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Project 2
Wi-Fi Signal Propagation

Random Processes

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INTRODUCTION

Wireless technologies have become much more relevant and present in the last few years, forcing companies and users to evolve into the new IEEE 802.11 devices, commonly known as WI-FI technology. The introduction of WI-FI, brought along new experiments and tests regarding positioning of the hotspots, modems and routers; such as WI-FI heat maps [1]. Nevertheless, tests like propagation model analysis used in WI-FI technologies are also implemented in the analysis of common signals such as radiofrequency, being that WI-FI technology relies on the propagation of signals [2].

The usage of propagations models has been an important part of the understanding of how signals move through different surfaces, areas and places, allowing the user to locate antennas in strategic spots that would enhance the signals and allow a better connectivity[2]. Likewise path loss analysis has important role in the comprehension of signal power received by a device, being that for both cellular and WI-FI technologies the signals send do not have the same power as the ones that are being received, due to power being loss in the environment and by attenuation caused by rain and specific surfaces [3].

Internet of Things (IoT) technologies have now become devices very important for our daily life and they will gain even more relevance in the near future, therefore experiments with this new technology are arising, along with testings for the understanding of signal limitations. Thanks to the accurate usage of propagation models, it has become more apparent that IoT devices would need to be deployed almost everywhere to enhance global communication, due to the fact that an IoT device by itself does not have sufficient power to connect to nearby devices, mostly on mountainous urban environments. Therefore, it is really important to utilize propagation model analysis to estimate the power received at different locations and quantities of the devices to minimize economic loss in massive inversion projects. [4].

OBJECTIVES

- To analyze propagation of Wi-Fi signals.
- To compare different propagation models and fit the best model obtained from measurements conducted at home.

MATERIAL AND METHODS

- 1 PC or laptop with at least 4GB RAM.

- MATLAB R2019a or later versions.
- Software (e.g., NetSpot) or an App (Airport) to measure power in dBm.
- Excel to store the data

The first thing to do was to recollect the measurements of the power received at different distances from the Wi-Fi modem at a fixed height. A grid was defined as a coordinate system to cover the entire room where the Wi-Fi modem is. For each point of the grid, the 10 readings were taken from the measurement software and the average of them were considered as the power received. The point where the modem is located was manually defined as 0 dBm since all points distances will be referenced according to this point. It was important to consider, for all the points in the grid, to not block the link with the body as much as possible. The coordinates and power received in dBm for each measurement were written down in the software Excel. Additionally, an average of 10 received power measurements (defined as PR_d0 in the code) at 1m (defined as $d_0$in the code) of distance in a Line Of Sight (LOS) link from the modem was included, since it will be the power received at a reference distance for the models discussed later. In this case, the measurements were taken in a living room as it can be seen in Figure 1.

Figure 1. Physical View of Living Room

After taking all the measurements for all points in the defined grid, they were read in MATLAB for statistical modeling and analysis. This can be done by using the MATLAB function $xlsread(filename, sheet, xlRead)$, where the file name with extension, the sheet number and the specified range are the parameters. In this case, the averaged measurements from table 1 are the data obtained from the living room.

Table 1. Map Coordinates of Living Room

[X,Y]	-3	-2.5	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2
0	-48.833	-47.5	-49.717	-58.25	-42.333	-37.25	0	-30.417	-26.75	-35.25	-31.833
0.5	-48..83	-51.417	-45.833	-33.833	-39.667	-39.167	-28.417	-28.667	-29.083	-28.583	-35.417
1	-54.917	-53.167	-42.833	-47.333	-37.833	-49.583	-31.333	-33.25	-32.417	-35.25	-35.583
1.5	-46.833	-50.833	-48.667	-38.167	-35.083	-51.5	-36.417	-30.167	-32.333	-32.917	-29.417
2	-41.833	-44.583	-43.25	-35.417	-34.5	-45.333	-46.25	-31	-35.25	-30.917	-33.417
2.5	-42.167	-47.833	-41.5	-48.083	-37.75	-37	-35.667	-32.583	-34.75	-35.083	-41.917
3	-50.75	-50	-39.417	-46.417	-39.75	-48	-38	-34	-38.667	-42.583	-45.583
3.5	-52.167	-51.366	-45.388	-47.533	-47.667	-45.083	-45.667	-37.083	-39.626	-41.167	-46.232
4	-54.215	-53.648	-47.853	-49.563	-48.529	-50.33	-48.568	-41.75	-42.057	-43.578	-47.87
LIVING ROOM											

For visualization purposes, an interpolated received power 3D map was generated to show the distribution of the power in the room. Hence, a meshgrid of the original coordinates and another one of the interpolated coordinates were used as parameters in the MATLAB interpolation function $griddata(x, y, data, xInt, yInt)$. After obtaining the interpolation of the data, the 3D map was shown using the function $surface(Z)$, where Z stands for the matriz of the data. In order to represent the distances of each point to the modem, it was necessary to obtain the euclidean distances using equation (1). Then, the power received and the euclidean distances were arranged as columns, sorted and stacked together as pairs. A for loop was used to iterate over each pair and the average of the power was taken if several measurements have the same distance. Then a base-10 logarithmic scale on the x-axis plot of distance in meters vs power received in dBm was provided by using matlab function $semilogx(distances, power)$.

