Modeling the Propagation of RF Signals

This example shows how to model several RF propagation effects. These include free space path loss, atmospheric attenuation due to rain, fog and gas, and multipath propagation due to bounces on the ground. This discussion is based on the International Telecommunication Union's ITU-R P series recommendations. ITU-R is the organization's radio communication sector and the P series focuses on radio wave propagation.

View MATLAB Command

Introduction

To properly evaluate the performance of radar and wireless communication systems, it is critical to understand the propagation environment. Using radar as an example, the received signal power of a monostatic radar is given by the radar range equation:

$$P_r = \frac{P_t G^2 \sigma \lambda^2}{(4\pi)^3 R^4 L}$$

where P_t is the transmitted power, G is the antenna gain, σ is the target radar cross section (RCS), λ is the wavelength, and R is the propagation distance. All propagation losses other than free space path loss are included in the L term. The rest of example shows how to estimate this L term in different scenarios.

Free Space Path Loss

First, the free space path loss is computed as a function of propagation distance and frequency. In free space, RF signals propagate at a constant speed of light in all directions. At a far enough distance, the radiating source looks like a point in space and the wavefront forms a sphere whose radius is equal to R. The power density at the wavefront is inversely proportional to R^2

$$\frac{P_t}{4\pi R^2}$$

where P_t is the transmitted signal power. For a monostatic radar where the signal has to travel both directions (from the source to the target and back), the dependency is actually inversely proportional to R^4, as shown previously in the radar equation. The loss related to this propagation mechanism is referred to as free space path loss, sometimes also called the spreading loss. Quantitatively, free space path loss is also a function of frequency, given by [5]

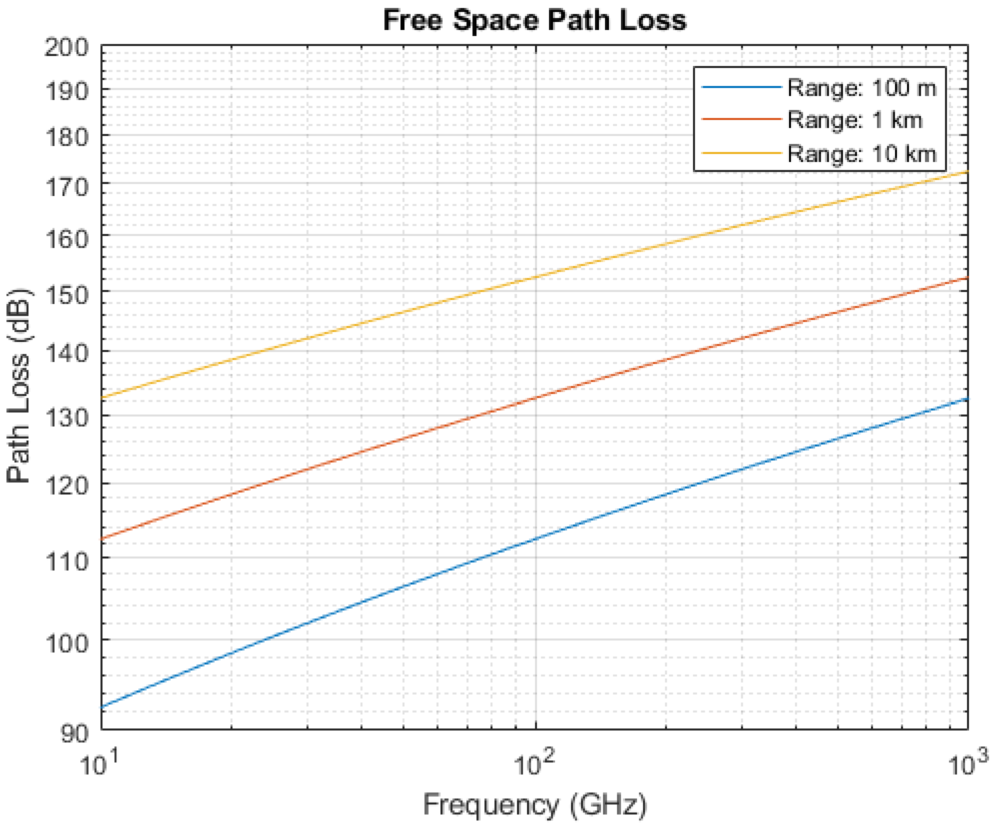
$$L_{fs} = 20 * \log_{10}(\frac{4\pi R}{\lambda}) \quad dB$$

As a convention, propagation losses are often expressed in dB. This convention makes it much easier to derive the two-way free space path loss by simply doubling the one-way free space loss.

