MOBILE LOCATION WITH BIAS TRACKING IN NON-LINE-OF-SIGHT

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ABSTRACT

The main impairment for location of terminals in wireless communications system is the Non Line Of Sight (NLOS) condition which is mainly due to blocking of transmitted signal by obstacles. It is well known that NLOS biases Time Of Arrival (TOA) and Time Difference Of Arrival (TDOA) estimates therefore providing biased position. The objective of this paper is to analyze the improvements in positioning accuracy by tracking the bias of the time measures with the Kalman filter proposed for location estimation. The evaluation of the approach has been carried out with measures taken in real scenarios, for positioning techniques based on TDOA and TOA+AOA (Angle Of Arrival) measurements.

1. INTRODUCTION

Determining the location of a User Equipment (UE) consist of two steps: signal measurements and position computation based on the measurements. The first step involves estimation of the signal parameters from received wireless communications signals: TOA, TDOA or AOA. The later step combines multiple timing or angles of arrival measured from a convenient number of Base Stations (BS).

There are two primary reasons for inaccuracies observed in the location systems due to the propagation conditions imposed by the wireless channel. The first one is the multipath, or delay spread of the channel impulse response. The second one is the NLOS condition, due to transmitted signal blocking. Both situations yield a biased estimation of the first arrival, which bears information related to the position of the mobile terminal. In particular, due to NLOS, the first arrival suffers stronger attenuation than later arrivals and therefore wrong timig information is obtained. In the multipath situation (be it LOS or NLOS) the late signal arrivals induce a displacement of the maximum of the impulse response, thus biasing timing estimates, if timing estimation algorithms which assume a simple frequency-flat channel are used [1]. The resulting positioning systems can only provide biased position estimation.

The scheme proposed in [2] by the authors, consists in deriving high-resolution timing estimation using the parametric Normalized Minimum Variance (NMV) [3] over the discrete Fourier transform (DFT) of the channel estimates. In this way, the first low power estimated arrivals are robustly estimated in severe multipath situations. Once an estimate of the TOA of the first arrival is obtained, a temporal filter can focus the detection over this path, allowing the AOA estimation if space diversity is available at BS. In Section 2 the TOA and AOA estimation algorithms are briefly presented.

The position computation is carried out by the Kalman tracker which deals with the bias of the measures caused by the NLOS situation. Section 3 is devoted to this utility. In Section 4, results on positioning in a real scenario on real measurements are shown.

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2. PARAMETER ESTIMATION FOR POSITIONING

The NMV TOA estimation [2], obtained from the power spectral density defined in (1), exhibits a good performance in bias and variance compared with the TOA estimation based only on the maximum of the channel response estimate. Assuming that we have array observations (taken at N antennas) of the transmitted signal and the propagation channel is estimated (using an unbiased technique) at time n and it is composed of L multipath arrivals, the DFT of the estimated channel follows the model:

$$\begin{aligned}\mathbf{Y}(n) &= \left[\mathbf{y}(\omega_o;n) \quad \mathbf{y}(\omega_1;n) \quad \cdots \quad \mathbf{y}(\omega_{M-1};n)\right] \\ &= \sum_{i=1}^{L}\mathbf{a}_i(n)\mathbf{F}\mathbf{e}_{\tau_i}^T + \mathbf{v}(n)\end{aligned} \tag{1}$$

where $\mathbf{a}_i$ is spatial signature of the i-th multipath arrival, $\mathbf{F}$ is a diagonal matrix containing the DFT of the pulse shaping filter and $\mathbf{e}_\tau$ is the steering vector for an arrival at timing τ. According to [3], the timing estimation of all the multipath channel components may be computed as the maxima of the expression:

$$S(\tau) = \frac{\mathbf{f}_\tau^H \mathbf{R}_d^{-1} \mathbf{f}_\tau}{\mathbf{f}_\tau^H \mathbf{R}_d^{-2} \mathbf{f}_\tau} \tag{2}$$

