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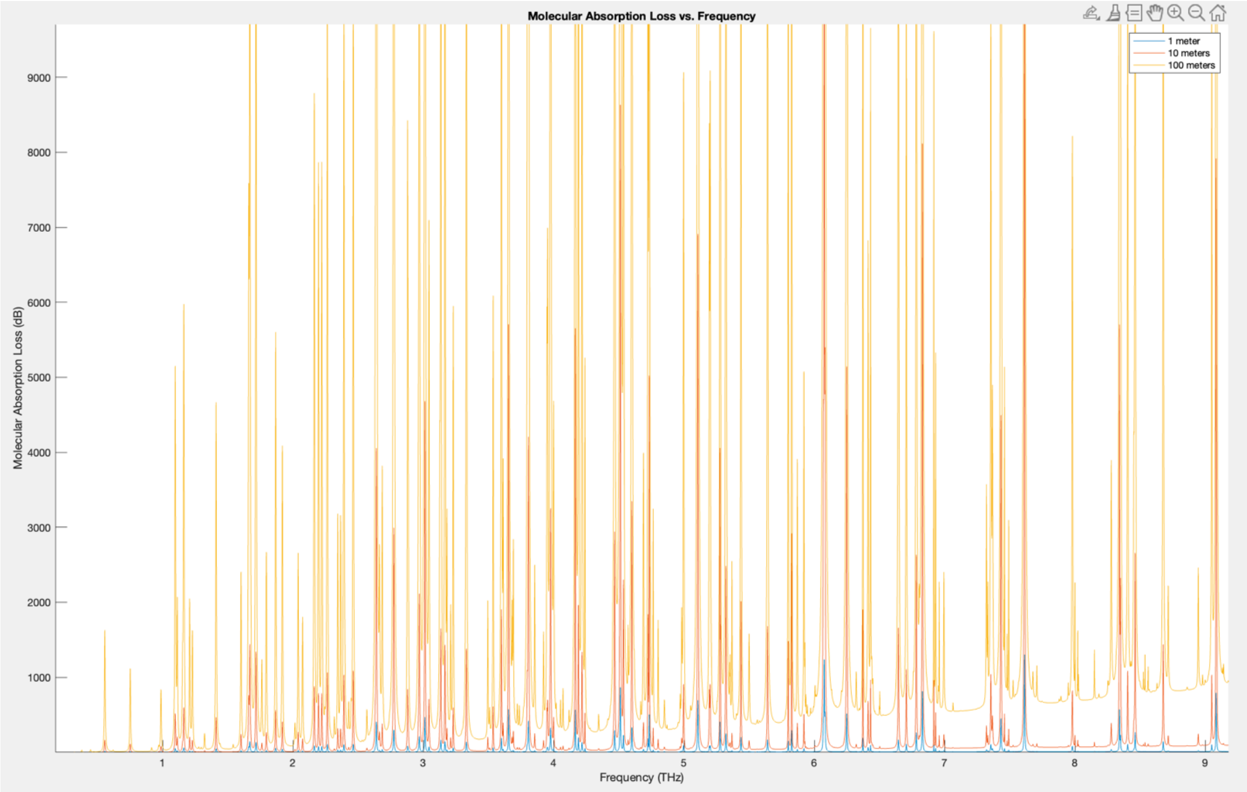
Part 1: Analytical Terahertz Channel Modeling

a) Load the molecular absorption coefficient. Compute and plot the molecular absorption loss (in dB) as a function of frequency (from 100 GHz to 10 THz only) for three different distances (1, 10 and 100 meters), in the same figure. Label the axis with magnitude and units (Hint: remember the xlabel and ylabel commands), include a legend to distinguish the three lines (Hint: remember the legend command). Mark the absorption-defined transmission windows. If needed, adjust the vertical scale (Hint: remember the xlim and ylim commands)

MATLAB Code:

```
clear all;
load('/Users/soniyanitinkadam/Desktop/NEU/Semester 2 (Spring 2024)/Terahertz
Communication for 6G/Assignments/HW2/Data/MATLAB/molecular_absorption.mat');
% Load file path
f_THz = f * 1e-12;  % Convert frequency to THz for easier handling
idx = (f_THz >= 0.1) & (f_THz <= 10);  %  0.1 THz and 10 THz
f_relevant = f(idx);
k_relevant = k(idx);
distances = [1, 10, 100];  % distances in meters
L = zeros(length(f_relevant), length(distances));  % loss value storage
for i = 1:length(distances)
    L(:,i) = 10*log10(exp(1)) * k_relevant * distances(i);
end
% range of loss values
disp(['Loss at 1m: Min = ', num2str(min(L(:,1))), ' dB, Max = ',
num2str(max(L(:,1))), ' dB']);
disp(['Loss at 10m: Min = ', num2str(min(L(:,2))), ' dB, Max = ',
num2str(max(L(:,2))), ' dB']);
disp(['Loss at 100m: Min = ', num2str(min(L(:,3))), ' dB, Max = ',
num2str(max(L(:,3))), ' dB']);
figure;
hold on;
plot(f_THz(idx), L(:,1),  'DisplayName','1 meter');  % plot for 1 meter
plot(f_THz(idx), L(:,2),  'DisplayName','10 meters');  % plot for 10 meters
plot(f_THz(idx), L(:,3),  'DisplayName','100 meters');  % plot for 100 meters
hold off;
% Label
xlabel('Frequency (THz)');
ylabel('Molecular Absorption Loss (dB)');
legend show;
xlim([0.1 1.6]);  % Set x-axis
ylim([0 100]);  % Set y-axis
title('Molecular Absorption Loss vs. Frequency'); %adding the title of the
plot
```



The code begins by loading molecular absorption data from a file containing the frequency vector f (in Hz) and absorption coefficient vector k (in m^-1). It then converts the frequencies to THz units for easier handling by multiplying f by 1e-12. Next, it defines an index idx to select only the frequencies between 0.1 and 10 THz that are relevant for the analysis. The corresponding frequency and absorption coefficient vectors f_relevant and k_relevant are extracted based on this index. Three distances - 1, 10 and 100 meters - are defined in a vector called distances. A matrix L is pre-allocated to store the loss values, with rows equal to the number of frequencies and 3 columns for each distance.

The code then loops through each distance and calculates the molecular absorption loss in dB. The resulting loss values are stored in the matrix L. After the calculation, the minimum and maximum loss at each distance is printed out. The loss is then plotted versus frequency for the 3 distances on a figure using hold on/off and legend commands. The figure is formatted by labeling the axes, setting the x-axis limits, automatically adjusting the y-axis limits, and adding a title.

- **In which cases would you utilize the absorption-free windows?**

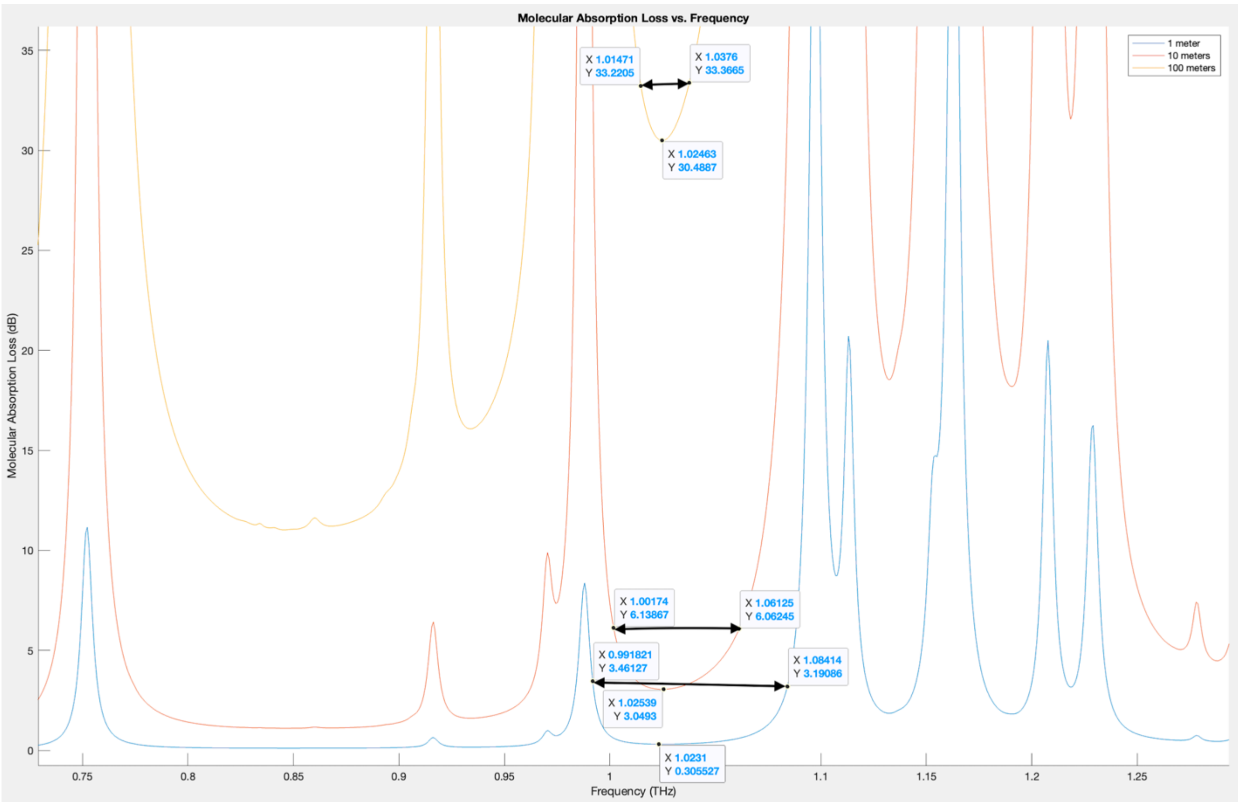
Solution: The absorption three windows can be used when we have a good hardware system which can work on those selective frequencies which can combine these selective frequencies. This absorption free windows also allow a good amount of bandwidth for various applications.

- **Would you ever consider communicating over the absorption lines instead? Justify your answer.**

Solution: We can consider communicating above the absorption lines only during sensing of environment. The amount of absorption can provide information about an object or an environment depending upon the amount of absorption that is taking place, we can use the target signal reflected and observer it or record it to create a database allowing us to identify the objects in question. Safety scanners at the airport are a great example of it.

- **For the first transmission window above 1 THz, how much does the 3-dB bandwidth change when increasing the distance? Provide a quantitative answer.**
Solution:

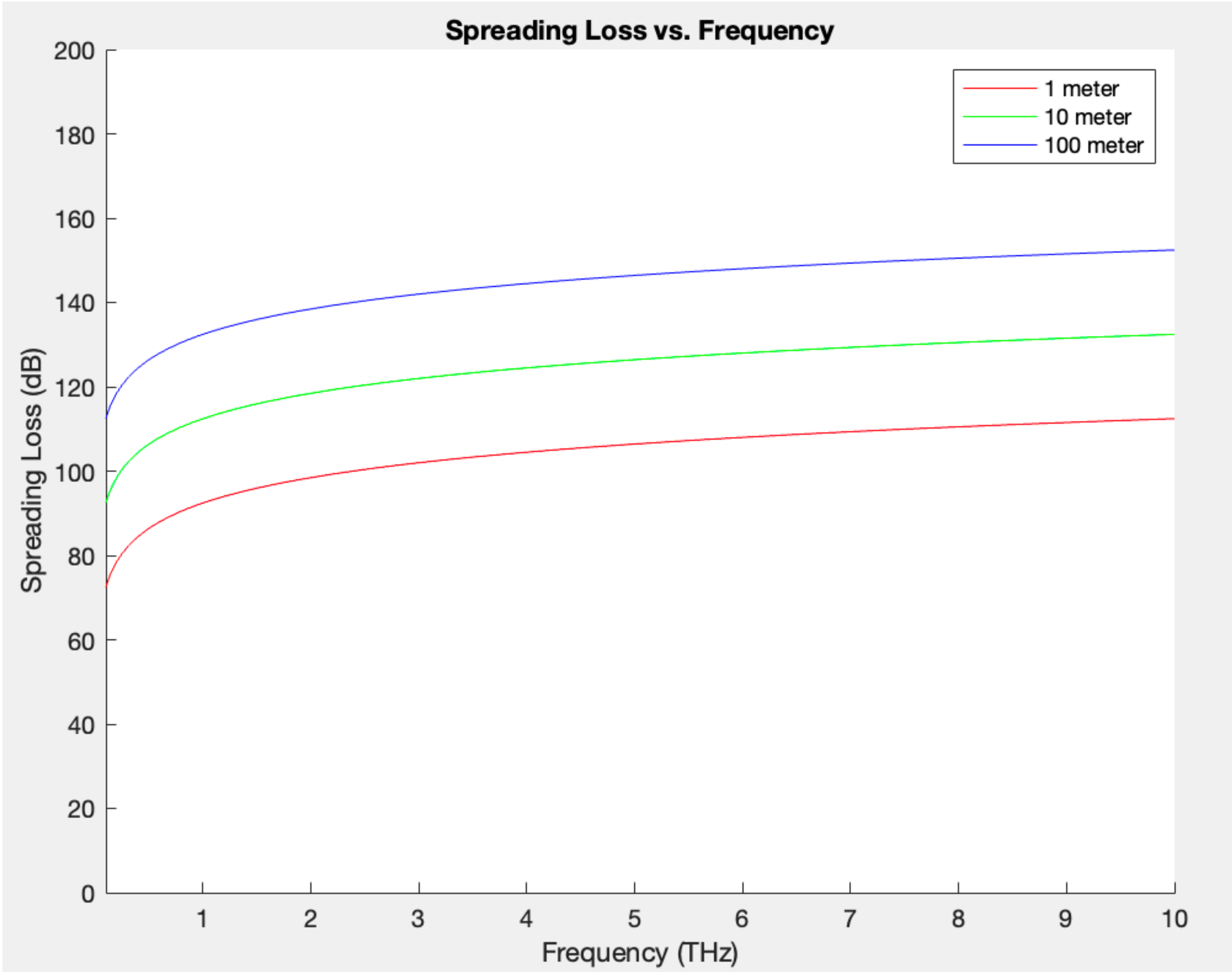
Distance	**F1 (THz)**	**F2 (THz)**	**3-dB Bandwidth (GHz)**
For 1 meter	0.991	1.064	73
For 10 meters	1.001	1.061	60
For 100 meters	1.014	1.037	23



b) Compute and plot the spreading loss (in dB) as a function of frequency for the same three distances, for an ideal isotropic omnidirectional antenna.

