Electronic and Telecommunication Engineering
University of Moratuwa, Sri Lanka

EN4384 - Wireless and Mobile Communications

Workshop 1

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Figures

Task 1: Large-Scale Path Loss and Shadowing

Figure 5 shows the large-scale path loss with and without log-normal shadowing.

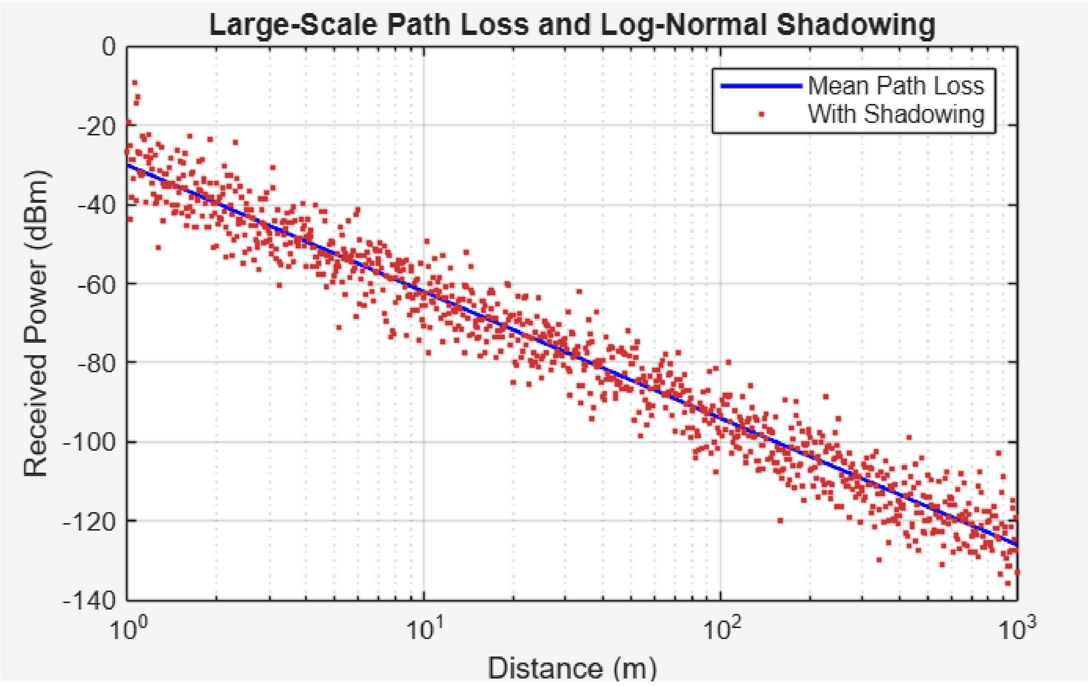


Figure 1: Large-Scale Path Loss and Log-Normal Shadowing: mean path loss (blue) and shadowed received power (red) versus distance.

Task 2: Small-Scale Fading (Rayleigh and Rician Models)

Figure 2 provides the Rayleigh and Rician fading amplitude PDFs.

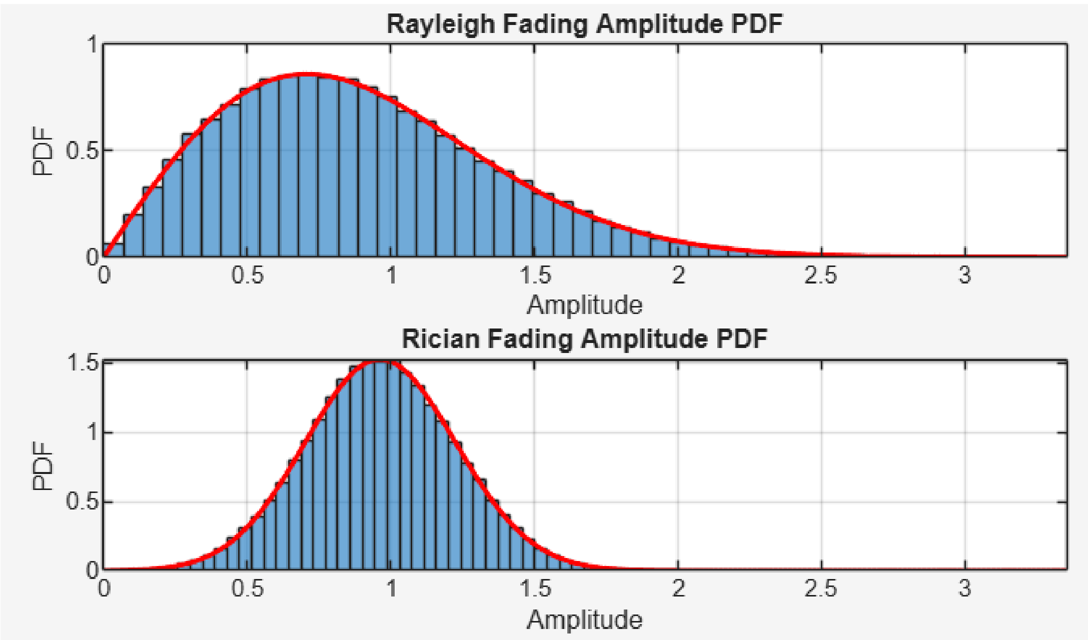


Figure 2: Amplitude PDFs of small-scale fading: Rayleigh (top) and Rician (bottom) histograms with theoretical overlays.