where $\mathbf{f}_\tau = \mathbf{F}\mathbf{e}_\tau$ and $\mathbf{R}_d = \sum_n \mathbf{Y}^H(n)\mathbf{Y}(n)$ is the correlation matrix of the channel estimates. Normally, the first maximum of equation (2) is selected as the timing bearing position information. Estimation of the AOA (once the TOA estimate is available) is possible using the filter $\mathbf{w}(\tau_1)$ which focus the observations on the first arrival τ_1 (see [3] for details). The spatial correlation matrix of the filtered signal is computed as follows:

$$\mathbf{R}_s = \sum_n \mathbf{Y}(n)\mathbf{w}(\tau_0)\mathbf{w}(\tau_0)^H \mathbf{Y}^H(n) \tag{3}$$

The proposed AOA estimation is based on the approximate ML estimator for dispersive sources presented in [4]. This procedure is preferred to conventional SVD-based techniques because of its low computational cost.

The estimator of the bearing angle with an array of N sensors can be written as follows:

$$\hat{\psi}_{k,k+1} = \arcsin\left(\frac{\text{angle}\{\mathbf{R}_d(k+1,k)\} - b_{k,k+1}}{A_{k,k+1}}\right) + \varphi_{k,k+1}$$

$$\hat{\theta} = angle\left(\sum_{k=1}^{N-1} \left|\mathbf{R}_d(k+1,k)\right| e^{-j\hat{\psi}_{k,k+1}}\right) \tag{4}$$

being $b_{k,k+1}$, $A_{k,k+1}$ and $\varphi_{k,k+1}$, parameters accounting for the calibration between sensors of the array: the electric phase, the distance (in terms of λ) and the angle between antennas k and k+1, respectively.

3. KALMAN FILTER WITH BIAS TRACKING

The Kalman filter proposed for location purposes allows tracking the position and speed of the mobile, yielding an accurate location prediction algorithm. Also the tracking of the bias due to NLOS is possible by increasing the dimension of the state vector by adding TOA bias as additional parameters to be estimated [5].

The transition equation defined for continuous movement, is linear:

$$\mathbf{s}'(k+1) = \mathbf{D}\mathbf{s}'(k) + \mathbf{w}(k) \tag{5}$$

The state vector **s'**(k) and the state matrix **D** are defined as follows:

$$\mathbf{s}'(k) = \begin{bmatrix} \mathbf{s}(k) \\ \mathbf{b}(k) \end{bmatrix} \qquad \mathbf{D} = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{bmatrix} \tag{6}$$

where the components of the vector **s**(k) represent the position of the mobile terminal and the speed in two-dimensional Cartesian co-ordinates at discrete time k and the components of the vector **b**(k) are the time measurement bias for each BS. **A** is the state matrix defined for continuous movement [6] and $\mathbf{B} = \beta\mathbf{I}$ is the state matrix which defines the time measurement bias at each BS as a random walk [7].

The disturbance transition vector is defined as $\mathbf{w}(k) = \begin{bmatrix} \mathbf{0} & \mathbf{w}_v & \mathbf{w}_b \end{bmatrix}^T$, where $\mathbf{w}_v$ and $\mathbf{w}_b$ are the speed and bias noise vectors with covariance matrix $\mathbf{Q}_v(k)$ and $\mathbf{Q}_b(k)$, respectively. Measurements of different nature (TDOA, TOA or AOA) are non-linear in the position state variables [8]:

$$\mathbf{z}(k) = g(\mathbf{s}(k)) + \mathbf{E}\mathbf{b}(k) + \mathbf{v}(k) \tag{7}$$

