IoT Scanning Through Walls Using Wi-Fi

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Abstract: Earthquakes are one of the most devastating and frightening natural disasters that can be experienced. After such occurrences, it may be vital to identify objects or (living) beings within buildings that have collapsed. In this context the usage of scanning techniques employing Wi-Fi allow an innovative approach to facilitate referred identification. By using wireless technology, this work presents a proposal for the detection and identification of object contours or silhouettes through walls. This goal was achieved by reading the radio signal strength (RSS) variations with an array of affordable IoT (Internet of Things) Wi-Fi antennas.

Keywords: Antenna, Emitter, Path loss, Radio Signal Strength (RSS), and Wi-Fi.

I.   INTRODUCTION

In recent years there has been a growing interest in IoT (Internet of Things) technologies. The evolution of technology has favored usage of Wi-Fi (Wireless Fidelity) devices that as they become more sophisticated are also smaller, more energy-efficient, and cheaper. The gathering of these factors has attracted not only the research departments of the universities but also the industry in general and the result is the appearance of numerous academic and commercial projects on this subject which in itself is very broad.

The work "Holography of Wi-Fi Radiation" [1] is a good example of the use of a coherent light (electromagnetic waves with precisely known amplitude and phase) emitted by Wi-Fi systems. In this work, the radiation that results from the propagation in the space of electromagnetic waves, forms a hologram that allows to identify objects located between the emitter and the receiver.

At the same time, there are commercial solutions about the TWI (Through-the-Wall Imaging) subject using RF (Radio-frequency) in security and rescue applications. The majority are Ultra-Wide Band like Cambridge Consultants' system Prism200 [2]. This is a commercial Through Wall Radar that provides a 3D view through brick or concrete walls over a range of up to 20 meters. This technology provides comprehensive coverage of indoor spaces and has well known advantages over conventional narrow band solutions, but its high cost and the susceptibility to receive interference from signals in overlapping spectral bands and low resolution are major disadvantages that must be considered. On the other hand, as Wi-Fi signals are present in a growing number of buildings all over the world, there are some TWI projects that use Wi-Fi sources to try to detect the position of people or objects inside of buildings. Nevertheless, if it is necessary to detect such targets in a building without a Wi-Fi source this TWI project doesn't offer an adequate solution.

Thus, the purpose of this work is to present a low cost project which can contribute to the detection of objects and living beings within buildings that do not have Wi-Fi Networks.

This way, in free space, RF power varies inversely with the square of the distance between the receiver and transmitter. The stronger the power, the higher the signal strength [3] [4]. It is well known that RF signals are influenced by the environment and by other factors [5]. This means that fog, objects, human beings or walls, attenuate signal power between the transmitters and receivers. In addition, it is important to note that the attenuation also depends on the frequency used [3]. RSSI (Received Signal Strength Indicator), describes the total signal power received and is usually expressed in dBm. Additionally, free space path loss model of propagation and Shadowing model are common methods of RSSI signal propagation for WSN (Wireless Sensor Network) [4] [5].

In this work a Raspberry PI 3 was used as a low cost Wi-Fi emitter. The receiver, a directional array composed by sixteen antennas (fig. 1) was prepared to measure RSSI values trough the wall and transmit it to the Raspberry PI. After that, images were computed showing the attenuation of objects like a book shelf or a metal-coated wooden cross, both near a real wall. The number of antennas on the array is related to the resolution, since each antenna will represent a pixel in the image of the TWI system.

Figure 1:*Antenna Matrix*

Section II presents the RSSI Matrix theory while section III presents our hardware implementation. Section IV presents the calibration process of the whole TWI system and section V presents the object detection tests. Finally, section VI presents the conclusion and section VII presents future work.