MATLAB Code:

```
c = 3e8; % Speed of light in m/s
load('/Users/soniyanitinkadam/Desktop/NEU/Semester 2 (Spring 2024)/Terahertz Communication for 6G/Assignments/HW2/Data/MATLAB/molecular_absorption.mat');  % path to file
f_THz = f * 1e-12; % Convert frequency to THz
idx = (f_THz >= 0.1) & (f_THz <= 10); % 0.1 THz and 10 THz
f_relevant = f(idx);
distances = [1, 10, 100]; % Distances in meters
% spreading loss array
SpreadingLoss_dB = zeros(length(f_relevant), length(distances));
% Calculate spreading loss
for i = 1:length(distances)
   SpreadingLoss_dB(:,i) = 20*log10(4*pi*f_relevant*distances(i)/c);
end
figure; % create figure
hold on; %
colors = ['r', 'g', 'b']; % Color for each line
for i = 1:length(distances)
   plot(f_THz(idx), SpreadingLoss_dB(:,i), colors(i), 'DisplayName', [num2str(distances(i)) ' meter']); % plot for each distance
end
hold off;
% Label
xlabel('Frequency (THz)');
ylabel('Spreading Loss (dB)');
legend show;
xlim([0.1 10]); % x-axis
ylim([0 200]); % y-axis
title('Spreading Loss vs. Frequency');
```



The code begins by defining the speed of light c. It then loads the molecular absorption data from a file. The frequencies f are converted to THz units and an index idx is created to extract only the relevant frequencies from 0.1 to 10 THz into the vector f_relevant. Three distances - 1, 10 and 100 meters - are defined in a vector called distances. An array SpreadingLoss_dB is preallocated to store the spreading loss values, with rows equal to the number of frequencies and 3 columns for each distance. The code then loops through each distance and calculates the spreading loss in dB using the formula: SpreadingLoss_dB = 20*log10(4*pi*f*distance/c). The resulting values are stored in SpreadingLoss_dB.
Next, we create a figure and a hold is set to overlay multiple plots. Three colors are defined for the lines. Within another loop, the spreading loss is plotted versus frequency for each distance with specific line colors and legend names. After plotting, the hold is released. The figure is formatted by labeling the axes, setting the x-axis limits, y-axis limits, and adding a title.

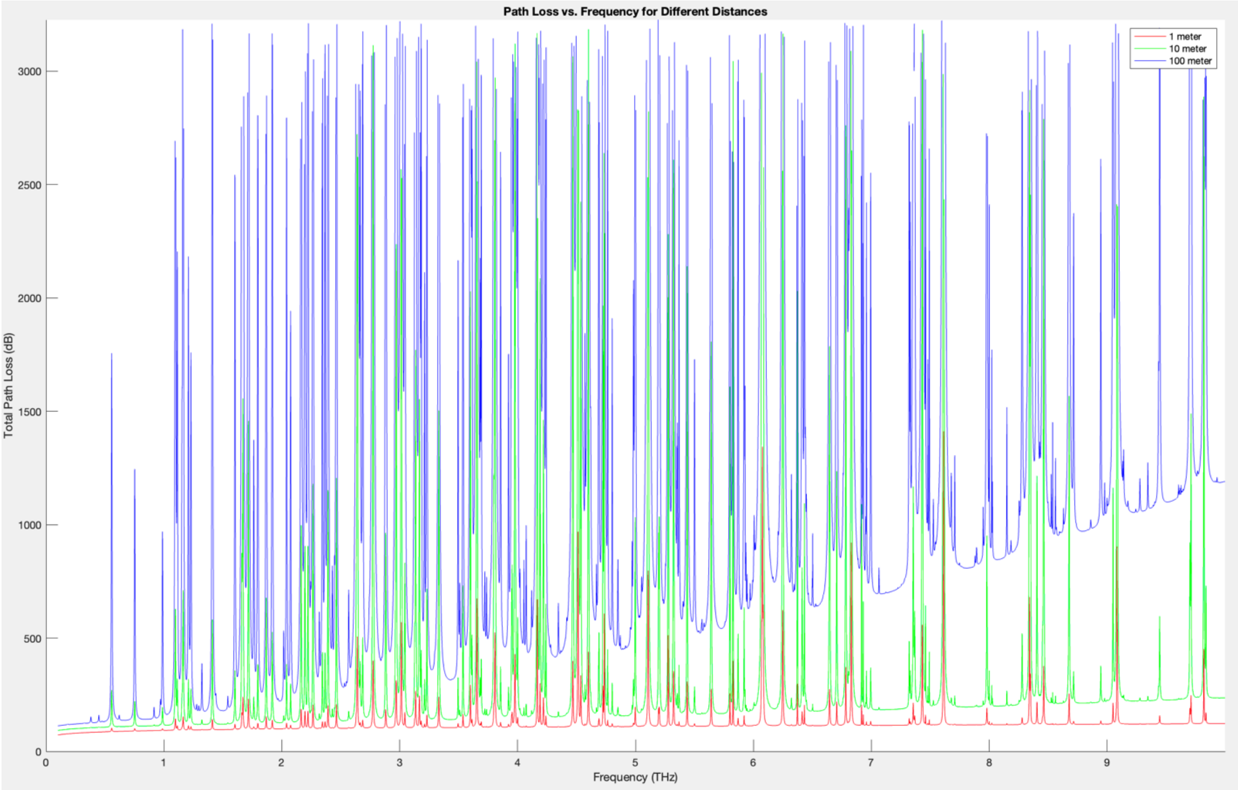
- **What would be the size of that antenna, if a dipole were considered?**
  Solution:
  The antenna size would be calculated with the Dipole antenna length = λ/2 formula. Which would eventually decide the size of the antenna. I have given a possible range for the values in consideration.
  At 1 THz:
  • Frequency f = 1 x 1012 Hz
  • Wavelength λ = c/f = (3x10^8 m/s) / (1x10^12 Hz) = 0.3 mm
  • Dipole antenna length = λ/2 = 0.15 mm = 150 µm
  At 10 THz:
  • Frequency f = 10 x 1012 Hz
  • Wavelength λ = c/f = (3x10^8 m/s) / (10x10^12 Hz) = 0.03 mm
  • Dipole antenna length = λ/2 = 0.015 mm = 15 µm

- **What can you do to reduce the spreading losses?**
  Solution: As electromagnetic waves travel over space, they spread, which results in spreading losses. Even though spreading losses can't be totally avoided, there are a number of methods and approaches that can be used to lessen their effects:
  <u>Directional Antennas:</u> These reduce spreading losses in unwanted directions by focusing energy in certain directions, as opposed to omnidirectional antennas that emit energy in all directions.
  <u>Antenna Gain:</u> By concentrating the radiated energy in one direction and minimizing dispersion losses in other directions, larger gain antennas can be used. <u>Antenna Height:</u> Especially in terrestrial communication systems, elevating antennas can decrease spreading losses by extending the line-of-sight between the transmitter and the receiver.
  <u>Beamforming:</u> By focusing radiation in particular directions, phased array antennas can reduce spreading losses in undesirable directions by utilizing beamforming techniques. Relay Stations: By generating and retransmitting signals across shorter distances, relay stations, also known as repeaters, can be added to wireless networks to reduce spreading losses.

c) By combining the two losses, compute the path loss as a function of frequency and for the same three distances.

MATLAB Code:

```
% Constants
c = 3e8; % Speed of light in m/s
load('/Users/soniyanitinkadam/Desktop/NEU/Semester 2 (Spring 2024)/Terahertz
Communication for 6G/Assignments/HW2/Data/MATLAB/molecular_absorption.mat');
f_THz = f * 1e-12; % Convert frequency to THz
idx = (f_THz >= 0.1) & (f_THz <= 10); % 0.1 THz and 10 THz
f_relevant = f(idx);
k_relevant = k(idx);
% Distances
distances = [1, 10, 100]; % Distances in meters
% Molecular Absorption Loss for each distance
L = zeros(length(f_relevant), length(distances)); % pre-allocate a matrix for absorption loss
values
for i = 1:length(distances)
   L(:,i) = 10*log10(exp(k_relevant * distances(i)));
end
% spreading loss
SpreadingLoss_dB = zeros(length(f_relevant), length(distances));
% Calculate spreading loss
for i = 1:length(distances)
   SpreadingLoss_dB(:,i) = 20*log10(4*pi*f_relevant*distances(i)/c);
end
% Total Path Loss
TotalPathLoss_dB = L + SpreadingLoss_dB;
figure; % create figure
 hold on; % hold on for multiple plots
 for i = 1:length(distances)
   plot(f_THz(idx), TotalPathLoss_dB(:,i), plot_colors(i), 'DisplayName', [num2str(distances(i)) '
meter']); % plot for each distance
 end
 hold off;
% Label
 xlabel('Frequency (THz)');
 ylabel('Total Path Loss (dB)');
 xlim([0 5]); % x-axis
 ylim([0 2000]);% y-axis
 title('Path Loss vs. Frequency for Different Distances');
```



The code begins by defining the speed of light constant c and loading the molecular absorption data from a file. It then converts the frequencies f to THz units and extracts the relevant 0.1 to 10 THz range into f_relevant and k_relevant. Three distances - 1, 10 and 100 meters - are defined in the vector distances. The molecular absorption loss L is calculated for each distance and stored in the matrix L. Next, the spreading loss is calculated using the given formula for each distance and stored in SpreadingLoss_dB.

The total path loss is computed by adding the molecular absorption loss L and spreading loss SpreadingLoss_dB element-wise and stored in TotalPathLoss_dB. A figure is created and a hold is set for overlaying multiple plots. The total path loss is plotted versus frequency for each distance in a loop using different line colors from plot colors. The plot is formatted by adding labels, axis limits and a title.

- **How does the path-loss at 300 GHz compare to spreading loss at 2.4 GHz, 60 GHz and 200 THz (1500 nm or infra-red wavelength)?**
  Solution:
  a) Pathloss at 300GHz is almost negligible over small distances and is still not that bad when the distance is increased.

  On the other hand when it comes to spreading loss :
  a) Spreading loss at 2.4 GHz – In general after my research the spreading loss for 2.5GHz is around 23dB
  b) Spreading loss at 60 GHz – According to the graph plotted the spreading loss for 60GHz is approximately 88.26 for 1 meter, 108.5 for 10 meters and 128.4dB for 100 meters. So it is safe to say that with the increase in distance the spreading loss also increases here.
  c) Spreading loss at 200 THz – Comparing to the previous observations, I feel that the spreading loss for 200THz will be a lot and will keep increasing as we move to higher frequencies and keep increasing distances.

- **Despite these results, why are we interested in moving towards higher frequencies?**
  Solution :
  - Extremely high bandwidth: THz frequencies correspond to wavelength of 30-3000 μm, allowing allocation of ultra-wide bandwidths (>100 GHz) for wireless links. This enables very high data rates (>100 Gbps).
  - High spatial resolution: The short wavelength enables greater antenna directivity and highly localized electromagnetic fields suitable for applications like imaging.
  - Low interference: THz frequencies occupy spectrum between microwave and infrared regions with minimal interference from existing services.
  - Compact transceiver components: Smaller antenna/electronic elements can be built at THz frequencies compared to microwaves due to shorter wavelengths.
  - Applications in spectroscopy: THz wavelengths correspond to rotational/vibrational modes of several molecules enabling spectral fingerprinting.

Part 2: Experimental Terahertz Channel Modeling

a) Utilizing the provided script and data files, complete the following table:

Material	Power in Transmission	Power in Reflection	Material type (e.g., mostly transparent, mostly reflecting, highly absorbing, etc.)
Air	21.07 dBm	NA	Mostly Transparent
Plastic	11.65 dBm	-6.58 dBm	Mostly Transparent with reflections
Metal	NA	20.62 dBm	Highly reflective
Glass	15.86 dBm	10.12 dBm	Mostly Transparent with reflections
Wood	2.32 dBm	7.85 dBm	Highly Absorbing

- **Air:** The majority of incident electromagnetic waves can travel through mostly transparent materials with little reflection. Because there is little to no reflection of the transmitted signal, the power in transmission is high, whereas the power in reflection is low or not applicable (NA). **Plastic:** Materials like plastic and glass, which are primarily transparent but also show reflections, let a significant amount of the incident wave through, leading to a high transmission power. However, some of the incident wave is reflected back because of these materials' reflecting qualities, resulting in a moderate to low power in reflection. The negative result in the case of plastic suggests that the power in reflection is reduced, probably due to absorption or scattering.
- **Metal:** Materials with a high reflectivity, like metal, show a strong reflection of incoming electromagnetic waves. Because little or no energy is passed through the medium, the power in transmission is low or not applicable (NA). On the other hand, since a large amount of the incident wave is reflected back, the power in reflection is considerable.
- **Glass:** Materials like plastic and glass that are primarily transparent but also show reflections allow a significant amount of the incident wave to pass through, which raises the transmission power. However, some of the incident wave is reflected back because of these materials' reflecting qualities, resulting in a moderate to low power in reflection. When it comes to plastic, the negative value means that the power in reflection is attenuated, likely due to absorption or scattering.
- **Wood:** Wood and other mostly absorbing materials absorb a large percentage of the incident electromagnetic wave instead of passing it through. As a result, transmission power is poor. However, surface reflections or scattering may still cause some of the incident wave to be reflected back, resulting in a moderate to high power in reflection.

b) Based on your obtained information, qualitatively explain how multi-path propagation at THz frequencies might look like in both indoor and outdoor scenarios.

