General selection criteria to mitigate the impact of NLoS errors in RTT measurements for mobile positioning

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Abstract—In this contribution, a new Mobile Station (MS) localization method is provided using Round Trip Time (RTT) measurements in the UMTS-FDD [1]. Three or more base stations (BS) performing RTT measurements of a signal from a mobile station (MS) are necessary for its localization. However, when some of the measurements are from Non-Line-Of-Sight (NLoS) paths, the location errors can be very large. We propose a method that takes into account possible large RTT error measurements caused by NLoS. To this end, the new method measures the best coherence between the RTT estimates and allows the mobile to select the three most reliable measures among the whole available RTT measurements. This method does not depend on a particular distribution of the NLoS error. Realistic simulations show the gain of positioning accuracy provided by the proposed algorithm.

Index Terms: Mobile positioning, Non-Line-of-Sight (NLoS), Round Trip Time (RTT), Coherence criterion.

I. INTRODUCTION

Nowadays, the determination of the position of a transmitting mobile station (MS) is becoming a compulsory requirement for mobile operators. Responding to E-911 calls, providing location specific service information, and navigation aid and user's tracking, are examples that require an MS location [2]. The frequency with which location requests are made and the accuracy desired varies with the application. The most widely employed location technologies are radio location systems that attempt to locate an MS by measuring radio signals between the MS and a set of base stations (BSs). The main approaches proposed to locate a mobile are based on either signal strength, angle of arrival (AoA), time of arrival (ToA), or time difference of arrival (TDoA) and can be network- or terminal-based. For an overview of various wireless location techniques and technologies, see [2] and [3]. In this paper, we are interested in the MS localization based on RTT (Round Trip Time) measurements in the UMTS-FDD [1]. The serving radio network controller (SRNC) may request measurements from a BS or the location measurement unit (if implemented). RTT constitutes the difference between transmission of the beginning of a downlink Dedicated Physical Channel (DPCH) frame and the reception of the beginning of

a corresponding uplink physical frame. RTT is measured by the UMTS Terrestrial Radio Access Network (UTRAN) after receiving the request from SRNC. Based on the information on how long the signal propagates from a BS to the MS, by using a certain propagation model, the distance from the BS can be estimated. In GSM, the corresponding location method is based on TA (Timing Advance) measurements. TA is quantized into 64 levels, each level corresponds to 1,84615 μs ($\cong 550m$). Fortunately in UMTS, RTT measurements are performed with a resolution of 1 chip, which gives about 80 meters location accuracy. Nowadays, oversampling methods allow RTT to be reported with 1/16 chip resolution, which gives about 5 m precision. Hence, the factors, which degrade the accuracy, are mainly the propagation effects.

The accuracy of radio location schemes depends on the propagation conditions of the wireless channels. If LoS propagation exists between the MS and all BSs, a high location accuracy can be achieved. However, in wireless communication systems in which the direct path from the MS to a BS is blocked by buildings and other obstacles, the signal measurements include an error due to the excess path length traveled because of reflection or diffraction, which is termed as the NLoS error. To obtain a precise localization, it is therefore important to take into account the problem of NLoS. Different solution for the NLOS problem exist in the literature including the statistical methods that distinguish between the LoS and NLoS scenarios using the measurements distribution (gaussian or non gaussian) [4] or the measurement error variance [5], the bayesian and model based methods that use side (a priori) information given by field measurements [6] and the non statistical methods that select the LoS measurements using a coherence criterion [7]. In this paper, we propose an extension of the latter method which, in addition to keeping a very simple implementation architecture of standard trilateration techniques, enables us to better identify and eliminates some strongly erroneous RTT measurements. The mobile position is then obtained only from the three most reliable RTT among the set of all RTT estimates. Simulation results are provided to illustrate the performance of the proposed method compared

to the one given in [7].

II. DATA MODEL AND TRILATERATION ALGORITHMS

Assuming a homogeneous propagation environment and the existence of a line of sight, the propagation delay is related to the mobile position according to:

$$t_i(j) = \sqrt{(x(j) - x_i)^2 + (y(j) - y_i)^2}$$
(1)

where $t_i(j)$ represents the time delay (TD) between BS *i* and the mobile position (x(j), y(j)) corresponding to the j^{th} measurement of the RTT $t_i(j) = RTT_i(j)/2$, *c* is the light celerity, (x_i, y_i) are the coordinates of the i^{th} BS. In practice, the RTT measurement is corrupted by estimation errors and possible NLoS effect leading to :

$$\hat{t}_i(j) = t_i(j) + w_i(j) + u_i(j)$$

where $w_i(j)$ represents the estimation noise, usually of zero mean and a variance depending on the near-far effect (often modeled as a gaussian noise) and $u_i(j)$ is a possible large bias due to the NLoS effect. Classical trilateration methods take into account only the estimation noise $w_i(j)$ by solving the nonlinear equation system (1) in the least squares sense or using a properly chosen statistical criterion. Two algorithm classes exist in the literature using either:

- an iterative resolution (ML or MSE) [8],
- or an explicit solution of (1) [9].