II. RSSI MATRIX

Assuming that antennas are in free space and are separated by a large distance d in the far field of each other, the received power P_r will be equal to the product of the power density P of the incident wave and the effective aperture area A_e of the receiving antenna (1) [6].

$$P_r = PA_e \tag{1}$$

G_t is the gain of the transmitting antenna in the direction of the receiving antenna and G_r is the gain of the receiving antenna in the direction of transmitting antenna. With the Friss transmission formula [7], the equation (1) can be rewritten in equation (2) where P_t is the power at the transmitter, P_r is the power at the receiver, d is the distance in meters and λ is the wavelength (speed of light/frequency):

$$P_r = (\frac{\lambda}{4\pi d})^2 G_t G_r P_t \tag{2}$$

The path loss model of free space propagation is an ideal transmission case. It is known that when there is an infinite vacuum around antenna, the signal transmission energy is only related to transmission distance. There is a linear relationship between the signal transmission energy and transmission distance [5]. Thus, this model has no effect on obstacles and scattered reflection.
However, as tests occur not in free space but in the real world with buildings, fog, rain, objects and living beings, it is necessary to consider their interference (scattered reflection, shade, and absorbance) in the process.

This way, to take into account attenuation caused by objects, living beings and walls in real situations, it is necessary to use a larger exponent $n>2$, in (3) [5]. The attenuation characteristic in the long distance is following the log-normal distribution, thus the path loss model is shown as follows:

$$P_L(d) = P_L(d_0) + 10n\log(\frac{d}{d_0}) + X_\sigma \tag{3}$$

Equation (3) computes the path loss of a receiving signal when the measuring distance is d [meters] and the absolute power value is expressed in dBm; $P_L(d_0)$ indicates the path loss of a receiving signal when the reference distance is d_0; n indicates the path loss index in a specific environment; X_σ is in dB and is a cover factor when the range of standard deviation σ is between 4~10 and the mean value is 0. The larger the σ the greater the uncertainty of the model [5].

RSSI equation is as follows:

$$RSSI = P_t - P_L(d) \tag{4}$$

In equation (4) P_t, is the power at the transmitter, P_L is the path loss when the distance is d.

The signal strength received from a reference node at the distance d_0 is $r_{i,j}$ as follows:

$$r_{i,j} = P_t - P_L(d_{i,j}) \ i = 1,...,M \ , \ j = 1,...,N \tag{5}$$

The signal strength received of an array of M x N antennas is $r_{i,j}$ and $d_{i,j}(m)$ is the real distance between the emitter and each receiver (i,j) in the antenna matrix.

The path loss model measured at distance $d_{i,j}$ is as follows:

$$P(d_{i,j}) = P(d_0) - 10n \log(\frac{d_{i,j}}{d_0}) - X_\sigma \tag{6}$$

Equation (6) computes the received signal strength when the measured real distance is $d_{i,j}$ and $P(d_0)$ is the received signal strength when the reference distance is d_0 and $X_\sigma \sim N(0,\sigma^2)$. The reference distance is considered as d_0 and has been set to 1 meter.

As per (7) the value A is the matrix of the RSSI values of the M x N receivers of our matrix antenna (Fig. 1) composed with M rows and N columns.

$$A = [\bar{r}_{i,j} - c] \ , \ i = 1,...,M \ , \ j = 1,...,N \tag{7}$$

The $\bar{r}_{i,j}$ is the average value of 100 RSSI readings (in one second). The c is also the average value of 100 RSSI readings of an extra antenna in any position out of the matrix antenna. For example, it can be equal to $\bar{r}_{M+1,N+1}$.

R is the matrix of $M \times N \times Q \times P$ RSSI values of the A Matrix that is used to compose an image of $M \times Q$ rows of pixels and $N \times P$ columns of pixels.

$$R = [A_{r,s}] \ , \ r = 1,...,Q \ , \ s = 1,...,P \tag{8}$$

with

$$A_{r,s} = \bar{r}_{i,j} - c \ , \ r = 1,...,Q \ , \ s = 1,...,P \tag{9}$$

III.   HARDWARE IMPLEMENTATION

A. Raspberry PI

Raspberry PI 3 is a small and affordable computer that has a general purpose usage. This device can send and receive data through Ethernet and/or Wi-Fi interfaces and can run, among others, operating systems like Raspbian, Windows 10 IoT Core or Ubuntu. Raspbian is the Raspberry PI Foundation's official operating system [8]. In this project the Raspbian operating system was used as Wi-Fi AP (Access Point) with a DHCP (Dynamic Host Configuration Protocol) server, providing an IP address to all Wi-Fi receivers within the antenna Matrix. Additionally it works as a web server and database server (MySQL).

