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Blind Position Location via Geometric Loci Construction

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Abstract A new position location technique is proposed, using received signal strength measurements, which can be implemented using inexpensive off-the-shelf equipment. The proposed technique is based on geometric loci construction, and overcomes the need for onsite calibration measurements or propagation prediction tools and topographical/architectural plans of the covered area. The proposed algorithm exhibits similar simulated performance compared to a recently proposed positioning technique, but without the need of model calibration. In addition, measurements results are also presented, demonstrating the performance of the algorithm.

Keywords Radio position measurement · Received signal strength · Geometric loci

1 Introduction

Position location of wireless units has received considerable attention during the past few years. The US Federal Communications Commission (FCC) and the European Commission suggest location information providing for E-911 and E-112 call services respectively [1,2]. These requirements have resulted to a rapid development of relative services and an increasing demand for ubiquitous positioning with the best possible accuracy. On the other hand, location based services are expected to have a high economic impact in the near future [3]. Location information can add many potential applications to telecommunications systems, such as location-sensitive billing, fraud protection, person/asset tracking, fleet management, intelligent transportation systems, etc.

In the literature, several positioning techniques are proposed. Global Positioning System (GPS) provides global coverage but specialized equipment is needed, which is not available to off-the-shelf wireless units. Thus, in the case of an emergency call, the network operator will fail to localize a user if she/he is not equipped with a GPS module. Also, certain

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security concerns have aroused regarding GPS. The corresponding signals are weak, can be spoofed, and are prone to jamming [4]. Moreover, with GPS it is the user that sends her/his position-information to the network; therefore, security may be compromised in the case where the user intentionally lies about her/his position. Hence, a secure localization system must not rely only upon GPS but should also incorporate network-based localization in order to leverage security levels [4–6]. Finally, GPS is not capable of operating indoors, because of the large attenuation introduced by buildings' walls and ceilings, therefore it cannot comprise a ubiquitous localization method.

Radio frequency techniques have been alternatively suggested, in order to locate wireless units. Radio frequency position location systems are classified into two broad categories: Direction-finding (DF) and range-based (RB) systems [7]. DF systems utilize antenna arrays and Angle-of-Arrival (AoA) estimation techniques in order to locate the Mobile Station (MS), and are mainly used in macrocells. On the other hand, RB systems measure the distance between the MS and a number of Base Stations (BSs), and then the MS's position arises as the intersection point of the corresponding curves. The range of the MS is calculated using either Time-of-Arrival (ToA) or Received Signal Strength (RSS) measurements.

AoA and ToA measurements are not available to inexpensive systems [8], due to the need for antenna arrays or time synchronization respectively. Also, AoA and ToA measurements may be degraded due to shadowing and multipath. On the contrary, RSS indicating-capable equipment is widely available and provides a cost-effective means of position location. RSS based distance estimation may also be degraded due to shadowing as well as multipath, but small-scale fading may be smoothed out by averaging over time or equivalent distance and frequency band [9].

RSS based positioning may be performed by using time and money consuming onsite pre-measurements, thus forming a database with RSS measurements throughout the coverage area, like in the indoor cases presented in [10–14]. The resulting indoors accuracy is considered to be satisfactory, but onsite calibration measurements are not practical, and some times not possible. Alternatively, onsite RSS propagation model estimation may be used in order to leverage indoor accuracy [15]. In outdoor cases topographical maps and propagation-prediction tools, as well as statistical modeling and neural networks, have been used instead of RSS pre-measurements [9,16–20]. However, topographical maps are not always available, while propagation prediction tools, statistical models and neural networks require calibration.

Concluding, RSS-based positioning is ubiquitous and inexpensive and such techniques are well eligible provided that they demonstrate satisfactory accuracy and do not require offline measurements, calibration, prior knowledge of the environment etc. A new position estimation technique is proposed herein, which is applicable in areas with unknown propagation characteristics, while using inexpensive RSS equipment. The technique is based on geometric loci construction [21] and uses RSS measurements from a number of BSs, theoretically greater than four. The BSs are clustered to groups of contiguous attenuation factors with respect to the MS, while all possible BS groupings are investigated and evaluated in a manner that results to the MS's position estimate, as discussed further below.

The proposed technique does not use any information about the propagation environment, either via onsite measurements or propagation prediction tools, and can be implemented using inexpensive equipment with RSS indicating capabilities. Furthermore, it is suitable both for outdoor as well as for indoor applications. Simulation results in an outdoor case demonstrate similar performance compared to a recently published technique, but the herein proposed technique exhibits the advantage that it is blind, i.e. no model calibration is required. On the other hand, measurements results in an indoor case demonstrate satisfactory performance, which is directly compared to state-of-the-art localization techniques, but with the specific advantage of being blind yet accurate.