Task 3: Combined Channel Model (Large-Scale + Small-Scale)

Figure 3 illustrates instantaneous received power versus distance under combined large- and small-scale effects.

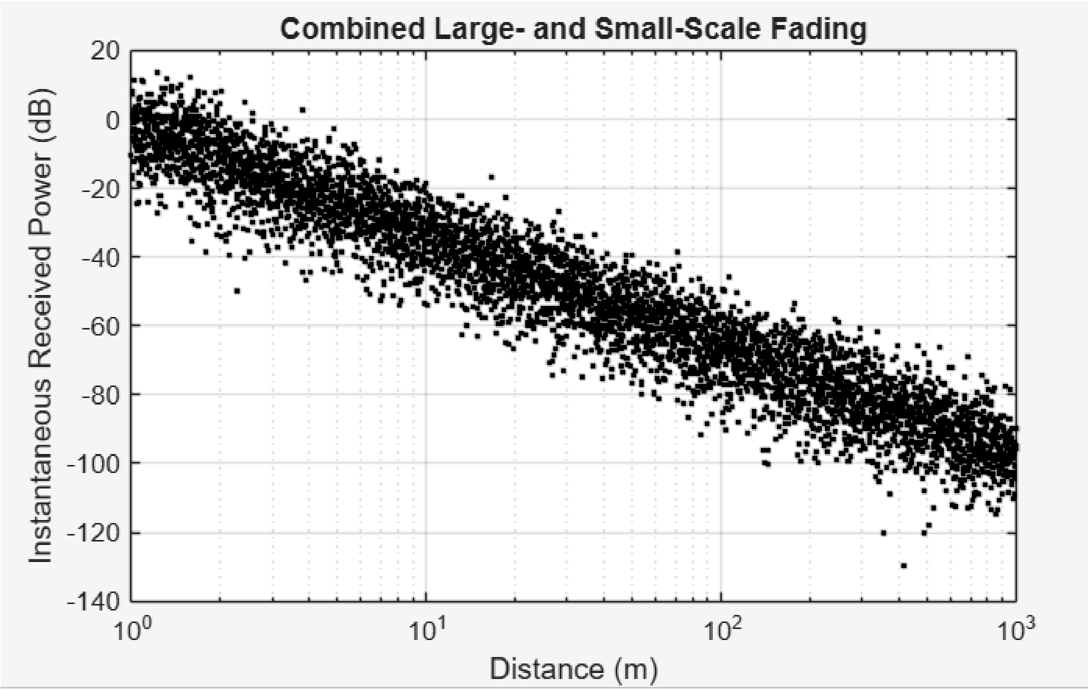


Figure 3: Combined large- and small-scale fading: instantaneous received power fluctuating around the mean path-loss trend with shadowing.

Task 4: Envelope Statistics and Doppler Effect

Figure 4 presents the time-domain fading envelope due to the Doppler effect.

