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Outdoor Location of Mobile Devices Using Trilateration Algorithms for Emergency Services

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ABSTRACT With the rise of mobile technologies, it seeks to solve a large number of needs that users have, for example locating people for emergency services. At present, there are a large number of applications dedicated to providing service of positioning through mobile devices, with the global positioning system (GPS) which is the main positioning technology used. However, other technologies exist that using the correct algorithms can give the position of a target with good precision; one of these technologies is the global system for mobile communications (GSM). The most popular positioning methods include the angle of arrival (AoA), time of arrival (ToA), triangulation, time difference of arrival (TDoA), and trilateration. At the beginning, the GSM service was simply a means of transmitting voice and short messages, with the passage of time the technologies evolved and expanded their characteristics, providing values that can be used to locate a person based on the signal strength received by a person, device, and in the known position of three or more reference nodes. When an emergency occurs, the current communication services (3G or 4G) are insufficient due to the high concentration of mobile subscribers in a single place that exceeds the capacity of an antenna. This means that calls to emergency services are not completed, which makes it difficult to rescue people in danger. Although GSM does not have a technology dedicated to positioning, it can provide valuable data for location by using dedicated algorithms, such as trilateration, with which the coordinates of the target device can be processed by the coordinates of three or more reference nodes.

INDEX TERMS Android, Cayley-Menger, emergency, location, outdoor.

I. INTRODUCTION

When an emergency occurs (earthquake, hurricane, flood, etc.), the time for the rescue bodies is vital. Therefore, the technologies in charge of dealing with emergency situations must be very precise to locate people at risk in the shortest possible time. One of the main problems that rescuers face is the inaccuracy of the location provided. As a consequence, the work they do is difficult.

In the beginning, the GSM service was simply a means of transmitting vozy short messages with the passage of time, the technologies were evolving and expanding their characteristics. Today there are 2G, 3G, 4G networks and the growing 5G that provide data service, voice, short messages or SMS (Short Message Service), among others. However, while all versions are robust and perform their main function is to communicate to people, to succeed an emergency these technologies collapse due to the large number of people trying to communicate with family and friends. In addition, the high concentration of mobile subscribers in one place exceeds the capacity that an antenna can support. This means that calls to emergency services are not completed or completed in a short time, making it difficult to rescue people in emergency.

Although GSM is not a technology dedicated to the positioning of a device, it can provide valuable data for

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localization with dedicated algorithms. looking to automate the entire process of the emergency call, preventing inaccuracies for emergency care.

To automate this process, applications are used that make use of Location Based Services (LBS) [1]. The most used technology is the Global Positioning System (GPS). However, its high consumption of resources and the need to use mobile data make it difficult to track the person in danger. An alternative to obtain the location of a mobile device is through technologies such as GSM using the cell-of-origin method. This method bases its accuracy on the geographical position of three base stations. Although GSM is not a dedicated location service, by extracting MCC data (*Mobile Country Code*), MNC (*Mobile Network Code*), the area code related to the current location of the subscriber objective, and the use of algorithms to process the data, can be located to a mobile subscriber with a good degree of accuracy.

This work focuses on the development of an application capable of extracting the necessary data for the location of a mobile device using GSM networks to automate the early emergency response process. The rest of the document is organized as follows: Section II presents the state of the art of the proposed system. Section III describes the proposed system for locating a mobile device with Android as the operating system. In Section IV the results obtained with the proposed system are shown. Finally, the conclusions drawn from the work are shown in Section V.

II. STATE OF THE ART

In the market there are a large number of applications dedicated to locating people during an emergency. In Mexico, the Command, Control, Computing, Communications and Citizen Contact Center (C5) of Mexico City developed an application capable of facilitating the help of local authorities during an emergency [2]. In addition, in countries such as Spain and France, there are applications such as the one developed by Alpify which seeks to provide the user with a panic button which, when pressed, sends the location of the device through mobile networks. Most applications use GPS technology to locate mobile devices because it provides great accuracy in locating a target. However, sometimes these applications have a high consumption of resources and need data to send the geographical position of a person at risk, which makes them inefficient. An alternative to this problem is the use of technologies such as GSM and Wifi.

