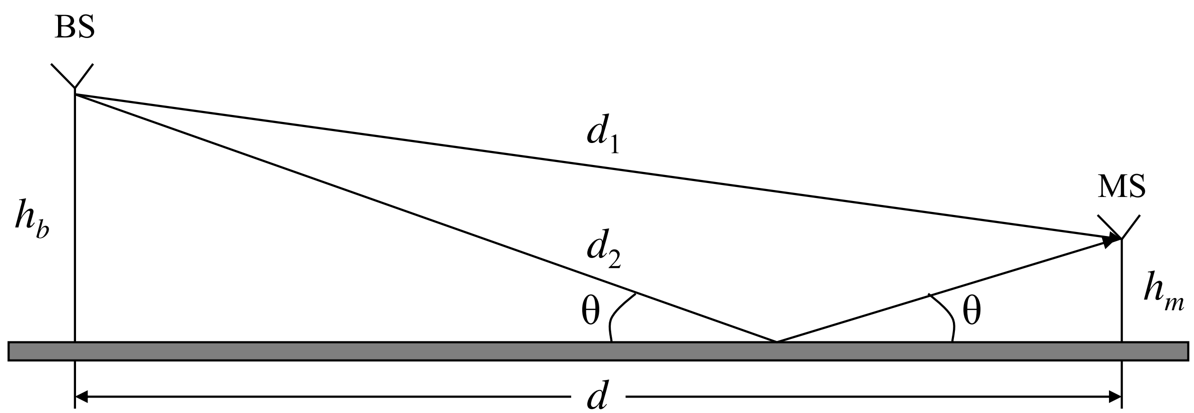
ECE6604
PERSONAL & MOBILE COMMUNICATIONS

Lecture 2

Path Loss, Co-channel Interference, Link Budget

PROPAGATION OVER A FLAT SPECULAR SURFACE



- **The length of the direct path is**

$$d_1 = \sqrt{d^2 + (h_b - h_m)^2}$$

and the length of the reflected path is

$$d_2 = \sqrt{d^2 + (h_b + h_m)^2}$$

d	$=$	**distance between mobile and base stations**
h_b	$=$	**base station antenna height**
h_m	$=$	**mobile station antenna height**

- **Given that $d \gg h_b h_m$, we have $d_1 \approx d$ and $d_2 \approx d$.**

- **The carrier phase difference between the direct and reflected paths is**

$$\phi_1 - \phi_2 = \frac{2\pi}{\lambda_c}(d_1 - d_2)$$

- **Taking into account the phase difference, the received signal power is**

$$\mu_{\Omega_p} = \Omega_t \left(\frac{\lambda_c}{4\pi d}\right)^2 G_T G_R \left|1 + a e^{-jb} e^{j(\phi_2 - \phi_1)}\right|^2 \quad ,$$

where a **and** b **are the amplitude attenuation and phase change introduced by the flat reflecting surface.**

- **If we assume a perfect specular reflection, then** $a = 1$ **and** $b = \pi$ **for small** θ**. Then**

$$\begin{aligned}\mu_{\Omega_p} &= \Omega_t \left(\frac{\lambda_c}{4\pi d}\right)^2 G_T G_R \left|1 - e^{j(\frac{2\pi}{\lambda_c}\Delta_d)}\right|^2 \\ &= \Omega_t \left(\frac{\lambda_c}{4\pi d}\right)^2 G_T G_R \sin^2\left(\frac{2\pi}{\lambda_c}\Delta_d)\right)\end{aligned}$$

where $\Delta_d = (d_1 - d_2)$**.**

- **Given that** $d \gg h_b$ **and** $d \gg h_m$**, and applying the approximation** $\sqrt{1+x} \approx 1 + x/2$ **for small** x**, we have**

