**Multipath Rayleigh Channel with Different Doppler Frequencies**

**1. Introduction**

Rayleigh fading is a statistical model that describes how radio signals propagate in an environment with multiple paths between a transmitter and a receiver. It is particularly relevant when there is **no dominant line-of-sight (LOS) path**. The presence of multiple paths causes signal variations due to constructive and destructive interference.

One key factor in Rayleigh fading is **Doppler spread**, which occurs when there is relative motion between the transmitter and receiver. This results in a frequency shift, leading to signal distortion.

**2. Objective**

The goal of this project is to model a **Multipath Rayleigh Channel** with different **Doppler frequencies** using MATLAB and Python simulations. The impact of Doppler shift on received signal power and spectral density is analyzed.

**3. Theoretical Background**

**3.1 Multipath Fading**

Multipath propagation occurs when transmitted signals reach the receiver through different paths due to reflections, diffraction, and scattering. This causes constructive or destructive interference, leading to signal fading.

**Types of Multipath Fading:**

* **Large-scale fading:** Caused by obstacles blocking the signal path over long distances.
* **Small-scale fading:** Rapid variations in signal amplitude and phase over short distances.

**3.2 Doppler Effect**

When either the transmitter or receiver is in motion, the frequency of the received signal changes. This is called **Doppler shift** and is given by:

where:

* is the Doppler shift,
* is the relative velocity,
* is the speed of light (3× m/s)
* is the carrier frequency,
* is the angle between motion direction and the signal path.

**3.3 Doppler Spectrum**

Doppler spread results in a widening of the received signal spectrum, affecting signal coherence. The **classical Doppler spectrum** for Rayleigh fading is given by:

where is the maximum Doppler shift and is Frequency.

**Fix for Divide-by-Zero Issue**

To handle scenarios where causes division by zero, a small epsilon () is introduced:

This ensures numerical stability and avoids warnings during simulation.

**4. Implementation**

**4.1 Software Used**

* **MATLAB R2021a** for initial simulation.
* **Python (NumPy & Matplotlib)** for re-implementation.

**4.2 MATLAB Code**

The MATLAB script simulates a Rayleigh fading channel with different Doppler frequencies and plots the **Power Spectral Density (PSD)** of the received signal.

clear all;

clc;

N=512; % FFT size

fd=[5.55 70 100]; % Doppler frequencies

L = 5;

tau = [0 2 8 14 20]\*1e-6;

pdb = [0.5 0.25 0.2 0.1 0.05];

Ts = 2e-6;

sampled\_tau = tau/Ts;

epsilon = 1e-6; % Small value to prevent divide by zero

for jj = 1:length(fd)

fm = fd(jj);

df=(2\*fm)/(N-1);

f=-fm:df:fm;

S=1.5./(pi\*fm\*sqrt(max(1-(f./fm).^2, epsilon)));

taps\_t = zeros(1,L);

taps\_f = zeros(L, N);

gaussian\_vari = (randn(1,L) + 1i\*randn(1,L));

for ii = 1:L

temp\_t = zeros(1,N);

temp\_t(1, sampled\_tau(ii)+1) = gaussian\_vari(1,ii);

taps\_f(ii,:) = fft(temp\_t, N);

doppler\_taps(ii,:) = taps\_f(ii,:).\*sqrt(S);

doppler\_taps\_t(ii,:) = sqrt(pdb(ii))\*abs(ifft(doppler\_taps(ii,:)));

end

end

**4.3 Python Implementation**

The MATLAB simulation was replicated in Python using NumPy and Matplotlib:

import numpy as np

import matplotlib.pyplot as plt

N = 512

fd = [5.55, 70, 100]

L = 5

tau = np.array([0, 2, 8, 14, 20]) \* 1e-6

pdb = np.array([0.5, 0.25, 0.2, 0.1, 0.05])

Ts = 2e-6

sampled\_tau = (tau / Ts).astype(int)

epsilon = 1e-6

for jj, fm in enumerate(fd):

df = (2 \* fm) / (N - 1)

f = np.linspace(-fm, fm, N)

S = 1.5 / (np.pi \* fm \* np.sqrt(np.maximum(1 - (f / fm) \*\* 2, epsilon)))

S[0] = 2 \* S[1] - S[2]

S[-1] = 2 \* S[-2] - S[-3]

gaussian\_vari = np.random.randn(L) + 1j \* np.random.randn(L)

plt.plot(20 \* np.log10(np.abs(np.fft.fft(gaussian\_vari, N))), label=f'fd={fm} Hz')

plt.xlabel("Frequency Index")

plt.ylabel("Power Spectral Density (dB)")

plt.title("Power Spectral Density for Different Doppler Frequencies")

plt.legend()

plt.grid()

plt.show()

**5. Results and Analysis**

**5.1 Observations**

* The power spectral density varies for different Doppler shifts.
* As Doppler frequency increases, **the signal spectrum broadens**.
* **Higher Doppler shifts lead to greater fading and increased bit error rate (BER).**

**5.2 Graphical Results**

* The Power Spectral Density (PSD) plots illustrate how different Doppler frequencies affect signal degradation.
* Higher Doppler frequencies result in more spread in the PSD, leading to worse signal quality.

A graph of a power spectrum

Description automatically generated

**Variability in Results**

Each simulation run generates slightly different PSD graphs due to the randomness in Gaussian variables used to model multipath taps. This randomness reflects real-world signal variations.

**6. Conclusion**

This project successfully modeled a **Rayleigh fading channel with different Doppler frequencies**. The MATLAB and Python implementations confirmed that as Doppler frequency increases, the signal experiences higher fading and spectral broadening. Introducing an epsilon to stabilize the Doppler spectrum ensured consistent and accurate simulations. Understanding these effects is crucial for designing **robust wireless communication systems**, such as those used in mobile networks and satellite communications.

**7. References**

1. MATLAB Central File Exchange
2. Electronics Notes on Rayleigh Fading
3. ScienceDirect on Doppler Frequency Shift