A. LOCATION BASED SERVICES

Location-based services, or LBS, are services that integrate the geographical position of a device with other information to provide added value to a user. In other words, an LBS refers to any service dedicated to geographic information in real time. Which can be activated by an entity which can be human or non-human [1], [3].

For LBS services to fulfill their function, some infrastructure components are necessary, including mobile devices, applications, communication network, positioning component and service provider.

- **Mobile Devices**: are tools used by LBS services, to send requests and receive results. Among which stand out portable navigation systems for cars, personal assistants, laptops, smartphones, tablets, etc.
- **Applications**: is the interface for users to access LBS. Which are developed by the provider of a service and downloaded and installed by the user who owns the mobile device. Although these applications have different limitations, the main one being the processing consumption and the capacity in RAM.
- **Communication Network**: it refers to the mobile network that transfers the user's service request to the provider, and the requested information back to the user. The Global System for mobile communications (GSM) is currently the most common standard for mobile networks and is used by most mobile devices globally.
- **Positioning Component**: a positioning component is necessary in an LBS application to determine the position of the user's mobile device. Nowadays, most LBS services do not require users to enter the location manually; on the contrary, the location can be obtained using some positioning technology: positioning provided by satellites, positioning by mobile network, WLAN stations or radio beacons, among others.

B. LOCATION BY GSM

Some institutions, especially those related to civil security worldwide, locate mobile phones using mobile networks for early attention to emergencies. This search is done in order to locate the telephone equipment of a person in danger. However, using GSM networks turns out to be risky because the coverage ranges are very large, which makes it difficult to locate the device. 200m in urban areas, from 5 to 32 km in suburban areas or small cities and 50 to 150 km in rural areas [4].

One of the most commonly used methods for localization using GSM is the so-called cell of origin. This method bases its accuracy on the so-called cell ID and improved cell ID. The main limitation of this method is that when obtaining the location it retrieves the location coordinates of the antenna to which the device is connected, but not that of the mobile device.

For the GSM location to be possible, the MCC (*Mobile Country Code*), MNC (*Mobile Network Code*), LAC (*Location Area Code*) and Cell ID (*Cell ID*) are necessary.

leftmargin = *,labelsep = 4mm

- Mobile Country Code: It is a three-digit code that identifies the country in which the PLMN (*Public Land Mobile Network*) GSM is located. Examples of this code is the 334 belonging to Mexico and the 214 that refers to Spain.
- Mobile Network Code: It is an identification code of the telephone network that emits the SIM (*Subscriber Identity Module*), the length of this code can change

being two numbers in the European standard and three in the American standard.

- Location Area Code: It is a number that determines the location of a group of GSM towers. The length of this code can be up to five decimal places.
- Cell ID: It is the unique number of the GSM tower to which the telephone is connected at that moment. the valid range of CID is between 0 to 65535 ($216^{16} - 1$) in GSM and CDMA networks.

MCC and MNC indicate the country where the mobile device and the mobile telephony provider are, respectively. Moreover, LAC indicates the geographical area where a base station and CID uniquely identifies the base station within a cellular network. To locate a device using these data are necessary triangulation methods to determine the approximate position of the target. However, the triangulation bases its position on the angle of arrival of the signal to the mobile device.

An alternative to this method is trilateration to determine the relative positions of objects. This method is based on the measured distances that exist between the mobile device and the base station using the geometry of triangles. Also, to calculate the position of a node in two dimensions it is necessary to know at least the distances of three beacons that are not aligned (not collinea) [5].

C. ANGLE OF ARRIVAL

The method of arrival angle (AoA) allows determining the direction of propagation of an incident radiofrequency wave in a set of antennas based on the signal intensity during rotations of the antenna (see figure 1). To calculate the AoA, the address is determined at the time of arriving at the arrival date (TDoA) individually in the elements of the matrix.