The rest of the paper is organized as follows: In Sect. 2 the proposed technique is analyzed. In Sect. 3, simulation results are presented in a specific outdoor environment and compared to relative results in the literature. Measurements results are presented in Sect. 4, where the applicability of the proposed method is demonstrated. The paper concludes with Sect. 5.

2 Algorithm Functionality

Let there be a number of BSs, namely $N_{\mathrm{BS,total}} \geq 4$. The position of the i-th BS is known and denoted by $(x_{\mathrm{BS},i}, y_{\mathrm{BS},i})$, while the position of the wireless device is unknown and denoted by $(x_{\mathrm{MS}}, y_{\mathrm{MS}})$. The unknown distance between the i-th BS and the device is given by

$$d_i = \sqrt{(x_{\mathrm{BS},i} - x_{\mathrm{MS}})^2 + (y_{\mathrm{BS},i} - y_{\mathrm{MS}})^2}. \tag{1}$$

The BS and MS antennas are assumed to be omnidirectional and vertically polarized. The RSS by the MS at a reference distance equal to $d_{0,i}$ from the i-th BS is denoted by $P_{0,i}$ and is considered to be known.

In the case where a positioning procedure is initialized, the MS measures the local mean RSS from all $N_{\mathrm{BS,total}}$ base stations. A number $N_{\mathrm{BS}} \leq N_{\mathrm{BS,total}}$ of BSs are then selected for positioning, where $N_{\mathrm{BS}} \geq 4$.

The propagation environment around the BS and the MS is modeled by the generic log-distance path loss model, where the received power P_i from BS_i at $(x_{\mathrm{MS}}, y_{\mathrm{MS}})$ is given by [22–24]

$$P_i|_{\mathrm{dBm}} = P_{0,i}|_{\mathrm{dBm}} - 10 \cdot n_i \log\left(\frac{d_i}{d_{0,i}}\right) \tag{2}$$

where n_i represents the attenuation factor between BS_i and the MS.

In the case where there is another BS, namely BS_j, for which $n_i = n_j = n$, the distances $d_i(n)$, $d_j(n)$ may be estimated by $\hat{d}_i(\hat{n})$, $\hat{d}_j(\hat{n})$, respectively, where

$$\hat{d}_i(\hat{n}) = d_{0,i} \cdot \left(\frac{P_{0,i}}{P_i}\right)^{\frac{1}{\hat{n}}} \tag{3}$$

$$\hat{d}_j(\hat{n}) = d_{0,j} \cdot \left(\frac{P_{0,j}}{P_j}\right)^{\frac{1}{\hat{n}}} \tag{4}$$

where $\hat{n}$ represents the estimate of n. Let the search space for n be denoted by $[n_{\min}, n_{\max}]$. As $\hat{n}$ scans $[n_{\min}, n_{\max}]$ with step n_{step}, the intersection points between the circles $(x_{\mathrm{BS},i}, y_{\mathrm{BS},i}, \hat{d}_i(\hat{n}))$ and $(x_{\mathrm{BS},j}, y_{\mathrm{BS},j}, \hat{d}_j(\hat{n}))$ form a geometric locus on which the MS must lie (the notation (x, y, R) represents a circle centered at (x, y) with radius R). As an example, consider locus T_1 in Fig. 1.

In the case where three BS pairs of equal attenuation factors exist, the MS position may be unambiguously estimated by the joint intersection point of the corresponding geometric loci. This is illustrated in Fig. 2 in the case of four BSs with the same attenuation factor (in Fig. 2, the loci T_1, T_2, T_3 correspond to the BS pairs BS_1–BS_2, BS_1–BS_3, BS_1–BS_4 respectively).

In Fig. 3 the case of four BSs with contiguous attenuation factors is presented; now there does not exist a unique joint intersection point among the three loci, but rather a small area

