TECHNISCHE UNIVERSITÄT WIEN
and
UNIVERSIDAD POLITECNICA DE CARTAGENA

Localization of moving RFID readers

by

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Declaration of Authorship

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

Francisco de Haro Baños Vienna, June, 2013

"Forever Hallein."

Tiago Ramos.

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Abstract

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The Radio Frequency Identification (RFID) has become an important technology during the last two decades due to the different fields it can be used, as specially on inventory systems, storage and supply chains. In those fields, localization is an interesting topic. Under indoor conditions, where another localization techniques (i.e GPS) cannot work properly, UHF RFID allows to localize and track an object with good accuracy.

In this thesis the problem of localization of RFID reader inside a room will be addressed. In order to explain correctly all the theory and the way all the conditions were simulated, this thesis is divided in five chapters. Chapter 1 is a little introduction about the basics of RFID technology. Chapter 2 will explain the scenario , with all the devices that are involved. Chapter 3 is an explanation about how the signal is modelled. Next, Chapter 4 will show the localization techniques. Chapter 5 will show how the simulations are prepared, detailing all the process behind them. Finally, there's an appendix with other simulations made to test the system.

Acknowledgements

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I also want to express my gratitude to Jelena, my supervisor, for all the help she granted me, and because it was a pleasure to work with her during this year. Thanks to all the people who supported me, from Spain, and also from Vienna, because they made me feel better in my worst days, and they helped me to recover myself to keep working on this thesis.

Last but not least, I would like to thank to my family, who helped and supported me in all difficult moments during all my life, especially during my studies.

Thank you all.

Contents

Dedicated to my family.

Chapter 1

Introduction

1.1 RFID History

The origins of Radio Frequency Identification (RFID) can be found the Second World War. During this time, all the investigations were focused in the Radar field, but this couldn't allow identification if the planes were allies or enemies. The British developed the first identity friend system (IFF), putting a transmitter on each British plane. When the transmitter received signals from radar stations, it began broadcasting a signal back that identified the plane as allied, working in the same way that RFID.

After the second world war, the radar technology were developing during 50s and 60s decades. But it was during de 70s decade when the RFID technology was discovered. In 1973 appeared the first patents about RFID by Mario W. Cardullo and Charles Walton.

Later, the lower frequency (125 kHz) RFID system was developed, featuring smaller transponder. But, was around the early 1990s, when IBM developed and ultra-high-frequency (UHF) RFID system, offering a large range and faster data transfer.

1.2 RFID basics

Radio Frequency Identification is a method of identifying items using radio waves. Normally, RFID systems are composed by three[1] elements: the reader (interrogator), the tags (transponders) and a system (or database) capable of collecting, storing and elaborating on the data sent by the readers. Nowadays, RFID is used in several applications, like security, access control, transportations, supply chain tracking, tracking or storage.

1.2.1 RFID frequency ranges

RFID system operate at widely differing frequencies [1] , ranging from 135 kHz (long wave) to 5.8 GHz in the microwave range. At the end, the range of the system varies from a few millimeters to above 15 meters. The systems with a small range (around up to 1 cm) are known as close-coupling systems. Those are working by introducing the transponder into the reader or putting it upon a reading surface. These system are normally used for security and contactless smart card system with payment functions.

Systems with range of up to 1 m are known as remote coupling systems. The normal frequencies for these systems are below 13.56 MHz, and some times 27.125 MHz are also used. The most common uses for this kind of systems are animal identification or industrial automation.

The system with a range significantly above 1 m are called long-range systems. They work using electromagnetic waves in the range of microwave length (Ultra High Frequency, UHF), in the range between the frequencies 860 MHz and 950 MHz, and the range between the microwaves frequencies 2.5 GHz and 5.8 GHz. In that case, ranges of 3 m can be easily achieved with passive transponders. Although, for the ranges above 15 m the using of active transponders (battery powered) will be needed . These systems are normally used in supply chain applications (like tracking of goods). In this thesis, this are the kind of system that will be used to achieve the objectives proposed.

1.2.2 RFID tags

Depending how the energy is supplied to the transponders, those will be passive or active transponders. The passive transponders don't have any kind of power supply, instead, is the electromagnetic field of the reader which provide all the energy needed for the backscattering transmission from the transponder. In order to be able to transmit, the transponder has to be inside the reader's range, otherwise, it will not receive enough power to backscatter the signal received.

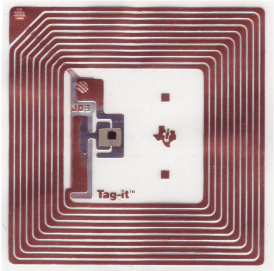

Figure 1.1: Example of passive RFID transponder (tag) (Image taken from Siong-Boon).

The active transponders have a power supply, like a battery or a solar cell for example. Therefore, the power received by the reader is not necessary for the power supply, so, the field can be much weaker, increasing also the range with the same field level. These kind of transponder are also called semi-passive transponders, due to the fact that they cannot generate a high frequency signal by themselves.

Figure 1.2: Example of active transponder with battery supply (Image taken from Veryfields).

1.2.3 RFID Reader

The reader is the device which communicates with the tags through an Radio Frequency channel to obtain the information needed for the identification. Normally, working with passive RFID tags, the reader will supply these tags with the necessary power to in order to be able to reply the reader.

The reader consists in two main parts, the transmitter section and the receiver section. For this thesis is assumed that in the transmitter part there is only one antenna. And for the receiver section, there will be several antennas, in different distribution depending on the purpose of the system. In Figure 1.3 is shown an example of a reader with the two sections clearly separated.

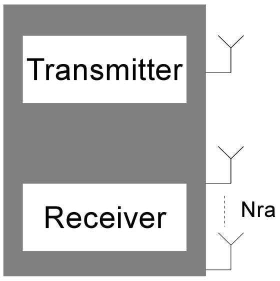

FIGURE 1.3: Example of reader with the two part involved in the transmission.

1.2.4 Database

The third part of an RFID system is the database where specific information is stored. This information will be associated with the rfid tag once the signal is received at the reader and correctly decoded. Depending on the purpose of the system, this information can be product information in case of a storage system, tracking logs, sales data...

In this thesis, the system will storage the position of each tag, and once the reader receive the signal, it will associate the id received in the signal with the correct position stored in the database.

Chapter 2

Scenario

For example, let there be a museum, which rooms have several tags on the walls. This museum has audio guides provided with an RFID reader. Then the tourist, once they take the audio guide and start visiting the museum, entering in the first room, the audio guide will automatically know that it is inside that room, no other one, and will start, automatically also, to talk about it. Furthermore, the reader will know in which position is exactly inside the room, tracking the path which is following. Once they change the room, the audio guide will detect they are in the second room, and will change automatically the explanation to start talking about the room number two. To do this, the audio guide (actually is the RFID reader) has to locate itself inside the room, using the information available around it to find its own position.

Following that philosophy, the scenario is a room, with a size of 8x4x2.5 meters (x,y,z). In order to offer an easy way to find an estimated position, there will be six tags fixed on the walls, as shown in the Figure 2.1. The tags are at the same height to reach the two dimensions problem. There is also a reader (inside this audio guide), which will be moving along the room. The height of this reader will be the same as the tags, also for the same reason.

The basic procedure of this scenario will start with the reader interrogating inside the room. The tags that will be inside the range of the reader (in that case all of them, due to the room dimensions) will respond once they have enough power to do it. When the reader receive all the answer will process the information about the tags, trying to find an estimated position inside the room with the best possible accuracy.

In this scenario there are some problems that will decrease the final accuracy, and will make more difficult the correct communication between reader and tags. The first of them, since there is several tags operating at the same time, there will be collisions. The

FIGURE 2.1: Scenario 2D views.

carrier leakage will be a problem, but it's possible to assume that is perfectly cancelled in the reader. Another problem will be the multipath (not only the influence of the direct path is taken in count), that will be a handicap to find an estimated position. The same for the Non Line of Sight (NLOS) between the reader and tags, which decrease and modify the received signal, making sometimes impossible to use it for localization. In the Figure 2.2 there is an example of multipath and NLOS between reader and a tag.

2.1 Non Line of Sight (NLoS)

Inside the room, the signal is travelling from the reader to the tag, and coming back from the tag to the reader. Not all times there is line of sight between transmitter and receiver, sometimes because someone is passing between them, or because there are some obstacles in the path. In that cases, we have to difference the wave propagation as line-of-sight (LOS) or non-line-of-sight (NLOS). LOS is the direct path between transmitter and receiver, like the air or any electromagnetically transparent material. The term NLOS denotes the delay in the signal due to reduced group velocity, produced by blocking the signal path with any materials.

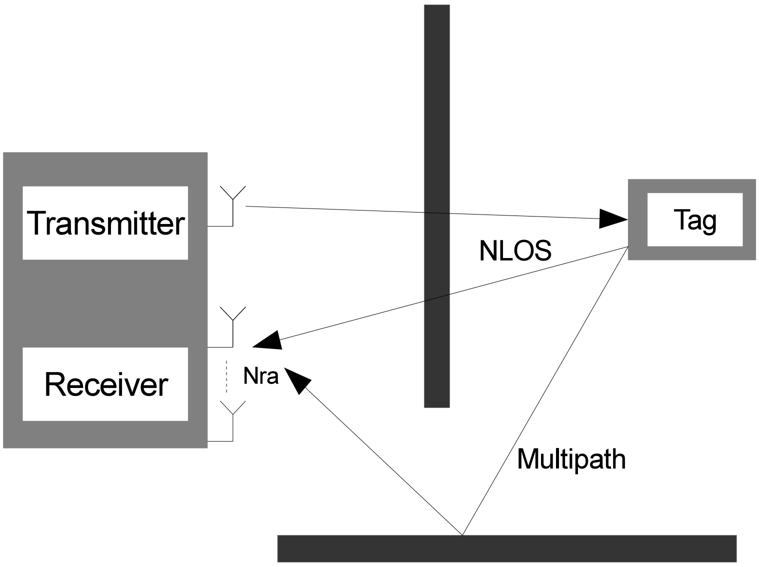

FIGURE 2.2: Multipath and NLOS in the communication between a reader and a tag.

