# Localization in Wireless Networks:
# The Potential of Triangulation Techniques

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**Abstract** User localization is one of the key service-enablers in broadband mobile communications. Moreover, from a different point of view, next steps towards automatic network optimization also depend upon the capability of the system to perform real-time user localization, in order to obtain the traffic distribution. The aim of this paper is to get deeper into the feasibility and accuracy of different localization mechanisms ranging from triangulation to database correlation. Call tracing data extracted from a real operating mobile network have been used to assess these algorithms after the execution of an extensive measurements campaign. Results show that enhanced triangulation offers the best performance even outperforming other more sophisticated mechanisms like fingerprinting, without introducing any change in the network and without requiring any special characteristic of the user equipment. Indeed, the lack of precision of channel estimates, which for the same position could differ up to 10 dB, introduces a large uncertainty that harms localization mechanisms based on database correlation. Finally, this paper identifies the areas for improvement in triangulation to reach its maximum potential, provides details for its implementation and analyzes the performance of the different proposed enhancements.

***Keywords*** *Localization, Triangulation, Fingerprinting, Wireless Networks*

## 1. Introduction

In an operating mobile network, continuous changes in the spatial-temporal traffic distribution and the Quality of Service (QoS) requirements occur. This variability also affects the interference distribution and makes necessary to continuously reconfigure the network parameters in order to keep the desired levels of QoS [1]. With this aim, in the last years some computer-aided optimization processes have been proposed that jointly integrate call-tracing, simulation fitted to actual measurements and optimization search [2]. The input data of the optimization tool encompass: the actual configuration of the radio parameters in the operating network, the list of target cells to optimize and their parameters subject to change, the possible set of values of these parameters and some information and statistics about user calls and traffic distribution. This last item is of paramount importance and, hence, user localization algorithms are to be employed so as to geo-reference the optimization input and outputs and give, for example, higher priority to those areas with higher traffic densities. Apart from optimization issues, localization in wireless systems is of great importance for other safety and commercial services.

The relevance of localization for the business model of operators has motivated plenty of techniques – good surveys can be found in [3] and [4] – that are mostly based on a set of available measurements ranging from signal arrival times to maps of received power. Indeed, current and future 3GPP radio access networks, through their associated messages in their respective Radio Resource Control (RRC) and Non-Access-Stratum (NAS) protocols, provide a set of parameters that allow operators to perform real-time user localization. Moreover, user equipments, through their feedback information transmitted in measurement reports (MR), also offer a favorable disposition for the development of localization services. The current question is whether there exists an algorithm achieving the lowest error in the estimation and if this algorithm could be implemented in practice.

Localization techniques can be divided into three main categories: based on triangulation, based on database correlation or fingerprinting and based on the use of Global Positioning System (GPS). The former group uses an estimation of distances or angles from three or more sites, to derive user location. The distance information is extracted from received signal strength (RSS) and/or propagation time measures from their neighbor base stations [5], whereas angles can be estimated if antenna arrays are available. However, most critics to these techniques come from the fact that received power suffers from large-scale and small-scale fading phenomena and hence is not reliable for positioning. Propagation time is a better parameter but quantization of the metric and the difference between line-of-sight (LoS) and non-LoS (NLoS) cases also implies huge mistakes in the estimation. Finally, time differences between base stations could be measured instead of absolute values, which could be more accurate. However, these multilateration techniques systems have several drawbacks [6] mainly related to the requirement of network synchronization, which does not exist in GSM or UMTS.

In order to improve the accuracy of RSS estimation, several localization algorithms proposed the inclusion of digital maps that contain either sophisticated predictions – including building height information – or actual data extracted from dedicated measurement scans [3]. This is the basis of the second category of localization algorithms. The measurements are compared with the entries of the database and the localization algorithm finds the best-matching entry, which leads to the location estimate [7].

The latter possibility lies in the use of a GPS receiver that can be assisted by the network (A-GPS) to work properly in urban scenarios [8]. This technique is valid for open areas with good satellite visibility but in indoor environments or in narrow streets the method is hardly applicable. Moreover, not all terminals have GPS availability.

