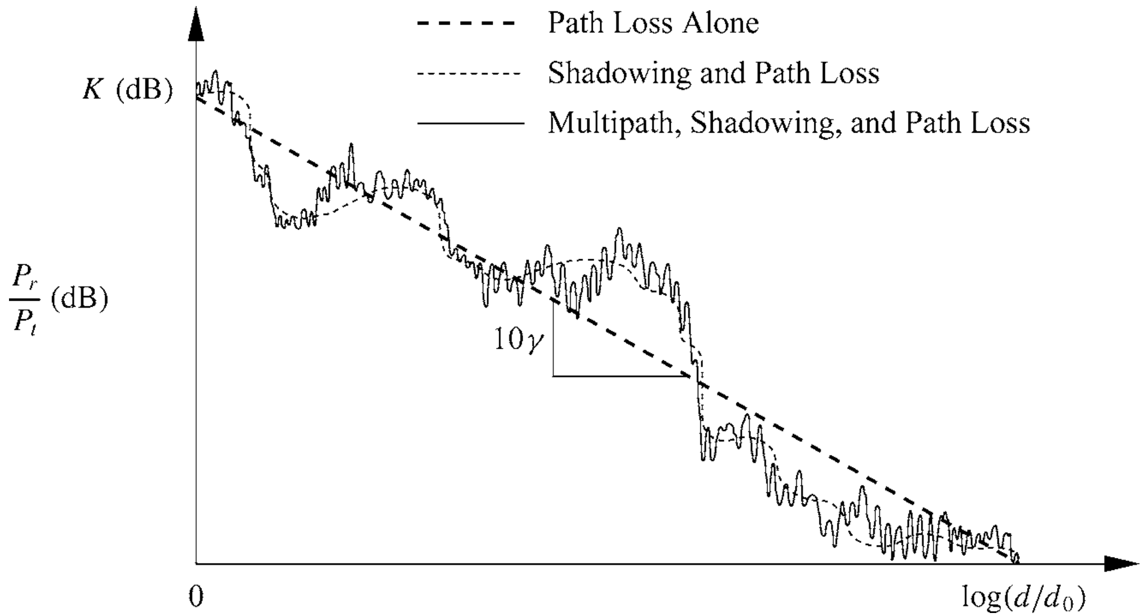


Figure 2.5: Received power versus distance for two-ray model.

Complex propagation environments: simplified model

3 components: path loss (d), shadowing (blockage), multipath (reflections, scattering, diffraction) add up in dB scale



3 models: suitable for system design and analysis

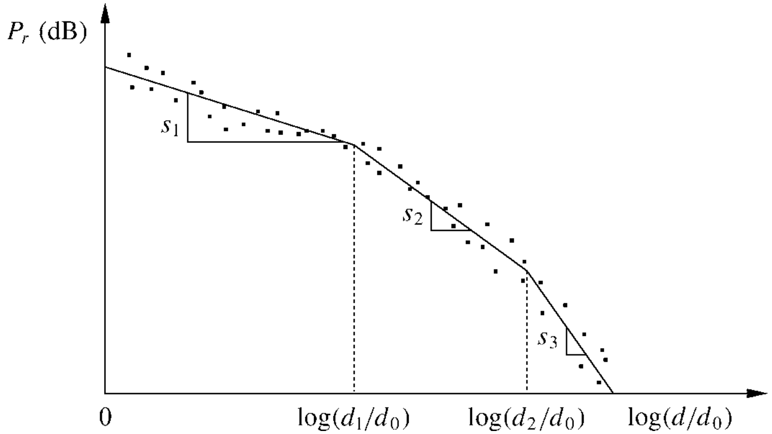
1. Path loss: deterministic
2. Shadowing: random, log-normal
3. Multipath fading: random

$$\boxed{\begin{aligned} P_r[\mathrm{dBm}] = P_t&[\mathrm{dBm}] \\ &+ \mathrm{pathloss}[\mathrm{dB}] \\ &+ \mathrm{shadowing}[\mathrm{dB}] \\ &+ \mathrm{multipath}[\mathrm{dB}] \end{aligned}}$$

