# Master thesis

# Localization of RFID tags (Fixed readers)

performed for the purpose of obtaining the academic degree a graduate engineer

under the direction of

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Vienna, February 2013

I hereby certify that the work reported in this thesis is my own, and the work done by other authors is appropriately cited.

Sergio Lluch Guirado
Vienna, February, 2013

# Abstract

Nowadays, the technologies of localization are very useful in real life. These technologies can help to storage in the warehouse, to identify or to locate objects between others applications. This project uses the Radio Frequency IDentification (RFID) to locate objects. The Radio Frequency IDentification technology uses a wireless system to transmit data a tag using radio frequency. The finality of this system is to locate the RFID tag using several fixed RFID readers.

This master thesis presents a simulation of a system to locate one RFID tag with several fixed RFID readers following the characteristics of these two elements. After a brief introduction, where I comment the elements and the basis in the communication, I describe the different techniques of localization and reasoning I choose one. Also, I present the different challenges that the signal can find during the communication and that it induces to an error. After the study of these challenges, I select and describe the channel model to simulate the system and its characteristics. Moreover, I explain how the RFID tag does the backscatter of the signal. On the other hand, I explain the MUSIC algorithm and how finds the angles of arrival from the incoming signal in the RFID reader. Finally, I implement this system using MATLAB, simulating the channel model and calculating the estimated position of the RFID tag.

Finally, I study the accuracy of the results in the simulations. To explain this results I compare different cases where is possible to study the influence of the different challenges in the system. Specifically I describe the influence of the distance, the noise and the Rician factor in the system.

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# 1. Introduction

The world of technology, especially in the telecommunications sector, is constantly innovating and improving. In the last years, the necessity to locate objects has increased in order to improve the performance in several sectors.

First of all, The Radio Frequency IDentification (RFID) uses a wireless system. This technology uses the radio frequency to transmit data a tag. This tag is attached to an object.

The Radio Frequency IDentification technology is an interesting area of work because several concepts of telecommunications are involved. On the other hand, RFID technology is an expanding area that has generated many studies until now. Finally, the RFID technology has a lot of applications in real life.

Nowadays, the location is an important tool in several areas of work. The location reduces the time and the errors in the working chain. Also it is an economic technology and can substitute others, for example the barcode. Between others, one of the more important advantages is that the location can work without a perfect line of sight.

As I will explain in the Chapter 3, there are two types of RFID tags, active and passive tags. This project has been focused on passive tags. This RFID tag is more economic than the active tag and more flexible.

The communication in the RFID technology is between the RFID readers and the RFID tags. The RFID reader is separated in two parts, the transmitter and the receiver. The operating basis of this system consists of two parts. First, the RFID reader transmits a signal. When this signal arrives to the tag,

in a second step, the RFID tag does a backscatter and the signal comes back to the RFID reader. This behaviour is shown in the Figure 1.1 [1].

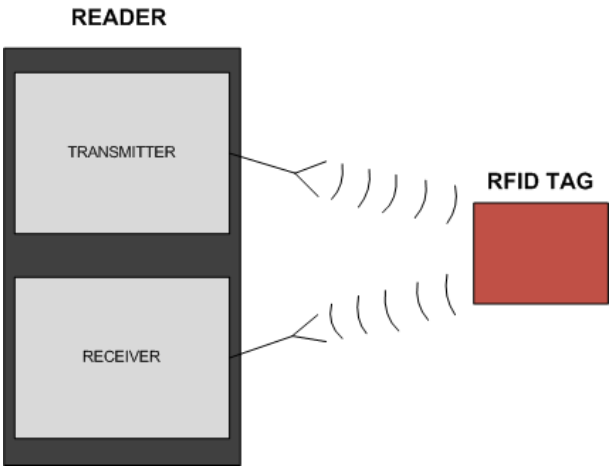


Figure 1.1: RFID technology communication.

Also the signal suffers modifications during transmission. For this reason, to find the exact position of the RFID tag is difficult. However, there are techniques that reduce the error.

I have used the Ultra High Frequency (UHF) band to transmit the signal. In several studies has been demonstrated that the UHF is good enough to determine the position of the RFID tag [2][3][4][5].

Finally, the main objective of this master thesis is to obtain the position of the passive RFID tag using several fixed RFID readers. To get this goal is required to simulate an indoor environment to have a realistic scenario. The last point is to obtain the results of the localization and study the accuracy in different cases.

# 2. Project scope

## 2.1. Background

The RFID technology has its origins in the Second World War. The German, Japanese, American and British used radars to detect airplanes. The problem was that they could not differentiate whether the airplanes were enemies or allies. In 1939 the British started to use a transponder to identify their aircrafts. This system was called "Identify Friend or Foe" (IFF).

The RFID started with Lone Theremin in 1945 for the Soviet Government and it was used to spy. Other important contribution was by Harry Stockman with his article "Communications by Means of Reflected Power" in 1948 [6].

In the 50's the sector of RFID technologies was driven by systems with transponders of long-range. The second contribution in this decade was the work "System of Radio Transmission with Modulator Passive Response" that it transformed the RFID technology from idea to a solution. In the 60's the first system "Electronic Article Surveillance" was created to detect theft in the warehouses.

In the 70's Mario W. Cardillo developed the first RFID device with rewritable memory. On the other hand, Charles Walton created a system that opened the doors without keys. In the 80's were developed several systems in the transport, access, industry and in the control of animals. In the 90's were created systems for the highway, above all in the tolls, to control the vehicles and some innovations in the automotive sector.

The revolution in the RFID technology was when the idea of Auto Identification appeared. The RFID technology has advantages in front other technologies such as the Barcode. It can identify in real time even with non-line-of-sight (NLOS). The utilization of this technology as a location system opened a new study and areas of work.

Nowadays, the main use that is being given to the RFID technology is to have a control the storages, replacing the Barcodes, in control of the Stock, the distribution management and provision. Other important application is in the baggage check, where each RFID tag provides a unique code of identification for each baggage. On the other hand, the RFID technology is used in the security controlling the access in the building or in the room and also the access to the car and to start the engine.

## 2.2. Motivations

In recent years the interest for RFID technology has been increased. It is introduced in the society to facilitate the life in different areas. For example, in the logistics and distribution process, the RFID technology makes easy the identification of the products or packages, to obtain data and to control the movements. Other possible application would be to locate in the museum using the audio guides.

The localization in an indoor environment using the RFID technology is a big challenge. There are several sources that drive an error to achieve the position with enough accuracy. The effect of these different sources has been one of the important points in this master thesis.

Nowadays, the positioning with a good accuracy is very important. As I said in the previous paragraph, there are several effects that modify the signal in the scenario. To detect the position of an airplane an error of some centimetres in not a problem since the dimensions of the object are much bigger. In contrast, in case of to localize small objects in a big warehouse a difference of centimetres is critical.

In the future will be needed more accuracy in the positioning. One possible application in the future is to use the RFID tags to replace the barcode in the products. So that, when the people will arrive to the cash register in the supermarket, the price will be calculated automatically. Then will be needed higher accuracy.

Last point of the motivations is to work with Radio Frequency (RF) sig-

nals especially in the UHF band. The UHF band works between 300-3000MHz. When the frequency increase is possible to improve the accuracy of the position.

## 2.3. Objectives

The main objective of this project is to locate a RFID tag using several fixed RFID readers. This principle objective of the master thesis has been divided in different goals that I will define here:

1. **Study the elements of the scenario.** It is essential to know how the different components of the system work.
2. **Study the algorithms of localization.** To compare the different techniques of localization and to choose the best option.
3. **Obtain the received signal.** To study the problems in the communication, to determine the channel model and to get the received signal.
4. **Test the system in different cases.** To simulate the system in MATLAB and to play with different cases to obtain the position.
5. **Study the accuracy comparing the results of different cases.** To determine if the results are good enough it is necessary to calculate the errors in the measures. Finally, it is possible to compare different cases.

## 2.4. Project structure

Briefly I will comment in which will consist each chapter of this master thesis.

First, in the Chapter 3 "Theoretical fundamentals of RFID", I will comment the different elements that appear in the scenario. Basically there are two different components in the system, the RFID readers and the passive RFID tag.

After that, in the Chapter 4 "Location basis", I will talk about how to locate the RFID tag. First, I will explain that there are several techniques to determine the position. On the other hand, the data that are needed to obtain the coordinates with each method. After that, I have compared the advantages and disadvantages. The last point of this section is to choose one method.

Later in the Chapter 5 "Channel model", I will explain how is modelled

the channel. In this section also I will comment the different obstacles that exist in the transmission of the signal and how it affect in the signal.

In the Chapter 6 “Simulation”, I will comment how I have simulated the scenario in MATLAB. The first part of the simulation consists of to simulate the scenario. Later, with this signal and applying the algorithms of localization, the position is estimated. Finally, I have calculated the error between the real and estimated position of the RFID tag.

After that, in the Chapter 7 “Results”, I will talk about the results that I have obtained in MATLAB comparing the different scenarios. The last point is to evaluate the accuracy.

Finally, in the Chapter 8 “Conclusions”, I will explain which conclusions I have extracted of this master thesis.

# 3. Theoretical fundamentals of RFID

## 3.1. Radio frequency identification

The operating principle of the system is based in one RFID tag and several RFID readers. To locate the RFID tag first the RFID reader sends a signal that is received for the RFID tag. Then, the RFID tag does a backscattering of the signal that arrives to the RFID reader. The backscattering consists of to reflect the signal. To get this system are needed mainly two blocks, the RFID tag and the RFID reader. Also, the RFID technology uses servers to process the received signal, however, in this project I have focused in the RFID readers and RFID tags.

### 3.1.1. RFID tag

The RFID tag is the object to locate and then is the most important element of the system. There are two types of tags, the passive and the active tags. In this master thesis I have used the passive RFID tag.

#### Passive RFID tag

The passive RFID tag, as it is shown in the Figure 3.1, is an element without energy, in other words, cannot function without an external stimulation. For

one hand, this is an advantage because it does not need battery to work and it is more economic. On the other hand, until this RFID tag does not receive any signal it is not work.

When the RFID tag receives a signal from the RFID reader, in the coiled antenna is created a magnetic field. Once the RFID tag has enough energy, the circuit is switched on and it does the backscattering of the signal to the RFID reader.

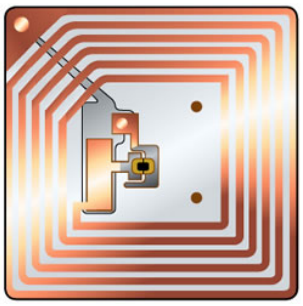

Figure 3.1: Passive RFID tag [7].

This RFID tag does not require any battery, the advantages of this are that it is more independent, it is smaller and it is more flexible. To put this element in the packages, boxes or other objects is easier because it is smaller and it is not necessary to change the battery when this is exhausted. The last advantage is that this RFID has an extensive useful life.

Obviously, the negative consequence is that the RFID tag needs feed from the reader to work. This implies that the distance to function properly is short [7].

Also, there are a semi passive RFID tags. This type of tags has a small battery and then does not need an external stimulation to work.

#### Active RFID tag

The active RFID tag is supplied with a battery. One example of this element is shown in the Figure 3.2. The main advantage is that this element does not need any external stimulation to work. On the other hand, if the battery is exhausted it does not work. As a consequence is not possible to use this type of RFID tag when is necessary that it works for a long time and with difficult access.

The main advantage of this RFID tag is that can be read from a long

distance. On the other hand, another good point is that it can start the communication.

The most important disadvantages for this device are that it cannot function without battery, it is more expensive, it is bigger than the passive tags, it is possible that the battery suffers courts and the maintenance could be expensive and with difficulties [7].


Figure 3.2: Active RFID tag [7].

### 3.1.2. Readers

In the RFID technology the reader, as it is shown in the Figure 3.3, is a device that interrogates the RFID tag. Its function is to send signals and to receive the responses from the tag. The important parameters of these elements are the frequency, the gain of the antennas, the orientation, the polarization and the transponder of the antenna [7]. In the Figure 3.3 is shown the fixed reader because it is used in this project but also there are portable readers.

Figure 3.3: Fixed RFID reader [7].

This element consists of two parts, the transmitter and the receiver. One example of this structure is shown in Figure 3.4. The function of the

transmitter (TX) is to send signals to interrogate the RFID tags in the room. The function of the receiver (RX) is to get the answer from RFID tags.

To combine the received signal of different readers is possible. As I will explain in the Chapter 6, to determine the position of the RFID tag is necessary to use several receiving antennas.

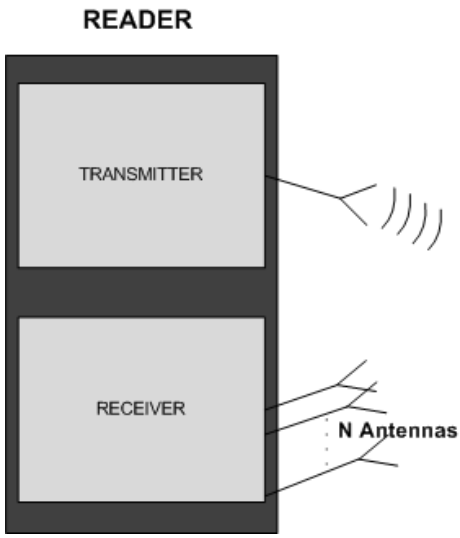


Figure 3.4: RFID reader (TX-RX).

## 3.2. Scenario

To obtain the position of the RFID tag is important to know the scenario. First, I have explained the elements of the system and now I show their influence in the scenario.

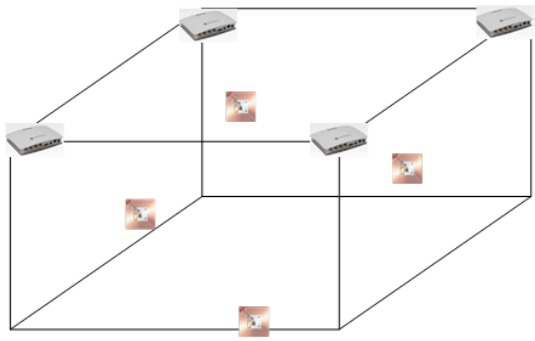

Figure 3.5: Scenario.

The main objective of this master thesis is to find the position of the RFID tag in an indoor environment. Then, I need a room where I can distribute several readers, for example, the scenario that is shown in the Figure 3.5.

In the Figure 3.5 is shown one possible real case. To simplify this scenario, in order to study the signals and accuracy between others, is created a scenario with only one RFID tag and some RFID readers as is depicted in the Figure 3.6.

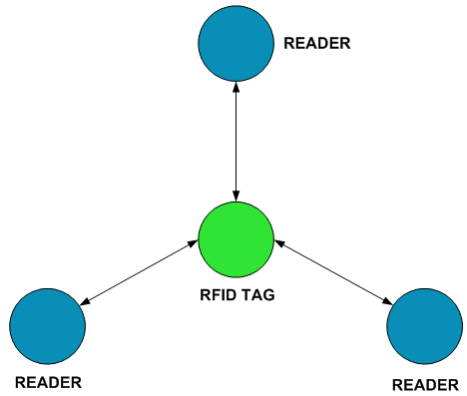


Figure 3.6: Scenario (Logical schema).

## 3.3. Wireless communication

The channel of communication of this system is the air. In wireless communications, normally, there are more problems than with cables. I will explain with more details the characteristics of this channel in the Chapter 5.

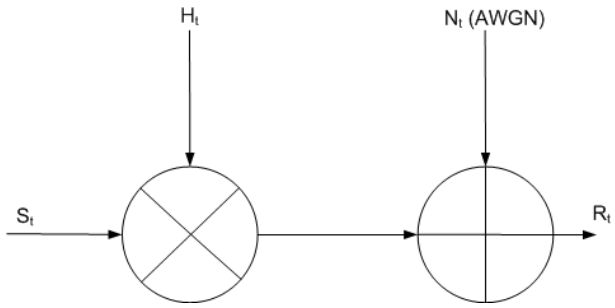


Figure 3.7: Channel model.

The ideal scheme of this communication is shown in the Figure 3.7 that

it consists of the type of channel. In this case, I will consider a combination of the Rician and Rayleigh distributions because the system could have line-of-sight (LOS) and non-line-of-sight (NLOS). On the other hand, in the system appears the Additive White Gaussian Noise (AWGN). In this scheme is only considered one way of the communication, for example the forward way. Using this scheme, the received signal in the RFID tag follows the formula (3.1).

$$R_t = H^f S_t + N_t \tag{3.1}$$

## 3.4. Conclusions

This system consists of a scenario where there are two types of elements, RFID readers and passive RFID tags. On the other hand, the medium of communication is the air and due to this the channel model suffers from several problems. With the simplest considerations the signal is only affected by AWGN.

# 4. Locating bases

## 4.1. Introduction to RFID localization

To achieve the objective of this project are needed two steps. First step is to acquire the received signal in the reader. Second step is starting with this signal to get the position of the tag. There are several techniques to determine the coordinates of the RFID tag. The main difference of each one is the parameters of the signal that are needed. In this chapter I will talk about different ways to obtain the second step.

## 4.2. Techniques of localization

The techniques of localization use parameters of the signal to calculate the position. Between others, there are these three techniques of localization Received Strength Signal (RSS), Angle of Arrival (AoA) or Direction of Arrival (DoA) and Time Difference of Arrival (TDoA) that I have studied [5][8].

First of all, in this section I will explain different techniques in two dimensions. In a second step I will compare the different techniques and I will choose one. In the last point, I will explain the possibility to extend to three dimensions.

### 4.2.1. RSS

The RSS is one of the most classical methods of localization. It is used in wireless communications and only three readers are needed to get the position in two dimensions.

The RSS is based on to estimate the distance between the RFID reader and the RFID tag. To get an accurate position must be taken into account several issues [5][8].

In the Figure 4.1 is shown graphically that to get the RSS parameter is necessary that each RFID reader interrogates the RFID tag. In the Figure 4.1 is shown that $\text{Reader}_\text{A}$, $\text{Reader}_\text{B}$ and $\text{Reader}_\text{C}$ are interrogating the RFID tag to get the RSS metric.

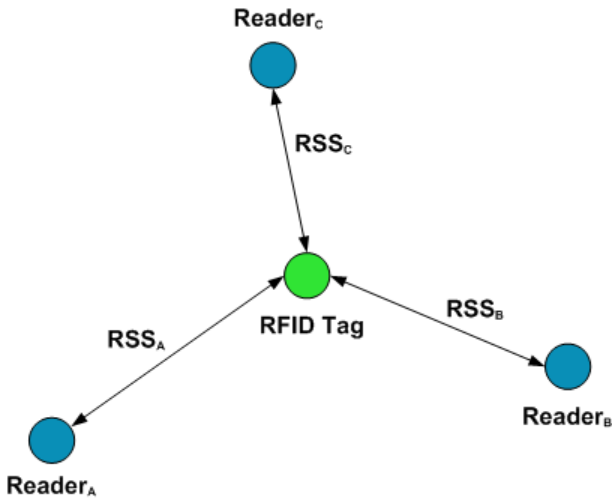


Figure 4.1: Process of interrogation with three readers and one RFID tag.

Later, the distance between RFID tag and RFID readers is estimated. The channel model is an important point to get an accurate distance. In indoor environments the signal could easily suffers multipath, furthermore of other problems as losses due to the distance or interferences. The channel model must be chosen to obtain a precisely estimation of the distance.

Now, I assume that this is an ideal scenario. Then, the readers obtain a good estimation of the distance between them and the RFID tag. I consider only the losses in the free space. At that time, with the estimated distance I have three circles, one of each reader. The radius is the distance between the corresponding RFID reader and the RFID tag, as it is depicted in the Figure

4.2.