$$\Delta_d \approx \frac{2h_b h_m}{d} \quad .$$

- **Finally, the received envelope power is**

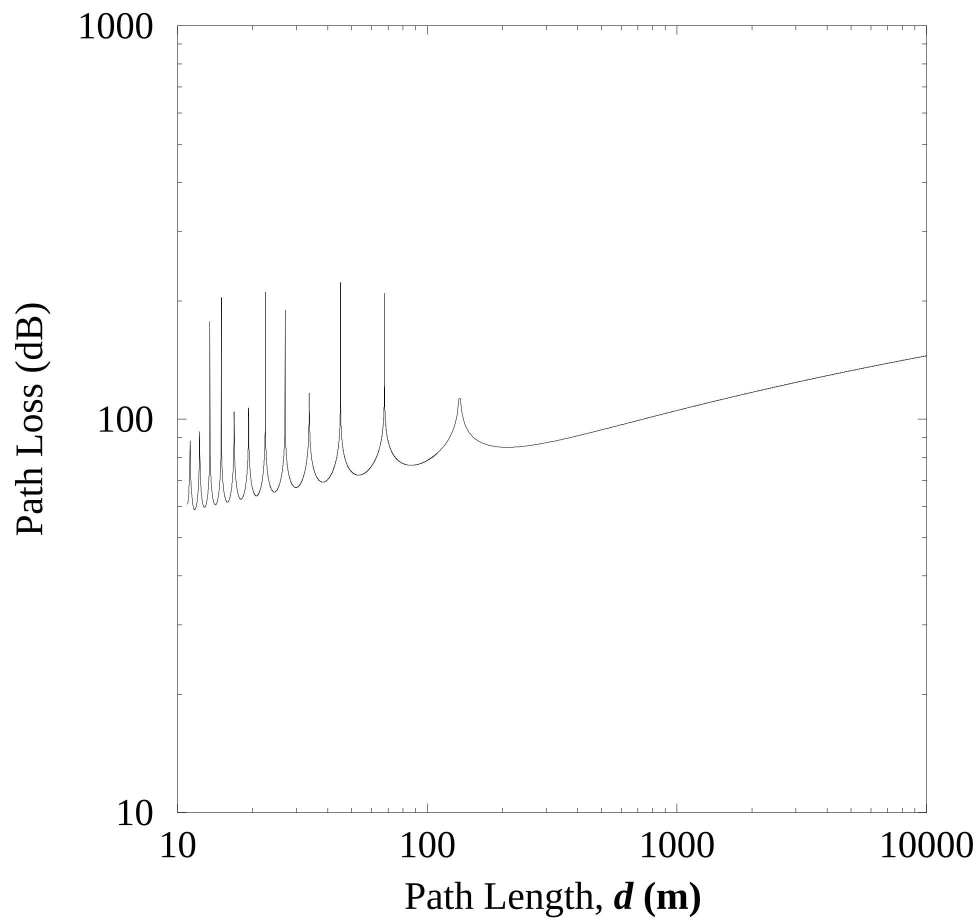
$$\mu_{\Omega_p} \approx 4\Omega_t \left(\frac{\lambda_c}{4\pi d}\right)^2 G_T G_R \sin^2\left(\frac{2\pi h_b h_m}{\lambda_c d}\right)$$

- **Under the condition that $d \gg h_b h_m$, the above reduces to**

$$\mu_{\Omega_p} \approx \Omega_t G_T G_R \left(\frac{h_b h_m}{d^2}\right)^2$$

  where we have invoked the small angle approximation $\sin x \approx x$ for small x.

- **Propagation over a plane reflecting surface differs from free space propagation in two respects**
  - **it is not frequency dependent**
  - **signal strength decays with the with the fourth power of the distance, rather than the square of the distance.**



Propagation path loss $L_{p\ \mathrm{(dB)}}$ *with distance over a flat reflecting surface;*
$h_b = 7.5\ m$, $h_m = 1.5\ m$, $f_c = 1800\ MHz$.

$$L_p = \left[\left(\frac{\lambda_c}{4\pi d} \right)^2 4 \sin^2 \left(\frac{2\pi h_b h_m}{\lambda_c d} \right) \right]^{-1}$$

