UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola Tècnica Superior d'Enginyeria
de Telecomunicació de Barcelona

STUDY OF SCALABILITY OF PASSIVE AND ACTIVE SOLUTIONS FOR TIME-BASED RANGING IN IEEE 802.11 NETWORKS

A Master's Thesis

Submitted to the Faculty of the

Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona

Universitat Politècnica de Catalunya

by

Marta Malpartida Tablado

In partial fulfilment

of the requirements for the degree of

MASTER OF SCIENCE IN INFORMATION AND COMMUNICATION TEHNOLOGIES

Advisor: Israel Martin Escalona

Barcelona, September 2015

Title of the thesis: Study of scalability of passive and active solutions for time-based ranging in IEEE 802.11 networks.

Author:Marta Malpartida Tablado

Advisor: Israel Martin Escalona

Abstract

Wireless positioning systems have become very popular in recent years. Outdoor positioning has been addressed successfully, but location indoor present some issues, such as the scalability. The aim of this study is evaluate the scalability and latency of two time based ranging positioning algorithms. In order to reach this purpose a simulation tool implementing the IEEE 802.11 b/g protocol stack and 2-Way TOA and passive TDOA algorithms was built. Thus, a comparison of both algorithms is done for different scenarios. Those scenarios evaluate both techniques under two different mobility models, static grid and Gauss Markov, and two different environments: outdoor and indoor. Results show that Passive TDOA is more scalable than 2-Way TOA in all proposed scenarios.

This work is dedicated to my family and Sergi, who have been there when most I needed; to Israel Martin who made this Master thesis possible.

Acknowledgements

I would like to express my sincere gratitude to my thesis supervisor, Israel Martín, for giving me the opportunity to carry out my thesis, which has entailed a stimulating and rewarding challenge for me. It has enabled me to put into practice the knowledge acquired during my academic formation and of course, learn more and improve my skills. Therefore, I would like to thank him for his valuable guidance and his support and patience.

Moreover, I would offer my gratitude to my parents, who have always been concerned about my education, and also to my sister. All of them have celebrated with me the joys and have given moral support when I most needed it.

Finally, I would like to thank to my friends: Alex, Xavi, Marta, Ale, Jordan, Simon, Arantxa, and in particular to Sergi, who always have been by my side encouraging me and supporting me in the worst moments.

In summary, I thank everyone who has contributed to achieve my thesis because without all the support received it had been not possible to reach it.

Revision history and approval record

Revision	Date	Purpose
0	24/08/2015	Document creation
1	02/09/2015	Document revision

Written by:		Reviewed and approved by:	
Date	24/08/2015	Date	02/09/2015
Name	Marta Malpartida Tablado	Name	Israel Martin Escalona
Position	Project Author	Position	Project Supervisor

Table of contents

List of Figures

List of Tables

1. Introduction

More and more, users are interested in knowing their own position with their mobile devices so that they can use such information to enrich services and applications they regularly use (e.g. geolocating the pictures they take).

The services that somehow use the location of network users are known as Location Based Services (LBS). Some of them, give to the user a position where he or she is interested in. For instance, a restaurant near his position. Other well-known LBS are those related with navigation, i.e. those guiding the user from one position to another. GPS users frequently use navigation LBS, specially outdoors due to its high accuracy and availability. Also, these services are used to assist emergency services, owing to the fact that it allows to locate the patient and thus be faster and more efficient during the emergency call.

These services could be used in two different environments: outdoors and indoors. Several technologies can be used globally in outdoor environments, such as those based in GPS. However, the same does not apply to indoors, where there is no positioning technology that can be used everywhere. The industry and the research community are interested in providing a global technology for indoors. Several approaches were proposed in the last years. Most of them try to take advantage of communication networks already deployed to position the network users as well. This approach often simplifies the deployment of location systems and boost their availability.

As it is known, communication networks based on IEEE 802.11 standard are widely deployed indoors, which makes this technology really appealing for location systems. However, location systems using IEEE 802.11 technologies present several limitations in terms of accuracy, latency, scalability and integrity, specially those based on temporal observations. The aim of this thesis is study the scalability and latency of two positioning algorithms, 2-Way TOA and Passive TDOA, both working in IEEE 802.11 networks.

In order to achieve this target, a simulation tool implementing the 802.11 b/g protocol stack and the 2-Way TOA and Passive TDOA algorithms will be built. This approach allows the scalability and latency of these algorithms in WiFi networks to be properly studied. The aim is thus to see how many users can support the system and how long it takes until a position can be computed by the system. A comparative study between the positioning algorithms will be done to understand how both can be properly coupled. Finally, weaknesses to improved and future work should be identified.

2. State of the art of location technology

The most relevant location techniques and approaches are explained in this section. Since the amount of location techniques is noticeable large, only the techniques and approaches related to the topics studied in this thesis are taken into account. These techniques and approaches are classified according to several parameters to offer the reader a taxonomy of the techniques frequently used in the location field.

2.1. Classical Approach: Standalone

Standalone location techniques are those that are able to compute a position on their own, i.e. without the assistance of other network entities.

Location techniques can be generally classified in outdoor or indoor depending on the environment where the positioning is taking place. This also applies to the location techniques used as standalone. In the following two sections the main location techniques used in both environments are described.

2.1.1. Outdoors

The techniques described in the next paragraphs are employed in outdoor scenarios.

2.1.1.1. Satellite positioning

Some positioning systems use the satellites that orbit the Earth. Nowadays, the main positioning system that use satellites in order to search the location of users is the Global Positioning System (GPS).

GPS [1] uses the satellites of NAVSTAR network to locate mobile devices. In the NAVSTAR network, all the satellites are perfectly synchronized by means of atomic clocks.

Generally speaking, GPS devices require at least three satellites at sight to get a 3D position and two for a 2D position. Owing to the fact that normally the clock of the terrestrial device that the GPS system tries to locate provides poor accuracy (i.e. in terms of bias and jitter), one more satellite is required. This latter is used to synchronize the user clock with the NAVSTAR network clock.and provide thus more accurate positions. Accordingly, most of the time, three and four satellites at sight are required respectively to get 2D and 3D positions.

Although, it is well known that GPS technology provides high accuracy and good coverage, it has some weaknesses. One of them is the time that the device needs to load the NAVSTAR constellation map before attending the location requests. This lapse of time is called Time-To-First-Fix (TTFF) and it could last up to 12.5 minutes. Besides this, the GPS satellites and receivers have to be in line of sight. Therefore, the GPS system losses efficiency in scenarios like urban canyons [2] and indoors.

2.1.1.2. Terrestial positioning

There are several techniques which use already deployed terrestrial mobile communication networks to get the position of their users.

The simplest approach in this context is the Cell ID, which estimates the position using the knowledge of the location of the base station which the user is associated with. The availability of the location system is thus the same than the communication network. The main drawback is related with the accuracy, which is tied to the cell size. Therefore, the positioning error would be greater in rural areas, where cells are larger than in urban areas.

A variation of Cell ID is used and it is called Enhanced Cell ID [3] [4]. It provides better accuracy by coupling the cell information with addition dada available at the radio access network. One approach consists of estimating the distance to several base stations by means of the round trip time (RTT) information. Another approach consists of estimating the Angle-of-Arrival (AoA)/Direction-of-Arrival (DoA) of the radio signal taking advantage of the MIMO radio technology. The fusion of Cell ID and these data allow the accuracy to be improved, but frequently is not enough for attending most of the LBS demands.

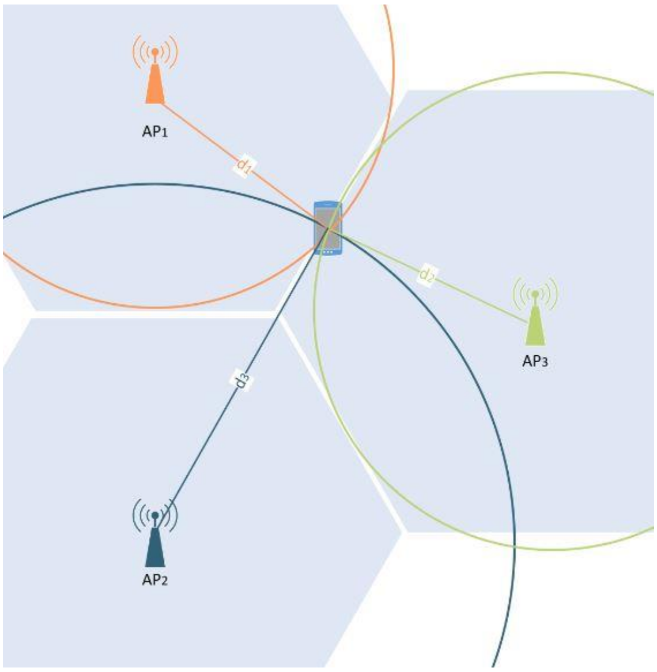

Figure 1. Enhanced Cell ID TOA method

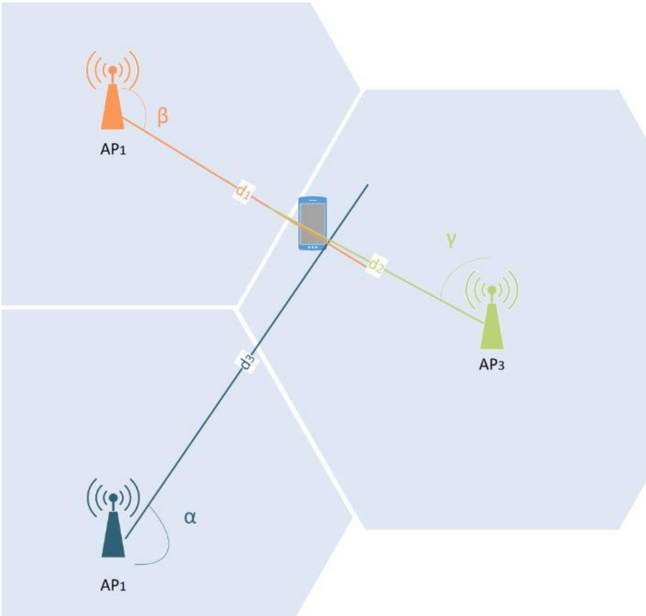

Figure 2. Enhanced Cell ID AoA method

Observed Time Difference of Arrival (OTDOA) [5] [6] is another example of technique used in Public Land Mobile Networks (PLMN) such as those based in UMTS and LTE technologies. In OTDOA, several base stations send a location signal to the mobile device to be positioned. The mobile device gather time differences of arrival of such signals. Then, it employs a hyperbolic multilateration algorithm to fix the user's position.

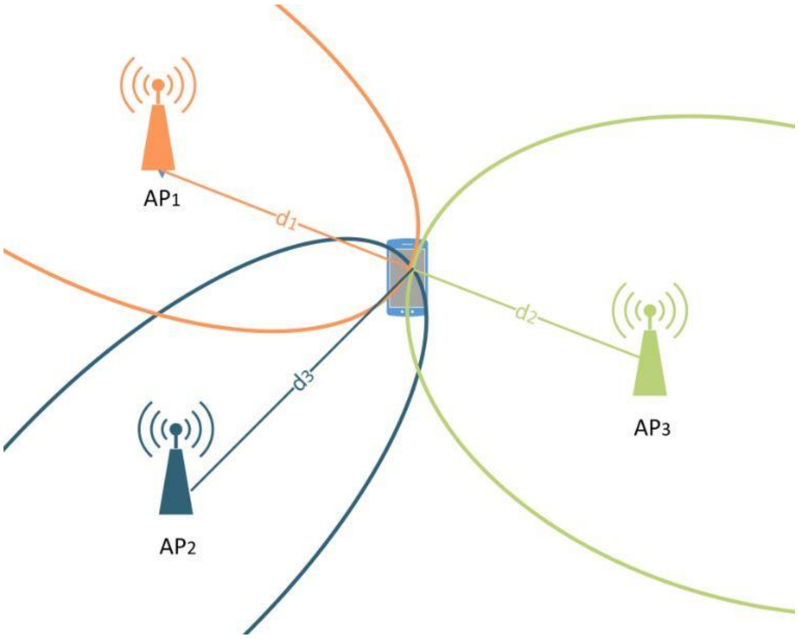

Figure 3. Hyperbolic trilateration due to OTDOA

2.1.2. Indoor

The following sections describe the main location techniques used indoors.

2.1.2.1. Proximity

Proximity algorithms rely on the fact that the device calculates its position by knowing elements around it. For instance the cell the device is attached to in a given time. In other words, this approach is based in the knowledge of the position of relevant elements, such as the access points in the case of IEEE 802.11 communication networks. When it detects more than one base station, several approaches can be taken: the target location is estimated according to the base station associated with the strongest received signal; coupling the positions of several base stations, etc.

2.1.2.2. AoA / DoA (Angle-of-Arrival or Direction-of-Arrival)

This technique [7] computes the device location by measuring the direction of arrival of a radio signal, as it is shown in Figure 4. In order to achieve a position it is necessary radio signals coming from at least two different base stations.

The main advantage of AoA is that no synchronization between the elements involved in the positioning is needed. Moreover, it usually provides excellent scalability. On the other hand, non-light-of-sight (NLOS) effects, such as multipath, degrade the performance and increase the positioning error.

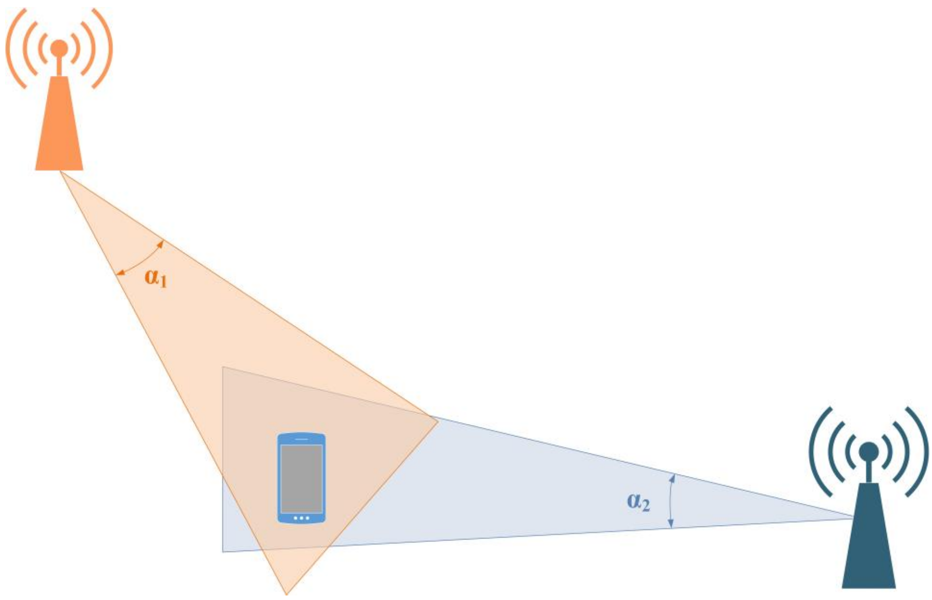

Figure 4. Positioning measuring AoA / DoA

In [8] the authors suggest to couple AoA and Received Signal Strength (RSS) measurements to mitigate the multipath effects on the resulting position. Their proposal involves the use of specific hardware added to IEEE 802.11 base stations, so that the angles and signal strength can be measured together and further coupled.

2.1.2.3. RSSI-Based Ranging

RSSI-based ranging techniques are those that compute positions according to mathematical models that are able to predict the distance from the signal strength measured in the device. During the process when a radio signal encounters an obstacle the following phenomena can occur: reflection, diffraction or absorption. To achieve better results the environment conditions are taken into account. When the distance estimation between the target device and three or more base station is known, the position can be estimated using multilateration algorithms. Past positions and additional information can also be used to refine the final position.

The main disadvantage of this technique is that very accurate propagation models are needed to properly estimate the radio propagation losses.

The authors of [9] propose an algorithm that uses real time RSS measurements to estimate the impact of multipath fading and other radio propagation effects in the received signal strength of IEEE 802.11 networks. The algorithm is able thus characterize the environment where the network is deployed and provide accurate RSSI values and hence better range estimations. Finally, multilateration approach is followed to fix the device's position.

2.1.2.4. Time-Based Ranging

Time-based ranging techniques use time metrics to estimate the distance from transmitters (e.g. access points) to the target node.

One example of this technique is Time-of-arrival (TOA), which is described in detail in the section 3.1 of this work. The location of the device is then the intersection of the circles generated from the propagation times from a reference node (e.g. a base station) to the target device, in the case of 2D positioning. The same applies to 3D positioning, where circles are indeed spheres. The following basic ranging mode, which relates the distance with the transmission time (t_{tx}) and the received time (t_{rx}) can be used to turn time measurements into distances:

$$d = c(t_{rx} - t_{tx})$$

The main disadvantage of this approach is that target devices and reference nodes must be synchronized. Also, accuracy depends on the Signal to Noise Ratio (SNR) of the received signal and the accuracy of the procedure followed to estimate the delivery times.

2.1.2.5. Fingerprinting

Fingerprinting is based on measuring the received power, as RSSI-based ranging. However, it is independent of the distance between the user device and the Base station.

In regard to the system operation, first of all, a database containing the Received Signal Strength (RSS) measured in the area of LBS is built. It has to be composed of enough measures, covering most of the locations where users are expected to be.

After the database is built, the system is considered completely deployed. To obtain the target position, an algorithm compares the reported RSS at user device with those previously stored in the database.

This technique it could be implemented as a software solution, in consequence it is no necessary to add hardware which reduce the implementation costs. The main drawback is that environmental features, such as presence of people or other obstacles, increase the difficulty to reach consistent RSSI-based ranges.

A fingerprint solution for IEEE 802.11, compatible with all manufactures of Wifi cards is proposed in [10]. To achieve this, during the building of the database a calibration phase takes place. Firstly, the authors of [10] normalize the collected measurements to identify the possible effects of walls and obstacles. Then, thanks to neural networks and the normalization of the measurements, it groups the data in clusters. The physical topology is also added to optimize the map. Finally, to determine the position it normalizes the measured RSSI and compares it with data base.

2.1.2.6. Assisted GPS (A-GPS)

Assisted GPS (A-GPS) was developed to improve the GPS performance, e.g. to improve the signal strength in those places where it is week or even unavailable. It uses additional information delivered by means of already deployed communication networks, such as WiFi networks, to improve the performance. This means decreasing the TTFF, increasing the sensitivity up to 20dB, which makes the positioning system to be available in light indoors, etc.