2.2 Path Loss

When the signal propagates along the space, in free space condition, without any obstacle between an emitter and a receiver, there is a reduction in the power density of the signal. This loss is called propagation loss or path loss. The power reduction is depending on the the distance by the relationship:

$$P \propto = \frac{1}{d^2} \tag{2.1}$$

And the total path loss is determined by:

$$L = \left(\frac{2 \cdot \pi \cdot d}{\lambda}\right)^2 = \left(\frac{2 \cdot \pi \cdot d \cdot f}{c}\right)^2 \tag{2.2}$$

Where d is the distance between transmitter and receiver and λ is the signal wavelength, f is the signal frequency, and c is the light speed. In the Figure 2.3 is shown how this losses are depending on the distance, for a frequency of 866 MHz.

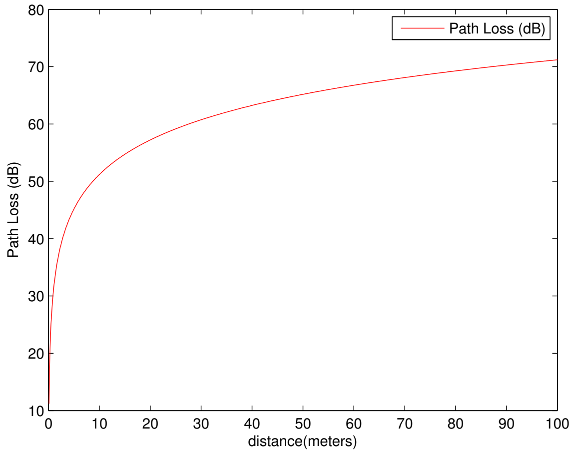

FIGURE 2.3: Path Loss depending on the distance.

2.3 Multipath

To model the channel, only using a free space channel path-loss model will not be sufficient to describe all the phenomena happening in the transmission. Normally, in typical scenarios there is a dominant LOS component of the signal. Furthermore, there is another non-predictable components from the non-line-of-sight reflected paths (multipaths) dependent on the ambient of the RFID installation. This multipaths will affect the performance, changing the reading range, or directly changing the phase delay in the signal, making impossible to receive the data.

In Figure 2.4, one RFID multipath scenario[2] is shown.

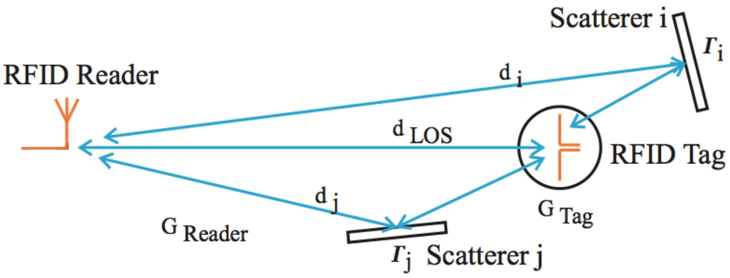

FIGURE 2.4: Example of multipath [3].

The multipath will be modelled by adding a random real and imaginary part to the forward and backward channel, in the non line of sight component, varying the phase in the signal received, and also influencing the attenuation. It will affect to the channel response, making more difficult the detection of the received signal. The weight of this multipath component will depend on K (Rician Factor).

2.4 Collisions

In a scenario with several tags, after reader interrogates all the tags, those will respond to the query commands. In the reader, once it receives the signals incoming form the tag, there can be collisions problems [4][3][5] between these incoming signals. Normally, dealing with several tags, RFID systems are scheduled on a medium access control layer, using Framed Slotted Aloha (FSA). In that case, there will be some slot that are not used for transmission, others used by only one tag, and other ones used by two or more tags, producing collisions. With FSA, without applying any collision recovery, the reader will be able to use only the slots used by only one tag.

In this thesis it's assumed that applying FSA, it's possible to use the slots with one single tag response , without collisions in these slots, so the reader will be able to use the signal from this slot for the localization.

Chapter 3

Signal Model

3.1 Signal received

Let there be R tags being interrogated by the reader, hence there will be R signals coming back to the reader. In that case, and supposing a reader with N_{ra} receiver antennas, the received signal (in the reader) will follow the relation shown in equation 3.1 [4] [6]. Where H$_c$ denotes the the $N_{ra} \times R$ channel matrix, $a(t)$ will be the $R \times 1$modulation vector. l is the carrier leakage, which will be a $N_{ra} \times 1$ vector, $n(t)$ will be the noise, with the same size, and $s_c(t)$ will be, also, a $N_{ra} \times 1$ vector.

$$s_c(t) = H_c \cdot a(t) + l + n(t) \tag{3.1}$$

Since collisions are not considering (It's assumed that using Frame Slotted Aloha there are enough slots with an unique signal), in each moment only the signal from one tag will be received. In that case H_c will be a $N_{ra} \times 1$ vector, l, n and s_c will keep their size. In this thesis will be assumed that the carrier leakage (l) is perfectly cancelled at the reception. Therefore, the signal without carrier leakage is showed in the equation 3.2.

$$s(t) = H_c \cdot a(t) + n(t) \tag{3.2}$$

3.2 Channel Model

The channel is modelled as a Ricean channel, with two component, one line-of-sight (LOS) component (which includes the direct path), and other component, corresponding with non-line-of-sight (NLOS) component (which includes the multipath), that is the Rayleigh fading. The NLOS term is modelled as a random number, which will affect all the channel components, changing it, depending on the Rician factor, which is the ratio power in the LOS component to the power in the NLOS component. If there is K=0, the channel corresponds to pure Rayleigh fading channel. Nevertheless, if the K$\rightarrow \infty$, the channel corresponds to a non-fading channel. Each channel coefficient will follow the equation 3.3

$$h = \sqrt{\frac{K}{1+K}} \cdot \overline{h} + \sqrt{\frac{1}{1+K}} \cdot h_w \tag{3.3}$$

Where K is the Rician factor, $\overline{h}$ is the LOS component, and h_w is the NLOS component. Moreover, as shown in the Figure 3.1 each channel coefficient $h_{i,j}$ is formed by two components, one for the forward channel (common to the all receiver antennas), and other for the backward channel, and is modelled as the multiplication of a forward channel ${h_j}^f$ and a backward channel ${h_{i,j}}^b$ as shown in the equation 3.4

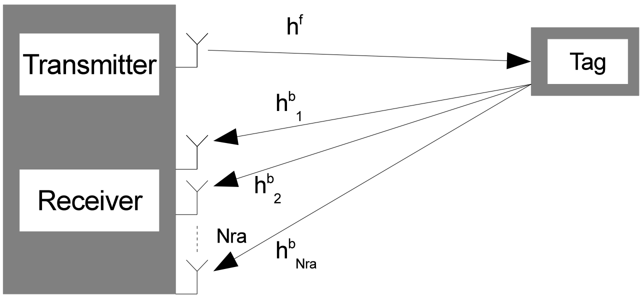

FIGURE 3.1: Channel model

$$h_{i,j} = {h_j}^f \cdot {h_{i,j}}^b \tag{3.4}$$

Where the index i represents the receiver antenna and j denotes the tag. The channel size will be N_{ra} rows by N_{tags} columns, where N_{ra} is the number of receiver antennas in the reader, and N_{tags} is the number on tags the reader is receiving in that moment.

Since in our scenario the reader receive only from one tag per time, the total size will be $[N_{ra} \ \times \ 1]$.

$$H_c = \begin{bmatrix} h_{1,1} \\ h_{2,1} \\ h_{3,1} \\ \vdots \\ h_{Nra,1} \end{bmatrix} \tag{3.5}$$

The LOS component will be modelled as an exponential term, which depends on the steering vector and the position of the receiver object (antenna or tag):

$$h_{los} = \frac{1}{\sqrt{2}} \cdot e^{\frac{-j\cdot 2\cdot \pi \cdot a' \cdot pr'}{\lambda}} \tag{3.6}$$

Where the steering vector has the formula:

$$a = \begin{pmatrix} -\sin(\theta)\cdot\cos(\varphi) \\ -\sin(\theta)\cdot\sin(\varphi) \\ -\cos(\theta) \end{pmatrix} \tag{3.7}$$

Where θ is the elevation angle and φ is the azimuth angle. These angles, are the true angles of arrival, and they will be used to generate the channel. Therefore, these angles depends on the position of the transmitter and receiver object. To find then, first to all is necessary to obtain the difference between the coordinates of transmitter and receiver object (x, y, z). Once these difference of coordinates is known, the angles will be:

$$\theta = \begin{cases} \arctan\frac{\sqrt{x^2+y^2}}{z} & z > 0 \\ \frac{\pi}{2} & z = 0 \\ \pi + \arctan\frac{\sqrt{x^2+y^2}}{z} & z \neq 0 \end{cases} \tag{3.8}$$

$$\varphi = \begin{cases} \arctan\frac{y}{x} & x > 0 \ \& \ y \geq 0 \\ 2\cdot\pi + \arctan\frac{y}{x} & x > 0 \ \& \ y \leq 0 \\ \frac{3\cdot\pi}{2} & x = 0 \ \& \ y \leq 0 \\ \frac{\pi}{2} & x = 0 \ \& \ y \geq 0 \\ \pi + \arctan\frac{y}{x} & x < 0 \end{cases} \tag{3.9}$$

The NLOS component is modelled as a random complex number, and represents all the multipath signals that they are arriving at the reader, producing a phase changing, which will be a handicap for the reader localization, because, basically, the angle of arrival (technique that will be used for localization) won't be the same as the LOS signal.

3.3 Tag signal

When the reader interrogates the tag, this one communicates with the reader using backscatter modulation, in which the tag switches the reflection coefficient between two states depending on the data sent. The backscatter signal uses ASK modulation, and will encode the signal using FM0 encoding.

3.3.1 FM0 baseband

The FM0 encoding [7] is composed of four basic symbols, the data-0 which is half period at maximum level, and half period at minimum, the data-1 which is at maximum level full time, and the inverses of them. FM0 inverts the baseband phase at every symbol boundary. Figure 3.2 shows the basis functions of FM0 encoding.

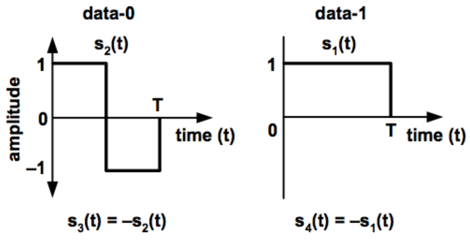

FIGURE 3.2: FM0 basis functions [7]

The state diagram in Figure 3.3 shows the logical sequence to the FM0 basis functions that are transmitted. The states S_1-S_4 represents the possible encoded basic FM0 symbols.