This paper presents a practical experience performed in collaboration with a mobile operator. Although GPS-based localization techniques are not contemplated due to their limitations, realistic implementations of the other two groups are presented, trying to figure out the trade-off between complexity, accuracy and dependence with outer processes. This paper proposes a set of innovations in the triangulation process that redound on better accuracy, namely, static user detection and track smoothing. Moreover, this work aims to assess if the pretended higher accuracy of fingerprinting-based methods holds in practice.

The rest of the paper is organized as follows. Section 2 describes the main characteristics of the basic localization techniques. Then, Section 3 presents the enhancement proposals made on triangulation techniques whereas in Section 4 all results are compared and discussed. Finally, main conclusions are drawn in Section 5.

## 2. Localization Mechanisms

This section makes an overview of some of the existing localization techniques in mobile networks mainly focusing on triangulation and fingerprinting-based localization.

## 2.1. Triangulation

Triangulation involves combining information obtained from measurements made by the User Equipment (UE) or the Base Station (BS) in order to estimate the user location [9]. Examples of measures that enable the triangulation are: RSS received by the UE from different BSs, angle of arrival of the signal received in different BSs, time of arrival of the signal received in different BSs or the difference of this time of arrival between different BSs [10].

Concerning signal strength measurements, the user location is estimated using the RSS measured by the UE from the best server and the neighboring cells. This information is included in the MRs that the UE sends to the network, periodically in the case of GSM and when certain events are triggered in the case of UMTS. The RSS – RxLevel in GSM and Common Pilot Channel Received Signal Code Power (CPICH RSCP) in UMTS – allows estimating the distance between the UE and each BS by means of the application of a propagation loss model and knowing the network topology, i.e. BS positions, transmission power, and antenna orientation.

Taking into account the limitations of the RSS measurements in terms of precision [12], in order to have an acceptable result from the triangulation method there is a need to take more input data into account. In GSM and UMTS there exists temporal information suitable to aid in the user localization. The Timing Advance (TA) in GSM and the Random Access CHannel Propagation Delay (RACH PD) in UMTS can be used as a complementary way of estimating the distance between the user equipment and the serving cell. The TA is the time the signal takes to reach the BS from the UE and has a precision of 550 meters [13]. This information is available in each MR. The RACH PD is the propagation delay measured during Physical RACH (PRACH) access and is only available for the BS where the UE initiates the call, but it can be used to improve the precision of the starting location point of the user. It has a precision of ±2 chips (~ ±156 meters) [12].

Figure 1 shows the basic operation of the triangulation method using CPICH RSCP and RACH PD information, for the estimation of the starting location point of a UMTS call. This procedure is similar to the GSM case [14], where RxLevel and TA data are used instead. The distance of the UE to the best serving BS is estimated using the RACH PD information and the distance to the neighboring

BSs is estimated applying a propagation loss model, antenna gain and CPICH transmission power. The crossing of the estimated distances from each BS generates different types of points, which are weighted to calculate the final estimation of the user location as:

$$p^* = \frac{\sum_{i=1}^{N}\left(\prod_{j=1}^{M} W_{ij} \cdot p^i\right)}{\sum_{i=1}^{N}\left(\prod_{j=1}^{M} W_{ij}\right)} \tag{1}$$

where $p^*$ is the UE position estimation, $p^i$ are the $N$ different points generated by the triangulation process and $W_{ij}$ the $M$ different weights each of those points has. This way, reliability of each point depends on several factors involved in the triangulation process. The value of the different weights can be adjusted using an iterative search. For the specific case of the results obtained in this study, Simulated Annealing optimization [15] has been carried out to adjust these weights. From the available test calls, approximately 70% of the calls were used in the iterative search to optimize the value of the weights while the remaining 30% were used in the validation process.

Once the starting location point is estimated, the following user positions are estimated using the variations in the RSS from the previous point. Using the RSS difference of each BS from the previous MR and applying a propagation loss model, the location point that best matches this information is estimated as the next user location.

## 2.2. Fingerprinting

In the last years, localization based on fingerprinting or database correlation has revealed as a substitute for traditional triangulation mainly because this technique is relatively simple to deploy as compared with other approaches. The operation of fingerprinting-based positioning comprises two phases. The first one is the off-line phase, in which the database of RSS is built up using either site surveys or path loss predictions. In the second phase, also referred to as on-line phase, the user reports measured RSSs to a central entity that estimates its location. Note that this second phase also applies the other way around, i.e. the base stations collecting RSSs from users, although this is not the most common case.

