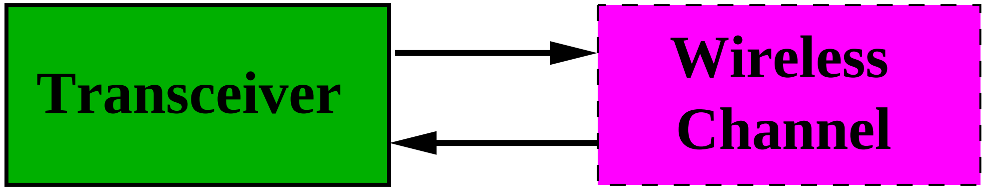
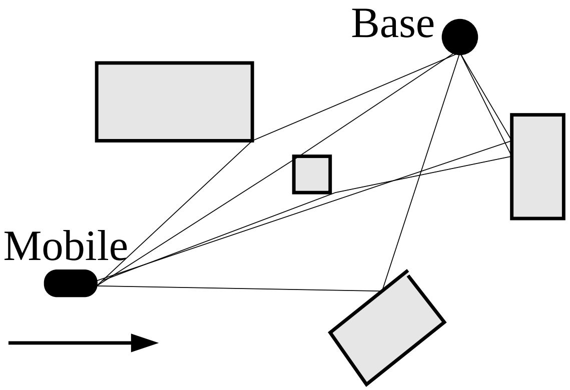
Revision of Lecture One



- **System blocks and basic concepts**
  - Multiple access, MIMO, space-time
- **Signal/System**:
  - Bandpass (Passband) ⇔ Baseband
  - Baseband complex envelope
- **Linear system**: complex (baseband) channel impulse response
- **Channel**: is medium for communication, understanding it is **key** to understand communication technology
  - Mobile channels are very hostile medium for communications
  - Wireless technologies have been developed in past four decades for achieving efficient and reliable mobile communication

Channel will be our main focus in next three lectures

Mobile Radio Channel Characterisations



- Mobile radio links
  - MS $\longrightarrow$ BS: *uplink*, also called *forward channel*
  - MS $\longleftarrow$ BS: *downlink*, also called *reverse channel*

- RF signals in hundreds MHz to GHz, channels inherent stochastic, and EM wave propagation by
  - reflection, diffraction, scattering

- Why mobile channels are so **hostile**
  - **Doppler spread**: *Moving changes frequencies*, and this causes serious problem (Recall spectrum of a communication signal must be carefully specified, but Doppler spread will change the signal spectrum!)
  - **Multipath**: copies of signal arrive at receiver with different attenuation and delays, cause *dispersive* (ISI) and *fading* (power level fluctuates rapidly) effects

- We first consider how mobile channel influences signal power
  - Received signal power level must be larger than certain threshold, for reliably detecting transmitted information
  - Power budget, i.e. predicting expected mean received signal power, is crucial in determining cell size, frequency reuse, and other system design issues

Power Budget Factors

How mobile channel influences signal power may be decomposed into three factors

1. **Propagation pathloss**: Distance effect – signal power is attenuated, as it travels in distance
   - One can simply use physical laws to derive theoretical formula for describing propagation pathloss, but more often, empirical models are sought
2. **Slow (large-scale) fading**: Shadow variations that caused by large terrain features, such as small hills and tall buildings, between BS and MS
   - Power variation statistics due to large-scale fading can be well quantified, as the process is "slow"
3. **Fast (small-scale) fading**: Multipath signals, having a range of delays, attenuations and frequency (Doppler) shifts, are summed at MS antenna, causing rapidly power level fluctuations
   - Small-scale fading is difficult to model accurately, as factors influencing fast fading characteristics are highly complex
   - When multipath signals cancel out each other because of different phase changes, signal level is in a deep fade
   - Deep fades typically occur every half-wavelength (180° phase), and for a carrier frequency of 1 GHz, wavelength is

$$\lambda = c/f = (3 \times 10^8 \text{ m/s})/(10^9 \text{ Hz}) = 30 \text{ cm}$$

Propagation Pathloss (Hata Empirical Model)

Let us use Hata empirical model to illustrate how propagation pathloss can be characterised