The second approach has been chosen here as it represents a better complexity-precision trade-off than the first one. Indeed, in the first case, the accuracy of the solution strongly depends on the initialization and eventually on the number of iterations. Let us estimate the mobile position from the three TD $(t_i(j), t_k(j), t_l(j))$ which are assumed not affected by the NLoS noise using the explicit solution of [9]. The solution corresponds to:

$$\begin{pmatrix} x_{i,k,l} \\ y_{i,k,l} \end{pmatrix} = \mathbf{A} \begin{pmatrix} c^2 e_{k,i} - k_k + k_i \\ c^2 e_{l,i} - k_l + k_i \end{pmatrix}$$
(2)

where $\mathbf{A} = -2 \begin{pmatrix} x_{k,i} & y_{k,i} \\ x_{l,i} & y_{l,i} \end{pmatrix}^{-1}$ with $x_{k,i} = x_k - x_i, y_{k,i} = y_k - y_i, k_i = x_i^2 + y_i^2$ and $e_{m,n} = t_m^2 - t_n^2$. The indices i, k, l are used here to indicate that this MS location estimates is obtained from the TD measurements at BS i, k and l. When L estimates of TD for each base station (i.e. $t_i(j)$ j =

when L estimates of TD for each base station (i.e. $v_i(j) = 1 \cdots L$) are available, one can calculate their mean average before using the trilateration algorithm to locate the mobile.

III. SELECTION ALGORITHM USING A COHERENCE CRITERION

In this work, we propose a new approach to deal with the NLoS noise (bias) u(j). A major problem here is the difficulty to simply predict or model the NLoS phenomenon and many existing solutions to the localization problem do not take the NLoS noise into consideration. We handle that problem by considering the situation where multiple (more than three)¹ TD measurements are available and only one

¹Most of the time, more than 5 BSs receive the MS positioning signal in urban or micro-cell environments.

or few of them are affected by the NLoS noise. More precisely, we propose a suboptimal (but yet simple and efficient) new trilateration algorithm which enables us to identify the incoherent TD measurements and to only select the three most reliable ones. The proposed selection algorithm, based on a coherence criterion, has the advantage to be easy to implement and not to require any change in the UMTS-FDD standard. The coherence criterion for 3 given BSs is simply a measure of the gap between the MS-BS distances calculated from the MS position given by the trilateration algorithm (i.e, $\hat{d} = \sqrt{(\hat{x}_{MS} - x_{BS})^2 + (\hat{y}_{MS} - y_{BS})^2)}$ and from the TD measurements (i.e, $\tilde{d} = c\hat{t}$). The gap (difference) between the 2 MS-BS distance estimates, expressed by $(\tilde{d} - \tilde{d})^2$, must be close to zero (or even zero) if there is no NLoS effect (or in the noiseless case). More precisely, for a reference BS mdenoted BS_m ($m = 1 \cdots M$, where M represents the total BS number), it was proposed in [7] to identify the three TDs $(\hat{t}_i, \hat{t}_k, \hat{t}_l)$ (associated to the BSs *i*, *k*, *l*, respectively) which minimize the following expression

$$\xi_{i,k,l}^m = \left(\hat{d}_{i,k,l}^m - c\hat{t}_m\right)^2,$$

where $\hat{d}_{i,k,l}^m \triangleq \sqrt{(x_{i,k,l} - x_m)^2 + (y_{i,k,l} - y_m)^2}$ and $(x_{i,k,l}, y_{i,k,l})$ being the solution of (2). This quadratic criterion measures the gap between the distance BS_m -MS estimated via the TD (\hat{t}_m) and via the mobile position given by the TD measurements ($\hat{t}_i, \hat{t}_k, \hat{t}_l$). It is used here as an indicator of the coherence between the TD measure at the reference BS *m* and any 3-tuple (*i*, *k*, *l*) of TD measures.