The following figure plots how the free space path loss changes over the frequency between 10 to 1000 GHz for different ranges.

```
c = physconst('lightspeed');
R0 = [100 1e3 10e3];
freq = (10:1000).'*1e9;
apathloss = fspl(R0,c./freq);
loglog(freq/1e9,apathloss);
```

```
grid on; ylim([90 200])
legend('Range: 100 m', 'Range: 1 km', 'Range: 10 km')
xlabel('Frequency (GHz)');
ylabel('Path Loss (dB)')
title('Free Space Path Loss')
```



The figure illustrates that the propagation loss increases with range and frequency.

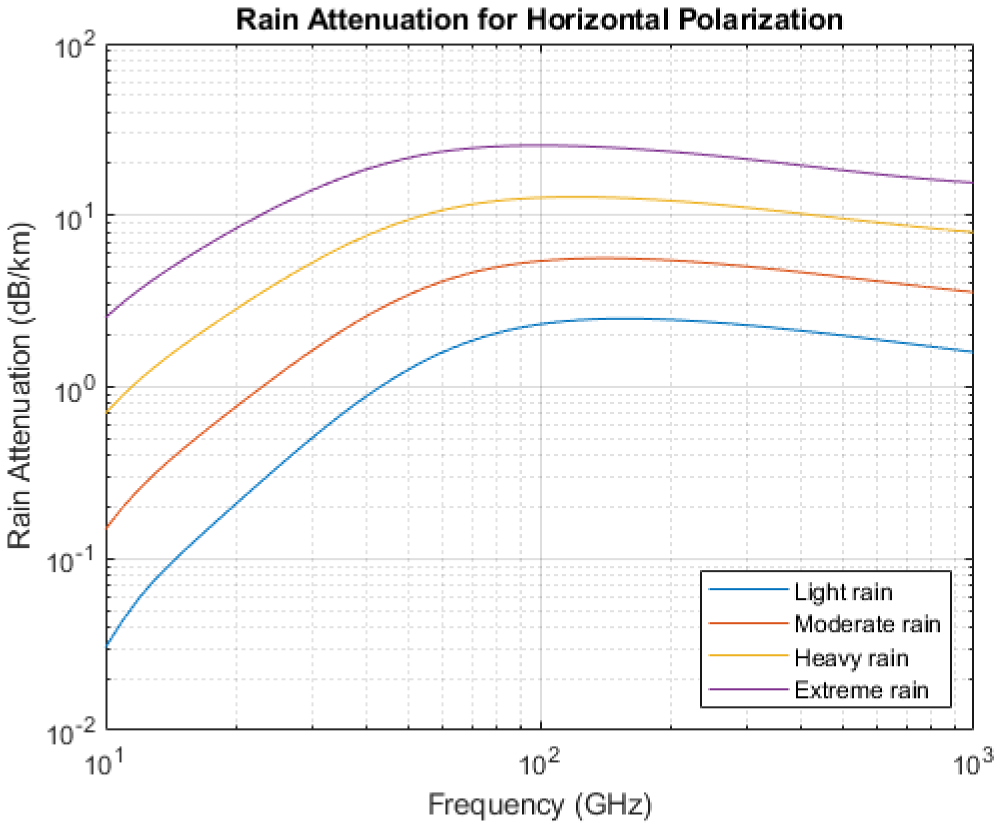
Propagation Loss Due to Rain

In reality, signals don't travel in a vacuum, so free space path loss describes only part of the signal attenuation. Signals interact with particles in the air and lose energy along the propagation path. The loss varies with different factors such as pressure, temperature, water density.

Rain can be a major limiting factor for a radar systems, especially when operating above 5 GHz. In the ITU model in [2], rain is characterized by the rain rate (in mm/h). According to [6], the rain rate can range from less than 0.25 mm/h for very light rain to over 50 mm/h for extreme rains. In addition, because of the rain drop's shape and its relative size compared to the RF signal wavelength, the propagation loss due to rain is also a function of signal polarization.