Finally, I have three circumferences that intersect in one point. In a real case, with multipath, interferences, etc. surely the circumferences will not cross in one point and I should calculate the accuracy of the results. At this point, the objective is to obtain in which coordinates intersect the circumferences.

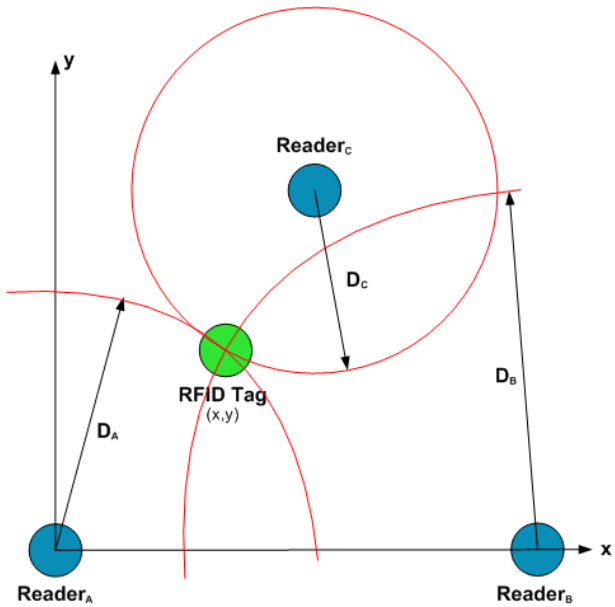


Figure 4.2: Localization using RSS.

#### Determining the position using RSS

If the ideal conditions are supposed in the scenario, the three circumferences will intersect in one point. Using trigonometric rules is possible to find the intersection point of three circumferences.

First of all, my starting point is to assume that I have estimated the distances between each reader and the RFID tag. The objective is to achieve the position (x,y) of the RFID tag. Other consideration that I have done is that I know the coordinates of my readers ($\text{Reader}_A$, $\text{Reader}_B$ and $\text{Reader}_C$).

I have supposed a generic scenario, where the positions of the readers $A$, $B$ and $C$ are ($x_A$,$y_A$), ($x_B$,$y_B$) and ($x_C$,$y_C$) respectively, as it is shown in Figure 4.3. To simplify the calculations, I have situated $\text{Reader}_A$ in (0,0), $\text{Reader}_B$ in ($x_B$,0) and the last $\text{Reader}_C$ in the coordinates ($x_C$,$y_C$).

Once I know the distance between RFID reader and RFID tag, the position of the RFID tag is the intersection of the circles. Each circle is centred in

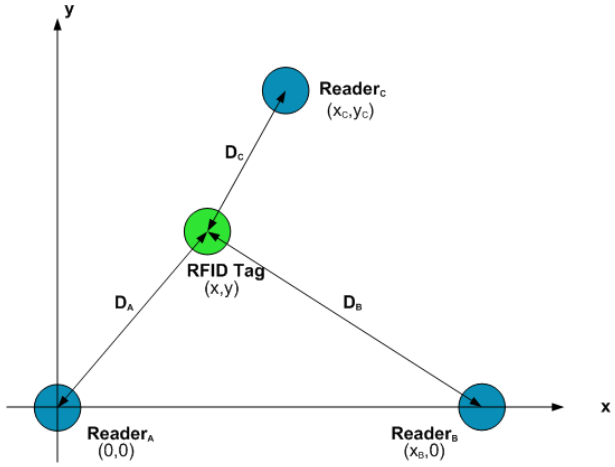


Figure 4.3: Definition of coordinates using RSS.

the position of the RFID reader and the radius is the distance with the RFID tag. The corresponding radius of Reader$_A$, Reader$_B$ and Reader$_C$ are $D_A$, $D_B$ and $D_C$ respectively. This scheme is depicted in the Figure 4.4.

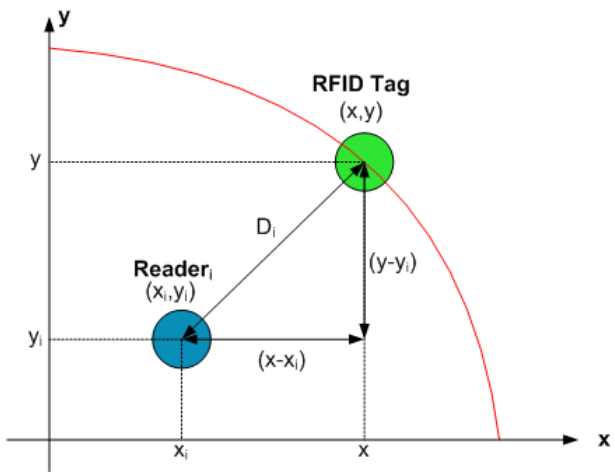


Figure 4.4: Mathematical definition of a circle.

Analytically, if the radius $D_i$ of one circumference that is centred in ($x_i$,$y_i$), circle is possible express as (4.1).

$$(x - x_i)^2 + (y - y_i)^2 = D_i^2 \tag{4.1}$$

Following (4.1), knowing the $D_A$, $D_B$ and $D_C$ and considering that the coordinates are (0,0), ($x_B$,0) and ($x_C$,$y_C$) respectively for Reader$_A$, Reader$_B$ and Reader$_C$, I can obtain the respectively expressions of each circumference

(4.2), (4.3) and (4.4) and then, I get a system of equations.

$$x^2 + y^2 = D_A^2 \tag{4.2}$$

$$(x - x_B)^2 + y^2 = D_B^2 \tag{4.3}$$

$$(x - x_C)^2 + (y - y_C)^2 = D_C^2 \tag{4.4}$$

I meet the coordinates of the three readers (($x_A$,$y_A$), ($x_B$,$y_B$) and ($x_C$,$y_C$)) and also I consider that the three distances are known ($D_A$, $D_B$ and $D_C$). I have a system of three equations with two unknowns. Then, solving this system is possible to obtain finally the (x,y) coordinates of the RFID tag.

First, combining the formula (4.2) and (4.3) the coordinate $x$ is determined by (4.5).

$$x = \frac{D_A^2 - D_B^2 + x_B^2}{2x_B} \tag{4.5}$$

In the same way is possible to find the $y$ coordinate. In this case I have used the expressions (4.2) and (4.4). Then, I get the $y$ coordinate using (4.6).

$$y = \frac{D_A^2 - D_C^2 + x_C \frac{D_A^2 - D_B^2 + x_B^2}{2x_B} + x_C^2 + y_C^2}{2y_C} \tag{4.6}$$

Finally, I can conclude that to obtain the coordinates of the RFID tag starting from the received signal in an ideal scenario is possible. To get the position of the RFID tag is necessary to follow the formulas (4.5) and (4.6).

### 4.2.2. AoA/DoA

The Angle of Arrival (AoA) or Direction of Arrival (DoA) is another important method of localization. This is a triangulation technique, where the trigonometric rules are essential. In two dimensions it only requires two readers to get the position of the RFID tag [3][5][8].

The triangulation technique consists of to estimate the angle of arrival of the signal ($\Theta_A$ and $\Theta_B$ respectively for $\text{Reader}_\text{A}$ and $\text{Reader}_\text{B}$). It is only necessary to know the angle of arrival of the signal in each reader and the position of the two readers. With this data, I can obtain one straight line for each RFID reader.

At that time, the scenario is composed by two readers ($\text{Reader}_\text{A}$ and $\text{Reader}_\text{B}$) where their position is known and one RFID tag. The position of this RFID tag is estimated calculating the intersection of two straight lines. In

Figure 4.5 this scheme is depicted. I will comment the calculations to obtain these coordinates in the next section.

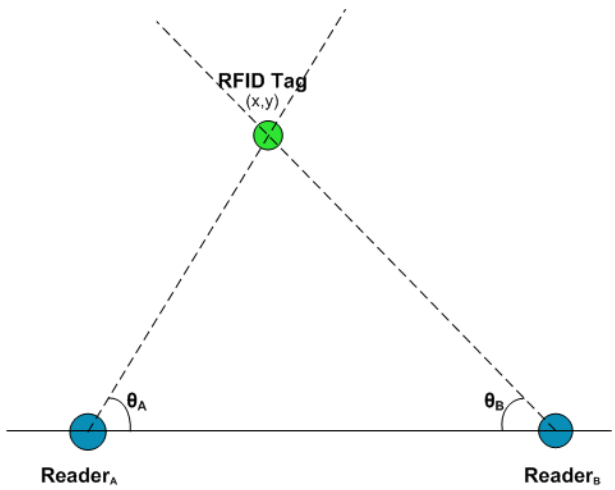


Figure 4.5: AoA scenario.

To compare the AoA or DoA with the previous method, RSS, is needed to say that the principle difference is the parameter to get the position. Remembering that the technique RSS requires the distance between reader and RFID tag. In contrast, with AoA is necessary to know with which angle arrives the signal to the RFID reader.

#### Determining the position using AoA

I have assumed that the conditions are ideal like in RSS. In a real case, the angles are not exactly estimated. In contrast with the RSS case, now with AoA, the straight lines will intersect in one point (except if these lines are parallel). However, in a real case, these coordinates will not determine perfectly the position of the RFID tag.

Starting from the ideal conditions, the angles are correctly estimated. The triangulation technique consists of to get the intersection of two straight lines. The first important formula that must be taken into account is (4.7).

$$f(x) = Mx + N \tag{4.7}$$

Where $M$ is the slope of the straight line and $N$ is the offset, which it is referring to the intersection with the $y$ axis.

In order to obtain the coordinates of the RFID tag is necessary to know

the position of the readers and the angles of arrival of each reader. Then, I can assume that I have estimated correctly the angles.

At that time, I consider that the coordinates of the $\text{Reader}_\text{A}$ and $\text{Reader}_\text{B}$ are respectively ($x_A$,$y_A$) and ($x_B$,$y_B$). On the other hand, I have assumed that the angles of arrival are $\Theta_A$ and $\Theta_B$ respectively for the $\text{Reader}_\text{A}$ and $\text{Reader}_\text{B}$.

Unlike with the RSS method, in this case I have not to simplify the coordinates. In the Figure 4.6, I have represented the $\text{Reader}_\text{A}$ in the position (0,0) and $\text{Reader}_\text{B}$ in the position ($x_B$,0). However, I have considered a generic coordinates in order to obtain a generic formulas.

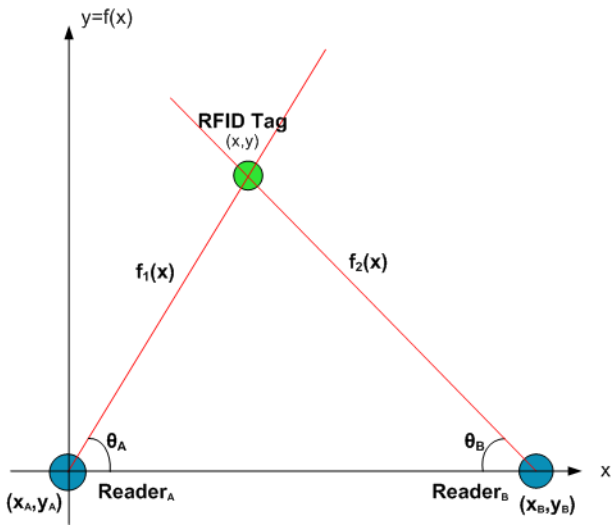


Figure 4.6: Localization using AoA.

Following (4.7), I have started with finding the equation that define each straight line, $f_1(x)$ in (4.8) and $f_2(x)$ in (4.9). First, the slope and at least one point of the line are known.

$$f_1(x) = M_1 x + N_1 \tag{4.8}$$

$$f_2(x) = M_2 x + N_2 \tag{4.9}$$

Using the trigonometric rules, the slope of the first straight line is (4.10).

$$M_1 = tan\Theta_A \tag{4.10}$$

Knowing one point of the line ($x_A$,$y_A$) to deduce the offset $N_A$ as it is shown in (4.11) is possible.

$$N_A = y_A - x_A tan\Theta_A \tag{4.11}$$

Afterwards, the formulas that describe the straight lines are (4.12) and (4.13).

$$f_1(x) = xtan\Theta_A + y_A - x_A tan\Theta_A \tag{4.12}$$

$$f_2(x) = xtan\Theta_B + y_B - x_B tan\Theta_B \tag{4.13}$$

Now, I have a system of two equations $f_1(x)$ and $f_2(x)$ and two unknowns $x$ and $y$. Then, if I solve the system of equations I will obtain the coordinates of the RFID tag. To obtain the solution of this system of equations, I have started to assume that there is the intersection point of both straight lines ($f_1(x)$=$f_2(x)$) (4.14).

$$xtan\Theta_A + y_A - x_A tan\Theta_A = xtan\Theta_B + y_B - x_B tan\Theta_B \tag{4.14}$$

Isolating $x$, I have obtained this coordinate (4.15).

$$x = \frac{y_B - y_A + x_A tan\Theta_A - x_B tan\Theta_B}{tan\Theta_A - tan\Theta_B} \tag{4.15}$$

Finally, I can obtain the coordinates of the RFID tag starting from the angles of arrival of the signal in an ideal scenario. The coordinate $x$ is gotten following (4.15) and replacing this value in (4.12) or (4.13) is possible to obtain the coordinate $y$ (4.16). Then, the position of the RFID tag is determined by the equations (4.15) and (4.16).

$$y = \frac{y_B - y_A + x_A tan\Theta_A - x_B tan\Theta_B}{tan\Theta_A - tan\Theta_B} tan\Theta_A + y_A - x_A tan\Theta_A \tag{4.16}$$

### 4.2.3. ToA/TDoA

The last techniques of localization that I have studied are Time of Arrival (ToA) and Time Difference of Arrival (TDoA). These methods consist of measuring how much time the signal takes to travel from the transmitting antenna to the receiving antenna. In case of ToA technique the RFID readers must be synchronized. The synchronization implies that the system requires more complexity. If the synchronization fails, the difference of the time will be wrong and consequently the coordinates will be bad estimated. Then, TDoA is used because do not need the synchronization of the RFID readers.

With TDoA is possible to obtain the position in two dimensions using at

least three readers. The scenario is the same as in case of RSS (Figure 4.1). However, TDoA technique needs the time of arrival instead of the distance [8][9].

To acquire the coordinates of the RFID tag, the first step is to measure the time of arrival in each RFID reader. The second step is to calculate the difference time between each pair of readers and the result is one hyperbola. Finally, to achieve the position is necessary to calculate the intersection of at least two hyperbolas.

In the same way as in the previous techniques, I will assume that the scenario is under ideal conditions and the measured time is accurate.

#### Determining the position using TDoA

In this case to get the position is more complex than in the previous techniques. This technique needs a previous step to relate the time of arrival and position of the RFID readers.

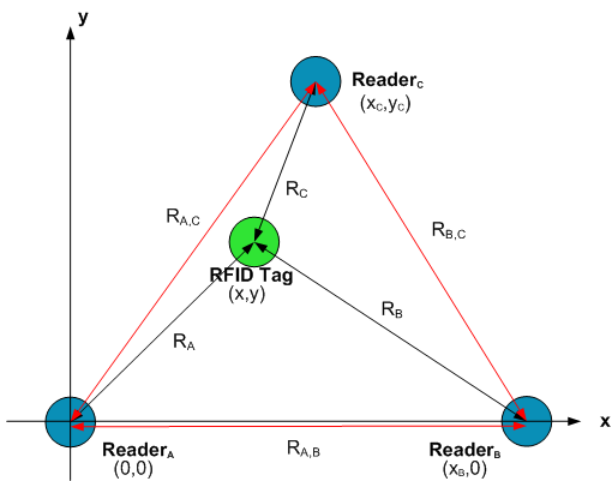


Figure 4.7: Scenario for TDoA technique.

Before starting the calculations, I have assumed that the coordinates of the Reader$_A$, Reader$_B$ and Reader$_C$ are respectively, (0,0), ($x_B$,0) and ($x_C$,$y_C$) in order to simplify the calculations. Finally, the position of the RFID tag is (x,y) as it is shown in Figure 4.7.

Then, supposing that $t_i$ is the estimated time for reader $i$ (where $i$=$A,B,C$), I have obtained the expression (4.17)[10], where $c$ is the speed of light.

$$R_i = ct_i = \sqrt{(x_i + x)^2 + (y_i - y)^2} \tag{4.17}$$

At that time, the expression of the TDoA is (4.18)[10]. Where, $R_{i,A}$ and $\tau_{i,A}$ are respectively the distance and difference of time between $\text{Reader}_\text{i}$ and $\text{Reader}_\text{A}$.

$$R_{i,A} = c\tau_i = \sqrt{(x_i + x)^2 + (y_i - y)^2} - \sqrt{(x_A + x)^2 + (y_A - y)^2} \tag{4.18}$$

To achieve the coordinates in TDoA is necessary to use the Fang's method [10]. The principle of this method is to convert the non-linear to linear expression. Then, applying this method in the $\text{Reader}_\text{A}$ is obtained the equation (4.19)[10].

$$2R_{i,A}R_A = x_i^2 + y_i^2 - 2xx_i - 2yy_i - R_{i,A}^2 \tag{4.19}$$

Applying the expression (4.19)[10] for the $\text{Reader}_\text{B}$ and $\text{Reader}_\text{C}$ the equations (4.20)[10] and (4.21)[10] are obtained.

$$2R_{B,A}R_A = x_B^2 - 2xx_B - R_{B,A}^2 \tag{4.20}$$

$$2R_{C,A}R_A = x_C^2 + y_C^2 - 2xx_C - 2yy_C - R_{C,A}^2 \tag{4.21}$$

Isolating $R_A$ in (4.20)[10] and (4.21)[10] is obtained (4.22)[10] equating the both previous formulas.

$$\frac{x_B^2 - 2xx_B - R_{B,A}^2}{R_{B,A}} = \frac{x_C^2 + y_C^2 - 2xx_C - 2yy_C - R_{C,A}^2}{R_{C,A}} \tag{4.22}$$

At this point is possible to obtain an expression that follows the equation of the straight line (4.23).

$$y = Mx + N \tag{4.23}$$

Where, taking into account the equation (4.22)[10], $M$ is (4.24)[10] and $N$ is (4.25)[10].

$$M = \frac{R_{C,A}(\frac{x_B}{R_{B,A}}) - x_C}{y_C} - \frac{x_C}{y_C} \tag{4.24}$$

$$N = \frac{x_C^2 + y_C^2 - R_{C,A}R_{B,A}[1 + (\frac{x_B}{R_{B,A}})^2]}{2y_C} \tag{4.25}$$

Substituting the expressions (4.18)[10] and (4.23) in the equation (4.20)[10], and knowing that the coordinates for the $\text{Reader}_\text{A}$ are (0,0), I obtain the formula (4.26)[10].

$$2R_{B,A}\sqrt{x^2 + (Mx + N)^2} = x_B^2 - 2xx_B - R_{B,A}^2 \tag{4.26}$$

Applying the square in both parts of the expression (4.26)[10] and dividing by $2{R_{B,A}}^2$ the equation (4.27)[10] is obtained.

$$gx^2 + hx + k = 0 \tag{4.27}$$

Where $g$, $h$ and $k$ are respectively (4.28)[10], (4.29)[10] and (4.30)[10].

$$g = 1 + M^2 - (\frac{x_B}{R_{B,A}}) \tag{4.28}$$

$$h = 2MN + x_B[(\frac{x_B}{R_{B,A}})^2 - 1] \tag{4.29}$$

$$k = N^2 - \frac{[(\frac{x_B}{R_{B,A}})^2 - 1]^2}{4} \tag{4.30}$$

Finally, I can obtain the coordinate $x$ applying the solution of a quadratic expression in (4.27)[10] only considering the positive solution. This coordinate is obtained following the equation (4.31).

$$x = \frac{-h + \sqrt{h^2 - 4gk}}{2g} \tag{4.31}$$

To obtain the coordinate $y$ is necessary to substitute the solution of (4.31) in equation (4.23).

