A Novel Method to Mitigate the Non–Line–of–Sight Error in AOA Measurements for Mobile Location

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Abstract

In this contribution, a mobile location method is provided using Angle Of Arrival's (AOAs) in UMTS-FDD systems using measurements from two different Base-Stations. Although computationally efficient, this method enhances state of the art algorithms based on a simple trilateration and takes into account error measurements caused by Non-Line-Of-Sight (NLOS) and near-far effect. The new method attributes an index of confidence for each measure, in order to allow the mobile to select the two most reliable measures and not to use all measures, equally.

1 Introduction

Mobile location is a growing practice in cellular communication systems and many applications are already forecasted: localizing traffic in order to balance the network, emergency interventions, billing tariffs depending on the mobile position, pursuit of criminals using cellular phones, etc.
Several approaches have been proposed to locate a mobile: Time of Arrival, strength measures or Angle-Of-Arrival [1]. Whatever, the selected approach, two main difficulties are present:

- The first difficulty encountered is characteristic of the UMTS-FDD system: the near-far problem which corresponds to the difficulty for a base-station (BS) to hear far-located mobile station (MS) because of the interference generated by close-located mobiles. One can notice, that one of the advantage of methods based on AOA with respect to these based on Time-Of-Arrival (TOA) is that only two measures at two different BS are sufficient instead of three.

- The second difficulty concerns the absence of LOS (i.e. The NLOS problem) which is a source of error for methods based on TOA as well as on AOA.

One of the considered solutions consists in trying to have more measures than necessary, in order to mitigate the effect of some wrong measures thanks to trilateration. However, if for example, only one of all measures is erroneous, the trilateration will reduce the mobile location performances, as shown by the simulation example in this paper.
In this article, we focus on AOA and a new method is proposed which selects the two most reliable AOA among the whole of the estimations. The general idea consists in computing the position probability of the mobile to be at the intersection of two given directions (two AOA's), knowing a certain distribution a priori of the mobile in the related cells. The paper is organized as follow:

- The first part of the article is dedicated to the data model and the description of the chosen AOA's estimations method.

- Principle and derivations of the new selection algorithm are presented in the second part.

- Finally, in the third part, some realistic simulations will show the improvement in mobile location performances brought by our new algorithm compared with a traditional trilateration in situations when NLOS or NFE problems appear.

2 AOA Estimation

The Angle–Of–Arrival is defined as the angle θ made by the mobile's signal arriving at the BS and an axis of reference (see figure 1). It is noteworthy to say that methods based on AOA need the use of complex antennaes containing several sensors, which can only be considered in the uplink scenario.

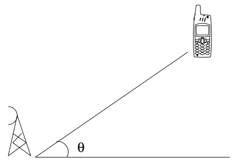

Figure 1: Definition of AOA

2.1 Uplink Signals

Throughout the rest of the document, the signals are generated according to the UMTS–FDD standards [5], [7].
Let us consider a network with U BS, each containing K MSs[1]. In the uplink, there are basically two dedicated physical channels (data and control) which are transmitted separately on two orthogonal branches I and Q. The separation of these two channel is ensured by using different spreading codes selected from the Walsh family as shown in figure 2. The separation of different MS is carried out by complex short scrambling codes of length 256. The sequence transmitted by the MS k to BS's is given by:

$$\begin{aligned} b_k &= (d_k^1 c_k^1 + d_k^2 c_k^2 \sqrt{F}) s_k \\ &= b_k^1 + b_k^2 \end{aligned}$$

In the sequel, $\sqrt{F}$ will be supposed to be equal to 1.