The following plot shows how losses due to rain varies with frequency. The plot assumes the polarization to be horizontal, so the tilt angle is 0. In addition, assume that the signal propagates parallel to the ground, so the elevation angle is 0. In general, horizontal polarization represents the worse case for propagation loss due to rain.

```
R0 = 1e3;                % 1 km range
rainrate = [1 4 16 50];  % rain rate in mm/h
el = 0;                  % 0 degree elevation
tau = 0;                 % horizontal polarization

for m = 1:numel(rainrate)
    rainloss(:,m) = rainpl(R0,freq,rainrate(m),el,tau)';
end
loglog(freq/1e9,rainloss); grid on;
legend('Light rain','Moderate rain','Heavy rain','Extreme rain', ...
    'Location','SouthEast');
xlabel('Frequency (GHz)');
ylabel('Rain Attenuation (dB/km)')
title('Rain Attenuation for Horizontal Polarization');
```



Similar to rainfall, snow can also have a significant impact on the propagation of RF signals. However, there is no specific model to compute the propagation loss due to snow. The common practice is to treat it as rainfall and compute the propagation loss based on the rain model, even though this approach tends to overestimate the loss a bit.

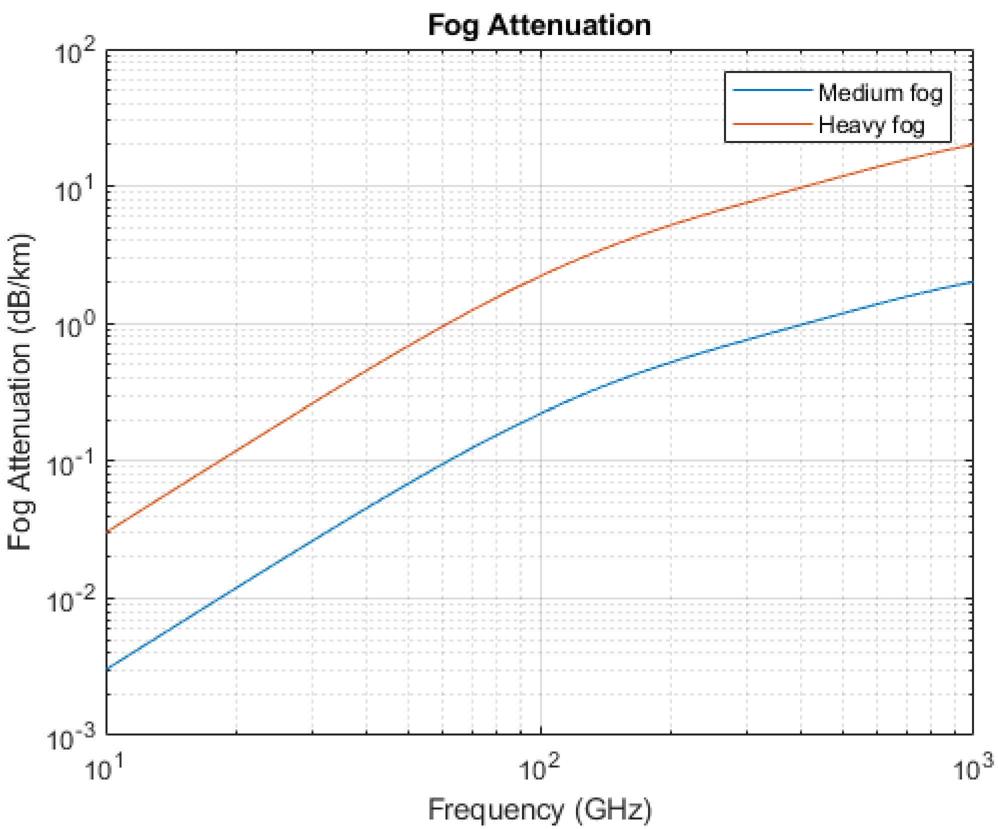
Propagation Loss Due to Fog and Cloud

Fog and cloud are formed with water droplets too, although much smaller compared to rain drops. The size of fog droplets are generally less than 0.01 cm. Fog is often characterized by the liquid water density. A medium fog with a visibility of roughly 300 meters, has a liquid water density of 0.05 g/m^3. For heavy fog where the visibility drops to 50 meters, the liquid water density is about 0.5 g/m^3. The atmosphere temperature (in Celsius) is also present in the ITU model for propagation loss due to fog and cloud [3].