At the end, the signal is composed of one preamble formed of 12 bits, and the data conforming a 45 bits signal, which will contain the tag ID and other data, which will be modulated in the backscattered tag reply.

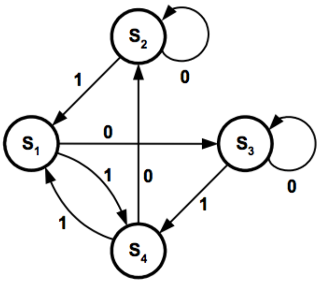

FIGURE 3.3: FM0 state diagram [7]

3.4 Noise

The noise is going to be modelled as a Additive Gaussian White noise (AWGN), which will affect all the frequencies in the signal spectrum in equal proportion. This noise comes from a ergodic source with zero mean and gaussian power spectral density. Furthermore, the noise is independent of the signal and, therefore, uncorrelated with it.

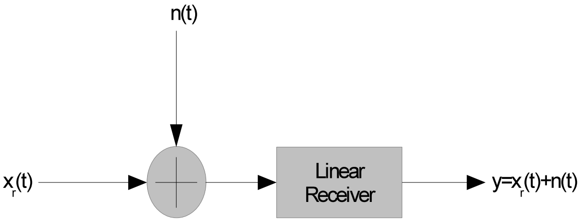

FIGURE 3.4: AWGN

Chapter 4

Localization Techniques

4.1 Localization

Once the reader has received all the possible tag signals, it has to obtain some parameters from this signal to find its own position. To achieve it, there are some localization techniques that can be applied, and depending on the technique, the position is estimated in different ways. In this case, Angle of Arrival (or Direction of Arrival) estimation will be applied, following the Multiple Signal Classification (MUSIC) method.

The localization by angle of arrival consist in, having the angle from the tag to the reader, it's possible to obtain a line between the tag and the reader. Therefore, using two tags, and finding the intersection of the lines from these two tags, it's possible to find an estimated position of the reader.

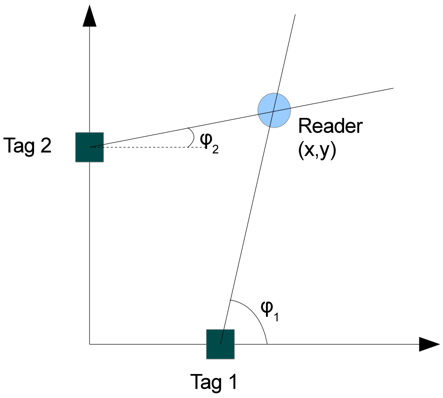

Figure 4.1: Angle of Arrival localization

4.2 Angle of Arrival estimation

4.2.1 MUSIC Algorithm

MUSIC algorithm is dependent on the correlation matrix of the signal received. So, calling x to the signal received[8][9]

$$\begin{aligned} x &= S \cdot \alpha + n \\ S &= [s(\phi_1), s(\phi_2), \cdots, s(\phi_M)] \\ \alpha &= [\alpha_1, \alpha_3, \cdots, \alpha_M] \end{aligned} \tag{4.1}$$

If matrix S is a N$_{ra}$ × M matrix of M steering vectors, and the different incoming signals are uncorrelated, the correlation matrix can be:

$$R = E\left[x \cdot x^H\right] = E\left[S \cdot \alpha \cdot \alpha^H \cdot S^H\right] + E\left[n \cdot n^H\right] = S \cdot A \cdot S^H + \sigma^2 \cdot I = R_s + \sigma^2 \cdot I \tag{4.2}$$

Where $R_s = S \cdot A \cdot S^H$ is the signal covariance matrix and:

$$A = \begin{bmatrix} E\left[|\alpha_1|^2\right] & 0 & \cdots & 0 \\ 0 & E\left[|\alpha_2|^2\right] & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & E\left[|\alpha_M|^2\right] \end{bmatrix} \tag{4.3}$$

$R_{nn} = \sigma^2 \cdot I$ is the noise correlation matrix. Since there are N receiver antennas and M incoming signal, the covariance signal matrix is $N \times N$ matrix with rank M. Therefore, $N - M$ eigenvectors correspond to the zero eigenvalue. If q_m is an eigenvector:

$$\begin{aligned} R_s \cdot q_m = S \cdot A \cdot S^H \cdot q_m &= 0 \\ \Rightarrow q_m^H \cdot S \cdot A \cdot S^H &= 0 \\ \Rightarrow S^H q_m &= 0 \end{aligned} \tag{4.4}$$

This final equation is valid only because the matrix A is positive definite. Therefore, it implies that N-M eigenvectors q_m of R$_s$ are orthonormal to all M signal steering vectors.

Let $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_M$ be the eigenvalues of the matrix R$_s$:

$$\begin{aligned} R_s q_m &= \lambda q_m \Rightarrow \\ \Rightarrow R q_m &= R_s q_m + \sigma^2 I q_m \\ &= (\lambda_m + \sigma^2) q_m \end{aligned} \tag{4.5}$$

Consequently, any eigenvector of matrix R$_s$ is also an eigenvector of matrix R with the eigenvalue $\lambda + \sigma^2$. So, if $R_s = Q \Lambda Q^H$:

$$\begin{aligned} R &= Q \left[\Lambda + \sigma^2 I\right] Q^H \\ &= Q \begin{bmatrix} \lambda_1 + \sigma^2 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & \lambda_2 + \sigma^2 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \lambda_M + \sigma^2 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & \sigma^2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \cdots & \sigma^2 \end{bmatrix} \end{aligned} \tag{4.6}$$

Basing on eigendecomposition, the matrix Q can be split into a Q$_s$ signal matrix with M columns, that correspond to the M signal eigenvalues, and a matrix Q$_n$ with N-M columns, which correspond to the noise eigenvalues σ^2. In consequence, Q$_n$ is the N × (N-M) matrix of eigenvectors that corresponds with the noise eigenvalues (σ^2), that defines the noise subspace, while Q$_s$ is the signal subspace.

As observation, the smallest eigenvalues of R will correspond to the noise eigenvalues and all of them will be equal to σ^2. A second observation will be that, by orthogonality of Q, Q$_s$ and Q$_n$ will be orthogonal between them.

$$Q_s \perp Q_n \tag{4.7}$$

With these observations, it can be said that all noise eigenvectors are orthonormal to the signal steering vector, which is the main assumption for MUSIC algorithm. Thus, at the end, the MUSIC pseudo-spectrum [9][10] will be:

$$P_{MUSIC}(\phi) = \frac{1}{\sum_{m=M+1}^{N} |q_m H s(\phi)|^2} \tag{4.8}$$

where q_m is one of the N-M noise eigenvectors. Thus, at the end, and following Equation 4.8, the MUSIC algorithm will identify the directions of arrival as the peaks in the function.

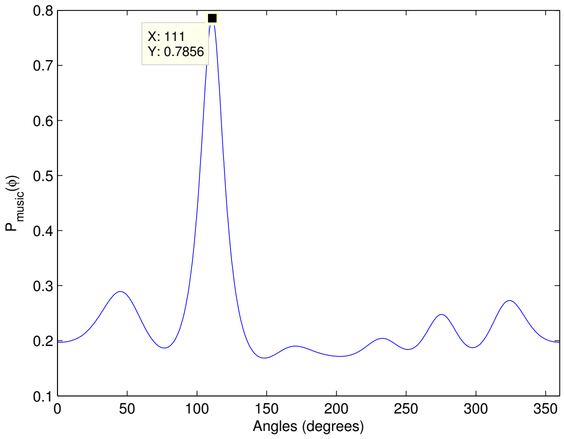

FIGURE 4.2: Example of MUSIC algorithm

4.3 Estimated position

Once the system know which angles of arrival are [11], and knowing all the position of the tags inside the room, it's easy to find an estimated position by the intersection of lines as in Figure 4.1.

Thus, focusing in a two dimension problem, let there be two tags, with the coordinates for the tag 1 (x_1,y_1) and (x_2,y_2) for the tag 2, and knowing the angles from each tag (ϕ_1 and ϕ_2) to the reader (those are calculated using the angles of arrival with respect to the reader), the estimated position will be found following the steps:

1. Calculation of the slope for each angle:

$$\begin{aligned} m_1 &= \tan\phi_1 \\ m_2 &= \tan\phi_2 \end{aligned} \tag{4.9}$$

2. Calculation of the line constant for each tag:

$$\begin{aligned} n_1 &= y_1 - m_1 \cdot x_2 \\ n_2 &= y_2 - m_2 \cdot x_2 \end{aligned} \tag{4.10}$$

3. Find the intersection of the two lines:

$$
\begin{aligned}
x &= \frac{n_2 - n_1}{m_1 - m_2} \\
y &= m_1 \cdot x + n_1
\end{aligned}
\tag{4.11}
$$

Where the pair (x,y) is the estimated position of the reader with these two tags.

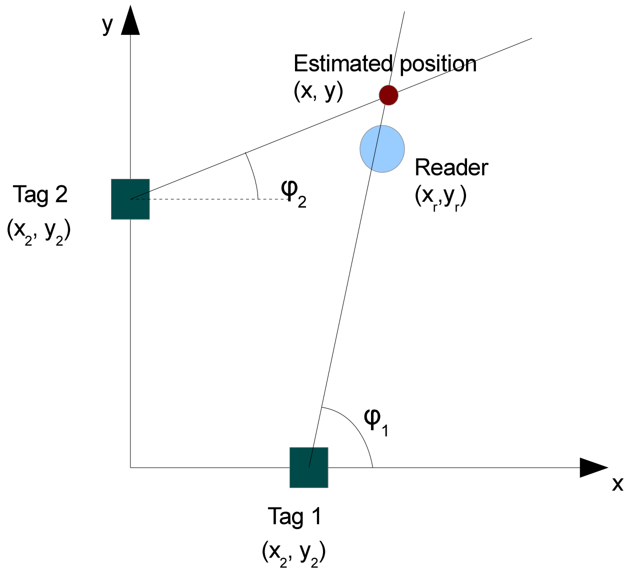

FIGURE 4.3: Example of estimated position by AoA

Chapter 5

Simulations

5.1 Set up

Before showing any results, it will be necessary to explain how the scenario is prepared for the simulation (set up). Those simulations will be done with Matlab software, following a series of steps to achieve it. First to all, and using the real position of reader and the tags, the angles between reader and tags will be found. Figure 5.1 shows how the coordinate origins is established with respect to tags and reader for this first step.