Path loss

$$P_r[\text{dBm}] = P_t[\text{dBm}] \\ \boxed{+\,\text{pathloss}[\text{dB}]} \\ +\,\text{shadowing}[\text{dB}] \\ +\,\text{multipath}[\text{dB}]$$

- Many models for different environments (book sec. 2.5): urban, indoors



- Simple model for system analysis

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

$$P_r[\text{dBm}] = P_t[\text{dBm}] + K[\text{dB}] - 10\gamma \log_{10} \frac{d}{d_0}$$

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

Path loss

Given

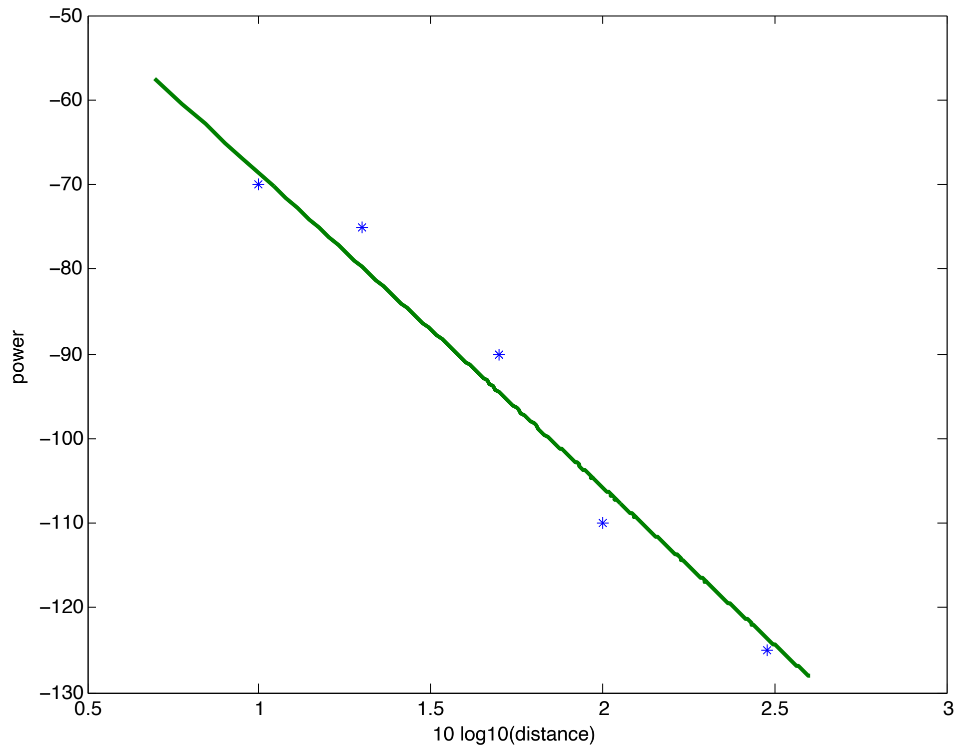
- Consider measurements of P_r/P_t below for an indoor system at 900 MHz
- Let d_0 =1 m and K given by $K \text{ dB} = 20\log_{10}\frac{\lambda}{4\pi d_0}$

Task

- Find the path-loss exponent that minimizes the MSE between the model and the dB measurements [answer 3.71]
- Find the received power at 150 m for $P_t = 1$ mW [answer -112 dBm]