$$d = \sqrt{x^2 + y^2} \tag{1}$$

To estimate the power received and path loss by using the free-space Friis model and the 2-ray model, the equation (2) was implemented in the code, which d_0 is the reference distance 1m,$P_{r,dB}(d_0)$ is the power received at 1m with LOS, d corresponds to the euclidean distances and n is the Path Loss exponent (PLE). The PLE of the 2-ray model is 4 and free-space is 2.

$$P_{r,dB}(d) = P_{r,dB}(d_0) + 10n\, log_{10}(\frac{d_0}{d})$$

(2)

A common mathematical tool such as linear regression was used to estimate the PLE. This was done by using MATLAB function $polyfit(x, y, n)$ to obtain the coefficients of the linear function. Considering that the distance d in (2) is the only variable, it seems that it can be represented as a linear function, so the PLE using linear regression can be then be estimated as the coefficient of the independent variable divided by 10. By having this, the model (2) with PLE obtained from the linear regression and the linear function itself are evaluated to see if they can represent the data. MATLAB function $polyval(coefficients, distances)$ was used to evaluate the linear function.

The statistical method of maximum likelihood (ML) is a powerful tool to estimate the PLE. Given (3) as the function of the sum of the squared error, the idea is to minimize it. This leads to the derivative of (3) and the result of PLE as (4) was implemented in MATLAB. The PLE obtained from this method to evaluate it in (2) is considered as the simple model.

$$F(n) = \sum_{i=1}^{N} \left(P_{r,dBm}(d_i) - \underline{P_{r,dBm}(d_0)} + 10n\, log_{10}(d_i)\right)^2$$

(3)

$$n = \frac{\underline{P_{r,dBm}(d_0)} \sum_{i=1}^{N} log_{10}(d_i) - \sum_{i=1}^{N} P_{r,dBm}(d_i) log_{10}(d_i)}{10 \sum_{i=1}^{N} [log_{10}(d_i)]^2} \quad (4)$$

For comparison purposes, the data points and the evaluation of the free model, 2-ray model, simple model, linear regression and PLE obtained by linear regression in the model were plotted together using $semilog(distances, power)$ in the same figure, which will be shown in the next section.

The sum of the squared error based on (3) was used as a criteria to determine the model that achieved the best fit of the data. The model with the minimum error was used and its propagation map was drawn using the function $surface(Z)$.

With the data obtained, the standard deviation was calculated using statistical method ML with equation (5). The standard deviation of the data was also determined by using MATLAB function $std(data)$.

$$\sigma = \sqrt{\sum_{i=1}^{N} \left(P_{r,dBm}(d_i) - \underline{P_{r,dBm}(d_0)} + 10n\, log_{10}(d_i)\right)^2}$$

(5)

Considering the graph of the best model, it was superimposed on the result of adding it to the Gaussian random number in dB with zero mean and deviation standard from (5) that simulated fading effects. After this, the received power 3D map from measurements and from the best model with a log-normal random variable of the standard deviation that best approximates the measurements. The Gaussian random number was achieved by using the MATLAB function $normmnd(mu, sigma, sz1, sz2)$ while the log-normal random variable was computed with the $lognrnd(mu, sigma, sz1, sz2)$, where *mu* stands for the mean value, *sigma* for the standard deviation, *sz1* and *sz2* for the size of the matriz.

Finally, the coverage was estimated by calculating in MATLAB the outage probability with the best model as shown in equation (6), where γ_{dBm} is the value in dBm for a threshold where the signal has to received above it . MATLAB function $qfunc(x)$ was helpful to implement this. Later, a map where the areas that did not satisfy the criterion of outage would be colored in black, this was done by using the *surface(Z)* function and it will be shown later in the result section.

$$P((P_{r,dBm}(d\quad) < \gamma\quad_{dBm}) = 1 - Q(\frac{\gamma\quad_{dbm} - P_{r,dBm}(d_0)}{\sigma}) \tag{6}$$