The next plot shows how the propagation loss due to fog varies with frequency.

```
T = 15;                        % 15 degree Celsius
waterdensity = [0.05 0.5];    % liquid water density in g/m^3
for m = 1: numel(waterdensity)
    fogloss(:,m) = fogpl(R0,freq,T,waterdensity(m))';
end
```

```
loglog(freq/1e9,fogloss); grid on;
legend('Medium fog','Heavy fog');
xlabel('Frequency (GHz)');
ylabel('Fog Attenuation (dB/km)')
title('Fog Attenuation');
```



Note that in general fog is not present when it is raining.

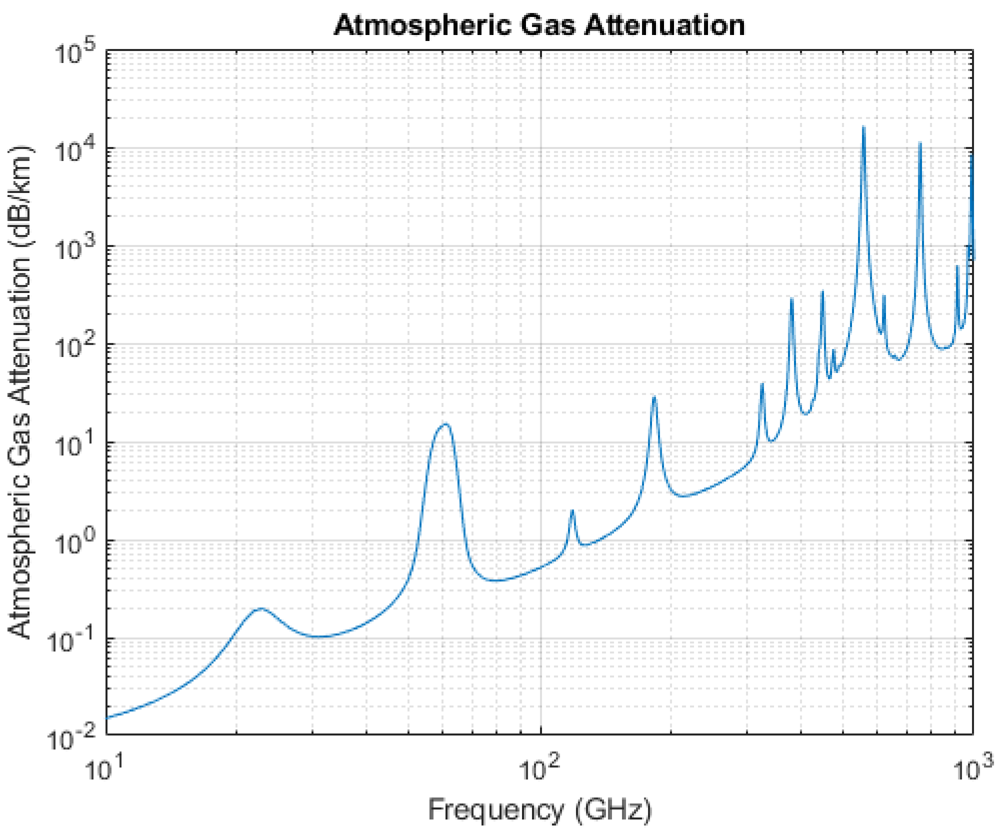
Propagation Loss Due to Atmospheric Gases

Even when there is no fog or rain, the atmosphere is full of gases that still affect the signal propagation. The ITU model [4] describes atmospheric gas attenuation as a function of both dry air pressure, like oxygen, measured in hPa, and water vapour density, measured in g/m^3.

The plot below shows how the propagation loss due to atmospheric gases varies with the frequency. Assume a dry air pressure of 1013 hPa at 15 degrees Celsius, and a water vapour density of 7.5 g/m^3.

```
P = 101300; % dry air pressure in Pa
ROU = 7.5;  % water vapour density in g/m^3
```

```
gasloss = gaspl(R0,freq,T,P,ROU);
loglog(freq/1e9,gasloss); grid on;
xlabel('Frequency (GHz)');
ylabel('Atmospheric Gas Attenuation (dB/km)')
title('Atmospheric Gas Attenuation');
```