Table 2.3: Path-loss measurements

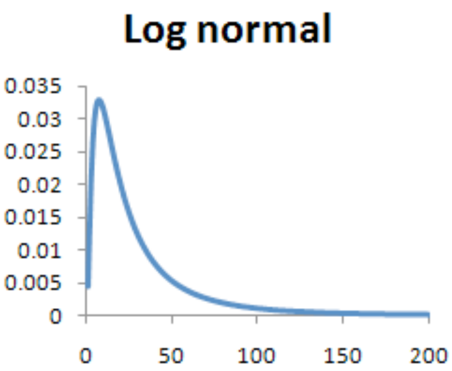
Distance from transmitter	$M = P_r/P_t$
10 m	−70 dB
20 m	−75 dB
50 m	−90 dB
100 m	−110 dB
300 m	−125 dB

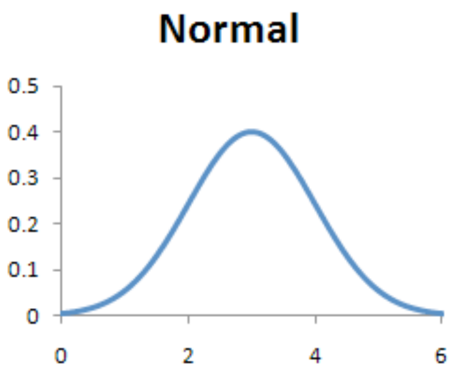


Shadowing

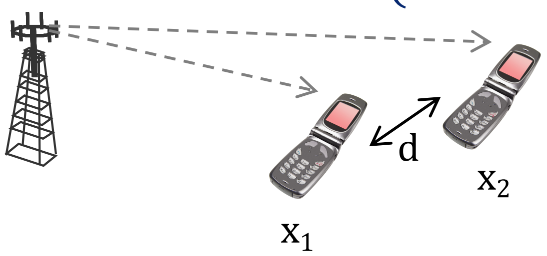
$$P_r[\text{dBm}] = P_t[\text{dBm}] + \text{pathloss}[\text{dB}] + \boxed{\text{shadowing}[\text{dB}]} + \text{multipath}[\text{dB}]$$

- Complex in practice, so again simplified model
- Large-scale variation around path loss
- Based on experimental data: log-normal
- In dB: $\psi_{\text{dB}} = 10\log_{10}\psi \sim \mathcal{N}(\mu_{\psi_{\text{dB}}}, \sigma^2_{\psi_{\text{dB}}})$
- Separate from path loss: $\psi_{\text{dB}} \sim \mathcal{N}(0, \sigma^2_{\psi_{\text{dB}}})$





- Gudmundson model (assuming $\psi_{\text{dB}} \sim \mathcal{N}(0, \sigma^2_{\psi_{\text{dB}}})$)



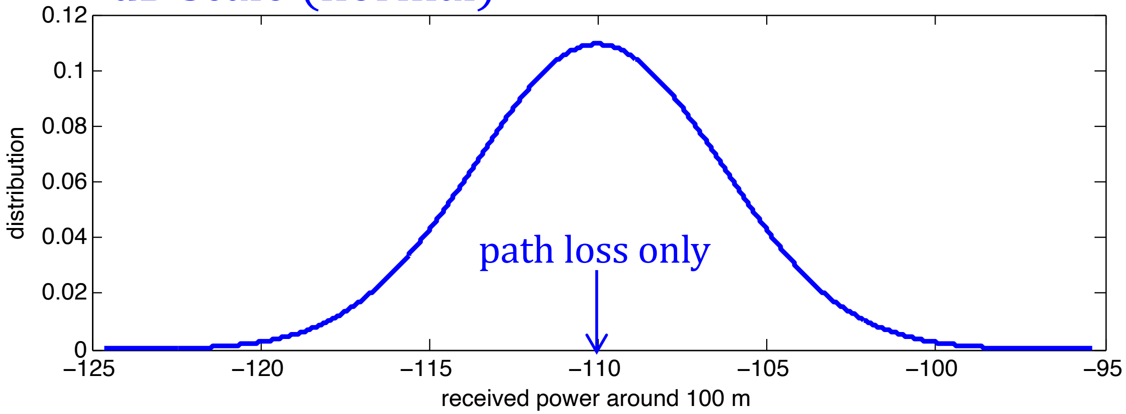
$$A(d) = \mathbb{E}\{\psi_{\text{dB}}(x_1)\psi_{\text{dB}}(x_2)\} = \sigma^2_{\psi_{\text{dB}}} e^{-\|x_1 - x_2\|/\boxed{X_c}}$$

decorrelation distance (50m-100 m)