### 4.2.4. Selection of technique

Once several techniques of localization have been studied, I have had to select one to apply for locate the RFID tag. First, I have had to compare the three methods and to study the advantages and disadvantages of each one.

In the previous sections, when I have explained the different techniques, I have said that I have assumed ideal conditions to obtain an accurate measure of distance, angle and time. In a real case, the measures of these parameters are not exactly as in ideal scenario.

In case of a real system, the distance, the angle and the time are obtained with a certain error. I need obtain these parameters for each RFID reader.

Then, if I need more readers surely the error will be higher. Remembering the study of the several methods, in case of RSS and TDoA are needed at least three RFID readers. In contrast with the AoA technique are only necessary two RFID readers. Finally, in this comparison the AoA is better.

In addition to this first comparison, more readers imply more cost of the system and maintenance. The system requires more complexity to determine the coordinates.

In the previous chapters I have explained that there are several problems in the communications. The multipath or NLOS between others affect more to determine the position with the TDoA technique and in less measure with RSS technique [11]. In case of TDoA and RSS techniques are used, the errors create areas of ambiguity when all the hyperbolas or circles do not intersect in one point.

Obviously, these problems affect using the AoA technique. However, it is the more robust method in front of these errors. Then, the AoA is better in comparison with TDoA and RSS when these problems appear [11].

Finally, the best option is to use the AoA technique because it achieves more accuracy and it requires less RFID readers.

#### 4.2.5. AoA in 3 dimensions

Until now, I have chosen a technique of localization and I have explained how is possible to determine the position in 2 dimensions. In this section, I will comment how would be possible to extends the AoA technique to scenario in 3 dimensions. This scenario is depicted in the Figure 4.8.

In the Figure 4.8 is possible to observe that there are 3 straight lines that I have named $A$, $B$ and $C$. I have considered that the positions of the $\text{Reader}_\text{A}$, $\text{Reader}_\text{B}$ and $\text{Reader}_\text{C}$ are, respectively, $(0,y_A,0)$, $(x_B,0,0)$ and $(0,0,z_C)$. Finally, the position of the RFID tag is (x,y,z). On the other hand, to determine the straight lines, in three dimensions is necessary to measure two angles ($\Theta$ and $\gamma$) for each RFID reader.

As I have explained in the previous sections, I have considered ideal conditions to calculate the coordinates. In this case, there are 3 straight lines that intersect in one point. To determine the position of the RFID tag in three dimensions is more complex than in two dimensions. If the angles are not exactly measured the straight lines will not intersect in any point. As a consequence, to estimate the position of the RFID tag in three dimensions would be necessary to estimate which point is the closest one to the three lines.

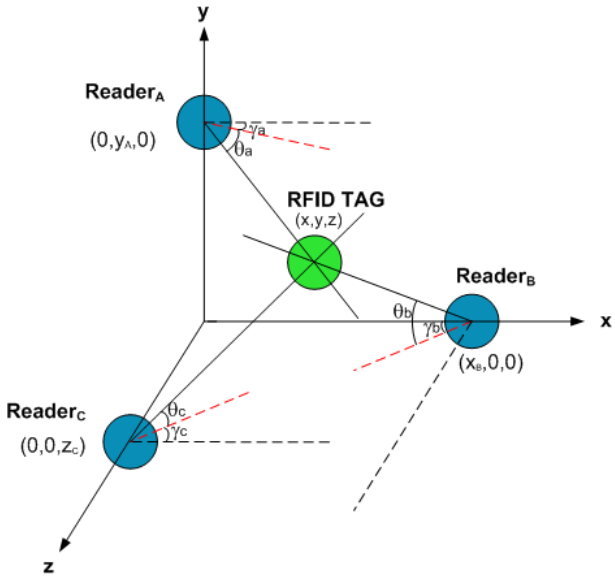


Figure 4.8: Scenario for AoA technique in 3 dimensions.

### 4.2.6. Conclusions

There are several techniques of localization to obtain the coordinates of the RFID tag. Each one needs some parameters of the received signal in the RFID reader. From this data, to get the position of the RFID tag is possible.

In real scenarios, I have found several problems that I will explain in the Chapter 5. I have considered ideal conditions to suppose that the parameters are perfectly measured. In real scenarios, these measures are not accurate and surely will drive to wrong coordinates.

The calculations to get the position are not easy, especially in the case of TDoA. In these three techniques has been necessary to apply the trigonometric rules. However, considering that the time, the distance and the angle are exactly obtained, the estimated position is correct.

These are the most common techniques although there are others. These three techniques have their advantages and disadvantages. Finally, after to study the comparison, I have decided that the best option for the system of this master thesis is the AoA technique. This method needs only two RFID readers in contrast, using RSS and TDoA techniques are needed three RFID readers. Also, using AoA technique the areas of uncertainty are not created.

# 5. Channel model

## 5.1. Challenges

In the transmission always there are challenges that produce distortion in the signal. These problems are normally propagation losses, carrier leakage, interferences and multipath. For this project, I have assumed that the antennas are perfectly isolated in front of the carrier leakage. In addition to this, another distorsion appears due to the obstacles and that is the non line of sight (NLOS) [2][3]. In the Figure 5.1 is depicted a summary of these challenges.

The scenario is developed in an indoor environment. This implies that some problems affect more than in an outdoor system. The multipath will be incremented because in an indoor environment there are walls, columns and machines between others. In addition to this, the system is surely in a warehouse, and then, other objects can appear between the antennas and the RFID tag. In contrast to this, the losses due to the distance decrease because inside the buildings the distances are not long.

Until now, I have explained the elements of the scenario. Also, I have explained how is possible to obtain the position knowing the distance between the RFID tag and the readers, the angle of arrival of the signal in the readers and the time that the signal needs to arrive to the readers. From now on, I will focus in the channel model because is the most important part of the communication.

To explain the received signal is very complex. For this reason, in this chapter I will describe the bases to determine the received signal. In the

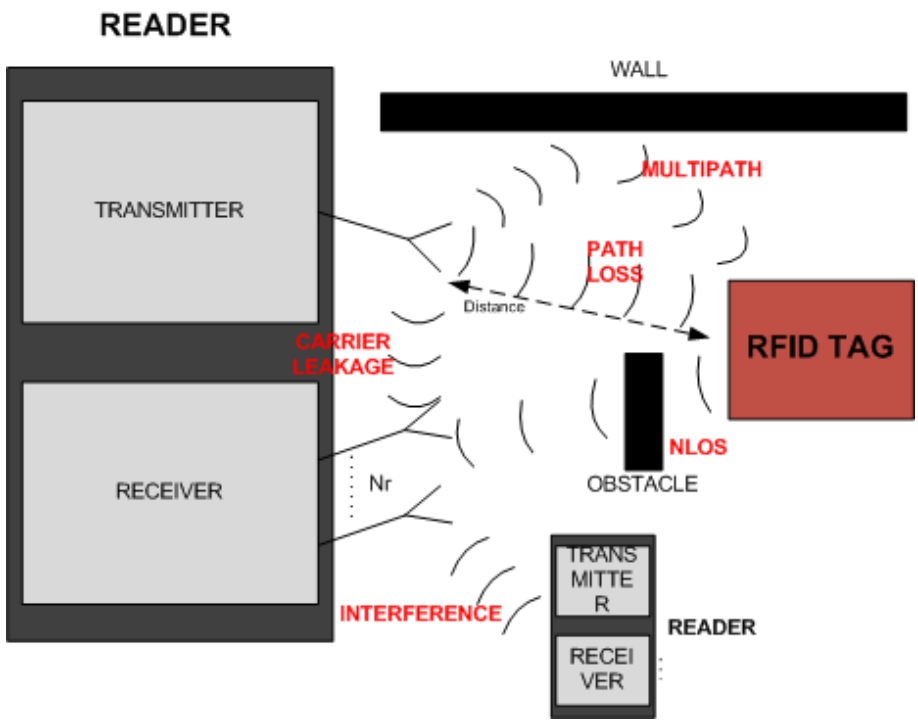


Figure 5.1: Challenges.

next chapter I will explain the formulas with more details and how I have implemented to simulate the system.

## 5.2. Path loss

In all communications, and specifically in the wireless communications, there are losses with the distance. There are several formulas to determine the losses due to the distance. Generally, these equations depend on the obstacles, the dimension of the rooms and the walls.

In this system, I have considered the free space losses. These are the minimum losses between two antennas. I have taken into account the walls and the obstacles in the others challenges.

Finally, I have followed the equation of the free space losses (5.1) to determine the losses due to the distance.

$$L = (\frac{4\pi d}{\lambda})^2 \tag{5.1}$$

In the formula (5.1) is possible to observe that the losses in the free space do not depend only on the distance also it depends on the frequency. So, the

losses increase with the distance, but it decreases with the frequency.

In this system, the frequency that I have used is 866MHz. At that time, the losses depend only on the distance. There are a relation between the losses and the distance as it is shown in the Figure 5.2. In this figure is possible to observe that the losses increase with the distance.

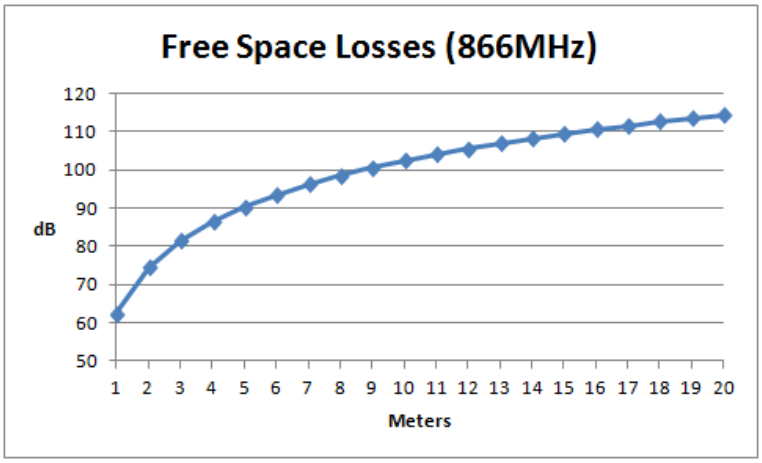


Figure 5.2: Free space losses for f=866MHz.

## 5.3. Interference

In the scenario there are several antennas. For each RFID reader there are one transmitting antenna and $N_r$ receiving antennas. In addition to this, the system is in an indoor environment. So, surely the antennas will be close to each other.

The simplest scenario is composed for two readers and one RFID tag. The signal travels from the transmitting antenna of one reader to all parts of the room. When this signal arrives to the RFID tag, this does a backscattering and the signal arrives to the receiving antenna.

On the other hand, the transmitted signal by the other RFID reader is added with the backscattering of the RFID tag creating interference. This scenario is resumed in the Figure 5.3.

The interference that arrives in one RFID reader is the transmitted signal by the other RFID reader, but it is attenuated for the free space losses. So, the interference can be expressed following the formula (5.2). Where, $L$ is

the losses in the free space.

$$I = LHS_{transmitted} \tag{5.2}$$

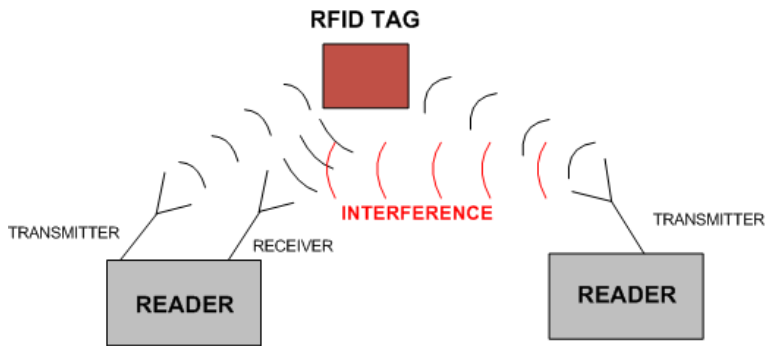


Figure 5.3: Interference.

Finally, the received signal in the RFID reader is a combination of the signal from the RFID tag and the interference. This expression is described in the formula (5.3).

$$S_{received} = LHS_{tag} + I \tag{5.3}$$

## 5.4. Multipath

When one antenna transmits a signal, this travels through the air until the receiver. There are several types of antennas as directives and omnidirectional between others.

In case of directives antennas, theoretically, the signal travels only in the direct path between a transmitting antenna and a receiving antenna. In contrast, the omnidirectional antenna radiates the signal in all directions. Obviously, the signal arrives to the receiver with the direct path, but to know what happens with the signal in the other directions is necessary.

The omnidirectional antenna radiates in all directions, consequently, the signal can have several destinations. First, the signal arrives to the receiver in the direct path. Second option is that the signal losses the power before this arrives to one receiver. Last option is that the signal finds an obstacle and it bounces changing the direction and this arrives to the receiver [5][12]. In the

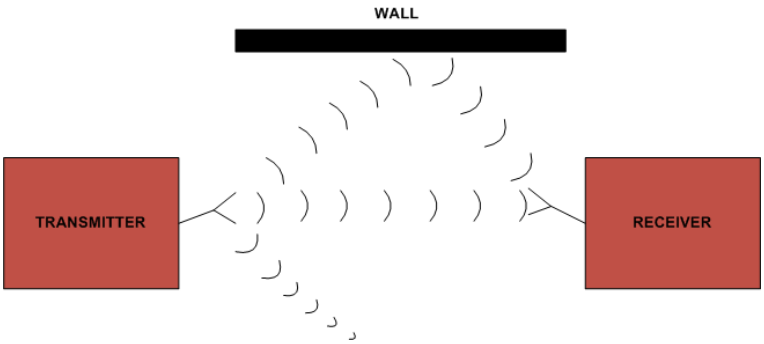


Figure 5.4: Multipath.

Figure 5.4 is depicted the different possibilities.

When the receiving antenna gets the same signal from different directions it is said multipath. In other words, when the transmitter sends a signal and this arrives to the receiver bouncing in different objects or walls by different ways, this is the multipath. This effect is shown in the Figure 5.5. This figure shows a simple example where the signal arrives to the receiver trough the direct path and two additional paths (path 1 and path 2), where the signals bounce in different walls.

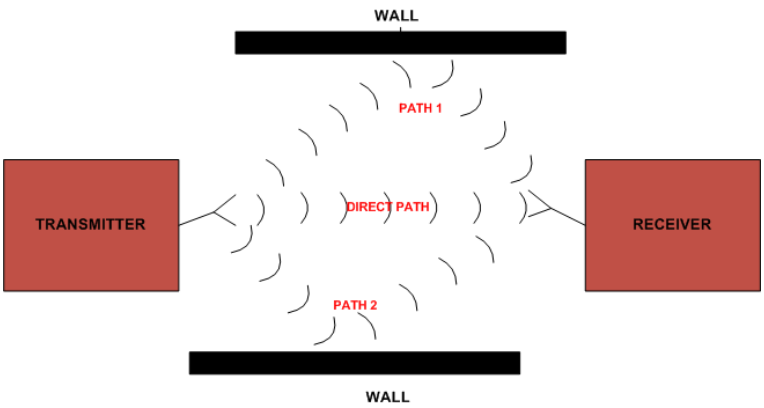


Figure 5.5: Simple example with multipath.

In an outdoor environment the distances between buildings or mountains are long. In contrast, in an indoor environment the distances between walls or columns are short. For this reason, in an indoor environment the multipath is more common. So, in this system the multipath appears easily.

Obviously, the signal that arrives from one path is different of the signal that arrives from the other path, although the transmitted signal is the same.

The signal arrives to the receiver with different power and phase.

Following the formula (5.1), the free space losses depend on the distance. It is very easy to observe that in the direct path the distance between transmitter and receiver is the minimum, and in any other way the distance is higher. As a consequence, the power is less when the signal bounces in a wall or in an object than in the direct path. There are other causes to decrease the power like obstacles.

On the other hand, the signals have a phase. The phase changes If the distance or time of transmission changes. The signal has a different distance and time of transmission in each way. Then, the phase is different in one path or other.

To determine the contribution of the multipath in the received signal is necessary to follow the expression (5.4). Where, $M$ is the contribution in the received signal due to the multipath and $N$ is the number of the received signals in the receiver for the same transmitted signal.

$$M = \sum_{i=0}^{N} L_i H_i S_{transmited} \tag{5.4}$$

The multipath is not necessarily a drawback, sometimes is possible to take benefits. The signal sometimes cannot arrive to the receiver in the direct path. However, the signal can bounce in the walls or columns and this arrives to the receiver using other path.

## 5.5. LOS/NLOS

The signal has to travel a certain distance between the transmitting and receiving antennas. During this way is possible to find obstacles that hind in its objective. Two options are possible. These options are depicted in the Figure 5.6 in a simplest example.

First option is that the signal does not find any obstacle during the transmission. This is said line-of-sight (LOS). On the other hand, the second possibility is that the signal finds an object during the transmission. This is said non-line-of-sight (NLOS).

The system is in an indoor environment. Inside the buildings, as in a warehouse, is easy that the signal finds columns, machines and boxes between other obstacles.

At this point, I have taken into account the two possibilities LOS and

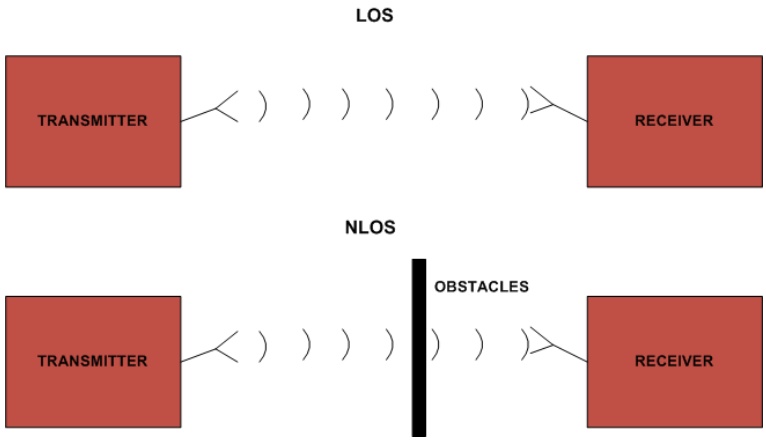


Figure 5.6: LOS and NLOS scenarios.

NLOS. As a consequence, I need the expression for both possibilities. I will explain these formulas in the next section. I have named the channel $h_{LOS}$ when the signal does not find obstacles during transmission and $h_{NLOS}$ in other case.

## 5.6. Rician and Rayleigh distributions

Finally, the most important point to determine the channel is to select its model. Once, the channel model is selected and combining with path losses, interferences and multipath, it is possible to determine the received signal in the RFID reader [2][3][4][13].

Following the previous section, the channel has two options, with or without obstacles. Then, it is necessary a formula (5.5)[13] that combines both possibilities, LOS and NLOS. Therefore, the channel model that I have used a combination of the Rician and Rayleigh distributions that are related by the Rician factor.

$$H = \sqrt{\frac{k}{1+k}} h_{LOS} + \sqrt{\frac{1}{1+k}} h_{NLOS} \tag{5.5}$$

Depending on the value of the Rician factor ($k$) the LOS component or the NLOS component has more or less relevance. The most extreme cases are when $k=0$ and $k \rightarrow \infty$.

When $k=0$, the channel depends only on the NLOS component, as is shown in the expression (5.6). This implies that the impact of the obstacles is

so high to neglect the component of LOS.

$$H = h_{NLOS} \tag{5.6}$$

On the other hand, when $k \to \infty$, the channel depends only on the LOS component. This is described in the formula (5.7). In contrast of the previous case, now the effect of NLOS is neglected.

$$H = h_{LOS} \tag{5.7}$$

These are only the most extreme cases. In a regular scenario the $k$ factor can have any value. Then, in general the channel follows the behaviour of the formula (5.5).