B. Antenna Matrix

To receive wireless signal from the emitter (Raspberry PI) a directional matrix of, at least, sixteen Yagi antennas was used. In this matrix, each antenna reads the RSSI signal and records it on a database. One of the antennas is the reference used for the RSSI value c of (7). An example of this antenna matrix is presented in fig. 1.

Each Yagi antenna includes an ESP8266-01S chip and was constructed as shown in fig. 2 and fig. 3 with 1 mm diameter copper rods. The copper rods length is presented on table 1 [9].
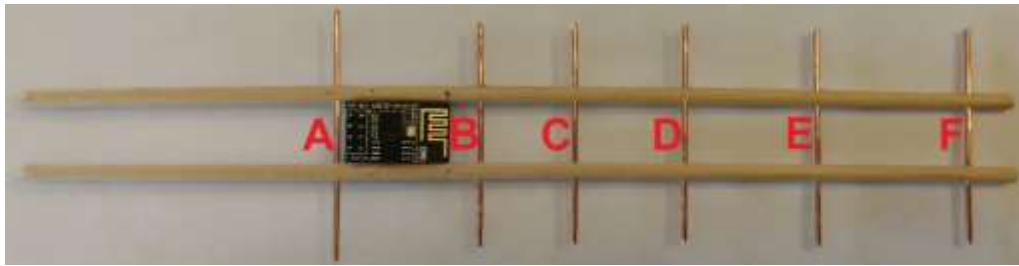

Figure 2:*Yagi Antenna*

Table 1: Yagi antenna dimensions

Position	Length
A	60 mm
B	53mm
C	52 mm
D	51.5 mm
E	51 mm
F	50 mm

The ESP-01S presented in fig. 3 is a low-cost Wi-Fi microchip. Its ESP8266EX microcontroller integrates a Tensilica L106 32-bit RISC processor which achieves extra-low power consumption and reaches a maximum clock speed of 160 MHz. The Real-Time Operating System (RTOS) and Wi-Fi stack allow about 80% of the processing power to be available for user application programming and development [10] [11].
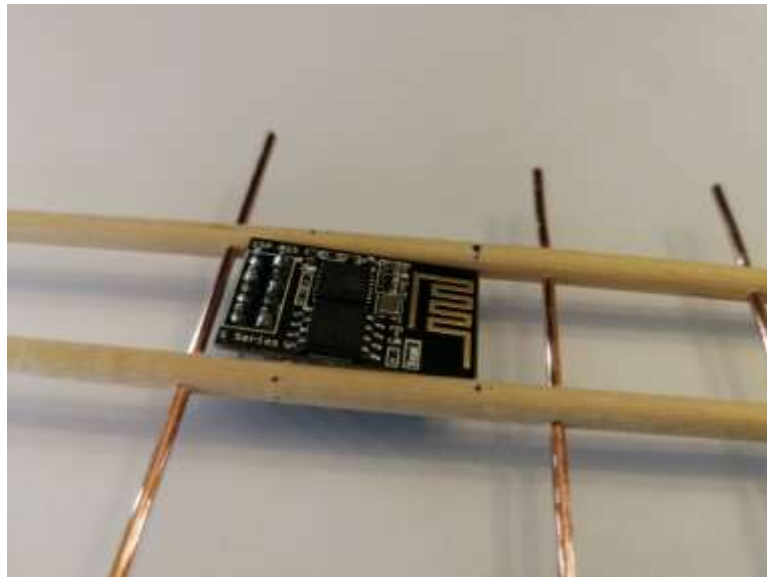
Figure 3:*ESP-01S*

ESP8266EX integrates the antenna switches, RF Balun, power amplifier, low noise receive amplifier and is designed to occupy minimal PCB (Printed Circuit Board) area [10] [11]. Developers can completely control ESP-01S behavior including its Wi-Fi power that, in this case, was set to 8 (min: 0 dBm - max: +20.5 dBm). This characteristic is very important to minimize neighbor device interference and saturation RSSI readings.