A solution that employs a mathematical algorithm to determine the best approximation of the target position, combining the position data obtained by GPS and WLAN location systems is proposed in [11].

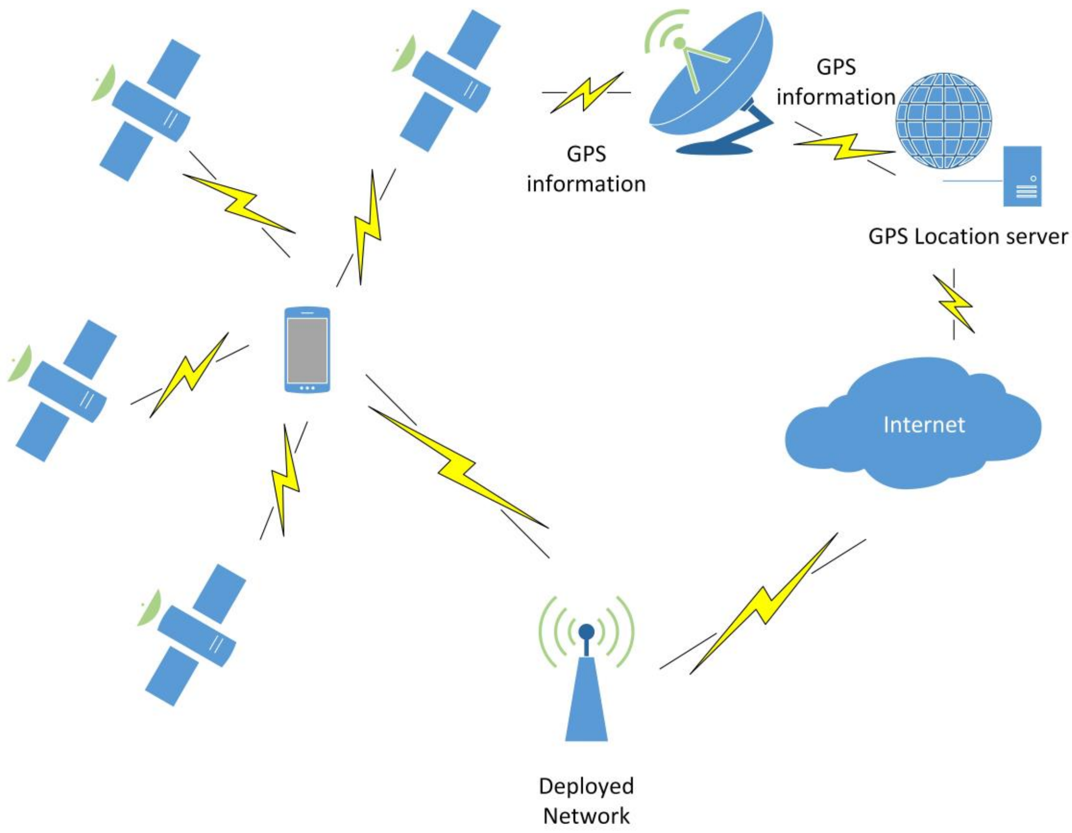

Figure 5. A-GPS performance procedure

2.2. Collaborative techniques

Location systems could be classified as beacon-based or beacon-less [12], according to the use of reference nodes in the system. Both concepts are described below:

2.2.1. Beacon-Based Localization

In these type of systems there are nodes in the network which position is known, because they have their own location capabilities. These nodes are called beacons, and the nodes which initial position is unknown are called unknowns. The unknown nodes compute their position measuring some metric related with the beacons. For instance using ranging based or proximity techniques, such as TOA [13] or Cell ID [14] and the known position of beacons in the same coverage area.

2.2.2. Beacon-Free Localization

In beacon-free localization systems the position of all nodes are initially unknown. In consequence, they have to collaborate with each other in order to reach their own position. For instance, nodes implementing the Passive TDOA algorithm, which is deeply described in section 3.3, listens to the network traffic sent by neighbor nodes to compute

TDOAs used finally to fix their own position following a hyperbolic multilateration approach.

3. Location Techniques Under Study

In this mark two location techniques are evaluated: 2 way-TOA and Passive TDOA

3.1. 2-Way TOA

2-Way TOA [15] determines the target position measuring the propagation time. As it is shown in Figure 6, the node measures the RTT. In order to do it, a packet in time t_1 is sent and when this packet is received by the station it sends an acknowledgement, which is received in time t_2. Then, the distance between the node and the access point is calculated using the following formula:

$$d = c(t_{rx} - t_{tx})$$

Once the distance between the node and several base station is known, a multilateration algorithm is run to resolve the node location.

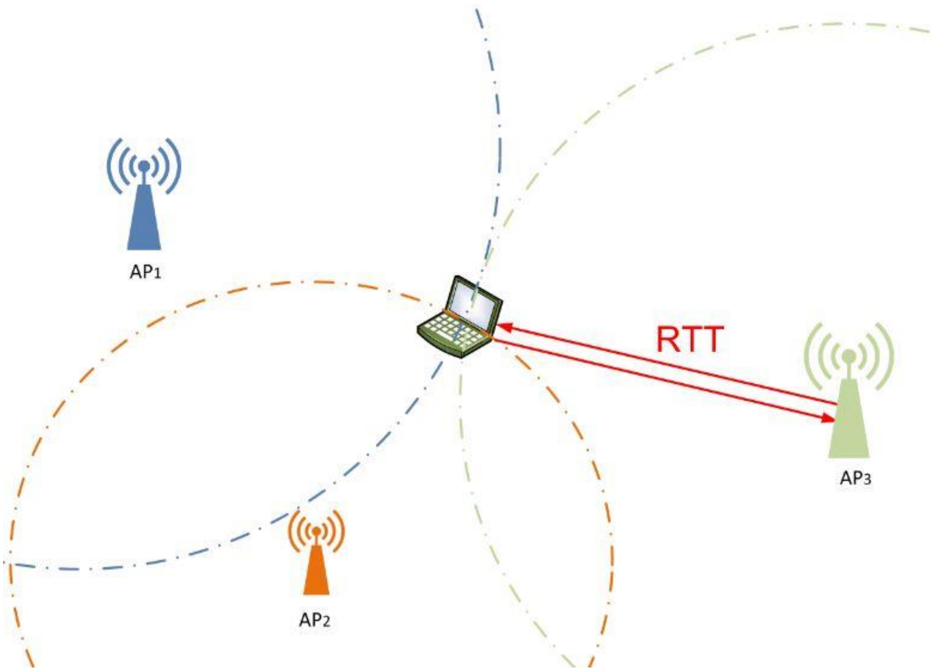

Figure 6. 2-Way-TOA

To achieve 2-D position at least three base stations are needed. In addition, it generates location traffic in the network, which leaves less bandwidth to other services.

In NLOS scenarios, because of the multipath, the distance computed is often not the one corresponding to the direct path. Consequently, the computed positions present a bias that must be further removed.

The main advantage of 2-Way TOA technique is that the measure and the calculation is done by the same clock. Thus, no synchronization between nodes and access points is necessary.

3.2. Passive TDOA

Passive TDOA [16] algorithm allows to locate a node using the information of neighbor nodes that are calculating its position by means of the 2-Way TOA technique.

The simplest scenario where Passive TDOA could be implemented is the one make up with four base station, one active node and one passive node, as depicted in Figure 7. In this scenario the active node gets its position using 2-Way TDOA and the passive node uses the passive TDOA algorithm to fix its own location.

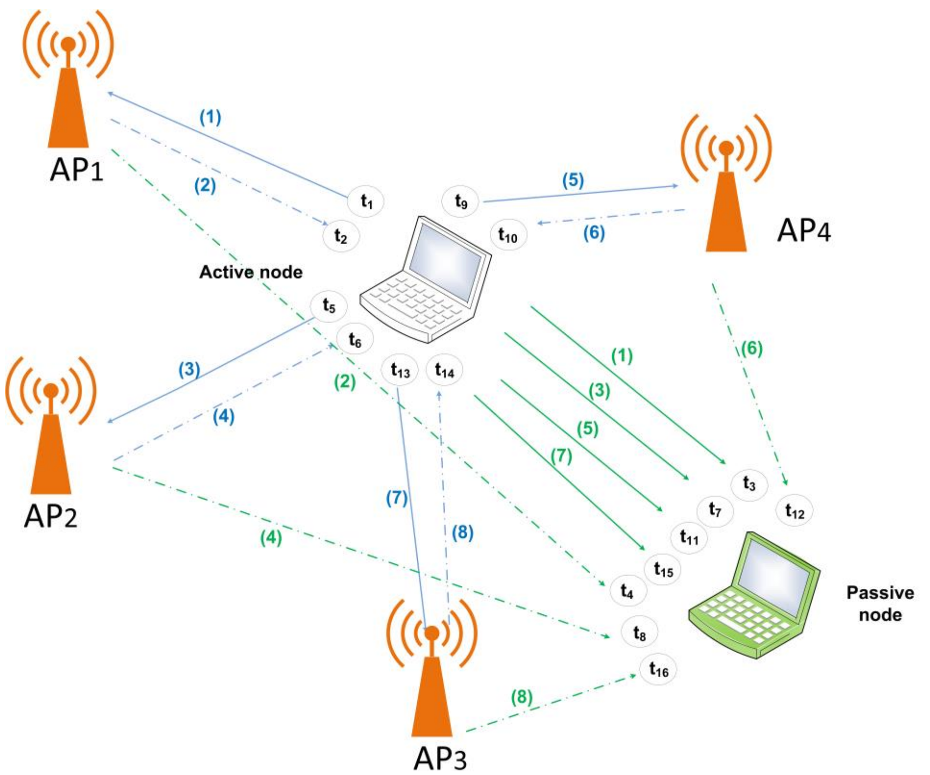

Figure 7. Passive TDOA location technique

The location process starts when the active node obtains its position using 2-Way TOA technique. Meanwhile, the passive node is listening to the radio medium and receiving those messages that the active node exchanges with the access point. Figure 7 illustrates the performance of the algorithm. The active node sends a message (1) to the station 1 in time t_1 and receives a response (2) from the base station in time t_2. From this two messages the active node is able to compute the distance to the access point. At the same time, the passive node receives the messages (1) and (2) at times t_3 and t_4

respectively. With the difference of these times, a hyperbola representing all the possible locations of the passive node is obtained. Consequently, the algorithm obtains a set of time differences to calculate the position of the passive node by performing a hyperbolic multilateration.

As it is explained, Passive TDOA is able to obtain a location without injecting traffic in the network. Also, thanks to the fact that uses the information from active nodes, it can achieve a position with at least one base station. Therefore, it could be used in dark areas, i.e. those where nodes cannot reach a position using 2-Way TOA [17] because not enough access points are at sight. Finally, in the Passive TDOA algorithm, such as in the 2-Way TOA one, all the time measurements take place at the node, so no synchronization with the access points is needed.

4. Simulator

4.1. OMNETOMNET++

OMNET ++ [18] an open-source network simulator framework is used to evaluate the scalability of 2-Way TOA and Passive TDOA in IEEE 802.11 networks. This software is based in Eclipse and NED/C++ programming languages.

OMNET simulation models are structured in networks which are then divided in modules, either simple or compound. Simple modules define a network action. On the other hand, compound modules are modules that consist of several simple and/or compound modules. Compound modules are thus used to build complex actions. Modules are communicated by gates. As it is shown in Figure 8 simple modules are in the lowest layer of module hierarchy.

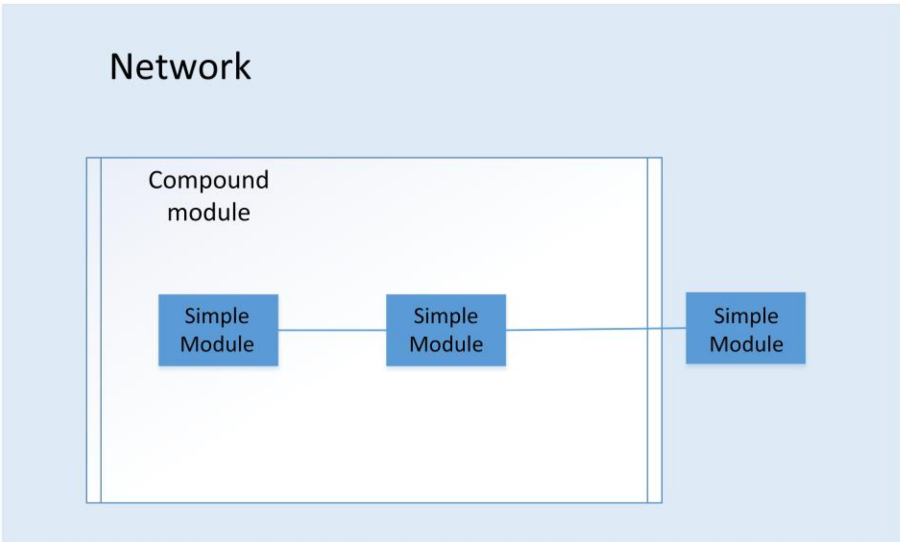

Figure 8. Module hirearchy

The topology of the network is defined in *NED* Files. The modules involved in the simulation scenarios could be added in *NED* file using the graphical mode or the textual mode.

How simulations should be executed and simulation scenarios are described in the configuration file, usually called *omnetpp.ini*.

When a simulation is run, the OMNET ++ first read the *NED* file and configuration file. Simulation results are recorded into two different files: output scalar files and output vector files. The extension used by these files is *.sca* and *.vec* respectively. First contains summary results, such as number of collisions. Second are time series data computed from simple modules, i.e. round trip time. Both files start with a header where the following information is written: the network NED type name, the values of iteration variables and the repetition counter, the date and time, the host name, configuration options and so on. Also, the data is recorded on vector files in data lines which begins with the vector id. Which made easier to extract the data in which the user is interested in. Finally, the files are composed by line oriented text that could be analyzed by other programs, such as Matlab.

4.2. INETMANET Framework

The INETMANET framework [19] contains IP and transport protocol implementations for OMNET ++. Furthermore, it implements several link layer models, such as IEEE 802.11, and several routing protocols as well. It also provides support for multiple radio models and several mobile patterns.

It follows the same structure than ONNET++. It is divided in modules that exchange messages to communicate between them. In this case, network devices, such as routers and hosts, are modeled as compound modules. Protocols and applications are modeled as simple modules. Thus, INETMANET is organized hierarchically according to the TCP/IP protocol stack. However, not all modules are protocols, for example Control Channel. This module is informed about the location and movement of nodes and determinates which nodes are within the communication.

4.3. Implementation on the simulator

Several parts of the code of the INETMANET framework have been modified in order to implement the 2-Way TOA and the Passive TDOA algorithms. To be able to know which nodes are active or passive a function that allows to difference it in *omnetpp.ini* file and during the rest of the code had been create. It is called *Ieee80211Location.h* and defines the location technique parameters. Depending on its value the node has: no location technique, 2-Way TOA or Passive TDOA.

4.3.1. 2-Way TOA

In the 2-Way TOA algorithm, two measures of the transmission time have been done to evaluate the performance of the algorithm, as it is shown in Figure 9. One of them measures the transmission time t_{tx} before the CSMA/CA procedure (T1) and the other is just before of sending the frame to physic layer (T2). The timestamp of received time (T3) is done at the same point in both cases, once the frame enters in the reception function of MAC layer.

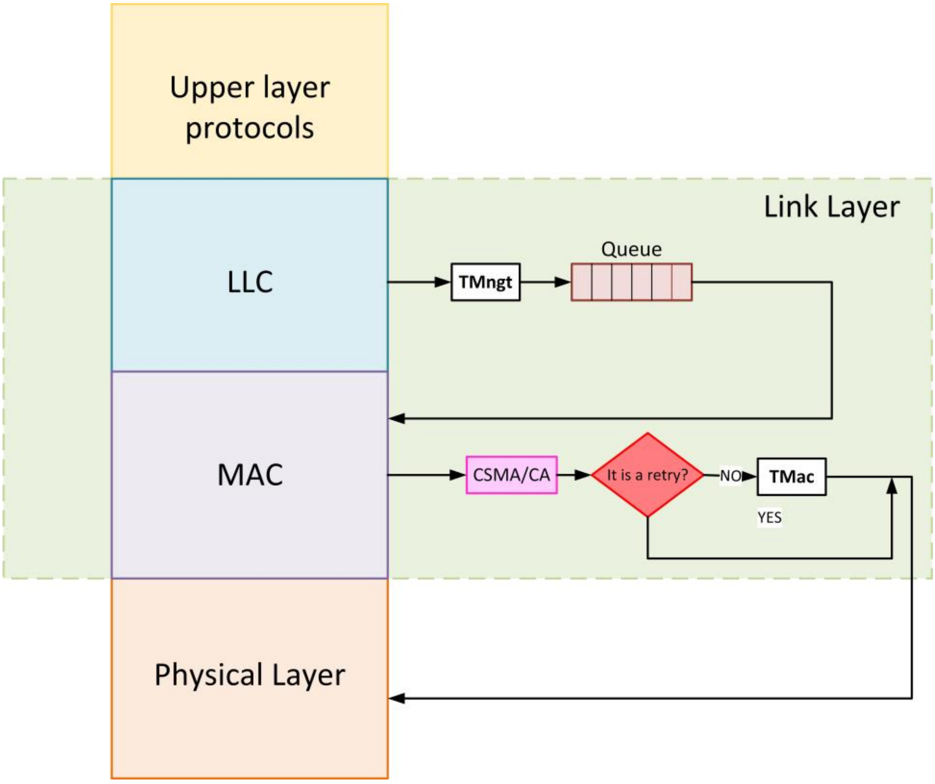

Figure 9. IEEE 802.11 protocol stack

The first time (T1) is measured in *Ieee80211MngmtSTATSimplified.cc* in the *handleUpperMessage* function. First, if the node is an active node is checked and if in the packet the time stamp is added or not. If it is not, the transmission time in Management function is added (T_{tx1}).

The second transmission time (T_{tx2}) is determined in Ieee80211Mac.cc in *SendDataFrame* function. After checking if the node is an active node and if T_{tx2} has been added before or not. In case that it is not added it is set in the data frame. In addition, in this point of the code the position of the active node at this moment is also stored in the data frame as *inipos* parameter. In order, to calculate the distance that the node go over during the process of estimating the RTT.

When the frame arrives to the access point the transmission times has to be copied to *ACKFrame*. First of all, it is ensured that the frame is from the AP and has *Ttx1* and *Ttx2*. Then, the timestamps are loaded in the acknowledgement.