## 5.7. Conclusions

I have observed that there are several challenges that affect in the signal, as free space losses, interferences, multipath and NLOS. To get an expression to determine these effects in the signal is possible using the formulas (5.1), (5.2), (5.4) and (5.5)[13].

As I could observe, the challenges normally affect negatively in the signal. These effects can decrease the power, to modify the phase or to add other signals from the others RFID readers.

On the other hand, not all effects are negative for the signal. For example, the multipath has positive properties. In case of the signal cannot arrive to the receiver in the direct path the signal can arrive to the receiver by other path.

Finally, the channel model is essential to calculate the received signal. In this chapter I have determined the general expression of the channel model that depends on the $h_{LOS}$, the $h_{NLOS}$ and the $k$ factor.

# 6. Simulations

At this point, to simulate the system to find the coordinates of the RFID tag is possible. In this chapter, I will explain the simulation setup. I have used the MATLAB to simulate this system.

The program has been divided in three parts. The first part consists of to simulate the scenario. Secondly, the position of the RFID tag is estimated. Finally, in the third part, the positioning error is calculated.

The simulation of the scenario consists of to calculate the received signal at the RFID reader. In other words, it is necessary to emulate the challenges that I have explained in the Chapter 5. Also, it is necessary to emulate the behaviour of the RFID tag when this receives the signal.

I have divided the second step in two parts. First part consists of obtaining the angle of arrival of the received signal in the RFID reader. In the second part, I have estimated the coordinates of the RFID using trigonometric rules as I have explained in the Chapter 4.

Finally, in the last step, I have studied the accuracy of the results depending on the distribution of the receiving antennas, the level of noise and the Rician factor. However, in this chapter I will explain only how I can calculate the accuracy. In the next chapter, I will show the results, and then, I will discuss the accuracy of these results.

## 6.1. Scenario

### 6.1.1. Initial conditions

First of all, the system is developed in an indoor environment, so, to simulate the scenario I have thought that the scenario is a room. Then, I have designed a simple scenario to estimate the position.

I have defined the position of the RFID tag and the RFID readers to describe the scenario. On the other hand, in order to do a realistic scenario, this system has obstacles inside the room, but the position and number of these obstacles are random. So, I need other considerations to include these obstacles inside the scenario as I will explain in the Section 6.1.3.

Finally, in the Figure 6.1 is depicted a simple scenario in two dimensions and in the Figure 6.2 is shown a possile extension of the scenario in three dimensions. I have considered that the dimensions of the room are 5x5 meters in two dimensions and 5x5x5 meters in three dimensions. In this project, I have focused in a scenario in two dimensions, however, I have commented one possibility to extends this system to three dimensions.

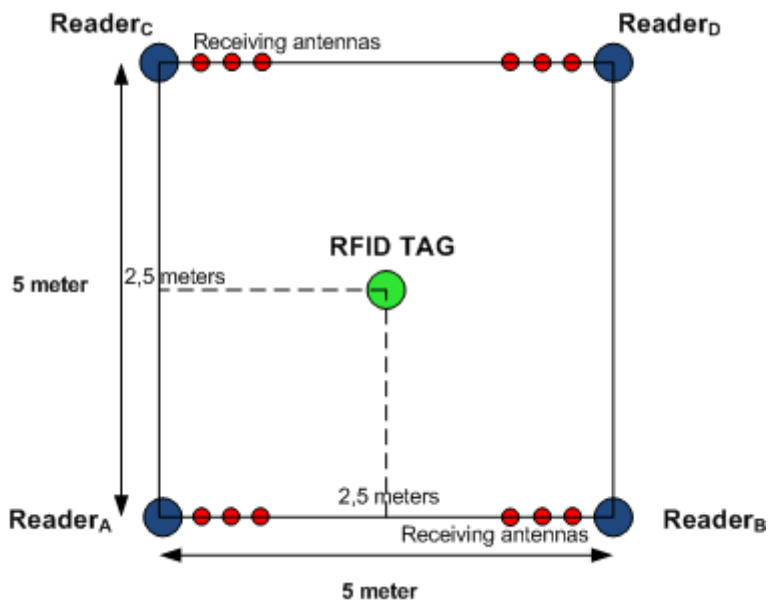


Figure 6.1: Simple scenario in two dimensions.

For clarification, I have used four RFID readers in order to improve the results. Using AoA the system only needs two RFID readers but when the estimated position is out of the room, the system uses the other two RFID

readers, however, at the same time only two RFID readers are used. In the Figure 6.1 is possible to observe that the RFID tag is in the centre of the room and the RFID readers are situated in the corners. Extending the scenario to three dimensions, in the Figure 6.2 is possible to observe the same conditions, the RFID tag is in the centre of the scenario and each RFID reader is situated in the corners.

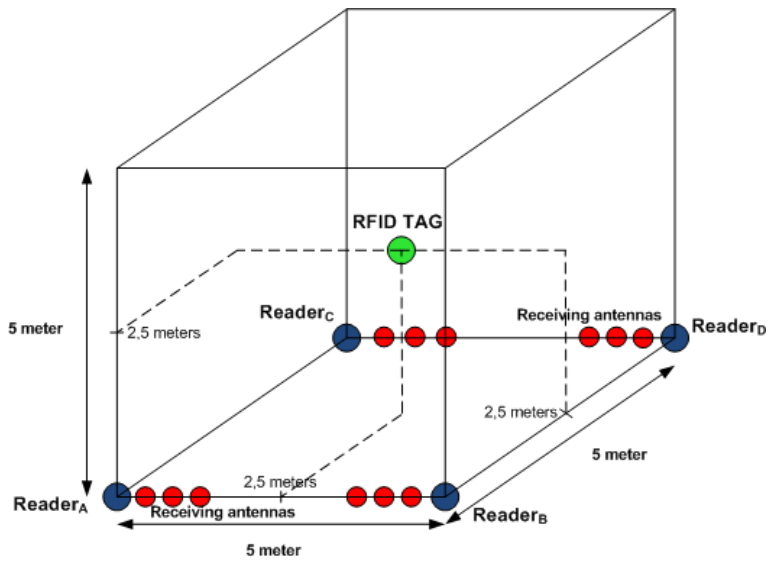


Figure 6.2: Simple scenario in three dimensions.

On the other hand, I have taken into account other initial conditions. First, the frequency that I have applied in this system is 866MHz. Second, I have assumed that the RFID readers do not generate interferences to the others RFID readers.

### 6.1.2. Received signal

The received signal in each RFID reader is expressed as it is shown in the formula (6.1). Where $H$ is the channel model that it is composed by the forward and backward channel, $A$ is the tag signal and $N$ is the Additive White Gaussian Noise (AWGN) [2][3][4][13].

$$S_{Received} = HA + N \tag{6.1}$$

The system is divided in three parts, first the forward channel, second RFID tag and third the backward channel [2][3][4], as is depicted in the Figure

6.3.

The forward and backward channel follow the same type of challenges, free space losses, multipath, interferences and non-line of sight. These challenges can affect differently on the forward and on the backward channel. On the other hand, when the RFID tag receives the signal, this device does a backscatter of the signal, so that, the RRID tag modifies the signal. For these reasons, I have divided the communication in these three parts.

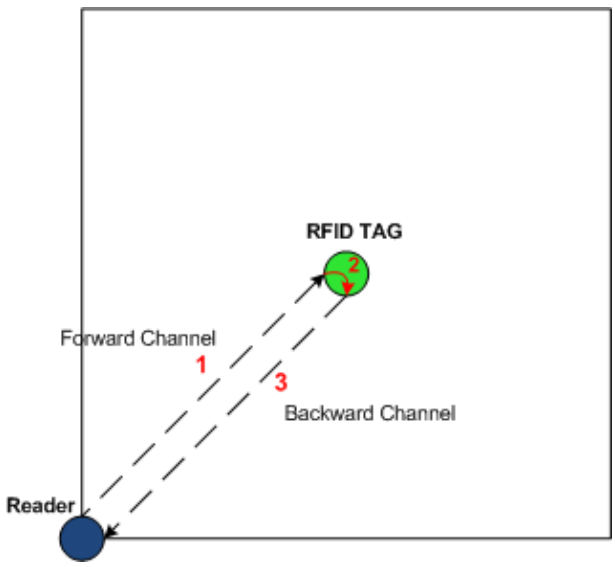


Figure 6.3: Forward channel, RFID tag and backward channel.

#### Forward and backward channel

The forward and the backward channel have a similar behaviour. In contrast, these channels are not exactly the same. To calculate both channels it is necessary to apply the same formulas, but the values of the parameters of these formulas are different depending on the forward and the backward channel. The challenges affect differently in forward channel in front of the backward channel. Then, to obtain the channel model is necessary to calculate the forward and the backward channels separately. Finally, I must multiply both channels to get the full channel of the system as is shown in the formula (6.2). Where, $H^f$ is the forward channel and $H^b$ is the backward channel.

$$H = H^f H^b \tag{6.2}$$

At this moment, I have explained in the Chapter 5 how to calculate the losses in the free space. On the other hand, I have said that I assume that the readers are perfectly isolated in front of interferences. Then, I must explain how to apply the multipath.

To obtain the multipath would be necessary to calculate the channel for each one of the possible paths. I have considered that the system has the direct path and two additional paths, as is shown in the example of the Figure 6.4.

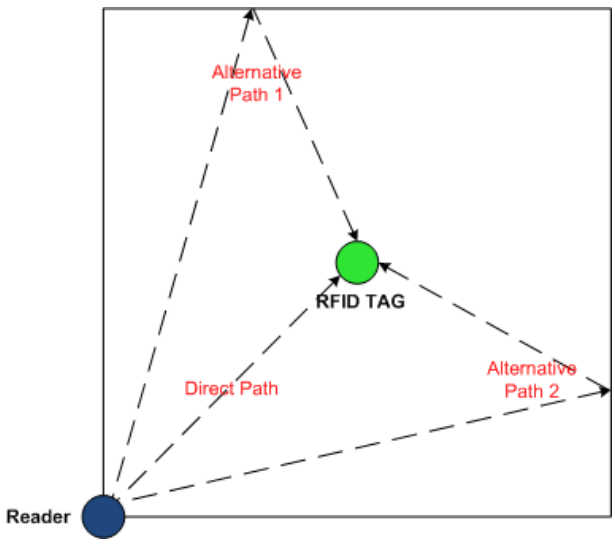


Figure 6.4: Example with two additional paths.

These two alternative paths have two parts. First part is between transmitter and wall and the second part is between wall and RFID tag. Once the channel of each part is obtained, the full channel for this path is the sum of both parts. Finally, the channel is expressed according to the formula (6.3). Where, $H_d$ is the channel for the direct path and $H_1$ and $H_2$ are the channels for the multipath.

$$H = H_d + H_1 + H_2 \tag{6.3}$$

In order to do a realistic scenario with multipath and simplify the operations I have used the combination of the Rician and the Rayleigh distributions. In addition to this, using these distributions I have the contribution of the LOS and NLOS. Then, to get the $H^i$ ($i$ is $f$ or $b$) the formula (6.4)[13] is used.

$$H^i = \sqrt{\frac{k}{1+k}} h_{LOS} + \sqrt{\frac{1}{1+k}} h_{NLOS} \tag{6.4}$$

The value of $k$ depends on the line of sight of the signal. Remember that when $k \rightarrow \infty$ the channel only depends on the LOS and when $k=0$ the channel only depends on the NLOS.
The $h_{LOS}$ follows the expression (6.5).

$$h_{LOS} = \frac{L}{\sqrt{2}} e^{-2j\frac{\pi}{\lambda}\mathbf{ap}} \tag{6.5}$$

Where, $L$ is the losses in the free space. The most important parameters are $\boldsymbol{p}$ and $\boldsymbol{a}$. First, $\boldsymbol{p}$ is the vector that describes the position of the receiver. In case of the forward link $\boldsymbol{p}$ is the position of the RFID tag. On the other hand, in the backward link $\boldsymbol{p}$ is the position of the receiving antenna. Taking into account that each RFID reader has several receiving antennas and consequently it is necessary to calculate the backward channel for each one. Second, $\boldsymbol{a}$ is the steering vector that follows the expression (6.6) [14].

$$\mathbf{a} = \begin{pmatrix} -\sin\theta\cos\phi \\ -\sin\theta\sin\phi \\ \cos\theta \end{pmatrix} \tag{6.6}$$

Where, $\theta$ is the elevation and $\phi$ is the azimuth. These are the angles of arrival of the signal. Then, in the forward link only is necessary to calculate the angles one time for each RFID reader. However, for the backward link is required to calculate these angles for each receiving antenna.

The angles depend on the coordinates of the receiver and the transmitter. To get these angles is necessary to follow the equations (6.7) for the elevation and (6.8) for the azimuth. Where $x$, $y$ and $z$ are the difference between the coordinates of the transmitter and the receiver.

$$\theta = \begin{cases} \arctan(\frac{\sqrt{x^2+y^2}}{z}) & \text{if } z > 0 \\ \frac{\pi}{2} & \text{if } z = 0 \\ \pi + \arctan(\frac{\sqrt{x^2+y^2}}{z}) & \text{if } z < 0 \end{cases} \tag{6.7}$$

$$\phi = \begin{cases} \arctan(\frac{y}{x}) & \text{if } x > 0 \text{ and } y > 0 \\ 2\pi + \arctan(\frac{y}{x}) & \text{if } x > 0 \text{ and } y < 0 \\ \frac{\pi}{2} & \text{if } x = 0 \text{ and } y > 0 \\ -\frac{\pi}{2} & \text{if } x = 0 \text{ and } y < 0 \\ \pi + \arctan(\frac{y}{x}) & \text{if } x < 0 \end{cases} \tag{6.8}$$

Finally, the $h_{NLOS}$ has a random attentions and random phase shift.

#### Tag signal

The RFID reader sends a continuous wave. With this continuous wave the RFID tag is powered up. After the continuous wave, the RFID reader sends the information. This information is codified using the FM0 encoding. The behaviour of the FM0 encoding follows the Figure 6.5.

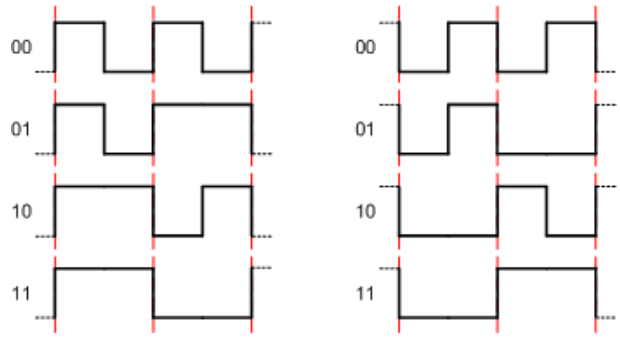


Figure 6.5: FM0 encoding.

When the RFID reader sends a “0” symbol, during half period of the symbol the level is high and during the other half of the period the level is low. In contrast, when the RFID reader sends a “1” symbol, during the full period the level is the same. Also, if the previous symbol finishes with low level, a new symbol starts with high level and vice versa [15].

On the other hand, the reader also sends a preamble before the information. This preamble consists of six bits. After the FM0 encoding the preamble has 12 bits. To send the information, I have used an array of 16 bits that there are transformed to 32 bits using the FM0 encoding. Finally, the signal has 44 bits.

#### Noise

In all communications appears the noise. In this simulation, I have used the Additive White Gaussian Noise (AWGN). This type of noise has a Gaussian power spectral density. Their average power is 0. It is a white noise because does not have any correlation with the time.

## 6.2. Estimated position

First of all, to estimate the position of the RFID tag I have had to divide this process in two parts. First part consists of to obtain the angle of arrival starting with the received signal. I have used the MUltiple SIgnal Classification (MUSIC) algorithm to get the angle of arrival. Second part consists of to use the angle of arrival to calculate the position of the RFID tag.

### 6.2.1. MUSIC algorithm

To use the AoA technique I have needed to use the MUSIC algorithm to find the angles. The MUSIC algorithm consists of four steps to get the angle of arrival. To use this algorithm is necessary an array of receiving antennas. The angle of arrival $\Theta$ is measured as is shown in the Figure 6.6 [16][17][18].

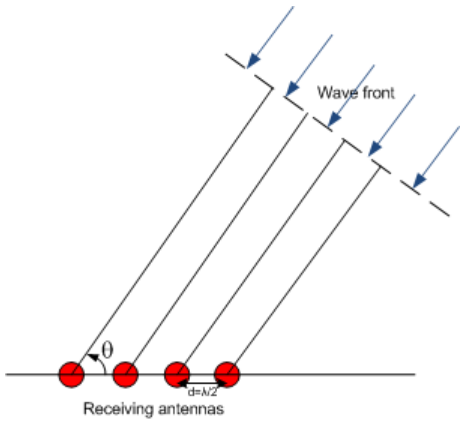


Figure 6.6: Array of receiving antennas.

First step is to calculate the autocorrelation matrix ($\mathbf{R_{xx}}$) of the signal. This $\mathbf{R_{xx}}$ is an $MxM$ matrix, where $M$ is the number of the receiving antennas in the array. The correlation matrix contains $L$ of incoming signals and it is expressed as (6.9)[16].

$$\mathbf{R_{xx}} = \mathbf{SDS}^H + \sigma^2\mathbf{I} \tag{6.9}$$

Where, $\mathbf{D}$ is the signal power matrix (6.10)[16] and $\mathbf{S}$ is the direction matrix (6.11)[16]. In the direction matrix, $\beta$ is the delay between sensor elements. On the other hand, $\sigma$ is the variance of the Gaussian White Noise.

$$\mathbf{D} = diag[P_1, P_2, \ldots, P_L] \tag{6.10}$$

$$\mathbf{S} = \begin{pmatrix} 1 & 1 & \dots & 1 \\ e^{j\beta(\theta_1)} & e^{j\beta(\theta_2)} & \dots & e^{j\beta(\theta_L)} \\ \vdots & \vdots & \vdots & \vdots \\ e^{j(M-1)\beta(\theta_1)} & e^{j(M-1)\beta(\theta_2)} & \dots & e^{j(M-1)\beta(\theta_L)} \end{pmatrix} \tag{6.11}$$

The second step consists of to find the eigenvalues and eigenvectors. Where, $\mathbf{R_{xx}}$ matrix has $M$ eigenvalues and $\mathbf{SDS^H}$ has $L$ eigenvalues. On the other hand, $\mathbf{q_1}$, $\mathbf{q_2}$, ..., $\mathbf{q_M}$ are the eigenvectors of the autocorrelation matrix. I can assume that the number of receiving antennas is higher than or equal to the incoming signals ($M \geq L$). In particular, in this system $L$=1 because I have only used one RFID tag.