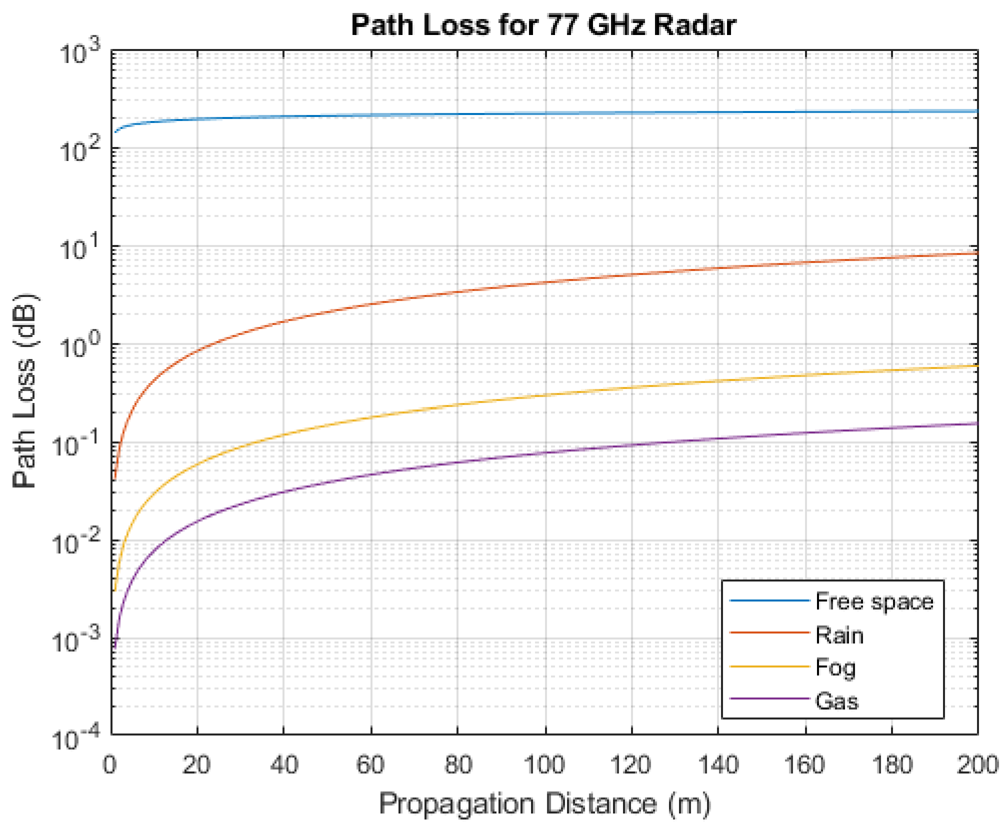


The plot suggests that there is a strong absorption due to atmospheric gases at around 60 GHz.

The next figure compares all weather related losses for a 77 GHz automotive radar. The horizontal axis is the target distance from the radar. The maximum distance of interest is about 200 meters.

```
R = (1:200).';
fc77 = 77e9;
apathloss = fspl(R,c/fc77);

rr = 16;  % heavy rain
arainloss = rainpl(R,fc77,rr,el,tau);
```

```
M = 0.5; % heavy fog
afogloss = fogpl(R,fc77,T,M);

agasloss = gaspl(R,fc77,T,P,ROU);

% Multiply by 2 for two-way loss
semilogy(R,2*[apathloss arainloss afogloss agasloss]);

grid on;
xlabel('Propagation Distance (m)');
ylabel('Path Loss (dB)');
legend('Free space','Rain','Fog','Gas','Location','Best')
title('Path Loss for 77 GHz Radar');
```



The plot suggests that for a 77 GHz automotive radar, the free space path loss is the dominant loss. Losses from fog and atmospheric gasses are negligible, accounting for less than 0.5 dB. The loss from rain can get close to 3 dB at 180 m.

Propagation Delay and Doppler Shift on Top of Propagation Loss

Functions mentioned above for computing propagation losses, are useful to establish budget links. To simulate the propagation of arbitrary signals, we also need to apply range-dependent time delays, gains and phase shifts.