The antenna applied on this module is a 3 dBi PCB-on-board antenna which is a Meandered Planar Inverted-F Antenna (MIFA). The MIFA design is space efficient where the RF performance is predictable and usually requires no more than 15.2 x 5.7 mm of space to ensure a Voltage Standing Wave Ratio (VSWR) of lessthan 2 across a 2.4 GHz ISM band.

The MIFA Antenna is quite functional and operates on a rather complex concept called quarter wave long system, which is to say, a quarter of 12.5 cm that is the wave length of a 2.4 GHz signal [12]. It is for this

reason that the antennas on the matrix were placed in order to guarantee 7.5 cm between each other, minimizing the interference between them.

Tests were performed to determine the benefit of using this Yagi antenna configuration. Thus, the performance of the ESP 01S mounted on a Yagi antenna was compared with performance of an ESP-01S without Yagi antenna and a difference of about 5 dB was obtained as seen on table II.

Table 2: Gain Difference

ESP-01	Power measured (dBm)
Mounted on Yagi Antenna	-62
Standalone	-67

IV. IDEAL TX POWER ON RASPBERRY PI

To determine the ideal transmission power on the Raspberry PI a test was made in which the transmission power on Raspberry PI was automatically decremented from the default value 31 to 0. To do this, the following script was executed on Raspberry PI:

```
#!/bin/bash
for i in {30..0..-1}
   do
        echo " "
        echo "txPower was changed to $i "
echo " "
        echo "Actual txPower: "
        echo " "
sudoiwconfig wlan0 txpower $i
sudoiwconfig
        sleep 15
   done
```

After the transmission power decrement, it was possible to conclude that the Raspberry PI transmission power should be between the 17 and 6. This means that when Tx Power was above 17 or Tx Power was below 6, antennas could not detect enough RSSI variation as seen on fig. 4.
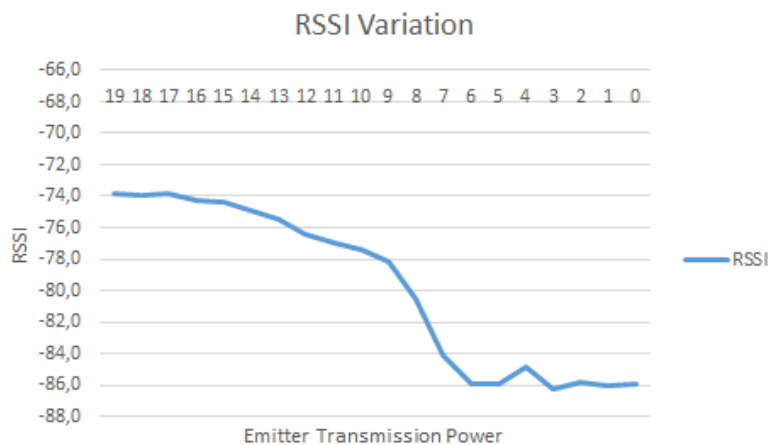

Figure 4:*RSSI Variation Detection*

V. OBJECT DETECTION

After Tx Power on Raspberry PI has been set to the level 7 and the Output Power of all antennas has been set to 8, RSSI tests were made on a real wall with obstacles depicted by fig. 5, 7, 9 and fig. 11. The numbers 1 to 16 of fig. 7, 9 and 11 represent the positions in which the Raspberry PI has transmitted its signal (as a Wi-Fi emitter) on the other side of the wall. At the same time each static Yagi antenna measured 100 RSSI values per second and its ESP 01S recorded the average values in the Raspberry PI database.

The test scenario is shown in fig. 5 where distance between obstacles and the matrix of antennas is about 4 meters.