RESULTS AND DISCUSSION

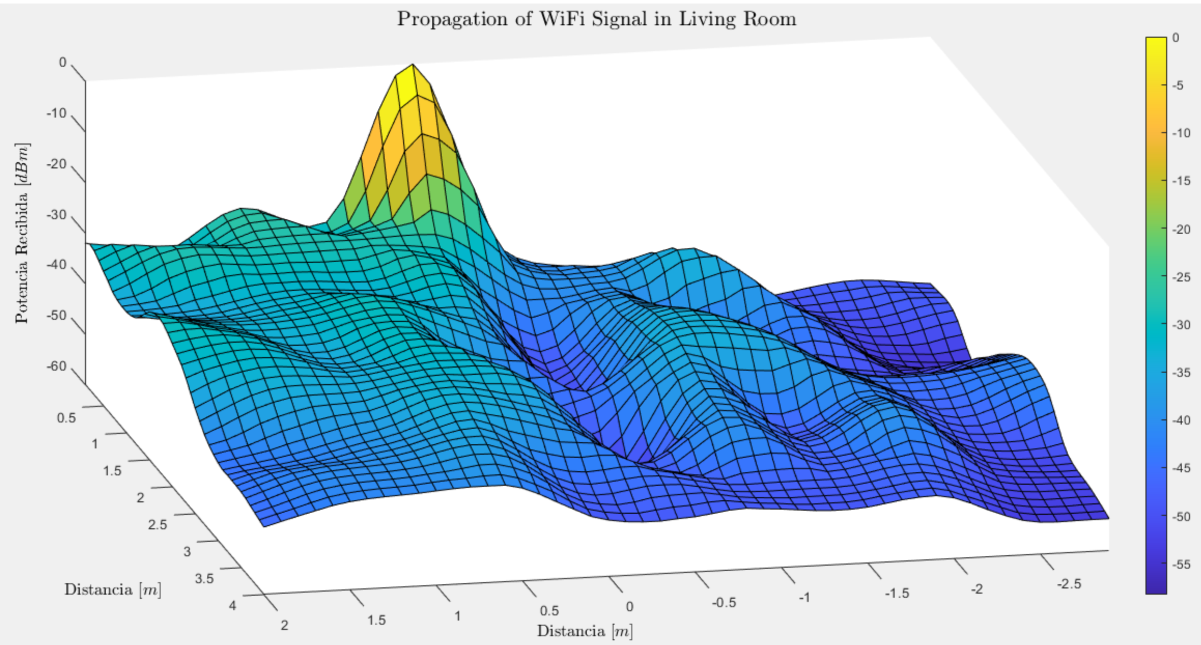


Figure 2. Interpolated Surface, Living Room Propagation.

The surface on Figure 2. was interpolated to visualize a smooth propagation surface, as the measurements taken showed abrupt changes and spikes all over the mapped area. The interpolation is only for visualization purposes. Another aspect to highlight is the unique height for the measurements, it was chosen high enough so that all the movable furniture could be shorter and do not affect the real environment of the physical place. The transmission height $H_T = 82.5$ $[cm]$and the reception height $H_T = 105$ $[cm]$. The outcome is expected as the areas near the antenna received less attenuated power compared to the further areas. There were not any object obstructions so the power received is uniformly distributed along the room.

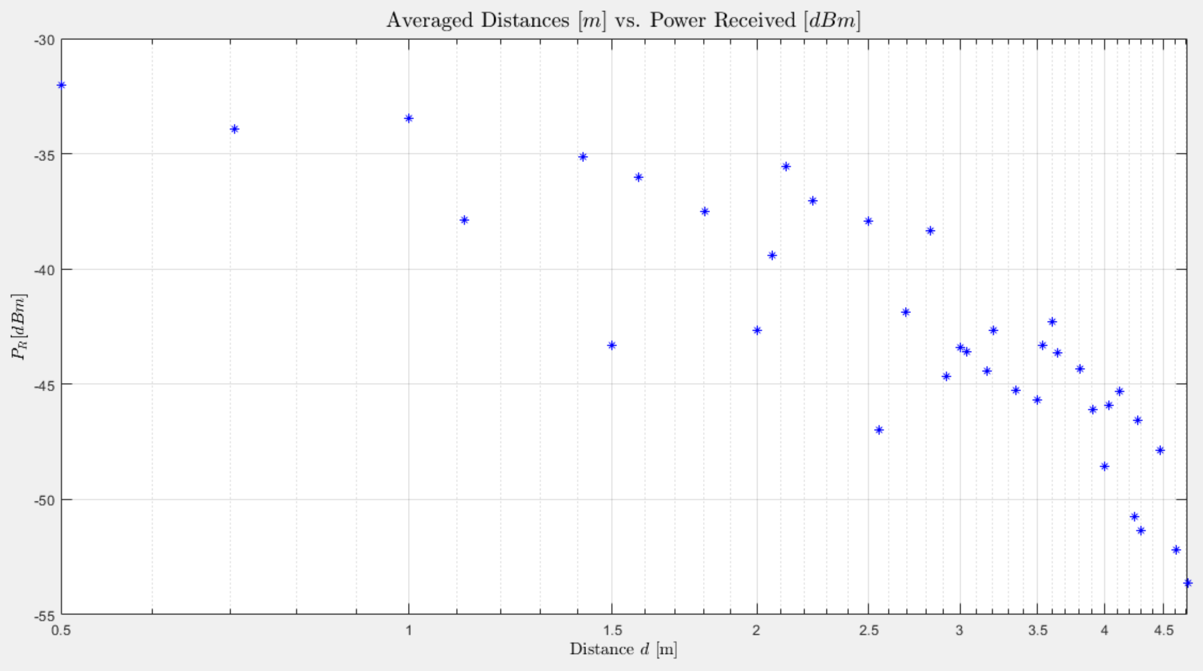


Figure 3. Averaged Euclidean Distances [m] vs. Power Received [dBm].