All this process is done at *IEEE80211Mac.cc* in the *buildACKFrame* function.

Finally, the RTT is computed in *Ieee80211Mac.cc* in *HandleLowerMsg* function. First, if it is an ACK frame, if it is for the node and if it is an active node are checked. Then, the RTT is calculated as the current simulation time minus T_{tx1} for *RTT MNGT* and minus T_{tx2} for *RTT MAC*. The values are recorded in two vectors: *RTT MAC* and *RTT MNGT*. The algorithm produce as many vectors as active nodes.

Also, the distance is computed in the same function as current position minus initial position that was previously added in the data frame. This values are saved in *DIST TOA* vector. It is generated one vector for each active node.

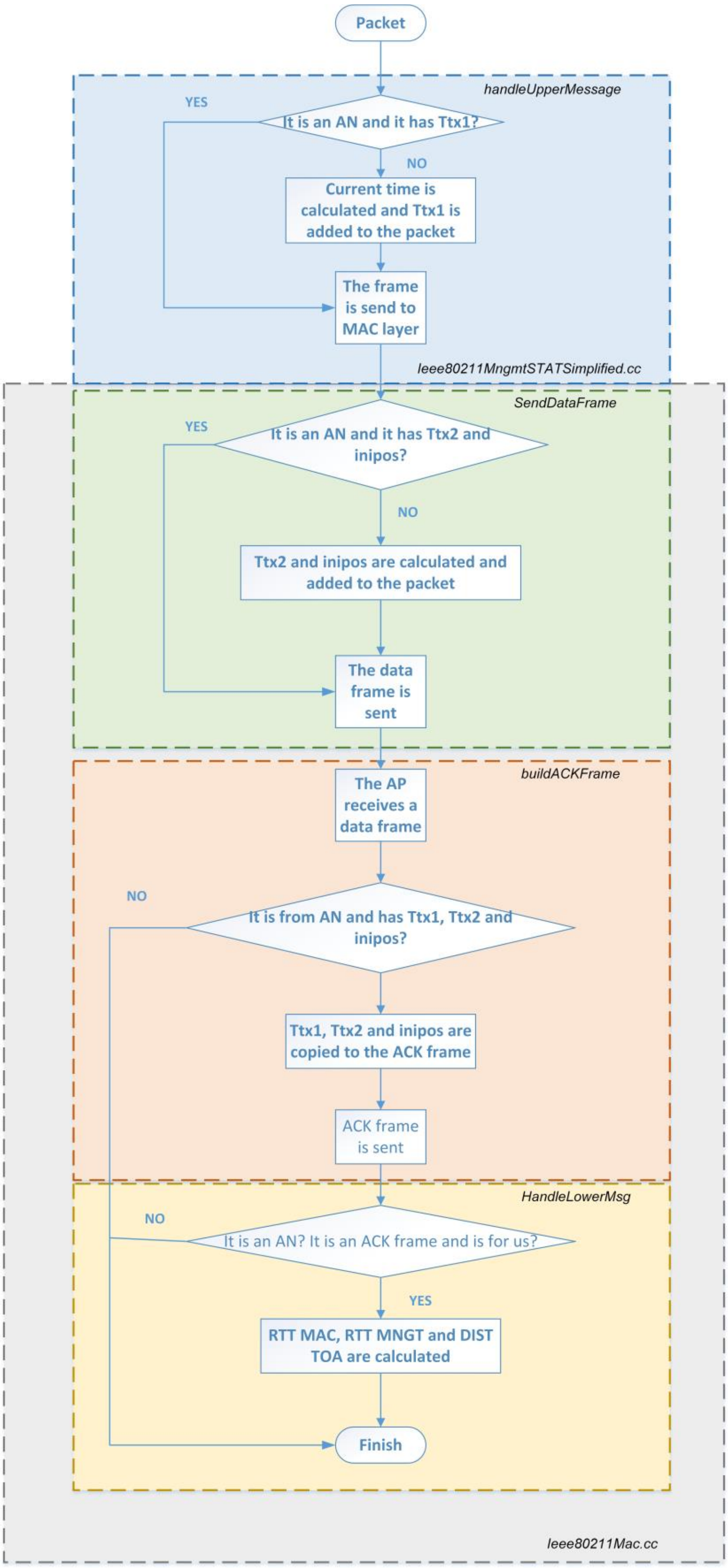

Figure 10. 2-Way TOA flow diagram

4.3.2. Passive TDOA Implementation

Due to the fact that Passive TDOA obtain timestamps listening a single 2-way-TOA process, it is implemented in the reception function of the MAC layer (*Ieee80211Mac.cc*, *HandleLowerMsg*). Figure 11 presents a flow diagram of Passive TDOA implementation. First, if node is a passive node is checked. Then, if the data frame listened is 2-Way-TOA traffic and it is from the active node to an access point is determined. The position of the passive node and the current simulation time are stored as *posini* and *pTDOAFirststamp*.

Even though, if the frame is an ACK and is 2-Way-TOA traffic the TDOA and the distance that the passive node go over during performance of the algorithm are calculated. The TDOA is assessed as the current simulation time minus *pTDOAFirststamp*. Before, saving the value in a vector the system checks if for the MAC of the active node which will receive the data frame exists a TDOA vector. If it exists the value will be recorded on it if not a new vector related with this MAC will be created. The process to store the distance is the same, first the system checks if it exists a TDOA vector for this active node MAC, if not one will be created.

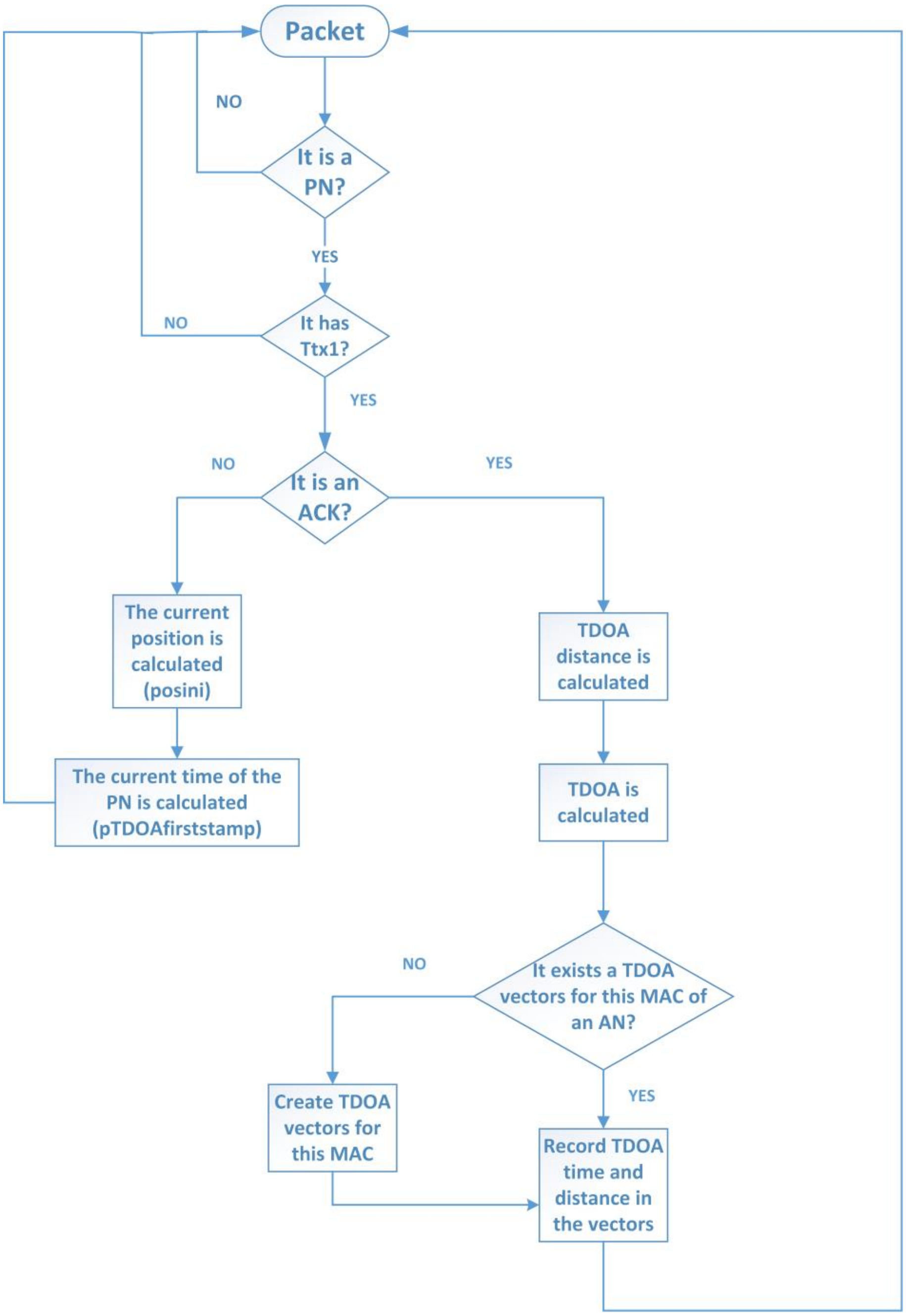

Figure 11. Passive TDOA implementation flow diagram

4.4. Script for analyse .vec files

OMNET++ stores all vectors created during simulations in a *.vec* file. However, the variables needs to be analyzed as separate vectors. In order to extract the vectors to analyze them later with Matlab, a script was created. It is called *extractvectors.sh*. The following parameters are used to know which is demanded by the user:

- *s*: This flag allows to the user to include a filter, such as "*DIST TOA*". The vectors matching with the filter will be extracted from the input file and saved in the output folder.

- *f*: With this optional flag the user provides a file which includes the filter strings which the user is interested in.
- *i*: It indicates the *.vec* file which gather the target data.
- *o*: it provides the folder in which the extracted information is going to be stored. If the folder does not exist, it will create it.
- *t*: It indicates that the time when the information was stored will be written.

As it is shown in Figure 12 ,first parameters are read. Then, *.vec* file is read in order to find if the filter values are on it and obtain the vectors IDs associated with each filter key. Finally, it reads again the file in order to gather the values of each vector ID and save them in separately vectors in the output folder.

For instance, if it is executed *./extractvectors.sh –s"DIST TOA" –ifile.vec –oresults*. It will extract as many "*DIST TOA*" vectors as active node were defined in the simulation and it will be saved in results folder. This procedure makes easier the process of analyze later the results with Matlab.

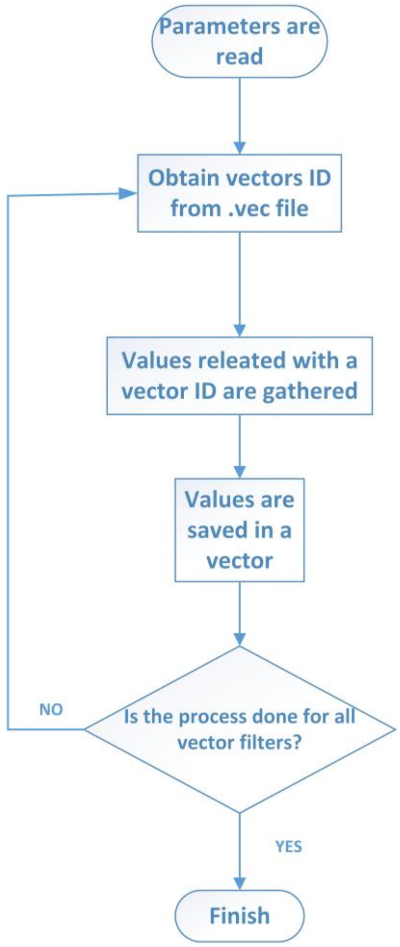

Figure 12. Extractvectors.sh flow diagram

5. Scenarios

To evaluate the scalability of the 2-Way-TOA and the Passive TDOA in IEEE 802.11 networks, eight scenarios are defined. They consist of one access point which is situated in the up left part of the simulation area and twenty six nodes.

The active nodes are sending pings to node zero, which does not have location capabilities. The ping cadence is 10ms. The amount of active and passive nodes change from one active node and twenty four passive nodes, until twenty five active nodes and none passive node. The IEEE 802.11b standard is used in simulations, although the results can be easily applied to other standards such as 802.11g or n.

Simulations are done in standard conditions. The scenarios could be divided in free space and indoor. For each environment two different type of simulations are launched: static and pedestrian.

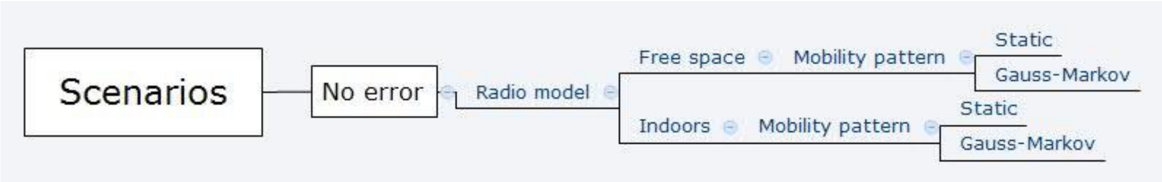

Figure 13. Scenarios scheme

With *no error free space static* scenario, the performance of the algorithm is evaluated in a free space environment and all the nodes remain in the same position during all the process. For this reason, radio path alpha is 2 and the maximum distance which the AP is capable to transmit is approximately 250m. It has been calculated with the following formula:

$$PL(dB) = PL(d_0) + 10\alpha \log\left(\frac{d}{d_0}\right) + X_\sigma$$

Where, P_r is the received power, P_t is the transmitted power, G_r and G_t are the gain of the transmitter and receiver antenna, λ could be calculated as the speed of light (c) divided by the carrier frequency. All the values are defined in Table 1.

P_r	P_t	G_r	G_t	f
-85dBm	3dBm	0dB	0dB	2,4GHz

Table 1. Radio parameters

To evaluate more realistic scenario the simulation has been calculated for coverage radio of 50m. Thus, the simulation area is a square of 70.71m x 70.71m dimensions.
The mobility model is static grid mobility. It positions all the nodes in rows and columns and with the same separation between them, as it is shown in Figure 14.

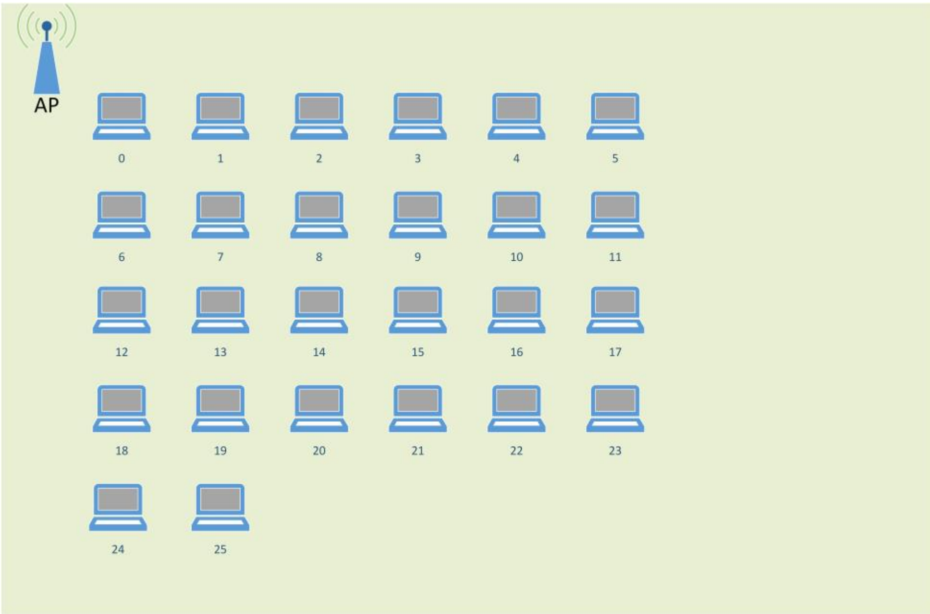

Figure 14. ***No error free space static scenario***

The *no error free space pedestrian* scenario has the same simulation area than the static and same performance values except the mobility model. This scenario is defined with the purpose of evaluating the performance of the algorithm when nodes are in movement.

Gauss Markov mobility model [20] have been chosen to model pedestrian movement. In this model, the speed of the node is modeled as a Gauss Markov stochastic process.

where and are the speed vector at time t and t-1 respectively. is the uncorrelated random Gaussian process with mean 0 and variance σ^2. , and are the vectors that represent the memory level.
As it is shown on the formula, the node has an initial speed and direction and are randomly changed at certain intervals of time. The node speed is defined as a truncnormal random variable, of mean 1 m/s and a standard deviation of 0.3m/s. The variation of the angle follows a uniform distribution between 0 and 360 degrees. The parameter alpha should be between 0 and 1, and it defines the degree of randomness in the mobility pattern. In this case α is 0.6. The variance is fixed to 0.325. Finally, the margin is an established distance to the boundaries of the simulation area. When, one

node arrive to the margin it is shifted 45 degrees to avoid going out of the simulation area, it is fixed to 1m.

Speed		Angle	α	$σ^2$	Margin
μ	**Std**	0º<x<360º	0.6	0.325	1m
1m/s	0.3m/s				

Table 2. Gauss Markov Mobility Model Parameters

The aim of indoor scenario is to evaluate the performance of the algorithm in deep indoor environments. In order to reproduce the behavior of the radio channel indoors, the lognormal shadowing propagation model [21] is chosen. It models random shadowing effects that might occur during the radio signal propagation and impact on the estimation of the computed location. It follows the equation:

where PL is the average path loss, $PL(d_0)$ is the path loss at reference distance d_0, α is the path loss exponent and $X_σ$ is a zero mean Gaussian distributed random variable with standard distribution σ.

α and σ are fixed to 4.02 and 7.36dB respectively. They are taken from a study [x] that calculates those values for IEEE 802.11 wireless networks in indoor environments.

The coverage radio of the base station is fixed to 10m and the dimensions are 7.07m x 7.07m, so that the rest of parameters of the radio model are equivalent to the free-space scenarios. This coverage and density conditions are similar to those present in a Wireless Sensor Network environment, which is one of the target applications of those location algorithms. Accordingly, the reduced simulation area was maintained and no other radio parameter was modified.

Finally, with this conditions simulations are done for two defined mobility models: static grid mobility and Gauss Markov mobility.