This is the preferable distance because as seen in fig. 6 in the first meter occurs a great loss of power which is to say that this is an unstable zone. Then as the distance increases the power variation decreases which means more stability from the first meter [13].
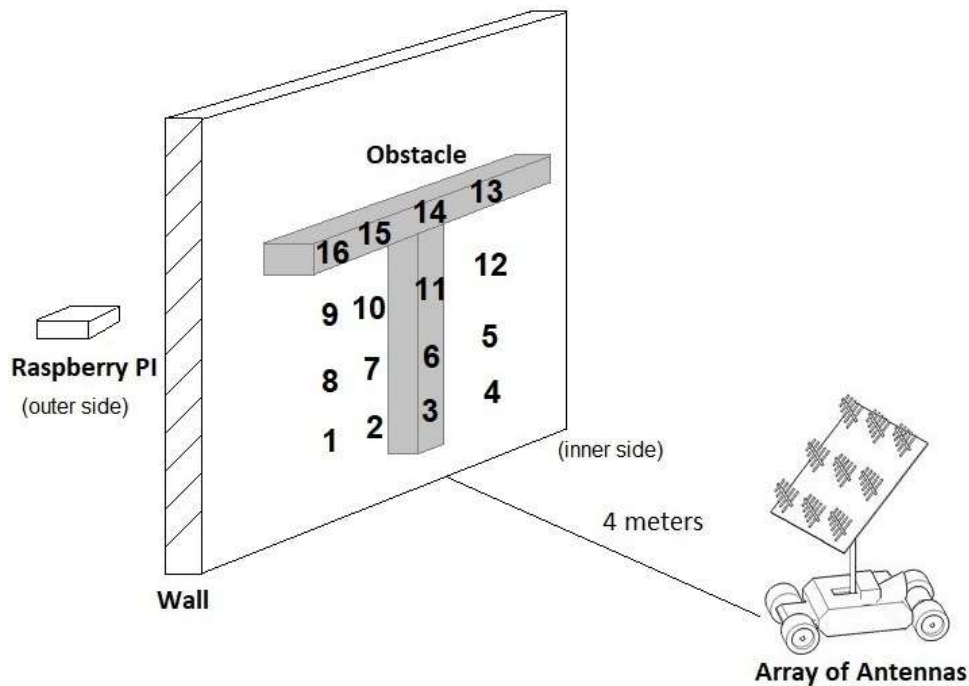

Figure 5:*Test scenario configuration*

Figure 6:*Loss variation as a function of distance*

Figure 7 depicts the bookshelf, the free wall to its left and the Raspberry PI 16 emitting positions. Equation 8 has been used in this scan. The result is presented in fig. 8 where one can see that at the right side, corresponding to the position of the bookshelf, there is an increase in the attenuation.

Figure 7:*Bookshelf with clear wall on the left*
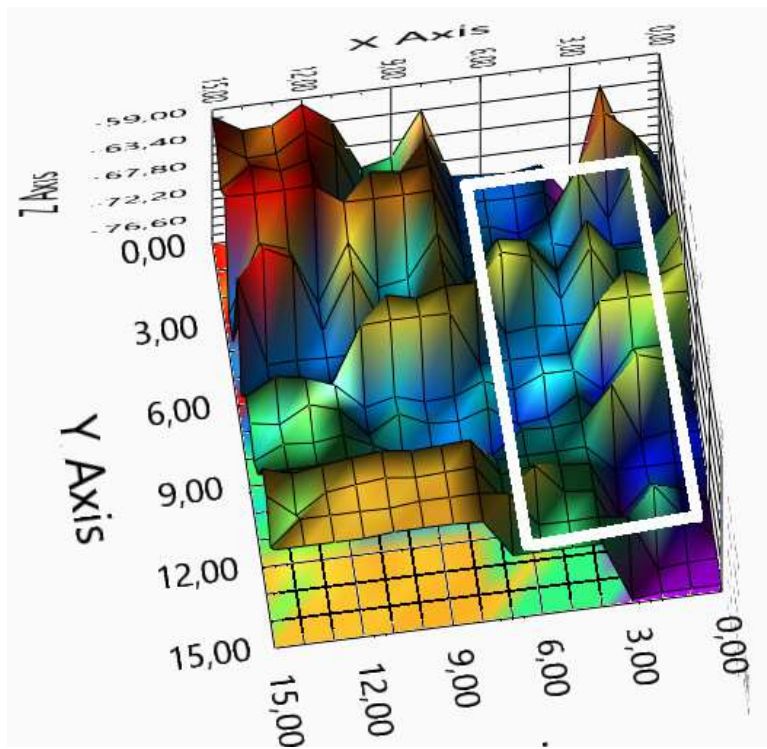