*Off-line phase*

The first option to generate the database of fingerprinting is the usage of conventional drive-testing equipment. This consists of a commercial terminal configured in engineering mode plus a computer to capture and analyze the signaling of the radio interface. The RSS must be measured with enough statistics and from as many base stations as possible to create the database that maps (x,y) position with a vector of the measured RSS values (see Figure 2). Ideally, the entire area should be covered by a rectangular grid of points.

As a positive aspect, operators are periodically doing these drive-tests since they use them to verify the end to end performance of the network and to check competence status. Per contra, drive-testing has several drawbacks. Firstly, drive-testing is an outer process that entails a significant cost. Second, metrics are only available at positions where the car could drive along. This means that the system will never be able to locate users out of these tracks, what avoids the localization algorithm to operate properly in indoor scenarios, parks and pedestrian zones. Third, measures are collected at the ground level and in the middle of the road. Therefore, they may differ significantly with the actual RSS in, for example, the third story of a building, since elevation and indoor penetration losses are not taken into account. Provided that most of calls are indoor, this represents an important handicap. Finally, the last problem of drive-testing is related to the equipment that performs measures. Mobile devices must be accurate in relative rather than absolute values. This is why all radio resource management mechanisms are based on relative comparisons. Thus, for the same position, the measured RSS value can vary up to 10 dB from one device to another.

These inconveniences motivated a second alternative for the off-line phase based on the use of accurate prediction tools. There exist powerful deterministic models, like the standard propagation model, that calculate propagation losses considering both topographical information – publicly available and stored in the form of a Digital Terrain Map (DTM) – and 3D building data – against payment (see Figure 3). Besides, these models allow making predictions in urban scenarios including indoor penetration. Finally, these models can be also calibrated with measurement data from drive-testing. Therefore, they can be used alone or together with drive-testing to calculate RSSs in those positions without available information – indoor, pedestrian areas, etc.

*On-line phase*

The most simple and common algorithm to estimate user locations calculates the Euclidean distance between the measured RSS vector and all fingerprints in the database. The estimated location is the coordinates with the fingerprint providing the smallest distance. Despite other algorithms have been proposed for the on-line phase – based, for instance, on neural networks or Bayesian modeling – their accuracy is quite similar to the minimum distance approach.

# 3. Error mitigation mechanisms for triangulation-based localization

Basic triangulation explained in Section 2 has several troubles. The first one is the high variability of the RSS reported in consecutive MRs. Due to small-scale fading, power levels may experience considerable variations even with static users. This variability hinders the knowledge of the relative position of the user with respect to the base station, causing errors when determining distances. As a solution, each MR is not independently processed but a sliding average window is used instead [16]. The average over several MRs reduces the RSS variability and improves performance as shown in Section 4. The average window is centered in the current MR and the input data for the localization are the mean RSSs of all the MRs included in the window.

Despite the average window, multipath effect cannot be absolutely counteracted and still causes some random variations around a path or movement trend that can be identified by visual inspection. In order to remove these variations and soften the route, the points derived from each MR – more precisely from each averaged group of MRs – could be used to calculate a smooth function that approximately fits the data and their corresponding weights, which represent the relevance of the different points in the fitting process. A point with higher weight makes the resulting curve be closer. This weight will depend on several factors, including the dispersion of the intersection points combined to get the final estimate of the location. If this dispersion is small, i.e. all intersections point to the same area, then the final estimate is more reliable. Mathematically, the objective of the approximation is to find the function that minimizes the following expression:

$$\sum_{i=1}^{N} w_i \left|(x_i, y_i) - (x_i, f(x_i))\right|^2 \quad (2)$$

where $w_i$ is the weight – or reliability – of the *i*-th point used in the interpolation and $N$ is the number of available points.

The last problem concerns static users. The RSS variation due to multipath provokes that the algorithm was unable to generate routes with a single point. Therefore, it is needed some post-processing to identify this kind of calls. Both geometrical and variability checks [17] are made in order to classify the call as static and finally generate a single-point output.

# 4. Results and Discussion

For the purpose of evaluating the different triangulation algorithms – including error mitigation mechanisms – and to compare them to the fingerprinting mechanisms, a measurement campaign was performed. This campaign took place in the city of Valencia in an urban environment using conventional drive-testing equipment, i.e. a commercial terminal configured in engineering mode plus a GPS receiver to capture signaling and GPS positions. Simultaneously, a call tracing tool was collecting all the signaling information available in an operating mobile network.