6. Metrics

In order to study and evaluate the performance of 2-way-TOA and Passive TDOA the following metrics are defined:

- **Delay until RTT.** It is the time that active nodes need to obtain enough RTT samples to calculate their position.
- **Delay until TDOA.** It is the time that passive nodes need to get enough TDOA samples to reach their position.
- **Distance from RTT.** It is the distance that an active node go over during RTT measurement.
- **Distance from TDOA.** It is the distance that the passive node go over during TDOA calculation.
- **Number of collisions.** It is the number of collisions that each node are aware during the simulation process.
- **Number of active and passive nodes. T**he number of active nodes increases from one until twenty five each simulation. At the same time, the number of passive nodes decreases from twenty four until zero each simulation. This metric allows to evaluate how many active and passive nodes are supported by the system without losing accuracy.

7. Procedure

Procedure followed to get the results is described in Figure 15. First of all, the scenarios with the values proposed in section 5 should be defined in OMNETpp.ini file. After this, the number of active and passive nodes should be set in the scenario that is going to be simulated. The number of active nodes start from one active and finish at twenty five. The passive nodes decreases from twenty four until zero. The following step is run the simulation. Then, the script which divide the obtained .vec file in vectors that contained the data for further analysis later on is executed. This process is repeated for each scenario until one simulation is done for all possible values of active and passive nodes.

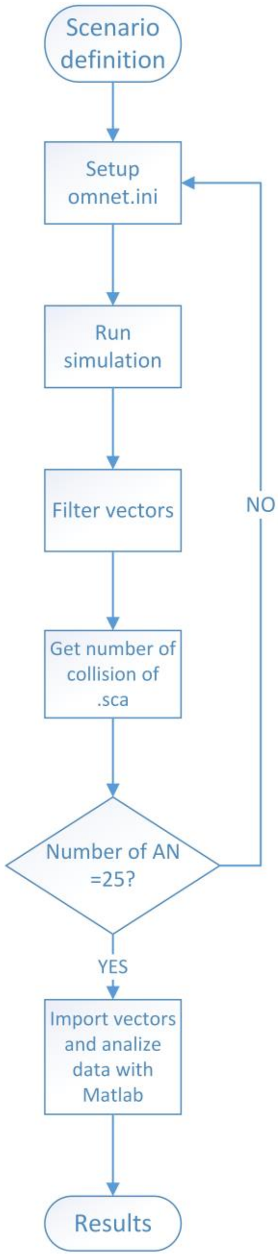

Figure 15. Simulation procedure flow chart

Different functions were done to import and analyse the data in Matlab. *Read_data.m* import the vectors files, such as *RTT MNGT*.txt* or *TDOA(time)*.txt*, to Matlab and then store the values in matrixes. These matrixes have the following dimensions: samples by nodes.

Different functions were programmed to obtain the following metrics and analyze the results.

- **Average:** It express the central or typical value of the data set.
- **Standard deviation:** Quantify the amount of variation of the data values. In other words, it is used to know if data values are concentrated or spread around the mean.
- **Median:** It is the central value when the data is ordered from the maximum value to the minimum value.
- **Percentiles at 25%, 50%, 75%:** The percentile at certain percentage of a set of data is the number such that percentage of data is less than that data.
- **Inter Quartile Rate (IQR):** It is the difference between the percentile at 25% and the percentile at 75%. This describe the spread of a set of data.
- **Histogram:** It is a graphical representation of the distribution of numerical data.
- **Ks- density:** It computes a probability density estimate of the samples in the data vector.
- **Confidence interval at 95%:** It determines the interval where the set of data should be with an error of a 5%. Due to the fact, that some metrics have less than fifty sample, like number of collisions, the central limit theorem could not be apply and the confidence interval could not be calculated as a normal distribution. Tstudent is used instead to compute the confidence interval.
- **Relative error:** It is determined as the confidence interval divided by the average.

8. Results

On the following paragraphs the results obtained from the simulations are explained. The different scenarios described on previous sections are analyzed and compared.

Furthermore, two location algorithms are contrasted, 2-way TOA and Passive TDOA. In order to discuss the scalability and the performance of one algorithm that injects location traffic on the network and other one that is able of reach its target position just listening the traffic on the network. How the number of nodes of one algorithm influences on the other algorithm it is also describe in this section.

In addition, the results achieve due to the two selected mobility patterns are compared between them. Also, the difference between the two environments, outdoor and indoor, are analyzed.

The analysis of the results is done using the metrics described in previous sections. Each simulation is done until get the enough samples that included all the possible values for the simulated scenario. Following this approach for static scenarios in order to evaluate the worst case for each simulation the active node and the passive node which are far away from the access point is selected. For pedestrian scenarios it could be assumed that the nodes are randomly positioned, in consequence all nodes are independent and the results obtained for each node are statically equal.

8.1. Free space scenario results

On the following sections the results obtained for the two scenarios performed in free space are presented.

8.1.1. No error free space static scenario results

The 2-Way TOA results are presented in Figure 16. It shows of measuring the round trip time in active nodes using the two metrics presented in previous sections, i.e. considering the transmission time before the CSMA/CA algorithm is run (RTT MNGT) and just before sending the data frame to the physical layer (RTT MAC). Both metrics are then compared.

On Figure 16, it is observed that the RTT MNGT, the one measured before CSMA/CA, grows faster than RTT MAC. This is due to the fact that data frame is inside a queue before entering in the MAC Layer and should wait its turn until previous frames can access to radio medium (i.e. cross the MAC sublayer).

According to data in Figure 16, 2-way TOA measurements such as RTT MNGT are not scalable and can involve a huge error in terms of positioning. RTT MAC on the other hand, seems to be much more stable, but often IEEE 802.11 hardware do not allow to take such kind of measurements.

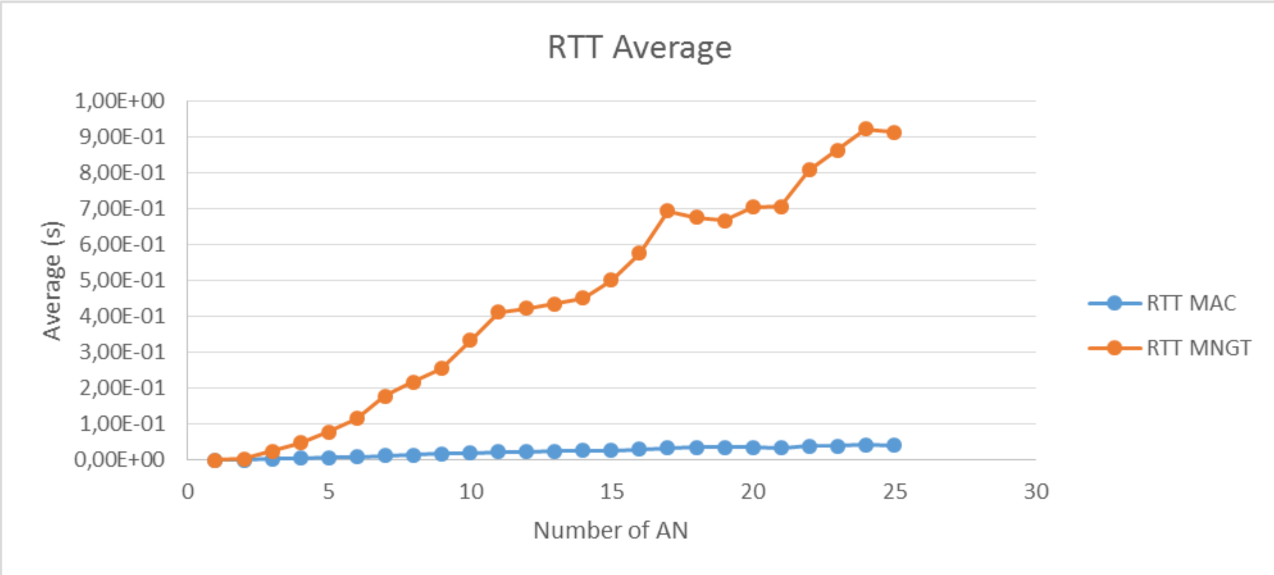

Figure 16. Average of RTTMNGT and RTT MAC

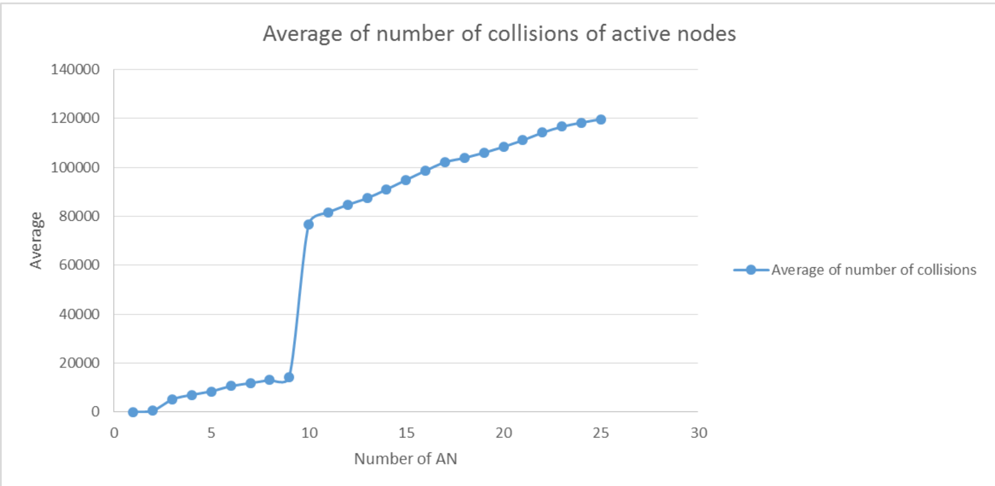

Figure 17. Average of number of collisions of active nodes

Figure 17 shows the average of number of collisions on TOA nodes. As it was expected the number of collisions increases with the number of active nodes present in the network. This is because active nodes injects location traffic on the network and consequently the amount of collisions increases. Moreover, the larger the number of collisions the longer the backoff period.

All these factors influence on RTT MNGT calculations. RTT MAC is more stable, because just after the transmission time is set, the frame is sent to the physical layer. In consequence its results are only influenced by the number of collisions.

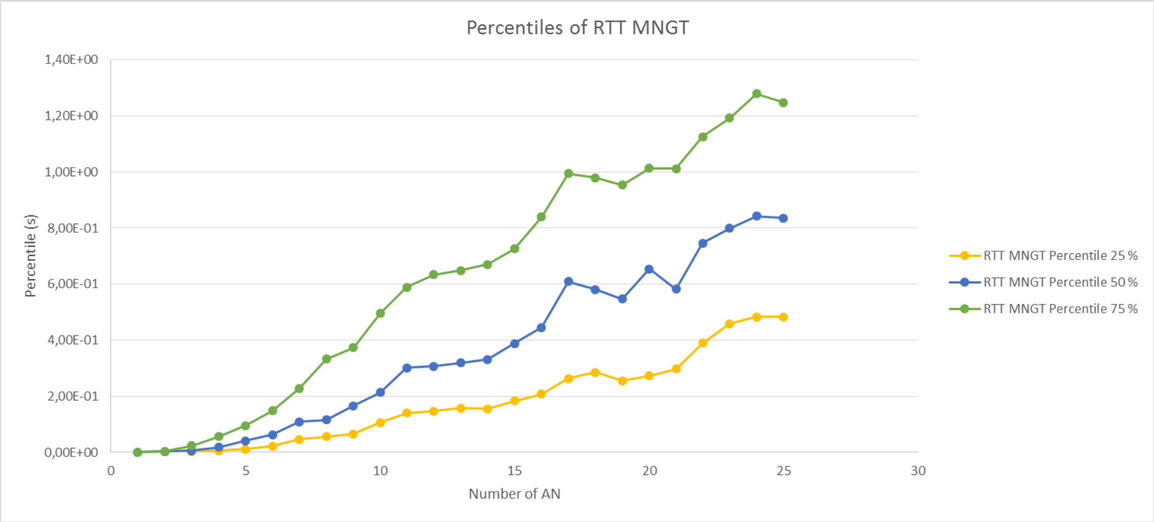

Figure 18. Percentiles of RTT MNGT

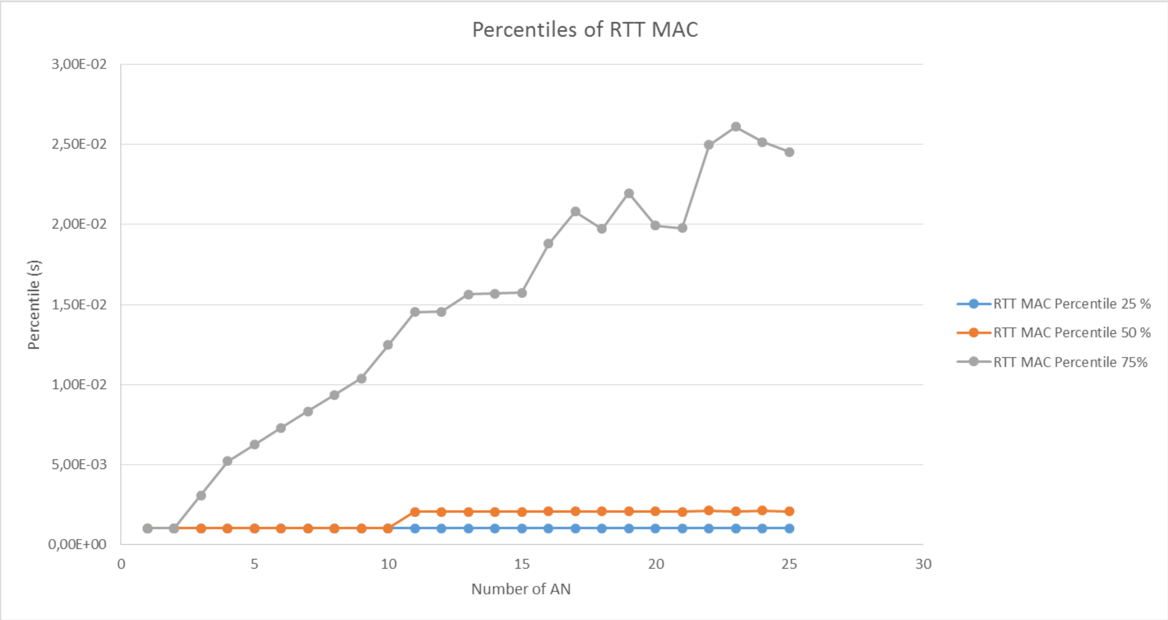

Figure 19. Percentiles of RTT MAC

Figure 18 and 19 presents the percentiles for the RTT MNGT and MAC metrics respectively. On Figure 18 is it observed that the RTT MNGT is more stable between 1 and 15 active nodes. In addition, Figure 19 shows that percentiles of RTT MAC at 25% and 50% are mostly the same from 1 active node until 15 active nodes. This means that in this interval, the 50% of the results are quite stable and equal to the estimated average. During this interval the growth of the percentile at 75% is more stable as well.

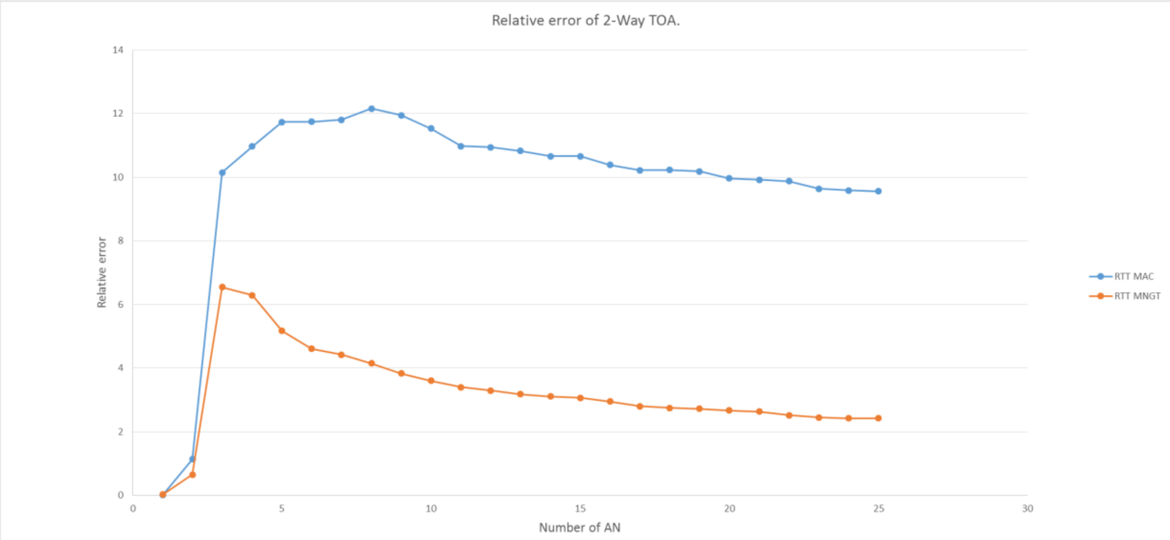

Figure 20. Relative error of 2-Way TOA RTT

Figure 20 shows the relative error of the two RTT measurements of 2-Way TOA Algorithm. If the relative error obtained in both metrics is compared, it is observed ion Figure 20 that both of them quickly increase from 1 active node until 3 active nodes and tend to decrease when the number of nodes increase. In RTT MNGT the maximum error is 6.5% and it is achieved with 3 active nodes. For RTT MAC, the maximum error is with 8 active nodes and it is 12.16%. It seems to be is much higher than for the case of RTT MNGT. This is due to the fact that the relative error is calculated as the confidence interval divided by the average. Both confident intervals are similar but RTT MNGT average values are higher than the RTT MAC which lowered the relative error.