- **In reality, the earth's surface is curved and rough, and the signal strength typically decays with the inverse β power of the distance, and the received power is**

$$\Omega_p = k\frac{\Omega_t}{d^\beta}$$

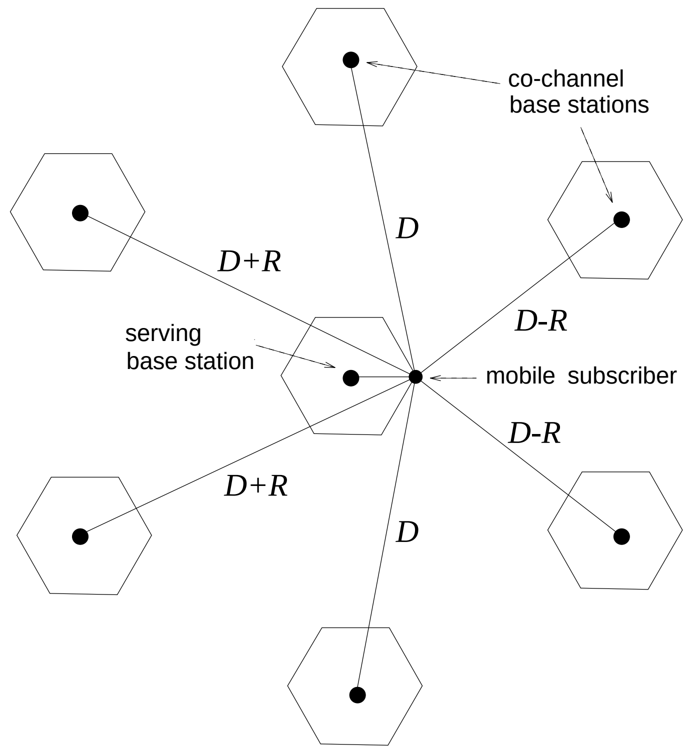
where k is a constant of proportionality. Expressed in units of dBm, the received power is

$$\Omega_{p\ (\text{dBm})} = 10\log_{10}(k) + \Omega_{t\ (\text{dBm})} - 10\beta\log_{10}(d)$$

- **β is called the path loss exponent. Typical values of β are have been determined by empirical measurements for a variety of areas**

Terrain	β
Free Space	2
Open Area	4.35
North American Suburban	3.84
North American Urban (Philadelphia)	3.68
North American Urban (Newark)	4.31
Japanese Urban (Tokyo)	3.05

Co-channel Interference



Worst case co-channel interference on the forward channel.

Worst Case Co-Channel Interference

- **There are six co-channel base-stations, two at distance $D-R$, two at distance D, and two at distance of $D+R$.**

- **The worst case carrier-to-interference ratio is**

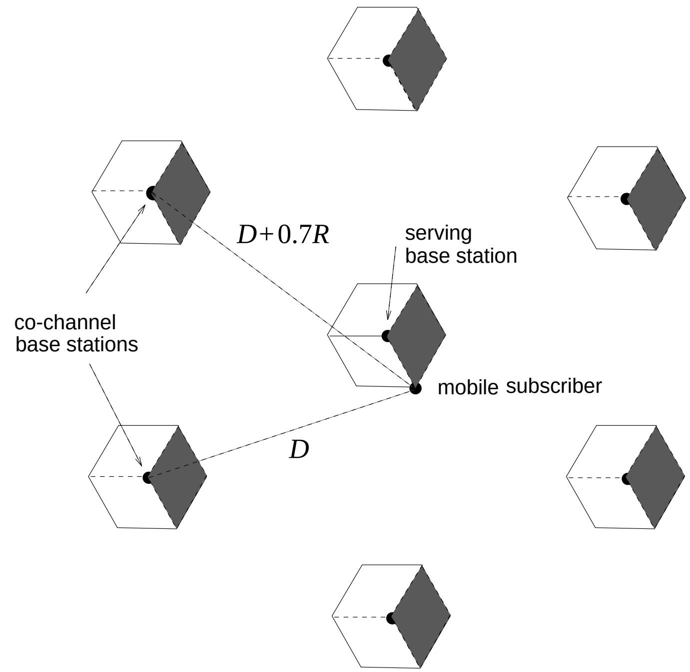
$$\begin{aligned}\Lambda &= \frac{1}{2}\,\frac{R^{-\beta}}{(D-R)^{-\beta}+D^{-\beta}+(D+R)^{-\beta}} \\ &= \frac{1}{2}\,\frac{1}{\left(\frac{D}{R}-1\right)^{-\beta}+\left(\frac{D}{R}\right)^{-\beta}+\left(\frac{D}{R}+1\right)^{-\beta}} \\ &= \frac{1}{2}\,\frac{1}{\left(\sqrt{3N}-1\right)^{-\beta}+\left(\sqrt{3N}\right)^{-\beta}+\left(\sqrt{3N}+1\right)^{-\beta}}\end{aligned}$$

