Extended Kalman Filter Channel Estimation for Line-of-Sight Detection in WCDMA Mobile Positioning

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In mobile positioning, it is very important to estimate correctly the delay between the transmitter and the receiver. When the receiver is in line-of-sight (LOS) condition with the transmitter, the computation of the mobile position in two dimensions becomes straightforward. In this paper, the problem of LOS detection in WCDMA for mobile positioning is considered, together with joint estimation of the delays and channel coefficients. These are very challenging topics in multipath fading channels because LOS component is not always present, and when it is present, it might be severely affected by interfering paths spaced at less than one chip distance (closely spaced paths). The extended Kalman filter (EKF) is used to estimate jointly the delays and complex channel coefficients. The decision whether the LOS component is present or not is based on statistical tests to determine the distribution of the channel coefficient corresponding to the first path. The statistical test-based techniques are practical, simple, and of low computation complexity, which is suitable for WCDMA receivers. These techniques can provide an accurate decision whether LOS component is present or not.

Keywords and phrases: extended Kalman filter, fading statistics, LOS detection, mobile positioning, WCDMA systems.

1. INTRODUCTION

For the public interest, mobile phone positioning in a cellular network with reliable and rather accurate position information has become unavoidable after the Federal Communications Commission mandate, FCC-E911 docket on emergency call positioning in USA, and the coming E112 in the European Union [1]. One method for locating the mobile station (MS) in two dimensions requires the measurement of line-of-sight (LOS) distance between the MS and at least three base stations (BSs). Hence, knowing which BS is reporting, LOS component is crucial for accurate position estimation. In many cases, the non-LOS (NLOS) signal components, arriving with delay less than one chip at the receiver, obscure the LOS signal. This situation of overlapping multipath propagation is one of the main sources of mobile positioning errors [2, 3, 4].

Previous studies dealing with LOS detection used range measurement-based techniques [5, 6, 7] (i.e., measurements of the time of arrival), which exploit the time history of the range measurements and the a priori knowledge of the noise floor in the system. These techniques can increase the accuracy of the mobile position estimation, but they require the knowledge of the a priori statistic parameters such as the standard deviation of the measurement noise. The use of a link level-based techniques where the signal processing
is made in the MS side as presented in this paper to detect whether the LOS component is present or not is a new topic. In this paper, accurate estimates of the channel coefficients and their corresponding delays in the context of closely spaced paths are obtained using extended Kalman filter (EKF) algorithm, aided by an interference cancellation (IC) technique. The channel coefficients will be used as basis for deciding whether the first arriving path is a LOS or NLOS component.

Many techniques were presented to cope with closely spaced multipath propagations, such as subspace-based methods [8] or least square (LS) approaches [9, 10]. These techniques can provide rather accurate estimation of the multipath delays, but they suffer from the high complexity for the implementation in WCDMA systems in tracking mode. Few authors have studied the problem of joint parameter estimation using Kalman filtering in multipath fading and multiuser environment. In [11], Iltis has developed a new technique for jointly estimating the channel coefficients and the first-path delay in frequency selective channel based on Kalman filtering in a single user system. Recently, the idea has been extended to multiuser scenario [12]. In order to solve the closely spaced multipaths, we propose here an EKF-based solution with IC scheme. EKF algorithm jointly estimates the delays and complex coefficients of all the paths from all the participating BSs and it is combined with a new IC scheme to enhance the estimation of the channel from the desired BS (serving BS). The obtained estimates are used to detect whether the LOS component is present or not. The detection procedure exploits the distribution of the first arriving path. If the distribution is Rayleigh, it is more likely that LOS component is absent. We point out that the proposed algorithm is not limited to a WCDMA system and it can be easily extended to other mobile positioning systems.

This paper is organized as follows. In Section 2, the channel and signal model are described. Then, the joint estimation of the channel coefficients and delays is described in Section 3 with an emphasis on the proposed IC algorithm. Section 4 is devoted to the novel LOS detection procedures. Simulation results are provided in Section 5, and conclusions are drawn in Section 6.