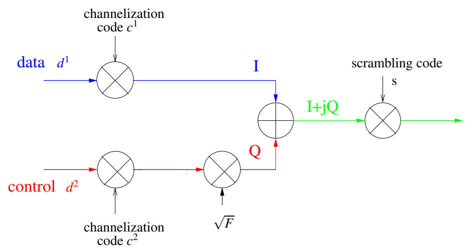

Figure 2: Design of the uplink signal

2.2 Channel model

The signals transmitted by different MS's are received, through discrete multipath channels, by all BS, with different powers. Each BS has an antenna

[1]For simplicity, the same number of users K have been chosen for all BSs.

with several sensors. Several geometrical configurations are possible: linear or circular. But, as previous studies have pointed out [4], circular arrays provide a significant enhancement with respect to linear ones for 2–D angle (elevation and azimuth) estimation.
At sensor n, the received signal emitted by the K users can be expressed by:

$$x_n(t) = \sum_{k=1}^{K} \sum_{l \in \mathbb{Z}} G_k b_k(l) h_{k,n}(t - lT_c) + w(t), \tag{1}$$

T_c denotes the chip period, $w(t)$ is an additive white Gaussian noise process , $h_{k,n}(t)$ is the impulse response of the k^{th} user channel at sensor n and G_k represents the attenuation factor of the k–th user with respect to the cell under consideration.
For an N–sensors array, the $(N \times 1)$ impulse response model vector is given by [2]:

$$\mathbf{h}_k(t) = \begin{bmatrix} h_{k,1}(t) \\ \vdots \\ h_{k,N}(t) \end{bmatrix} = \sum_{i=1}^{d_k} \mathbf{a}(\theta_{k,i}) \beta_{k,i} g(t - \tau_{k,i}) \tag{2}$$

where d_k is the number of distinct propagation paths, $g(t)$ is the known modulation pulse shape (square-root raised cosine). Each path is characterized by its delay $\tau_{k,i}$, its complex attenuation $\beta_{k,i}$ and its direction of arrival $\theta_{k,i}$. $\mathbf{a}(\theta_{k,i})$ is the steering vector of the array characterizing the complex response to a planar wavefront arriving from direction $\theta_{k,i}$. The sensors are assumed to be identical and omni-directional, uniformly distributed over the circumference of a circle of radius r. The angle between sensor i and sensor 1 is denoted $\gamma_i = \frac{2(i-1)\pi}{N}$. Let the array center be the phase reference point. The array response vector $\mathbf{a}(\theta_{k,i})$ is then given by:

$$\mathbf{a}(\theta_{k,i}) = \begin{bmatrix} e^{j\xi cos(\theta_{k,i} - \gamma_1)} \\ \vdots \\ e^{j\xi cos(\theta_{k,i} - \gamma_N)} \end{bmatrix}$$

where $\xi = \frac{2\pi r}{\lambda}$ and λ is the wavelength. Denote by $\mathbf{H}_k$ the matrix containing the impulse response samples collected at each sensor, by L_k the channel length and by P the oversampling factor. The $(N \times L_k P)$ dimensional matrix

$\mathbf{H}_k$ can be written as [2]:

$$\begin{aligned}\mathbf{H}_k &\stackrel{\text{def}}{=} \left[\ [\mathbf{h}_k(0) \quad \mathbf{h}_k(\tfrac{T_c}{P}) \quad \ldots \quad \mathbf{h}_k(L_k Tc - \tfrac{T_c}{P})\ \right] \\ &= [\mathbf{a}(\theta_{k,1})\ldots\mathbf{a}(\theta_{k,d_k})] \begin{bmatrix} \beta_1 & & 0 \\ & \ddots & \\ 0 & & \beta_{d_k} \end{bmatrix} \begin{bmatrix} \mathbf{g}_{\tau_{k,1}} \\ \vdots \\ \mathbf{g}_{\tau_{k,d_k}} \end{bmatrix} \\ &= \mathbf{A}(\theta_k)\mathbf{B}_k\mathbf{G}(\tau_k)\end{aligned}$$

where $\mathbf{g}_{\tau_k}$ is a L_kP-dimensional row vector containing the samples of $g(t-\tau_k)$

$$\mathbf{g}_{\tau_k} \stackrel{\text{def}}{=} \left[\ g(-\tau_k) \quad g(\tfrac{T_c}{P} - \tau_k) \quad \ldots \quad g(L_kT_c - \tfrac{T_c}{P} - \tau_k)\ \right]$$

2.3 TOA and AOA estimation algorithm

Under the assumption of a line–of–sight, the angle between the first path and the axis of reference corresponds to the desired AOA. In this respect, the BS has to estimate the time of arrival of the different paths in order to select the first one (i.e. the LOS path is associated with the smallest time delay).

