NOVEL WIRELESS LOCATION APPROACH FOR W-CDMA SYSTEMS BASED ON MULTIPLE SLIDING CORRELATORS

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ABSTRACT

[1] Mobile locationing using Time Difference of Arrival (TDOA) measurements has received considerable attention over the last few years. The classical two-step approach consists of acquiring TDOA measurements followed by a separate computation of the mobile position. This approach suffers from issues such as high outlier probabilities in the TDOA measurement acquisition.

This paper presents an approach to estimating the mobile's position in one single step, improving the performance of the classical approach. Numerical simulations show the gain in terms of outlier probability and positioning accuracy.

1. INTRODUCTION

A problem of growing importance in cellular communication networks (such as GSM and W-CDMA) is finding the position of mobile terminals. This will be mandatory for public-access cellular networks and very useful for future position-based services.

One of the most common approaches to mobile position estimation is based on measuring several pseudo-Time-Of-Arrivals (pTOA) between the mobile station and neighboring Base Stations (BSs).

This classical approach is normally decomposed into two steps: in the first step, the pTOA measurements (delays) associated with the visible BSs are obtained in an absolutely independent and non-assisted way [1]. In the second step, a locationing algorithm of choice ([2] ,[3],[4]) is implemented to obtain the position estimate, fusing the pTOAs obtained in the first step into a position estimate. The geometric relationship between the different pTOA's is logically exploited in the second step to obtain the position estimate but it is normally not used to assist in the delay estimation of the first step.

[1]This work has been partially supported by the European Comission under IST project EMILY IST-2000-26040 and by the following research projects of the Spanish/Catalan Science and Technology Commisions (CICYT/CIRIT): TEC2004-04526, TIC2003-05482

The main disadvantage of this approach is the high outlier probability in the delay estimation of the first step, specially in scenarios where the near-far phenomena of CDMA is present. For instance, if the mobile is placed near to the serving BS, the low signal to interference ratio (SIR) of neighboring BSs signals will present a problem in delay estimation. This phenomenon is partially ameliorated by the Idle period DownLink (IPDL) technique forcing BSs to respect a periodic period of silence. This technique allows the mobile to measure the delays of neighboring BSs when the serving BS is quiet.

Additional disadvantages of the two-step classical approach are: • An additional algorithm is needed to estimate the quality (variance) of the pTOA estimates obtained in the first step to be used in the location algorithm implemented in the second step ([2],[3],[4]). • It is quite difficult to add additional information of the area, for instance a city-map, to the estimation process. • Important information regarding Non-Line-Of-Sight (NLOS) phenomena is lost in the first step. Because of this, only high-level algorithms can be implemented in the second step to ameliorate the NLOS phenomena [5].

This paper presents a new approach to location estimation for W-CDMA systems, taking as input the incoming CDMA signal and not only the estimated pTOAs. To obtain such an estimator, a generalization of the classical sliding correlator is developed that fuses the vector-outputs of all correlators to obtain a position estimate. This approach is an alternative to the IPDL technique but without perturbing the normal functionalities of the BSs while allowing tracking capabilities. Additionally, the new approach is shown to decrease the impact of the problems, mentioned above, associated to the classical two-step approach. Finally, a numerical simulation section will show the improvements in locationing accuracy and a significant reduction in outlier probability.

2. SIGNAL MODEL

First some basic notation conventions. $\lfloor m \rceil_\alpha$ is the modulus α of m. This is, given α, $\lfloor n + k\alpha \rceil_\alpha = \lfloor n \rceil_\alpha = n$, for all $n \in [0, \alpha)$ and for all integers k. Second, $\lfloor m \rfloor$ is the low integer part of m, also defined as $\lfloor m \rfloor = \lfloor m \rfloor_1$, i.e., $\lfloor n + \delta \rfloor = n$ for all integers n and $\delta = [0, 1)$.

The system under consideration is the downlink of a DS-CDMA system operating over an additive Gaussian noise (AWGN) channel, where N different BSs are visible from the mobile. In general, the n-th BS sends the modulated information of K_n users plus the pilot signal (considered user number 0). This n-th BS spreads the information of its k-th user with the associated spreading code $c_{n,k}(m)$, $m = 0, \cdots, SF_{n,k}-1$, and randomizes the global signal with the cell-specific scrambling code $d_n(m)$, ($m = 0, \cdots, CP-1$), where $SF_{n,k}$ is the spreading factor of the k-th user on the n-th BS and CP is the scrambling code period common to all BSs.