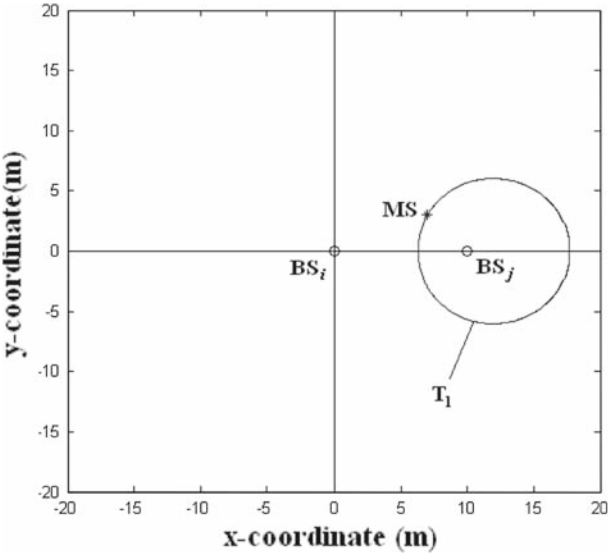

Fig. 1 Intersection points locus for two BSs having equal attenuation factors to the MS

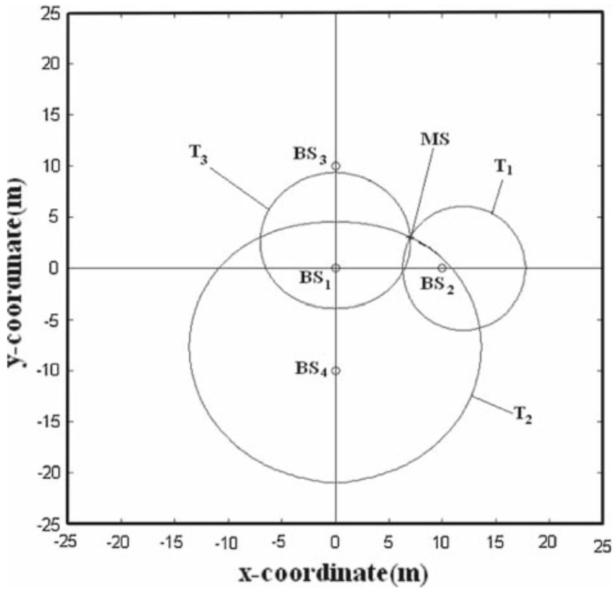

Fig. 2 Position estimation using four BSs having equal attenuation factors to the MS

within which the MS lies. In such cases, the positioning error may be evaluated by the *measure of applicability* which is defined later in this section. The measure of applicability is also used in order to select the optimum BS grouping.

Depending on the number of BSs used for positioning, the proposed algorithm consists of the following steps (a simplified flow chart of the proposed positioning algorithm is illustrated in Fig. 4):

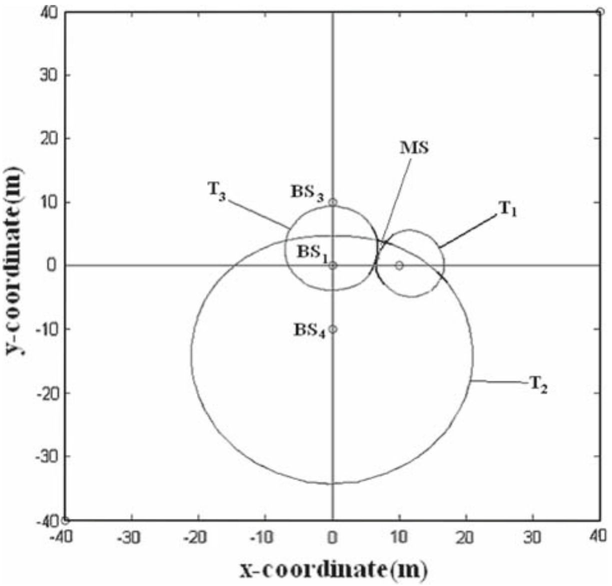

Fig. 3 Position estimation using four BSs with contiguous attenuation factors to the MS

(A) $N_{\mathrm{BS}} \geq 4$.