- Typical urban Hata model: $L_{Hu} = 69.55 + 26.16 \log_{10} f - 13.82 \log_{10} h_{BS} - a(h_{MS})$

$$+ (44.9 - 6.55 \log_{10} h_{BS}) \log_{10} d \ \ (\text{dB})$$

where f is frequency (MHz), h_{BS}/h_{MS} are BS/MS antenna heights (m), d is BS-MS distance (km) and $a(h_{MS})$ a correction factor. For small/medium city:

$$a(h_{MS}) = (1.1 \log_{10} f - 0.7) h_{MS} - (1.56 \log_{10} f - 0.8)$$

For large city:

$$a(h_{MS}) = \begin{cases} 8.29 \left(\log_{10}(1.54 h_{MS})\right)^2 - 1.1 & f \leq 400 \text{ MHz} \\ 3.2 \left(\log_{10}(11.75 h_{MS})\right)^2 - 4.97 & f \geq 400 \text{ MHz} \end{cases}$$

- Typical suburban Hata model: (L_{Hu} without $a(h_{MS})$ factor)

$$L_{Hsub} = L_{Hu} - 2 \left(\log_{10}(f/28)\right)^2 - 5.4 \ (\text{dB})$$

- Typical rural Hata model: (L_{Hu} without $a(h_{MS})$ factor)

$$L_{Hrur} = L_{Hu} - 4.78 \left(\log_{10} f\right)^2 + 18.33 \log_{10} f - 40.94 \ (\text{dB})$$

Slow (Large Scale) Fading

- Shadow variations by large terrain features contribute to power variation about mean of propagation pathloss, and probability distribution of this power variation is **log-normal**, i.e. Gaussian in dB

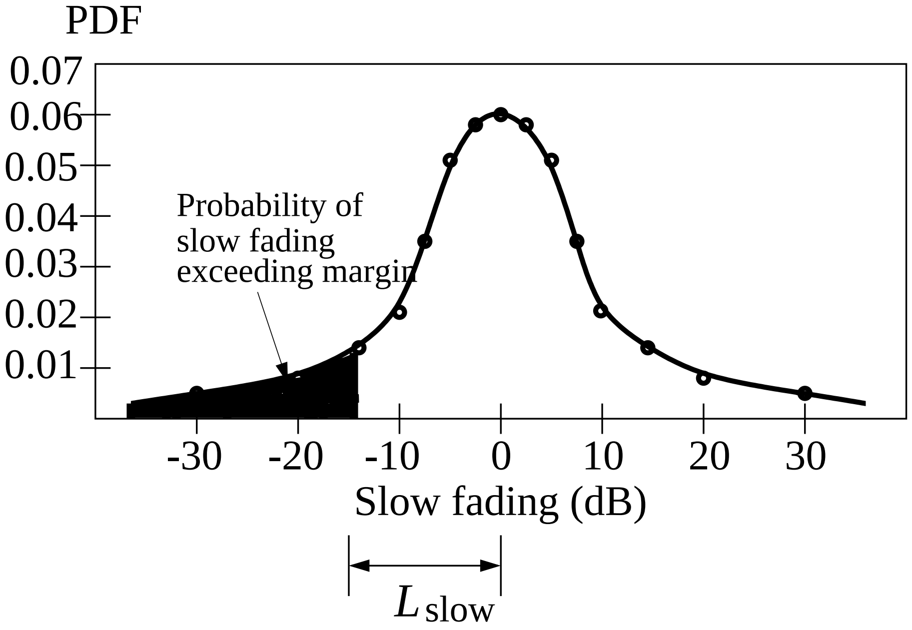
$$\mathrm{PDF}_{\mathrm{slow}}(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(- \frac{x^2}{2\sigma^2} \right)$$

  where power variation x is measured in dB, and σ is standard deviation
  - Large scale fading causes further power variation on the mean power level due to propagation pathloss, i.e. it may boost or attenuate signal power

- To guard against power loss due to slow fading, a margin L_{slow} must be allocated
  - From the definition of Q-function, 2% probability that loss due to slow fading exceeding margin gives $L_{\mathrm{slow}} = 2\sigma$:

$$Q(2.0) \approx 0.02 \rightarrow L_{\mathrm{slow}} = 2\sigma$$

  - In figure, $\sigma = 7$ and $L_{\mathrm{slow}} = 14$ dB



Fast (Small Scale) Fading

- Small scale fading contributes to fast power variations on top of mean of propagation pathloss and large scale fading
  - Factors influence this fast fading characteristics are highly complex