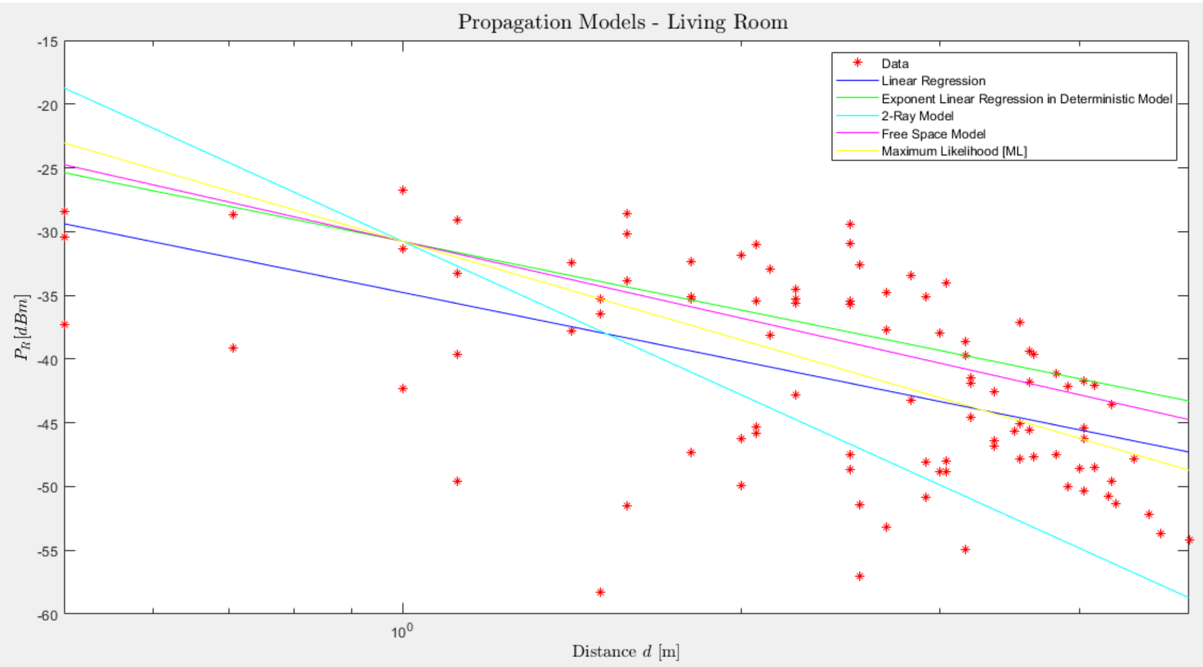


Figure 4. Five Propagation Models along with Data measured.

The best exponent for the propagation of signal was determined by the linear regression (LR) of the measured data. This was an expected outcome as the linear regression takes into consideration the data by itself, not tying it to a propagation model. Linear regression is a mathematical tool that fits the given data into a polynomial of order 1 (line) whereas the other models (2-Ray Model, Free Space Model and Exponent of Linear Regression in D.M.), see

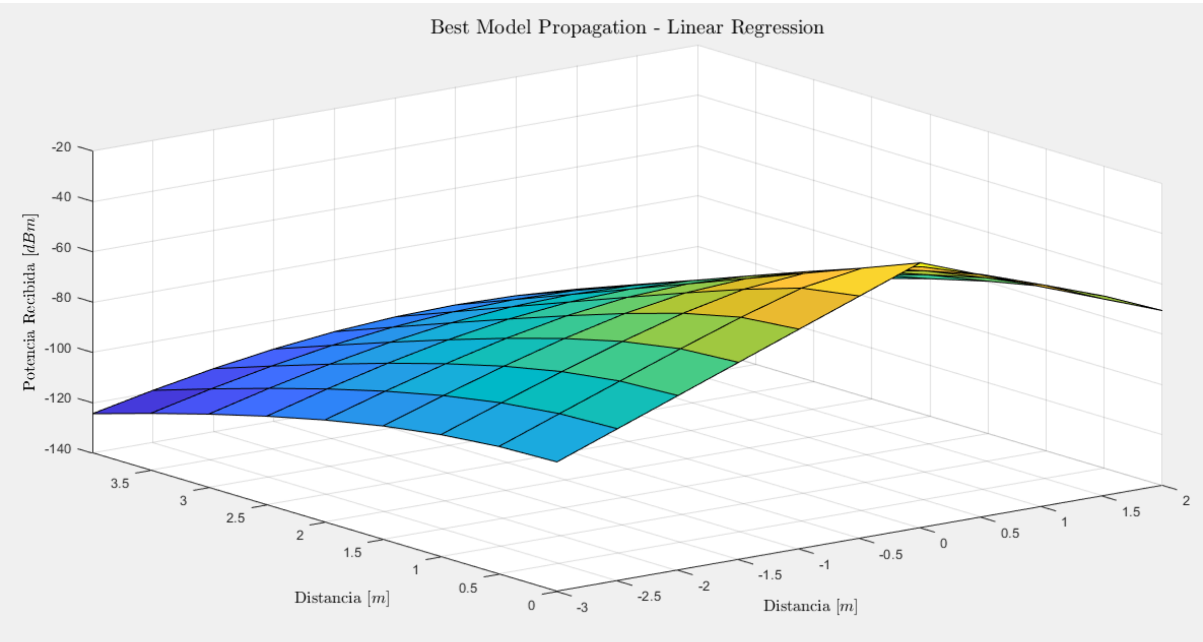
Figure 4, were based in the deterministic model of equation (2) and the n exponents vary according to the model e.g. in the 2-Ray Model $n = 4$ and in the Free Space Model $n = 2$. Therefore it was difficult for the measured data to couple on a predefined model with the limitations mentioned above.