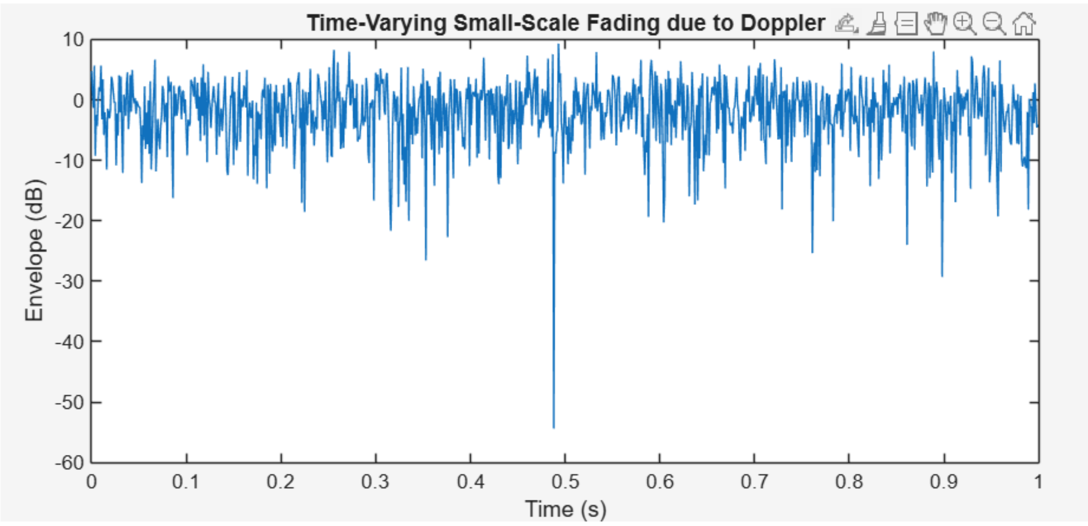


Figure 4: Time-varying small-scale fading envelope in dB due to Doppler; deeper nulls correspond to rapid phase decorrelation.

Questions and Answers

1. How does the path-loss exponent influence signal coverage range?

The **path-loss exponent** (n) is a fundamental parameter in wireless propagation models that determines how rapidly the received signal power decays with distance. It reflects the impact of the environment on signal attenuation.

The general path-loss model is expressed as:

$$P_r(d) = P_r(d_0) - 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma$$

- $P_r(d)$ is the received power at distance d,
- $P_r(d_0)$ is the received power at a reference distance d_0,
- n is the path-loss exponent,
- $X_\sigma \sim \mathcal{N}(0, \sigma^2)$ represents large-scale shadowing in dB.

In **free space**, $n \approx 2$, indicating an inverse-square decay of power with distance. In more complex environments such as **urban areas** or **indoor settings**, n typically ranges from 3 to 6 due to reflection, diffraction, and scattering from surrounding objects.

A larger path-loss exponent implies **faster signal attenuation** and thus a **smaller coverage range**. For example:

- With $n = 2$ (free-space), a transmitter may cover several kilometers.
- With $n = 4$ (dense urban), coverage may shrink to only a few hundred meters.

Therefore, the path-loss exponent plays a crucial role in **network design and planning**, since environments with higher n values require either higher transmit power or a denser deployment of base stations to maintain reliable communication coverage.

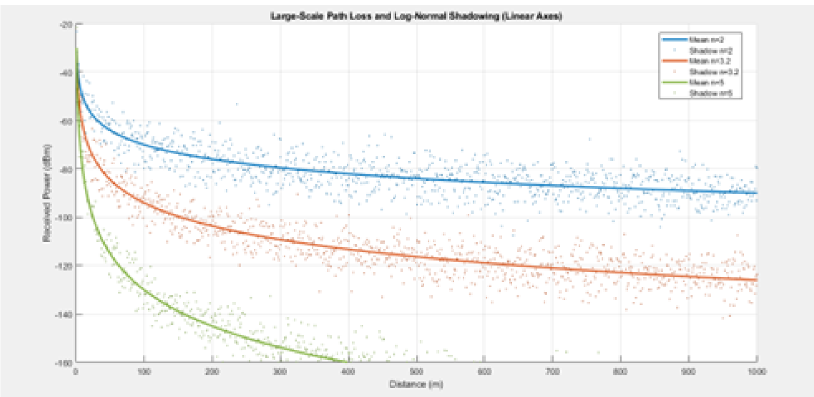


Figure 5: Path loss for different path loss exponents.

2. Why does shadowing follow a log-normal distribution?

Shadowing arises from large obstacles such as buildings, trees, or terrain features obstructing the signal path, causing random variations in received power around the mean path loss. Each obstruction introduces a **multiplicative attenuation** on the signal.

When these effects are expressed in decibels (dB), the multiplicative attenuations become additive:

$$PL_{\text{total}}(\text{dB}) = PL_{\text{mean}}(\text{dB}) + X_\sigma$$

where $X_\sigma \sim \mathcal{N}(0, \sigma^2)$ is a zero-mean Gaussian random variable with standard deviation σ in dB.

According to the **Central Limit Theorem**, the sum of many independent random attenuations is approximately Gaussian in dB. Consequently, the received power in the **linear scale** follows a **log-normal distribution**.

This log-normal shadowing model aligns well with empirical measurements and is widely used in wireless system simulations to represent large-scale variations in signal strength.

3. What is the physical difference between Rayleigh and Rician Fading?

Rayleigh and Rician fading describe two types of small scale amplitude variations in wireless channels caused by multipath propagation. The main physical distinction lies in the presence or absence of a dominant line-of-sight (LOS) component.

Rayleigh Fading

Rayleigh fading occurs when there is **no dominant LOS path** between the transmitter and receiver. The received signal is formed by the superposition of many scattered multipath components with random amplitudes and phases. The complex baseband signal therefore has a zero mean Gaussian distribution, and its envelope r follows a **Rayleigh distribution**:

$$p(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right), \quad r \geq 0$$

where σ^2 represents the variance of the in-phase and quadrature components of the received signal. Rayleigh fading typically results in *deep fades* because of frequent destructive interference between multipath components.