- **Hence, for $\beta = 3.5$**

$$\Lambda_{(\mathrm{dB})} = \begin{cases} 14.3 \text{ dB} & \textbf{for } N=7 \\ 9.2 \text{ dB} & \textbf{for } N=4 \\ 6.3 \text{ dB} & \textbf{for } N=3 \end{cases}$$

  - **Shadows will introduce variations in the worst case C/I.**

Cell Sectoring



Worst case co-channel interference on the forward channel with 120° cell sectoring.

- 120° **cell sectoring reduces the number of co-channel base stations from six to two. The co-channel base stations are at distances** D **and** $D + 0.7R$**.**

- **The carrier-to-interference ratio becomes**

$$\begin{aligned}\Lambda &= \frac{R^{-\beta}}{D^{-\beta} + (D+0.7R)^{-\beta}} \\ &= \frac{1}{\left(\frac{D}{R}\right)^{-\beta} + \left(\frac{D}{R}+0.7\right)^{-\beta}} \\ &= \frac{1}{\left(\sqrt{3N}\right)^{-\beta} + \left(\sqrt{3N}+0.7\right)^{-\beta}}\end{aligned}$$

- **Hence**

$$\Lambda_{(\text{dB})} = \begin{cases} 21.1 \text{ dB} & \textbf{for } N=7 \\ 17.1 \text{ dB} & \textbf{for } N=4 \\ 15.0 \text{ dB} & \textbf{for } N=3 \end{cases}$$

- **For** $N=7$, 120° **cell sectoring yields a 6.8 dB** C/I **improvement over omni-cells.**

- **The minimum allowable cluster size is determined by the minimum** C/I **requirement of the radio receiver. For example, if the radio receiver can operate at** $\Lambda = 15.0$ **dB, then a 3/9 reuse cluster can be used (3/9 means 3 cells or 9 sectors per cluster).**

Receiver Sensitivity

- Receiver sensitivity refers to the ability of the receiver to detect radio signals. We would like our radio receivers to be as sensitive as possible.
- Radio receivers must detect radio waves in the presence of noise.
  - External noise sources include atmospheric noise (e.g, lightning strikes), galactic noise, man made noise (e.g, automobile ignition noise).
  - Internal noise sources include thermal noise.
- The ratio of the desired signal power to thermal noise power before detection is commonly called the carrier-to-noise ratio, Γ.
- The parameter Γ is a function of the communication link parameters including transmitted power (or effective isotropic radiated power (EIRP)), path loss, receiver antenna gain, and the effective input-noise temperature of the receiving system.
- The formula that relates the link parameters to Γ is called the link budget.