- In the case there exists a line-of-sight path, probability density function (PDF) of this power variation due to fast fading is Rice distribution

$$\mathrm{PDF}_{\mathrm{Rice}}(x) = \frac{x}{\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2} - K\right) I_0\left(\frac{x}{\sigma}\sqrt{2K}\right)$$

  - K is the ratio of LOS power to total power of all indirect paths, $I_0(\cdot)$ is the modified 0th order Bessel-function of 1st kind, σ is standard deviation
  - x is not measured in dB

- In the case of no LOS, $K = 0$ and this leads to the worst case Rayleigh distribution

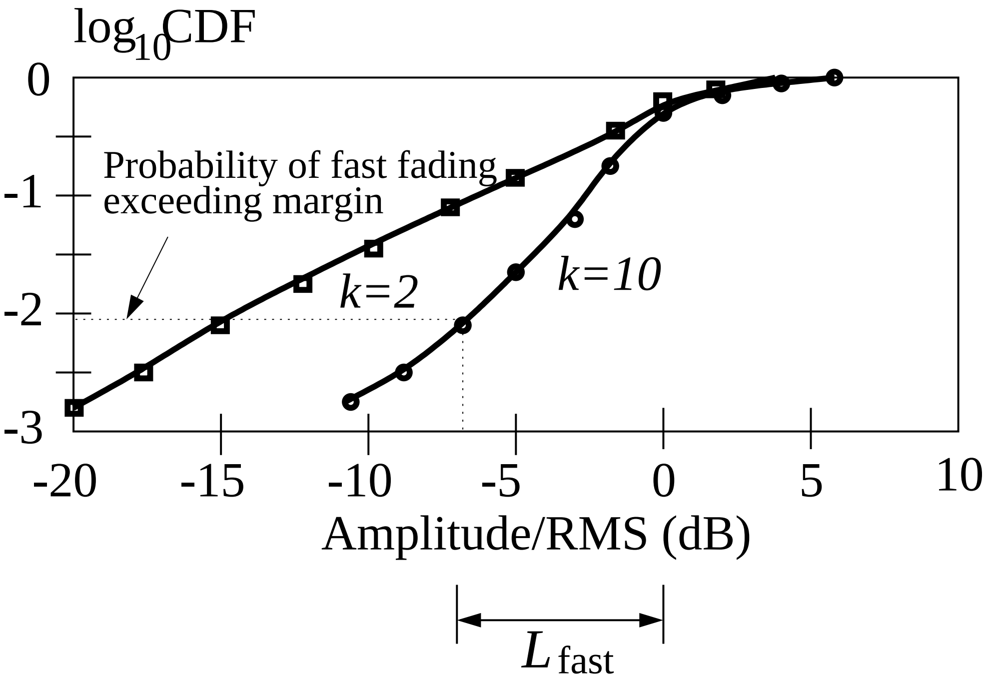
$$\mathrm{PDF}_{\mathrm{Rayleigh}}(x) = \frac{x}{\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2}\right)$$

Small Scale Fading Margin

- There is more general fast fading distribution model, which includes Rice and Rayleigh as special cases, but Rayleigh model is widely used
  - Small scale fading causes further power variation on the mean power level due to propagation pathloss and large scale fading

- To guard against power loss due to this fast fading, a margin L_{fast} must be allocated
  - For convenience, let power x be measured in dB
  - Value of cumulative distribution function (CDF) is:

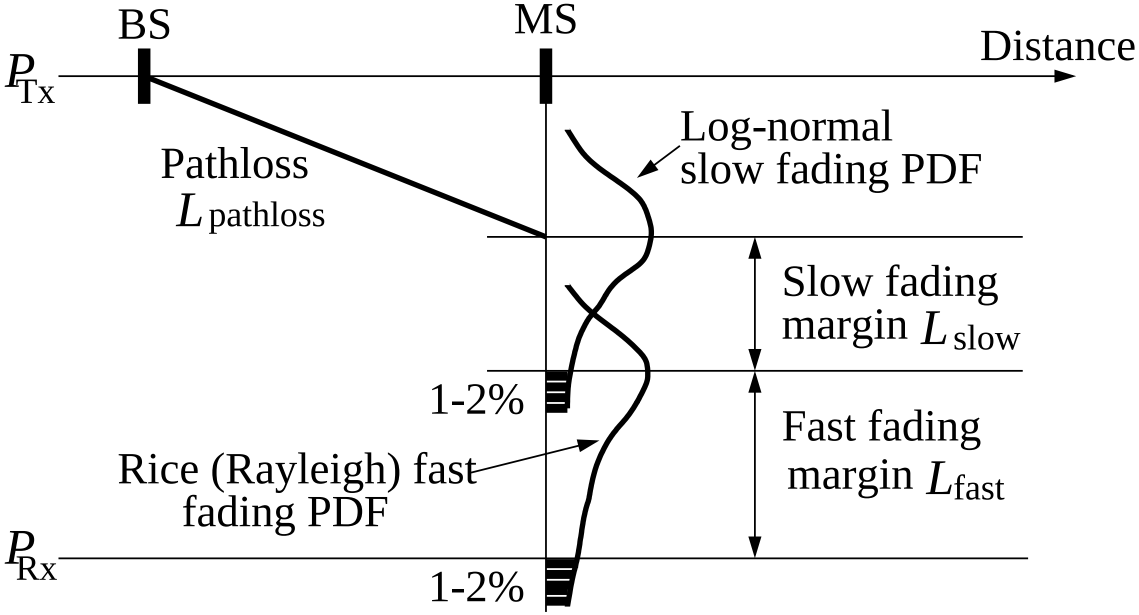
$$\text{Prob}(x \leq -L_{\text{fast}}) = \int_{-L_{\text{fast}}}^{\infty} \text{PDF}(y) d\, y$$



  - In figure, for 1% (0.01) probability of exceeding margin with $K = 10$, $L_{\text{fast}} = 7$ dB

Power Budget Rule

Let P_{Rx} be the required power level at MS receiver, then what the designed level of power P_{Tx} at BS transmitter should be?



- The calculation rule:

$$P_{\text{Tx}} = P_{\text{Rx}} + L_{\text{total}}$$

with

$$L_{\text{total}} = L_{\text{pathloss}} + L_{\text{slow}} + L_{\text{fast}}$$

- Provisions are made for the worst case pathloss, slow fading overload margin and fast fading overload margin
- Probability of exceeding fading margin is typically set at 1 to 2%

Power Budget Example

Question: Assume that the propagation pathloss can be calculated using the typical urban Hata model L_{Hu} with a small/medium city correction factor $a(h_{MS})$. The mobile antenna height $h_{MS} = 1$ m, the base antenna height $h_{BS} = 100$ m, the carrier frequency is $f = 1$ GHz, and the cell radius is $d = 300$ m. Further assume that 2% slow fading overload margin is $L_{\text{slow}} = 14$ dB, and 2% fast fading overload margin is $L_{\text{fast}} = 7$ dB. The receiver sensitivity is -104 dBm (dBm: dB with respect to a 1 mW reference). Calculate the transmitter power.

Solution:

$$L_{\text{pathloss}} = 69.55 + 26.16 \log_{10} 10^3 - 13.82 \log_{10} 10^2 + (44.9 - 6.55 \log_{10} 10^2) \log_{10} 0.3$$

$$-(1.1 \log_{10} 10^3 - 0.7) \times 1 + (1.56 \log_{10} 10^3 - 0.8)$$

$$= 69.55 + 78.48 - 27.64 - 16.63 - 2.6 + 3.88 = 105.04 \text{ (dB)}$$

$$L_{\text{total}} = L_{\text{pathloss}} + L_{\text{slow}} + L_{\text{fast}} = 105.04 + 14 + 7 = 126.04 \text{ (dB)}$$

$$P_{\text{Tx}} = L_{\text{total}} + P_{\text{Rx}} = 126.04 - 104 = 22.04 \text{ (dBm)} = 0.16 \text{ (W)}$$