Figure 8:*RSSI matrix scan result employing eq. 8 shows attenuation of the shape of the bookshelf with free wall on the left*

In the following test the bookshelf has been moved to the left side of the wall, as seen in fig. 9. In this way, fig. 10 shows that the side with major attenuation moved to the left side corresponding to the new position of the bookshelf.
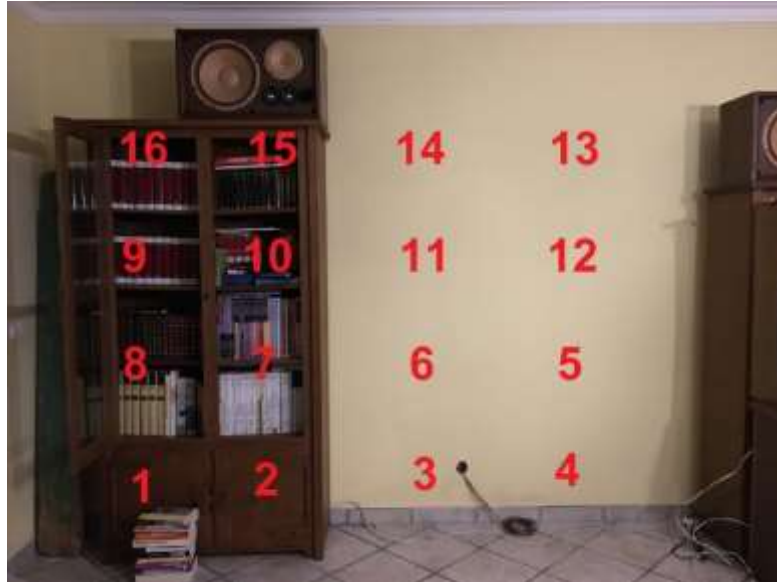
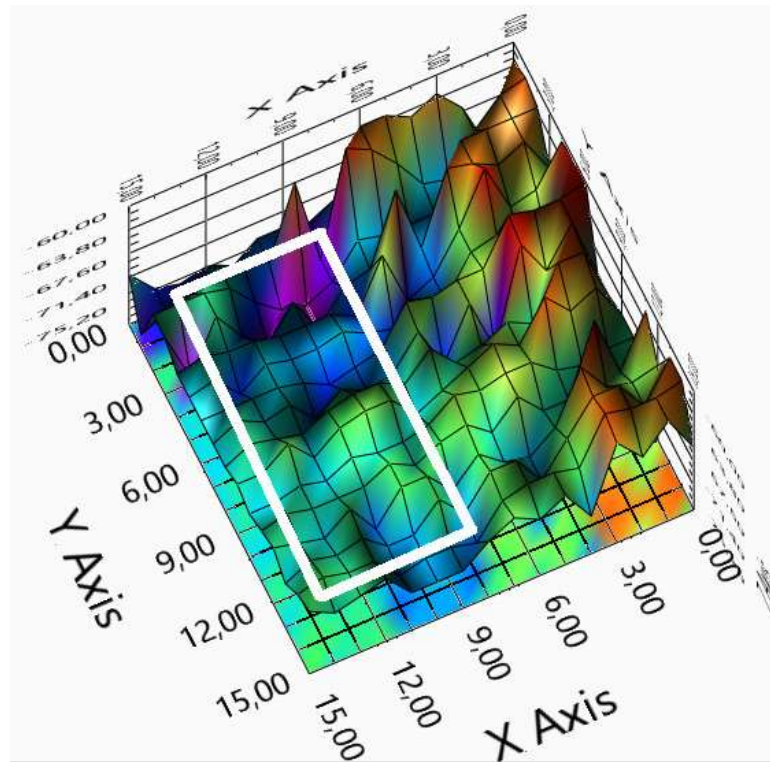**Figure 9:***Bookshelf with clear wall on the right*