The base-band signal created by the n-th BS can be decomposed into the contribution of the pilot signal and the contribution of the K_n users as follows:

$$s_n(t) = p_n(t) + \sum_{k=1}^{K_n} u_{n,k}(t) \quad (1)$$

$$p_n(t) = \sum_{m=-\infty}^{m=\infty} c_{n,0}\left(\lfloor m \rceil_{SF_{n,0}}\right) d_n\left(\lfloor m \rceil_{CL}\right) q\left(t - mT_c\right)$$

$$u_{n,k}(t) = \sum_{m=-\infty}^{m=\infty} i_{n,k}^m c_{n,k}\left(\lfloor m \rceil_{SF_{n,k}}\right) d_n\left(\lfloor m \rceil_{CL}\right) q\left(t - mT_c\right)$$

where $q(t) = \prod(t/T_c)$ is the chip pulse and the term $i_{n,k}^m$ contains the user modulated bits as:

$$i_{n,k}^m = \Gamma_{n,k} b_{n,k}\left(\left\lfloor \frac{m}{SF_{n,k}} \right\rfloor\right) \quad (2)$$

where $\Gamma_{n,k}$ is the relative gain given to the k-th user relative to the pilot signal, and $b_{n,k}(l)$ is the l-th BPSK/QPSK symbol associated with the k-th user of the n-th BS.

Assuming that the receiver consists of a standard IQ-mixing stage followed by an integrate and dump filter with integration period $T_i = T_c/Q$, the complex discrete output sequence can be expressed as follows:

$$r(l) = n(l) + \sum_{n=1}^{N} h_n \frac{1}{T_i} \int_{(l-1)T_i}^{lT_i} s_n(t - \tau_n)\, dt \quad (3)$$

where h_n and τ_n are the random unknown amplitude and location-dependent delay of the n-th BS and $n(t)$ is additive white Gaussian noise with a two-sided power spectral density $N_0/2$.

Let us assume that M consecutive samples are collected in a vector $\mathbf{r} = [r(1), \cdots, r(M)]^T$. We can then write the received vector $\mathbf{r}$ as:

$$\mathbf{r} = \mathbf{n} + \sum_{n=1}^{N} h_n \left[(1 - \delta_n)\, \mathbf{a}_n(\beta_n, \gamma_n) + \delta_n \mathbf{a}_n(\beta_n, \gamma_n + 1)\right] \quad (4)$$

where $\tau_n = (\beta_n Q\mathrm{CL} + \gamma_n + \delta_n)\, T_i$ such that β_n is an integer, γ_n is an integer in the range $[0, CLQ-1]$ and $\delta_n \in [0, 1)$. Note that in (4) the elements $\mathbf{a}_n(\beta_n, \gamma_n)$ and $\mathbf{a}_n(\beta_n, \gamma_n + 1)$ are the contributions of the n-th BS and can be decomposed into the contribution of the pilot and user signals, $\mathbf{a}_n(\beta_n, \gamma_n) = \mathbf{ap}_n(\gamma_n) + \mathbf{au}_n(\beta_n, \gamma_n)$ where:

$$[\mathbf{ap}_n(\gamma_n)]_l = \frac{1}{T_i} \int_0^{T_i} p_n\left(t - (\gamma_n Q + l)\, T_i\right) dt$$

$$= c_{n,0}\left(\left\lfloor \left\lfloor \frac{l}{Q} \right\rfloor + \gamma_n \right\rceil_{SF_{n,0}}\right) d_n\left(\left\lfloor \left\lfloor \frac{l}{Q} \right\rfloor + \gamma_n \right\rceil_{CL}\right),$$

$$\mathbf{au}_n(\beta_n, \gamma_n) = \sum_{k=1}^{K_n} \frac{1}{T_i} \int_0^{T_i} u_{n,k}\left(t - (\beta_n QCL\gamma_n Q + l)\, T_i\right) dt$$

Closed-form solutions to $\mathbf{au}_n(\beta_n, \gamma_n)$ can be found. However, the solution, dependant on the unknown user bits, will not further the developments of this paper and is therefore left out.