A Look at Collaborative Communication

- Increasing interest on collaborative communication recently under "green" radio initiative
  - This can be explained by wireless channel's effect on signal power
- A physical/empirical model for propagation pathloss: distance effect on signal power is known to be

$$P_{Rx}(d) \propto \left(\frac{1}{d}\right)^{\alpha}$$

  - d is the distance that signal travels, $\alpha \geq 2$ is an empirically determined **pathloss exponent**
  - $P_{Rx}(d)$ denotes the received signal power at distance d
- By first measuring the received signal power $P_{Rx}(d_0)$ at a reference distance d_0, a simple model for propagation pathloss and large-scale fading is given by

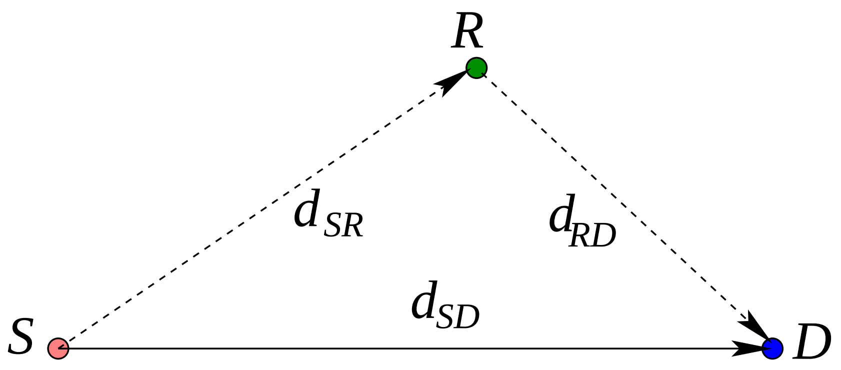
$$P_{Rx}(d) = P_{Rx}(d_0)\left(\frac{d_0}{d}\right)^{\alpha}$$

- Received signal power P_{Rx} at distance d is related to transmitted signal power P_{Tx} by

$$P_{Rx} = P_{Tx} \cdot h \cdot d^{-\alpha}$$

  - Typical pathloss exponent α value in $2.5 \sim 3.0$, small-fading channel gain h is not dependent of d (h is exponentially distributed with mean $\frac{1}{\mu}$)

Relay Aided Communication



- For receiver to correctly recover transmitted information, received signal power $P_{Rx} \geq P_{th}$
- Direct $S \to D$ needs $P_{Tx}^{S\to D} \geq P_{Th} \cdot h^{-1} \cdot d_{SD}^{\alpha}$, so minimum required transmit power is

$$P_{Tx}^{S\to D} = P_{Th} \cdot h^{-1} \cdot d_{SD}^{\alpha}$$

- Despite $d_{SR} + d_{RD} > d_{SD}$, potential benefit in transmit power saving by relaying as long as

$$d_{SD} > d_{SR} \text{ and } d_{SD} > d_{RD}$$

- Assuming h is the same for all links, for $S \to R \to D$ link, minimum required transmit power is

$$P_{Tx}^{S\to R} + P_{Tx}^{R\to D} = P_{Th} \cdot h^{-1} \cdot (d_{SR}^{\alpha} + d_{RD}^{\alpha})$$

  - As $\alpha \geq 2$, even $d_{SR} + d_{RD} > d_{SD}$, it can easily have $d_{SR}^{\alpha} + d_{RD}^{\alpha} < d_{SD}^{\alpha}$
- Relay causes half duplexing throughput loss: $S \to R$ in 1st time slot and $R \to D$ in 2nd time slot
  - Other techniques, such as successive relaying, may be used to recover this half duplexing throughput loss

Summary

- Mobile channels are hostile due to Doppler spread and multipath, as will be shown
  - Doppler spread $\longrightarrow$ causing frequency dispersion
  - Multipath $\longrightarrow$ causing time dispersion

- Propagation loss, slow (large scale) fading and fast (small scale) fading must be taken into account
  - Power budget Rule:

$$P_{\text{Tx}} = P_{\text{Rx}} + L_{\text{total}}$$
$$L_{\text{total}} = L_{\text{pathloss}} + L_{\text{slow}} + L_{\text{fast}}$$

- Collaborative or relaying communication from mobile channel point of view: Simple model for receive signal power

$$P_{Rx} = P_{Tx} \cdot h \cdot d^{-\alpha}$$

  - pathloss exponent α: pathloss exponent, h: small-fading channel gain, d: distance, P_{Tx}: transmit signal power