1. Given the N_{BS} selected BSs, four of them are selected in all possible ways (i.e. all combinations of N_{BS} base stations taken four at a time). For each quadruplet, all possible combinations of three BS pairs are formed, under the constraint that each combination must contain every BS in the quadruplet. For each three-pairs combination the following sub-steps are executed:
   (i) It is assumed that all BSs of the combination are characterized by a common—and unknown—attenuation factor to the device, denoted by n_1. The estimate $\hat{n}_1$ of n_1 is generated. For each value of $\hat{n}_1 \in [n_{\min}, n_{\max}]$, and for each BS pair of the combination, e.g. BS_i–BS_j, the estimates $\hat{d}_i(\hat{n}_1), \hat{d}_j(\hat{n}_1)$ of the distances between BS_i, BS_j and the MS respectively, as well as the intersection points of the circles $\left(x_{\mathrm{BS},i}, y_{\mathrm{BS},i}, \hat{d}_i(\hat{n}_1)\right)$ and $\left(x_{\mathrm{BS},j}, y_{\mathrm{BS},j}, \hat{d}_j(\hat{n}_1)\right)$ are calculated.
   (ii) As $\hat{n}_1$ scans $[n_{\min}, n_{\max}]$ the corresponding geometric loci of the intersection points defined in (i) is constructed. Thus, a total of three geometric loci are constructed, corresponding to the three BS pairs. The wireless device should lie on these loci.
   (iii) For each value of $\hat{n}_1 \in [n_{\min}, n_{\max}]$, the sum of the corresponding distances between the geometric loci is calculated as a function of $\hat{n}_1$ (sum error). The distance between two geometric loci is calculated using the following definition: If for a value $\hat{n}_{\mathrm{val},1} \in [n_{\min}, n_{\max}]$ the corresponding points on locus 1 are A and B, and for a value $\hat{n}_{\mathrm{val},2} \in [n_{\min}, n_{\max}]$ the corresponding points on locus 2 are C and D, the distance between these two loci is a function of $(\overline{n}_{\mathrm{val},1}, \overline{n}_{\mathrm{val},2})$, and is defined by

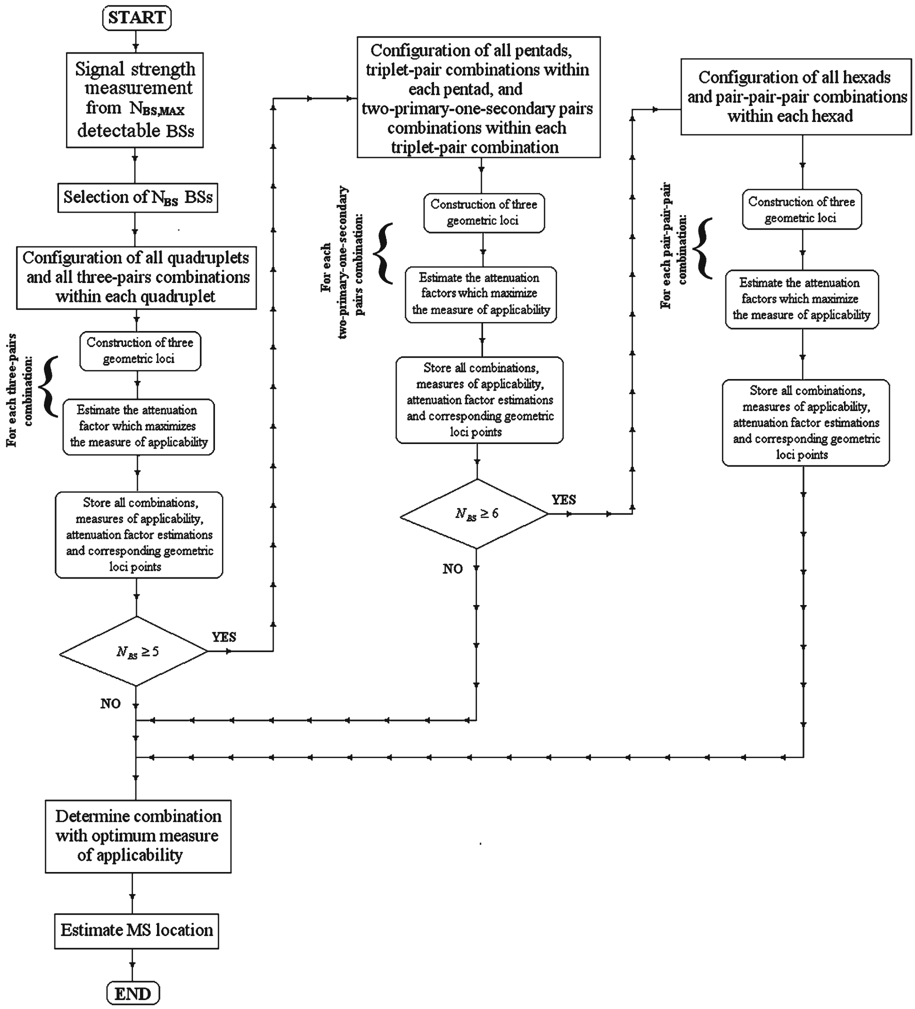

Fig. 4 Simplified flow chart of the proposed positioning algorithm

$$\text{Distance}(\overline{n}_{\text{val},1}, \overline{n}_{\text{val},2}) = \min\{d(\text{A,C}), d(\text{A,D}), d(\text{B,C}), d(\text{B,D})\} \quad (5)$$

where $d(X, Y)$ represents the Euclidean distance between the points X and Y.