The objective of this measurement campaign is twofold. On the one hand, the information obtained in the drive test allows getting the fingerprints necessary to evaluate database correlation algorithms. This is because most relevant indicators required for this purpose can be monitored, like CPICH RSCP in UMTS or RxLevel in GSM. On the other hand, test calls were made while specific network signaling was collected by a call trace tool developed by Ingenia Telecom S.L, NeO. This system gathers data through the information provided by the network signaling messages of the 3GPP standard protocols: RRC, NBAP, RNSAP and RANAP. NeO also supplies information about the network topology, including location and configuration of the cells involved in the monitored calls. All this information constitutes the input data for the triangulation-based algorithms.

Next subsections present results obtained with different implementations of both triangulation and fingerprinting mechanisms. The list of compared mechanisms is the following:

- Triangulation-based Localization Algorithm (TLA). This algorithm is based on the basic triangulation method described in Section 2.
- Triangulation-based Localization Algorithm with time Averaging (TLA-A). This mechanism includes the sliding average window concept described in Section 3.
- Triangulation-based Localization Algorithm with time Averaging and Smoothing (TLA-AS). This mechanism includes, in addition to the time averaging of MRs, the polynomial approximation described in Section 3.
- Enhanced Triangulation-based Localization Algorithm (ETLA). The ETLA comprises all the enhancements included in TLA-AS plus the mechanism defined in Section 3 to detect static users.
- Fingerprinting-based Localization Algorithm with Topographic data (FLA-T). The FLA-T works with a prediction of RSS levels generated with a propagation engine and using elevation maps publicly available from the Shuttle Radar Topography Mission [18]. This algorithm is free of cost since there is no need for drive-testing or for the acquisition of clutter heights. In order to perform channel estimations, the standard propagation model was used.
- Fingerprinting-based Localization Algorithm with Topographic data and Building heights (FLA-TH). This algorithm is similar to FLA-T but considering also clutter heights in the calculation of the propagation losses.
- Fingerprinting-based Localization Algorithm with Drive Test data (FLA-DT). In this case a massive drive test is available in the city center. This information is complemented in the areas not covered with the drive test with the information derived from the propagation engine fed with topographic and 3D building data.

### 4.1 Triangulation results

Results for the implemented triangulation algorithms are presented in Table 1. As it can be observed, each of the proposed error mitigation mechanisms implies some improvement in the obtained localization accuracy. It is worth noting the light difference between the results produced by TLA-AS and ETLA algorithms.

The reason for this small improvement is that the proportion of static calls among all the calls made during the measurement campaign was less than 10%.
For the sake of a better observation of the improvements introduced in TLA, some estimated routes are presented. Next figures show location results from the urban scenario. The routes according to the GPS are marked in blue. The other lines connect the location estimates obtained with the different localization algorithms. Figure 4 reflects the improvement achieved by the approximation using splines made in TLA-AS, while Figure 5 shows the potential of the detection of static users.
These results show that an acceptable accuracy can be achieved with an enhanced version of a triangulation-based localization mechanism. Besides, the main advantage of using ETLA is that good results are obtained without introducing any change in the network and without requiring any special characteristic of the user equipment. Only already available signaling data are used to get users location.

### 4.2 Fingerprinting results

Results for the implemented fingerprinting mechanisms are shown in Table 2. The accuracy obtained is poor in FLA-T as expected due to the fact that diffraction in the buildings is not taken into account in the RSS map calculation. However, FLA-TH and FLA-DT were supposed to achieve a much better performance.
The reason for these poor results can reside in the difficulties of finding the best matching point in the RSS maps, as a high variability between measures taken by different terminals was observed during the measurement campaign, and different terminal models were used for the test calls and the drive-test measurements.
An example route depicting the performance of these algorithms can be observed in Figure 6.
In terms of processing time, it has to be considered the difference computational burden needed for the generation of the RSS maps in the different alternatives. The burden introduced by considering the building heights entails a higher calculation time (more than four times higher for an area of 20 $km^2$).