Rician Fading

Rician fading, on the other hand, occurs when a **strong LOS component** is present along with scattered multipath components. The envelope r follows a **Rician distribution**, given by:

$$p(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2 + A^2}{2\sigma^2}\right) I_0\left(\frac{Ar}{\sigma^2}\right), \quad r \geq 0$$

- A is the amplitude of the LOS component,
- σ^2 is the variance of the scattered components,
- $I_0(\cdot)$ is the modified Bessel function of the first kind and zero order.

The severity of fading is characterized by the **Rician K-factor**, defined as the ratio of LOS power to scattered power:

$$K = \frac{A^2}{2\sigma^2}$$

As K increases, the LOS component becomes more dominant, and the channel approaches an *AWGN-like* condition (no fading). When $K = 0$, the Rician model reduces to the Rayleigh model.

4. How does combining shadowing and fading yield realistic power variations?

In practical wireless environments, the received signal power is influenced by both large scale and small scale effects. Large scale effects include **path loss**, the average signal attenuation with distance and **shadowing**, which represents slow variations in the mean power due to obstacles such as buildings or terrain. Small scale effects, represented by **fading**, cause rapid fluctuations in signal amplitude over short distances or time intervals as a result of multipath interference.

The combined received power model is given by:

$$P_r(d,t) = P_0 \left(\frac{d_0}{d}\right)^n S|h(t)|^2$$

- P_0 is the reference received power at distance d_0,
- n is the path-loss exponent,
- S is the log-normal shadowing factor (modeling large-scale variations),
- $|h(t)|^2$ represents the small-scale fading power (Rayleigh or Rician).

This model reflects how real wireless channels behave: the received power exhibits **slow fluctuations** due to shadowing and path loss, around which **rapid variations** occur because of small-scale fading. The combination of these two effects produces realistic power variations observed in measurements and enables accurate simulation of performance metrics such as *outage probability*, *bit error rate*, and *link reliability*.

5. What happens to the received signal envelope as the Doppler frequency increases?

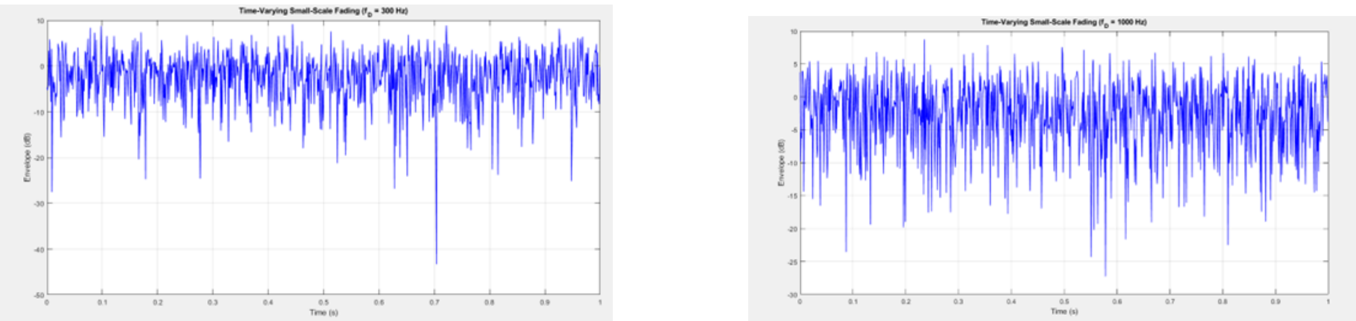
The **Doppler frequency** (f_D) arises from relative motion between the transmitter, receiver, or surrounding scatterers. It represents the rate at which the multipath channel characteristics change over time.

As f_D increases due to higher mobility or a higher carrier frequency the wireless channel varies more rapidly. The **channel coherence time**, which indicates how long the channel can be considered approximately constant, is inversely related to Doppler frequency:

$$T_c \approx \frac{1}{2f_D}$$

A higher f_D therefore leads to a smaller T_c, meaning the received signal envelope fluctuates more quickly and experiences more frequent and deeper fades.These rapid fluctuations make the channel less predictable and pose challenges for communication systems.

For example, comparing Doppler frequencies of $f_d = 300$ Hz and $f_d = 1000$ Hz, we observe that higher Doppler frequencies lead to faster variations in the signal envelope as shown below.



(a) Doppler frequency $f_d = 300$ Hz

(b) Doppler frequency $f_d = 1000$ Hz

Figure 6: Received signal envelope at different Doppler frequencies.