### 2. CHANNEL AND SIGNAL MODELS

The system under consideration is a DS-CDMA system with \( N_{\text{BS}} \) base stations and \( N_u \) users per BS. In baseband system (fully digital implementation), the received signal complex valued at sample level, transmitted over an \( L \)-path fading channel, can be written as [13]

\[
r(i) = \sum_{m=-\infty}^{\infty} \sum_{u=1}^{N_u} \sum_{l=1}^{L} \sqrt{E_b \alpha_{l,u}(m) s_i^{(m)}(iT_s - \tau_{l,u}(m))} + \eta(i),
\]

where \( i \) is the sample index (we assume that there are \( N_i \) samples per chip), \( E_b \) is the bit energy of the \( u \)th BS (we assume that all bits of the same BS have the same energy), \( L \) is the number of discrete multipath components, \( T_s \) is the sampling period (\( T_s = T_c/N_b \), \( T_c \) is the chip period), \( \alpha_{l,u}(m) \) and \( \tau_{l,u}(m) \) represent, respectively, the complex-valued time varying channel coefficient and delay of the \( l \)th path of base station \( u \), during the \( m \)th symbol. The delays are treated as complex values, but only the magnitudes rounded to the nearest integer values are retained. We denote by \( s_i^{(m)}(\cdot) \) the signature of the \( u \)th BS during symbol \( m \) including data modulation, spreading code, and pulse shaping, and \( \eta \) is an additive circular white Gaussian noise of zero mean and double-sided spectral power density \( N_0 \).

### 3. EKF CHANNEL ESTIMATION FOR LOS DETECTION IN WCDMA MOBILE POSITIONING

The intracell interference is assumed Gaussian distributed by virtue of central limit theorem, and it is included in the term \( \eta(\cdot) \).

The output of the matched filter corresponding to the desired BS \( u \) during the symbol \( n \) with lag \( \tau \) is as follows:

\[
y_u(n, \tau) = \sum_{v=1}^{N_{\text{BS}}} \sum_{l=1}^{L} \sqrt{E_b v \alpha_{l,v}(n)} R_{u,v}(\tau - \tau_{l,v}(n)) + \eta(n),
\]

where \( R_{u,v}(\cdot) \) is the cross correlation between the signature of the BS of interest (\( u \)th BS) and the signature of the \( v \)th BS, \( \eta(n) \) is the filtered noise plus interchip and intersymbol interference, and \( \alpha_{l,v}(n) \) and \( \tau_{l,v}(n) \) are the complex channel coefficients and the path delays, respectively, at symbol level. We point out that the channel coefficients and delays are assumed to be constant within one symbol. This assumption is reasonable since the symbol period (e.g., 66.5 \( \mu \)s for \( S_F = 256 \)) is much less than the coherence time of the channel. The constant delays assumption is also reasonable for terrestrial communications due to the negligible Doppler shift. The channel coefficients and delays are modeled as a Gauss-Markov process [11, 12, 15]

\[
\begin{align*}
\alpha_{l,v}(n + 1) &= \beta_v \alpha_{l,v}(n) + w_{\alpha_{l,v}}(n), \\
\tau_{l,v}(n + 1) &= \gamma \tau_{l,v}(n) + w_{\tau_{l,v}}(n),
\end{align*}
\]

where \( w_{\alpha} \) and \( w_{\tau} \) are mutually independent additive circular white Gaussian noise processes, \( \gamma \) is a coefficient accounting for the delay variation, and \( \beta_v \) is a coefficient accounting for the maximum Doppler spread, \( f_d \), of the \( v \)th BS, defined as [16]

\[
\beta_v = I_0(2\pi f_d T_{\text{sym}}),
\]

where \( I_0(\cdot) \) is the zero-order Bessel function and \( T_{\text{sym}} \) is the symbol interval. We assumed that for each BS, all the paths have the same maximum Doppler spread. The coefficient \( \beta_v \) is close to unity when the Doppler spread is significantly less than the Nyquist bandwidth. We assume here that the coefficient \( \gamma \) is constant for all the BSs and all the paths. This is a reasonable assumption in terrestrial communication when the Doppler shift is negligible, and \( \gamma \) can be set to a value close to unity for all multipath delays of all users. However,
EKF can be easily modified to use different \( y \) coefficients [12]. We point out that the channel models of \([11, 12, 17]\) are different from (3) in the sense that, earlier, the paths have been assumed uniformly spaced at chip period \( T_c \), and the only delay modeled with (3) is the delay of the first path. In this paper, we derive an extension of the EKF model for all the path delays. This should not affect the EKF algorithm; it will only increase slightly the number of parameters to be estimated, and hence, the complexity. Also, we point out that the Gaussian assumption of multiple access interference (MAI) can be relaxed and the algorithm is straightforward to extended to non-Gaussian MAI case by using some IC within each cell in a similar manner to the intercell IC algorithm presented in the next section.