Link Budget

- **The link budget can be expressed in terms of the following parameters:**

$$
\begin{aligned}
\Omega_t &= \text{transmitted carrier power} \\
G_{\mathsf{T}} &= \text{transmitter antenna gain} \\
L_p &= \text{path loss} \\
G_{\mathsf{R}} &= \text{receiver antenna gain} \\
\Omega_p &= \text{received signal power} \\
E_c &= \text{received energy per modulated symbol} \\
T_o &= \text{receiving system noise temperature in degrees Kelvin} \\
B_w &= \text{receiver noise equivalent bandwidth} \\
N_o &= \text{white noise power spectral density} \\
R_c &= \text{modulated symbol rate} \\
k &= 1.38 \times 10^{-23} = \text{Boltzmann's constant} \\
F &= \text{noise figure, typically about 3 dB} \\
L_{\mathsf{R_x}} &= \text{receiver implementation losses} \\
L_{\mathrm{I}} &= \text{losses due to system load (interference)} \\
M_{\mathsf{shad}} &= \text{shadow margin} \\
G_{\mathsf{HO}} &= \text{handoff gain} \\
S_{\mathsf{RX}} &= \text{receiver sensitivity}
\end{aligned}
$$

- **The effective received carrier power is**

$$\Omega_p = \frac{\Omega_t G_{\mathsf{T}} G_{\mathsf{R}}}{L_{\mathsf{R_x}} L_p} \quad .$$

- **The total input noise power to the receiver is**

$$N = kT_o B_w F$$

- **Very often the following kT_o value at room temperature of** 17 ^{o}C (290 ^{o}K) **is used** $kT_o = -174$ **dBm/Hz,**

- **The received carrier-to-noise ratio defines the link budget**

$$\Gamma = \frac{\Omega_p}{N} = \frac{\Omega_t G_{\mathsf{T}} G_{\mathsf{R}}}{kT_o B_w F L_{\mathsf{R_x}} L_p} \quad .$$

- **The carrier-to-noise ratio, Γ, and modulated symbol energy-to-noise ratio, E_c/N_o, are related as follows**

$$\frac{E_c}{N_o} = \Gamma \times \frac{B_w}{R_c} \quad .$$

- **Hence, we can rewrite the link budget as**

$$\frac{E_c}{N_o} = \frac{\Omega_t G_{\mathsf{T}} G_{\mathsf{R}}}{kT_o R_c F L_{\mathsf{R_x}} L_p} \quad .$$

- **Converting into decibel units gives**

$$E_c/N_{o(\mathrm{dB})} = \Omega_{t\ (\mathrm{dBm})} + G_{\mathrm{T}\ (\mathrm{dB})} + G_{\mathrm{R}\ (\mathrm{dB})} - kT_{o(\mathrm{dBm})/\mathrm{Hz}} - R_{c\ (\mathrm{dB\ Hz})} - F_{(\mathrm{dB})} - L_{\mathrm{R_x}\ (\mathrm{dB})} - L_{p\ (\mathrm{dB})} \quad . \tag{1}$$

- **The receiver sensitivity is defined as**

$$S_{\mathrm{R_x}} = L_{\mathrm{R_x}} kT_o F (E_c/N_o) R_c$$

or converting to decibel units

$$S_{\mathrm{R_x}\ (\mathrm{dBm})} = L_{\mathrm{R_x}\ (\mathrm{dB})} + kT_{o(\mathrm{dBm/Hz})} + F_{(\mathrm{dB})} + E_c/N_{o(\mathrm{dB})} + R_{c\ (\mathrm{dB\ Hz})} \quad .$$

- **All parameters are usually fixed except for E_c/N_o. The receiver sensitivity (in dBm) is determined by the minimum acceptable E_c/N_o.**

- **Substituting the determined receiver sensitivity $S_{\mathrm{R_x}\ (\mathrm{dBm})}$ into (1) and solving for $L_{p\ (\mathrm{dB})}$ gives the maximum allowable path loss**

$$L_{\max\ (\mathrm{dB})} = \Omega_{t\ (\mathrm{dBm})} + G_{\mathrm{T}\ (\mathrm{dB})} + G_{\mathrm{R}\ (\mathrm{dB})} - S_{\mathrm{R_x}\ (\mathrm{dBm})} \quad .$$