Solution:

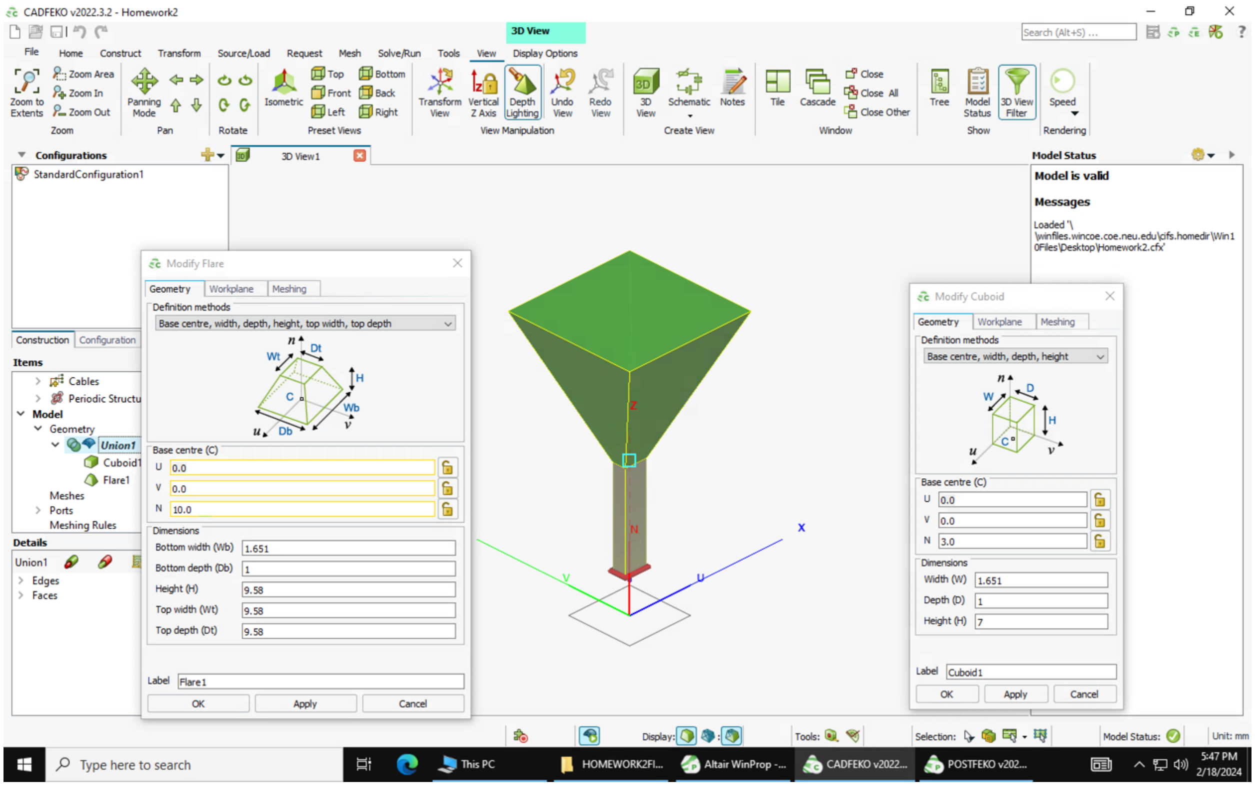
Indoor:

- Many objects like walls, furniture etc. will cause reflections and scattering. This will lead to a high density of multipath components.
- Materials like wood, plastic and glass will allow some THz transmission but also cause partial reflections. Metallic objects will strongly reflect THz waves.
- Overall, there will be rich multipath propagation with many reflected/scattered components interacting with each other constructively or destructively before arriving at the receiver.

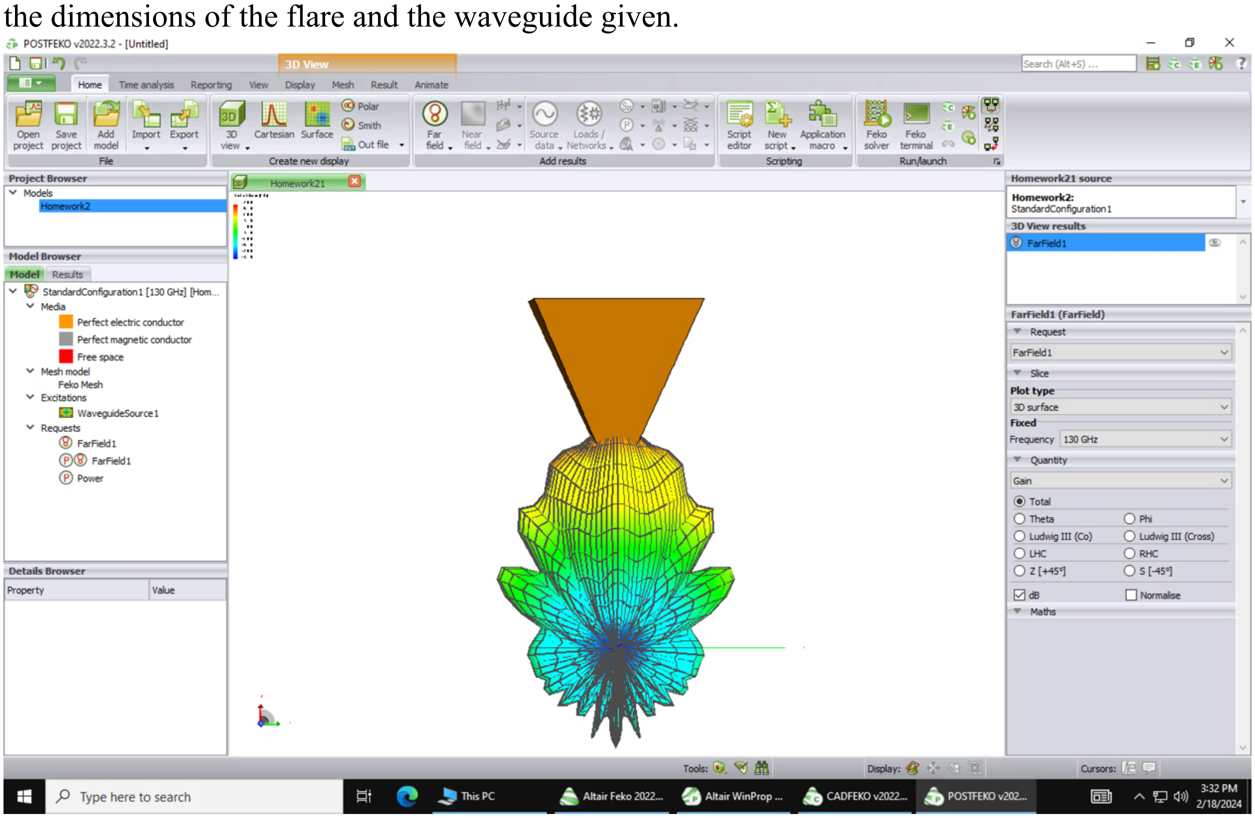
Outdoor:

- Smooth surfaces like building walls may cause strong specular reflections. Diffraction over roof edges can occur.
- Foliage and vegetation will strongly absorb THz waves and attenuate some multipath components.
- Suspended moisture/vapor in the air will cause molecular absorption of THz waves.
- There may be fewer but more spaced-out multipath components outdoors coming from distinct reflections off buildings, trees etc.
- The multipath propagation will be dependent on the specific environment urban/suburban/rural areas will have different effects.
- Overall, there will be multipath propagation but with fewer components than indoors due to greater spacing between reflectors and more molecular absorption.

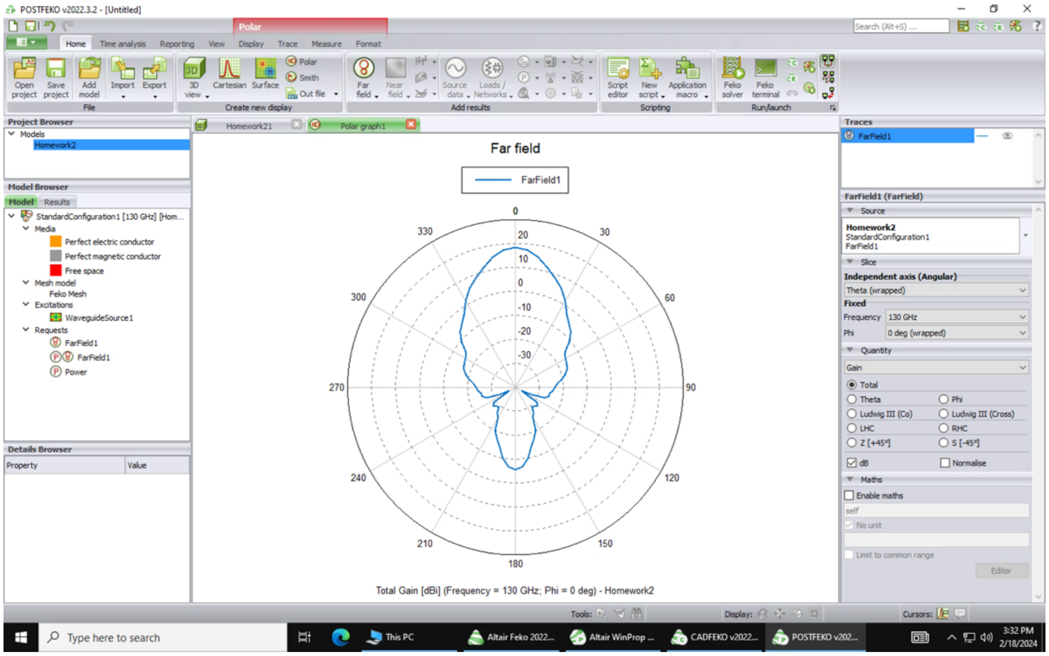
Part 3: Ray Tracing
INDOOR



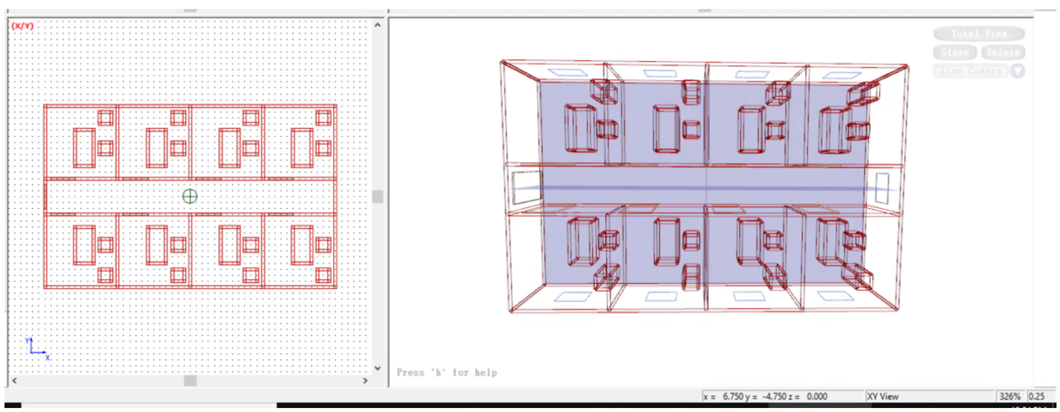
Here I have made the antenna incorporating the given values and putting them together according to step we followed in the 1st homework assignment. It is a typical horn antenna with the dimensions of the flare and the waveguide given.



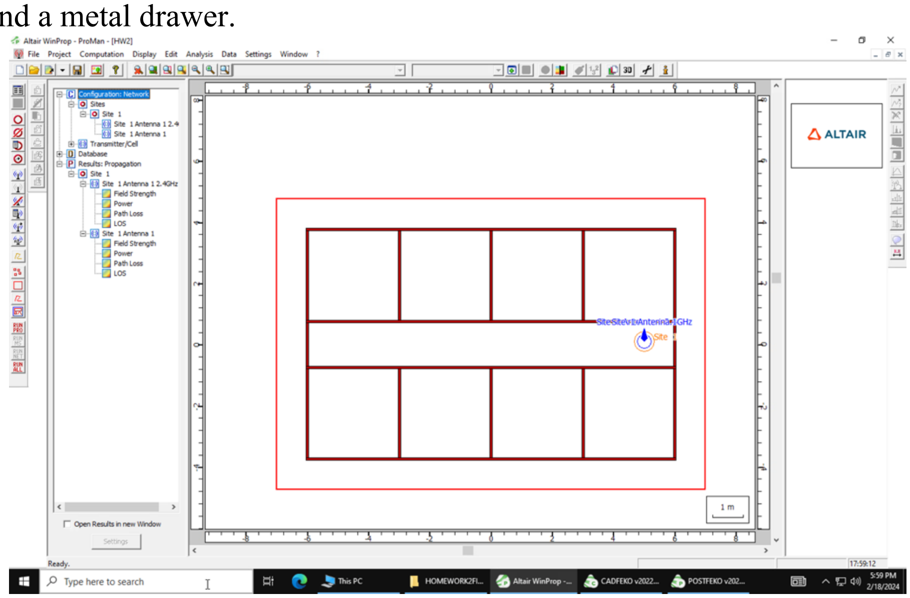
This image is the 3D radiation pattern of the antenna for the frequency of 130Ghz.



This graph is showing the far field radiation pattern of the horn antenna I created.

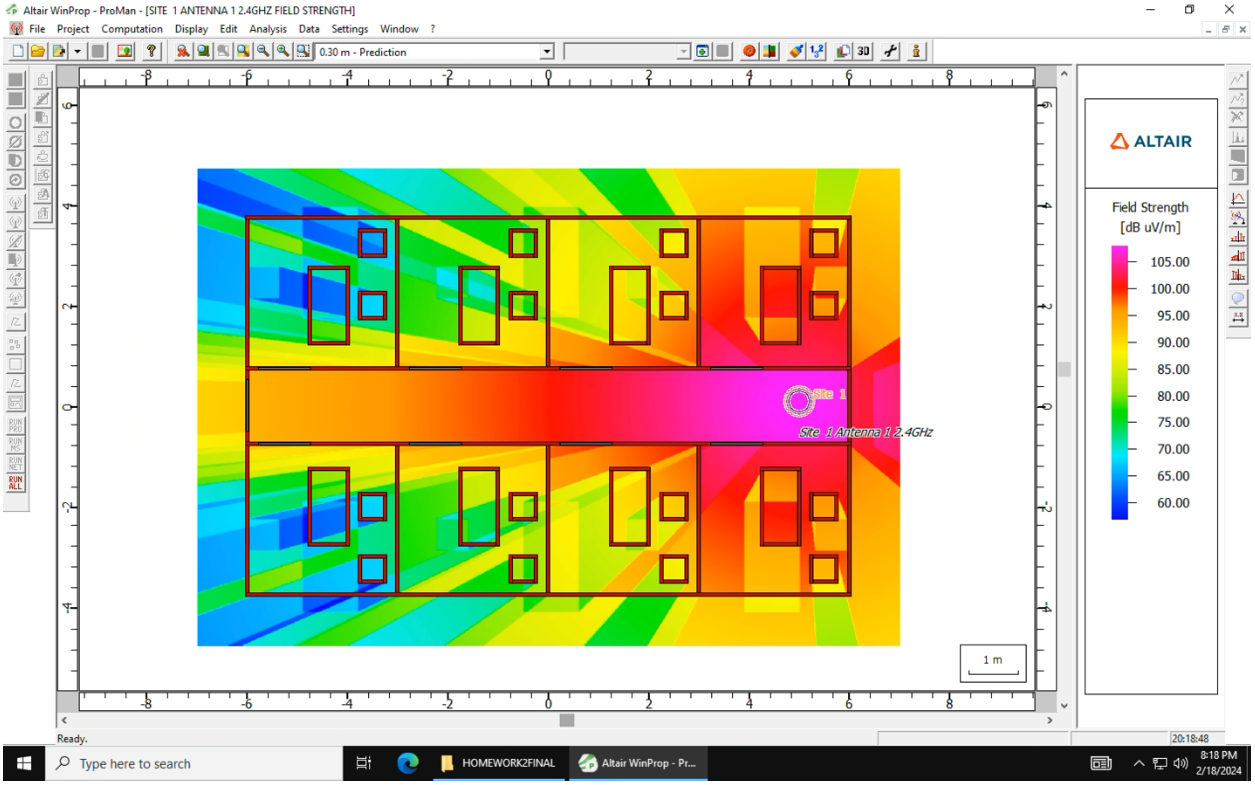


This is the indoor structure we will be using for the observation of how antenna and frequency would react to this indoor setup. This setup includes walls , doors, windows and furniture namely table, chair and a metal drawer.