3. JOINT CHANNEL COEFFICIENTS AND PATH DELAYS ESTIMATION

The joint estimation of multipath delays and complex channel coefficients of the serving BS is done in two steps. First, we jointly estimate all the path delays and channel coefficients from all participating BSs, which leads to an estimation of the interference due to CPICH channels. Then, an IC scheme is used to estimate the interference \( \hat{y}_i(n) \) coming from the nonserving BSs, which is the combined interference from all BSs, associated with all BSs.

\[
x(n) = [x_1, \ldots, x_{N_{BS}}]^T,
\]

where \( x_v = [\alpha_{v,1}(n), \alpha_{v,2}(n), \tau_{v,1}(n), \tau_{v,2}(n)] \), for \( v = 1, \ldots, N_{BS} \). Due to the fact that the received signal is not a linear function of the multipath delays \( \tau_{v,j} \), an EKF is needed. The state and observation models are described by the following equations, respectively,

\[
x(n + 1) = Fx(n) + w(n), \quad z(n) = \mathcal{H}(x(n)) + v(n),
\]

where \( w(\cdot) \) and \( v(\cdot) \) are circular white Gaussian noises, \( F \in \mathbb{R}^{2LN_{BS} \times 2LN_{BS}} \) is defined by \( F = \text{Block diag}(F_1, \ldots, F_{N_{BS}}) \), where \( F_v = \text{diag}(\beta_1, \ldots, \beta_{\nu}, y_v, \ldots, y_v) \), \( z(n) \) is the observation vector which depends nonlinearly on the state vector \( x(n) \), \( z(n) = [y_1(n), \ldots, y_{N_{BS}}(n)]^T \), and the nonlinear transform \( \mathcal{H}(\cdot) \) is given as follows:

\[
\mathcal{H}(x(n)) = [H_1(x(n)), \ldots, H_{N_{BS}}(x(n))]^T,
\]

where \( H_i(x(n)) = \sum_{v=1}^{N_{BS}} \sum_{l=1}^{L} \sqrt{E_k} \alpha_{v,l}(n) \mathcal{R}_{l,v}(nT_{sym} - \tau_{v,l}(n)) \), for \( i = 1, \ldots, N_{BS} \).

Here, we assume that we have no data modulation, which is true for the CPICH reference channels used for positioning in WCDMA [14]. However, this assumption is not crucial in the sense that data can be removed in a decision-directed mode before we proceed with EKF estimation. The circular white Gaussian noise vector \( w(\cdot) \) is defined as

\[
w(n) = [w_1(n), \ldots, w_{N_{BS}}(n)]^T,
\]

where \( w_v(n) = [w_{a_{v,1}}, \ldots, w_{a_{v,2}}, w_{r_{v,1}}, \ldots, w_{r_{v,2}}] \).

The EKF algorithm requires the linearization of the transform \( \mathcal{H}(\cdot) \). The most common linearization method used is the first-order Taylor expansion defined as follows [11, 17, 18]:

\[
\mathcal{H}(x(n)) \approx \mathcal{H}([x(n) - 1]) + \sum_{m=1}^{2LN_{BS}} \left( x_m(n) - \hat{x}_m(n) - 1 \right) \times \frac{\partial}{\partial x_m} \mathcal{H}(x(n)) \bigg|_{x(n) = \hat{x}(n) - 1},
\]

where \( \hat{x}(n) \) is the predictor at step \( n \) conditional to previous observations, \( x_m(n) \) are the elements of the state vector \( x(n) \), and \( \hat{x}(n) - 1 \) are the elements of the predictor vector \( \hat{x}(n) - 1 \), \( m = 1, \ldots, 2LN_{BS} \).