Following this definition, for each value of $\hat{n}_1$, the sum of the corresponding distances among the three geometric loci is calculated. The minimum value of the sum of distances between the geometric loci, as well as the value $\hat{n}_{1,\text{opt}}$ of $\hat{n}_1$ for which this minimization occurs, are calculated. The inverse of the minimum sum value is *the measure of applicability of the specific three-pairs BS combination*. Furthermore, the three points on the geometric loci corresponding to the measure of applicability are also determined.

2. All significant data are stored, i.e. all quadruplets, all three-pairs BS combinations, the measure of applicability and the corresponding $\overline{n}_{A,\text{opt}}$ value of each combination, as well as the corresponding points of the geometric loci.

(B) $N_{\text{BS}} \geq 5$.
In the case where $N_{\text{BS}} \geq 5$, the following steps are additionally executed:

1. Given the N_{BS} base stations, five of them are selected in all possible ways (i.e. all combinations of N_{BS} transmitters taken five at a time). In each pentad, three BSs are selected in all possible ways (i.e. all combinations of five BSs taken three at a time). These three BSs form a triplet, while the remaining two BSs form a secondary pair. In each triplet, all possible combinations of two BS pairs are formed, under the constraint that each combination must contain every BS in the triplet. These two pairs are called primary.

   For each combination of two primary and one secondary BS pairs, a procedure similar to the one in steps A.1.(i)–A.1.(iii) is followed. More specifically, the primary pairs BSs are assumed to be characterized by a common and unknown attenuation factor, n_1, to the device; the estimate $\hat{n}_1$ of n_1 is defined and two geometric loci on which the MS must lie are constructed as $\hat{n}_1$ scans $[n_{\min}, n_{\max}]$. Then, another geometric locus is constructed using the secondary pair of the pentad, assuming a common and unknown attenuation factor to the MS, n_2, as well as its estimate, $\hat{n}_2$.

   Finally, for each value of $\hat{n}_1$ and for each value of $\hat{n}_2$, the sum of the corresponding distances between these three geometric loci is calculated. The sum of loci distances is now a function of $\hat{n}_1$ and $\hat{n}_2$. The minimum value of the sum of distances between the geometric loci, as well as the values $\hat{n}_{1,\text{opt}}, \hat{n}_{2,\text{opt}}$ of $\hat{n}_1$ and $\hat{n}_2$ respectively for which this minimization occurs, are determined. The inverse of the minimum sum value is *the measure of applicability of the specific two-primary-one-secondary-pairs BS combination*. Furthermore, the three points on the geometric loci corresponding to the measure of applicability are also determined.
2. All significant data are stored, i.e. all pentads, all triplet-pair combinations, all two-primary–one-secondary-pairs combinations, the measure of applicability and the corresponding $\hat{n}_{1,\text{opt}}, \hat{n}_{2,\text{opt}}$ values of each combination, as well as the corresponding points of the geometric loci.

(C) $N_{\text{BS}} \geq 6$.
In the case where $N_{\text{BS}} \geq 6$, the following steps are additionally executed:

1. Given the N_{BS} base stations, six of them are selected in all possible ways (i.e. all combinations of N_{BS} transmitters taken six at a time). For each one hexad, two BSs are selected in all possible ways (i.e. all combinations of six BSs taken two at a time). For each two BSs selected, there is a corresponding remaining quadruplet. In this quadruplet, two BSs are selected in all possible ways (i.e. all combinations of four transmitters taken two at a time). Thus, for each hexad, all possible combinations of the type pair–pair–pair are formed.
   For each pair–pair–pair combination, a procedure similar to the one in steps A.1.(i)–A.1.(iii) as well as step B.1 is followed. More specifically, each pair is assumed to be characterized by one unknown attenuation factor to the MS, denoted by n_1, n_2 and n_3 for each pair respectively. Then, the estimates of $\hat{n}_1$ of n_1, $\hat{n}_2$ of n_2 and $\hat{n}_3$ of n_3 are defined. As each estimate scans $[n_{\min}, n_{\max}]$, the corresponding geometric

locus is constructed, resulting to three geometric loci each of which corresponds to one of the configured BS pairs.