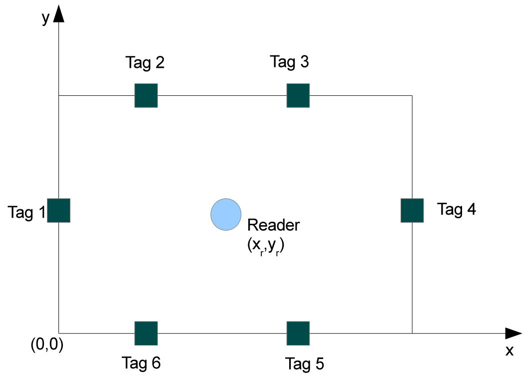

FIGURE 5.1: Set up for the angle calculation.

The next step is, using this calculated angles, to generate the channel for the transmission between reader and tag. Once the channel is generated, the signal can be modelled. At this point, in order to use MUSIC algorithm to find the angles of arrivals, is necessary to change the coordinates origin from the room corner to the reader (specifically, in Matlab script, it will be centered in the transmitter antenna, that is actually the reader position also). In Figure 5.2 an example of the scenario, with the coordinates origin changed to the reader is shown.

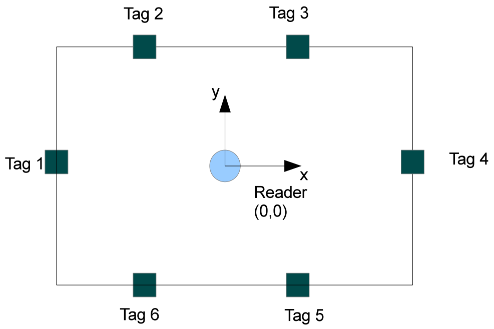

Figure 5.2: Example of coordinates origin changing.

Therefore, doing it, the receiver antenna positions will be set respecting the transmitter antenna. Focusing in a linear antenna array to model the reader, the distribution of antennas with respect to the origin (transmitter antenna) is shown in Figure 5.3.

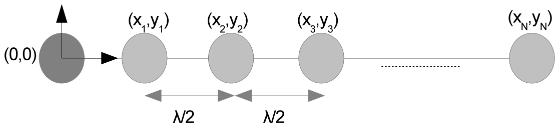

Figure 5.3: Example of a linear array of antenna.

Now it's time to use the MUSIC algorithm and find the angle of arrival (AoA) as is shown in Figure 5.4.

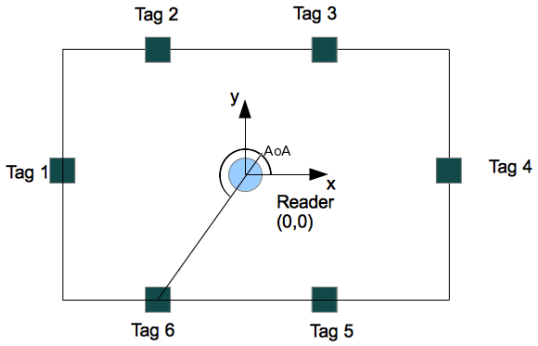

Figure 5.4: Angle of Arrival.

Once the angles of arrivals are known, it will find the tag's ID according to the received signal and, searching in the list stored in the database, it will find the coordinates of the tag. Afterwards is necessary to change again the coordinates origin to the original point. Then, using the known tag position and the angles of arrival, it's possible to find the angle with respect to the tag to the reader, as shown in Figure5.5.

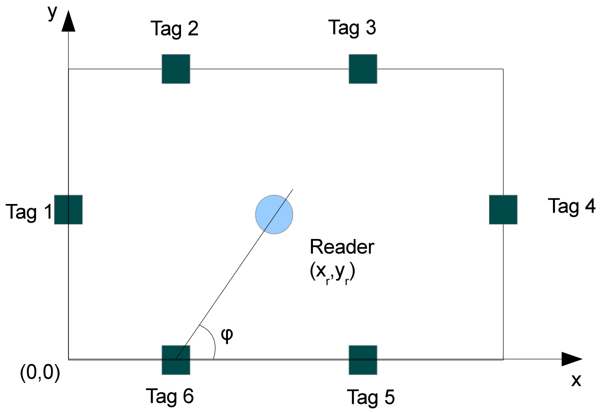

Figure 5.5: Angle with respect to the tag.

When all the angles are calculated, taking two tags, and using their angles and known position, is easy to calculate an estimated reader position, which accuracy will depend on conditions, like the noise level inside the room, or the LOS or NLOS between reader and tag. The Figure 4.3 shows an example of estimated position. For measure the accuracy of the estimated positions will be used the Root Mean Square Error (RMSE):

$$\mathrm{RMSE} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(\widehat{x}_i - x)^2 + (\widehat{y}_i - y)^2} \tag{5.1}$$

Where n will be the number of estimated positions obtained from the combination of tags.

5.2 Simulations

In this section the simulation order will be explained. The first point is choosing which antenna distribution is the optimal to get a good accuracy in the simulation results. The next simulations will test how the error is varying depending on the reader position. To finalize, the reader will start to move along the room, checking and estimating the next position with different techniques, comparing which one is the best options for tracking the reader.

5.2.1 Antenna distribution

In this section different antenna distribution will be tested. For the procedure, the reader will be set in the center of the room, and using all the tags divided in pairs, the results will be presented as an rmse all average for all the estimated position. The simulations will be done first, fixing the K Rician factor, and checking for different values of SNR.

5.2.1.1 Linear antenna array along x axis

The first antenna distribution will be the linear array distribution along the x axis, set in the center of the room. The receiver antennas will be arranged around the transmitter antenna along the x axis, as shown in Figure 5.6.

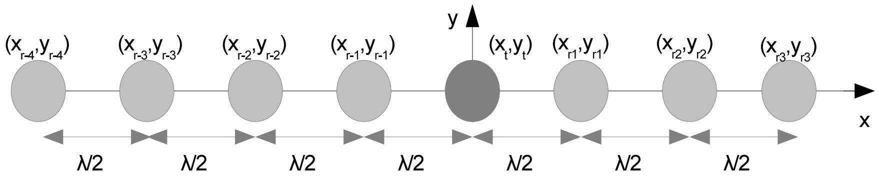

FIGURE 5.6: Linear antenna array along x axis.

As was said, the reader will be set in the center of the room, with the tags arranged on the wall as was explained in Chapter 2, with two tags on the long walls, and one tag per short wall. A representation in two dimensions is shown in Figure 5.7

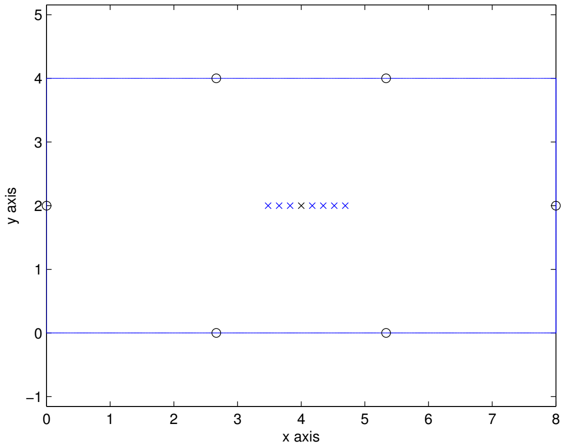

FIGURE 5.7: 2-D scenario with linear array antenna (x axis).

Now, fixing the K Rician factor 7 dB, and checking for different values of SNR, the all average rmse will be shown in Figure 5.8.

As Figure 5.8 shows, this antenna distribution doesn't work properly with this scenario, producing at the end a high rmse (specifically 1.52). Furthermore, from the point of view of implementation, it's not a good option, due to the fact that, with a separation between antennas of $\lambda/2 = 0.1732$, the size of the antenna array will be 1.2125 m, that means a really big reader.

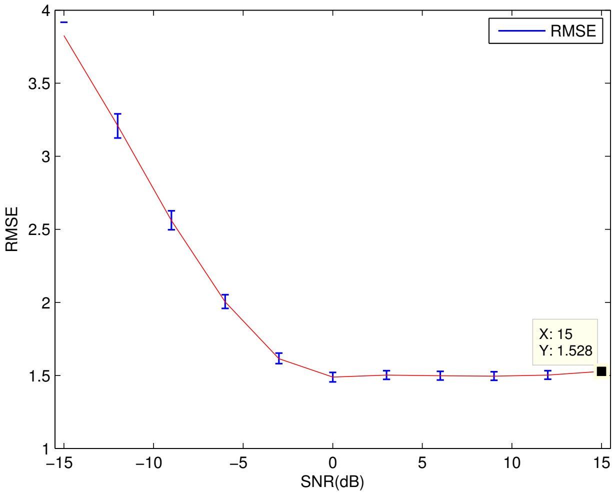

Figure 5.8: RMSE for K=7 dB with linear antenna array (x axis).

5.2.1.2 Linear antenna array along y axis

The second antenna distribution will be the linear array distribution along the y axis, set in the center of the room. The receiver antennas will be arranged around the transmitter antenna along the y axis, as shown in Figure 5.9.

Again, the reader will be set in the center of the room, with the tags arranged on the wall as mentioned in Chapter 2, with two tags on the long walls, and one tag per short wall. A representation in two dimensions is shown in Figure 5.10

Now, fixing the K Rician factor 7 dB, and checking for different values of SNR, the all average RMSE will be shown in Figure 5.11.

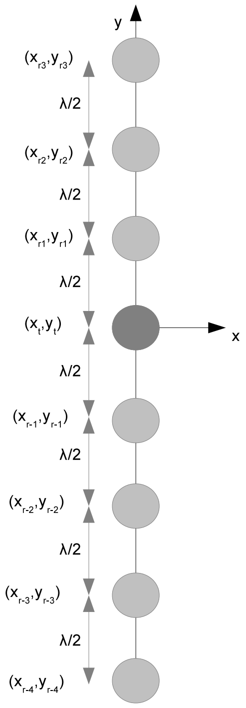

FIGURE 5.9: Linear antenna array along y axis.