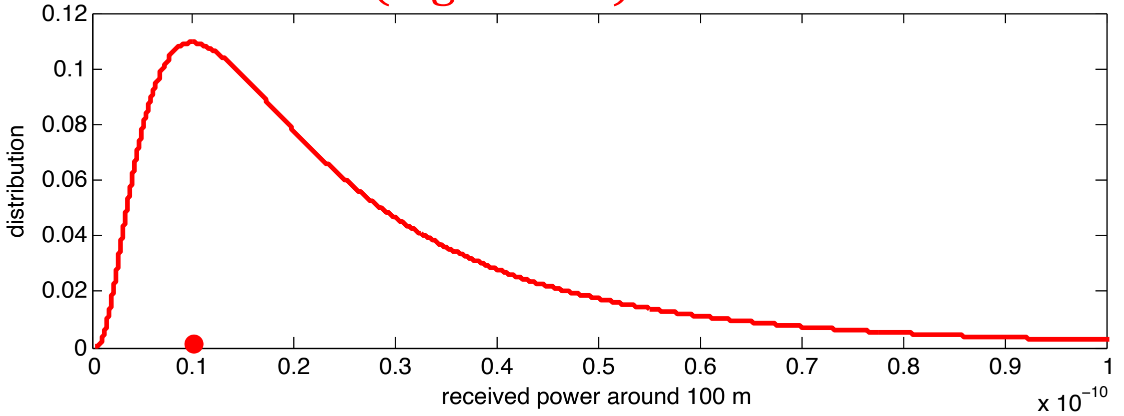
Normal and lognormal distribution

- Received power at 100 m due to path loss = -110 dBm (=0 dBm – 110 dB)
- Shadowing with standard deviation of 3.65 dB

dB scale (normal)



linear scale (lognormal)



Shadowing

Given

- Consider measurements of P_r/P_t below for an indoor system at 900 MHz, γ=3.71
- Let d_0 =1 m and K given by $K \text{ dB} = 20\log_{10}\dfrac{\lambda}{4\pi d_0}$

Table 2.3: Path-loss measurements

Distance from transmitter	$M = P_r/P_t$
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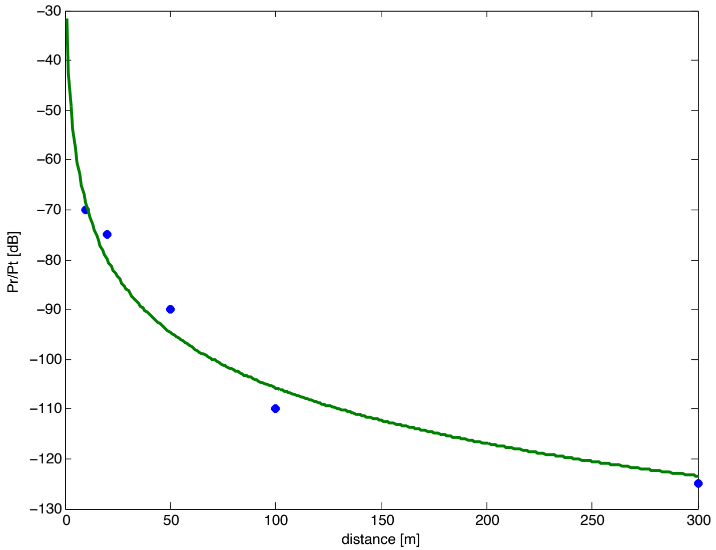
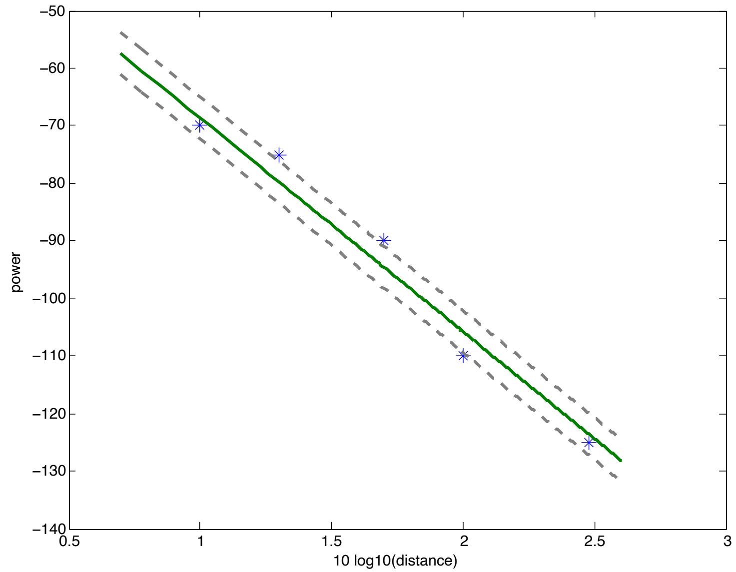