3. PROPOSED ALGORITHM

3.1. Classical Sliding correlator

The sliding correlator is the most common delay estimation algorithm for CDMA systems. The assumption made is that the received signal is composed of the pilot signal of the BS of interest plus white noise. This approach is motivated by the fact that signals associated with neighboring BSs are randomized by different scrambling codes, meaning they can be approximated as Gaussian noise. Under this strong assumption, the signal model presented in (4) is reduced to:

$$\mathbf{r} \approx \mathbf{n}' + h_n \left[(1 - \delta_n)\, \mathbf{ap}_n(\gamma_n) + \delta_n \mathbf{ap}_n(\gamma_n + 1)\right] \quad (5)$$

where $\mathbf{n}'$ is the Gaussian noise term encapsulating all noise contributions. Using this simplified model, the Maximum Likelihood (ML) estimator of the unknown parameters h_n, γ_n and δ_n is found by maximizing the ML cost function $\Phi_n(h_n, \gamma_n, \delta_n)$ defined as:

$$\Phi_n = \left\| \mathbf{r} - h_n \left[(1 - \delta_n)\, \mathbf{ap}_n(\gamma_n) + \delta_n \mathbf{ap}_n(\gamma_n + 1)\right] \right\|^2$$

Note that using this simplified signal model, we can only resolve delays in the range $[0, CLT_c)$. In other words, there is an unresolvable ambiguity of CLT_c seconds in the delay estimation. The parameter to be estimated is therefore defined as $\widetilde{\tau}_n = \lfloor \tau_n \rfloor_{CLT_c} = (\gamma_n + \delta_n) T_i$.

Through compression of h_n in $\Phi_n(h_n, \gamma_n, \delta_n)$ we obtain the delay estimator $\widehat{\widetilde{\tau}}_n = \arg\max_{\gamma_n,\delta_n} \Psi_n(\gamma_n, \delta_n)$ where

$$\Psi_n(\gamma_n, \delta_n) = \left\| \frac{(1-\delta_n)\phi_n(\gamma_n) + \delta_n \phi_n(\gamma_n+1)}{\sqrt{(1-\delta_n)^2 + (\delta_n)^2}} \right\|^2 \tag{6}$$

and $\phi_n(\gamma_n)$ is the output of the discrete sliding correlator, defined as $\phi_n(\gamma_n) = \mathbf{r}^T \mathbf{ap}_n(\gamma_n)$.

3.2. Multiple sliding correlator

We now aim to formulate an estimator of the the mobile location, directly from (4), without intermediate estimation of all τ_n.

In this case, we assume that only the user modulated signal can be considered Gaussian noise. In this way, all the common pilot channels of all the visible BSs are present in the model. Under this hypothesis, the signal model presented in (4) is simplified to:

$$\mathbf{r} \approx \mathbf{n}' + \sum_{n=1}^{N} h_n \left[(1-\delta_n)\mathbf{ap}_n(\gamma_n) + \delta_n \mathbf{ap}_n(\gamma_n+1)\right]$$

where the ML cost function can be expressed in vectorial notation as follows:

$$\Phi(\mathbf{h}, \gamma, \delta) = \left\| \mathbf{r} - \left[\mathbf{A}(\gamma)\mathbf{\Lambda}(\delta) + \mathbf{A}(\gamma+\mathbf{1})\mathbf{\Lambda}(\mathbf{1}-\delta)\right]\mathbf{h} \right\|^2$$

where $\gamma = [\gamma_1, \cdots, \gamma_N]^T$, $\delta = [\delta_1, \cdots, \delta_N]^T$, the n-th column of $\mathbf{A}(\gamma)$ and $\mathbf{A}(\gamma+\mathbf{1})$ are $\mathbf{ap}_n(\gamma_n)$ and $\mathbf{ap}_n(\gamma_n+1)$, $\mathbf{\Lambda}(\delta) = diag[\delta_1, \cdots, \delta_N]$ and $\mathbf{\Lambda}(\mathbf{1}-\delta) = diag[1-\delta_1, \cdots, 1-\delta_N]$.