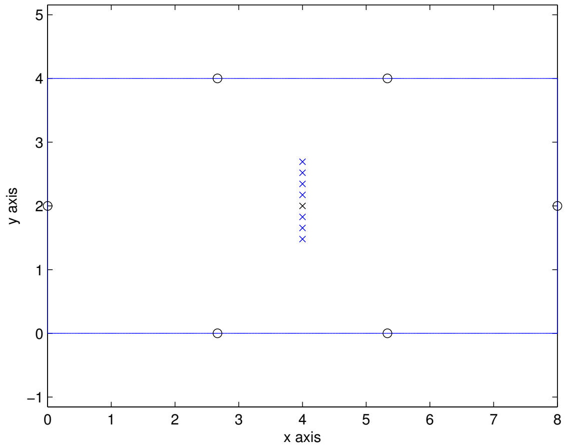

FIGURE 5.10: 2-D scenario with linear array antenna (y axis).

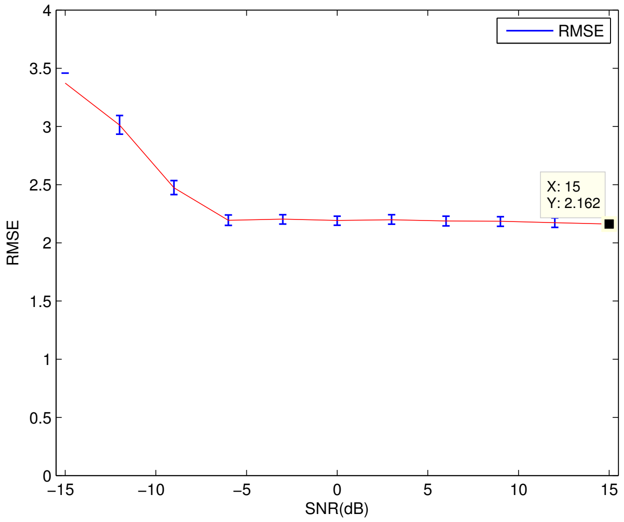

FIGURE 5.11: RMSE for K=7 dB with linear antenna array (y axis).

As Figure 5.11 shows, this antenna distribution doesn't work properly neither, producing at the end a high RMSE, even in the case of high SNR (specifically 2.162 for SNR=15 dB). Furthermore, from the point of view of implementation, it's not a good option, due to the fact that, with a separation between antennas of $\lambda/2 = 0.1732$, the size of the antenna array will be 1.2125 m, that means a really big reader.

5.2.1.3 Circular antenna array

The third antenna distribution to test will be the circular antenna array. In this array, the antennas also have a separation of $\lambda/2$, but, in that case, the diameter of the distribution will be exactly 0.3859 cm, more realistic dimensions that the other distributions for a mobile reader. In Figure 5.12 a circular array with these characteristics is shown.

Once again, the reader will be set on the center of the room as shown in Figure 5.13

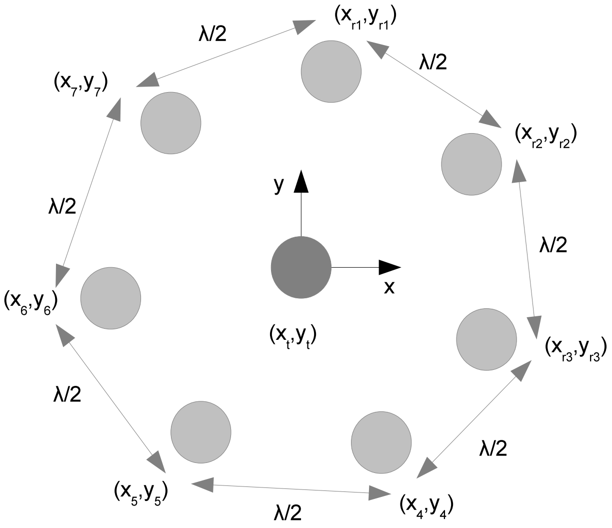

FIGURE 5.12: Circular antenna array.

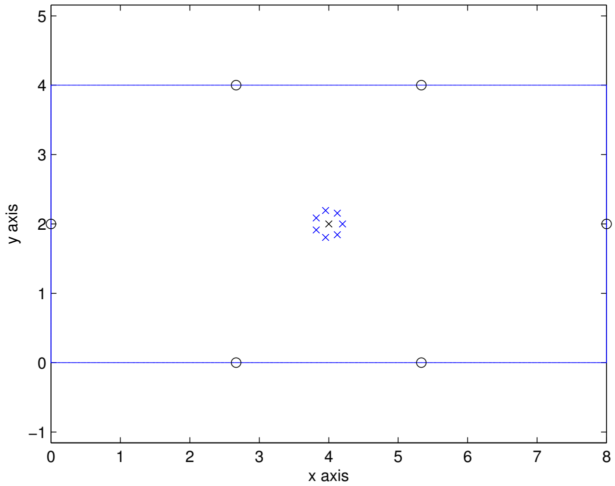

FIGURE 5.13: 2-D scenario with circular antenna array.

Now, newly, the K Rician factor will be fixed to K=7 dB, and the error will be checked for different values of SNR. Figure 5.14 shows how the RMSE is varying with these parameters.

It's easy to check that the error when SNR=15 dB the error is equal to 0.1183. Because of that, this is the antenna distribution that will be used for the reader simulation.

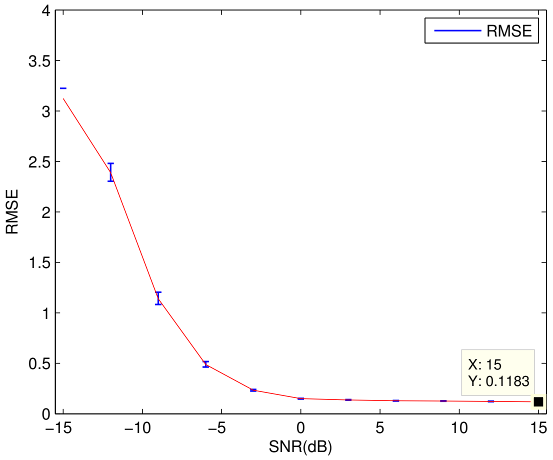

FIGURE 5.14: RMSE for K=7 dB with circular antenna array.

Furthermore, as was mentioned, the dimensions of this array are easy to implement in a real device.

5.2.2 Simulation using two tags

Until now, different distributions have been tested, in a static scenario, without moving, and using all the tag to find different estimated position. However, the behaviour of the error respecting two tags, for different reader position has not been tested. Therefore, the reader will be placed in different points of the room, and the error with different parameters will be shown, with respect to two tags (tag 1 and tag 2).

Two points will be presented as a example of the variation of the accuracy with the position respecting the tags. The first point is x=3, y =3, a close position from the two tags. Figure 5.15 shows the reader situation with respect to the tags inside the room.

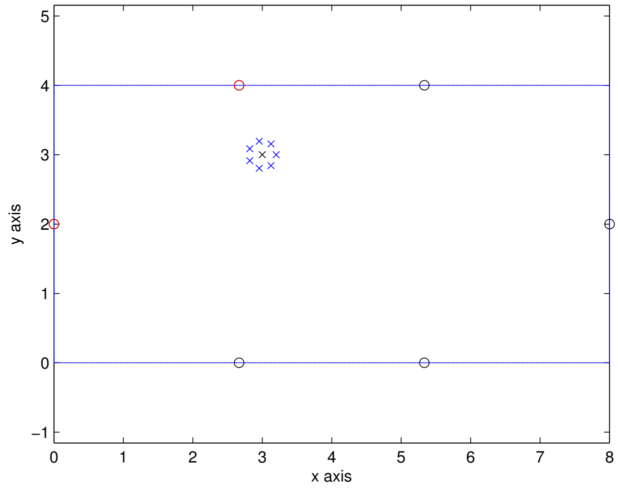

FIGURE 5.15: Reader position x=3, y=3.

In that case, if K Rician factor is fixed to K=7 dB, the behaviour of the error for different values of SNR is shown in Figure 5.16.

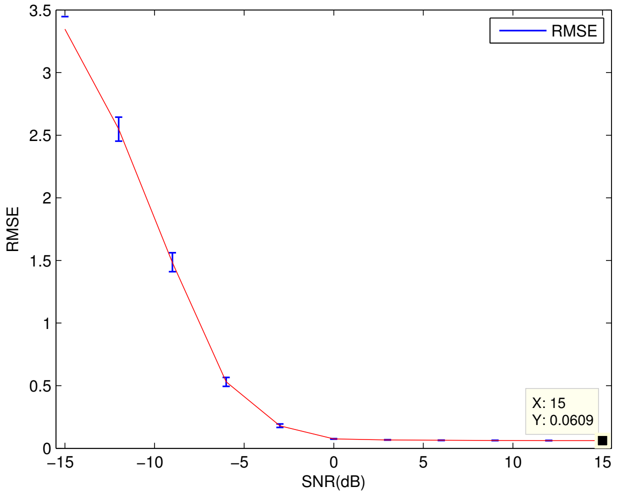

FIGURE 5.16: RMSE for K=7 dB with circular antenna array in x=3, y=3.

In that case, for SNR=15 dB RMSE is equal to 0.06, really low value, due to the fact that the reader is very close to the both tags, and there isn't any blind point (in that case, the blind points will be the line between the two tags). Nevertheless, if the SNR is fixed to 10 dB, the error for different values of K is shown in Figure 5.17.

Is easy to check that the RMSE is a low value when K=10 dB. The reason is the same, so, it's possible to say that, at this point, the detection will have a really good accuracy.

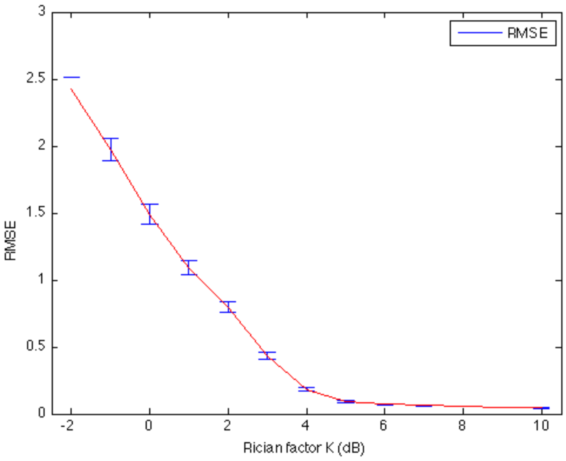

FIGURE 5.17: RMSE for SNR=10 dB with circular antenna array in x=3,y=3.