2.3.1 TOA estimation

As in [2], a Fourier transform (FT) is used in order to estimate the delays since it translates a delay into a certain phase progression. Given the channel model in (2), the Fourier coefficient $\mathbf{h}_F(f) \stackrel{\text{def}}{=} FT(\mathbf{h}(t))$ can be written as:

$$\mathbf{h}_F(f) = \sum_{i=1}^{d} \mathbf{a}(\theta_i)\beta_i g_F(f) e^{-j2\pi\tau_i f}$$

where $g_F(f)$ is the Fourier transform of $g(t)$. In matrix form, this yields to

$$\mathbf{H}_F = \mathbf{A}(\theta)\mathbf{B}\mathbf{V}(\tau)\text{diag}(\mathbf{g}_F)$$

Where $\mathbf{H}_F$ is the Fourier transform channel matrix, i.e., $\mathbf{H}_F \stackrel{\text{def}}{=} \mathbf{HF}$ with $\mathbf{F}$ is the $(LP \times LP)$ Fourier transform matrix [2]. $\mathbf{g}_F$ represents the vector of Fourier transform coefficients of the pulse shape filter $g(t)$ and $\mathbf{V}(\tau)$ is the Vandermonde matrix given by:

$$\mathbf{V}(\tau) = \begin{bmatrix} 1 & \chi_1 & {\chi_1}^2 & \ldots & {\chi_1}^{LP-1} \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & \chi_d & {\chi_d}^2 & \ldots & {\chi_d}^{LP-1} \end{bmatrix}$$

where $\chi_i = e^{\frac{-j2\pi\tau_i}{L}}, 1 \le i \le d$.
The structure of matrix $\mathbf{H}_F$ has the shift-invariance properties which allows the estimation of τ_i by the ESPRIT algorithm.

2.3.2 AOA Estimation

Once the estimation of the delays is carried out, it is possible to limit the study to matrix $\mathbf{H}_1$ obtained by right multiplying $\tilde{\mathbf{H}}_F$ by the pseudo–inverse of $\mathbf{V}(\tau)$, e.g. $\mathbf{V}(\tau)^{\#}$.

$$\begin{aligned} \mathbf{H}_1 &= \tilde{\mathbf{H}}_F \mathbf{V}(\tau)^{\#} \\ &= \mathbf{A}(\theta)\mathbf{B} \end{aligned} \quad (3)$$

where $\tilde{\mathbf{H}}_F \stackrel{\text{def}}{=} \mathbf{H}_F \text{diag}(\mathbf{g}_F)^{-1}$. At this step, it is possible to select the column of matrix $\mathbf{H}_1$ corresponding to the first path. Several techniques can then be considered [2], [3].

2.4 Interference Suppression

For the AOA estimation, we will assume that the impulse response of each user has been estimated. Classically, this is done by using the Rake receiver which consists of correlations of the received signal with delayed versions of the pilot control sequence of the considered user.

$$\hat{h}_{k,n}(l) = \frac{1}{J} \sum_{i=0}^{J-1} x_n(i+l) b_k^{1*}(i)$$

J being the size of time correlation and * denotes the complex conjugation operator. Usually, this channel estimate suffers from the near–far problem. As a consequence, it is better, particularly in the uplink, to use an interference cancellation algorithm.
The following figure illustrates such an algorithm called PIC (Parallel Interference Cancellation). The principal steps of this algorithm are :

1. Estimation of the channel for all users thanks to the control sequence whose symbols are known, $\hat{h}_{k,n}$.

2. Estimation of the symbols of all user's data sequences $\hat{d}_k^1$ and therefore of all user's emitted sequences $\hat{b}_k$. [2]