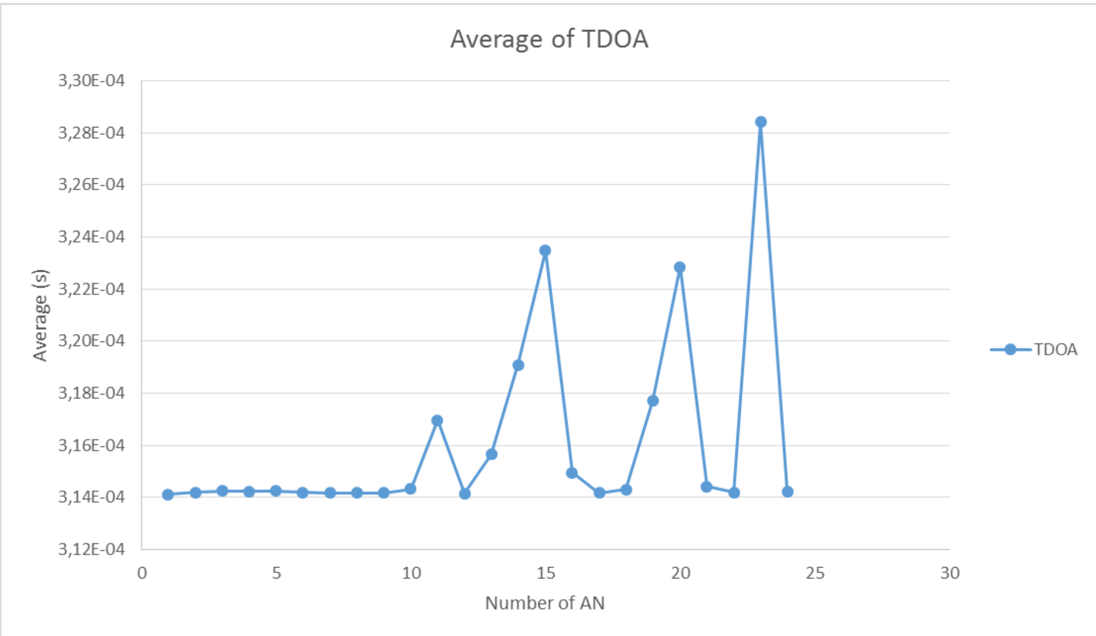

Figure 21. Average of TDOA results.

Figure 21 plot the obtained average of TDOA measurements for each number of active nodes. Passive TDOA measurements are shown to be very stable for an amount of actives nodes up to 10. Anyway, passive TDOA seems to provide better performance than 2-Way TOA. As it is shown in Figure 21, the maximum difference between TDOA measurements are in order of hundred of microseconds. This is due to the fact that the backoff period barely impacts the passive measurements and the computational time of the TDOA is less than in 2-Way TOA.

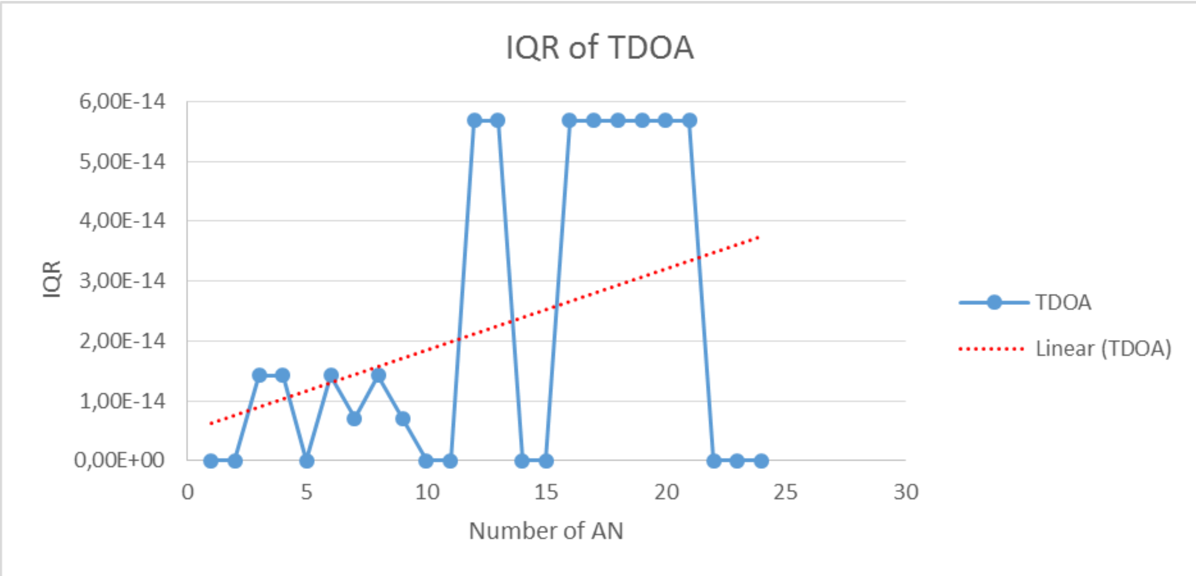

Figure 22. IQR calculated from TDOA values

On Figure 22 the IQR calculated for the different obtained TDOA values is presented. On Figure 22 it could be observed that TDOA data is very stable and it is quite insensitive to the number of active nodes in the network. Red line is the linear regression which shows that the IQR values will increase with the time.

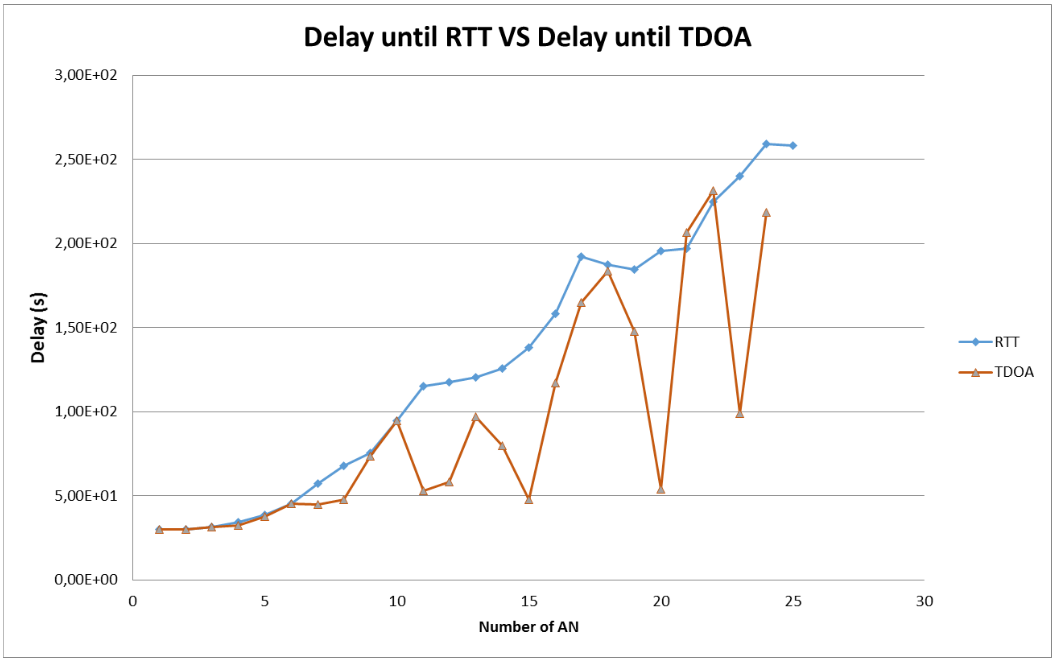

Figure 23. Delay until RTT VS Delay until TDOA

Figure 23 shows the time needed to achieve the enough samples to position the user. From 1 active node until 7 active nodes the time is less than 1 minute, which is reasonable. The Passive TDOA measurements are less stable, because not all passive TDOA listens the same number of collisions. It depends on the node location if it is able to listen the collision or just noise. This later happens when the collision signal strength at the node is below the sensitivity of the wireless receiver.

8.1.2. No error free space pedestrian results

Figure 24 shows that RTT MNGT values are higher than RTT MAC values, as in the case of the static scenario presented above. It is consequence of the backoff period and the queue situated before of entering on the MAC layer.

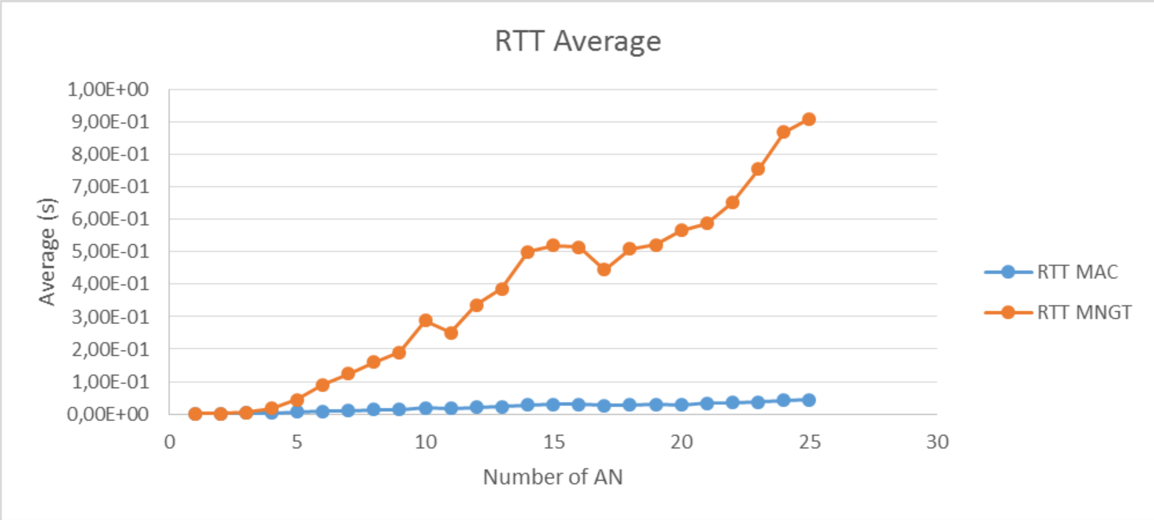

Figure 24. Average of RTT MNGT and RTT MAC of pedestrian scenario

Figure 25 compares the results of the simulations done with nodes deployed in a static grid and the scenario where nodes follow a Gauss Markov mobility pattern. In the case of RTT MAC measurements, the performance is almost the same. On the other hand, the results for RTT MNGT measurements on the static scenario are higher, but involve more stability. It is because in pedestrian scenario, nodes move randomly around the simulation area and location techniques could perform different depending on the place where the position is being computed.

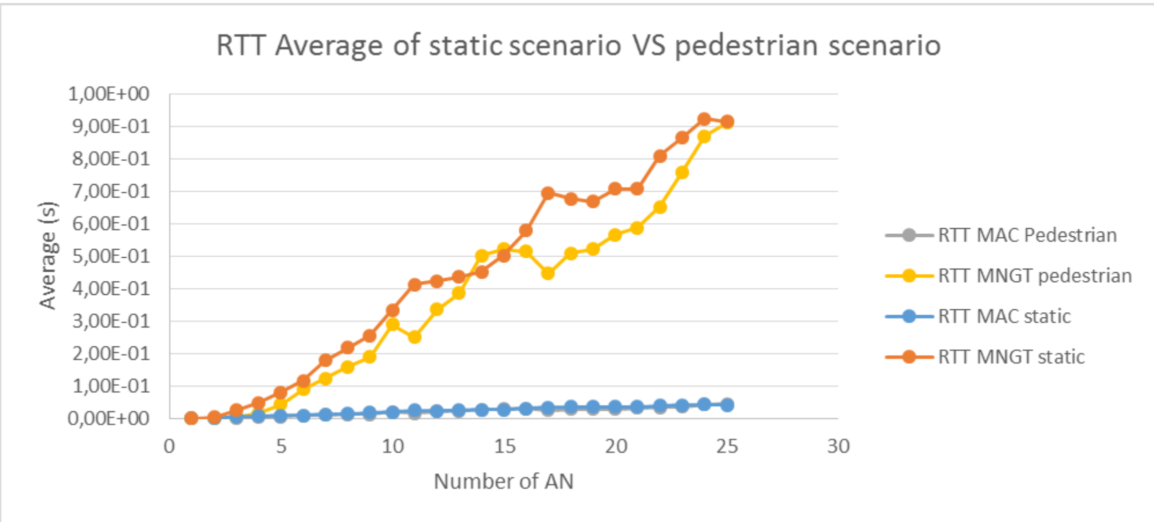

Figure 25. RTT average of static scenario Vs pedestrian scenario

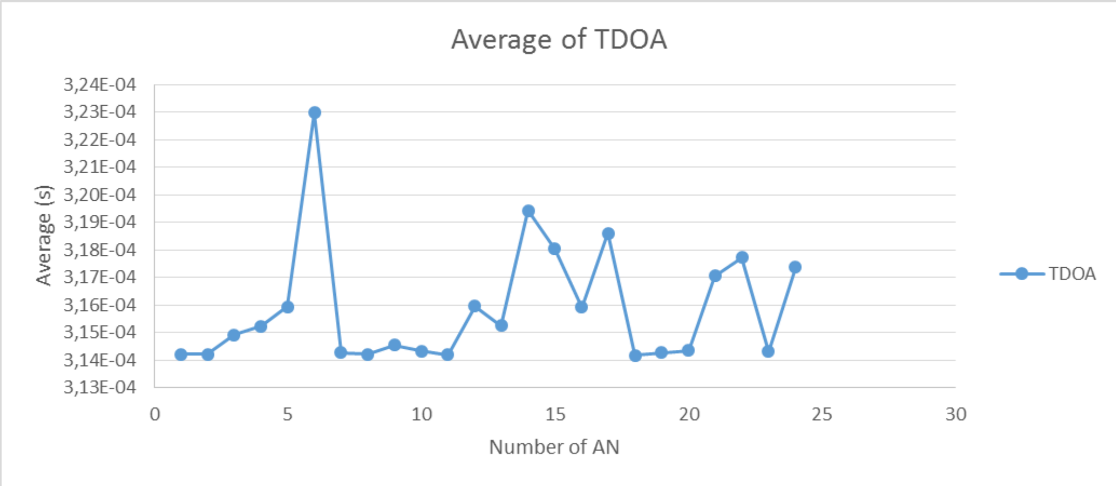

Figure 26. Average of TDOA

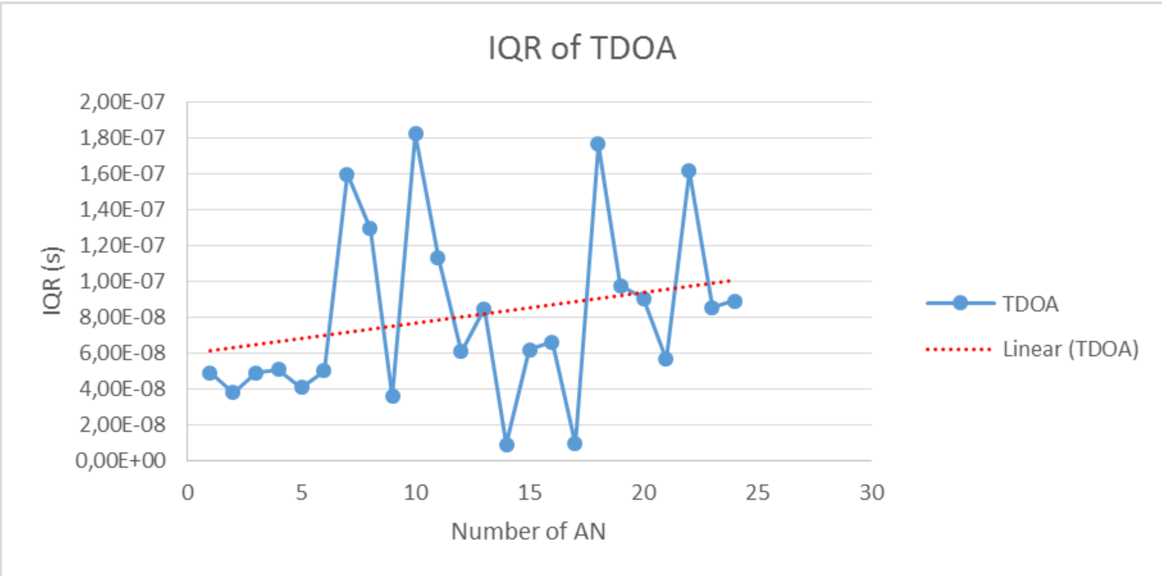

Figure 27. IQR of TDOA

Figure 26 and Figure 27 displays the average of TDOA and the IQR calculated based on this TDOA measurements respectively. Figure 26, are less stable than in static scenario, because the position of the node changes at a certain time. Also, all TDOA the difference between different TDOA measurements are in the order of microseconds, which means that Passive TDOA is also insensitive to the number of nodes in the network when Gauss Markov mobility pattern is implemented. Even though, Figure 27 shows that the values are concentrated around a central value and linear regression increases moderately, which means it is stable.

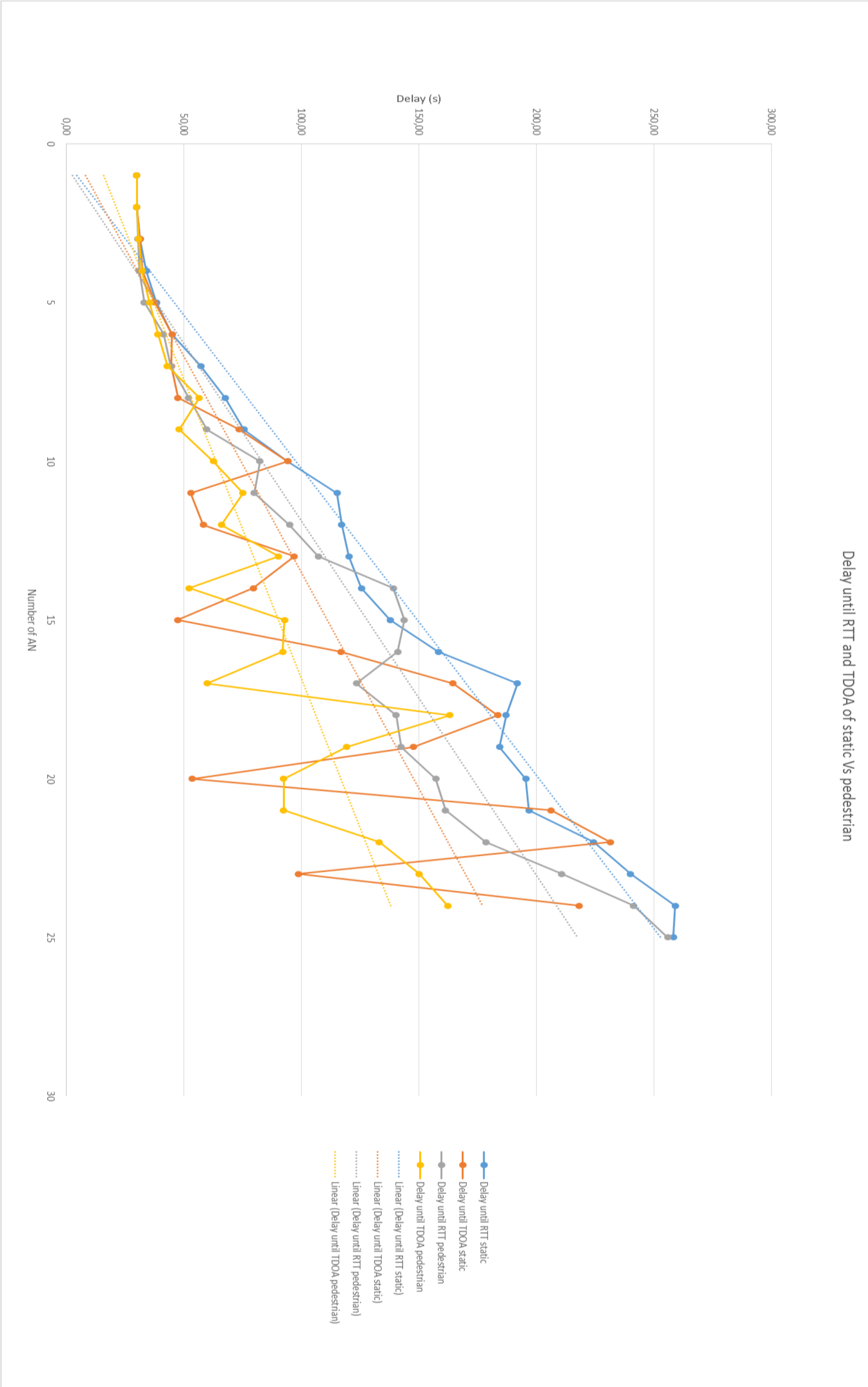

Figure 28. Delay until RTT and TDOA of static Vs pedestrian

The time needed until enough samples are available for positioning is shown in Figure 28. In both scenarios, this delay is mostly stable until 5 active nodes are set up for positioning. It's worth to notice that values in the pedestrian scenario are less stable because they are randomly moving around simulation area, which changes continuously the reception conditions and hence the delay until enough samples are gathered. Linear regression (discontinuous lines) shows that evolution of the delay over the number of actives nodes. It shows that static scenario is more influenced by the number of collisions because they are not moving around the simulation area, thus the station is always fixed on the worst case meanwhile in pedestrian scenario the nodes are moving and could be in a part of the simulation area with best conditions to reach the target position.