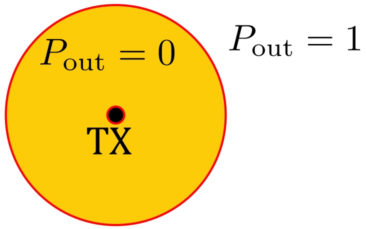


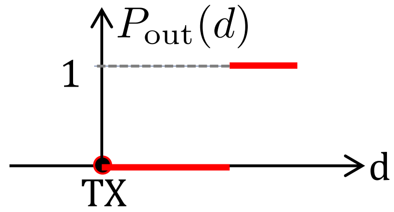
Task

- Find the shadowing variance around the path loss [answer 13.29]

Outage probability

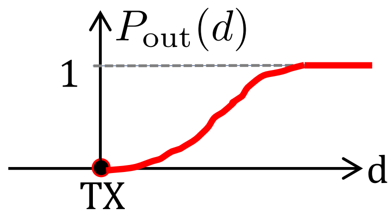
- Ignoring multipath, what is probability received power is above threshold? $P_{\text{out}} = p(P_r < P_{\min})$
- Path loss only:





- Path loss and shadowing:

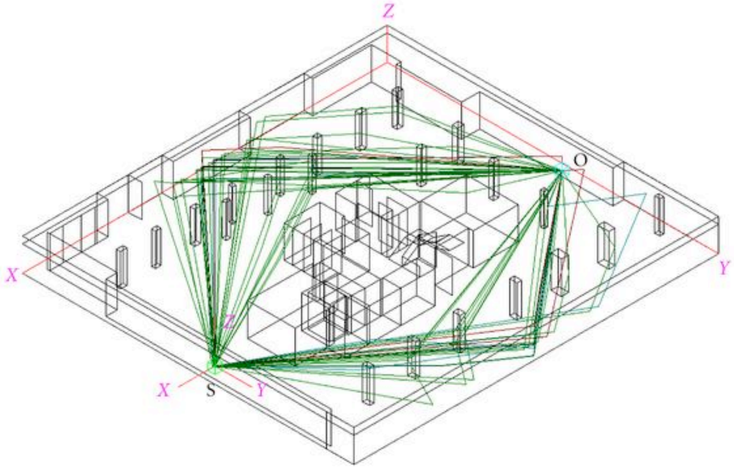
$$\begin{aligned}
P_{\text{out}}(x) &= p(P_r(x) \leq P_{\min}) \\
&= p(P_r(x)\ [\text{dBm}] \leq P_{\min}\ [\text{dBm}]) \\
&= p\left(P_t\ [\text{dBm}] + K\ [\text{dB}] - 10\gamma \log_{10}\frac{d}{d_0} + \overset{\text{Gaussian R.V.}}{\boxed{\psi_{\text{dB}}}} \leq P_{\min}\ [\text{dBm}]\right)
\end{aligned}$$