Figure 10:*Attenuation of the wooden furniture with free wall on the right*

Finally, in the last test a metal-coated wooden cross was used as seen in fig. 11. In this test, the attenuation produced only by the wall without obstacles is shown in fig. 12 while in the fig. 13 it is shown the wall and object attenuation. This time, the obstacle was a metal-coated wood object and in this case the white line represents its attenuation. The dimensions of the vertical and horizontal components of the metal-coated wood object were approximately 1 x 0.1 x 0.1 meters.
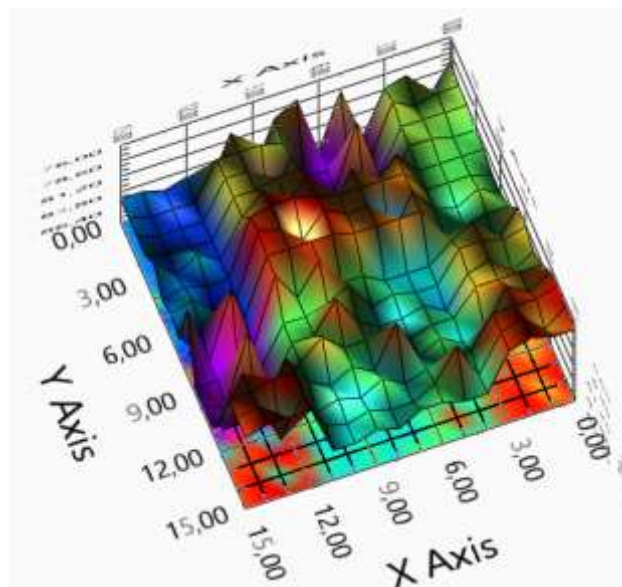
Figure 11:*Raspberry PI sixteen outdoor positions*

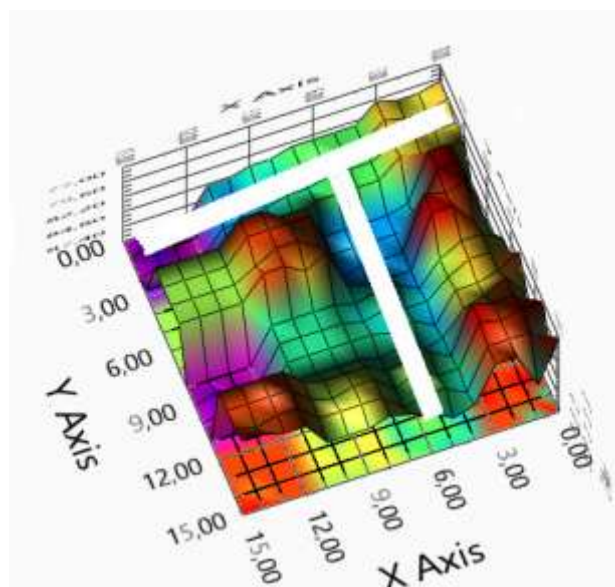**Figure 12:***Wall without object attenuation*

Figure 13:*Wall with metal-coated wood object attenuation*

VI. CONCLUSION

This work is a direct result of the motivation to obtain results in the TTW (Trough the Wall) specific area, using affordable IoT technologies.

In this TTW approach sixteen ESP8266-01S microprocessors were used. Additionally, they were coupled in directional antennas that were assembled in the form of an array to improve resolution and transmission power.

With a Raspberry PI as an emitter and, at same time, as a database and web server, this technique allowed to carry out tests that can contribute to the detection of objects within buildings in the most diverse contexts, including security and catastrophic situations.

VII. FUTURE WORK

As future work it is proposed that taking advantage of the constant evolution of IoT technologies will better control the gain of the devices and replace Raspberry PI with a smaller device that allows the Wi-Fi authentication of an increasing number of client devices.

It is further proposed, that the array of antennas can be installed in an autonomous vehicle and that the Raspberry PI or a smaller device can be coupled to an unmanned aerial vehicle.

On the other hand, as a final result, it is desirable to reproduce in 2D and 3D the objects detected.

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