Nevertheless, if the reader is on a position far away from the two tags, the results will be different, due to the distance between them, the attenuation will be bigger, producing a higher error in the measurements. Is the reader is placed in the position x=7, y=3.4, the scenario will look as in Figure 5.18

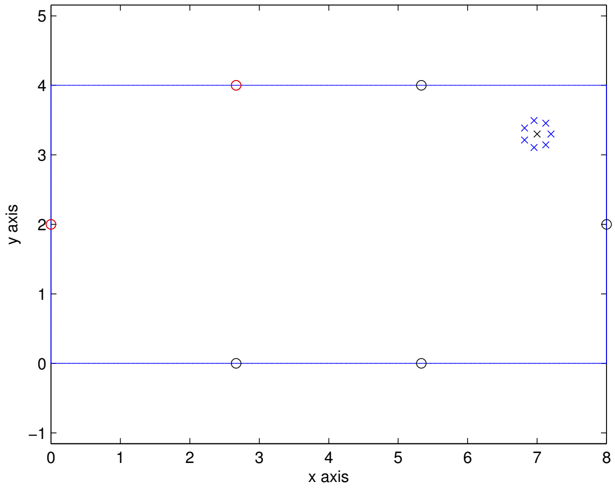

FIGURE 5.18: Reader position x=7, y=3.4.

Now, using the same values of the Rician factor (K=7 dB), different values of noise will be checked again. Figure 5.19.

And, fixing the SNR to SNR=10 dB, and checking for different values of K, the results are shown in Figure 5.20

Now, the RMSE is higher (0.5259 in the first case and 0.3773 in the second). The reason for this change is basically the distance between the reader and the two tags, and

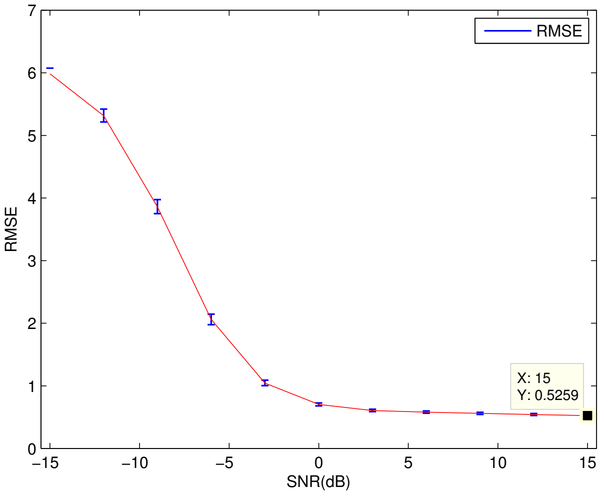

FIGURE 5.19: RMSE for K=7 dB with circular antenna array in x=7,y=3.4.

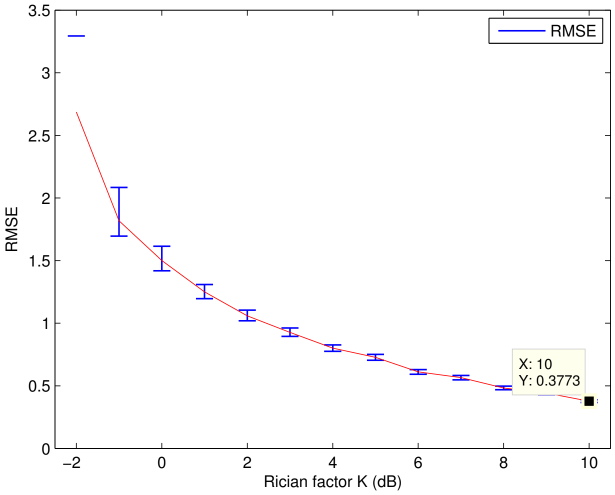

FIGURE 5.20: RMSE for SNR=10 dB with circular antenna array in x=7,y=3.4.

depending on it, keeping the rest of the conditions, the error will vary with the distance along the room.

To show it, the reader is now going to change the position, checking all the possible positions along the room, but keeping the static condition, cause the reader is not really moving. With the parameters K=7 dB and SNR=10 dB, the error variation along the room, using the same two tags as previously, is shown in Figure 5.21

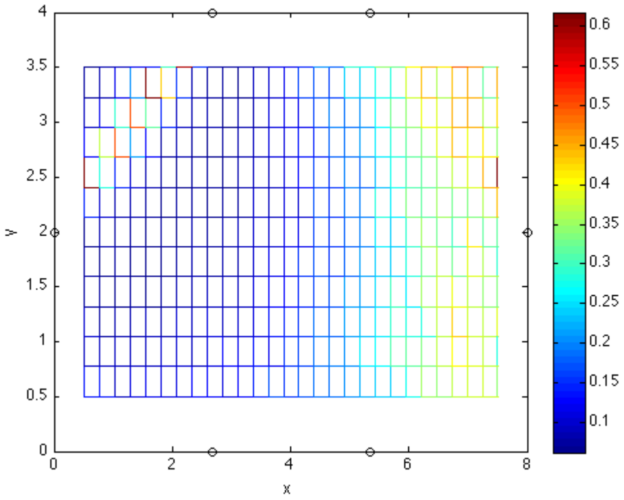

FIGURE 5.21: Error variation along the room.

It's easy to check in Figure 5.21 that the zones in the room near the tags, the error has a low value. If the reader is going away from the tags, as far is going, the error is increasing.

5.2.3 Best case simulation

Now, placing the reader in the center of the room, and using all the tags, is shown a simulation using the best estimated position in each case. To make it, the tags are going to be selected by pairs to find an estimated position. Figure 5.22 shows how the pairs are taken. Each ellipse surrounds two tags, hence, from which pair an estimated point will be obtained, resulting in eight estimated points.

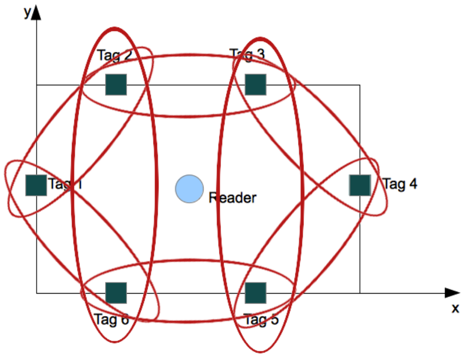

FIGURE 5.22: Tag election for position estimating.

For this simulation, the error is obtained only from the pair of tags which has the minimum error from the eight pairs in each iteration. Again fixing the K factor to a value K=5 dB, and checking the error for different values of SNR, the rmse is varying as shown in Figure 5.23

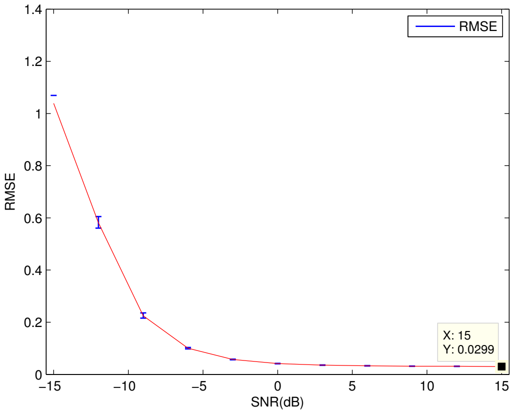

Figure 5.23: RMSE for the best case simulation.

5.2.4 The moving reader

In that point, the reader will move along the room, following a path. The noise, will be fixed at a value of 10^{-3} Watt. Therefore, in the reader, the signal received will have different value of SNR depending from which tag is coming. So, it will be very important the way the tags are chosen for calculating the estimated position, and depending on that choice, the error will vary in different way.

So, if the reader is inside the room, as Figure 5.24 shows, the SNR in the reader will be different depending on which tag is the signal coming from.

Therefore, the reader will be moving along the room, following a path and, for the localization, two cases will be studied, first to all the case when the path the reader is following is known. In that case, the election for a good estimated position will be done following the Least Square Fitting (LSF). Another case is when the path is unknown, in that case, and basing on the fact that the reader is moving slowly, the way to find the best estimated position will be by comparing with the previous estimated position.

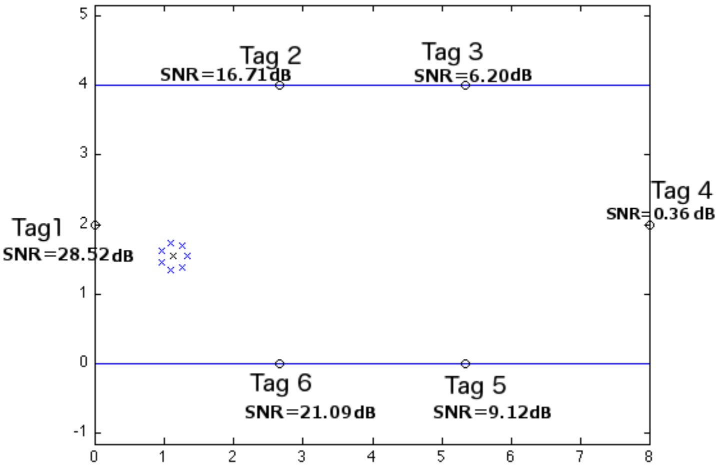

FIGURE 5.24: Example of SNR values for a reader position.

For the simulations the path the reader will follow is shown in Figure 5.25. In the simulations that won't be exactly the path. It will follow this shape, but will be more dense, in order to show also how the error is varying along the room following the two ways to obtain a final position.

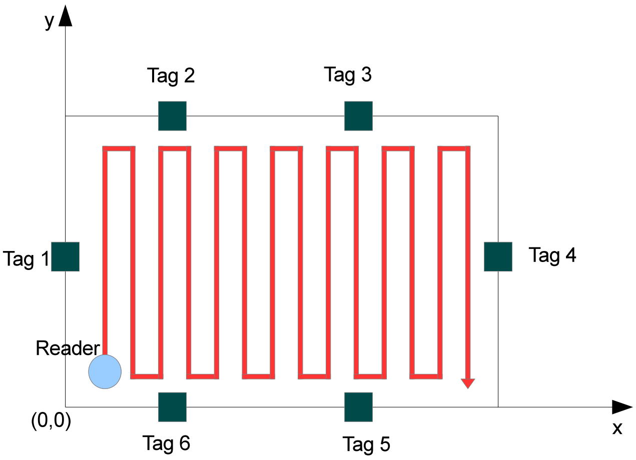

FIGURE 5.25: Path followed by the reader.