Using the eigenvalues and eigenvectors, the finality of the third step is to separate $\mathbf{R_{xx}}$ in the signal subspace and the noise subspace ($\mathbf{Q_N}$). These subspaces are formed by the eigenvectors $\mathbf{q_1}$, $\mathbf{q_2}$, ..., $\mathbf{q_M}$. The firsts $L$ eigenvectors correspond on the signal subspace and the remaining $M$-$L$ eigenvectors correspond on the noise subspace as is possible to observe in the expression (6.12)[16]. In this case, as $L$=1 the $\mathbf{Q_N}$ are formed by $\mathbf{q_2}$, ..., $\mathbf{q_M}$.

$$\mathbf{R_{xx}q_i} = \sigma^2\mathbf{q_i} \qquad i \geq L+1 \tag{6.12}$$

Finally, the last step consists of to apply the noise subspace to get the angle of arrival. The signal subspace and noise subspace are orthogonally. When a directional vector of the signal is projected on the noise subspace the result is zero. Combining the formulas (6.9)[16] and (6.12)[16] is easy to observe that the signal subspace and noise subspace are orthogonal. This is shown in the formula (6.13)[16].

$$\mathbf{SDS}^H q_\mathbf{i} = 0 \qquad i \geq L+1 \tag{6.13}$$

Then, the angle of arrival is obtained following the formula (6.14)[16]. Where, $\mathbf{v}$ is the steering vector.

$$P_{MUSIC} = ||\mathbf{Q_N^H v}||^2 \tag{6.14}$$

To obtain the angle of arrival is necessary to apply the formula (6.14)[16] for each angle between 0° and 360°. Then, I obtain the power of the received signal for each angle. The result that I get applying the MUSIC algorithm is shown in one example in the Figure 6.7. In this example I expected that the angle of arrival was 45° and in the Figure 6.7 is possible to observe that the

minimum power is for 45°.

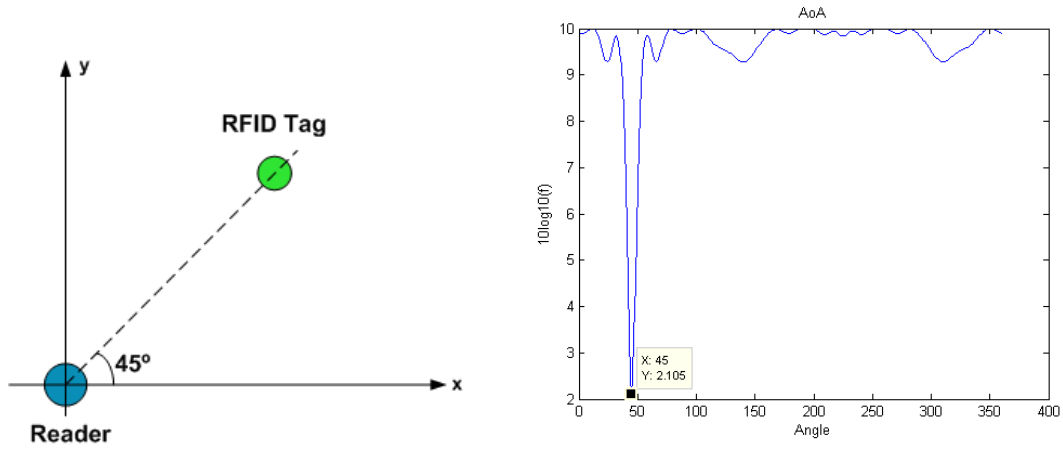


Figure 6.7: Example using MUSIC algorithm in 2D.

Extending the MUSIC algorithm to three dimensions I have obtained the elevation and azimuth angles. To obtain the azimuth angle, the process is the same as in case of 2D, I must apply the formula (6.14)[16] for each angle between 0° and 360° in the plane $x$-$y$. To get the elevation angle I must apply the formula (6.14)[16] for each angle between 0° and 180° respect $z$ axis. The result to apply the MUSIC algorithm in 3D is shown in the Figure 6.8.

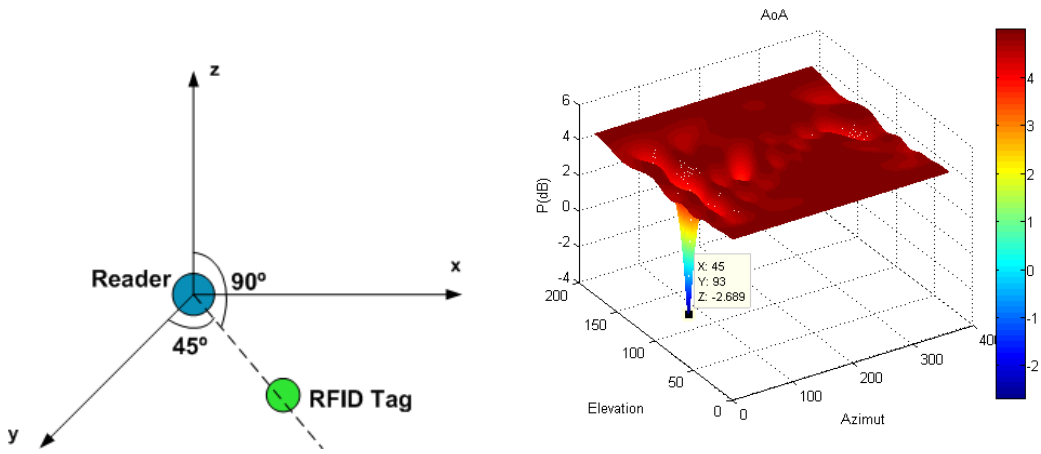


Figure 6.8: Example using MUSIC algorithm in 3D.

### 6.2.2. Localization

To obtain the position of the RFID tag in 2 dimensions I need to apply the formulas of the Section 4.2.2. Using MUSIC algorithm I get the angles $\theta_A$ and $\theta_B$ as is shown in the Figure 6.9.

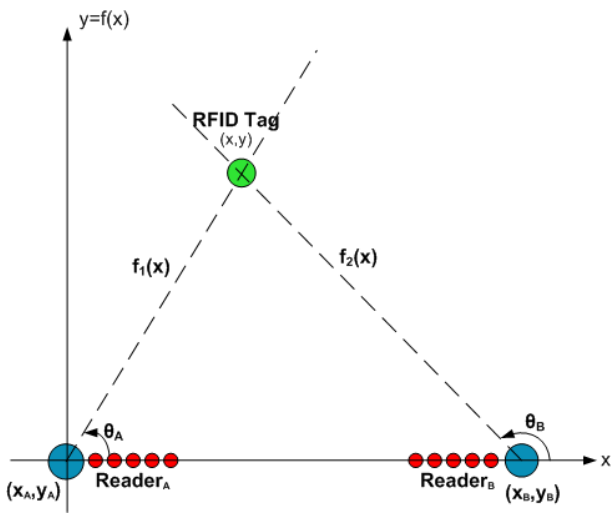


Figure 6.9: Angle of arrival.

After that, I meet the coordinates of the RFID readers ($x_A$,$y_A$) and ($x_B$,$y_B$) and their respective angles of arrival $\theta_A$ and $\theta_B$. Finally, applying the formulas (6.15) and (6.16) I obtain the estimated position of the RFID reader.

$$x = \frac{y_B - y_A + x_A tan\Theta_A - x_B tan\Theta_B}{tan\Theta_A - tan\Theta_B} \tag{6.15}$$

$$y = xtan\Theta_A + y_A - x_A tan\Theta_A \tag{6.16}$$

In case of 3 dimensions, the lines surely do not intersect in one point. Then, the system has an uncertainty area. In order to simplify the calculations, in 3 dimensions I have only found the angles of arrival and the study of accuracy is related with the angles instead of the estimated position.

## 6.3. Accuracy

The last point of the simulations is to calculate the errors in the results. To evaluate the accuracy in two dimensions is necessary to get the error between the real position of the RFID tag and the estimated position. To obtain this

error I have used the root mean square error (6.17). Where, $n$ is the number of measures, (x,y) is the real position of the RFID tag and ($\hat{x}_i$,$\hat{y}_i$) are the estimated coordinates.

$$\epsilon = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(\hat{x}_i - x)^2 + (\hat{y}_i - y)^2} \tag{6.17}$$

On the other hand, also is interesting in the study of the accuracy to calculate the average and the range of confidence of the error. To calculate these is necessary to simulate several times the system for different parameters of the channel. The average of the error is calculated adding the errors of all iterations and dividing by this number of iterations. The confidence implies to establish a percentage and it determines a range of the error values and it excludes the extreme results.

## 6.4. Conclusions

I have emulated the scenario in the first step. After that, with the received signal I get the position of the RFID tag. In the last point, I can study the accuracy of the results.

Using the combination of the Rician and Rayleigh distributions the challenges that I have explained in the Chapter 5 are applied. The multipath and NLOS depend on the value of the Rician factor and the free space losses are also included.

It is important to note that in the backward channel, the system has to calculate the channel for each receiving antenna.

In order to apply the AoA technique I have had to use the MUSIC algorithm to find the angles.

Finally, using MUSIC algorithm is necessary that the number of receiving antennas is higher than the number of incoming signals. If the number of incoming signals is higher than the number of receiving antennas the subspace of noise is null.

# 7. Results

First of all, I have explained the elements of the system, the localization techniques, the channel model and the implementation of the system. Now, to study different cases is possible. The receiving antennas could be distributed of different ways. The scenario could have more or less level of noise and it could have more or less line of sight. On the other hand, although using AoA technique is only needed two RFID readers I have used four readers in the simulations in order to improve the results. I have located each one of these readers in one different corner.

I have compared different geometrical arrangements of the receiving antennas and I have chosen the best option. After that, I have studied the effect of the noise and the Rician factor in the system.

## 7.1. Comparison between geometrical arrangement of receiving antennas

I have compared four different geometrical arrangements of the receiving antennas. First geometrical arrangement is in a straight line following the wall of the room (Figure 7.1), the second geometrical arrangement is in a straight line with 45° respect the wall (Figure 7.2), the third geometrical arrangement is to cover the corner dividing the receiving antennas in two straight lines (Figure 7.3), one for each wall, and the fourth geometrical arrangement is forming a quarter of circle (Figure 7.4). In all cases, the receiving antennas are separated

by $\lambda/2$.

In this moment I have studied which of these configurations have the best performance for this system. To determine the best option I have assumed that the system is under low level of noise and also the system is in case of perfectly line of sight.

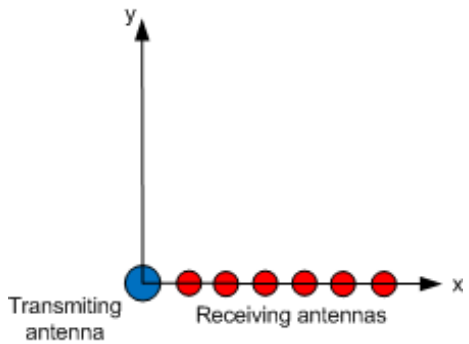


Figure 7.1: Distribution of receiving antennas following the wall (First geometrical arrangement).

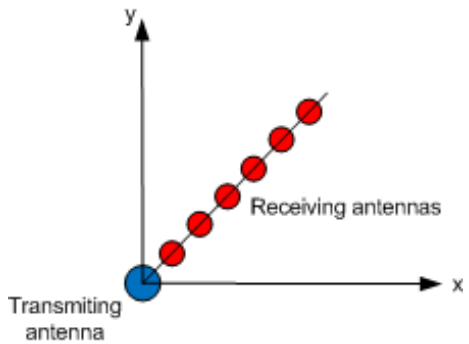


Figure 7.2: Distribution of receiving antennas with 45° respect the wall (Second geometrical arrangement).

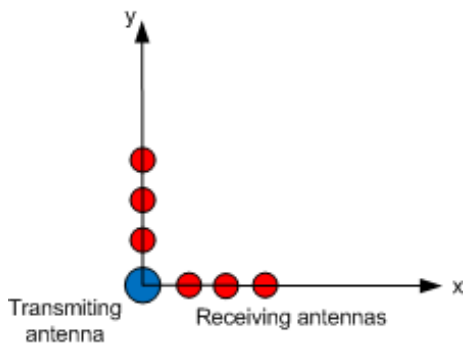


Figure 7.3: Distribution of receiving antennas covering the corner (Third geometrical arrangement).

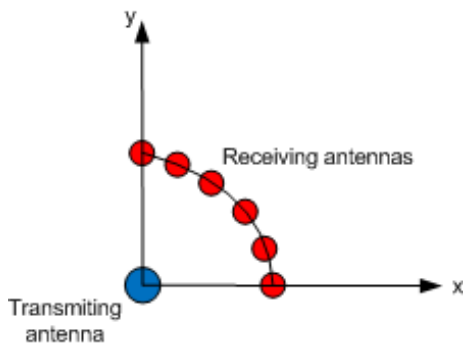


Figure 7.4: Distribution of receiving antennas forming a quarter of circle (Fourth geometrical arrangement).

First I have studied the difference of the obtained results using the different geometrical arrangements in some points of the room. Assuming that the RFID tag is situated in the coordinates $x$=*1m* and $y$=*2.5m* the estimated position for the different geometrical arrangements are shown in the Figures 7.5, 7.6, 7.7 and 7.8. There are more figures for different positions of the RFID tag in the Appendix A. The distance between the estimated and the real position of the RFID tag is the error.

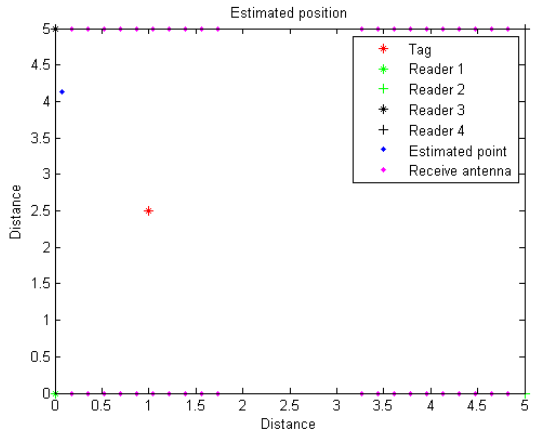


Figure 7.5: Estimated position for the first geometrical arrangement (x=1m y=2.5m).

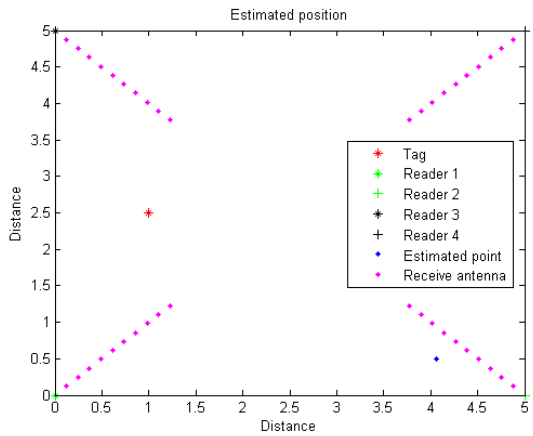


Figure 7.6: Estimated position for the second geometrical arrangement (x=1m y=2.5m).

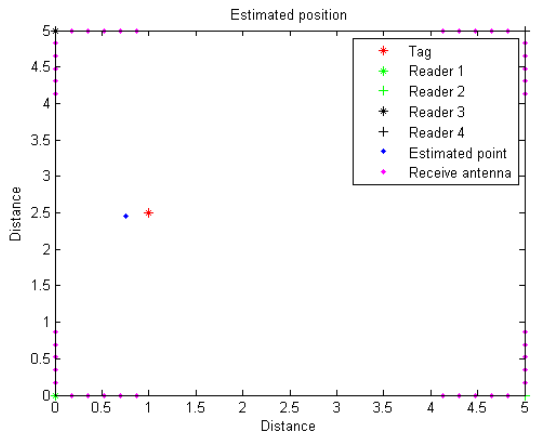


Figure 7.7: Estimated position for the third geometrical arrangement (x=1m y=2.5m).

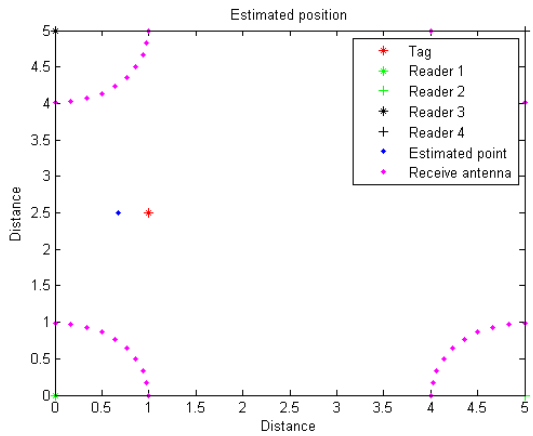


Figure 7.8: Estimated position for the fourth geometrical arrangement (x=1m y=2.5m).

To compare better these four different geometrical arrangements I have measured the root mean square error for all possible positions of the RFID tag inside the room. I have assumed that the RFID tag is not just in the wall and consequently I have started the scan with a certain distance from the wall.

In addition to this, to scan all the possible positions of the RFID tag in the room, I have assumed a separation of two different position of 0.1m. Then, for each geometrical arrangement of the antennas, the respective results are shown in the Figure 7.9, Figure 7.10, Figure 7.11 and Figure 7.12.

To calculated the average rmse, I have measured the error in the estimated position several times for one position of the RFID tag. After that, I have applied the rmse. Once, I have measured the error in one position I put the RFID tag in other position and I have calculated the error in each one of the different possible posisiton of the RFID tag.

For the first and second geometrical arrangements the error is very high respect with the third and the fourth geometrical arrangements. With these results the first and second geometrical arrangements are discarded. With third and fourth distribution the error is low in a high number of positions of the RFID tag. However, in some points with these geometrical arrangements the error is a little bit higher.

The results for the third and fourth geometrical arrangements are more or less the same. To determine the best option I have compared these distributions using the average of rmse for different positions of the RFID tag that is depicted in the Figure 7.13.

For clarification, in this figure the axis $x$ represent the number of the geometrical arrangement following the order in which I have presented these.

In the Figure 7.13 is confirmed that the first and second geometrical arrangements are not good for this system.

On the other hand, the third geometrical arrangement has less average of error and its confidence interval is maintained below of the error of the others geometrical arrangements. Finally, the best geometrical arrangement of the receiving antennas is the third option. From now, I have only used the third geometrical arrangement of the receiving antennas.

To extend the system to three dimensions should be necessary to add more receiving antennas in the $z$ axis as is shown in the Figure 7.14. From this project I have studied the accuracy only in two dimensions.

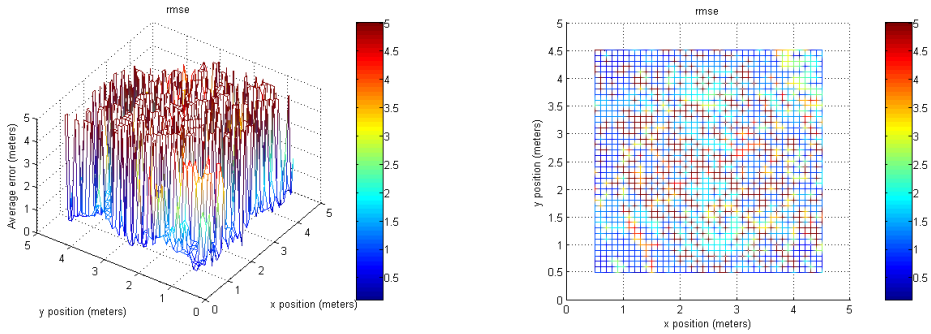


Figure 7.9: Error using the first distribution of the receiving antennas.

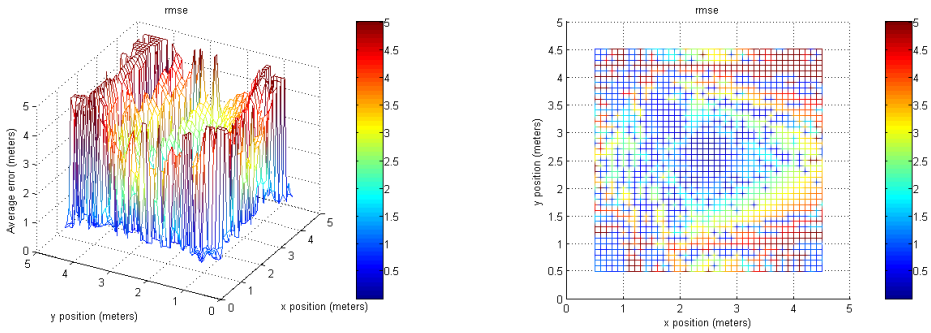


Figure 7.10: Error using the second distribution of the receiving antennas.