Here we have added 2 antennas of 2 different frequencies. One antenna is a 2.4Ghz antenna and one is 130Ghz directional antenna.

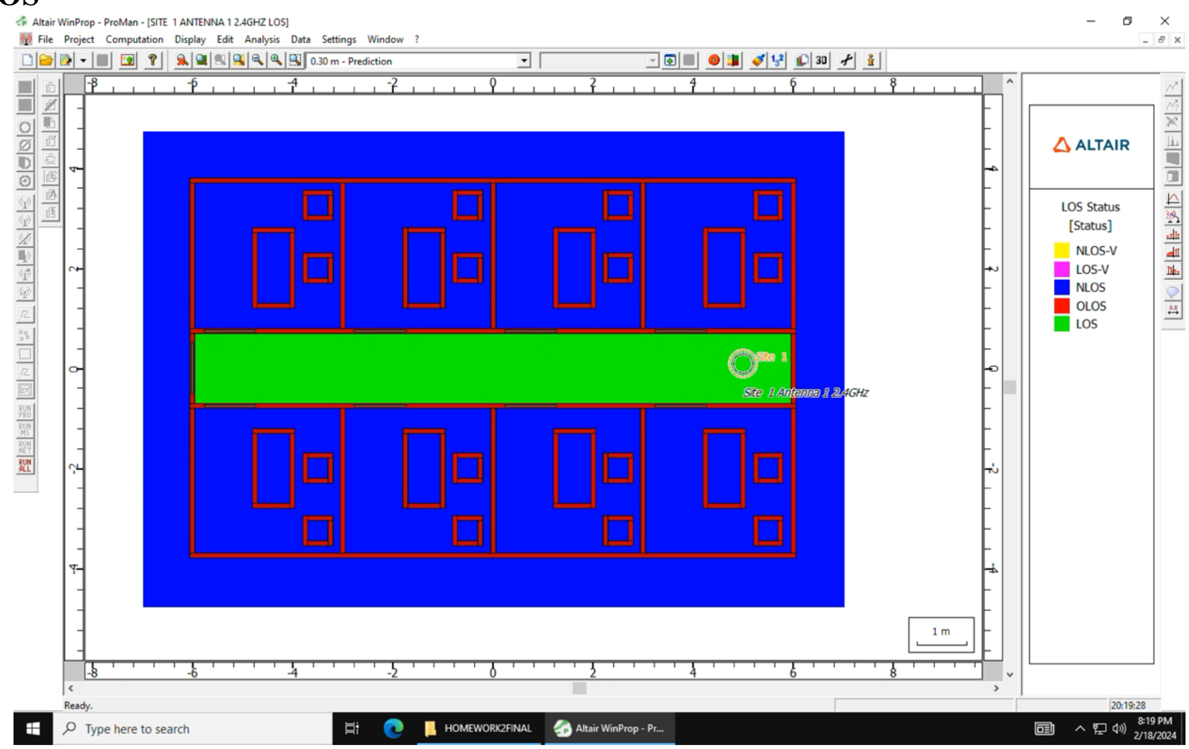
Antenna 1 with 2.4GHz
Field Strength



Field Strength plot at 2.4 GHz:

- Shows the signal propagation from the Tx antenna through the indoor environment
- Strongest signal (red) is seen along the line-of-sight path between Tx and Rx
- Moderate signal penetration (yellow/green) through front wooden door
- Very low penetration (blue) through brick side walls

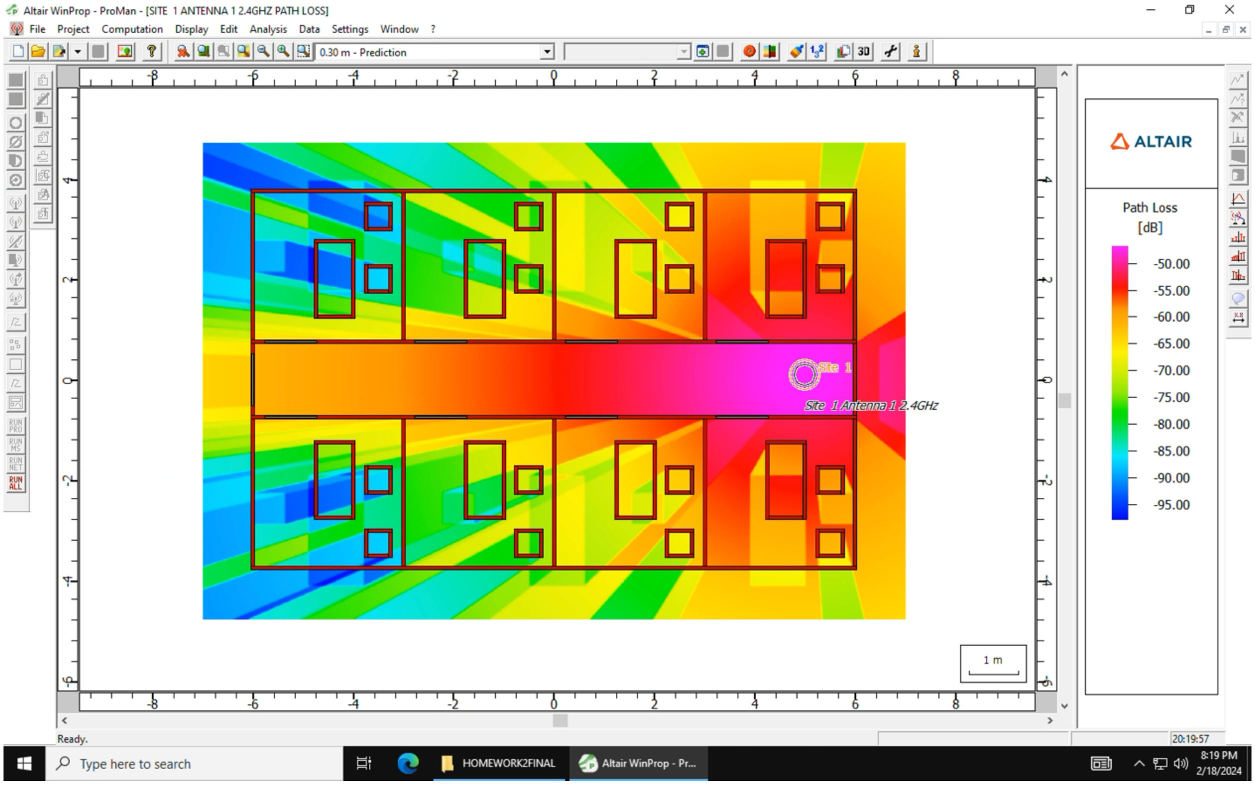
LOS



Line of Sight plot at 2.4 GHz:

- Shows the line of sight visibility propagation for this antenna
- The line of path is unobstructed at the corridor which have no obstruction at all.

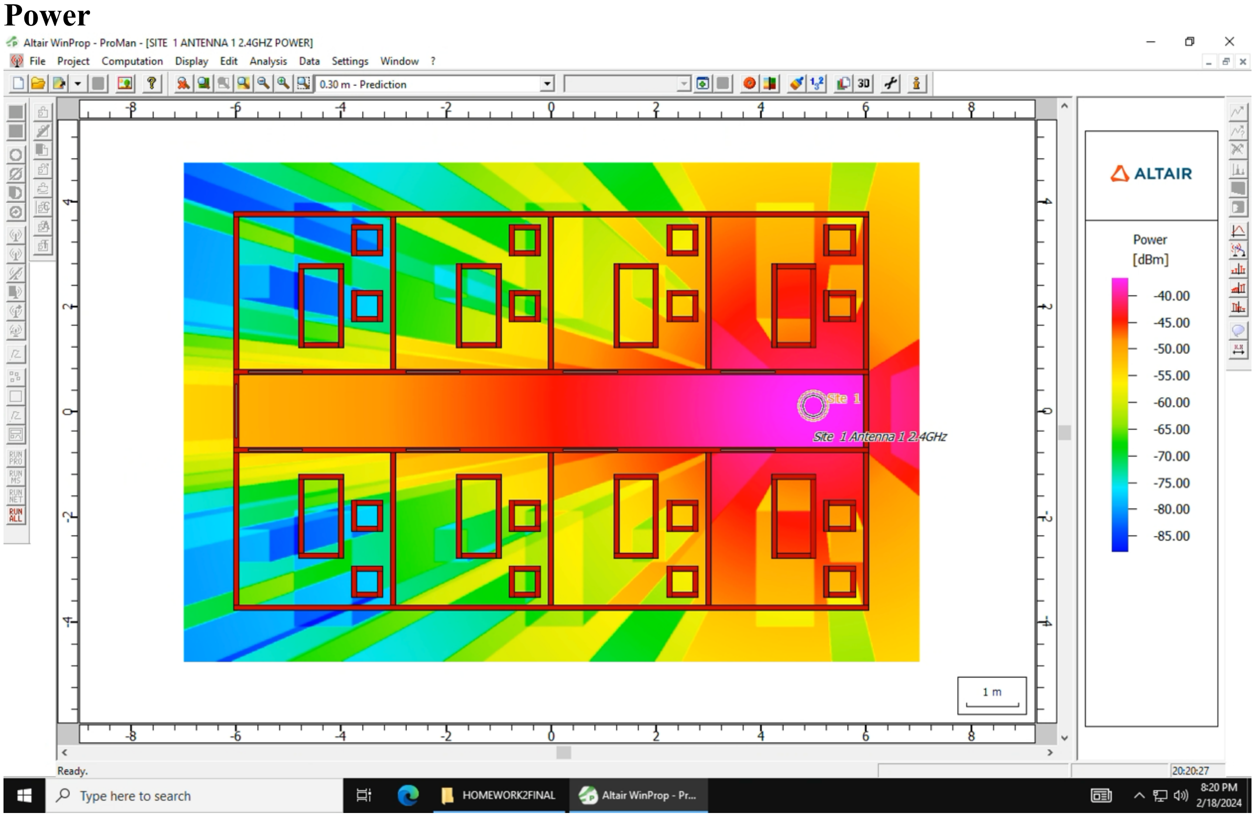
Path Loss



Path Loss plot at 2.4 GHz:

- Shows higher path loss (red) along non-line-of-sight paths with obstacles
- Lowest loss (blue) along direct line-of-sight path between Tx and Rx
- Moderate loss (green/yellow) through front door and side walls

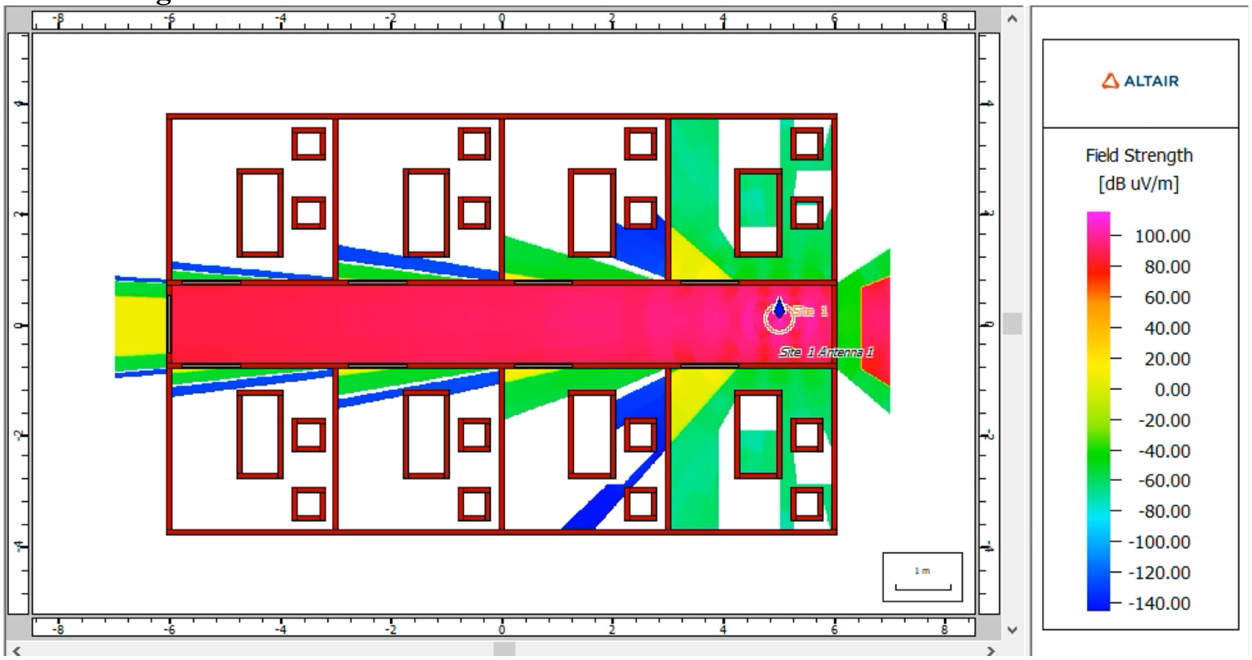
Power



Power plot at 2.4 GHz:

- Shows higher power (pink) , Lowest power (dark blue)
- Here we can see the power being scattered in almost all directions.
- The effect of various materials on this frequency is almost negligible.
- This increase in distance might be decreasing the power

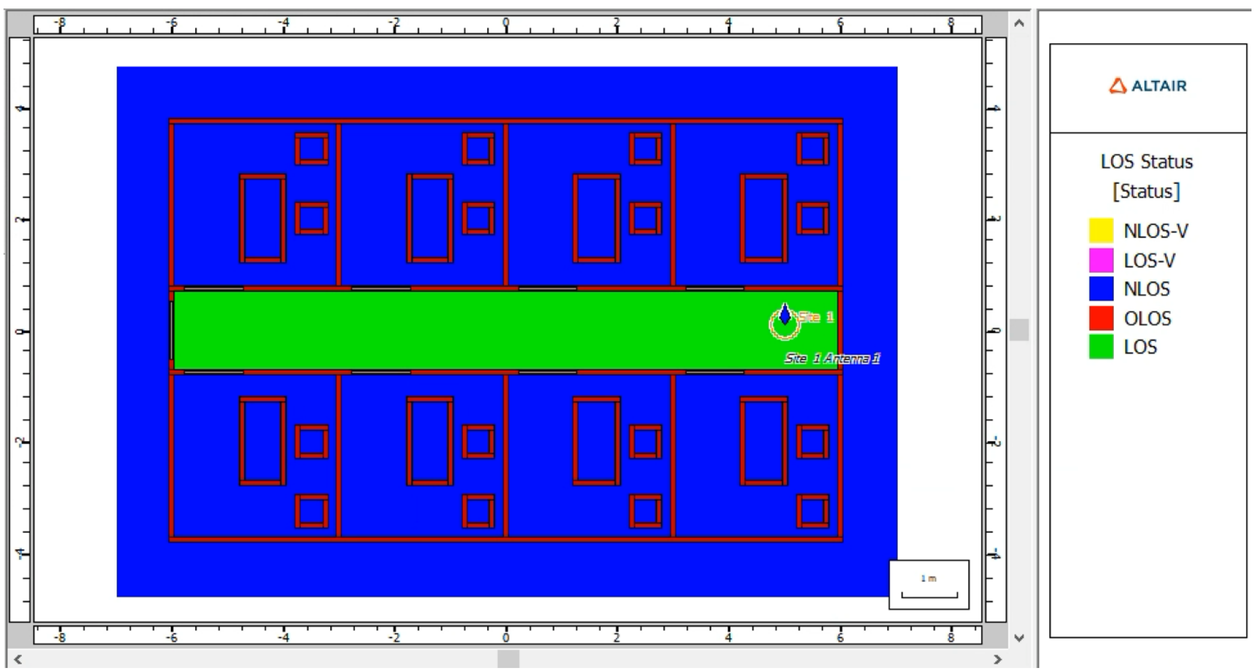
Antenna with 130 GHz
Field Strength



Field Strength plot at 130 GHz:

- Much lower penetration through walls and objects compared to 2.4 GHz
- Signals confined to single room with Tx and unable to penetrate side walls
- Higher reflection from obstacles like desks and cabinets

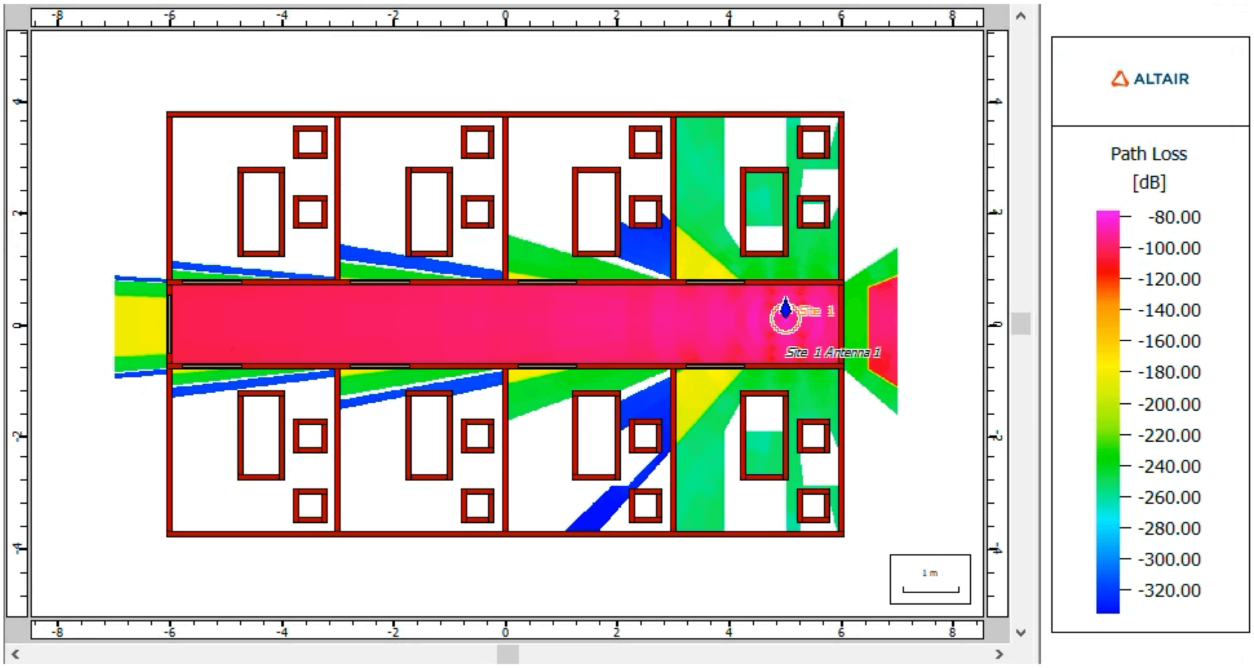
LOS



Line of Sight plot at 130 GHz:

- Shows the line of sight visibility propagation for this antenna
- The line of path is unobstructed at the corridor which have no obstruction at all.

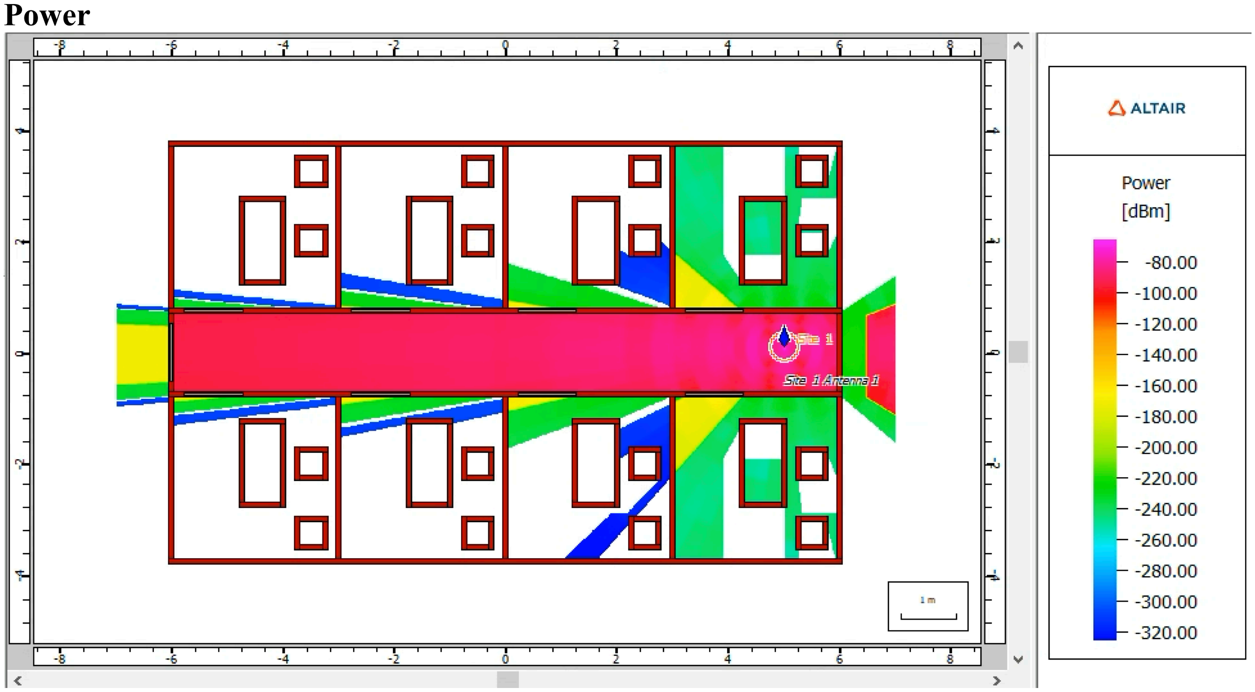
Path Loss



Path Loss plot at 130 GHz:

- Very high loss (red) through brick side walls
- Lower loss (green/blue) only along line-of-sight and through front door
- Smaller coverage area overall compared to 2.4 GHz
- Here we can see that the furniture of the house is causing the path loss.

Power



Power plot at 130 GHz:

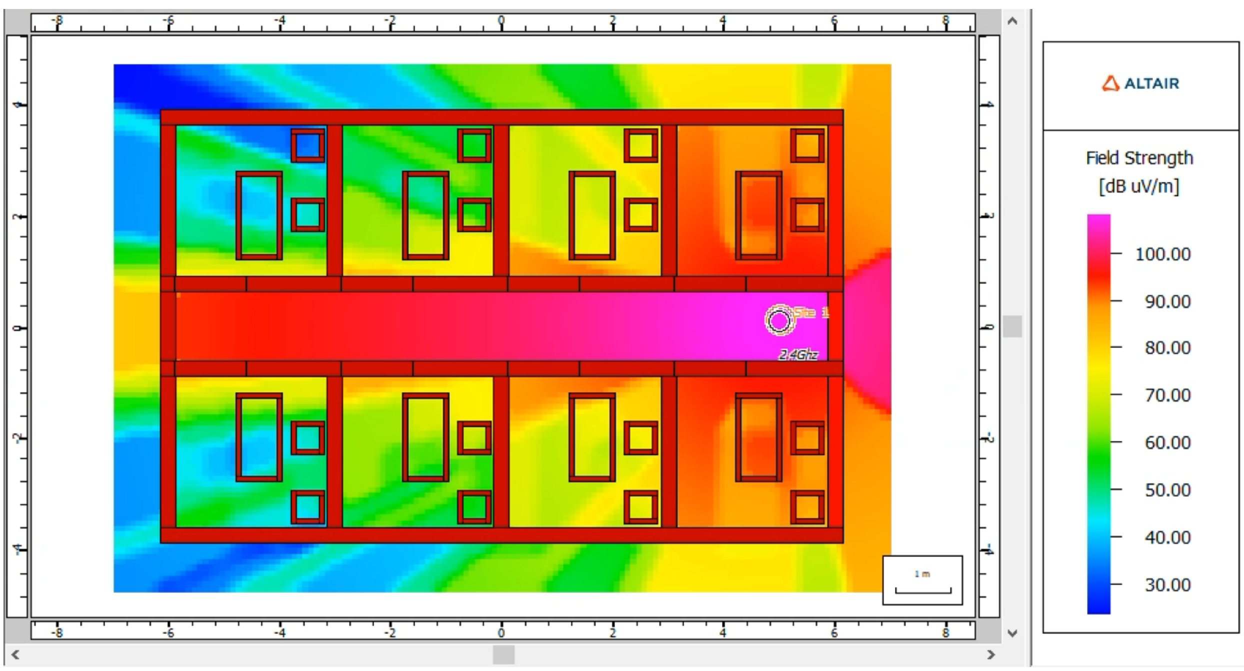
- The power is similar corresponding to the obstacles.
- Here we can see that the furniture is causing the decrease in power, some materials affecting it more than the other.

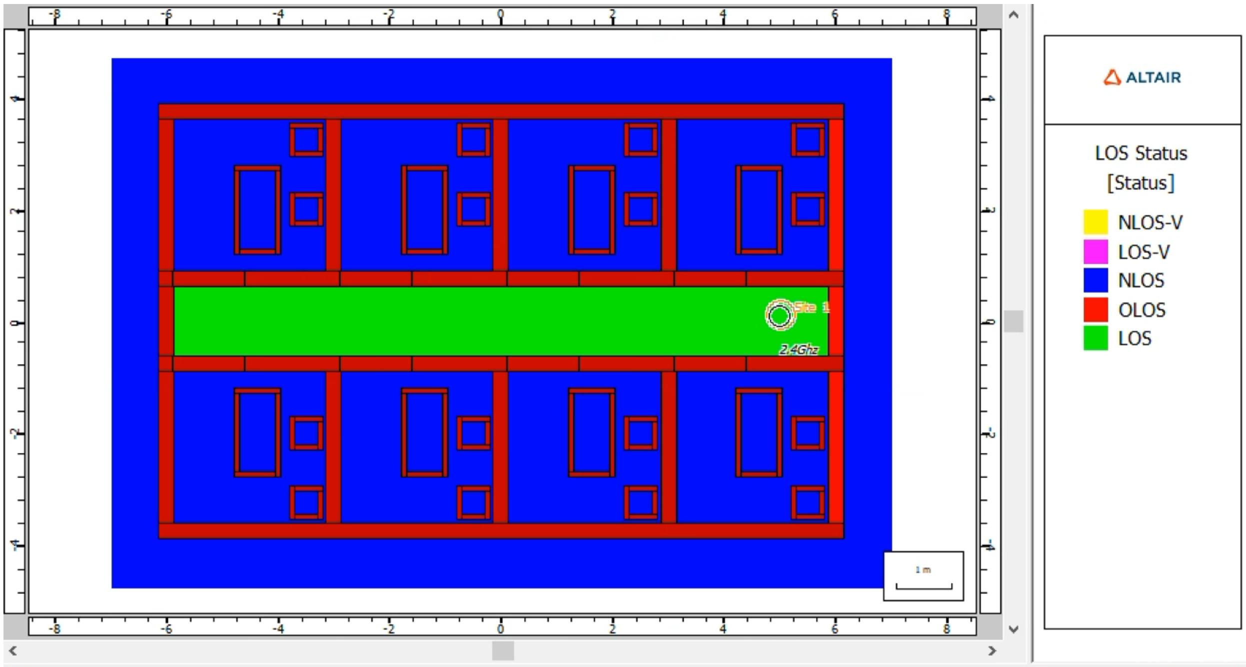
- **What are the main obstacles of the signal?**
  Solution: The walls, furniture, and other items in the room are the most significant impediments to indoor signal propagation. The electromagnetic waves are reflected and attenuated by the brick and wood walls, obstructing the transmission of signals between the transmitter and receiver. The filing cabinet and other metallic objects likewise powerfully reflect the signals.

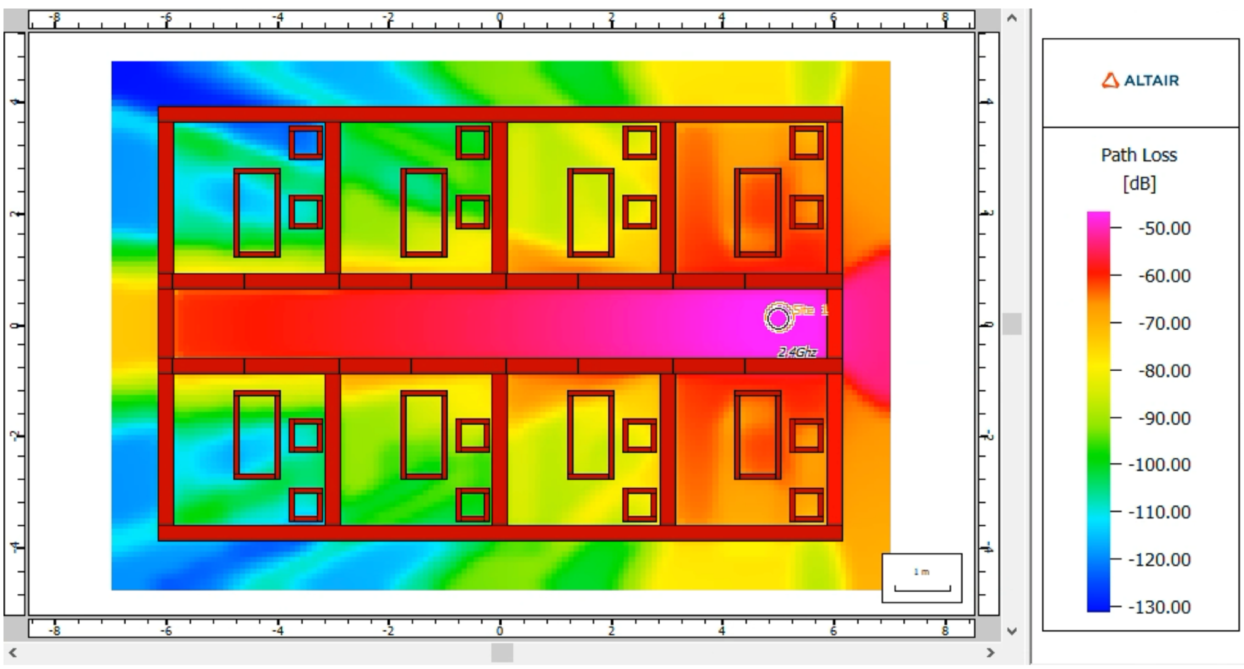
- **How does each material (i.e., brick, wood, metal, ...) affect the signal? Which material is causing more losses?**
  Solution: Signals are significantly reflected and diffraction-dipped by brick and concrete walls, with some penetration. More penetration is possible with wood, however some reflection and absorption can occur. Cabinets made of metal reflect signals very well and allow very little through. Because of their limited penetration, the massive brick walls appear to generate the most loss.