where $\mathbf{z}(k) = \begin{bmatrix} \mathbf{z}_{TDOA}^T & \mathbf{z}_{TOA}^T & \mathbf{z}_{AOA}^T \end{bmatrix}^T$ is the measurement vector obtained from the different BS and $\mathbf{v}(k) = \begin{bmatrix} \mathbf{v}_{TDOA}^T & \mathbf{v}_{TOA}^T & \mathbf{v}_{AOA}^T \end{bmatrix}^T$ is the measurement noise with covariance matrix:

$$\mathbf{C}(k) = \begin{bmatrix} \mathbf{H}\boldsymbol{\sigma}_{TDOA}^2\mathbf{H}^T & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\sigma}_{TOA}^2 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{\sigma}_{AOA}^2 \end{bmatrix} \tag{8}$$

assuming that the measures obtained are uncorrelated, $\boldsymbol{\sigma}_{TDOA}^2$, $\boldsymbol{\sigma}_{TOA}^2$ and $\boldsymbol{\sigma}_{AOA}^2$ are diagonal matrix of dimensions equal to the number of available measurements N_TDOA, N_TOA and N_AOA, respectively. **H** is the (N_TDOA-1) × N_TDOA matrix that defines the difference of times in the TDOA method [8].

The matrix **E** in equation (7) is defined as:

$$\mathbf{E} = \begin{bmatrix} \mathbf{H}^T & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} & \mathbf{0} \end{bmatrix}^T \tag{9}$$

where the dimension of the identity matrix is N_TOA. The zero rows are due to the AOA measurements, for which no bias estimation is considered.

Because of the non-linear measurement equation, the Extended Kalman Filter (EKF) has to be used, being the linear relation between the measurement and the position state vectors defined as:

$$\mathbf{G}(k) = \left.\frac{\partial g}{\partial \mathbf{s}}\right|_{\mathbf{s}=\hat{\mathbf{s}}(k/k-1)} \tag{10}$$

where $\hat{\mathbf{s}}(k/k-1)$ is the state vector prediction, equal to the conditioned mean $\hat{\mathbf{s}}(k/k-1) = E\{\mathbf{s}(k)|\mathbf{z}(k-1)\}$

The matrix **G**(k) can be expressed as a concatenation of matrix corresponding to the linearization of each measurement type:

$$\mathbf{G}(k) = \begin{bmatrix} \mathbf{G}_{TDOA}(k) \\ \mathbf{G}_{TOA}(k) \\ \mathbf{G}_{AOA}(k) \end{bmatrix} \tag{11}$$

The matrix corresponding to the TDOA method can be formulated as $\mathbf{G}_{TDOA}(k) = \mathbf{H}\mathbf{F}(k)/c$ where c is the propagation speed and **F**(k) is the matrix formulated in (12) with N equal to N_TDOA, the number of available downlink time measurements:

$$\mathbf{F}(k) = \begin{bmatrix} (\hat{\mathbf{s}}(k-1) - \mathbf{r}_1)/d_1(k-1) \\ \vdots \\ (\hat{\mathbf{s}}(k-1) - \mathbf{r}_N)/d_N(k-1) \end{bmatrix} \tag{12}$$

$$d_i(k-1) = \left\|\hat{\mathbf{s}}(k-1) - \mathbf{r}_i\right\|$$

with $\hat{\mathbf{s}}$(k-1) the UE position vector estimated at the previous algorithm iteration and $\mathbf{r}_i$ the location of the i-th BS.

The matrix corresponding to the TOA method is $\mathbf{G}_{TOA}(k) = \mathbf{F}(k)/c$, being in this case the rows number of **F**(k) in (12) equal to N_TOA, the number of available uplink time measurement.