### 4.3 Hybridation

After observing worse results in the fingerprinting algorithms than those obtained with ETLA, different hybrid alternatives emerge as candidate to evaluate in order to obtain a better performance. Taking into account the better results achieved by ETLA, a first approach – called Triangulation Bounded FLA (TBFLA) – is based on combining both methods in order to restrict the search area during the map correlation process to a bounded area close to the ETLA output.

Another hybrid possibility, named Fingerprinting Assisted ETLA (FAETLA), intends to improve the ETLA results adding new points to the weighted solution in each averaging window. This new points come from the search of the best matching points obtained during the correlation of the information in the MRs with the fingerprinting maps.

The results for both alternatives are presented in Table 3. A better accuracy is obtained when comparing TBFLA with FLA but ETLA is not outperformed by the hybrid methods. In TBFLA, the reduced search area does not avoid the shift in the map correlation resulting point, caused by the mismatch of the measurements taken by different terminals for the same location. Moreover, although this shift is reduced if the bounded search area is smaller, TBFLA is not able to outperform ETLA performance. On the other hand, FAETLA introduces more inaccuracy when considering FLA points in the ETLA weighted solution. In fact, when adjusting the weights of the different ETLA points, the optimization process tends to minimize the weight of these new points.

# 5. Conclusions

This paper has assessed different localization algorithms based on triangulation and fingerprinting. The proposed enhanced version of the basic triangulation has resulted to be the optimum choice in terms of accuracy. This enhanced version surprisingly outperforms other database correlation approaches that use drive-testing fingerprints. In order to reach the maximum potential of triangulation, two main problems must be tackled. The former concerns channel variability provoked by small-scale fading. To solve this, a slide average window together with a polynomial interpolation of the resulting estimates was proposed. According to the obtained results, with this solution accuracy is improved up to 35%. The second problem is that most of calls are static and hence they should be detected to act accordingly. A joint geometrical and statistical variability check has proven useful to detect these static calls.

Concerning fingerprinting-based localization algorithms, different alternatives have been evaluated ranging from a free alternative that uses public information up to a more sophisticated alternative using drive-testing. Obviously, if fingerprints come from drive tests the location estimates are more accurate. However, this improvement is not as significant as expected. This is due to the lack of precision of the terminals used in the drive test. Although they fulfilled the accuracy requirements set in the specifications [12], for the same position the measures could differ up to 10 dB, which introduces a large uncertainty in the localization mechanisms.

Comparing enhanced triangulation with fingerprinting, triangulation obtains better results while saving costs, because no change in the network or outer process is required for its operation. Compared with the actual route, enhanced triangulation achieves a mean error of 100 m whereas fingerprinting gets worse results (149 m). Finally, the hybrid operation of both mechanisms improves the performance of fingerprinting but does not make triangulation better. The aforementioned reasons for the reduced precision obtained in the fingerprinting-based localization algorithms still apply for the hybrid approaches. Therefore, in order to choose one specific localization method it seems reasonable to make use of enhance triangulation in current wireless networks.

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## FIGURE LEGENDS

Figure 1. Triangulation

Figure 2. Example of drive-test

Figure 3. Examples of RSS estimation considering only the DTM map (a) and also the building heights (b)

Figure 4. Output examples of TLA-A (a), yellow line, and TLA-AS (b), white line, for the same call, blue line

Figure 5. Output example of ETLA (white) for a static call (blue)

Figure 6. Output examples of FLA-T (green), FLA-TH (red) and FLA-DT (white) for the same call (blue)

## TABLES

Table 1. Triangulation mechanisms comparison

| | *Mean error (m)* | *70th-%tile (m)* | *95th-%tile (m)* |
|---|---|---|---|
| TLA | 155 | 184 | 269 |
| TLA-A | 133 | 147 | 257 |
| TLA-AS | 102 | 120 | 189 |
| ETLA | 100 | 111 | 187 |

Table 2. Fingerprinting mechanisms comparison

| | *Mean error (m)* | *70th-%tile (m)* | *95th-%tile (m)* |
|---|---|---|---|
| FLA-T | 191 | 263 | 389 |
| FLA-TH | 172 | 237 | 318 |
| FLA-DT | 149 | 201 | 284 |

Table 3. Hybrid mechanisms comparison

| | *Mean error (m)* | *70th-%tile (m)* | *95th-%tile (m)* |
|---|---|---|---|
| TBFLA | 125 | 168 | 222 |
| FAETLA | 136 | 170 | 241 |