Using the linearization in (9), the set of EKF equations can be written as [11, 12, 17]

\[
\dot{x}(n) = \dot{x}(n) - 1 + K(n) [z(n) - \mathcal{H}(\hat{x}(n) - 1)],
\]

\[
K(n) = P(n - 1) \mathcal{H}'(n) [\mathcal{H}'(n) P(n - 1) \mathcal{H}'(n) + \Sigma_v]^{-1},
\]

\[
P(n) = \left[ I - K(n) \mathcal{H}'(n) \right] P(n - 1).
\]

Here, \( \Sigma_v \) is the covariance matrix of the measurement noise and \( \mathcal{H}'(n) \) is the partial derivative matrix

\[
\mathcal{H}'(n) = \begin{bmatrix} \mathcal{H}_1'(n), \ldots, \mathcal{H}_{N_{BS}}'(n) \end{bmatrix},
\]

where

\[
\mathcal{H}_i'(n) = \begin{bmatrix} \frac{\partial \mathcal{H}_i(\hat{x}(n) - 1)}{\partial \hat{x}_1}, \ldots, \frac{\partial \mathcal{H}_i(\hat{x}(n) - 1)}{\partial \hat{x}_{L_i}} \end{bmatrix} H.
\]

To ensure real and integer values for the estimated delays, \( \hat{x}_j(\cdot) \) are the rounded to the nearest integer value of \( [\hat{x}_j(\cdot)] \) for \( j = L + 1, \ldots, 2L \), and for \( i = 1, \ldots, N_{BS} \). The one step predictions of the state vector and error covariance matrix satisfy, respectively,

\[
\hat{x}(n + 1) = F\hat{x}(n),
\]

\[
\dot{P}(n + 1) = FP(n) F^T + Q,
\]

where \( Q = \text{Block diag}(Q_1, \ldots, Q_{N_{BS}}) \) and

\[
Q_i = \begin{bmatrix} \sigma_{w_{a_{i,1}}}, \sigma_{w_{a_{i,2}}}, \sigma_{w_{r_{i,1}}}, \sigma_{w_{r_{i,2}}} \end{bmatrix}.
\]

When the first stage of estimating all the path delays and channel coefficients is achieved, it becomes possible to estimate the interference \( \hat{y}_{int}(n, \tau) \) coming from the nonserving BSs (we suppose that the serving BS has the index 1):

\[
\hat{y}_{int}(n, \tau) = \sum_{v=2}^{N_{BS}} \sum_{l=1}^{L} \sqrt{E_k} \alpha_{v,l}(n) \mathcal{R}_{l,v}(\tau - \hat{t}_{v,l}(n)).
\]

To reine the estimation of the desired BS channel, we cancel
the estimated interference
\[ \hat{y}_{\text{des}}(n, \tau) = y_1(n, \tau) - \hat{y}_{\text{arr}}(n, \tau), \] (16)
and, then, we introduce a second estimation stage based on EKF with a state vector \( x_{\text{des}}(n) \in \mathbb{C}^{2L \times 1} \) and with an observation vector \( z_{\text{des}}(n) \) given, respectively, by
\[ x_{\text{des}}(n) = \left[ a_{\text{L}_1}(n), \ldots, a_{\text{L}_L}(n), t_{\text{L}_1}(n), \ldots, t_{\text{L}_L}(n) \right]^T, \]
\[ z_{\text{des}}(n) = \hat{y}_{\text{des}}(n). \] (17)

The EKF set of equations for single BS channel estimation can be retrieved easily from the equation presented for multiple BSs case. In this algorithm, we try to cancel only the interference coming from other BSs (interference due to CPICH channels). The interference coming from the other users (i.e., DPCH channels [14]) is considered as additive white noise and it will be neglected by the IC algorithm for simplicity. To cancel the intracell interference, the spreading codes of all users should be known by the receiver. Besides, in WCDMA systems, CPICH power is usually significantly higher than the individual DPCH power [14]. Therefore, using only intercell interference in the interference canceller is reasonable.

4. LOS DETECTION

The probability density function (pdf) of a fading channel with amplitude \(|a|\) which relates the Rayleigh, Rician, and Nakagami distributions is given by [19]
\[ p_r(|a|, \Omega, K_r) = \frac{2|a|(1 + K_r)}{\Omega} \exp \left( -\frac{|a|^2}{2} \right) \frac{\Omega}{K_r(1 + K_r)} I_0 \times \left( 2|a| \sqrt{\frac{K_r(1 + K_r)}{\Omega}} \right), \] (18)
where \( \Omega \) is the average fading power, \( \Omega = E[|a|^2] \), and \( K_r \) is the Rician factor. For \( K_r = 0 \), the pdf becomes Rayleigh distribution and it is Nakagami-\( n \) when \( n^2 = K_r \). We point out here that the Rayleigh distribution is a particular case of Nakagami and Rician for \( n^2 = K_r = 0 \). The question is how to detect the LOS and NLOS situations. This detection problem can be redefined in terms of a statistical test. First, we estimate \( \{(a_{\text{L}_i}, t_{\text{L}_i}), i = 1,\ldots,N_{\text{BS}} \} \) with the EKF algorithm. Then, by using statistic tests, we check if the channel is Rayleigh or not.