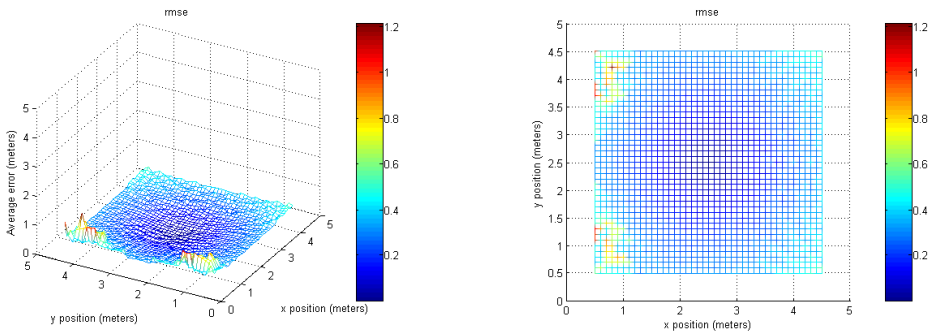


Figure 7.11: Error using the third distribution of the receiving antennas.

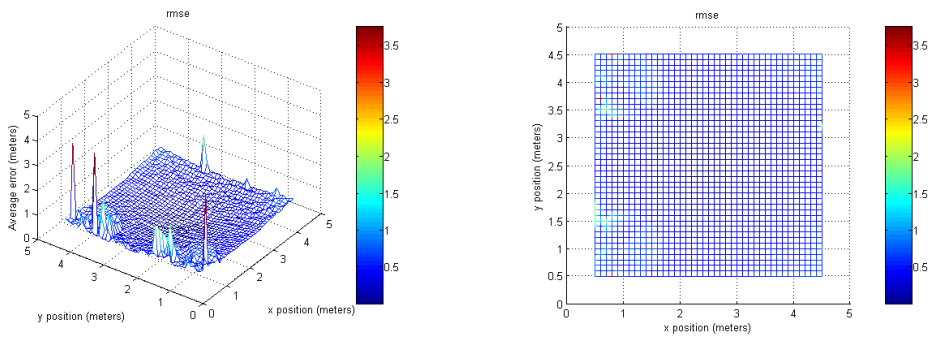


Figure 7.12: Error using the fourth distribution of the receiving antennas.

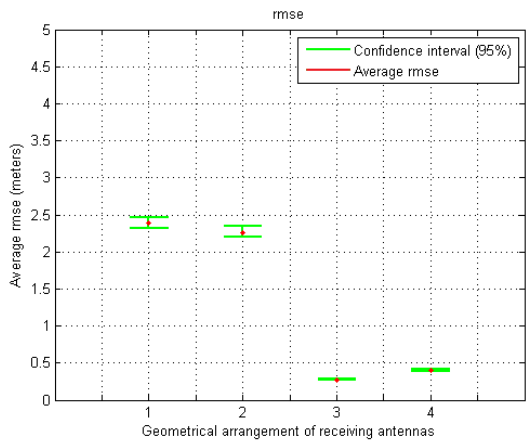


Figure 7.13: Rms error to compare the different distributions.

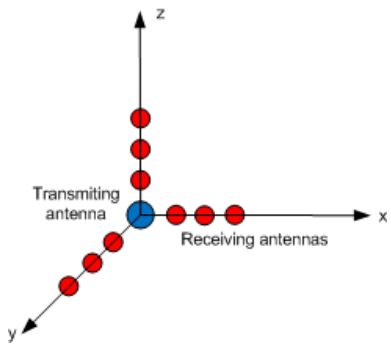


Figure 7.14: Distribution of the receiving antennas in 3D.

## 7.2. The error and distance

In the Section 5.2, I have studied the free space losses. I have observed that when the dimensions of the room are larger and the separation between readers increase the error is higher.

To study the effect of the distance in the system I have compared the confidence interval of error for different dimensions of the room (Figure 7.15). I have compared the results for a room of 5x5m, 10x10m, 15x15m and 20x20m. In the Figure 7.15 I have observed that the average error increase when the dimensions of the room increases. Then, the error increases with the distance.

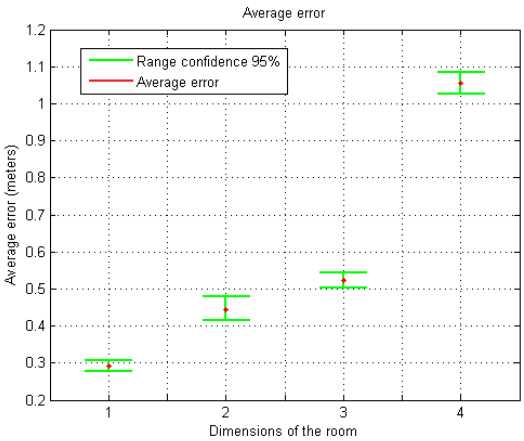


Figure 7.15: Rms error to compare different distances.

## 7.3. The influence of the noise in the system

In the communications the noise always appears. In this system, I have used the AWGN to simulate the noise. To study the effect of the noise in the system I have observed the evolution of the error depending of the Signal to Noise Ratio (SNR). I have simulated from *SNR=-20dB* to *SNR=20dB*, increasing 5dB in each step. In the same way of the previous section, I have measured the average error for different positions of the RFID tag.

In the Figures 7.16, 7.17, 7.18 and 7.19 the effect of the noise is shown. When the *SNR* increases the error decreases. Obviously, when the level of noise is high the signal suffers more distortion than when the level of noise is low.

More specifically, I have studied the effect of noise in the system calculating the average error for different levels of the *SNR*. In the Figure 7.20 is shown that from *SNR*$\geq$*5dB* the position of the RFID tag is estimated with an error lower than 0.3*cm*.

After that, I have situated the RFID tag in the center of the room and I have calculated the average error for different level of the *SNR*. In the Figure 7.21, I have observed that from *SNR*$\geq$*-10dB* the position of the RFID tag is perfectly estimated.

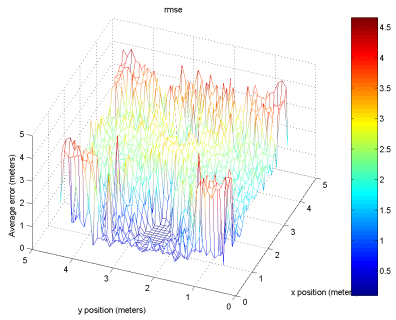


Figure 7.16: Localization error with SNR=-20dB.

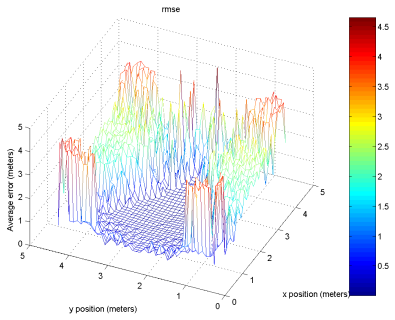


Figure 7.17: Localization error with SNR=-10dB.

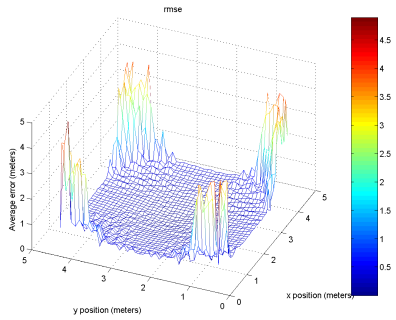


Figure 7.18: Localization error with SNR=0dB.

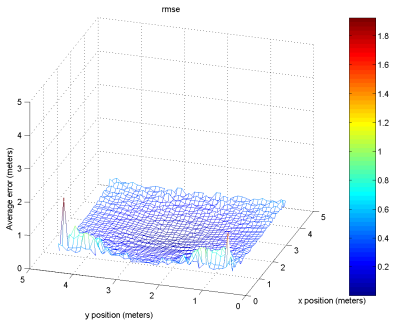


Figure 7.19: Localization error with SNR=10dB.

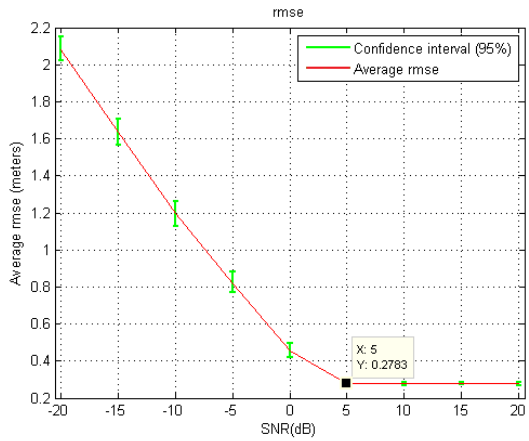


Figure 7.20: Rms error to compare different levels of SNR.

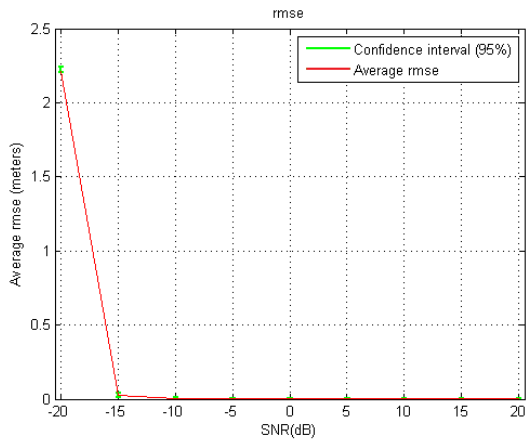


Figure 7.21: Rms error to compare different levels of SNR with RFID in the ceter of the room.

## 7.4. The influence of the strength of LOS component in the system

In a real scenario the system has noise, multipath and NLOS. Then to study the Rician factor I have simulated the system for different values of the Rician factor combining with *SNR=5dB*.

Now, from the Figure 7.22 to Figure 7.25 I can observe that when the Rician factor increases the error of localization decreases. In other words, in case of the system is in NLOS, there are obstacles between antennas, to estimate the position is not possible. In contrast, in case of the system is in

LOS, there are not obstacles between antennas, the position is estimated with less error.

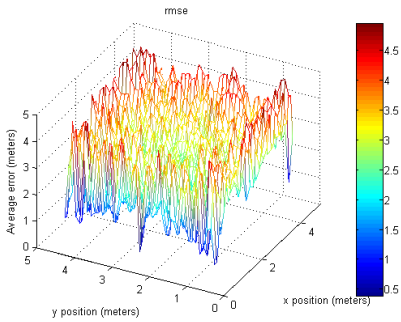


Figure 7.22: Localization error with SNR=5dB and k=-10dB.

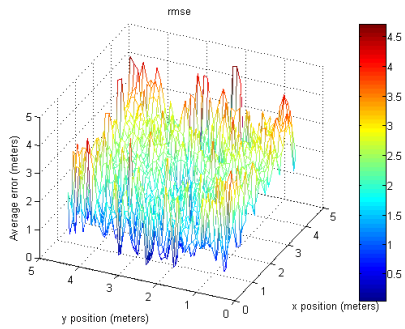


Figure 7.23: Localization error with SNR=5dB and k=-4dB.

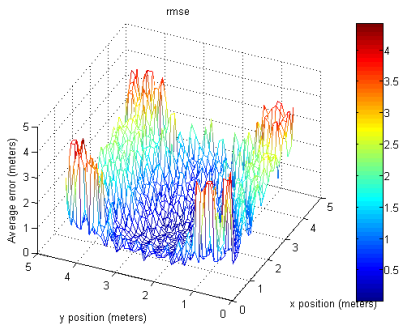


Figure 7.24: Localization error with SNR=5dB and k=4dB.

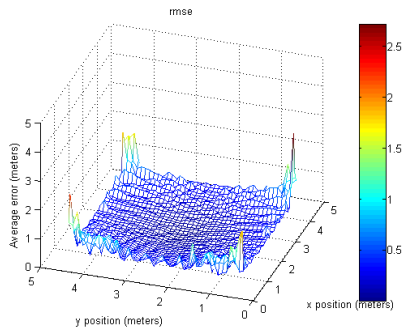


Figure 7.25: Localization error with SNR=5dB and k=10dB.

I have simulated also the system to study the effect of the Rician factor for different values of *SNR* (from *SNR=-20dB* to *SNR=20dB*). These simulations are in the Appendix B, C, D and E. In all cases I have observed that when the Rician factor increases the error of the estimated position decreases. In general, when the levels of $k$ is low the error is high, but the system needs a minimum level of *SNR* and $k$ to estimate correctly the position.

To observe better the effect of the $k$ I have calculated the average of rmse. In the Figure 7.26 is shown that from $k \geq 10dB$ the position of the RFID tag is estimated with an error lower than $0.6cm$.

Finally, I have situated the RFID tag in the center of the room and I have calculated the average error for different level of the $k$. In the Figure 7.27,

I have observed that from $k \geq 0dB$ and $SNR=5dB$ the position of the RFID tag is perfectly estimated.

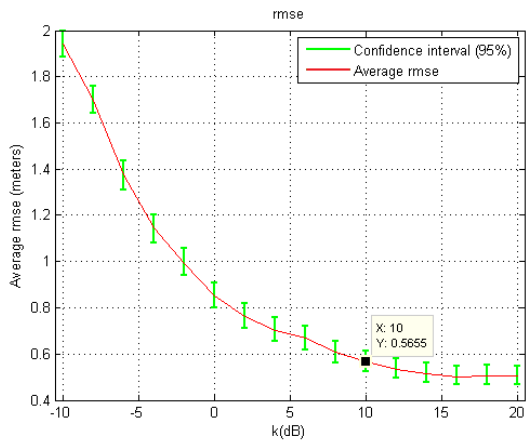


Figure 7.26: Rms error to compare different levels of k.

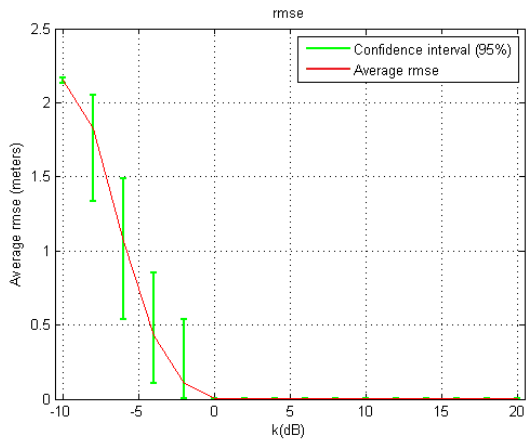


Figure 7.27: Rms error to compare different levels of k with RFID in the ceter of the room.

# 8. Conclusions

The system that I have studied can be applied in an indoor environment. This system needs one RFID tag and two RFID readers to obtain the position of this RFID tag.

There are several techniques to get the position of the RFID tag. I have studied three of these techniques (RSS, TDoA and AoA) and I can conclude that the AoA technique is the best technique for this system. Using AoA only two RFID readers are needed. In addition to this, in two dimensions this technique does not create areas of uncertainty like could happen with RSS and TDoA.

The signal is affected by several challenges. These challenges are losses of free space, multipath, NLOS and interference. In order to simplify the system, I have assumed that the antennas are perfectly isolated in front of the carrier leakage and the RFID readers are enough separated and it does not generate interferences. To simulate these challenges in MATLAB I have used a combination of Rayleigh and Rician distributions. This channel models the multipath and NLOS using the Rician factor and also includes the losses of the free space.

I have observed that the multipath could have advantages in the system. Sometimes, in the direct path could appear objects and the signal cannot arrive to the receiver. However, this signal can bounce in the walls and arrives to the receiver by an alternative path. On the other hand, to simulate the multipath I have used a combination of Rayleigh and Rician distributions because is more realistic.

Using AoA technique I have needed to use the MUSIC algorithm. To calculate the angle of arrival with MUSIC algorithm the RFID reader needs several receiving antennas. I have used several geometrical arrangements of the receiving antennas. I have observed that the geometrical arrangement with best performance is to put the antennas covering the corner (third geometrical arrangement).

In the results I have observed that when the distance increases the error is higher. Also with the results I can conclude that when the *SNR* and Rician factor increase the error decreases. More specifically, from a *SNR=5dB* and under LOS condition, the average error is maintained lower than $0.3cm$. This is because in the corners the error is higher because I have used MUSIC algorithm. When the RFID tag is situated in the center of the room, from a *SNR=-10dB* the position is perfectly estimated.

Finally, with a *SNR=5dB* I have observed the influence of the Rician factor. From *k=-10dB* the error decreases slowly and the average error is lower than $0.6cm$. When the RFID tag is situated in the center of the room and *SNR=5dB*, from *k=0dB* the position is perfectly estimated.

# Acknowledgment

This work has been funded by the Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility, and its industrial partner Infineon Technologies. The financial support by the Federal Ministry of Economy, Family and Youth and the National Foundation for Research, Technology and Development is gratefully acknowledged.

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[17] Claudio A.Lopez Miranda, Carlos Alberto Brizuela Rodriguez, David H. Covarruvias Rosales "Algoritmo Genetico Estocastico Modificado (StGA2) aplicado a comunicaciones moviles".

[18] Andy Vesa "Direction of Arrival Estimation using MUSIC and Root - MUSIC Algorithm".

# Appendix A.

# Estimated positions for different distributions of the receiving antennas

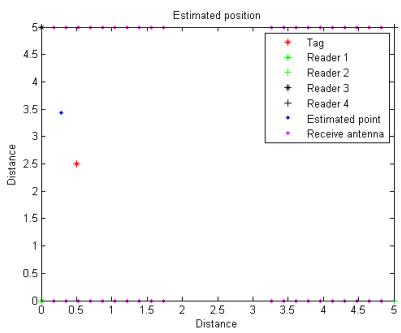


Figure A.1: Estimated position for the first distribution (x=0,5m y=2.5m).

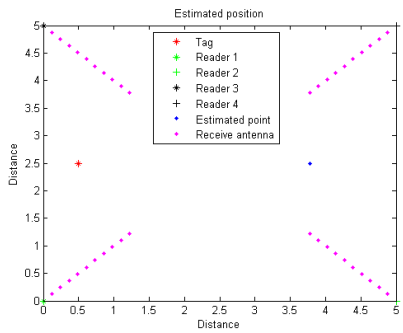


Figure A.2: Estimated position for the second distribution (x=0,5m y=2.5m).

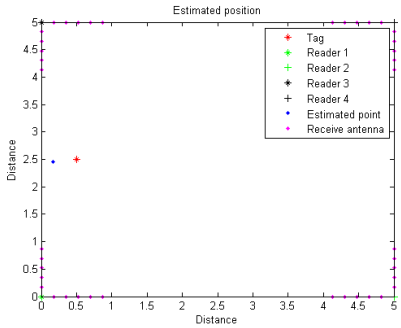


Figure A.3: Estimated position for the third distribution (x=0,5m y=2.5m).

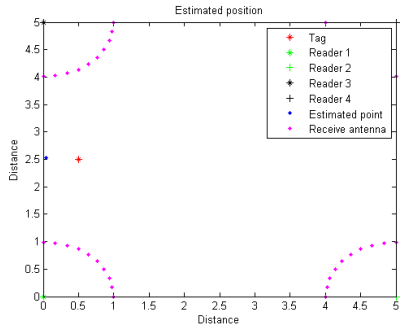


Figure A.4: Estimated position for the fourth distribution (x=0,5m y=2.5m).

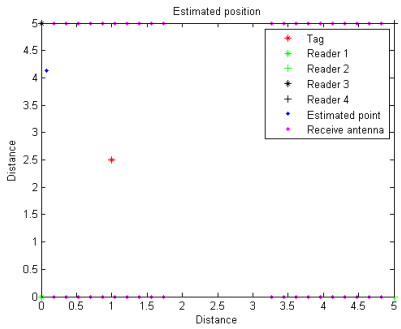


Figure A.5: Estimated position for the first distribution (x=1m y=2.5m).