$\mathbf{G}_{AOA}(k)$ is the matrix defined in (13) for the AOA method, with N equal to N_AOA, the number of available uplink angle measurement.

$$\mathbf{G}_{AOA}(k) = \begin{bmatrix} -(\sin\ \phi_1(k-1))/d_1(k-1) & (\cos\ \phi_1(k-1))/d_1(k-1) \\ \vdots & \vdots \\ -(\sin\ \phi_N(k-1))/d_N(k-1) & (\cos\ \phi_N(k-1))/d_N(k-1) \end{bmatrix} \tag{13}$$

being ϕ_i(k-1) the angle between the i-th BS and the estimated UE position at the previous algorithm iteration. After the linearization, the observation equation (7) can be rewritten as:

$$\mathbf{z}(k) = \mathbf{J}(k)^H \mathbf{s}'(k) + \mathbf{v}(k) \tag{14}$$

where the observation matrix is defined as:

$$\mathbf{J}(k)^H = \begin{bmatrix} \mathbf{G}(k) & \mathbf{E} \end{bmatrix} \tag{15}$$

The mean square error of the estimate is the trace of the covariance matrix, which contains the accuracy parameter that will characterize the behavior of the Kalman tracker:

$$\boldsymbol{\Sigma}(k/k-1) = E\left\{\left|(\mathbf{s}'(k) - \hat{\mathbf{s}}'(k/k-1))\right|^2 \left|\mathbf{z}(k-1)\right.\right\} \tag{16}$$

The prediction of the state vector and error covariance matrix are obtained from the time and the measurement update equations, being **K**(k) the Kalman gain matrix:

$$\hat{\mathbf{s}}'(k+1/k) = \mathbf{D}\hat{\mathbf{s}}'(k/k)$$
$$\mathbf{\Sigma}\left(k+1/k\right) = \mathbf{D}\mathbf{\Sigma}\left(k/k-1\right)\mathbf{D}^{H} + \mathbf{Q} \qquad (17)$$
$$\hat{\mathbf{s}}'(k/k) = \hat{\mathbf{s}}'(k/k-1) + \mathbf{K}(k)\left[\mathbf{z}(k) - g\left(\hat{\mathbf{s}}(k/k-1)\right) - \mathbf{E}\hat{\mathbf{b}}(k/k-1)\right]$$
$$\mathbf{\Sigma}\left(k/k\right) = \left[\mathbf{I} - \mathbf{K}(k)\mathbf{J}(k)^{H}\right]\mathbf{\Sigma}\left(k/k-1\right)$$
$$\mathbf{K}(k) = \mathbf{\Sigma}\left(k/k-1\right)\mathbf{J}(k)\left[\mathbf{J}(k)^{H}\mathbf{\Sigma}\left(k/k-1\right)\mathbf{J}(k) + \mathbf{C}(k)\right]^{-1}$$

It is worth noting that although the Kalman filter has been described generically, for a combined use of multiple signal measurements, only the cases of TDOA and TOA+AOA will be tested.

4. EVALUATION IN REAL SCENARIOS

The objective of this section is to evaluate the proposed approach in a real UMTS scenario. The measurement equipment consists of a 35 dBm-power UE transmitter with single dipole antenna of 4dB gain, and four independent receivers connected to an antenna array of four elements with $\lambda/2$ separation between them and 15 dB gain. The bandwidth is 5MHz at 1800 MHz. The baseband stage consists of a set of DSPs performing channel parameter estimates and the mobile position computation. The transmitted signal is a pilot sequence of 256 chips shaped with a root-raised cosine pulse, sampled at two samples by chip. Additionally, a GPS receiver is located in the mobile terminal, so the true position is stored during the recording time and can be compared offline with the estimated position. The number of channel estimates is around 200 per second and per receiving antenna.

Although the test-bed has only one BS, it is possible to emulate a scenario with multiple BS selecting different routes, all with the same shape, but with different position and orientations. One experiment is performed for each route trying to maintain similar UE speeds for all. Next, the spatial reference is changed to get all the routes at the same position and orientation, thus the BS will change the position, and each experiment will result in a different BS. Finally, the time reference is changed to meet the speed of the mobile at every point.

In order to achieve realistic conditions, extra noise has to be added, to simulate the effect of other BS interferences or other terminals. This will depend on the UMTS channel used to compute the positioning.