Table 2. Exponents of all models, from left to right LR, DMwLRE[1], 2RM[2], FSM[3], MLM[4]

Model	Linear Regression	DMwLRE	2RM	FSM	MLM
Exponents	1.7915	1.7915	4	2	2.5671
Best: LR					

It should be stressed that the Maximum Likelihood Model (MLM) can be considered as a good alternative, the reason is it comes from the Minimum Mean Squared Error (MMSE), which minimizes the error, by considering the equation (3) and taking the derivative equal to zero, where the rate of change is the minimum consequently resulting in an optimum n exponent calculation, see equation (4).

The two exponents $n_{LR} = 1.7915$and $n_{ML} = 2.5671$where similar because the ML model also considers the measured data to calculate an exponent, the slope of the ML model is slightly more pronounced than the LR model which can be seen in Figure 4.



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[1] **DMwLRE**. Deterministic Model with Linear Regression Exponent.
[2] **2RM.** 2-Ray Model.
[3] **FSM.** Free Space Model.
[4] **MLM.** Maximum Likelihood Model.

Figure 5. Linear Regression Propagation Model 3D.

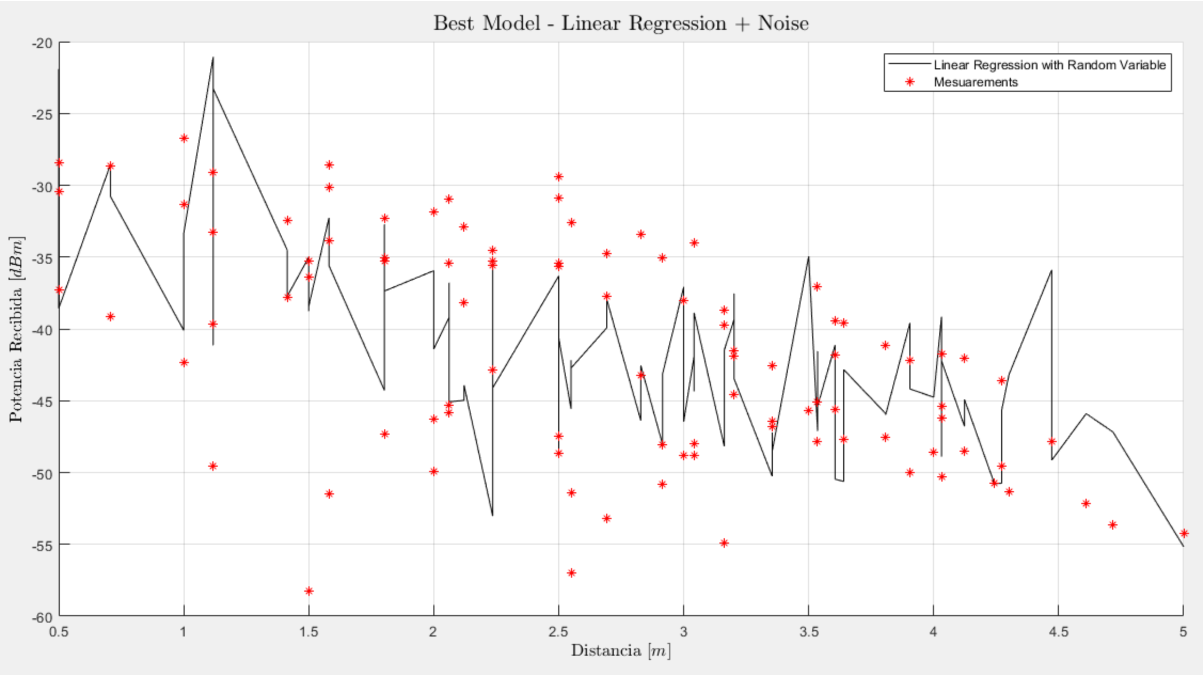

Figure 6. Linear Regression polynomial with Gaussian normal noise and data measured.