Finally, for each value of $\hat{n}_1$, $\hat{n}_2$ and $\hat{n}_3$, the sum of the corresponding distances between these three geometric is calculated. The sum of loci distances is now a function of $\hat{n}_1, \hat{n}_2$ and $\hat{n}_3$. The minimum value of the sum of distances between the geometric loci, as well as the values $\hat{n}_{1,\text{opt}}, \hat{n}_{2,\text{opt}}, \hat{n}_{3,\text{opt}}$ of $\hat{n}_1, \hat{n}_2$ and $\hat{n}_3$ for which this minimization occurs, are determined. The inverse of the minimum sum value is *the measure of applicability of the specific pair-pair-pair BS combination*. Furthermore, the three points on the geometric loci corresponding to the measure of applicability are also determined.

2. All significant data are stored, i.e. all hexads, all pair-pair-pair combinations, the measure of applicability and the corresponding $\hat{n}_{1,\text{opt}}, \hat{n}_{2,\text{opt}}, \hat{n}_{3,\text{opt}}$ values of each combination, as well as the corresponding points of the geometric loci.

(D) In all cases, after storing all significant data, the following steps are also executed:

1. From all examined combinations the one with the *optimum maximum of applicability* is selected. This combination is named "dominant" combination.
2. The position of the wireless device is estimated as the average of the three geometric loci points corresponding to the measure of applicability of the dominant combination. The average (x, y) of three points, (x_1, y_1), (x_2, y_2), (x_3, y_3) respectively, is calculated by

$$x = \frac{x_1 + x_2 + x_3}{3}, \quad y = \frac{y_1 + y_2 + y_3}{3}. \tag{6}$$

3. Finally, the attenuation factor between the MS and each BS is estimated by solving Eq. (2) for n_i, where $i = 1, \ldots, N_{\text{BS,total}}$ corresponds to the respective BS.

3 Simulation Results

In order to demonstrate the applicability of the proposed technique in outdoor cases a simulated evaluation of the technique's performance is presented in this section. Since outdoor measurements using real-life networks require expensive equipment and licenses (e.g. a GSM-network based evaluation), measurements results from a recently reported testbed [9] were used instead. Propagation as well as network parameters are appropriately selected in order to match the corresponding measured parameters in [9], thus leveraging the validity of the presented results despite the lack of direct measurements.

In the work presented in [9], two positioning algorithms are evaluated in a commercial GSM-900 MHz network, which consists of 12 Base Transceiver Stations (BTSs). Propagation model parameters are calibrated via network parameters or onsite measurements. The MS distance from six strongest signal BSs is calculated. A reference distance is selected among the calculated distances, and then all distances are expressed as ratios of the reference distance. Based on this, a hyperbolic and a circular positioning algorithm are applied.

Furthermore, the generic and well-known log-distance propagation model with log-normal shadow fading is used [22–24]. The local mean of the received signal strength is given by

$$P_r(d)\,[\text{dBm}] = P_0\,[\text{dBm}] - 10n\log(d/d_0) + X \tag{7}$$

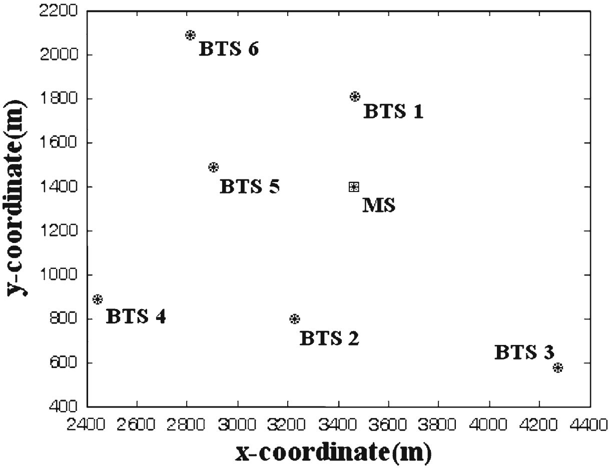

Fig. 5 BTS and MS positions for the outdoor simulation test case

Table 1 Outdoor simulation: BTS positions, attenuation factors and standard deviations; $(x_{MS}, y_{MS}) = (3{,}462, 1{,}400\,\text{m})$ [9]

# BTS	Position (m)	Attenuation factor	Shadowing standard deviation (dB)
1	(3,468, 1,807)	3.54	4.1
2	(3,226, 7,98)	3.42	7.8
3	(4,274, 5,77)	3.45	10.8
4	(2,443, 8,87)	3.45	10.2
5	(2,903, 1,486)	3.45	7.9
6	(2,814, 2,085)	3.56	8.7

where P_0 is the received signal strength at distance d_0 from the transmitter, n is the attenuation factor and X is a zero-mean (in dB) log-normally distributed random variable with standard deviation σ (also in dB).