3. Interference cancellation according to:

$$\tilde{x}_n(i) = x_n(i) - \sum_{u \neq k} \hat{x}_{n,u}(i)$$

[2]Remark : Note that the two first steps of the algorithm are already considered for signal detection purpose and thus, they don't induce any extra computation.

where $\hat{x}_{n,u}(i) = \sum_l \hat{h}_u(l)\hat{b}_u(i-l)$
and channel re-estimation:

$$\tilde{h}_{k,n}(l) = \frac{1}{J}\sum_{i=0}^{J-1} \tilde{x}_n(i+l) b_k^{1*}(i)$$

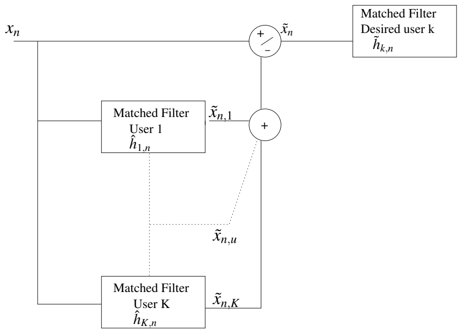

Figure 3: PIC algorithm

3 AOA selection algorithm

The new method considers the probability that a mobile is located at the intersection of two given AOA based on a certain a priori distribution of the mobile inside the considered cells. This can be interpreted as an index of the coherence of measures between them.

3.1 Choice of the a Priori Distribution of the Mobile Location

The "a priori information" of the probability of presence of the mobile can be obtained mainly by two approaches:

- A first approach is the estimation of AOAs combined with a mobile distance estimation. The TOAs, represent the best distance information that can be used. Another possibility consists in using the strength measures, always available at the BS.
- The second approach is the use of a distance information only. As described previously, the distance information is computed from the TOA.

Based on the 'a priori information' at hand, several solutions for the probability distribution of the mobile location are possible. Among them, we have chosen here a gaussian distribution which is only based on the knowledge of the mean and the variance of the position estimate.
In this work, the mean value is set equal to the estimated (angle or distance) parameter for a given BS. The variance is chosen 'ad–hoc' based possibly on an a priori evaluation of the estimation variance of the considered parameters. The Gaussian distribution has the advantages to be easy to implement and rather realistic in this context. The following figures represent gaussian distributions based on angle-distance information and distance information only. In the example of figure 4, the considered BS is located at $(0, 0)$ and the parameters of the distribution D are :

- For the angles: mean (μ_θ) and variance (σ_θ) respectively equal to $\pi/4$ and 0.2 rad.
- For the distances: mean (μ_r) and variance (σ_r) respectively equal to 100m and 5m.

$$D(r,\theta) = \frac{1}{2\pi\sigma_r\sigma_\theta} exp(-(\frac{r-\mu_r}{\sqrt{2}\sigma_r})^2) exp(-(\frac{\theta-\mu_\theta}{\sqrt{2}\sigma_\theta})^2) \tag{4}$$

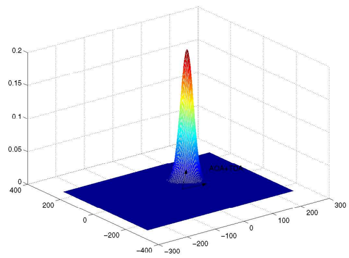

Figure 4: angle and distance distribution

In the example of figure 5, the considered BS is located at $(0, 0)$ and the distance parameters are : $\mu_r = 100$m and $\sigma_r = 5$m.

$$D(r) = \frac{1}{\sqrt{(2\pi)}\sigma_r} exp(-(\frac{r-\mu_r}{\sqrt{2}\sigma_r})^2) \tag{5}$$