The code below simulates an air surveillance radar operated at 24 GHz.

```
fc = 24e9;
```

First, define the transmitted signal. A rectangular waveform will be used in this case

```
waveform = phased.RectangularWaveform;
wav = waveform();
```

Assume the radar is at the origin and the target is at a 5 km range, of the direction of 45 degrees azimuth and 10 degrees elevation. In addition, assume the propagation is along line of sight (LOS), a heavy rain rate of mm/h with no fog.

```
Rt = 5e3;
az = 45;
el = 10;
pos_tx = [0;0;0];
pos_rx = [Rt*cosd(el)*cosd(az);Rt*cosd(el)*sind(az);Rt*sind(el)];
vel_tx = [0;0;0];
vel_rx = [0;0;0];

loschannel = phased.LOSChannel(...
    'PropagationSpeed',c,...
    'OperatingFrequency',fc,...
    'SpecifyAtmosphere',true,...
    'Temperature',T,...
    'DryAirPressure',P,...
    'WaterVapourDensity',ROU,...
    'LiquidWaterDensity',0,...    % No fog
    'RainRate',rr,...
    'TwoWayPropagation', true)
```

```
loschannel = 

  phased.LOSChannel with properties:

         PropagationSpeed: 299792458
       OperatingFrequency: 2.4000e+10
```

```
         SpecifyAtmosphere: true
               Temperature: 15
            DryAirPressure: 101300
        WaterVapourDensity: 7.5000
        LiquidWaterDensity: 0
                  RainRate: 16
         TwoWayPropagation: true
                SampleRate: 1000000
     MaximumDistanceSource: 'Auto'
```

The received signal can then be simulated as

```
y = loschannel(wav,pos_tx,pos_rx,vel_tx,vel_rx);
```

The total loss can be computed as

```
L_total = pow2db(bandpower(wav))-pow2db(bandpower(y))
```

```
L_total =

  289.3914
```

To verify the power loss obtained from the simulation, compare it with the result from the analysis below and make sure they match.

```
Lfs = 2*fspl(Rt,c/fc);
Lr = 2*rainpl(Rt,fc,rr,el,tau);
Lg = 2*gaspl(Rt,fc,T,P,ROU);

L_analysis = Lfs+Lr+Lg
```

```
L_analysis =

  289.3514
```

Multipath Propagation

Signals may not always propagate along the line of sight. Instead, some signals can arrive at the destination via different paths through reflections and may add up either constructively or destructively. This multipath effect can cause significant fluctuations in the received signal.

Ground reflection is a common phenomenon for many radar or wireless communication systems. For example, when a base station sends a signal to a mobile unit, the signal not only propagates directly to the mobile unit but is also reflected from the ground.

Assume an operating frequency of 1900 MHz, as used in LTE, such a channel can be modeled as

```
fc = 1900e6;
tworaychannel = phased.TwoRayChannel('PropagationSpeed',c,...
    'OperatingFrequency',fc);
```

Assume the mobile unit is 1.6 meters above the ground, the base station is 100 meters above the ground at a 500 meters distance. Simulate the signal received by the mobile unit.

```
pos_base = [0;0;100];
pos_mobile = [500;0;1.6];
vel_base = [0;0;0];
vel_mobile = [0;0;0];
y2ray = tworaychannel(wav,pos_base,pos_mobile,vel_base,vel_mobile);
```

The signal loss suffered in this channel can be computed as

```
L_2ray = pow2db(bandpower(wav))-pow2db(bandpower(y2ray))
```

```
L_2ray =

  109.1524
```

The free space path loss is given by

```
L_ref = fspl(norm(pos_mobile-pos_base),c/fc)
```

```
L_ref =

   92.1673
```

The result suggests that in this configuration, the channel introduces an extra 17 dB loss to the received signal compared to the free space case. Now assume the mobile user is a bit taller and holds the mobile unit at 1.8 meters above the ground. Repeating the simulation above suggests that this time the ground reflection actually provides a 6 dB gain! Although free space path loss is essentially the same in the two scenarios, a 20 cm move caused a 23 dB fluctuation in signal power.

```
pos_mobile = [500;0;1.8];
y2ray  = tworaychannel(wav,pos_base,pos_mobile,vel_base,vel_mobile);
L_2ray = pow2db(bandpower(wav))-pow2db(bandpower(y2ray))
L_ref  = fspl(norm(pos_mobile-pos_base),c/fc)
```

```
L_2ray =

   86.2165
```

```
L_ref =

   92.1666
```

Wideband Propagation in a Multipath Environment

Increasing a system's bandwidth increases the capacity of its channel. This enables higher data rates in communication systems and finer range resolutions for radar systems. The increased bandwidth can also improve robustness to multipath fading for both systems.