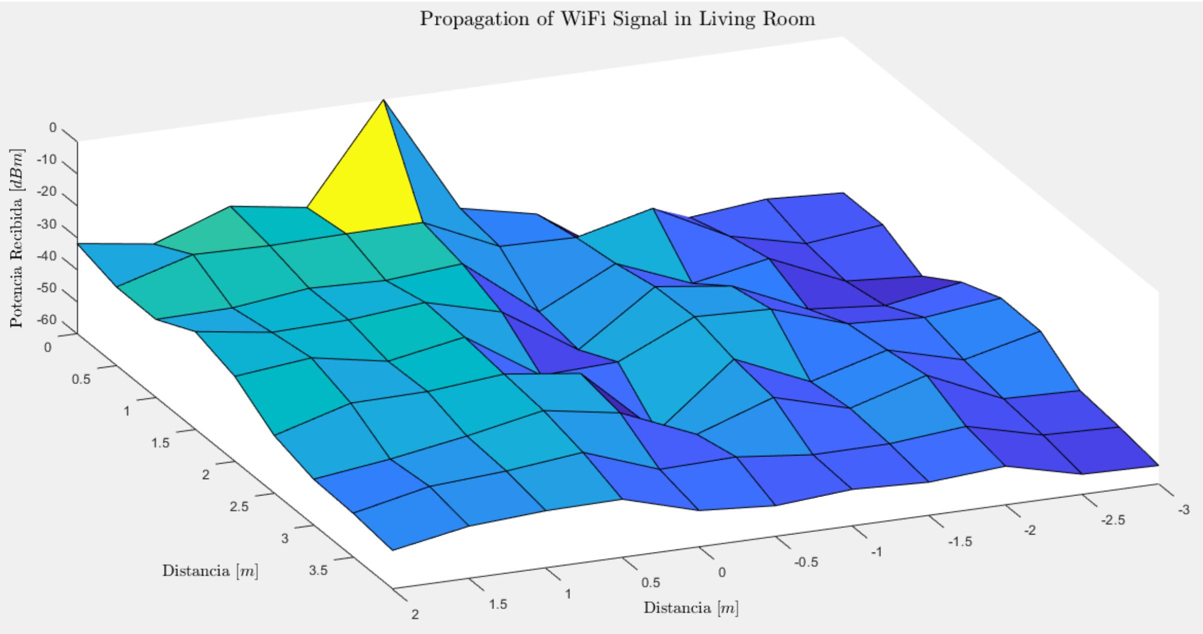

Figure 7. Non-interpolated Surface, Living Room Propagation.

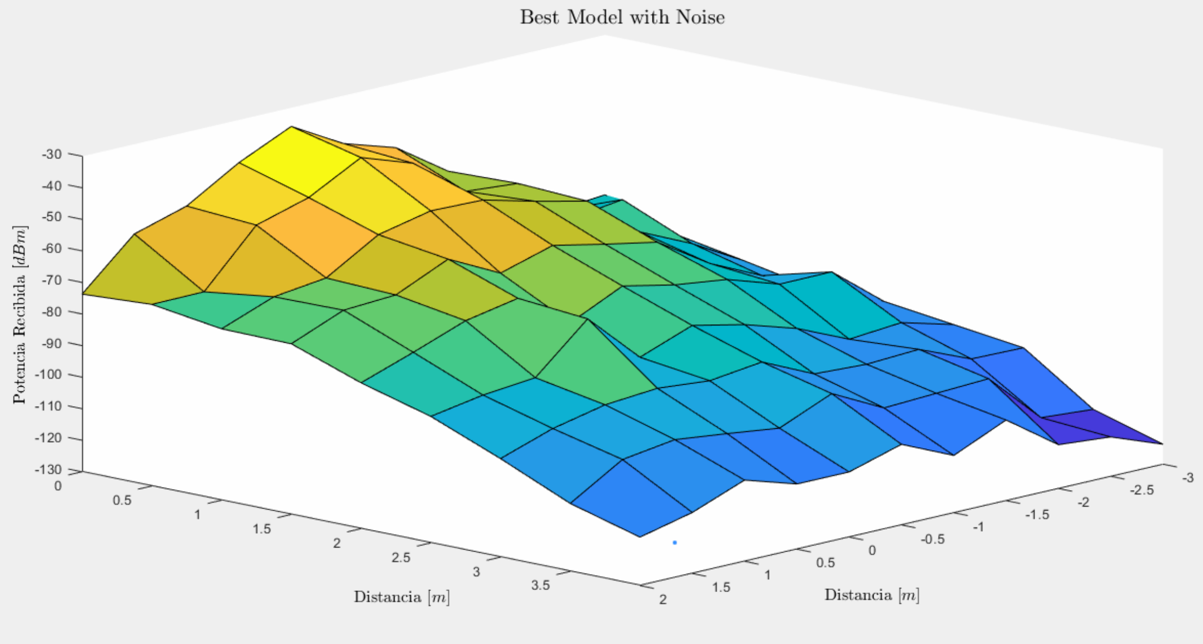

Figure 8. Linear Regression plane with noise.

A two dimensional view is needed in order to simplify the comparison between one another. The first differentiation is how the propagation uniformly decreased despite the gaussian random noise added, which is embedded in any signal transmission. Notice in Figure 6 the data dispersion and the LRM with the random variable fairly fit, reassuring the idea that noise is present in all environments and the synthetic immersion of it can be a wise case analysis of real life. Theoretically, the antenna receives signals and tries to propagate them without losses, but it can be seen in Table 1 that all of the measurements were negative values, since the antenna is a passive element and can not amplify any signal. The intense yellow color indicates the location of the modem, as the outcome of the LRM is a line, the propagation of the signal is also linear, therefore the attenuation decays constantly. The abrupt change in power received seen in Figure 11 is because the epicentre of propagation is where the maximum power is received (0 dBm).