Given medium correlator lengths, we can assume that

$$\mathbf{A}(\gamma)^T \mathbf{A}(\gamma+\mathbf{1}) = \mathbf{A}(\gamma+\mathbf{1})^T \mathbf{A}(\gamma) = \mathbf{0}$$
$$\mathbf{A}(\gamma)^T \mathbf{A}(\gamma) = \mathbf{A}(\gamma+\mathbf{1})^T \mathbf{A}(\gamma+\mathbf{1}) = \mathbf{I}.$$

Using this simplification and after compressing the ML estimate of $\mathbf{h}$ in $\Phi(\mathbf{h}, \gamma, \delta)$, the ML estimators of the N delays $\widetilde{\boldsymbol{\tau}} = [\widetilde{\tau}_1, \cdots, \widetilde{\tau}_N]$ are obtained as follows:

$$\widehat{\widetilde{\boldsymbol{\tau}}} = \arg \min_{\gamma_n, \delta_n \forall n} \sum_{n=1}^{N} \Psi_n(\gamma_n, \delta_n) \tag{7}$$

Although it is clear that (7) is the natural generalization of (6), we can now make use of the N delays included in $\widetilde{\boldsymbol{\tau}}$ that only depend on two unknown parameters: the position $\mathbf{x}$ of the mobile and the clock-offset τ_0. These relationships can be expressed as:

$$\widetilde{\tau}_n = -\beta_n CLT_c + \frac{d_n(\mathbf{x})}{c} + \tau_0 = \tau_n^0 + \frac{d_n(\mathbf{x})}{c} + \tau_0 \tag{8}$$

where c is the speed of the light, β_n shows the ambiguity produced by the repetition of the the scrambling code, $\mathbf{x}$ is the unknown position of the mobile, τ_0 is the unknown clock-offset between the network and the local mobile clock and $d_n(\mathbf{x}) = \|\mathbf{x} - \mathbf{x}_n\|$ is the distance between the mobile position and the n-th BS position $\mathbf{x}_n$.

In long-code scrambling systems, like W-CDMA, the ambiguity shown by the first term in (8) can be translated into a distance ambiguity of $cCLT_c$ meters. This large ambiguity in distance can normally be erased, we will therefore assume that τ_n^0 known.

From (7) and (8), we formulate the ML estimator of the mobile position and clock offset as:

$$\widehat{\mathbf{x}}, \widehat{\tau}_0 = \arg \max_{\mathbf{x}, \tau_0} \Psi(\mathbf{x}, \tau_0) \tag{9}$$

where

$$\Psi(\mathbf{x}, \tau_0) = \sum_{n=1}^{N} \Psi_n(\gamma_n(\mathbf{x}, \tau_0), \delta_n(\mathbf{x}, \tau_0)) \tag{10}$$

and

$$\gamma_n(\mathbf{x}, \tau_0) = \left\lfloor \tau_n^0 + \frac{d_n(\mathbf{x})}{c} + \tau_0 \right\rfloor \tag{11}$$
$$\delta_n(\mathbf{x}, \tau_0) = \tau_n^0 + \frac{d_n(\mathbf{x})}{c} + \tau_0 - \gamma_n(\mathbf{x}, \tau_0) \tag{12}$$

3.3. Practical implementation

The major problem in the maximization of (10) is that in general, the clock offset τ_0 is unknown, meaning the estimation of this parameter could present difficulties. Assuming that the mobile is attached to the network (τ_1 is known), we can obtain the time offset estimation from (8) as: $\tau_0 = \widetilde{\tau}_1 - \tau_1^0 - \frac{d_1(\mathbf{x})}{c}$. Using this expression we can formulate the ML position estimator and the ML cost function as follows:

$$\widehat{\mathbf{x}} = \arg \max_{\mathbf{x}} \Psi(\mathbf{x}) \tag{13}$$

$$\Psi(\mathbf{x}) = \sum_{n=1}^{N} \Psi_n(\gamma_n(\mathbf{x}), \delta_n(\mathbf{x})) \tag{14}$$