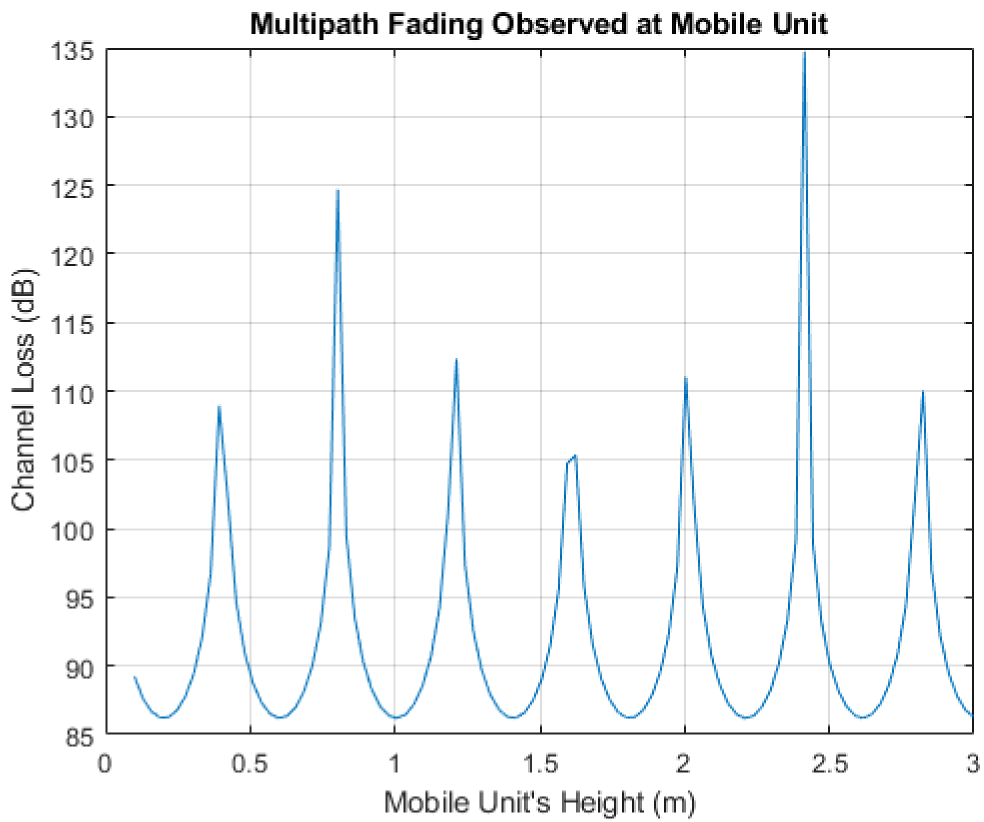
Typically, wideband systems operate with a bandwidth of greater than 5% of their center frequency. In contrast, narrowband systems operate with a bandwidth of 1% or less of the system's center frequency.

The narrowband channel in the preceding section was shown to be very sensitive to multipath fading. Slight changes in the mobile unit's height resulted in considerable signal losses. The channel's fading characteristics can be plotted by varying the mobile unit's height across a span of operational heights for this wireless communication system. A span of heights from 10cm to 3m is chosen to cover a likely range for mobile unit usage.

```
% Simulate the signal fading at mobile unit for heights from 10cm to 3m
hMobile = linspace(0.1,3);
pos_mobile = repmat([500;0;1.6],[1 numel(hMobile)]);
pos_mobile(3,:) = hMobile;
vel_mobile = repmat([0;0;0],[1 numel(hMobile)]);

release(tworaychannel);
y2ray = tworaychannel(repmat(wav,[1 numel(hMobile)]),...
    pos_base,pos_mobile,vel_base,vel_mobile);
```

The signal loss observed at the mobile unit for the narrowband system can now be plotted.

```
L2ray = pow2db(bandpower(wav))-pow2db(bandpower(y2ray));

plot(hMobile,L2ray);
xlabel('Mobile Unit''s Height (m)');
ylabel('Channel Loss (dB)');
title('Multipath Fading Observed at Mobile Unit');
grid on;
```



The sensitivity of the channel loss to the mobile unit's height for this narrowband system is clear. Deep signal fades occur at heights that are likely to be occupied by the system's users.