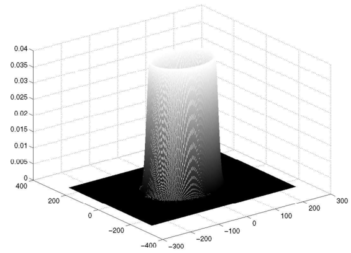

Figure 5: distance distribution

3.1.1 Selection algorithm

The idea of the proposed selection algorithm is to use a coherence criterion for the angle measures based on the selected a priori distribution. More precisely, for a given probability density function (pdf) D_k, the coherence criterion of two angles θ_i and θ_j, with respect to BS i and j, respectively, is equal to the value of the pdf D_k at the intersection point M of the half–lines S_i and S_j of respective directions θ_i and θ_j, i.e. $D_k(r, \theta)$
where (r, θ) are the polar coordinates of the intersection point M.

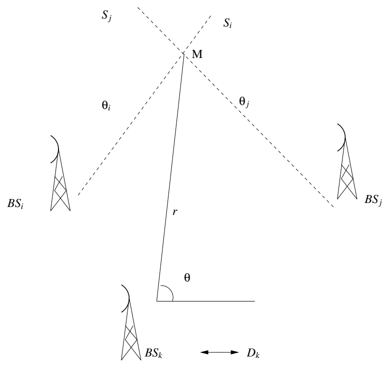

Figure 6: Selection algorithm

This coherence criterion will be denoted by $P(\theta_i, \theta_j / D_k)$ Each BS can provide parameters (mean, variance) for a new a priori distribution. It is then possible to obtain for each distribution D_k, the most reliable couple of angles corresponding to the highest probability $P(\theta_i, \theta_j / D_k)$ obtained for this distribution:

$$(\hat{\theta}_1, \hat{\theta}_2)_k = \max_{i \neq j} P(\theta_i, \theta_j / D_k) \tag{6}$$

Two strategies, at this step, can be developed:

- On the one hand, we can consider the distribution of the serving BS for the selection algorithm. This choice can be justified by the fact that the AOA and TOA estimations suffer less from NFE for this BS than for the other ones and therefore can be considered more reliable.
- On the other hand, rather than to privilege one BS with respect to others, final selection can be done by choosing the most probable couple through all distributions as follows

$$(\hat{\theta}_1, \hat{\theta}_2) = \max_k (\hat{\theta}_1, \hat{\theta}_2)_k \tag{7}$$

4 Simulations

The simulations carried out have been chosen in order to show the improvement of the accuracy of the mobile location with the proposed method. Performance comparisons with classical trilateration techniques are also provided.

As mentioned previously, main location errors are due to:

- Near–far effect.
- NLOS.

Thus, two kind of simulations have been carried out to study the impact of the proposed selection with respect to the NLOS and NFE respectively :

- The first one illustrates the Near–Far problem effect, with in particular, a strong attenuation of the signal with the distance, and a large number of users.
- In the second part, the problem of NLOS is highlighted. The attenuation of the signals, and the number of users are lower.

A microcell environment containing 4 SBs has been simulated according to [6]. Three paths with time–varying complex amplitudes corresponding to a mobile speed of 3 km/h for each channel have been considered. The AOA of the second path (resp. of the third path) was supposed to be at 20 degrees from the AOA of the first path (resp. at 10 degrees). Each cell contains $K^c = K$ interfering mobiles randomly distributed. A background noise representing 10% of the maximum signal power received by a BS has been added. For figures 7, 8 and 9, mobile location results, obtained by the following methods, have been represented:

- our proposed selection method
- a trilateration with the two nearest (first) BSs,
- with the three nearest BSs,
- with the four BSs.

The four corresponding sets of curves, are represented by circular error cumulative probability density function (CDF). The error is given in terms of meters. They have been obtained from 100 runs corresponding to any fixed position of the mobile for $K = 30$ users. During the observation period (chosen equal to 80 slots), the channel fading coefficients $\beta_{k,i}$ are supposed to be independent random (complex) gaussian variables of power $\sigma_{k,i}$ whereas delays $\tau_{k,i}$ and angles $\theta_{k,i}$ are supposed to be constant. The results clearly demonstrate the efficiency of our proposed selection algorithm with respect to a classical trilateration method, (i.e. least square mobile position estimation using the AOAs estimates).