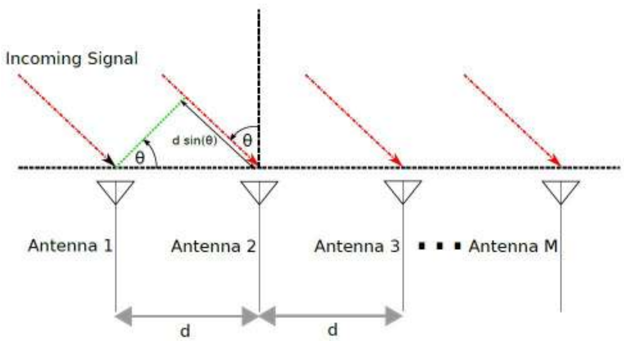

FIGURE 1. Incoming signal to an array of antennas.

Since the signal has to travel farther to reach each subsequent antenna, a phase change is introduced. This phase change between two subsequent antennas can be calculated as follows (equation 1):

$$\Delta_\phi = -2\pi \frac{dsin(\theta)}{\phi} \tag{1}$$

where θ is the AoA, d is the distance between the two antennas, f is the frequency of the signal and λ is the wavelength of the signal.

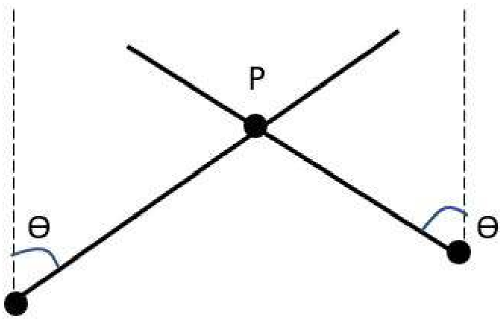

FIGURE 2. Location of a point through an arrival angle.

The equation 2 is used to calculate θ to satisfy the equation 1:

$$\theta = arcsin\left(\frac{\Delta_\phi \cdot \lambda}{-2\pi d}\right) \tag{2}$$

The AoA method can estimate the position of a target by intersecting several parts of angle direction lines (see Figure 2), each formed by the circular radius of the base station. This can be achieved with:

- Directional antennas through the point of highest signal strength.
- A set of antennas measuring the arrival time.

In order to locate a beacon in a bidimentional plane, at least two receiver sensors are required for the estimation of the location with an improved precision comes from at least three or more receiving sensors (triangulation).

D. TRILATERATION

Trilateration is a method that trivially seeks the intersection of three circles [6]. The main difference between triangulation and trilateration is that the first bases its precision on the measure of angles formed by its reference nodes, and the second, is based on the distance that exists from the reference node to the objective. The trilateration is the process of localization of $\mathbb{R}^m$ taking into account only the distance between at least m-1 reference nodes and the mobile device. With $m + 1$ distances, the problem of nonlinear Trilateration is to find the intersection of three circles with radii centered on each reference node which equals the distance obtained (see Figure 3).

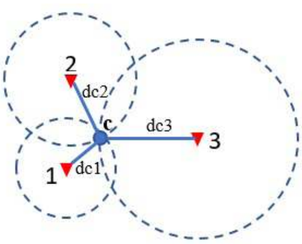

FIGURE 3. Location in $\mathbb{R}^2$.

To solve the problem of trilateration it is enough to find the system solutions of the equation 3:

$$\begin{bmatrix} l_1^2 = (x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2 \\ l_2^2 = (x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2 \\ l_3^2 = (x-x_3)^2 + (y-y_3)^2 + (z-z_3)^2 \end{bmatrix} \tag{3}$$

where (x_i, y_i, z_i) represents the coordinates of the base stations and l_i are the distances associated with them from the target to each reference node.

E. SPHERICAL TRILATERATION

According to [7] given three points in the space p_1, p_2, p_3 the problem of trilateration is to find the location of a fourth point p_4 where the distances to the three reference nodes are known, for which use is made of spherical trilateration.