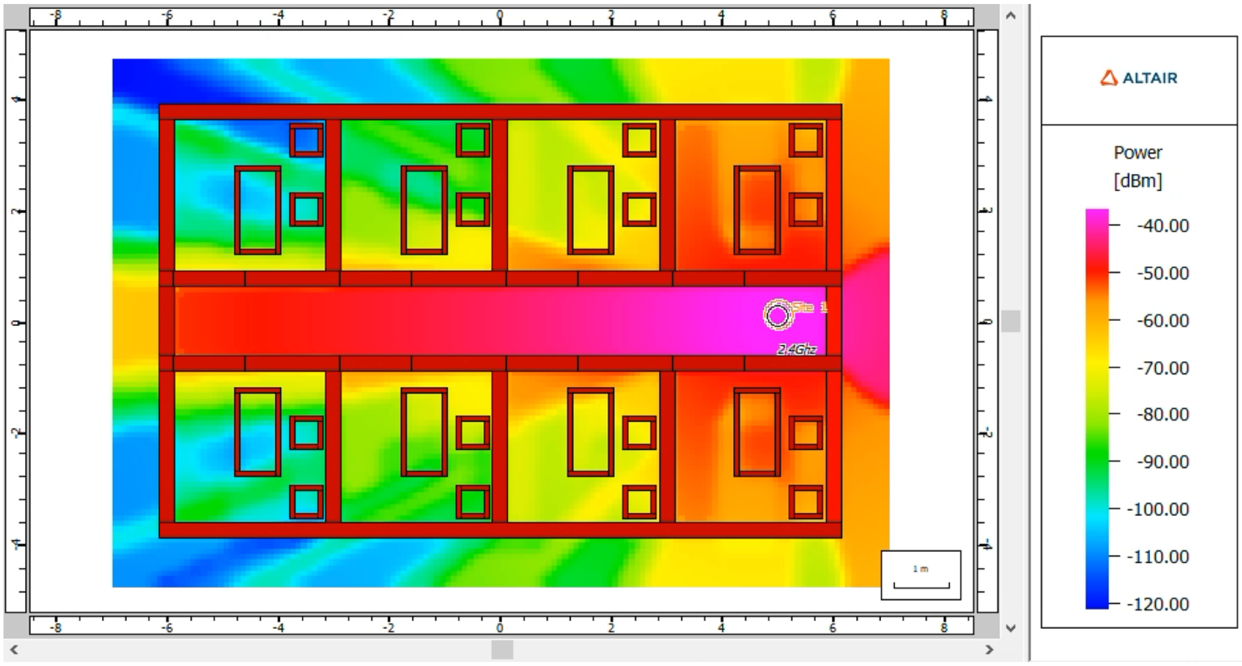
- **Save a copy of the database developed in Part b. Change the thickness of one of the walls and repeat Part c. Does that affect the signal?**
  Solution: Here I have changed the thickness of to 30 cm , so I have made the wall much more thicker.

  For 2.4Ghz the Filed strength is a bit less , but the frequency is still penetrating through the walls. The LOS remains the same. While there is a small difference in the pathloss measurements and the measurements for Power, the frequency is able to penetrate throughout the area.

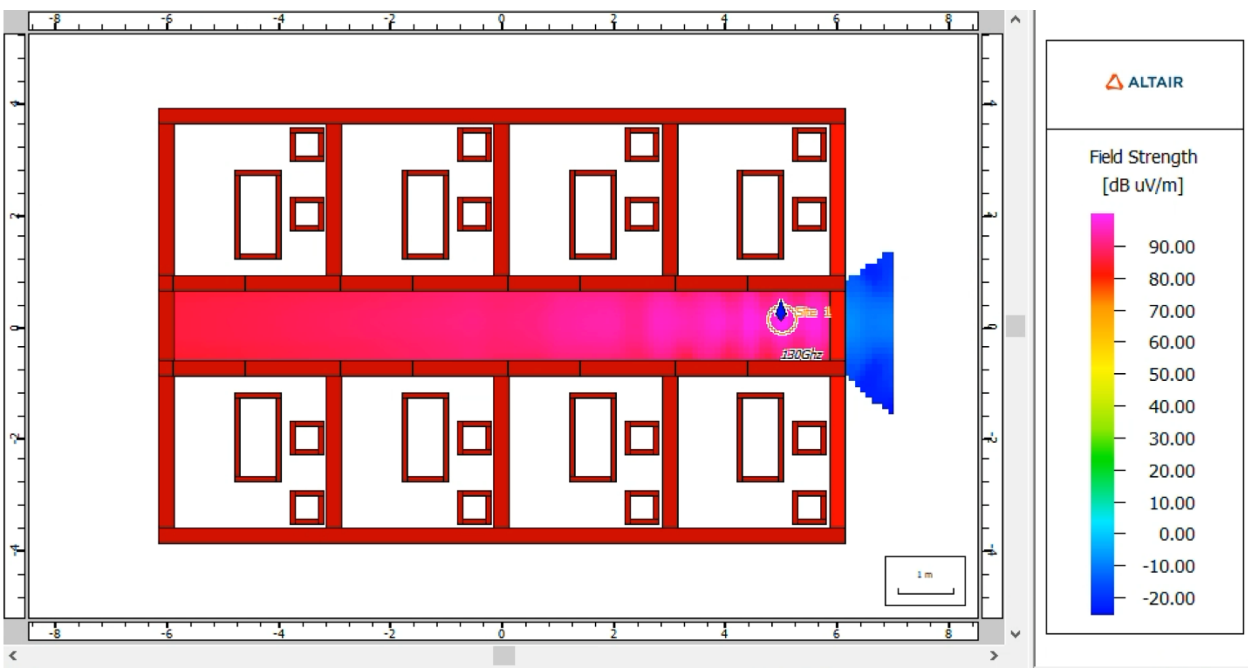


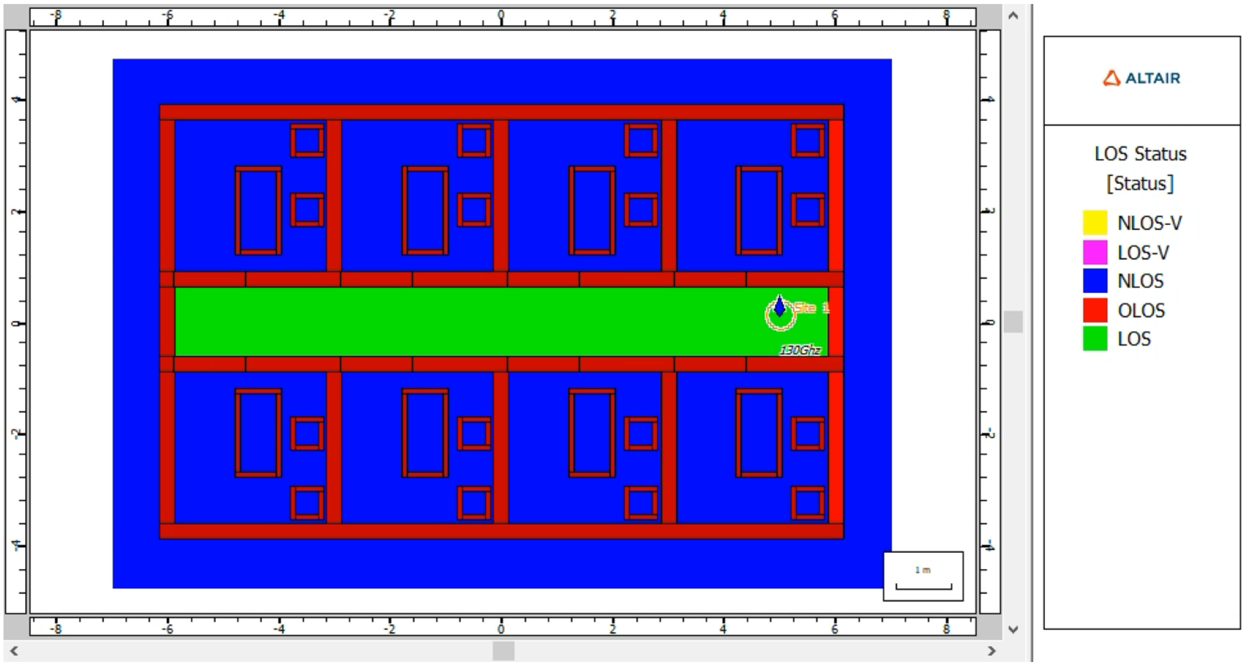

ALTAIR
LOS Status
[Status]
NLOS-V
LOS-V
NLOS
OLOS
LOS
Site 1
2.4Ghz
1 m

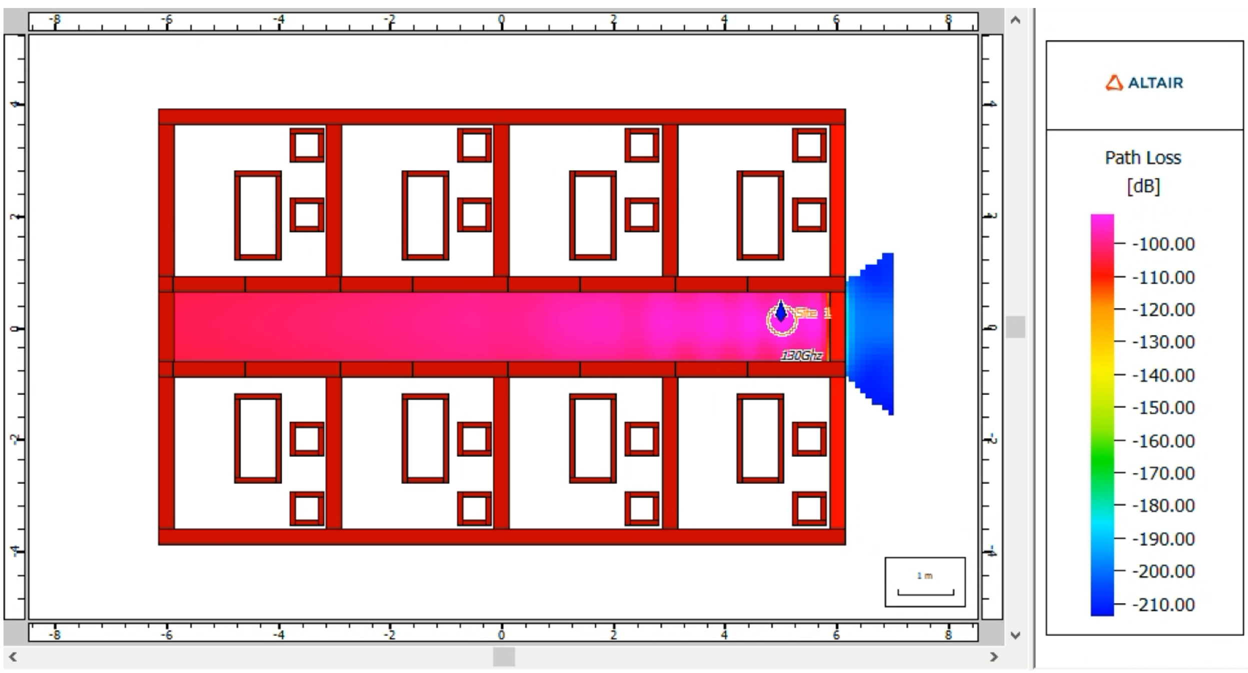

ALTAIR
Path Loss
[dB]
-50.00
-60.00
-70.00
-80.00
-90.00
-100.00
-110.00
-120.00
-130.00
Site 1
2.4Ghz
1 m

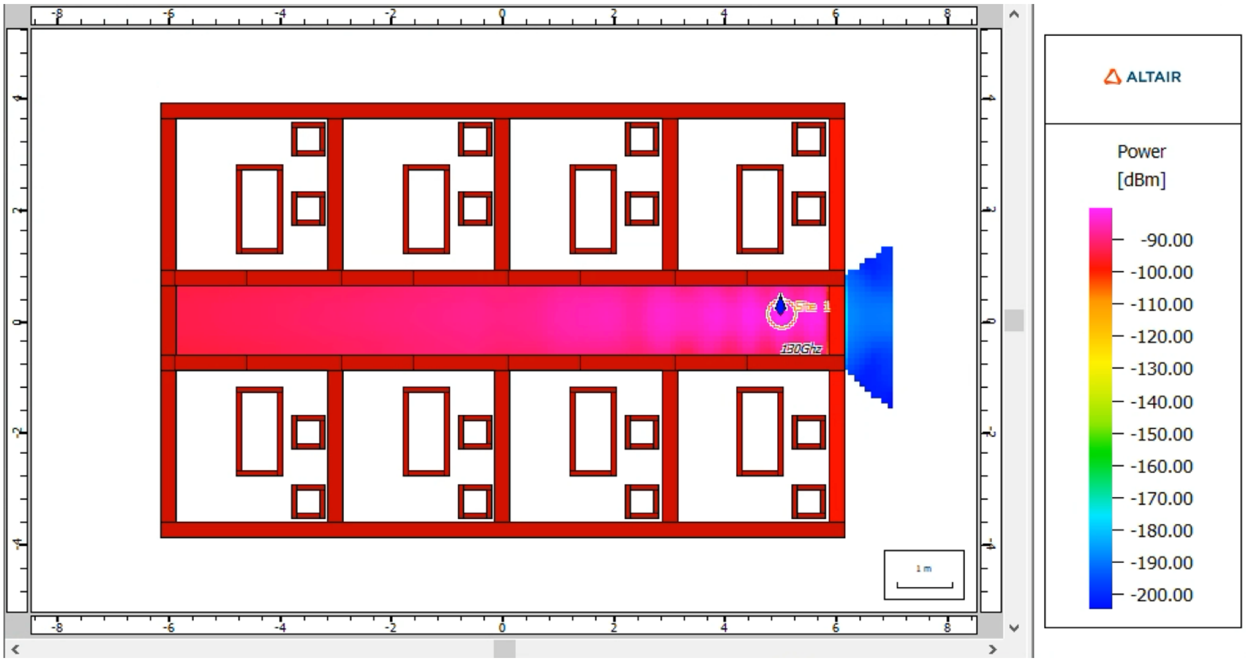


For 130 Ghz the Filed strength is a very less and strictly directional, but the frequency is not at all able to penetrate through the walls and the only reason it is showing the blue area is because of the presence of a window. The LOS remains the same. The pathloss and powers have not changes drastically but because this frequency is not able to penetrate thought the walls it is very directional.