4.1 Dedicated Physical Channel (DPCH) in Up Link (UL)

The DPCH channel is strictly power controlled in every slot both in UL and DL. It may be assumed that the objective E_b/N_0 is fixed by the serving BS. Equal noise and interference powers are considered in all BS, while the signal power is different for each BS, determining a different SINR for each link. Some reasonable figures for the vehicular channels are listed in the next table, with the related SINR at the estimated channels [9]:

Bit rate (kbps)	12.2	16	32	64	144	384
E_b/N_0 (dB)	5	4	3	2	1.5	1
SINR (dB)	4.10	4.28	6.29	8.30	11.32	15.08

Positioning using TOA and AOA measures is tested in this first experiment. It is assumed that the TOA is computed as one half of the round trip time in the DPCH, and the AOA is computed at the BS equiped with an antenna array. In Figure 1 the mean square error in positioning (RMSE) and the standard deviation of the RMSE are shown. These values are averaged over three different routes. In all cases, NLOS is found more than the 50 % of the time. The results show the accuracy improvement obtained when tracking the position and speed compared with the static estimator, and the degradation when using the bias tracking.

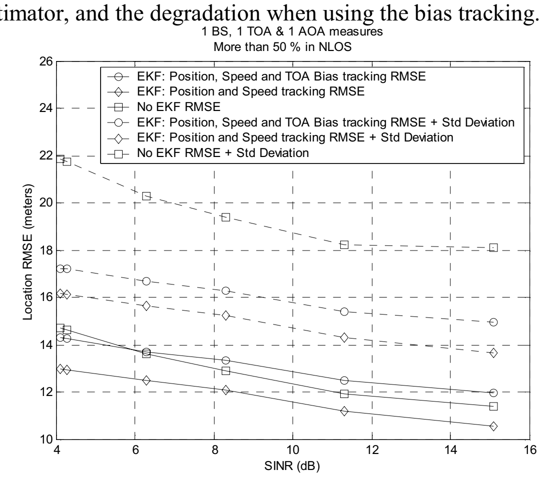

Figure 1. RMSE and standard deviation of the positioning error from TOA and AOA measures with one BS

Now, the same routes as in the previous case are used but combining them in groups of two, emulating two BS. The results are depicted in Figure 2. The use of EKF with bias tracking of the TOA exhibits significant gains in positioning accuracy.

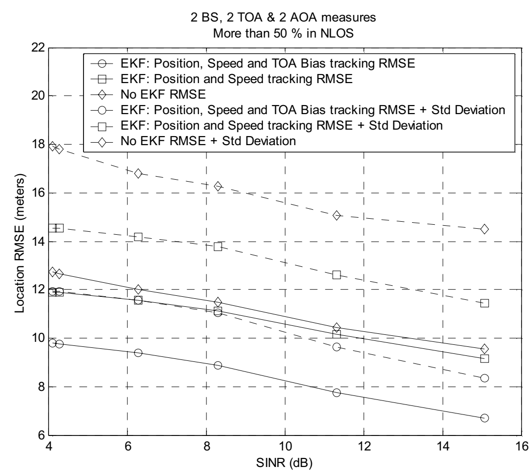

Figure 2. RMSE and standard deviation of the positioning error from TOA and AOA measures with two BS

4.2 Common Pilot Channel (CPICH) in Down Link (DL)

In the CPICH channel no power control is used. The noise and interference power are determined from:

$$SINR(dB) = S_{CPICH}(dBm) + \alpha(dB) - S_{other}(dBm) \qquad (17)$$

being S_{CPICH} the received power of the desired CPICH and S_{other} the total received intracell and intercell interfering power. α is the gain factor due to the correlation between the scrambling sequences used at different cells. This factor depends on the number of pilot slots used in the CPICH for the channel estimation [9]:

Slots used	4	2	1	1/2	1/4
α (dB)	35	32	29	26	23

Positioning using TDOA measures is tested in this case. Four different routes are combined in a multiple BS emulation (see figure 3 for a display of the BS and the route). Three BS are in NLOS more than 90 % of the time with a mean bias of the TOA of 60 meters and only one BS is in LOS more than the 50 % of the time. These conditions fit in an urban environment. The results of this test are represented in Figure 4 for different number of used slots for channel estimation (thus translated to different conditions of SNR). It may be observed that a reduction from 45 to 15 meters of positioning error is achieved when using the EKF with bias tracking. Also the variance is highly reduced, from a standard deviation of 30 meters to less than 10 meters. The factor which mostly impacts this gain is the excellent tracking of the bias.
Figure 5 shows the mean square in the TOA estimates when the bias is compensated through Kalman tracking. Note the effective error reduction.

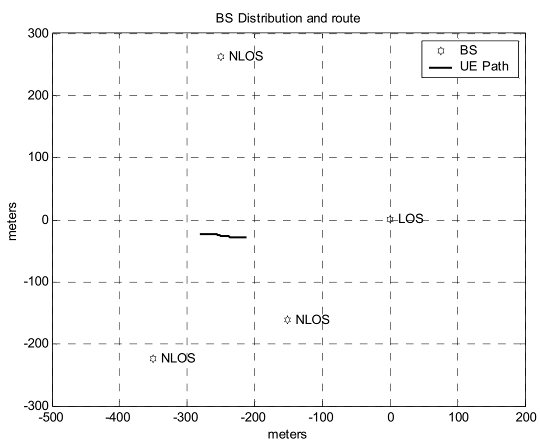

Figure 3. Scenario considered with four 4 BS.

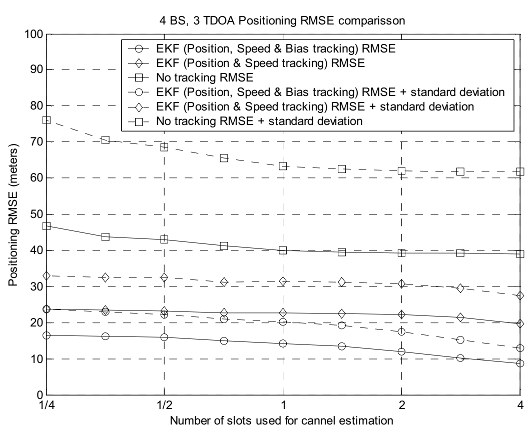

Figure 4. RMSE and standard deviation of the positioning error from TDOA measures with four 4 BS.

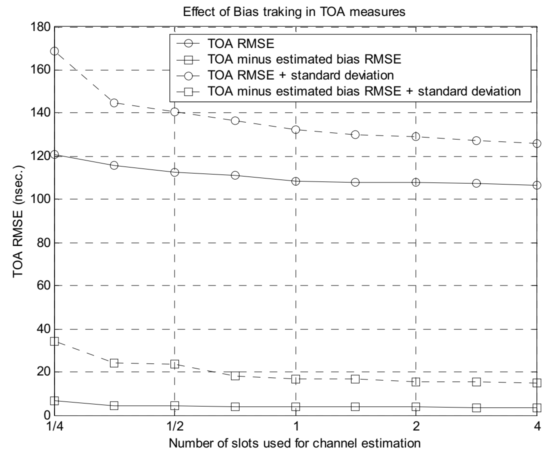

Figure 5. RMSE of the TOA, in nsec.

4. CONCLUSIONS

In this paper a mobile location system with timing bias tracking has been proposed and evaluated in real UMTS scenarios. TOA and AOA have been estimated from the DPCH channel in the cases that only one or two BS are considered, a scenario which is representative of a suburban or rural area. Location based on TDOA from the DL-CPICH has been the choice when measures from 4 BS are available (mainly representing urban situations). The improvement in positioning accuracy achieved by tracking TOA bias is significant even in severe NLOS conditions.

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