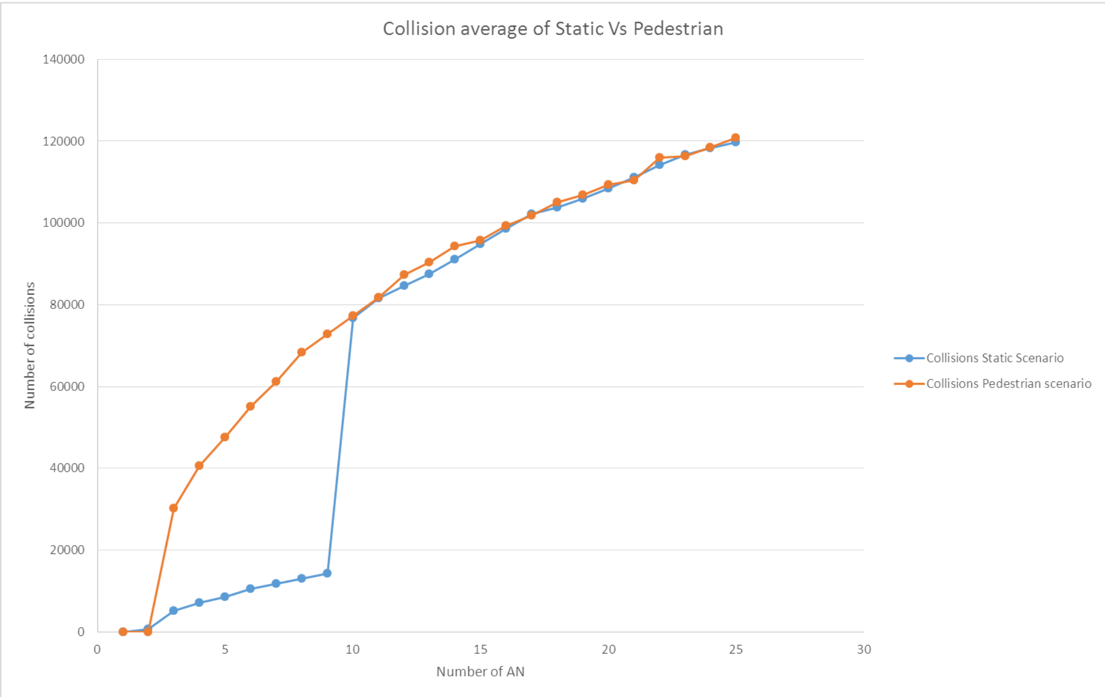

Figure 29. Collision average of Static Vs Pedestrian

The average number of collisions if both scenarios is shown in Figure 29. It can be observed that from 1 to 10 active nodes, the scenario with static nodes experiments less collisions than the pedestrian scenario. From 10 active nodes onwards, the evolution of the number of collisions in both scenarios is pretty close one to each other. The increment of the number of collisions at 11 active nodes is due to the nodes are positioned further from the access point. On contrary, on pedestrian scenario these increment is done progressively because they are moving randomly around the simulation area.

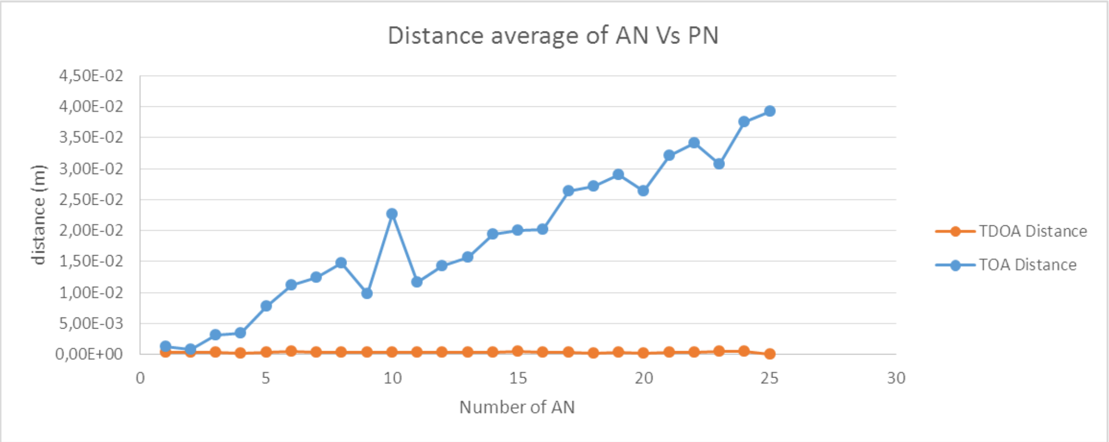

Figure 30. Distance average of AN Vs PN

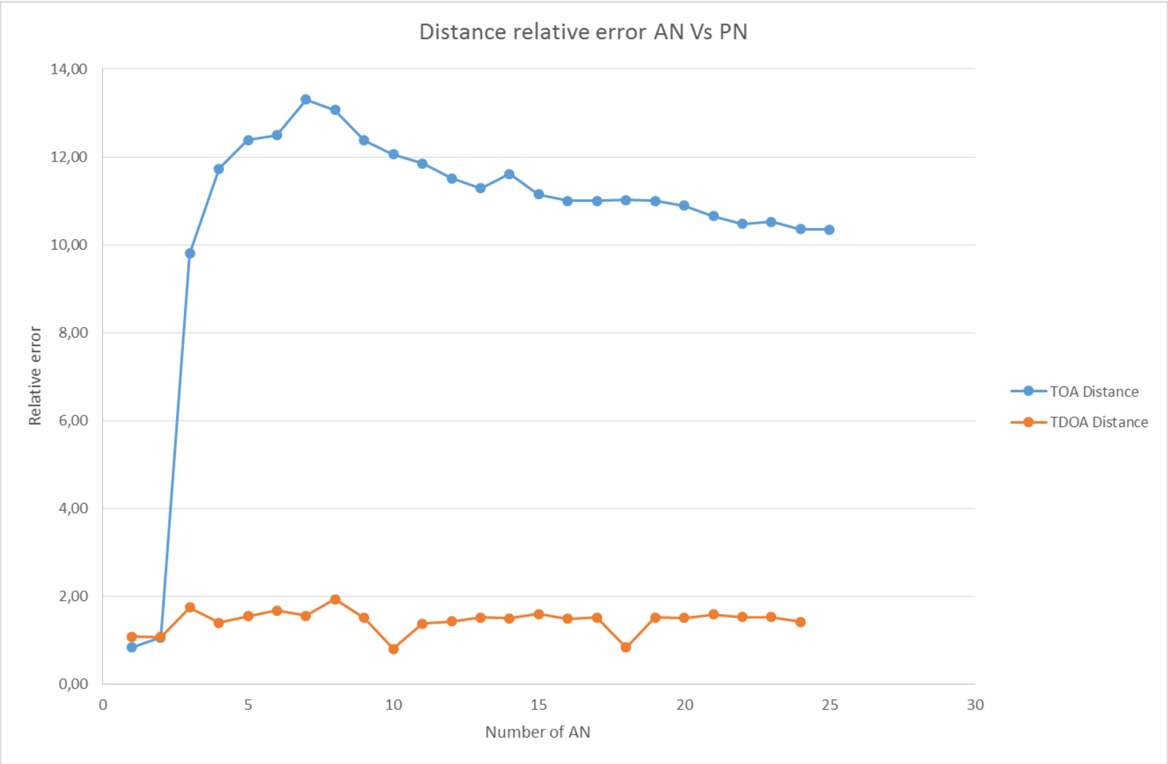

Figure 31. Distance relative error AN Vs PN

Figure 30 compares the distance traversed from the moment the position is requested until it is finally computed. The results obtained with the 2-Way TOA and Passive TDOA algorithms are shown in such figure. It can be seen that Passive TDOA results are more stable, slightly oscillating around a central value. Moreover, the distance traversed is noticeably shorter than in the case of the 2-way TOA location technique. The results achieved with this latter show that the relative error increases with the number of active nodes, which demonstrates one of the main drawbacks of this technique: the scalability. Furthermore, as it is observed in Figure 31, the maximum value of the relative error using the 2-way TOA technique happens with 7 active nodes and it is 13.3%. For Passive TDOA the maximum relative error is 1.74% for 3 active nodes.

Anyway, it can be stated that in scenarios with more than 2 active nodes, the distance traversed until the positioning is fixed grows noticeably and so does its impact on the final position error.

8.2. <u>Indoor scenario results</u>

The following sections evaluate the results obtained for the two indoor scenarios. The behavior of the both scenarios are also compared with the results achieve in free space conditions.

8.2.1. No error indoor static results

Figure 32 illustrates the RTT MNGT average and the RTT MAC average. As in previous scenarios the RTT MNGT growths faster than RTT MAC as a consequence of measuring the transmission time before the CSMA/CA and the queue introduced before the MAC layer. Otherwise, RTT MAC is more stable and it is only influenced by the number of collisions.

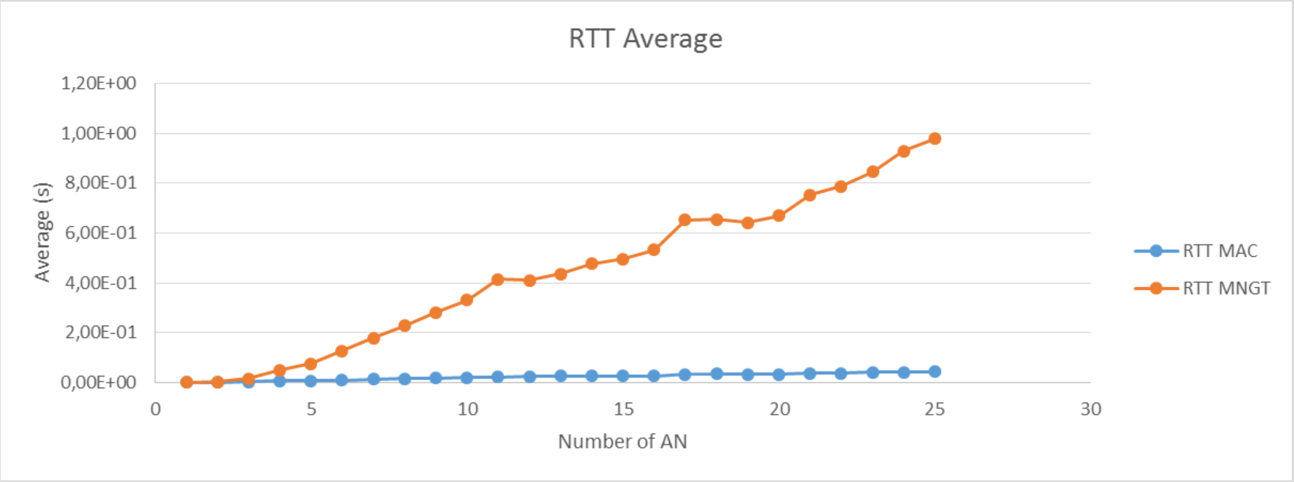

Figure 32. Average of RTT MNGT and RTT MAC of indoor static scenario

Figure 33 compares the RTT average calculated for this scenario in free space and indoor. It shows that measurements of scenarios are similar. This is due to the fact that the indoor simulation area was reduced to mitigate the effects of the multipath.

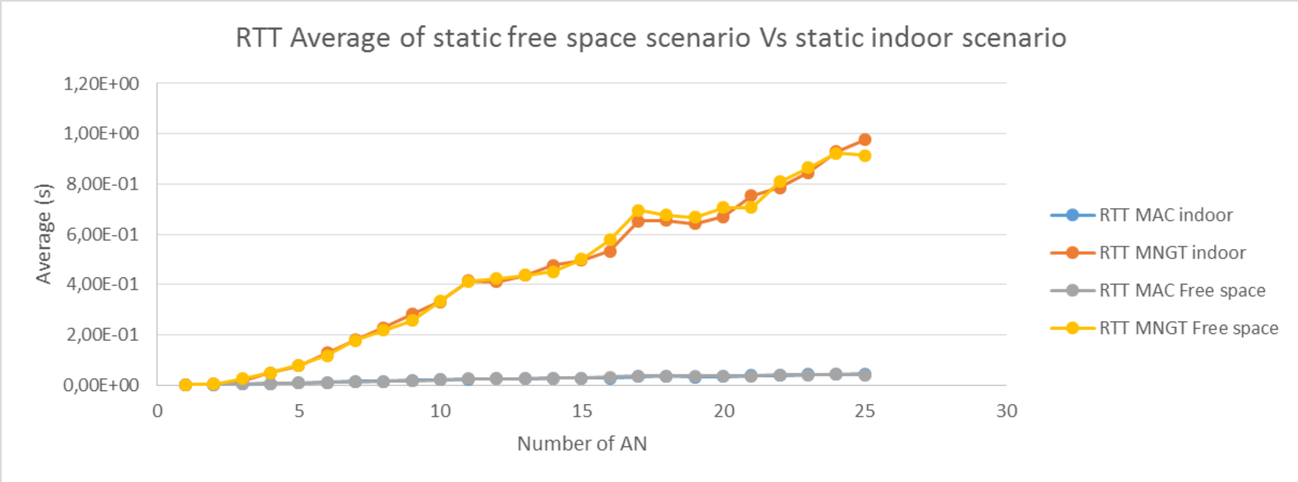

Figure 33. RTT average of static free space scenario Vs static indoor scenario

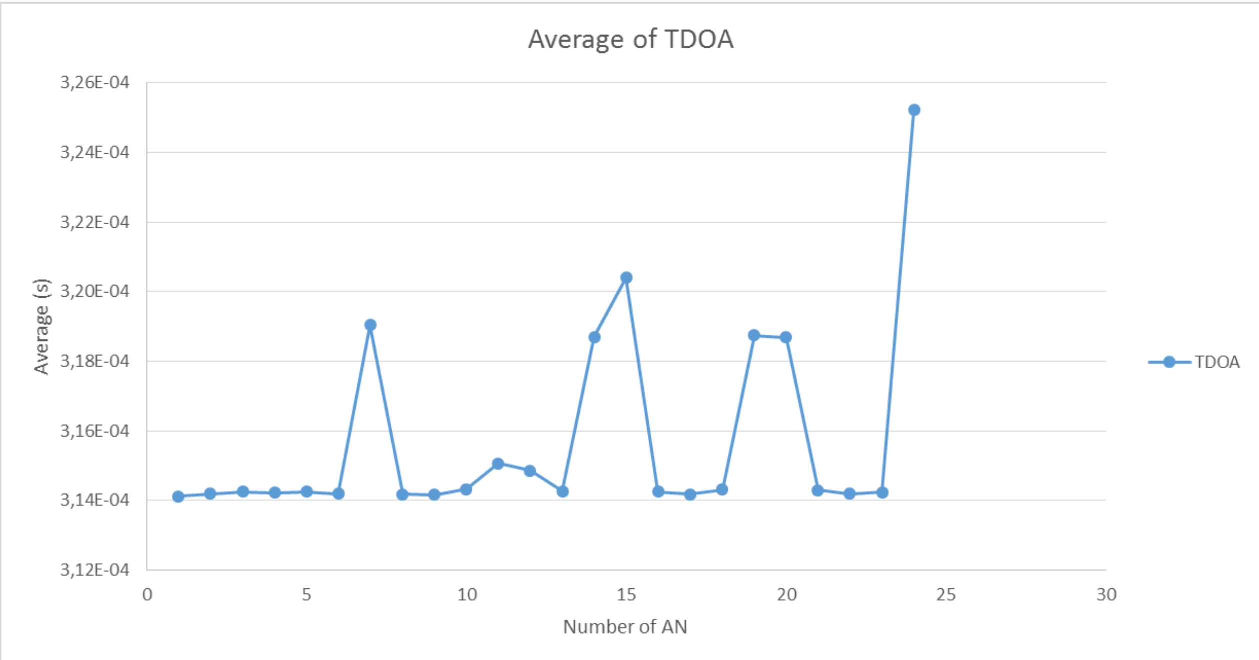

Figure 34. Average of TDOA results for indoor static scenario

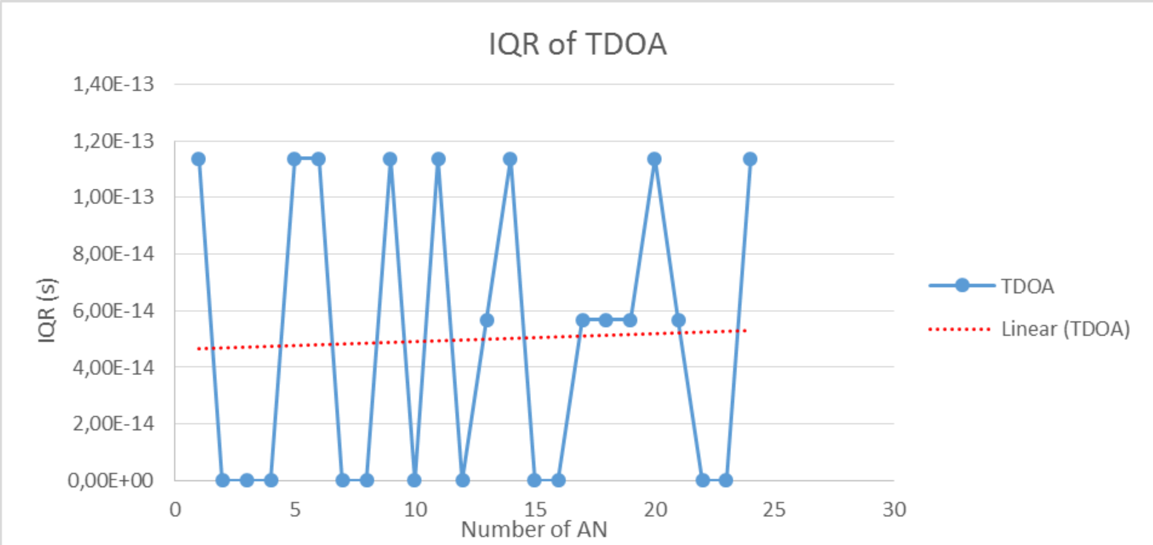

Figure 35. IQR calculated from TDOA indoor static values

Figure 34 shows the average of TDOA for this scenario, if is compared with the average of 2-Way TOA results it provide better performance. This is because Passive TDOA nodes estimate TDOAs from several active nodes at the same time and hence they can get enough samples before a single active node is able to position itself. As in previous scenarios the difference between TDOAs are in the order of hundreds of microseconds. Moreover, Figure 35 shows the IQR of the TDOA values, which increases slowly, demonstrating the Passive TDOA values to be more stable. This is also supported by the linear regression of this variable, presented in the same figure, which involves a low slope,