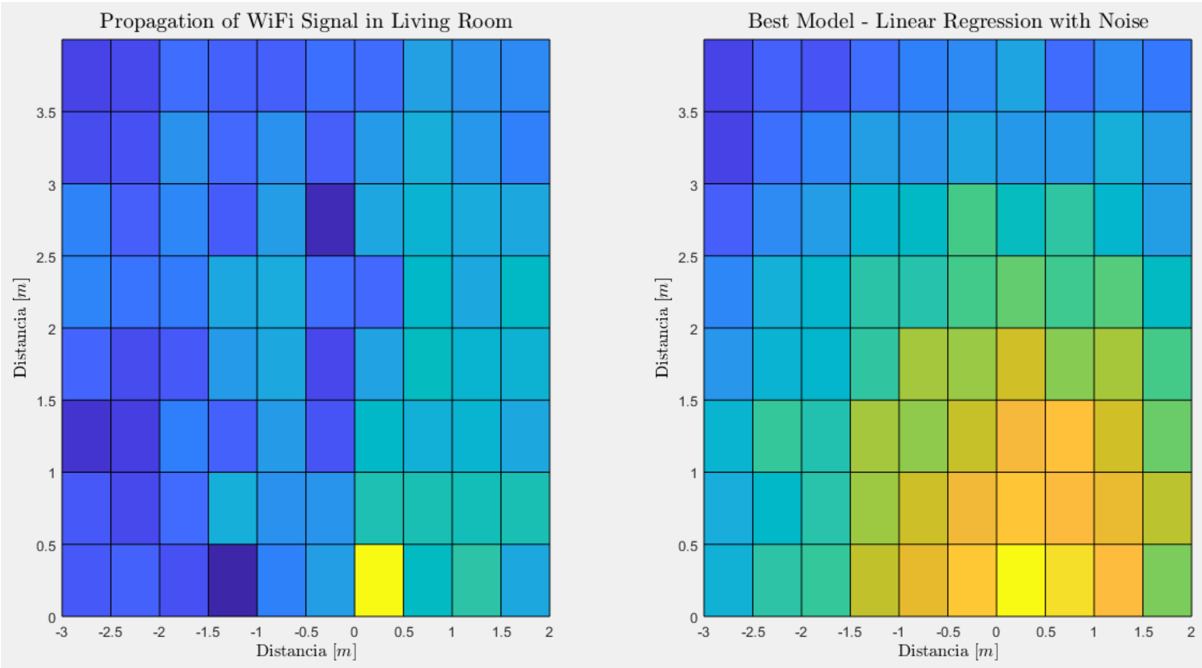

Figure 9. Propagation of Wi-Fi Signal in the Living Room vs. Linear Regression with Noise 2D.

A three dimensional view can provide more useful information when talking about physical spaces, such as this case. The order 1 polynomial is seen as a plane in the 3D, having its maximum in [0,0] coordinates.

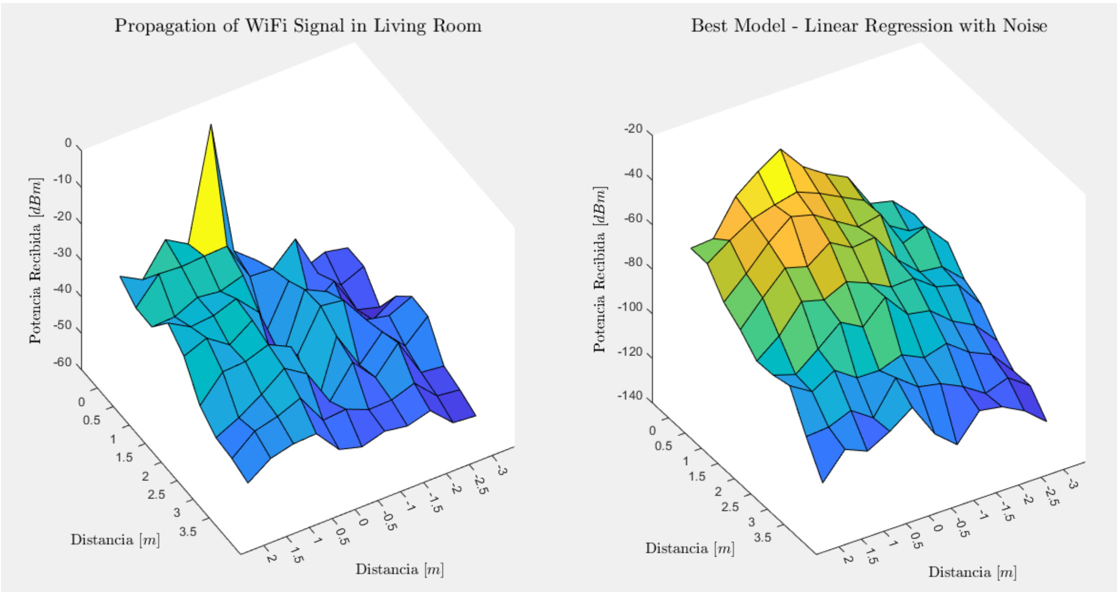

Figure 10. Propagation of Wi-Fi Signal in the Living Room vs. Linear Regression with Noise 3D.