Measurements results are presented in [9], while the MS is moving along a predetermined path of length 2 km with constant speed equal to 0.417 m/s. At each positioning measurement, the RSS is averaged over a distance of 25λ–38λ. The 67th and 95th positioning

error percentile for the circular and the hyperbolic positioning algorithm are equal to 285 m and 464 m for the circular, and 333 m and 526 m for the hyperbolic algorithm respectively. Also, the corresponding mean errors are equal to 246 and 282 m respectively. Furthermore, separate results are presented in the case where the MS is located at $(x_{MS}, y_{MS}) = (3{,}462, 1{,}400\,\text{m})$. The corresponding BTS positions are illustrated in Fig. 5, as well as in Table 1 together with the respective attenuation factors and standard deviations.

As analyzed in [9], the positioning error strongly lies on the selection of an appropriate reference distance. In the case where the distance is calculated via the underlying propagation model, the achieved positioning error for $(x_{MS}, y_{MS}) = (3{,}462, 1{,}400\,\text{m})$ is minimized if the serving BTS distance is selected as a reference distance. Then, the corresponding achieved positioning error is equal to 318 and 346 m for the hyperbolic and the circular positioning algorithm respectively.

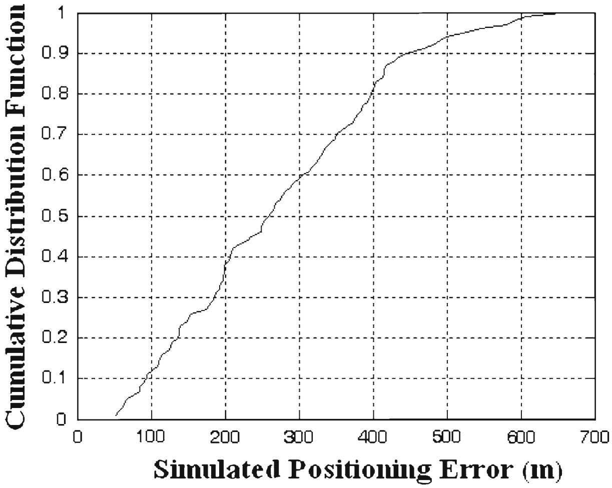

Fig. 6 Empirical cdf of simulation results positioning error; network and propagation parameters as in [9]

For comparison purposes, our proposed method is evaluated using the network and propagation parameters of Table 1, while the MS position is $(x_{MS}, y_{MS}) = (3{,}462, 1{,}400\,\text{m})$. The BTS positions, attenuation factors and standard deviations are used for generating RSS samples. It should be noted that, unlike in [9], the propagation parameters of Table 1 are not considered to be known during our algorithm's execution. Since the effective shadowing correlation distance is not reported for the experiment in [9], the MS is assumed stationary during simulation.

A total of 100 algorithm executions are performed and the resulting positioning error cumulative distribution is displayed in Fig. 6. The error mean, median, 67th and 95th percentiles are equal to 274, 261, 338 and 522 m respectively. According to simulation results, our algorithm exhibits similar performance compared to the algorithm presented in [9], but exhibits the advantage that it is blind, i.e. neither model calibration nor measurement of the attenuation factor or selection of an appropriate reference distance are required. Nevertheless, the proposed technique exhibits superior or similar performance compared to the one in [9].

4 Measurements Results

The proposed algorithm is further tested via measurements results, contacted on the 3rd floor of the School of Electrical and Computer Engineering, National Technical University of Athens, Greece. A 2.4 GHz Wireless Local Area Network (WLAN) was set up, consisting of six transmitting Access Points (APs) as well as a standard IBM laptop equipped with a receiving PCMCIA network adapter. The APs were of type LINKSYS WAP11 [25], while the network adapter was of type CISCO LMC-352 [26]. The transmitting as well as receiving antennas were linear, while the corresponding radiation patterns are omnidirectional with a maximum gain of 2 dBi on the horizontal plane, measured in an anechoic chamber. The APs' output power was set to 15 dBm, while each AP's reference received power $P_{0,i}$, at distance $d_0 = 1.25\,\text{m}$, was measured in the anechoic chamber. The RSS at the receiving network