5.2.4.1 Known path

In the case the path is known, the choice of the final estimated position will follow the criteria of Least Square Fitting. That is, taking the current estimated position, check the all possible position some distance forward in the path, and some distance backward in the path. Then, checking all the estimated positions from the tags, the new position will be the one in the path with the least square fitting comparing with the estimated positions.

$$\text{LSF} = \sum_{i=1}^{n} \sqrt{(\widehat{x}_i - x)^2 + (\widehat{y}_i - y)^2} \tag{5.2}$$

Where n is the number of estimated positions. Thus, at the end, the position will be one of the spots checked inside the path around the previous estimated position, as shown in Figure 5.26.

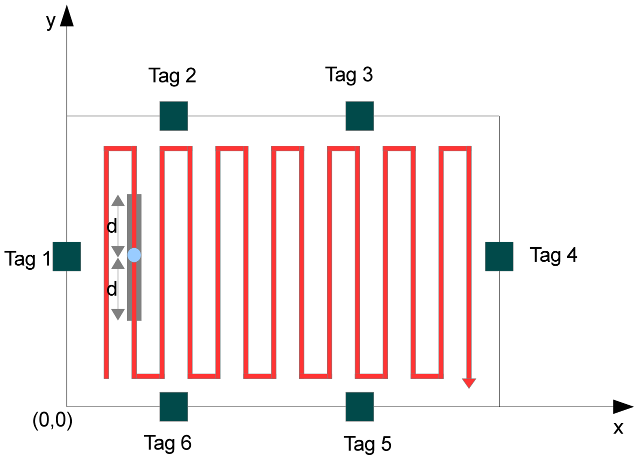

FIGURE 5.26: Example of LFS criteria with a previous estimated position.

Where the blue circle indicates a previous estimated position, and around it, and using the different points calculated with the information from the tags, will try to find a new estimated position.

Now, simulating the reader moving along the path, with the parameters shown in the Table 5.1, the error along the room will be shown in Figure 5.27.

TABLE 5.1: Parameters.

Signal Power	$500 \cdot 10^{-3}$ Watt
Noise Power	10^{-6} Watt
K	5 dB

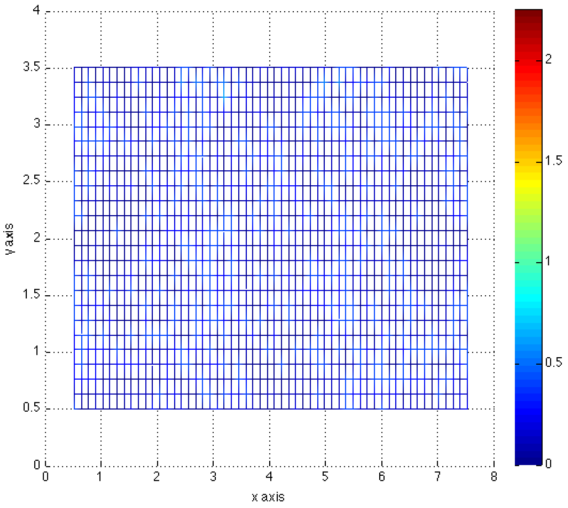

FIGURE 5.27: Error along the room with LSF (known path) with scale up to 2.2.

Now the same simulation is shown with a scale up to 0.75, in order to show clearly what is happening along the path.

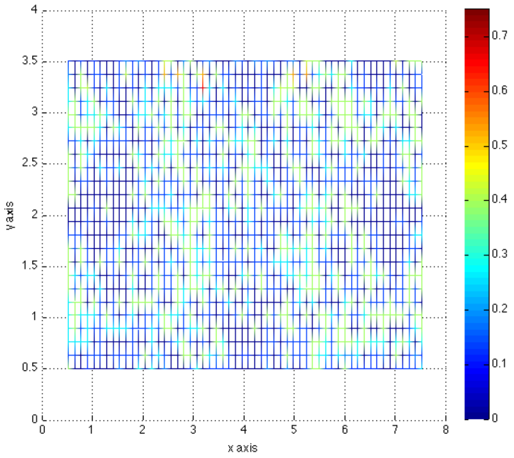

FIGURE 5.28: Error along the room with LSF (known path).

Figure 5.29 shows a example of the same simulation, but showing the error in three dimensions:

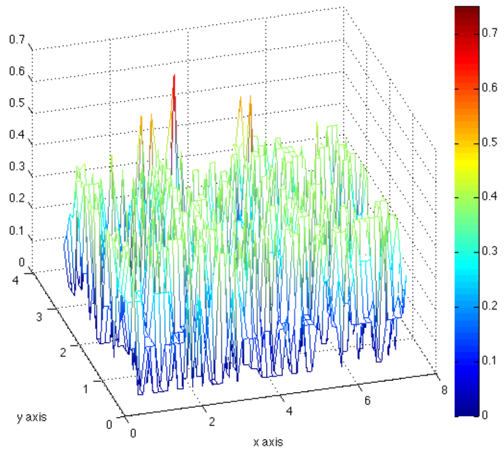

FIGURE 5.29: Error along the room with LSF (known path) in three dimensions.

Now, if the path chosen is not than dense (a path similar to Figure 5.25), the simulation following this path, and showing the error is shown in Figure 5.30. This figure is shown with two different scales, in order to make easier the comparison with the unknown path case.

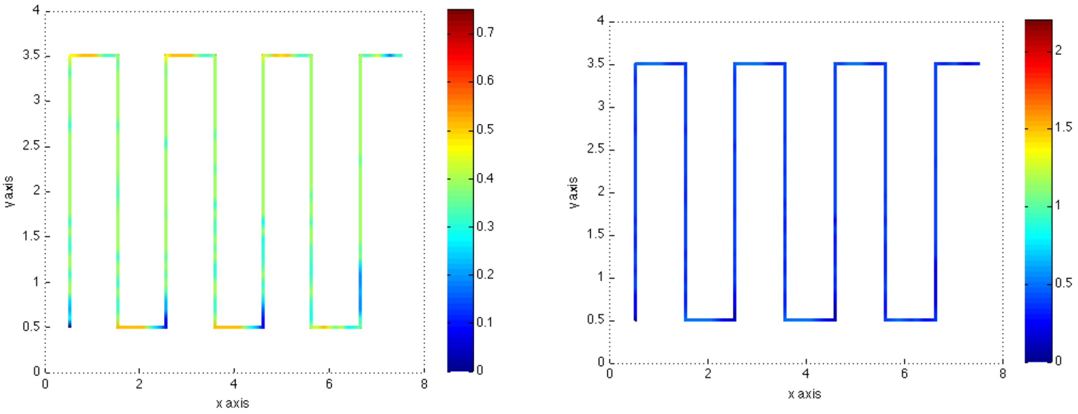

FIGURE 5.30: Error along the room with LSF (known path) in wider path.

5.2.4.2 Unknown path

The second criteria, in the scenario when the path is unknown, will be, once obtain all the estimated positions, compare with the previous final estimated position. Supposing the reader is moving slowly, that would be a good criteria due to the steps the reader is moving between interrogations are 0.125 meters.

The tag selection for estimate the position will be made by choosing the strongest signal in reception, supposing that one as the best signal incoming for the angle of arrival calculation. Then, choosing the second strongest signal, an estimated position will be calculated with the strongest signal and the second one. Then, choosing the third strongest signal, the same will be done. At the end, five estimated position will be found, and comparing with the previous final estimated position, the closest one to this position will be chosen.

Table 5.2 shows the parameters used for the simulation.

TABLE 5.2: Parameters.

Signal Power	$500 \cdot 10^{-3}$ Watt
Noise Power	10^{-6} Watt
K	5 dB

The error along the room for this case, are shown in the Figure 5.31.

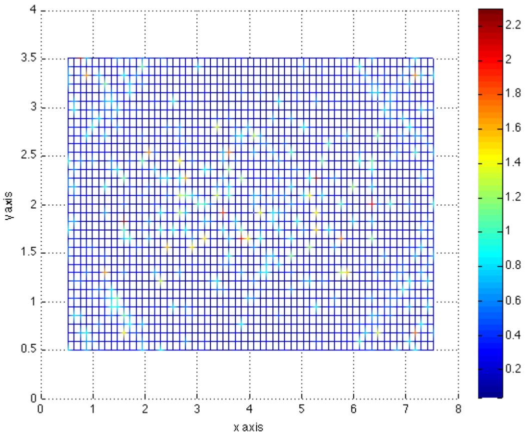

FIGURE 5.31: Error along the room unknown path.

Figure 5.32 shows a example of the same simulation, but showing the error in three dimensions:

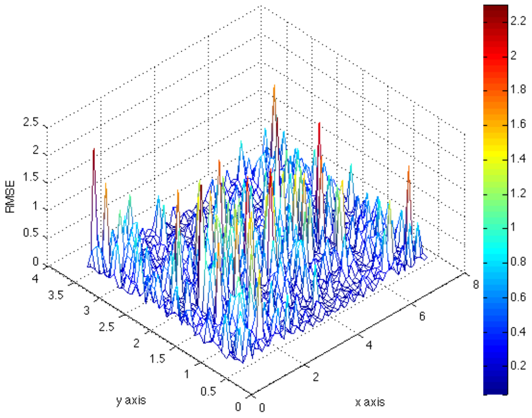

FIGURE 5.32: Error along the room (unknown path) in three dimensions.

Again, if the path chosen is not than dense, the simulation following this path is shown in Figure 5.33.

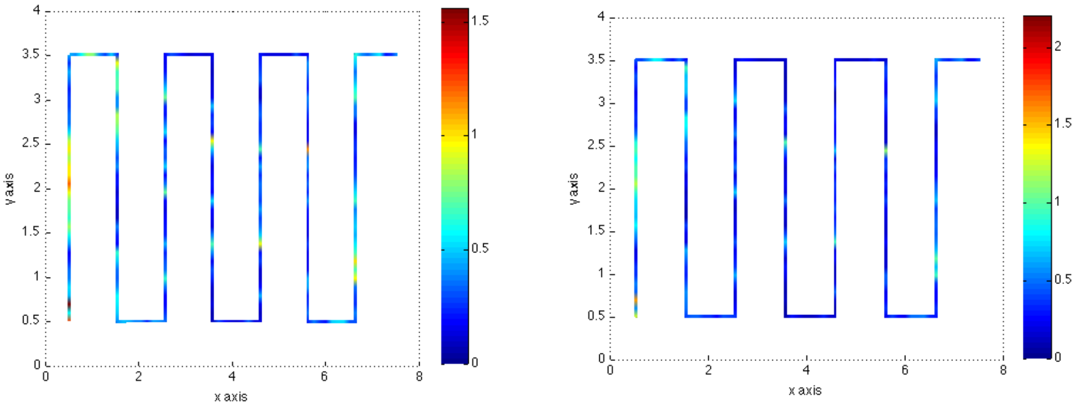

FIGURE 5.33: Error along the room (unknown path) in a wider path.