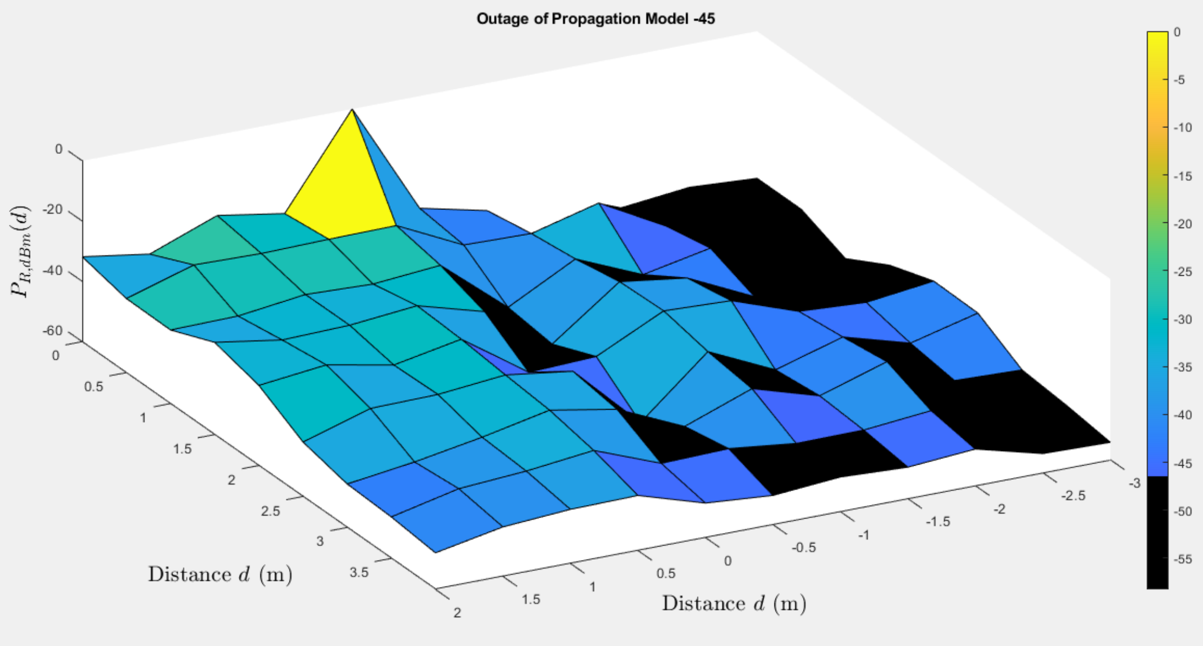

Figure 11. Outage -40 dB in propagation model.

Outage is a further revision concept which includes the coverage area along with the power received. In this specific case, it is an introduction to an important deployment and quality evaluation of telecommunications deployment; taken into consideration the data gathered a threshold power reception value was defined $\gamma_{dBm} = -40\ [dBm]$as it was a good indicator of where the power oscillated and therefore can be established as a non problematic zone of reception (below the γ_{dBm}, as it is a negative value), which can be seen in Figure 11.

It is inaccurate to assure that below the threshold power reception the connection is in imminent danger, because along all the physically analyzed areas, adequate reception can be experienced, but highly resource demand tasks, i.e. streaming, video conference, etc. can experience intermittencies of service when above the threshold power reception.

METHODOLOGY TO ACHIEVE A PROPAGATION STUDY FOR A NETWORK

1. Consider an area to be analyzed (interior or exterior), where you can have measurements at different distances from your Wi-Fi modem.
2. Define a fixed height at which you will place the receiver (laptop or cellphone), a chair can be used.
3. Measure the height at which your modem is.
4. All measurements must be conducted in a similar way, e.g., do not stand next to the receiver. Try to recreate the conditions for all measurements i.e. time of the day.
5. Reference the area you choose by making a grid as a reference where you will take some measurements, i.e., define a grid in an equally distributed area.
6. Define a coordinate system for the entire zone.

7. Take note of possible obstruction propagation materials in the area, this will be an important discussion point in a further analysis.
8. With a measurement software, e.g. NetSpot, determine the frequency at which the modem is transmitting.
9. Create a table referring to it with the coordinates previously stated.
10. For each point of your grid, consider the power received as the average of 10 or 20 readings from the software, consider a high attenuation value for unmeasurable points.
11. Measure the power received at 1m of distance in a LOS link from the modem, be careful performing this step, as this is a critical distance in propagation models.
12. Use a data analysis and visualization software to read the data.
13. Obtain the power received 3D map, which will tell you how the signal is propagating through the area analysis.
14. Plot of the power received vs distance.
15. Apply linear regression for the gathered data and plot it.
16. Propose a propagation model using the deterministic as a starting point along with the coefficients of each one of them.
17. Define a discard parameter that will determine which model works best for the data.
18. Add random variables as noise to analyse and compare how it plays a role in the data.
19. Estimate the coverage and define a threshold value where the signal has to be received above it, see which spaces do not satisfy the criterion.
20. Present results.

CONCLUSION

In conclusion, the usage of a WI-FI heat map is very important for the understanding of the propagation of signals through a specific space. In our particular case, it allowed us to graphically observe the power received by each sector inside an enclosure and comprehend how a WI-FI modem radiates its signal. Once each propagation model was tested, we can affirm that for our particular case the linear regression was the one which fitted the best our data, due to fact that it came directly from the data itself and the sigma obtained from it, is lower than the one obtained from the other models.

Furthermore, it is worth mentioning that the propagation models perform an important function in our understanding of how the signal propagates in space, as well as to predict how the model would behave at different zones, even though we do not have the data yet.

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