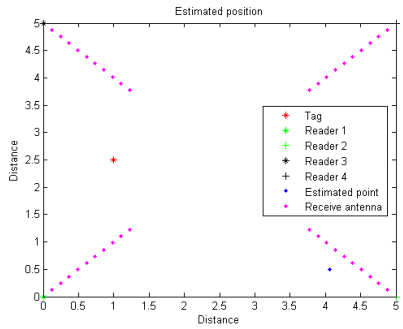


Figure A.6: Estimated position for the second distribution (x=1m y=2.5m).

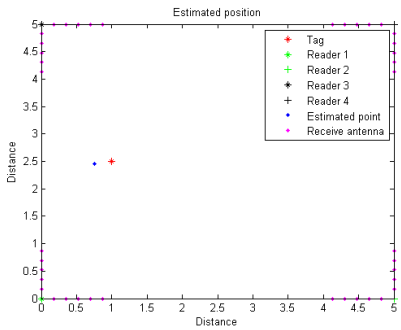


Figure A.7: Estimated position for the third distribution (x=1m y=2.5m).

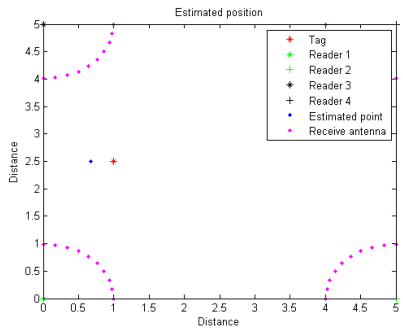


Figure A.8: Estimated position for the fourth distribution (x=1m y=2.5m).

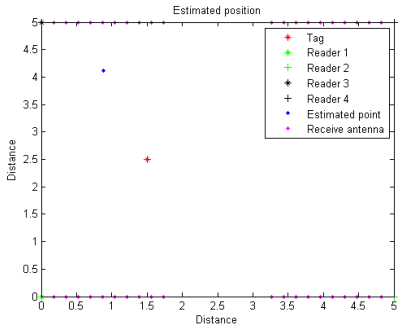


Figure A.9: Estimated position for the first distribution (x=1,5m y=2.5m).

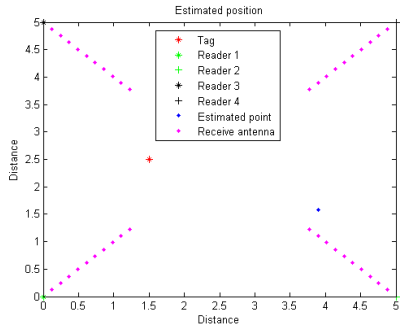


Figure A.10: Estimated position for the second distribution (x=1,5m y=2.5m).

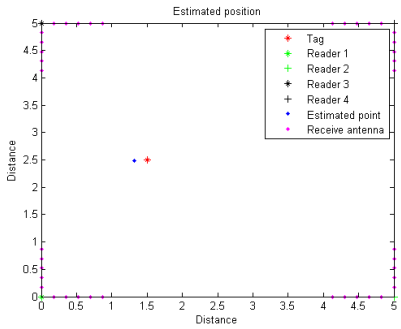


Figure A.11: Estimated position for the third distribution (x=1,5m y=2.5m).

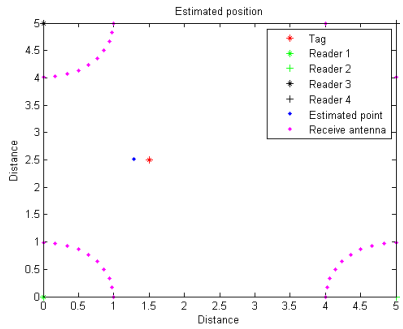


Figure A.12: Estimated position for the fourth distribution (x=1,5m y=2.5m).

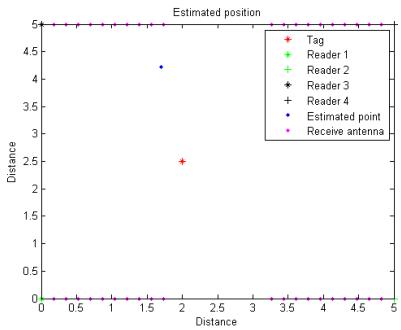


Figure A.13: Estimated position for the first distribution (x=2m y=2.5m).

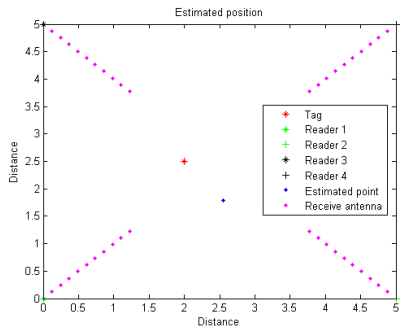


Figure A.14: Estimated position for the second distribution (x=2m y=2.5m).

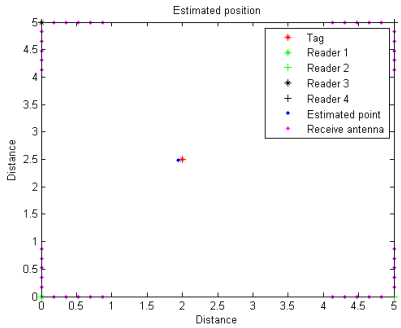


Figure A.15: Estimated position for the third distribution (x=2m y=2.5m).

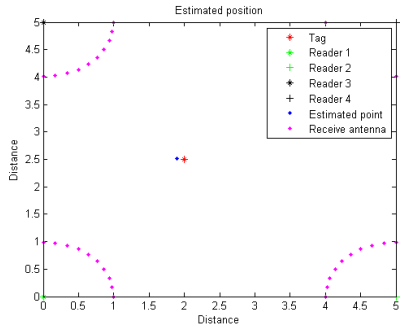


Figure A.16: Estimated position for the fourth distribution (x=2m y=2.5m).

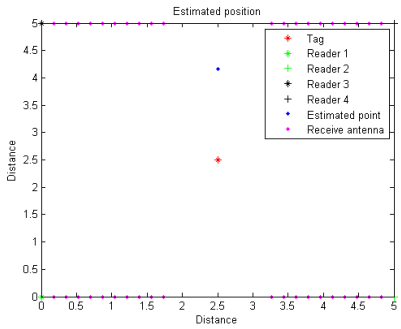


Figure A.17: Estimated position for the first distribution (x=2,5m y=2.5m).

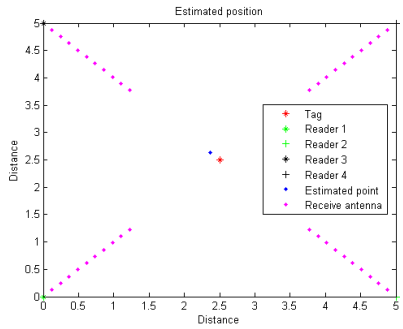


Figure A.18: Estimated position for the second distribution (x=2,5m y=2.5m).

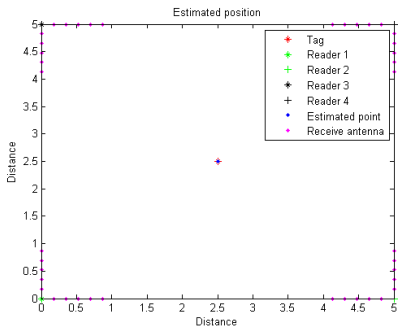


Figure A.19: Estimated position for the third distribution (x=2,5m y=2.5m).

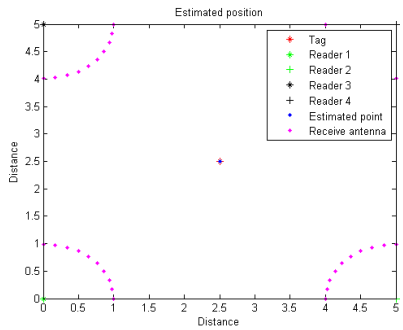


Figure A.20: Estimated position for the fourth distribution (x=2,5m y=2.5m).

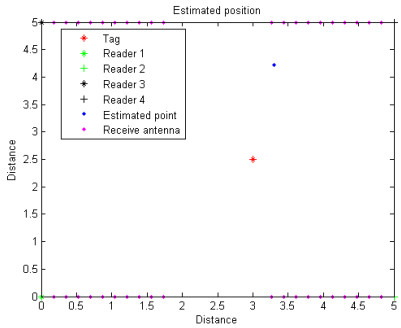


Figure A.21: Estimated position for the first distribution (x=3m y=2.5m).

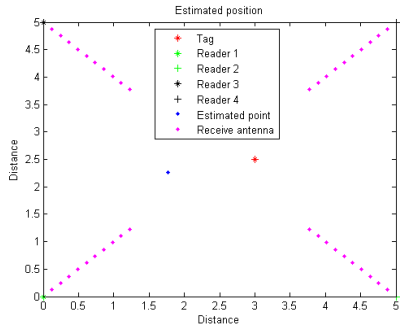


Figure A.22: Estimated position for the second distribution (x=3m y=2.5m).

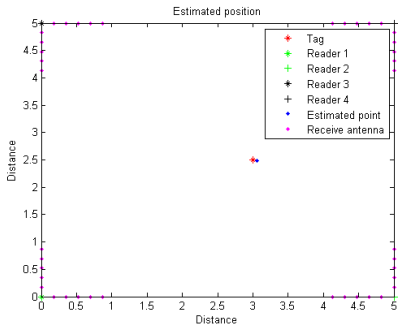


Figure A.23: Estimated position for the third distribution (x=3m y=2.5m).

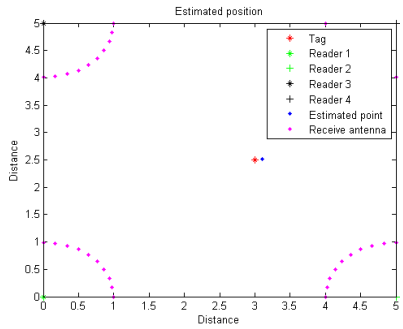


Figure A.24: Estimated position for the fourth distribution (x=3m y=2.5m).

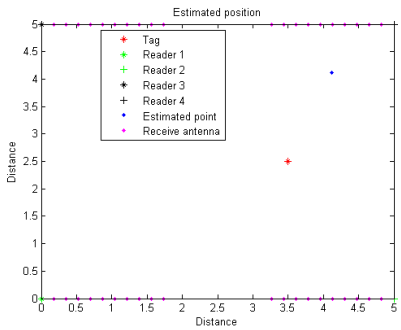


Figure A.25: Estimated position for the first distribution (x=3,5m y=2.5m).

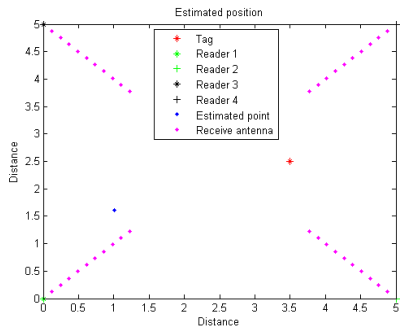


Figure A.26: Estimated position for the second distribution (x=3,5m y=2.5m).

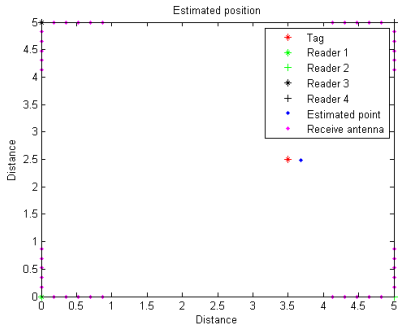


Figure A.27: Estimated position for the third distribution (x=3,5m y=2.5m).

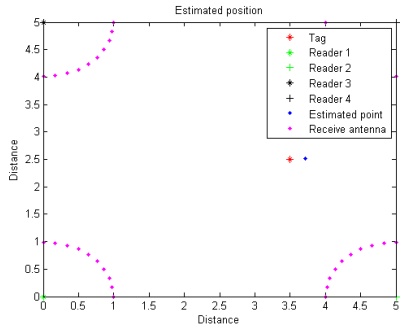


Figure A.28: Estimated position for the fourth distribution (x=3,5m y=2.5m).

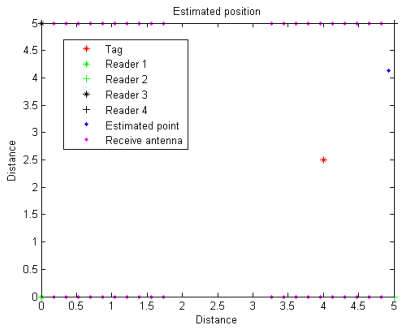


Figure A.29: Estimated position for the first distribution (x=4m y=2.5m).

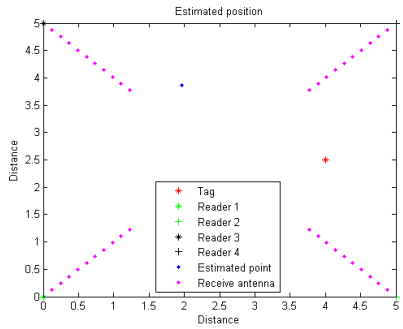


Figure A.30: Estimated position for the second distribution (x=4m y=2.5m).

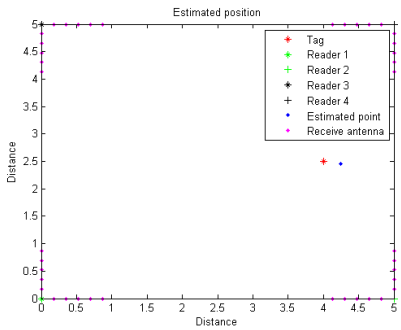


Figure A.31: Estimated position for the third distribution (x=4m y=2.5m).

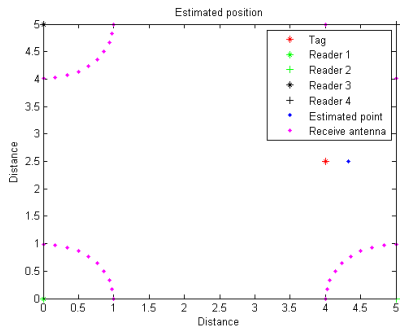


Figure A.32: Estimated position for the fourth distribution (x=4m y=2.5m).

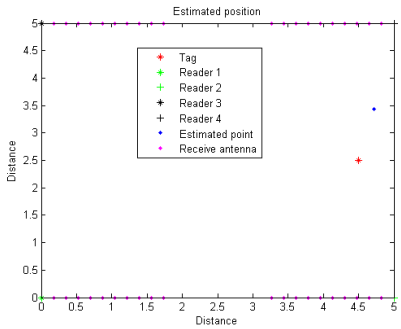


Figure A.33: Estimated position for the first distribution (x=4,5m y=2.5m).

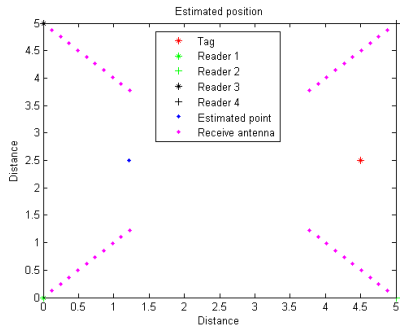


Figure A.34: Estimated position for the second distribution (x=4,5m y=2.5m).

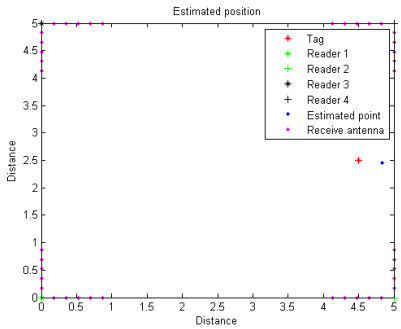


Figure A.35: Estimated position for the third distribution (x=4,5m y=2.5m).

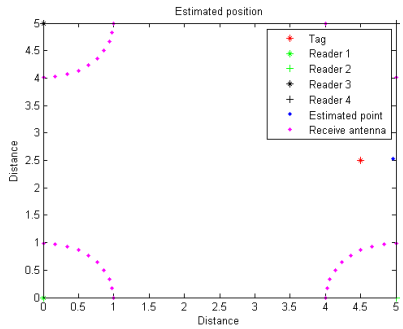


Figure A.36: Estimated position for the fourth distribution (x=4,5m y=2.5m).

# Appendix B.

# The effect of Rician factor with SNR=-20dB

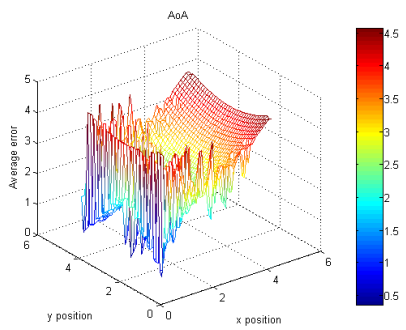


Figure B.1: Localization error with SNR=-20dB and K=-10dB.

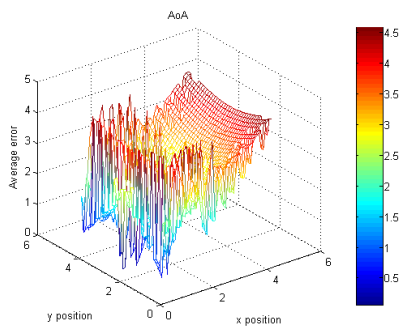


Figure B.2: Localization error with SNR=-20dB and K=-8dB.

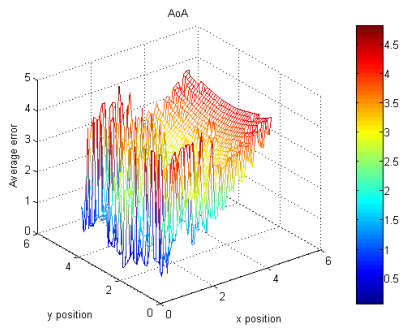


Figure B.3: Localization error with SNR=-20dB and K=-6dB.

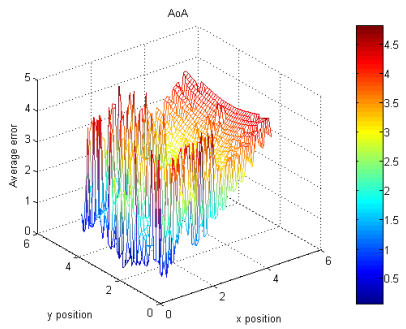


Figure B.4: Localization error with SNR=-20dB and K=-4dB.

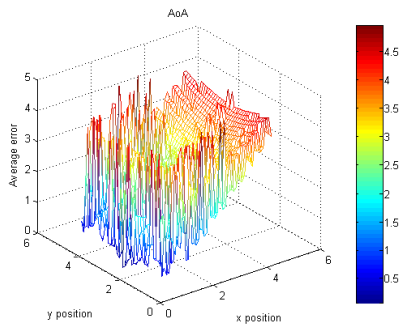


Figure B.5: Localization error with SNR=-20dB and K=-2dB.

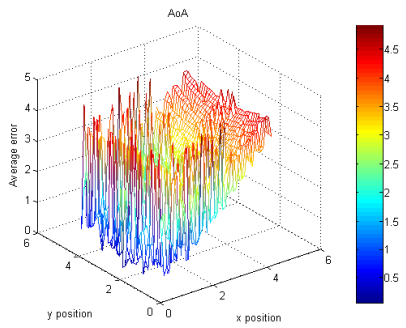


Figure B.6: Localization error with SNR=-20dB and K=0dB.