In order not to privilege one particular BS with respect to the others, the coherence criterion is evaluated in [7] by considering successively each BS m as a reference and hence, the selection criterion consists in solving :

$$(\hat{i}, \hat{k}, \hat{l}) = \arg\min_{i,k,l} (\min_{m} \xi^{m}_{i,k,l}).$$
(3)

This criterion mitigates part of the NLoS effect but is quite sensitive to the TDs measurements noise. An alternative selection method is proposed here using the 'averaged distance gap measure' for any given 3-tuple (i, k, l), i.e

$$\zeta_{i,k,l} = \left(\hat{d}_{i,k,l}^{i} - c\hat{t}_{i}\right)^{2} + \left(\hat{d}_{i,k,l}^{k} - c\hat{t}_{k}\right)^{2} + \left(\hat{d}_{i,k,l}^{l} - c\hat{t}_{l}\right)^{2}.$$

Using this criterion, the (most reliable) 3 BSs measurements are obtained by solving :

$$\hat{i}, \hat{k}, \hat{l} = \arg\min_{i,k,l} \zeta_{i,k,l}.$$
(4)

Despite its simplicity and its low computational cost compared to the existing one, simulation experiments and theoretical analysis show that the proposed criterion is quite efficient and performs better than the existing one. These two selection criteria are shown to be consistent in the sense that, neglecting the effect of the measurement noise w, they enable us to select 3 BSs measurements free from the NLoS bias. We have the following Lemma :

Lemma 1: Let consider the noiseless case, i.e $\hat{t}_i(j) = t_i(j) + u_i(j)$, and assuming that there exist at least 3 BS

measurements free from the NLoS bias. Then, the selection criteria in (3) and (4) provide an NLoS free mobile location estimate.

Proof: It is clear that in the noiseless case the 2 criterion values are minimum and equal to zero when the 3 TD measurements are LoS. In which case we obtain the exact mobile position.

Besides its consistency, it is shown here that the selection criterion (4) is less sensitive to measurement noise than criterion (3). More precisely, we have the following Lemma :

Lemma 2: Our selection criterion (4) provides a better discrimination rate (higher rate of correct selection) between the LoS and the NLoS scenarios than criterion (3).

Proof: we attempt to study in a simple way the criteria efficiency of distinguishing between the LoS and NLoS. To this end, we consider the reference BS $m(\hat{t}_m)$ and the three TDs $(\hat{t}_i, \hat{t}_k, \hat{t}_l)$ (associated to the BSs i, k, l, respectively), we denote the value of $(\hat{d}_{i,k,l}^m - c\hat{t}_m)^2$ by

- Δ_m when it corresponds to a NLoS (i.e. when at least one of $(\hat{t}_i, \hat{t}_k, \hat{t}_l, \hat{t}_m)$ is affected by a NLoS noise).
- δ_m when it corresponds to a LoS, this value is due to the estimation noise (it is clear that Δ_m >> δ_m).

Let us start with the LoS case. Using the selection criterion given in equation (3), we can write :

$$\xi_{i,k,l}(LoS) = \arg\min_{m=1\cdots M} \delta_m$$

In this LoS case, our proposed criterion in equation (4) can be written as :

$$\zeta_{i,k,l}(LoS) = \delta_i + \delta_k + \delta_l.$$

Otherwise, when the estimation of at least one TD of the (t_i, t_k, t_l) is affected by NLoS noise, the two criterion values are given by

$$\xi_{i,k,l}(NLoS) = \arg \min_{m=1\cdots M} \Delta_m.$$

$$\zeta_{i,k,l}(NLoS) = \Delta_i + \Delta_k + \Delta_l.$$

Thus, by calculating the difference of the criterion values between the NLoS and LoS cases, one can see the efficiency of this criterion to discriminate between these two cases and then to obtain the right mobile position (the higher is the difference value the more efficient is the discrimination criterion). Therefore, we obtain for the proposed criterion in [7]:

$$\Delta \xi = (\xi_{i,k,l}(NLoS) - \xi_{i,k,l}(LoS))$$

$$= \arg \min_{m=1\cdots M} \Delta_m - \arg \min_{m=1\cdots M} \delta_m.$$
(5)

Similarly, for our proposed criterion, we get :

$$\Delta \zeta = (\zeta_{i,k,l}(NLoS) - \zeta_{i,k,l}(LoS))$$

$$= \Delta_i + \Delta_k + \Delta_l - \delta_i - \delta_k - \delta_l.$$
(6)

It is clear that, with high probability, $\Delta \zeta > \Delta \xi$ which means that our criterion performs better than the existing one. This observation is confirmed by simulation results.