Increasing the channel's bandwidth can improve the communication link's robustness to these multipath fades. To do this, a wideband waveform is defined with a bandwidth of 10% of the link's center frequency.

```
bw = 0.10*fc;
pulse_width = 1/bw;
fs = 2*bw;

waveform = phased.RectangularWaveform('SampleRate',fs,...
    'PulseWidth',pulse_width);
wav = waveform();
```

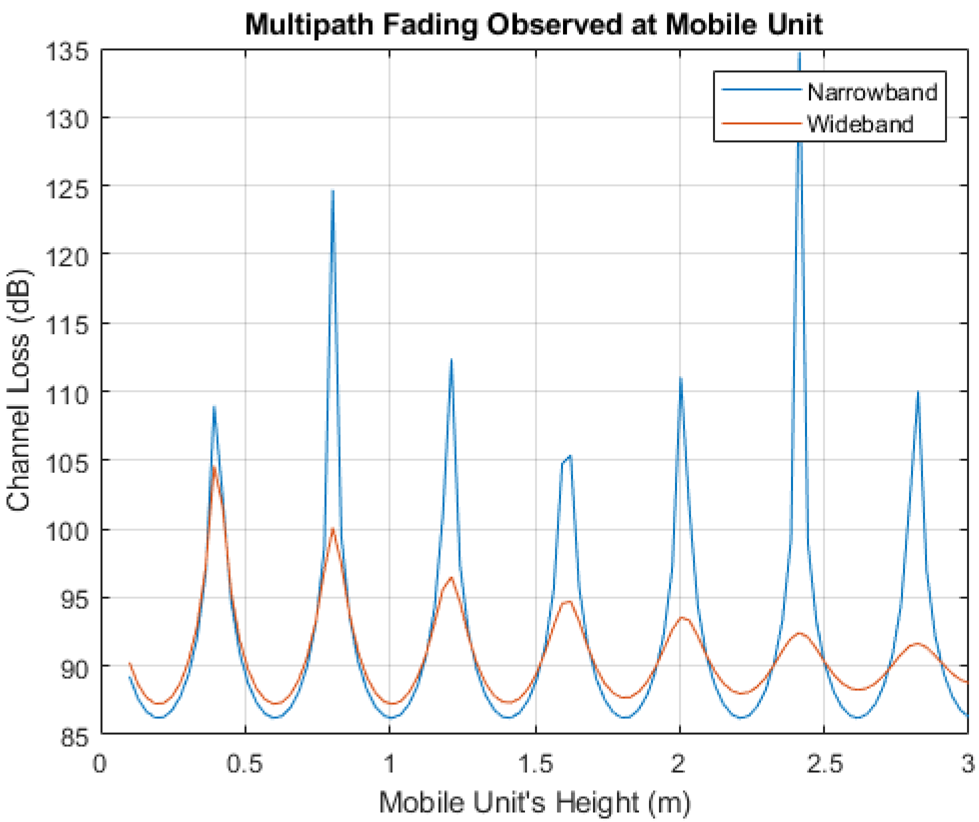
A wideband two-ray channel model is also required to simulate the multipath reflections of this wideband signal off of the ground between the base station and the mobile unit and to compute the corresponding channel loss.

```
widebandTwoRayChannel = ...
```

```
    phased.WidebandTwoRayChannel('PropagationSpeed',c,...
    'OperatingFrequency',fc,'SampleRate',fs);
```

The received signal at the mobile unit for various operational heights can now be simulated for this wideband system.

```
y2ray_wb = widebandTwoRayChannel(repmat(wav,[1 numel(hMobile)]),...
    pos_base,pos_mobile,vel_base,vel_mobile);
L2ray_wb = pow2db(bandpower(wav))-pow2db(bandpower(y2ray_wb));

hold on;
plot(hMobile,L2ray_wb);
hold off;
legend('Narrowband','Wideband');
```



As expected, the wideband channel provides much better performance across a wide range of heights for the mobile unit. In fact, as the height of the mobile unit increases, the impact of multipath fading almost completely disappears. This is because the difference in propagation delay between the direct and bounce path signals is increasing, reducing the amount of coherence between the two signals when received at the mobile unit.

Conclusion

This example provides a brief overview of RF propagation losses due to atmospheric and weather effects. It also introduces multipath signal fluctuations due to bounces on the ground. It highlighted functions and objects to calculate attenuation losses and simulate range-dependent time delays and Doppler shifts.

References


```
[1] John Seybold, Introduction to RF Propagation, Wiley, 2005

[2] Recommendation ITU-R P.838-3, 2005

[3] Recommendation ITU-R P.840-3, 2013

[4] Recommendation ITU-R P.676-10, 2013

[5] Recommendation ITU-R P.525-2, 1994
```