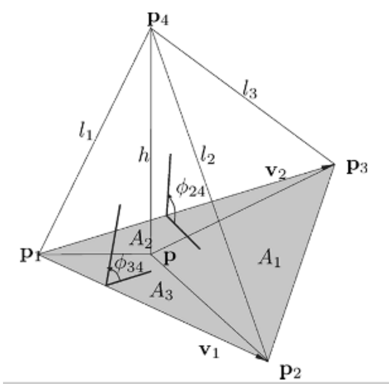

FIGURE 4. **Baricentric coordinates of the projection of p_4.**

As can be seen in the Figure 4 to find the location of the target, use baricentric coordinates, therefore the location of the orthogonal projection of p_4 on the base ie p, can be expressed as:

$$p = \frac{A_1 p_1 + A_2 p_2 + A_3 p_3}{A_b} \tag{4}$$

where A_1, $A2$ and A_3 is the area formed by the triangles $p_1p_2p_4$, $p_3p_1p_4$ and p_1p_2p respectively, and A_b is the area of the triangle $p_1p_2p_3$. Decomposing and simplifying the equation 4 can be expressed as in 5:

$$p = p_1 + \frac{A_2}{A_b} v_1 + \frac{A_3}{A_b} v_2 \tag{5}$$

where v_1 and v_2 corresponds to $p_2 - p_1$ and $p_3 - p_1$ respectively

As can be seen in the Figure 4 the area A_2 can be obtained by projecting the triangle formed by the points p_3, p_4, p_1 on the base plane p_1, p_2, p_3, it is enough to multiply that area of p_3, p_4, p_1 by the angle formed by the two surfaces ϕ_{24}.

$$\begin{aligned} \frac{A_2}{A_b} &= +\sqrt{\frac{D(p_1, p_3, p_4)}{D(p_1, p_2, p_3)}} \\ \frac{A_3}{A_b} &= +\sqrt{\frac{D(p_1, p_2, p_4)}{D(p_1, p_2, p_3)}} \end{aligned} \tag{6}$$

Simplifying the equation 5 can be expressed as:

$$p = p_1 + k_1 v_1 + k_2 v_2 \tag{7}$$

where k_1 and k_2 equals $\frac{A_2}{A_b}$ and $\frac{A_3}{A_b}$, and these are represented in the equations 8 and 9 respectively.

$$k_1 = \frac{D(p_1, p_2, p_3; p_1, p_3, p_4)}{D(p_1, p_2, p_3)} \tag{8}$$

$$k_2 = \frac{D(p_1, p_2, p_3; p_1, p_3, p_4)}{D(p_1, p_2, p_3)} \tag{9}$$

Once obtained an expression for the calculation of the projection of p_4 can be written as shown in the equation 10.

$$p_4 = p \pm k_3(v_1 \times v_2) \tag{10}$$

K_3 corresponds to the height ratio ''h'' tetrahedron initially raised and the module vector product of v_1 and v_2. As for the sign preceding k3, it has to do with whether the point sought is on one side or the other of the base plane defined by the reference points. In the particular case that the module of the vector product was one, then k_3 will conclude with ''h'', the height of the tetrahedron In the equation 11 it is shown how to obtain the value of the height .

$$\begin{aligned} D(p_1, p_2, p_3, p_4) &= 36V^2 \\ h &= +\sqrt{\frac{D(p_1, p_2, p_3, p_4)}{D(p_1, p_2, p_3)}} \end{aligned} \tag{11}$$

Since the vector result module of the vector product of v_1 and v_2 can be expressed as a Cayley-Menger determinant as shown in the equation 12.

$$\begin{aligned} \|v_1 \times v_2\| &= \sqrt{D(p_1, p_2, p_3)} \\ k_3 &= \frac{\sqrt{D(p_1, p_2, p_3, p_4)}}{D(p_1, p_2, p_3)} \end{aligned} \tag{12}$$

Combining all the above results, a final expression expressed in the equation 13 can be obtained in which the coordinates of the mobile (p_4) can be obtained directly as input parameters the distances measured from the mobile to the reference nodes, the distances measured between the coordinates of the first point (p_1) and the vectors define between the other two reference points and the first.

There is ambiguity in obtaining the point sought because it can not be distinguished with the measure of distances if the point p_4 is located on one side or the other of the base plane that contains the beacons, what remains of manifest in the final expression by means of the $\pm$ sign that appears inside it.

$$\begin{aligned} p_u = p_1 + \frac{1}{D(p_1, p_2, p_3)} &(-D(p_1, p_2, p_3; p_1, p_3, p_u) v_1 \\ &+ D(p_1, p_2, p_3; p_1, p_2, p_u) v_2 \\ &\pm \sqrt{D(p_1, p_2, p_3, p_u)}(v_1 \times v_2)) \end{aligned} \tag{13}$$

In the equation 13 the location of the mobile device will be determined when $D(p_1, p_2, p_3, p_4) = 0$, this is when the mobile device is located in the plane formed by p_1, p_2, p_3.