ALTAIR
LOS Status
[Status]
NLOS-V
LOS-V
NLOS
OLOS
LOS
130Ghz
1 m


ALTAIR
Path Loss
[dB]
-100.00
-110.00
-120.00
-130.00
-140.00
-150.00
-160.00
-170.00
-180.00
-190.00
-200.00
-210.00
130Ghz
1 m



- **How does the height of the antenna affect the signal?**

Solution: Increasing the antenna height improves coverage as it enables the signal to propagate over obstructions more easily through diffraction. It reduces the impact of losses caused by indoor clutter. Height also increases the line-of-sight range. Optimally, antennas should be mounted as high as feasible in indoor spaces.

- **Mention at least two factors to consider when optimizing antenna placements for maximizing coverage in the given scenario.**

Solution:
- Minimizing obstructions in the line-of-sight between antennas
- Placing antennas high on walls or ceilings to enable propagation over obstacles

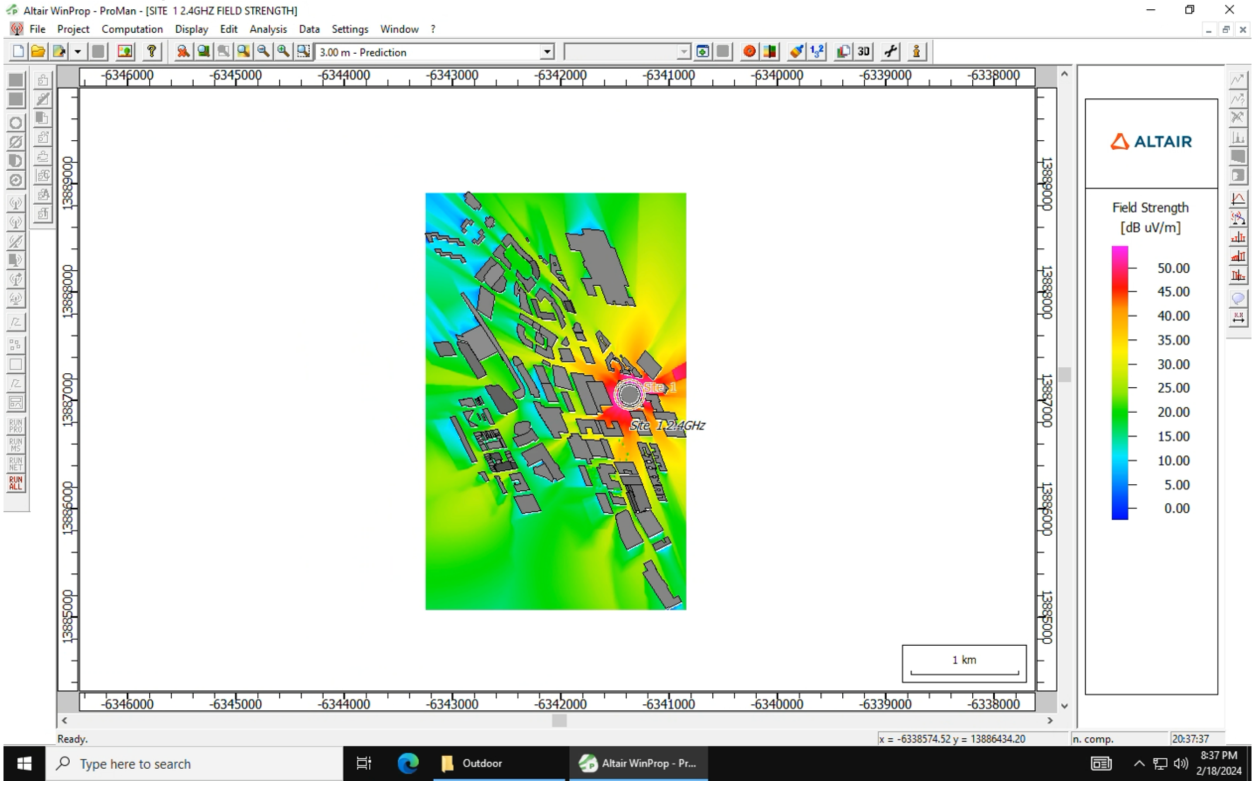
- **Compare the propagation characteristics (i.e., wall penetration, path loss, coverage area, ...) of 2.4 GHz and 130 GHz waves.**

Solution:

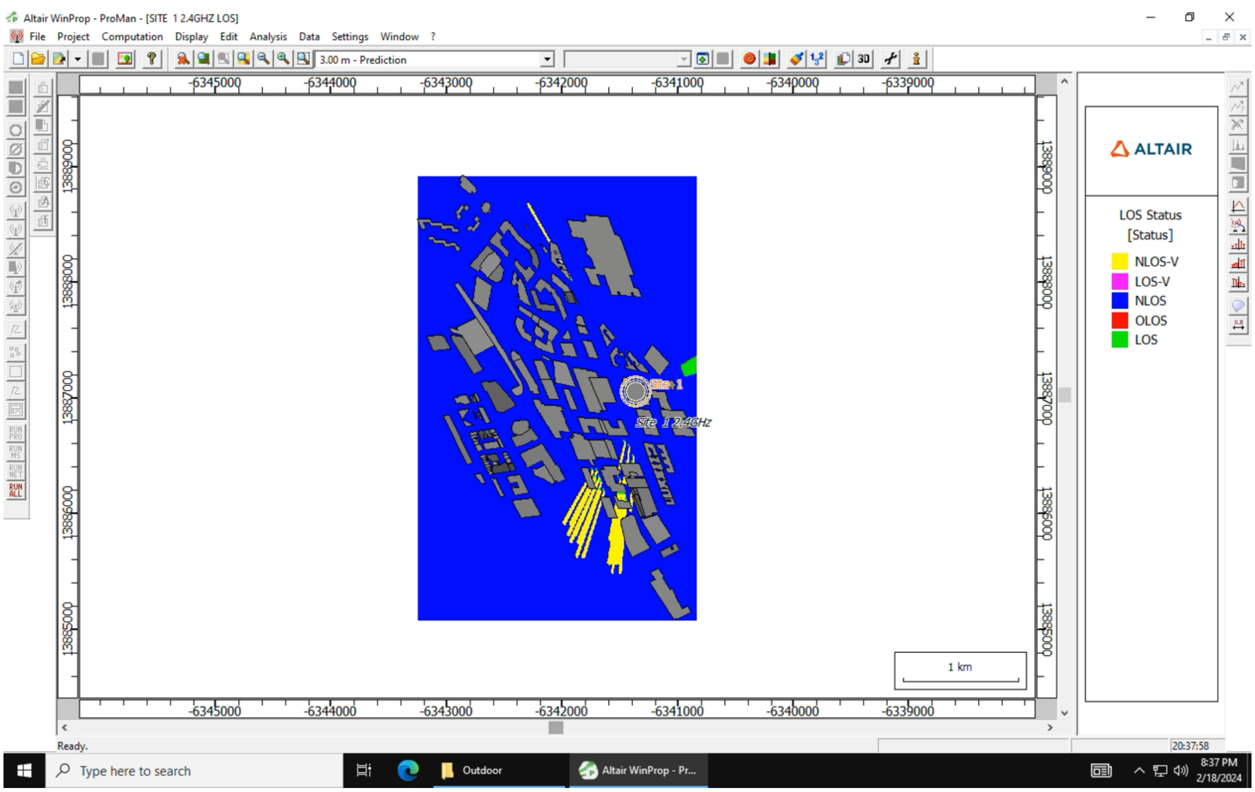
Frequency	Field Strength	LOS	Path Loss	Power	Wall Penetration	Coverage Area	Furniture Penetration
2.4 GHz	Max - 105 (A little Higher)	Same	Much Lower	Much Lower	Better penetration through walls	Coverage area is large.	Higher penetration low losses
130 GHz	Max – 100 (A little Lower)	Same	Much Higher	Much Higher	Not so good in comparison	Directional antenna, coverage area is low , better for confined spaces	Lower penetration more losses.