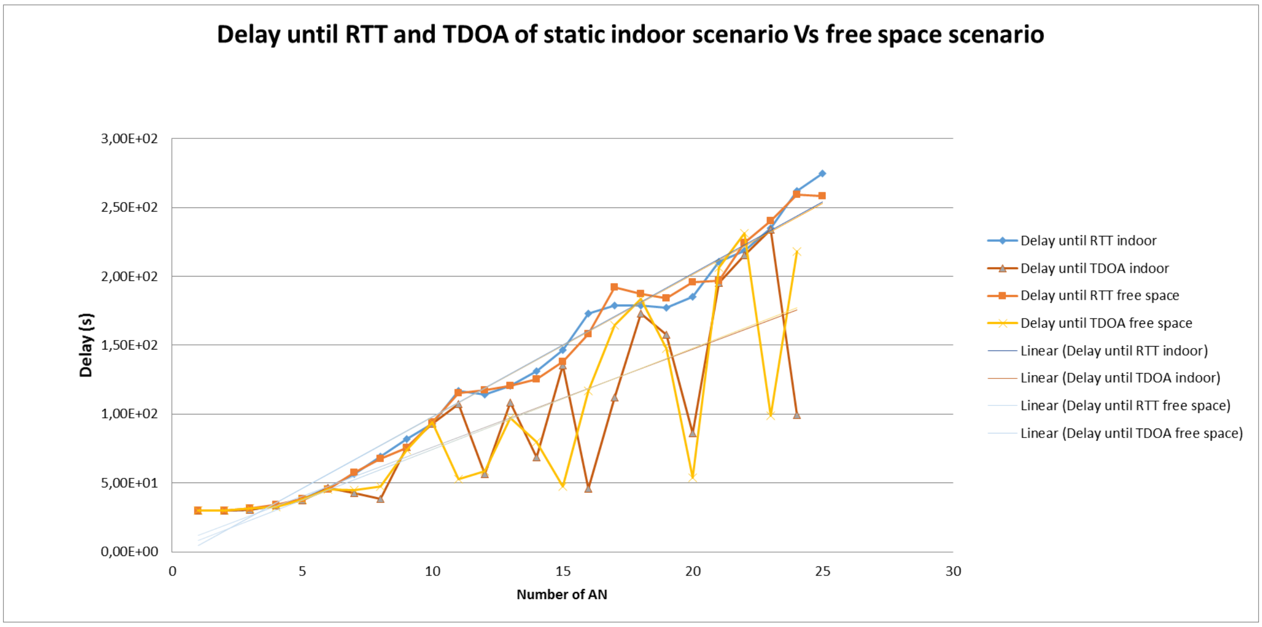

Figure 36. Delay until RTT and TDOA of static indoor scenario Vs free space scenario

Figure 36 shows the time needed until each node gathers enough samples to positioning itself, in both the free space static scenario and the indoor scenario. In both scenarios the delay the active nodes incur until they gather enough samples to fix their own position is more stable than those associated with the passive nodes. As in previous scenarios, this is due to the fact that not all the passive nodes listen to the same number of collisions. Again, identifying a collision as a real one or as noise depends on the specific location the node is.

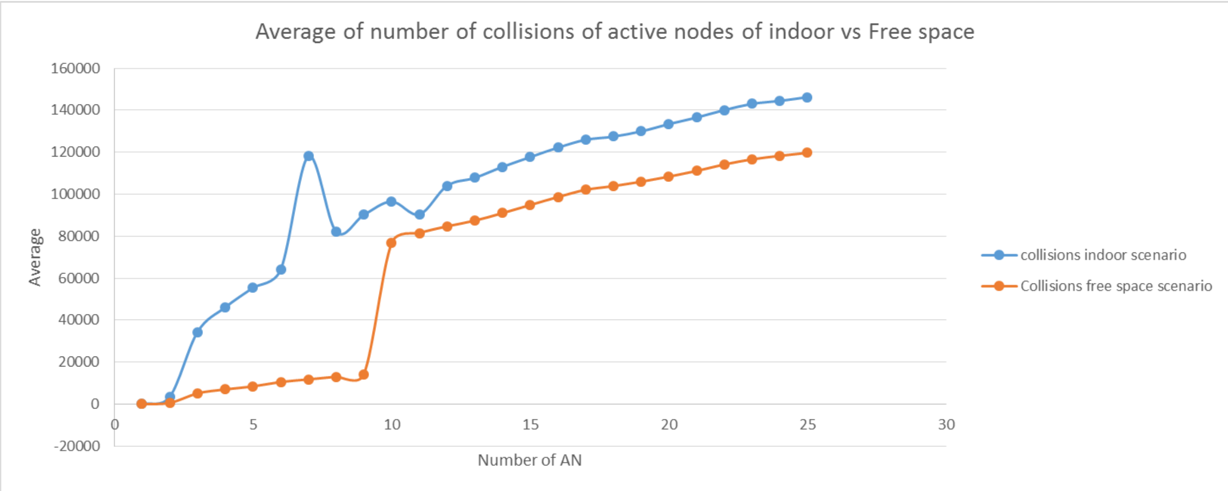

Figure 37. Average of number of collisions of active nodes of indoor vs free space

Figure 37 compares the average of number of collisions of active nodes in the indoor scenario and free space scenario. It could be observed that indoor results are less stable and present higher amount of collisions, owing mainly to multipath and radio propagation effects.

8.2.2. No error indoor pedestrian results

Figure 38 shows the average for RTT MAC and RTT MNGT in this scenario. As in previous scenarios, RTT MNGT is less stable than RTT MAC and presents longer values. The explanation for that is that RTT MNGT results are influenced by the backoff period and the transmission time is set before a queue. As number of collisions increases the queue contains more packets and therefore introduce more delay.

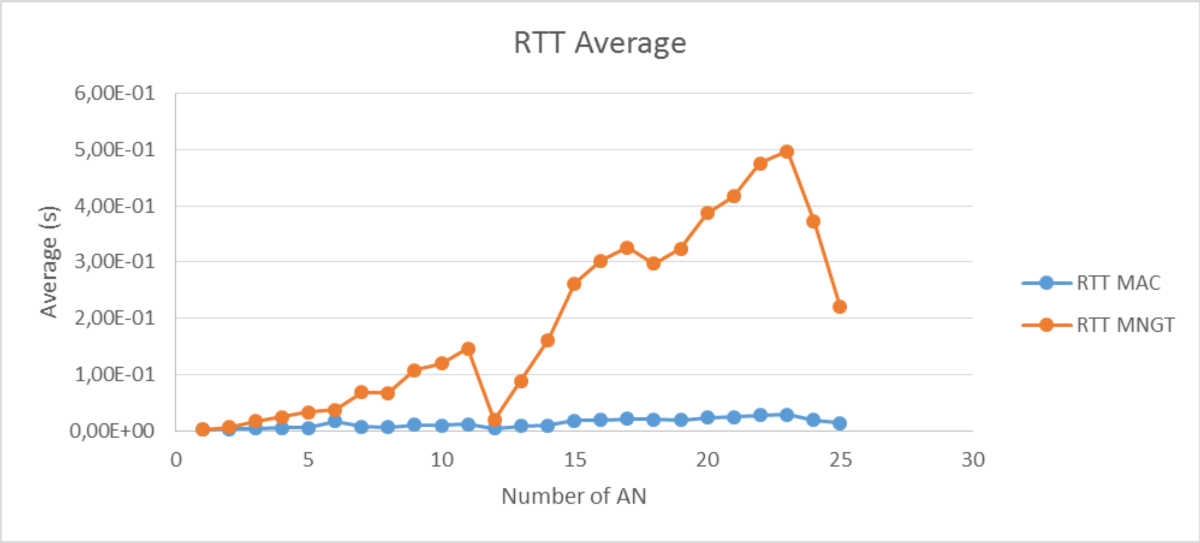

Figure 38. RTT average for indoor pedestrian scenario

Figure 39 compares the RTT average obtained in the static indoor scenario with the average obtained in the pedestrian scenario. It could be observed that values of RTT MAC for both scenarios are very similar, because these time values are more insensitive to collisions than those reported in the RTT MNGT. RTT MNGT values are less stable than the static ones because active nodes are in movement and they can be in different places, which yields to different positioning conditions.

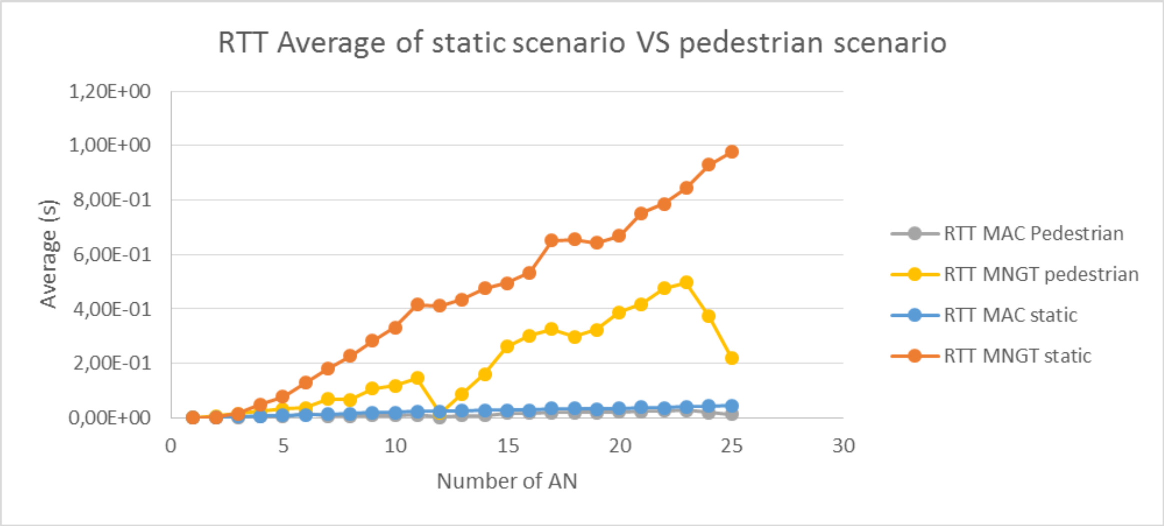

Figure 39. RTT average of indoor static scenario Vs pedestrian

Figure 40 compares RTT average in pedestrian scenarios, i.e. free space and indoors. RTT MNGT in the free space scenario involve higher values than those achieved in the indoor scenario, due to the fact that active nodes have calculated the RTT in a larger area if compared with the indoor scenario. In both scenarios, RTT MAC reports more stable values than those achieved by means of the RTT MNGT measurements. This again is because the transmission time is set just before entering to the physical layer.

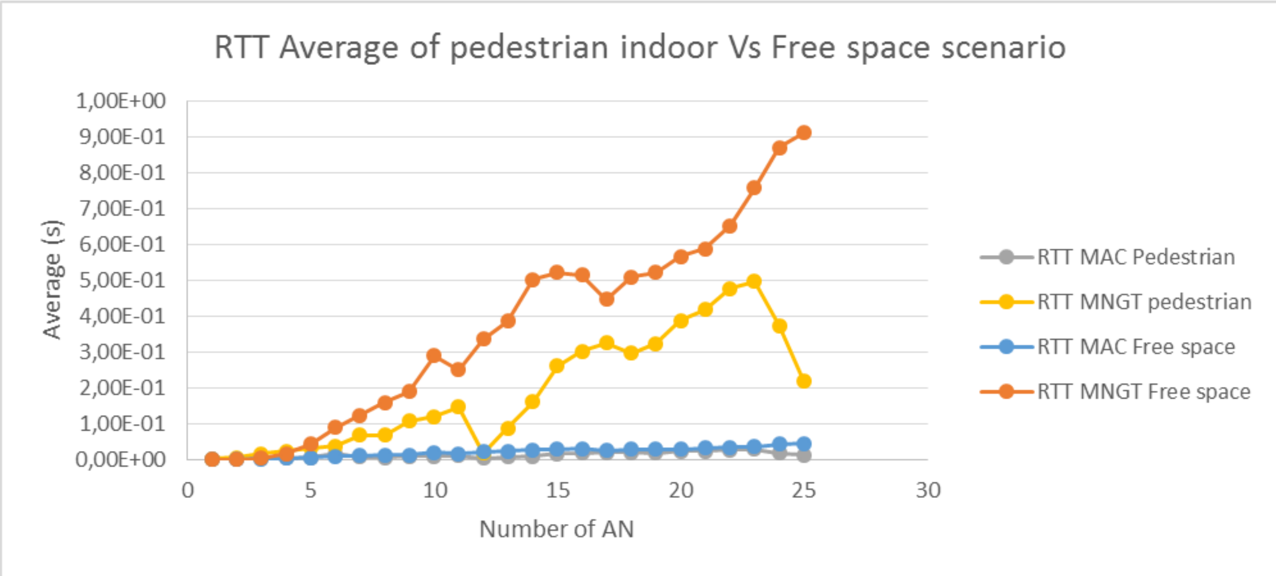

Figure 40. RTT Average of pedestrian indoor Vs free space scenario.

Figure 41 and Figure 42 present the TDOA and TDOA IQR values respectively. Linear regression in Figure 42shows that the TDOA tends to be less stable and increase its values. However, the difference between TDOA values is still in the order of microseconds, which makes the Passive TDOA algorithm to be more scalable than the 2-Way TOA algorithm. This is because it is less sensitive to the increment of collisions and multipath effects.

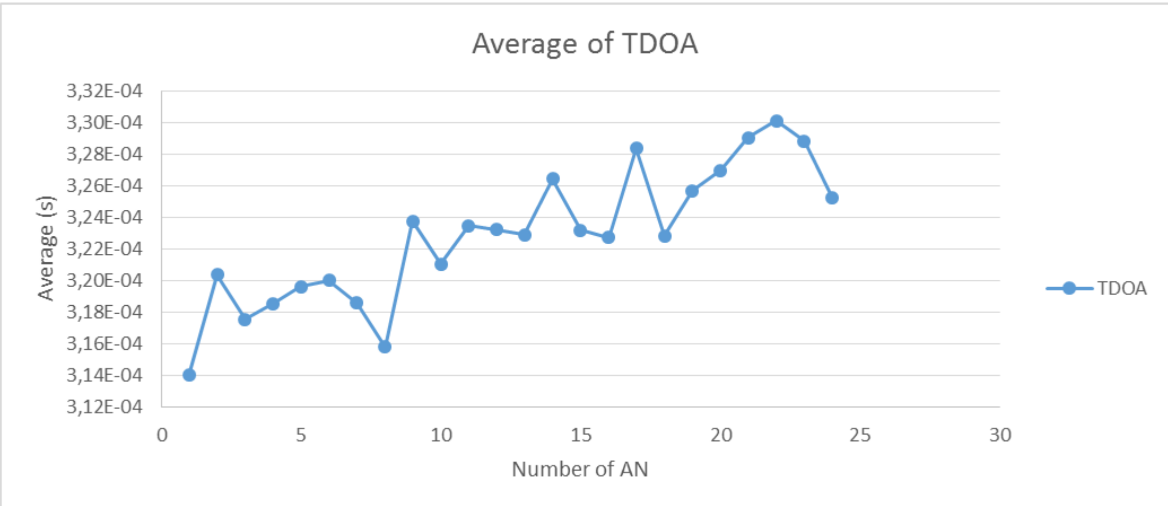

Figure 41. Average of TDOA in indoor pedestrian scenario

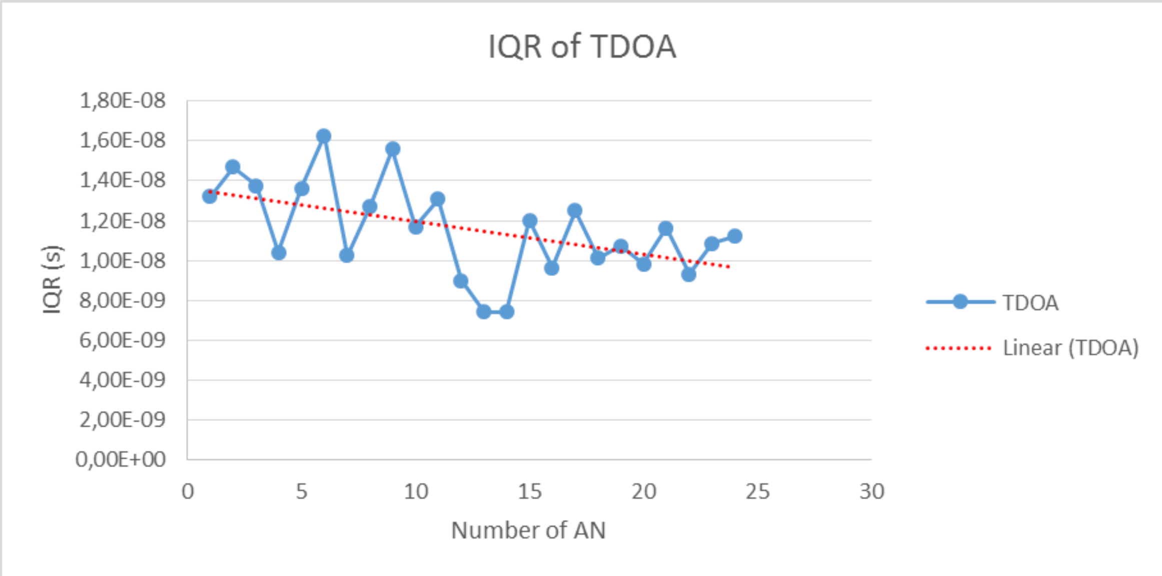

Figure 42. IQR of TDOA in indoor pedestrian scenario

Figure 43 compares the distance that one node traverses during a RTT or TDOA calculation. As it is shown, distances reported by the passive nodes (i.e. TDOA distances) are more stable and shorter than those required in the active nodes using the 2-Way-TOA algorithm. The main reason for that is that passive nodes estimate their position from several active nodes at the same time, so they require less time to gather enough samples to calculate their own position.