F. LOCATION BY WiFi

The IEEE 802.11 standard, also known as WiFi, is the most popular wireless network technology. It uses radio waves to provide wireless Internet access at high speed and network connection. This technology allows to connect electronic equipment (computers, tablets, smartphones, laptops, etc.) to the Internet.

Like GSM, WiFi is not a technology dedicated to the location of a device. However, it can provide valuable data from it with very high accuracy. In order to locate a device, the following four data are necessary:

- *BSSID*: MAC address of the Access Point that is serving. For example 7c: b7: 33: e5: b8: 74.
- *Channel*: Channel on which the signal is transmitting.
- *Frequency*: Frequency at which the signal is being transmitted.
- *Signal Strength*: Signal strength received by the mobile device.

III. PROPOSED LOCATION SYSTEM

The proposed system is divided into two phases: (1) An application to extract the necessary information for the location of a mobile device within a GSM network when making an emergency call. (2) An application on a server that interprets the data extracted from the Android device to obtain the coordinates of the device.

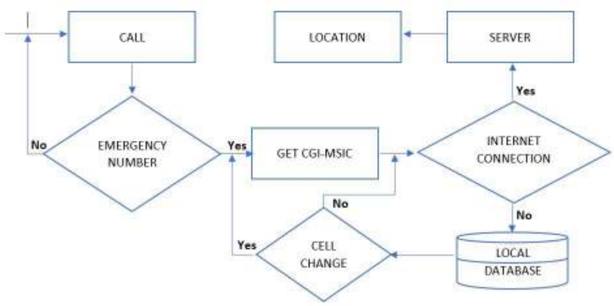

FIGURE 5. **General diagram of the proposed system.**

In Figure 5 the operation of the data extraction system is shown. In which two macroprocesses can be highlighted: Detection of the call to the emergency number 911 and sending data to the server for processing.

Once the application is installed, the monitored numbers are monitored. When the service detects that the emergency number is dialed, the data of the base stations necessary for the location and the power of the received signal are extracted. Subsequently, the data is sent to the server that executes a script so that the position is processed following the method presented in [8].

A. DETECTION OF A CALL TO THE EMERGENCY NUMBER

A *Broadcast Receiver* responsible for responding to the event when dialing 911 was developed to implement the monitoring module for the dialed numbers. This process is carried out by executing a service to extract information

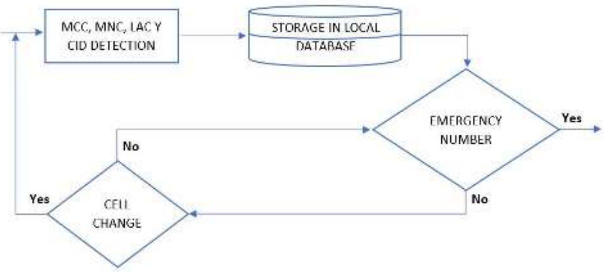

FIGURE 6. **Data extraction module for the location by GSM.**

about the cells to which it is connected. a device As the user advances or changes geographical area, the application captures data on the cell that gives coverage and stores them in a local database in SQLite to be sent to the server (see Figure 6).

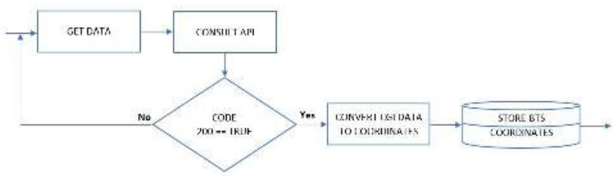

FIGURE 7. **Data processing module on the server.**

B. SENDING AND PROCESSING THE TARGET COORDINATES

The extracted data is sent to the server for processing. The server consults them on a platform to convert the data from the base stations extracted from the smartphone to geographic coordinates. These coordinates are stored in a database of the server to serve as a basis for calculating the final position of the target. It should be noted that the accuracy of the application depends on the data provided by the platform. Figure 7 shows the general operation of the module.