Moreover, other simulations have been done corresponding to a random mobile position (figure 10) in order to show that the efficiency of the algorithm doesn't depend on a particular mobile position i.e. on a particular BSs configuration with respect to the mobile. Moreover, the main difference between the two scenarios corresponds to the choice of the means μ_r and μ_θ used for the distribution D_k. Indeed, the first scenario corresponding to a fixed mobile position allows us to obtain μ_r and μ_θ by averaging over several runs. This reduces the impact of some erroneous estimations on the selection algorithm, particularly estimation errors corresponding to a mobile position very close to a BS. In figure 11, we illustrate the impact of interference cancellation (IC) on the mobile location estimation. We can observe a slight improvement for the classical trilateration methods but the IC has negligible impact for the proposed method.
In figure 12, we study the impact of the variance parameters σ_r and σ_θ on the mobile location. Fortunately, for a large range of values, we can see little impact of these parameters on the position estimation accuracy. As a consequence, the proposed selection algorithm is robust to an a priori mis–selection of the angle and distance variance parameters.

5 Conclusion

This paper introduces a new 'probabilistic' trilateration method for the mobile location in wireless communications. This method is based on a criterion

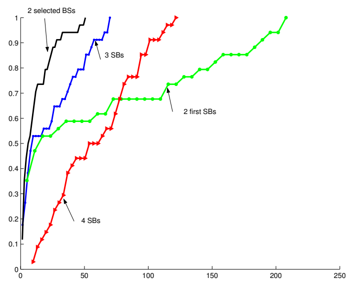

Figure 7: NFE for a fixed mobile position

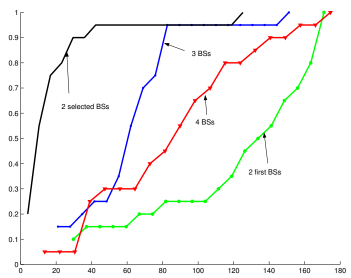

Figure 8: NFE for a fixed mobile position

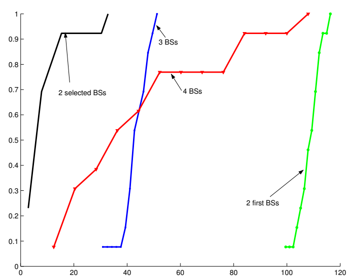

Figure 9: NLOS for a fixed mobile position

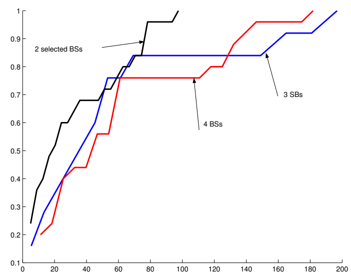

Figure 10: NFE for an averaged mobile position

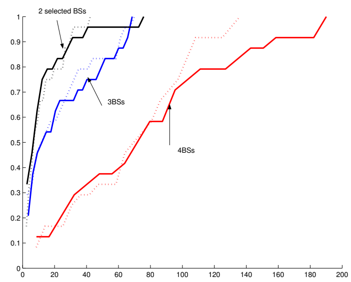

Figure 11: IC influence in the case of a fixed mobile position (dotted–line with IC and solid–line without IC)

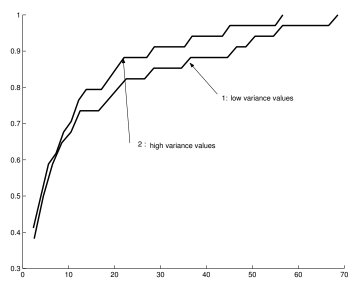

Figure 12: Influence of the variance parameters of the BS 1

which selects the AOA measurements that fit best according to an a priori distribution of the mobile position. Simulation results illustrate the effectiveness of the proposed method compared to classical trilateration methods in NLOS and NFE situations.

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