A. Multi TDs observation

In this part, we consider that L > 1 TD measurements are available for each BS. These TD measurements correspond to the same MS location and eventually the same NLoS bias but are affected by independent noise terms, i.e $\hat{t}_i(j) =$ $t_i + w_i(j) + u_i$, $j = 1 \cdots L$, where $w_i(j)$ are independently and identically distributed iid estimation (measurement) noise errors. We propose here to adopt the selection criterion given in equation (4) to that case. Two suggestions for the criterion generalization are considered :

$$\hat{i}, \hat{k}, \hat{l} = \arg\min_{i,k,l} ((\bar{d}^{i}_{i,k,l} - c\bar{t}_{i})^{2} + (\bar{d}^{k}_{i,k,l} - c\bar{t}_{k})^{2} + (\bar{d}^{l}_{i,k,l} - c\bar{t}_{l})^{2})$$
(7)

where $\bar{t}_i = \frac{1}{L} \sum_{j=1}^{L} \hat{t}_i(j)$ and $\bar{d}_{i,k,l}^i$ is the MS- BS_i distance calculated from the MS position obtained by the solution of (2) when using \bar{t}_i , \bar{t}_k , \bar{t}_l . Or otherwise :

$$\hat{i}, \hat{k}, \hat{l} = \arg\min_{i,k,l} \frac{1}{L} \sum_{j=1}^{L} ((\bar{d}^{i}_{i,k,l} - c\hat{t}_{i}(j))^{2} + (\bar{d}^{k}_{i,k,l} - c\hat{t}_{k}(j))^{2} + (\bar{d}^{l}_{i,k,l} - c\hat{t}_{l}(j))^{2})).$$
(8)

In other words, we have the choice between calculating the selection criteria from the averaged TD measurements or otherwise calculate the averaged value of the selection criterion over all TD measurements.

To decide on the best choice, theoretical performance analysis is performed. Similarly to what is done in the previous section, we calculate the mean of the criterion difference value between the NLoS and LoS cases (we didn't present the details because of lack of space). We obtain that the criterion given in equation (8) behaves better than the other one presented in equation (7) according to the following Lemma :

Lemma 3: The selection criterion (8) provides a better discrimination rate between the LoS and the NLoS scenarios than criterion (7).

IV. EXPERIMENTAL RESULTS

In order to illustrate the new method in a realistic scenario, a microcell environment has been considered. There are five BSs, and their locations, as shown in figure 1, are at (0,50), (110,1600), (600,800), (975,1650), (1350, 250).

Different scenarios have been simulated to illustrate the impact of the proposed selection algorithms in the case of some NLOS errors. For the simulations carried out, the corresponding sets of curves represent either the selection efficiency (i.e. the rate of correct selection of the TDs which are not affected by the NLOS error) or the mobile position accuracy expressed in terms of the cumulative distribution function CDF [7]. These two quantity measures are evaluated over 500 Monte–Carlo runs.

A. Coherence Criteria efficiency

To obtain an averaged value of our criteria efficiency, a random mobile position in the covering zone of the BS_1 is considered at each MonteCarlo run. The number of available TD measurements is L = 5 except for figure 10.

1) Gaussian NLoS noise: Let us consider first, the case where the NLOS error is Gaussian distributed. In figures 2, 3, 4 and 5, the problem of NLoS is highlighted with the NLoS case concerning respectively the BSs (1 and 4), (2 and 4), (2 and 3) and BS 2. Note that the indices are numbered according to the clothers of the BS to the MS. When TDs measurements are affected with a NLoS noise, one will allot to these NLoS error the following realistic values : $u_1(j) \sim \mathcal{N}(80, 30), u_2(j) \sim \mathcal{N}(85, 30), u_3(j) \sim \mathcal{N}(90, 35), u_4(j) \sim \mathcal{N}(100, 40) \text{ and } u_5(j) \sim \mathcal{N}(110, 45), \text{ where } \mathcal{N}(\mu, \sigma)$ represents the normal distribution of mean μ and variance σ^2 . As we can notice, the bias mean & variance is higher when the MS-BS distance increases. The estimation noise $w_m(j)$ are iid zero mean Gaussian random variables with a variable variance σ_m , at each run $\sigma_m, \ m = 1 \cdots 5$ can have a uniform value between 0 and σ_{max} (σ_{max} takes the following values 10, 20, 30 and 40 as shown in the different figures). In these simulations, we illustrate first the efficiency of the criteria by selecting the 3 BSs which corresponds to the LOS measurements. The dashed line marked with * corresponds to our proposed criterion given in equation (8). The dashed line with \triangleleft corresponds to the one given in equation (7). The dashed line with \circ corresponds to what is was proposed in [7]:

$$\hat{i}, \hat{k}, \hat{l} = \arg\min_{i,k,l} \left\{ \min_{m} \frac{1}{L} \sum_{j=1}^{L} \left(\bar{d}_{i,k,l}^{m} - c \hat{t}_{m}(j) \right)^{2} \right\}.$$
 (9)