FIGURE 8. **Target coordinate processing module.**

The data extracted from the device serves as input to the method described in [8]. This method converts the coordinates data of the base stations to the coordinates of the target device. Its general operation is shown in Figure 8.

Finally, as a result of the positioning method, a given coordinate is obtained in latitude, longitude and altitude, this

TABLE 1. Characteristics of the mobile devices of the experiment.

Device Name	Android Version	RAM	Frequency Band
Samsung Galaxy J5	6.0.1	1 GB	850, 900 y 1800 MHz
Samsung Galaxy J5	5.1.1	1 GB	850, 900 y 1800 MHz
Sony Xperia Tipo	4.2.1	1 GB	850, 900 y 1800 MHz
Huawei G7	6.0	1 GB	850, 900 y 1800 MHz

being the position of the device. This resulting coordinate is entered into a map to obtain a clearer and easier way to interpret the position of the objective.

IV. EXPERIMENTS AND RESULTS

It should be noted that for proper operation of the application it is necessary to meet certain hardware and software requirements which are found in most of the devices that are currently on the market, ensuring that the application will reach the largest number of Android devices.

A point to consider is the version of Android that is running the device to avoid application failures because sometimes depending on the version of android change the names of the variables that contain the data that will be extracted.

To evaluate the system, four devices with Android versions of 4.2.1 or higher were used because they represent the 97.6 % of the most used Android versions. Mobile devices were positioned in different geographical areas of Mexico City to test the effectiveness of the system. As an emergency telephone number, 123 was configured so as not to harm your activities. The emergency number was dialed at different times of the day and in different circumstances. Table 1 shows the characteristics of the devices used in the tests.

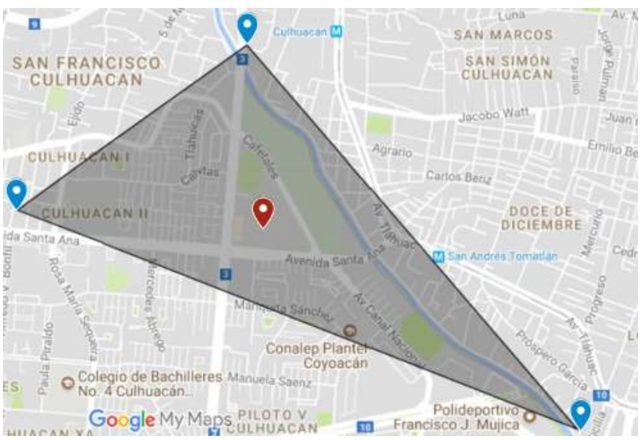

FIGURE 9. Problem to solve.

Figure 9 shows the problem to solve. It shows the geographical position of three base stations and in the center the position of the target. An important point to consider is that the objective is within the area formed by the three base stations. This ensures a good functioning of the proposed location system.

TABLE 2. Time to obtain coordinates.

	MCC + MNC = **334020**					
	CID	**LAC**	**RSSI**	**Latitude**	**Longitude**	**Time**
BTS1	5017	1023	-89dBm	19.409087	-99.034092	3.3483s
BTS2	16314	1023	-103dBm	19.408821	-99.043416	3.1332s
BTS3	34877	1023	-91dBm	19.413918	-99.036105	3.0878s
BTS4	20190	1023	-71dBm	19.411534	-99.041689	3.0886s
BTS5	10190	1023	-83dBm	19.418529	-99.041514	4.2200s
BTS6	30190	1023	-97dBm	19.412764	-99.047631	3.0980s
BTS7	24903	1023	-95dBm	19.4189	-99.044197	3.0660s
BTS8	14789	1023	-93dBm	19.412764	-99.047631	2.9898s
BTS9	20189	1023	-97dBm	19.417967	-99.053807	3.0235s
BTS10	20451	822	-79dBm	19.398551	-99.114455	3.0768s
BTS11	10453	822	-87dBm	19.39622	-99.112557	2.9703s
BTS12	34435	1011	-95dBm	19.403269	-99.11065	3.1330s

Once the application is executed, the monitoring of the dialed numbers begins. If the dialed number is 123, the data is extracted for the location. These data are sent to the server so that the target coordinates are processed. Table 2 shows the data extracted by the application and the coordinate given by the commercial positioning platform as well as the time used for its processing.