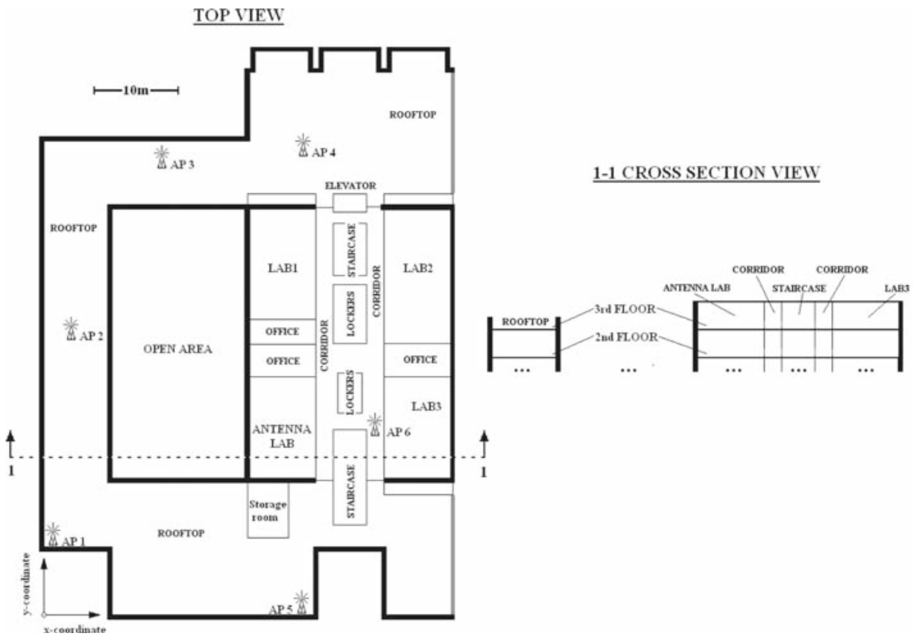

Fig. 7 Layout of the measurements area

Table 2 Testbed WLAN AP positions

AP 1 (m)	AP 2 (m)	AP 3 (m)	AP 4 (m)	AP 5 (m)	AP 6 (m)
(0.0, 6.6)	(0.7, 29.1)	(9.07, 52.5)	(23.3, 51.3)	(23.7, 0.0)	(31.2, 18.1)

adapter was provided by the NetStumbler network planning tool [27], which was calibrated using an Agilent E4403B Spectrum Analyzer [28].

The WLAN was deployed over an area of about 50 m $\times$ 50 m size as illustrated in Fig. 7, while the exact APs' positions are tabulated in Table 2. A set of RSS measurements was taken from each AP at 60 different laptop positions. The laptop positions were selected appropriately in order to form a uniform grid of dimensions 2.8 m $\times$ 2.8 m over the coverage area. Furthermore, the transmitting and receiving antennas were placed at a height of 2.2 and 1.5 m over the 3rd-floor level respectively. The proposed positioning method was then applied for each laptop location, while the attenuation factor search space and step were equal to $[n_{\min}, n_{\max}] = [1, 9]$ and $n_{\text{step}} = 0.05$ respectively.

The cumulative distribution of the achieved positioning error accuracy is illustrated in Fig. 8. The positioning error mean, median, 67th and 90th percentile are equal to 6.39, 5.88, 7.37 and 10.50 m respectively. The achieved accuracy is comparable to relative results for indoor environments in the literature [10], but it is again noted that the proposed algorithm exhibits the advantage that it is totally blind, i.e. it is not based on a RSS pre-measurements database or model calibration, neither uses a propagation prediction tool.

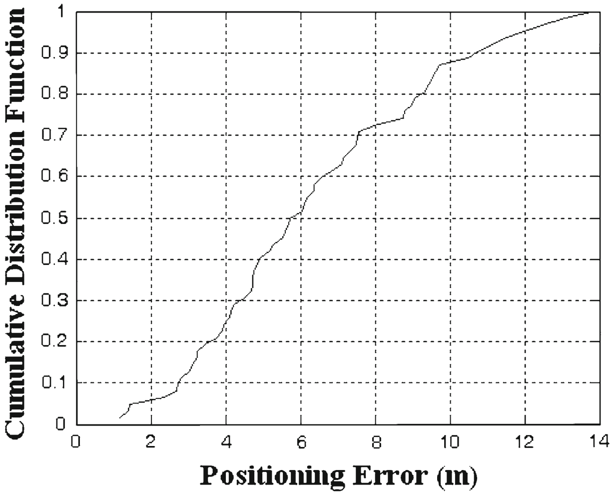

Fig. 8 Empirical cdf of measurements results positioning error

5 Conclusion

A new technique for position location is proposed, based on geometric loci construction using simple RSS measurements. The method is blind and relies neither upon onsite RSS pre-measurements or propagation model calibration, nor a propagation prediction tool and topographical/architectural maps. Simulation as well as measurements results are presented, demonstrating the applicability of the proposed technique.

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