And finally the dashed line with \Box corresponds to :

$$\hat{i}, \hat{k}, \hat{l} = \arg\min_{i,k,l} \left\{ \min_{m} \left(\bar{d}_{i,k,l}^m - c\bar{t}_m \right)^2 \right\}.$$
(10)

2) Uniform NLoS noise: In this subsection we have the same context as previously but the NLoS error when it exists, has a continuous uniform distribution on the corresponding interval : $u_1(j) \in [40, 130], u_2(j) \in [50, 140],$ $u_3(j) \in [50, 150], u_4(j) \in [50, 160]$ and $u_5(j) \sim [50, 180]$. The different scenarios are illustrated in figures 6, 7, 8 and 9 which correspond respectively to the NLoS TDs of the BSs (1 and 4), (2 and 4), (2 and 3) and (2) only.

As we can see, our proposed criterion behaves better than the other criteria in all considered scenarios and it reaches a high correct selection accuracy.

3) Influence of the number of TDs: In order to observe the influence of the number L of TD measurements, we present the following simulation. In figure 10, we compare our proposed criterion with the proposed one in [7] in the case of a gaussian NLoS error for BS 2 and 5 for different values of the number of TD measurements L. It is clear that the larger L is, the higher is the criteria selection accuracy.

B. Mobile position accuracy

In this subsection, the same context is adopted as before. To observe the mobile position accuracy for the different criteria. We calculate the CDF of the error on the mobile position, for three different scenarios, i.e. $(\sqrt{(\hat{x} - x)^2 + (\hat{y} - y)^2})$, where (\hat{x}, \hat{y}) represent the estimate of the mobile co-ordinates and (x, y) are the exact one). In figures 11 and 13, we consider a gaussian NLoS noise for BS (1, 3) and (1, 5), respectively,

with a number of TD measurements L = 5 and $\sigma_{max} = 40$. In figure 12, we change the gaussian NLoS noise to a uniform noise for the BS (1, 3). As we can see, our proposed criterion provides the best mobile position accuracy for the different scenarios.



Fig. 1. Configuration of the microcell



Fig. 2. Selection criteria efficiency, Gaussian NLoS noise on BS 1 and 2.

V. CONCLUSION

In this paper, a new trilateration technique has been introduced in order to reduce the NLoS effects on mobile localization. This technique exploits the redundancy available when more than 3 BSs are in connection with the MS in which case we select the best TD measurements using a coherence criterion. The theoretical and simulation results clearly demonstrate the efficiency of the proposed trilateration algorithm with respect to the existing one in [7]. The proposed algorithm has the advantage of requiring no change in the UMTS-FDD standard and allows us to keep the very simple implementation architecture of existing trilateration techniques. The proposed algorithm doesn't require a large number of measurement to reach a good correct selection accuracy and it does not depend on a particular distribution function of the NLoS error.



Fig. 3. Selection criteria efficiency, Gaussian NLoS noise on BS 2 and 4.



Fig. 4. Selection criteria efficiency, Gaussian NLoS noise on BS 2 and 3.

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Fig. 5. Selection criteria efficiency, Gaussian NLoS noise on BS 2 only.



Fig. 6. Selection criteria efficiency, uniform NLoS noise on BS 1 and 2.



Fig. 7. Selection criteria efficiency, uniform NLoS noise on BS 2 and 4.



Fig. 8. Selection criteria efficiency, uniform NLoS noise on BS 2 and 3.



Fig. 9. Selection criteria efficiency, uniform NLoS noise on BS 2 only.



Fig. 10. Criteria efficiency comparison, Gaussian NLoS noise on BS 2 and 5, for different numbers of TD measurements ${\cal L}$



Fig. 11. Mobile position accuracy, Gaussian NLoS noise on BS 1 and 3 for $\sigma_{max}=40.$



Fig. 12. Mobile position accuracy, Uniform NLoS noise on BS 1 and 3 for $\sigma_{max}=40.$



Fig. 13. Mobile position accuracy, Gaussian NLoS noise on BS 1 and 5 for $\sigma_{max}=40.$