TABLE 3. Error of the obtained position.

	Royal coordinates	Coordinate Algorithm	Error
Position 1	19.40979, -99.03319	19.41092, -99.03263	141m
Position 2	19.41421, -99.04326	19.41383, -99.04316	39m
Position 3	19.41518, -99.04568	19.41485, -99.04452	129m
Position 4	19.4176, -99.05183	19.41764, -99.05245	75m
Position 5	19.41765, -99.05198	19.41769, -99.05273	80m
Position 6	19.39919, -99.11351	19.40023, -99.11303	116m
Position 7	19.42759, -99.14885	19.42743, -99.14875	37m
Position 8	19.40983, -99.03322	19.40960, -99.03167	156m
Position 9	19.47382, -99.10817	19.47332, -99.10816	54m

With the geographic coordinates of the base stations, we enter the algorithm responsible for calculating the coordinates of the objective [8]. The Table 3 shows the result of the calculation of the position of the objective as well as the error measured between the real position of the device and the position calculated by the proposed system. This error is compared with the initial search radius, observing that it is considerably reduced.

In the Figures 10, 11 and 12 the obtained results are shown on a map to check the accuracy of the method in a visual way. As it is observed, the error of the real coordinate and the one obtained with the proposed positioning system does not exceed 200 meters. This position is compared with the area formed by the base stations that provide the service, appreciating a reduction in the search area for emergency services. This result shows that the proposed system is reliable and that it does not affect the large coverage areas of the base stations. Being a service that is present in most devices and with the appropriate algorithms can be a technology that can replace GPS providing accurate results.

Coordenada BTS	Distancia al Objetivo	Coordenada Real	Coordenada Algoritmo	Error
19.474005,-99.112083	441m	19.47382, -99.10817	19.4733202229700,-99.1081666293541	54m
19.47178,-99.105653	390m			
19.477054,-99.102063	733m			

FIGURE 10. Result number 1 obtained by the proposed system.

Coordenada BTS	Distancia al Objetivo	Coordenada Real	Coordenada Algoritmo	Error
19.427065,-99.150314	163m	19.42759, -99.14885	19.4274342385447, -99.1487592369192	37m
19.425264,-99.149142	258m			
19.42923,-99.14714	262m			

FIGURE 11. Result number 2 obtained by the proposed system.

Coordenada BTS	Distancia al Objetivo	Coordenada Real	Coordenada Algoritmo	Error
19.409881,-99.052504	840m	19.4176, -99.05183	19.4176412899237, -99.0524537489022	75m
19.411254,-99.046356	840m			
19.421442,-99.054867	500m			

FIGURE 12. Result number 3 obtained by the proposed system.

V. CONCLUSION

In this work, a system has been presented to locate a mobile device within the GSM network in case of emergency by means of a method that involves the known positions of three base stations and the power of the received signal.

For the application responsible for extracting data from mobile networks used smartphones with an operating system Android 4.1 or higher as it was found that in these versions the application worked correctly for long periods of time, in addition, the extraction and sending of data had a lower use of mobile data, and the time of data extraction was reduced, which is concluded that to obtain good results are recommended versions of Android 4 or higher, also include the largest number of devices that are currently on the market.

The experimental results, comparing the local database and the database of the web server, showed that there are no significant data losses, it only generates errors when there is a null variable between the data sent.

One of the most important limitations is the use of the platform in charge of obtaining the coordinates of the BTS, since the result of the tests depends on the result of the query to said API and the accuracy of the data shown.

Also, the evaluation results for the phase of processing the target coordinates, the time taken to obtain these is very low because they are used determinants for processing, obtaining better results when the coordinates of the three base stations form a triangle and the objective is inside this one. When performing the analysis of the results obtained by comparing the position obtained by the script against the actual objective position, it was observed that the search area of the target is significantly reduced, making the emergency services act more quickly, decreasing the time used for provide assistance.

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