OUTDOOR
Antenna with 2.4 GHz

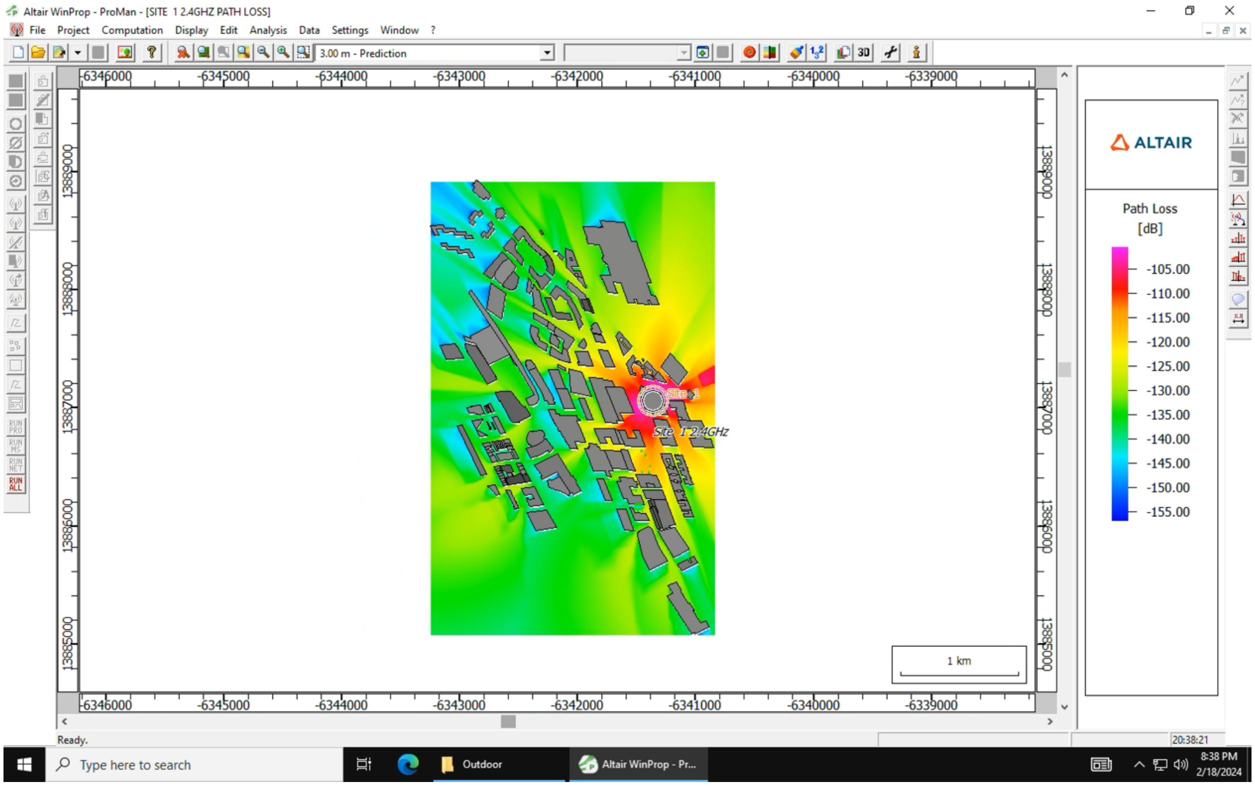
Field Strength



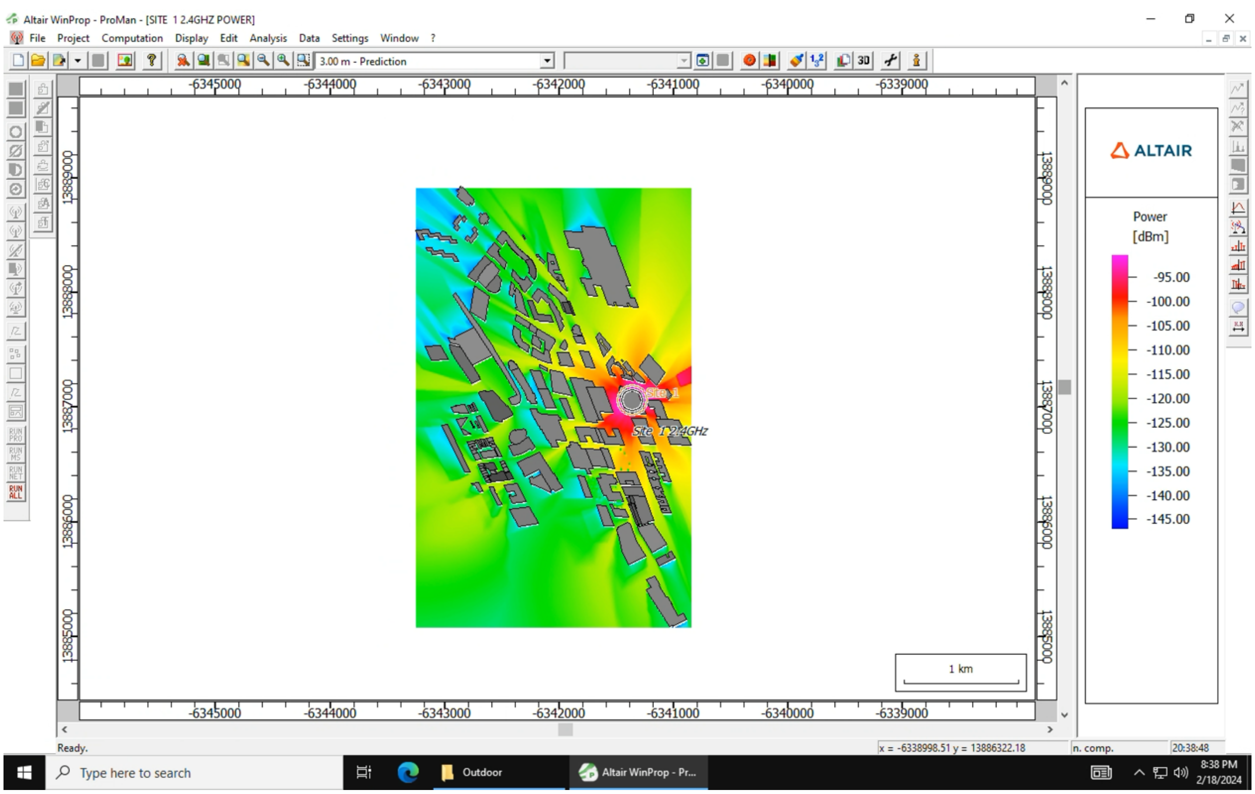
LOS



Path Loss

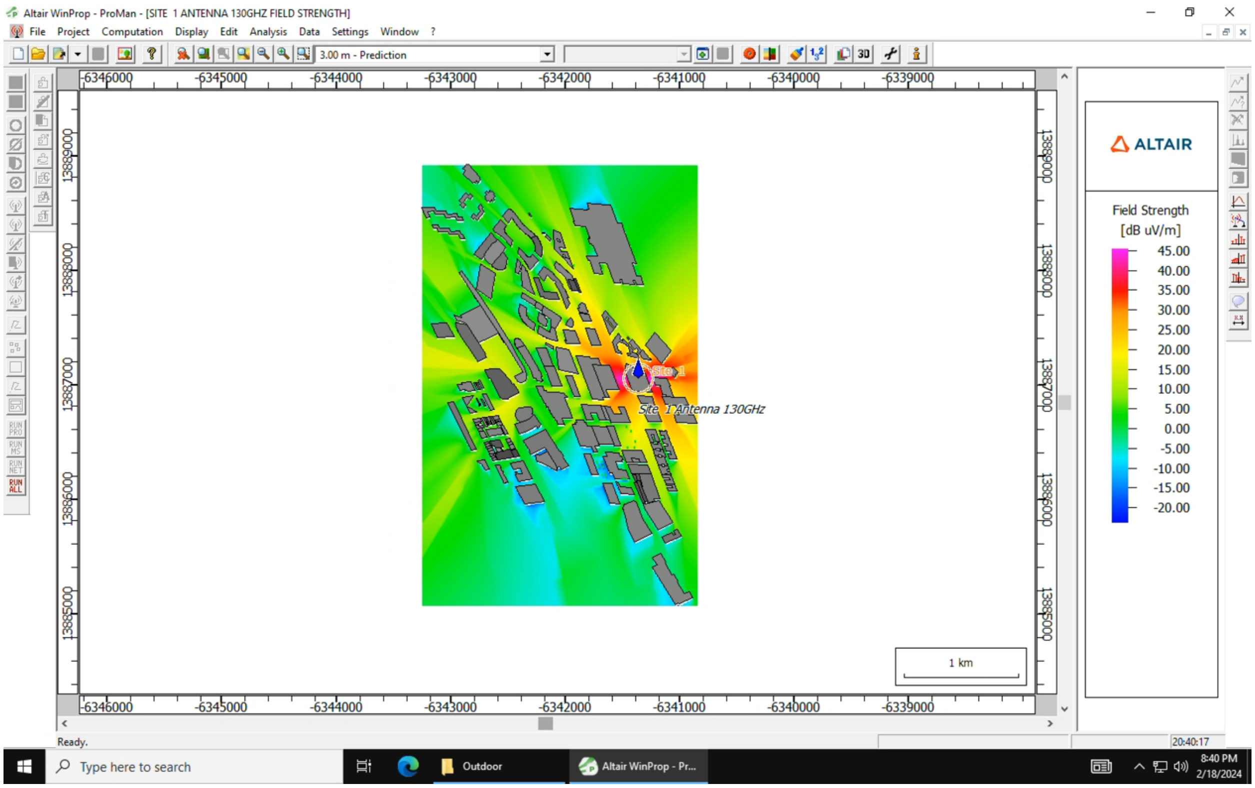


Power

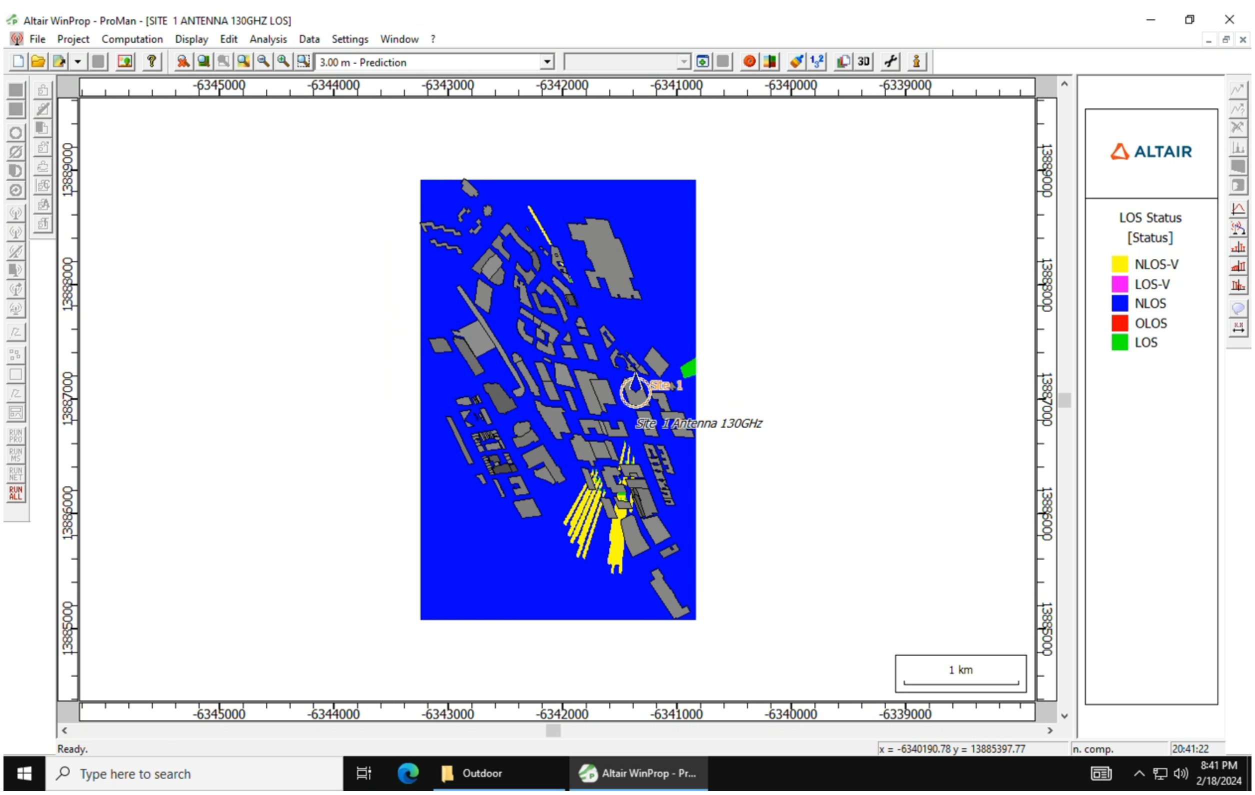


Antenna with 130 GHz

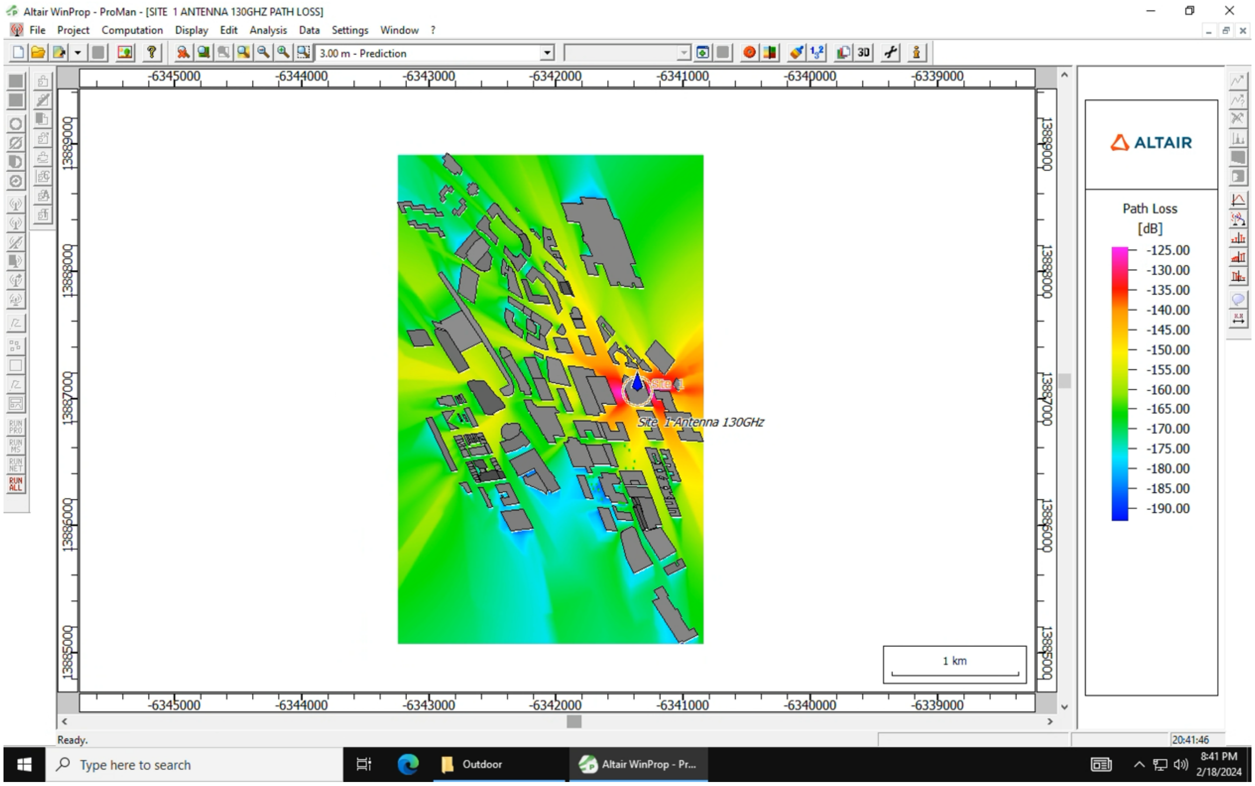
Field Strength



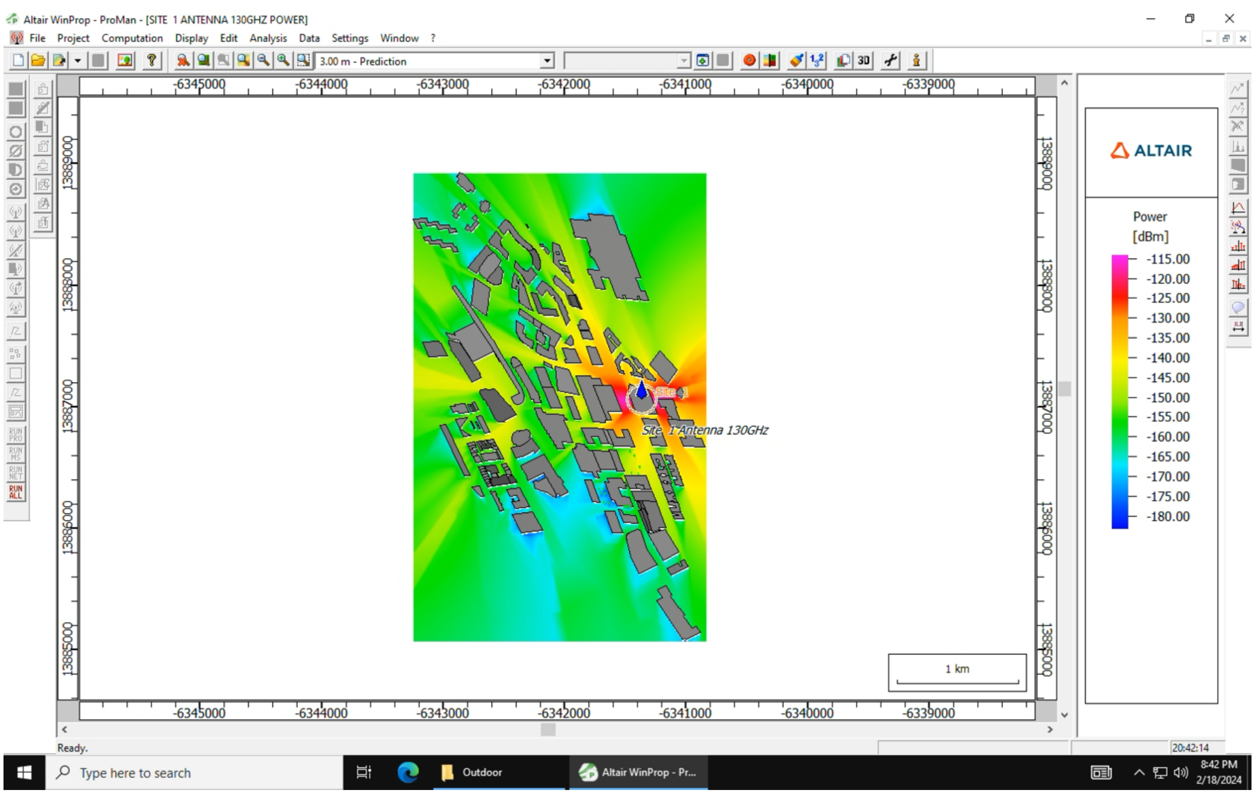
LOS



Path Loss


Altair WinProp - ProMan - [SITE 1 ANTENNA 130GHZ PATH LOSS]
File Project Computation Display Edit Analysis Data Settings Window ?
3.00 m - Prediction
-6345000 -6344000 -6343000 -6342000 -6341000 -6340000 -6339000
13889000 13888000 13887000 13886000 13885000
Site 1 Antenna 130GHz
1 km
ALTAIR
Path Loss
[dB]
-125.00
-130.00
-135.00
-140.00
-145.00
-150.00
-155.00
-160.00
-165.00
-170.00
-175.00
-180.00
-185.00
-190.00
Ready.
20:41:46
Type here to search
Outdoor
Altair WinProp - Pr...
8:41 PM
2/18/2024

Power


Altair WinProp - ProMan - [SITE 1 ANTENNA 130GHZ POWER]
File Project Computation Display Edit Analysis Data Settings Window ?
3.00 m - Prediction
-6345000 -6344000 -6343000 -6342000 -6341000 -6340000 -6339000
13889000 13888000 13887000 13886000 13885000
Site 1 Antenna 130GHz
1 km
ALTAIR
Power
[dBm]
-115.00
-120.00
-125.00
-130.00
-135.00
-140.00
-145.00
-150.00
-155.00
-160.00
-165.00
-170.00
-175.00
-180.00
Ready.
20:42:14
Type here to search
Outdoor
Altair WinProp - Pr...
8:42 PM
2/18/2024