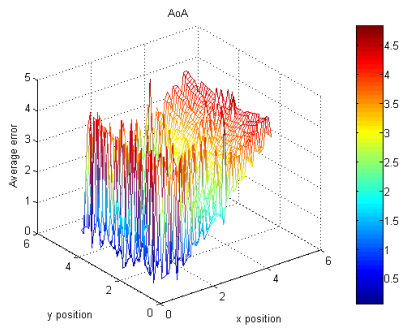


Figure B.7: Localization error with SNR=-20dB and K=2dB.

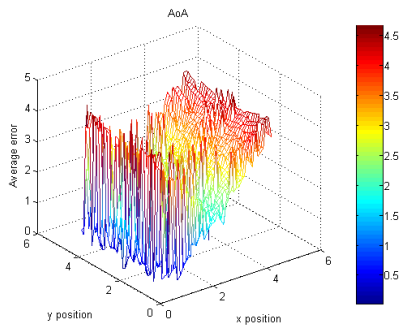


Figure B.8: Localization error with SNR=-20dB and K=4dB.

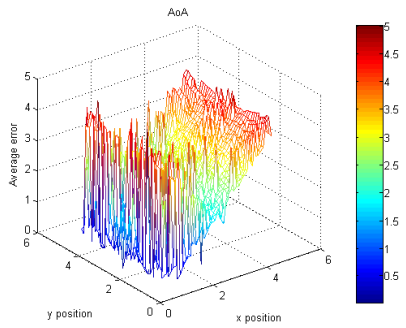


Figure B.9: Localization error with SNR=-20dB and K=6dB.

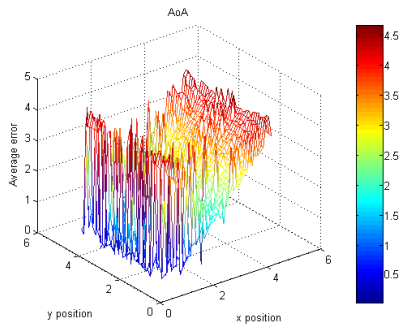


Figure B.10: Localization error with SNR=-20dB and K=8dB.

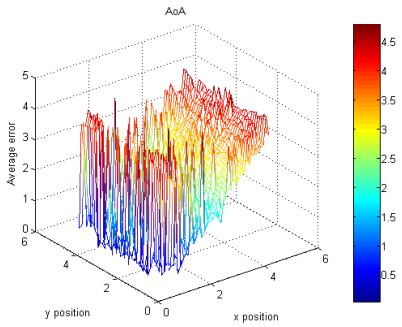


Figure B.11: Localization error with SNR=-20dB and K=10dB.

# Appendix C.

# The effect of Rician factor with SNR=-10dB

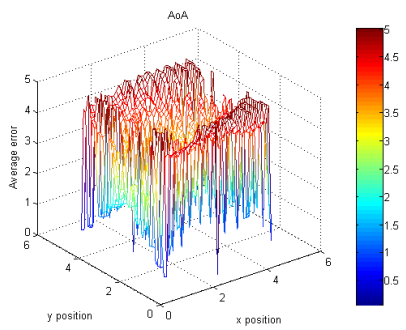


Figure C.1: Localization error with SNR=-10dB and K=-10dB.

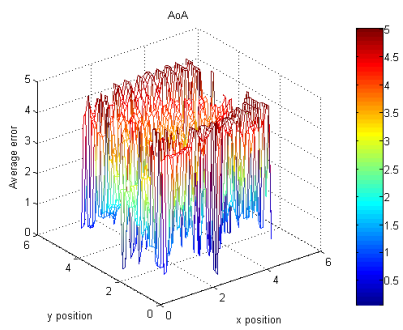


Figure C.2: Localization error with SNR=-10dB and K=-8dB.

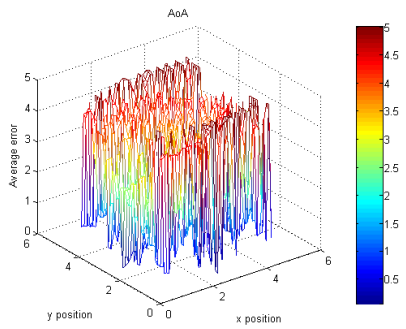


Figure C.3: Localization error with SNR=-10dB and K=-6dB.

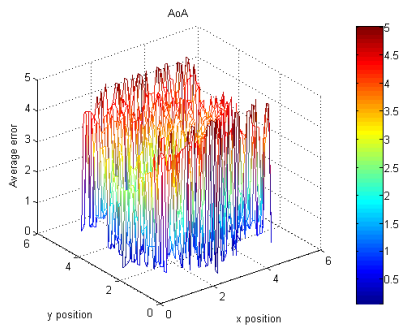


Figure C.4: Localization error with SNR=-10dB and K=-4dB.

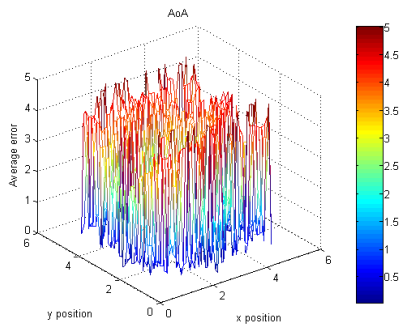


Figure C.5: Localization error with SNR=-10dB and K=-2dB.

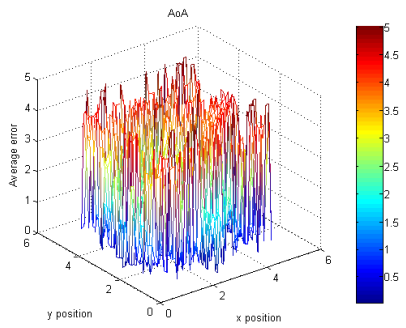


Figure C.6: Localization error with SNR=-10dB and K=0dB.

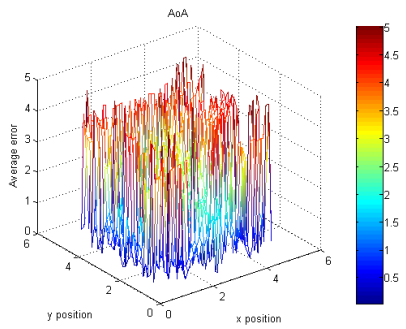


Figure C.7: Localization error with SNR=-10dB and K=2dB.

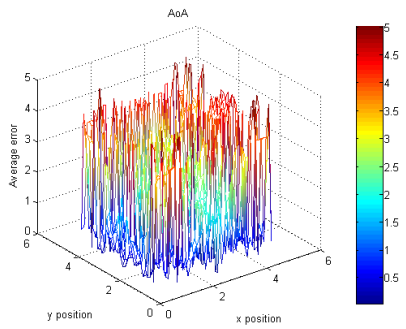


Figure C.8: Localization error with SNR=-10dB and K=4dB.

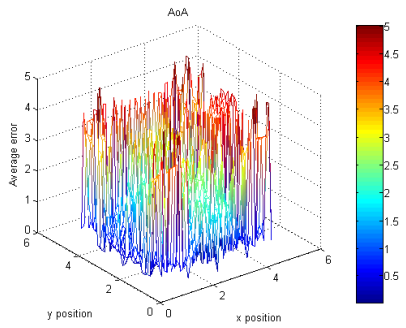


Figure C.9: Localization error with SNR=-10dB and K=6dB.

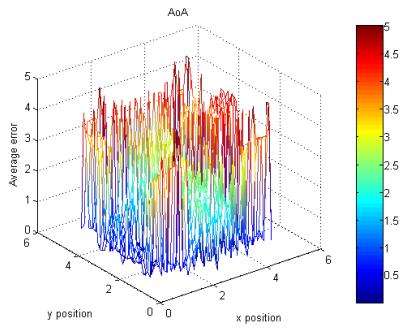


Figure C.10: Localization error with SNR=-10dB and K=8dB.

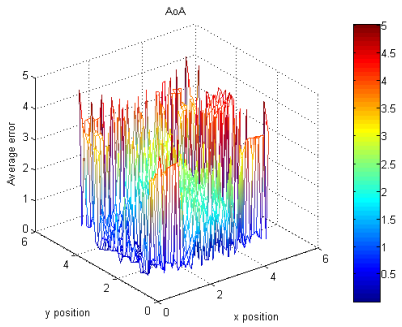


Figure C.11: Localization error with SNR=-10dB and K=10dB.

# Appendix D.

# The effect of Rician factor with SNR=10dB

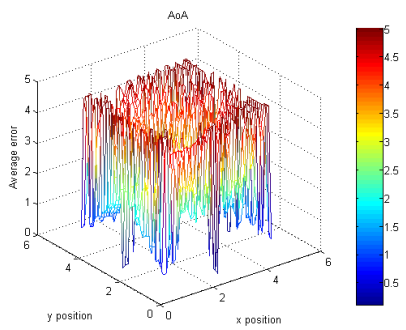


Figure D.1: Localization error with SNR=10dB and K=-10dB.

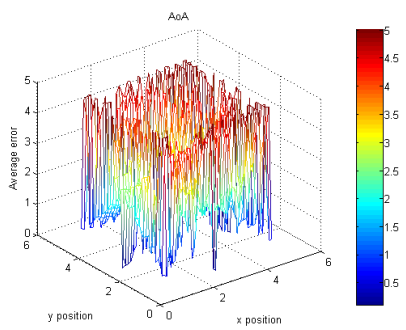


Figure D.2: Localization error with SNR=10dB and K=-8dB.

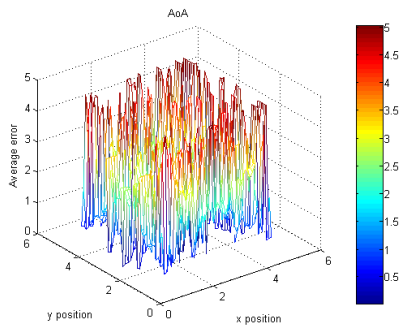


Figure D.3: Localization error with SNR=10dB and K=-6dB.

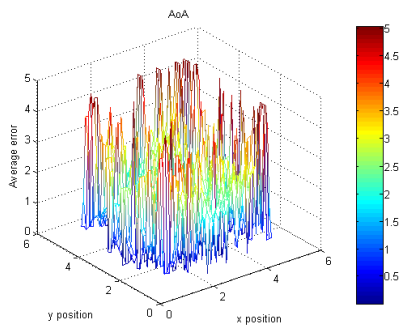


Figure D.4: Localization error with SNR=10dB and K=-4dB.

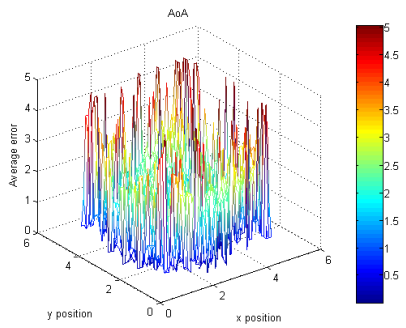


Figure D.5: Localization error with SNR=10dB and K=-2dB.

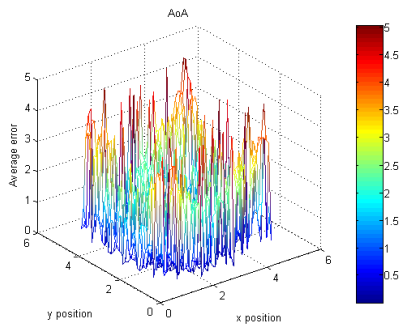


Figure D.6: Localization error with SNR=10dB and K=0dB.

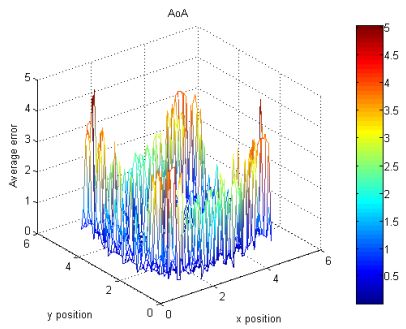


Figure D.7: Localization error with SNR=10dB and K=2dB.

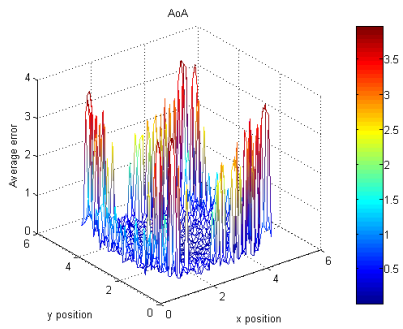


Figure D.8: Localization error with SNR=10dB and K=4dB.

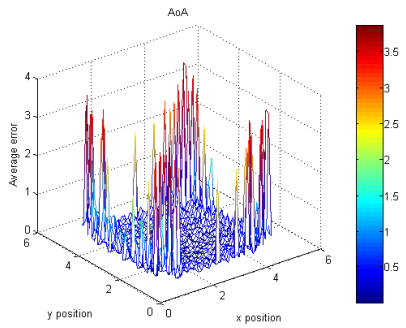


Figure D.9: Localization error with SNR=10dB and K=6dB.

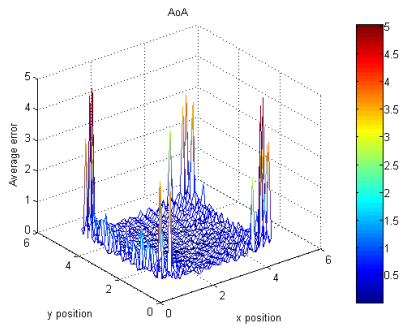


Figure D.10: Localization error with SNR=10dB and K=8dB.

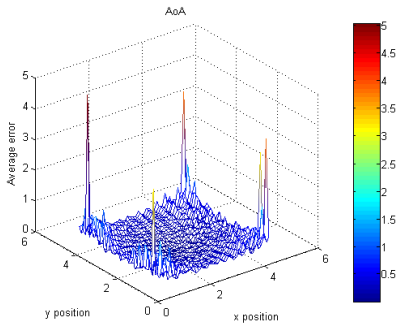


Figure D.11: Localization error with SNR=10dB and K=10dB.

# Appendix E.

# The effect of Rician factor with SNR=20dB

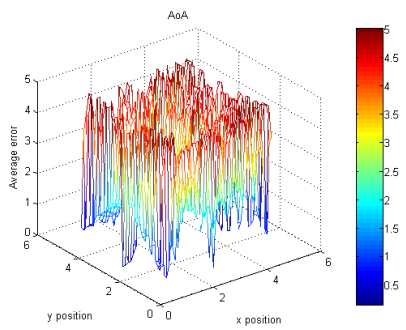


Figure E.1: Localization error with SNR=20dB and K=-10dB.

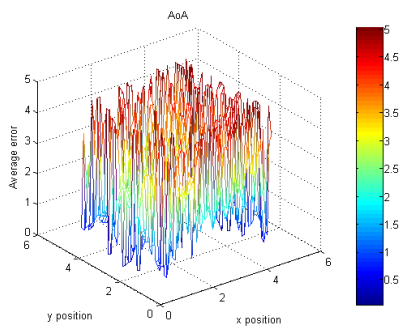


Figure E.2: Localization error with SNR=20dB and K=-8dB.

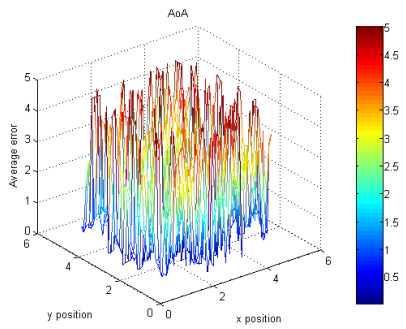


Figure E.3: Localization error with SNR=20dB and K=-6dB.

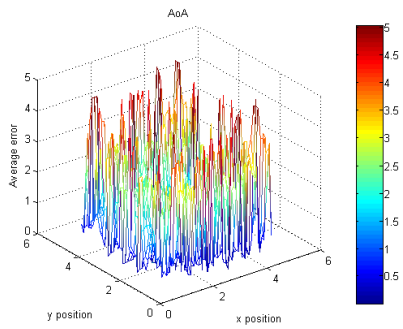


Figure E.4: Localization error with SNR=20dB and K=-4dB.

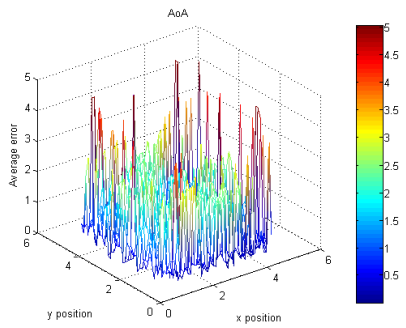


Figure E.5: Localization error with SNR=20dB and K=-2dB.

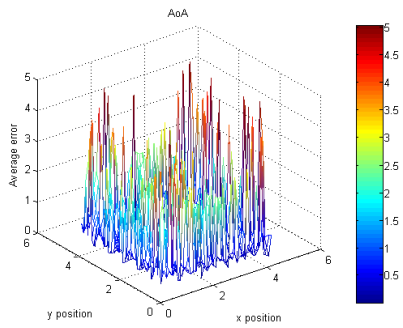


Figure E.6: Localization error with SNR=20dB and K=0dB.

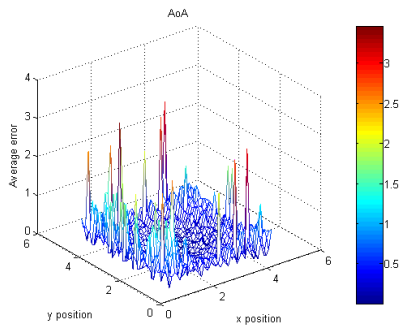


Figure E.7: Localization error with SNR=0dB and K=2dB.

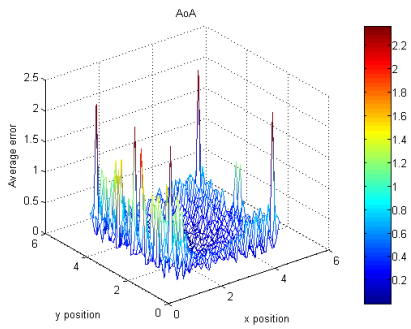


Figure E.8: Localization error with SNR=20dB and K=4dB.

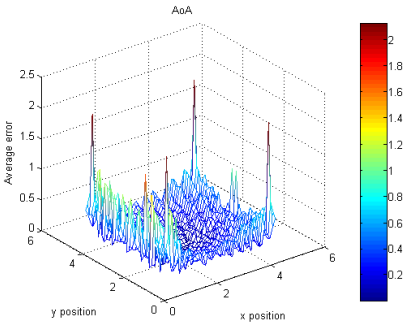


Figure E.9: Localization error with SNR=20dB and K=6dB.

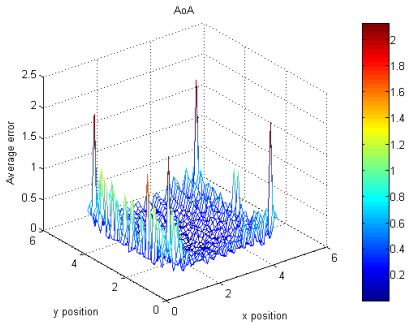


Figure E.10: Localization error with SNR=20dB and K=8dB.

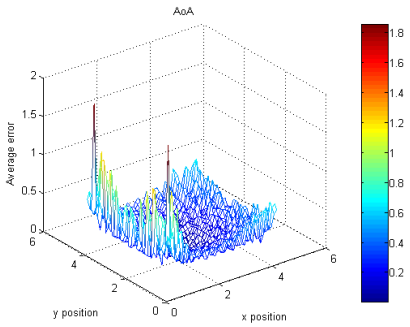


Figure E.11: Localization error with SNR=20dB and K=10dB.