5.2.4.3 Comparison

Comparing both simulations, under the same conditions, it's easy to see that in the case of known path, the error is lower, with a good accuracy. The problem is that in a real scenario, normally, the path is unknown, so, if the reader is moving slowly, it's possible to track it, with a good accuracy, as Figure 5.31 shows.

Chapter 6

Conclusions

The first conclusion I reached is that, after testing different kind of antenna distribution to model the reader, the best option was the circular antenna array. This one had the best results in accuracy, and, moreover, the dimensions for this reader (using seven antennas, 0.3858 cm of diameter) is easy to implement in a device for testing, comparing with the linear array that had bigger dimensions (1.2125 meters, using seven receiver antennas).

Once checked the variation of the accuracy with the distance respecting two tags and started the simulations of the moving reader, I could say that in conditions of low line of sight (K<5 dB) is not possible to obtain a good estimated position, therefore, the simulation showed are for a K=5 dB, and the noise power is 10^{-6} Watts. With those parameters, the final results obtained in the simulations were suitable for obtaining a good results for the accuracy.

With respect to the two criteria I used to discard the bad estimated positions, the best result was obtained with the least square fitting. Although, this criteria is only valid if the path the reader is following is known. Therefore this criteria cannot be applied for a real case where the reader is moving without knowing the path. So, the second criteria, where the new estimated position is the closest one with the last estimated position, is a good option if the reader is moving slowly, and the time between interrogation from the reader is not so long. Otherwise the last estimated position will be far away from the new position of the reader, and then will be necessary some prediction about the new position of the reader. Even though this exceptions, the results with this criteria are good, resulting in the best option after studying these cases.

A way to continue in this line of investigation could be trying to find some way to predict the new estimated position, or maybe elect the tags in another way in order to obtain a better estimated position.

Appendix A

Simulations graphics

A.1 Simulation with known path

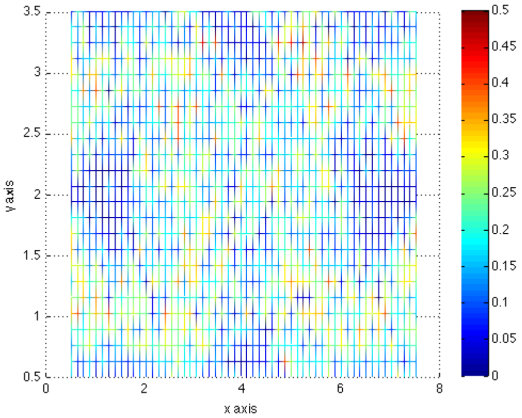

FIGURE A.1: Error along the room with unknown path, K=5, Noise power= 10^{-6}.

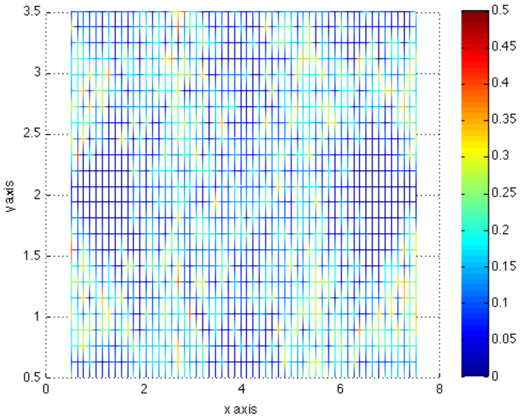

FIGURE A.2: Error along the room with known path, K=10, Noise power= 10^{-6}.

A.2 Simulations with unknown path

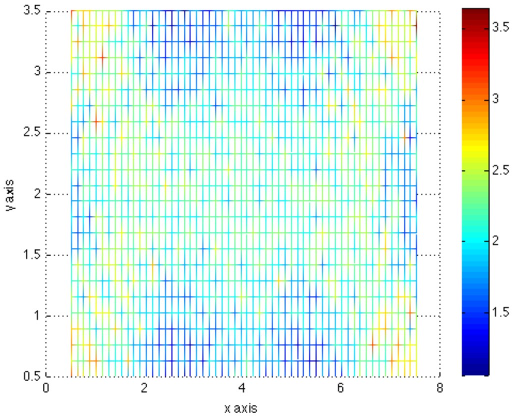

FIGURE A.3: Error along the room unknown path, K=-10, Noise power= 10^{-4}.

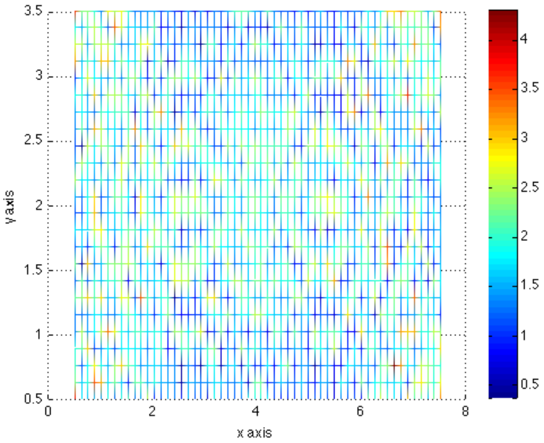

FIGURE A.4: Error along the room unknown path, K=0, Noise power= 10^{-4}.

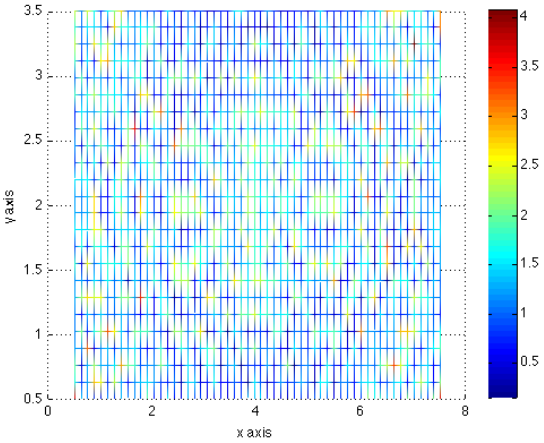

FIGURE A.5: Error along the room unknown path, K=5, Noise power= 10^{-4}.

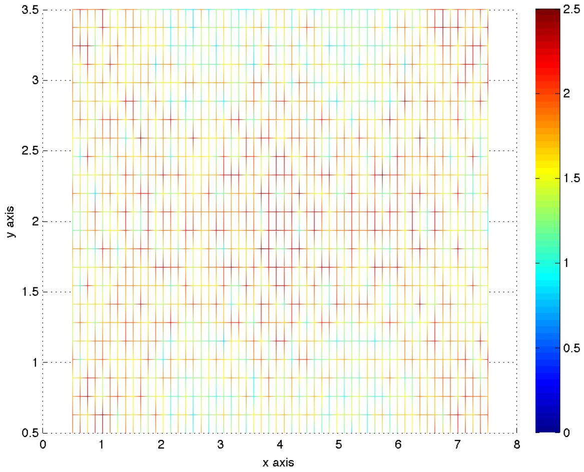

FIGURE A.6: Error along the room unknown path, K=-10, Noise power= 10^{-6}.

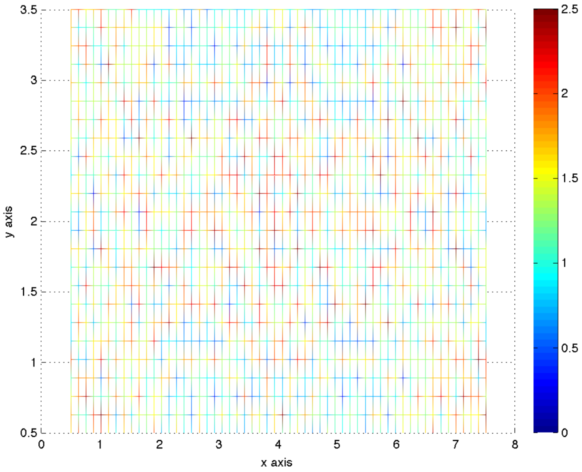

FIGURE A.7: Error along the room unknown path, K=-5, Noise power= 10^{-6}.

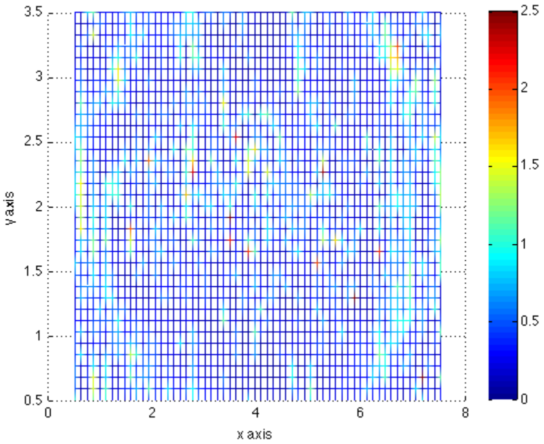

FIGURE A.8: Error along the room unknown path, K=5, Noise power= 10^{-6}.

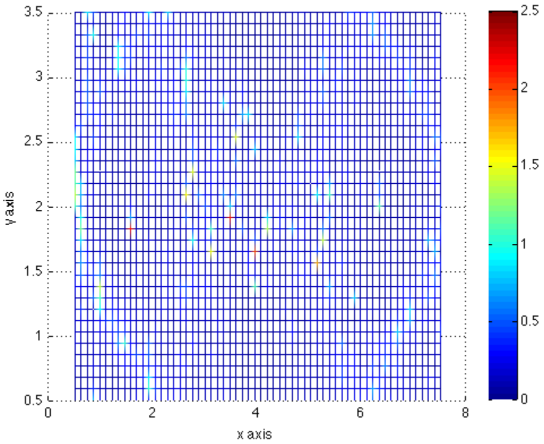

FIGURE A.9: Error along the room unknown path, K=10, Noise power= 10^{-6}.

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