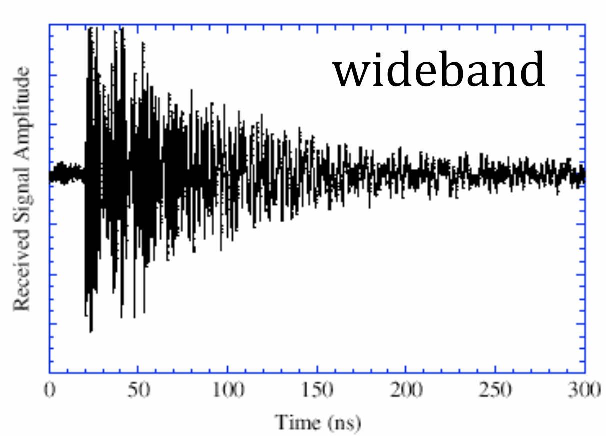


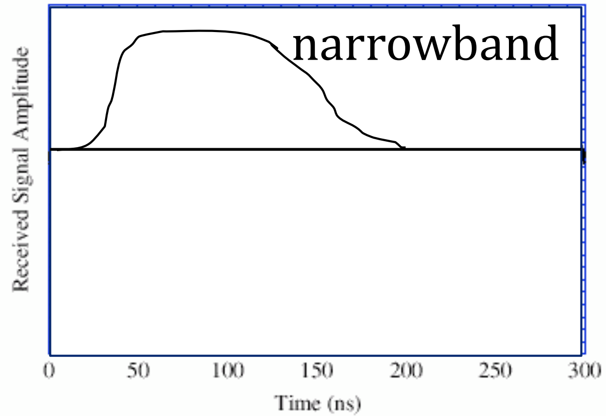
Multipath fading

$$P_r[\mathrm{dBm}] = P_t[\mathrm{dBm}] + \mathrm{pathloss}[\mathrm{dB}] + \mathrm{shadowing}[\mathrm{dB}] + \boxed{\mathrm{multipath}[\mathrm{dB}]}$$

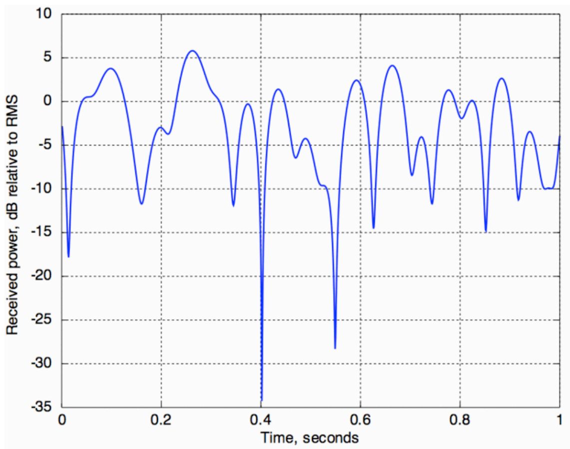
- Many signal paths add up

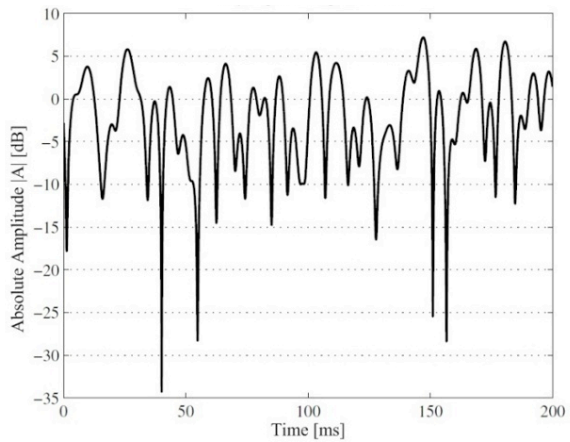






- Signal varies over time due to mobility





Today's learning outcomes

At the end of this lecture, you must be able to

- state and interpret Friis' law
- state the differences between path loss, shadowing, and multipath fading
- mathematically describe at least two path loss models
- compute outage probabilities due to shadowing and path loss