where

$$\gamma_n(\mathbf{x}) = \left\lfloor \tau_n^0 - \tau_1^0 + \widetilde{\tau}_1 + g_n(\mathbf{x}) \right\rfloor$$
$$\delta_n(\mathbf{x}) = \tau_n^0 - \tau_1^0 + \widetilde{\tau}_1 + g_n(\mathbf{x}) - \gamma_n(\mathbf{x}, \tau_0)$$

and

$$g_n(\mathbf{x}) = \frac{d_n(\mathbf{x})}{c} - \frac{d_1(\mathbf{x})}{c}$$

Now, the ML estimate of the mobile position can be found through a grid-search of possible positions around the serving BS.

4. NUMERICAL SIMULATIONS

Numerical simulations have been performed using standard values for W-CDMA systems. The main parameters are: Spreading Factor $SF = 250$ $\forall$ users and BSs, chip rate is 3.8 Mchips/second, 10 users/BS and 4 samples/chip. The 6 neighboring base stations with a radius of 1km are placed using an hexagonal geometry around the serving BS (7BS in total). Only 20% of the available power at each BS is used in the common channel. The SNR of the common channel of the serving BS is 25 dB. An attenuation of 10 dB is applied to the neighboring BSs to simulate a moderate near-far effect.

Figure (1) shows the outlier probability in position estimation for the classical approach and the proposed one. An outlier is defined as a position estimate with an error greater than 100 m.

Raised cosine pulses with a roll-off factor of 0.22 have also been used in the simulations. As can be seen, the performances are similar.

Simulation of the classical approach included estimation of delays followed by application of the ML position estimator using TDOA measurements, assuming that the first pTOA τ_1 is known. The proposed algorithm was implemented using (13) in a grid of possible positions.

Figure (2) shows the cumulative distribution function (CDF) of the position error using sliding correlators of length 500 chips to illustrate the gain in position accuracy.

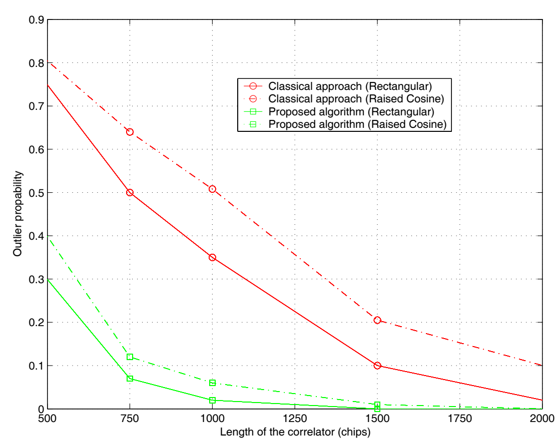

Fig. 1. Outlier probability of the position estimator

5. CONCLUSIONS

Simulation results have shown that the high outlier probability in the position estimation, present in the classical approach, is clearly reduced in the proposed algorithm.

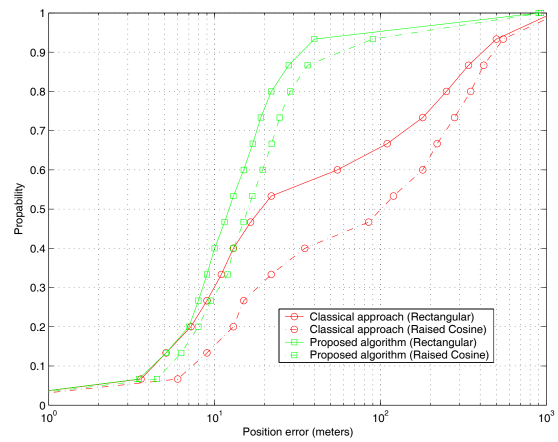

Fig. 2. CDF of the position error

Additional information, such as a city-map, is easily introduced in (13) by weighting of possible positions.

It is clear from the formulation of the proposed algorithm that robust performances in the presence of NLOS phenomena is a result, this is because BS measurements suffering from NLOS error enhancement will be interpreted by the algorithm as outliers.

Finally, it has been demonstrated in (13) that it is unnecessary to implement a variance estimator for the individual pTOA estimates since the mobile position is estimated directly.

6. REFERENCES

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