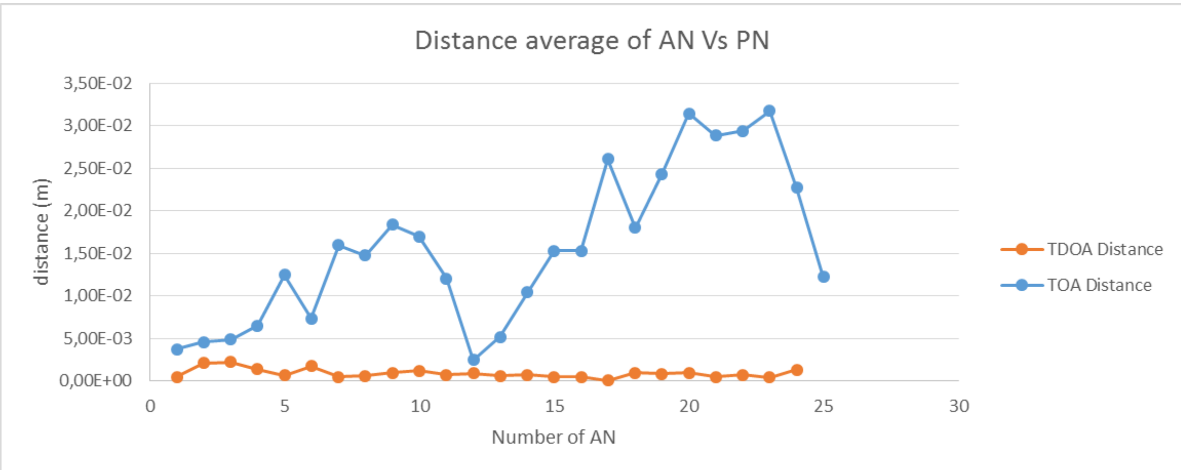

Figure 43. Distance average of indoor pedestrian AN Vs PN

Figure 44 extends the results presented in Figure 43 to those achieved in the free space scenario, so that they can be properly compared. As it could be observed, Passive TDOA performance is more or less the same in both scenarios, which enforces the statement about its scalability. On the other hand, 2-Way TOA measurements are less stable, owing to the fact that this algorithm is more dependent on the traffic carried by the network (in terms of the amount of collisions) and radio conditions.

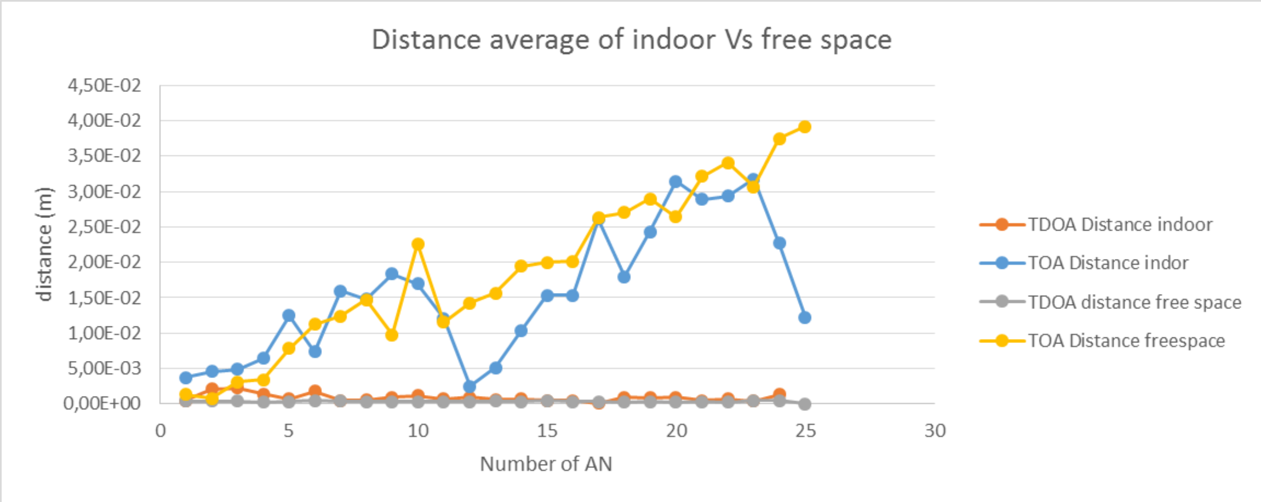

Figure 44. Comparison of distance average between pedestrian indoor and free space

Then, it can be stated that the Passive TDOA algorithm is more stable than 2-Way TOA, owing to the fact that is capable to estimate positions from several active nodes at the same time and it is less sensitive to the growth of the number of collisions and multipath radio effects.

9. Budget

9.1. Thesis Schedule

The work done during the thesis development can be classified into different tasks or activities, as is shown below.

A. **Training.** It is the first activity to be done and involve gathering information related with the topic of location based services in order to acquire the knowledge necessary to continue with the following tasks.
B. **Simulator learning.** In this phase, the operation of the simulator has been understood. It has been necessary to widen the knowledge of the programming languages, in particular C++ and Omnet++.
C. **Definitions of the scenarios.** Different scenarios have been analyzed and taking into account as a possibilities and then, the more suitable and relevant scenarios have been selected.
D. **Modification of the simulator.** The simulator has been adapted to carry out the analysis proposed. In particular:
   - Modifying the IEEE808.11 stock protocol to made it able of performance the location algorithms under study.
   - The defined scenarios have been implemented with the objective of evaluate the scalability of selected location techniques.
   - Modifying the code to save the results of different metrics defined in this work.
E. **Carry out the functions to analyze the results.** The functions to analyze de data and obtain the statistical metrics where programmed in Matlab.
F. **Execution of the simulation.** The simulations described in the thesis have been released through the graphic interface of the program, in order to obtain data to evaluate the behavior of algorithms in the defined scenarios.
G. **Analysis of the results.** Once the results have been obtained, they have been analyzed and statistical values and different graphics have been generated for represent the results.
H. **Report writing.** It involves the drafting of the documents that explain all the procedure done and the results and conclusions extracted.

The work planning and the time dedicated to each activity is shown in the following Gantt diagram.

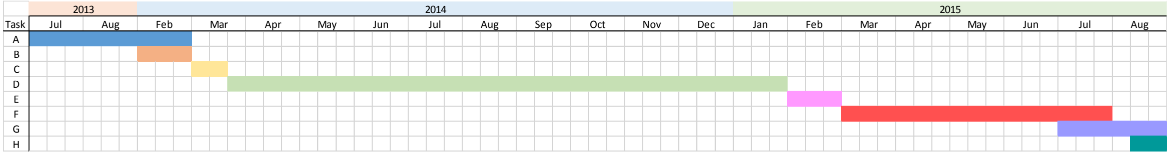

Figure 45. Thesis Gantt Diagram

9.2. Budget

In order to carry out this thesis, several elements as well as engineering work have been incurred. The main costs involved in the development of the thesis can be resume in software, hardware and personnel costs. The electricity consumption has been omitted due to it is not significant compared with the global amount.

9.2.1. Software costs

Software costs involves the software executed on the university server and on the personal computers. On the server OMNET++ open source framework have been used with costs zero. In addition, to evaluate the results of different scenarios Matlab has been employed. The student version costs 69 Euros.

On the computer, the graph of results have been done using Excel the report have been written with word and figures were designed and draw with Visio. Excel and Word are inside of the Office packet which a cost of 99 Euros per year. Visio is sold separately by 739 Euros. In addition, two computers have been used during thesis realization. One with Windows 7 with a cost of 199.99 euros and other with Ubuntu, an open source operating system.

Concept	Cost/time	Time	Total
Windows 7	199.99€/ 7 years	21 months	49.99€
Ubuntu	Free	21 months	0€
Microsoft Office	99€ / 1 year	21 months	173.25€
Visio professional	-	21 months	739€
OMNET++	Free	21 months	0€
Matlab (student version)	-	21 months	69€
Total cost	1031.24€		

Table 3. Software Costs

9.2.2. Hardware costs

Hardware costs include the server, the two computers used and a hard drive. It has considered the depreciation costs corresponding to the moths of the project.

The physical server has two microprocessors composed by four cores each one working at 2.5GHz and it has 24GB of RAM memory.

Computer 1 has ani5 microprocessor which works at 3,26GHz and 8GB of RAM memory. The second is an i7 microprocessor with a frequency 2.21 GHz and 8GB of RAM memory. The hard drive of the last one has been change by Samsung SDD 850 EVO of 250 Gb to increase the speed of filtering the vectors.

Concept	Cost/time	Time	Total
Server	4000€/7 years	21 months	1000€
Computer 1	1000€ /7 years	21 months	250€
Computer 2	750€ /5 years	21 months	262.5€
Samsung SDD 850 EVO of 250 Gb	-	21 months	199.99€
Total cost	1712.49€		

Table 4. Hardware costs

9.2.3. Personnel costs

Personnel costs cover the salary of an engineer working throughout the 21 months that has last the thesis. The estimated cost for a company of a salary of an engineer is 2000 euros per month.

9.2.4. Final cost

In the table below, the costs derived from software, hardware and labor are detailed and the total amount is, consequently,44743.73€.

Concept	Cost
Software Costs	1031.24€
Hardware Costs	1712.49€
Personnel Costs	42000€
Total Costs	44743.73€

Table 5. Total costs

10. Conclusions and future development

In this thesis the IEEE 802.11 b/g protocol stack was enhanced to implement two position algorithms, 2-Way TOA and Passive TDOA, and subsequently evaluate their accuracy, consistency and scalability. Four scenarios defined in section 5 were compared and analyzed, so that representative conditions for positioning LBS were studied.

Furthermore, two different approaches for measuring the round trip time (RTT), variable required by the 2-Way TOA algorithm to compute a position were carried out: RTT MNGT and RTT MAC. In the RTT MNGT, the transmission time is measured before the CSMA/CA stage and consequently before of entering the queue where frames are allocated until the MAC layer attends them. On the other hand, RTT MAC takes time measurements just before entering the physical layer, so that all the artifacts of the MAC layer are overcome.

Accordingly, in all scenarios RTT MNGT values were seriously affected by all the transmission chain: the backoff period, the lapse of time spend in such queue until transmission, the radio effects, the protocol stack, etc. As consequence, RTT MNGT do not seem to be a scalable measurement, because it might involve a large error in terms of positioning. However, it is most of the time the only measurement available for researchers and developers to be taken. Consequently, it had to be studied.

On the other hand, results show that RTT MAC are more stable, but generally IEEE 802.11 hardware do not provide these kind of measurements unless it is modified, which makes this solution less appealing (in terms of cost) than a software-based one.

The obtained results let to state that TDOA measurements are more stable, owing to the fact that the Passive TDOA algorithm is based on listening the traffic injected in the network and backoff period barely impacts such measurements. Moreover, passive nodes are able to estimate their position quicker than active nodes. It is because passive nodes are able to estimate TDOA measurements from several active nodes at the same time, so they can get enough samples before an active node can position itself.

Furthermore, it is important to notice that not all passive nodes listen to the same number of collisions. It depends on the position the node has when the collision is heard. If the collision signal strength at the node is below the sensitivity of the wireless receiver, then the node is not aware of the collision and assumes that the signal is simply noise.

In case of pedestrian scenarios the results are less stable, because nodes are in movement along the simulation area. So they ask for positioning in different places with different positioning conditions, which yields to different performance.

Results indoors are similar to those obtained in the free space simulations. This is due to the fact that Passive TDOA is able to obtain the measurements in less time, in consequence is less sensitive to the growth of the number of collisions and multipath effects. On the contrary, 2-way TOA is less stable because it more dependent on the network traffic in terms of number of collisions and radio conditions.

Finally, this study could be extended by evaluating the performance of the same scenarios but with larger areas, increasing the number of access points and determining how the problem of the hidden terminal could impact on the scalability and the accuracy of both algorithms.

Bibliography

[1] X. Guachang, “GPS: theory, algorithms and applications”, Berlin: Springer, 2007.

[2] I. Martín Escalona, F. Barceló, C. Manete, “A field study an terrestrial and satellite location sources for urban cellular networks”, *IEEE Global Communications Conference (GLOBECOM)*, pp. 1-5, 2006.

[3] 3GPP TS 23.271 2004, “Functional stage 2 description of Location Services (LCS)”, http://www.3gpp.org.

[4] 3GPP TS 03.71 2004, “Functional description stage 2 Location Services (LCS)”, http://www.3gpp.org.

[5] M. Thorpe, M.Kottkamp, A. Rössler, J. Schütz. “LTE Location Based Services Technology Introduction White Paper”. *Rohde&Schwarz*, April 2013.

[6] An overview of LTE positioning. Spirent, USA, February 2012.

[7] A.H. Sayed, A. Tarighat, N. Khajehnouri. “Network-Based Wireless Location: Challenges faced in developing techniques for accurate wireless location information”. *IEEE Signal Processing Magazine*, July 2005.

[8] D. Niculescu, B. Nath. “Ad Hoc Positioning System (APS) Using AOA”. *IEEE Infocom,* 2003.

[9] H. Lim, L. Kung, J. C. Hou, H. Luo. “Zero-Configuration, Robust Indoor Localization: Theory and Experimentation”. August 2005, University of Illinois at Urbana-Champaign, USA.

[10] R. Singh, M. Guainazzo and C.S. Regazzoni. “Location determination using WLAN in conjunction with GPS network (global positioning system)”. *Proc. IEEE Vehicular Technology Conference (VTC)*, vol.5, pp. 2695-2699, 2004.

[11] L.Mengual, O. Marbán, S. Eibe. “Clustering-based location in Wireless networks”. *Expert Systems with Applications,* no. 37, pp. 6165-6175, 2010. DOI: 10.1016/j.eswa.2010.02.111.

[12] G. Sun, J. Chen, W. Guo, K. J. R. Liu. “Signal Processing Techniques in Network-Aided Positioning: A survey of state-of-the-art positioning designs”. *IEEE Signal Processing Magazine*, vol. 22, no. 4, pp. 12-23, July 2005.

[13] S. A. Golden, S. S. Bateman. “Sensor Measurements for Wi-Fi Location with Emphasis on Time-of-Arrival Ranging”. *IEEE Transactions on Mobile Computing*, vol. 6, no 10, pp. 1185-1198, October 2007. DOI: 10.1109/TMC.2007.1002.

[14] H. Liu, H. Darabi, P. Banerjee, J. Liu. “Survey of Wireless Indoor Positioning Techniques and Systems”. *IEEE Transactions on Systems, Man, and Cybernetics – Part C: Applications and reviews*, vol.37, no. 6, pp. 1067-1080, November 2007.

[15] I. Martín Escalona, F. Barceló Arroyo, “A new time-based algorithm for positioning mobile terminals in wireless networks”, *EURASIP Journal on Advances in Signal Processing*, Vol. 2008, pp. 1-10, 2008.

[16] I. Martín Escalona, F. Barceló Arroyo, M. Ciurana, “Passive TDOA location in mobile ad-hoc networks”, *IEEE International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, pp. 1218-1225, Oct. 2010.

[17] I. Martin, M. Malpartida, F. Barcelo-Arroyo. “Performance evaluation of the passive TDOA algorithm in dark areas”. *Ubiquitous Positioning, Indoor Navigation, and Location Based Service, UPINLBS 2012,* 3-4 Oct. 2012, Helsinki. pp. 1-8. DOI: 10.1109/UPINLBS.2012.6409767.

[18] “OMNET++ User Manual”, https://omnetpp.org/doc/omnetpp/manual/usman.html.

[19] “INET Framework for OMNETT++ Manual”, https://omnetpp.org/doc/inet/api-current/neddoc/index.html.

[20] F. Bai, A. Helmy. “Wireless Ad Hoc and Sensor Networks. Chapter 1: A survey of mobility models in Wireless Adhoc Networks”, pp. 1-29, California, USA: Kluwer Academic Publishers, 2004.

[21] D. B. Faria. “Modeling Signal Attenuation in IEEE 802.11 Wireless LANs, vol. 1”. Standford University, 2005.

Glossary

ACK Acknoledgement

A-GPS Assisted GPS

AoA Angle-of-Arrival

AP Access Point

CSMA/CA Carrier Sense Medium Access / Collision Avoidance

DoA Direction-of-Arrival

GPS Global Positioning System

IP Internet Protocol

IQR Inter Quartile Rate

LBS Location Based Service

LTE Long Term Evolution

MAC Media Access Control

MIMO Multiple-input Multiple-output

MNGT Management

NLOS Non-light-of-sight

OTDOA Observed Time Difference of Arrival

PLMN Public Land Mobile Networks

RSS Received Signal Strength

RSSI Received Signal Strength Indicator

RTT Round Trip Time

SNR Signal to Noise Ratio

TCP Transport Control Protocol

TDOA Time Difference of Arrival

TOA Time-of-Arrival

TTFF Time-To-Firs-Fix

UMTS Universal Mobile Telecommunication System

WLAN Wireless Local Area Network