Path loss

Given

- Consider measurements of P_r/P_t below for an indoor system at 900 MHz
- Let d_0 =1 m and K given by $K \text{ dB} = 20 \log_{10} \frac{\lambda}{4\pi d_0}$

Table 2.3: Path-loss measurements

Distance from transmitter	$M = P_r/P_t$
10 m	−70 dB
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300 m	−125 dB

Task

- Find the path-loss exponent that minimizes the MSE between the model and the dB measurements
- Find the received power at 150 m for $P_t = 1$ mW

Solution

We want to minimize the following function with respect to gamma

$$F(\gamma) = \sum_{i=1}^{5} (M_i - K + \gamma 10 \log_{10} d_i)^2$$

where we know M_i and have used the fact to d_0=1m. We also know d_i.

K is given by
$$K = 20 \log_{10} \frac{c/f}{4\pi} = 20 \log_{10} \frac{3 \times 10^8/(9 \times 10^8)}{4\pi}$$
$$= 20 \log_{10} \frac{1}{12\pi} \approx -31.5 \, \mathrm{dB}$$

We see that F is a second degree polynomial in gamma $F(\gamma) = 21676.3 - 11654.9\gamma + 1561.74\gamma^2$ with root $\gamma = 3.71$

The received power and 150 m for P_t = 0 dBm is now

$$P_r = P_t + (-31.5) - 10(3.71) \log_{10} 150 = -112.27\mathrm{dBm}$$

Shadowing

Given

- Consider measurements of P_r/P_t below for an indoor system at 900 MHz, γ=3.71
- Let d_0 =1 m and K given by $K \text{ dB} = 20\log_{10}\frac{\lambda}{4\pi d_0}$

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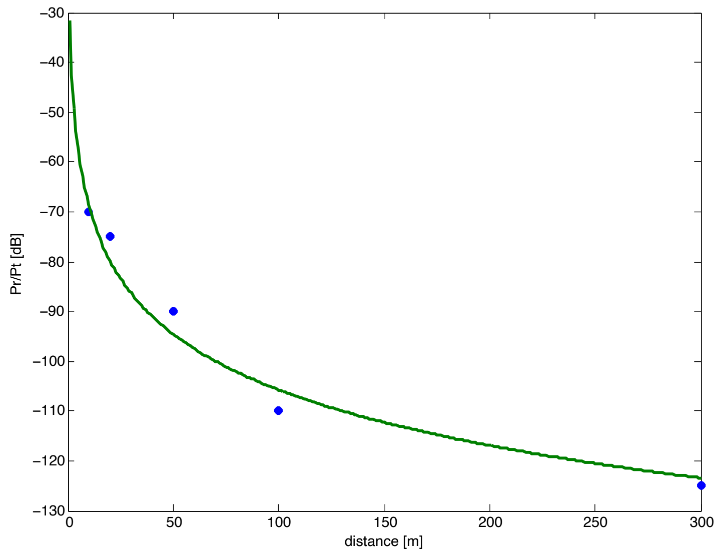

Task

- Find the shadowing variance [dB]

Solution

The shadowing variance is $\frac{1}{5}\sum_{i=1}^{5}\left(M_i - K + \gamma 10 \log_{10} d_i\right)^2$

which is 13.29. Hence $\sigma_{\psi_{\mathrm{dB}}} = 3.65\mathrm{dB}$