The most straightforward method is to estimate the pdf of the first arriving path, and compare it to some reference pdfs such as Rayleigh, Rician, Normal, Lognormal. To estimate correctly the distribution of the first arriving path, a set of independent fading coefficients are needed. The fading coefficients can be considered independent if they are at least a coherence time (\( \Delta t_{\text{coh}} \)) apart. When the carrier frequency is 2.15 GHz, and for a mobile velocity \( v \) in m/s, the coherence time is [20]
\[ \Delta t_{\text{coh}} = \frac{9}{16\pi f_D} \approx 0.025 \frac{v}{\nu}. \] (19)

In WCDMA mobile positioning, two techniques have been proposed to let the MSs measure different BSs within their coverage. The first one is the idle period-downlink (IP-DL) transmission proposed in [21]. It imposes to each BS to turn off its transmission for a well-defined period of time to let the MSs measure other BSs. In this case, the MS cannot measure continuously all the links, and the number of independent points sufficient for the positioning can be only acquired from the serving BS. As an alternative to IP-DL method, Jeong et al. [22] proposed an IC scheme in conjunction with the delay lock loops (DLLs) to reduce the intercell interference. By using this technique, the MS can measure continuously all the BSs in its coverage. In our algorithm, we use the EKF-based IC scheme to be able to measure continuously all available links.

We consider that \( N \) independent values are available in the MS memory to be used in the estimation of the channel distribution whenever the positioning is needed. For these \( N \) independent points \( x_i \), we test the hypothesis that \( P_{\text{df}} = Q_{\text{df}} \), where \( P_{\text{df}} \) is the measured pdf and \( Q_{\text{df}} \) is the reference pdf (e.g., Rayleigh, Rician, etc.). We define the two states \( H_0 \) and \( H_1 \), respectively, such that [23]
\[ P_{\text{df}}(x_i) = Q_{\text{df}}(x_i) \quad \text{for } 1 \leq i \leq N, \]
\[ P_{\text{df}}(x_i) \neq Q_{\text{df}}(x_i) \quad \text{for some } i. \] (20)

We introduce the \( m \) events \( X_i = \{x_{i-1} < x \leq x_i\}, i = 1,\ldots,m \), where \( x_0 = -\infty \) and \( x_m = +\infty \). We denote by \( k_i \) the number of successes of \( X_i \), that is, the number of samples in the interval \([x_{i-1}, x_i]\).

Under the hypothesis \( H_0 \),
\[ P(X_i) = P_{\text{df}}(x_i) = Q_{\text{df}}(x_i), \]
\[ p_{\text{hr}} = (x_i - x_{i-1}) P(X_i). \] (21)

Thus, to test the hypothesis, we form the Pearson’s test statistic (PTS) [23]
\[ \text{PTS} = \sum_{i=1}^{m} \frac{(k_i - np_{\text{hr}})^2}{np_{\text{hr}}}, \] (22)
where \( n \) is the total number of observed samples (\( n = N\Delta t_{\text{coh}} \)). The hypothesis \( H_0 \) is accepted if the PTS value satisfies \( \text{PTS} < \chi^2_{1-\lambda}(m-1) \), where \( \chi^2_{1-\lambda}(m-1) \) is taken from the standard chi-square tables corresponding to the confidence level \( \lambda \) and to the degree of freedom \( m-1 \).

This technique is efficient when the observation interval is long enough, the simulation results showed that around 1 second is needed to make reliable decision for a mobile velocity of 22.22 m/s. To decrease the duration of the observation and hence the hardware needed for storage, we propose a new algorithm using the estimation of Rician factor parameter \( K_r \) with respect to the channel profile of the \( v \)th BS defined by [20]
\[ K_r^v = \frac{\mu^2}{2\sigma^2}, \] (23)
Algorithm 1: Rician factor-based LOS detection.

For $i = 1, \ldots, N_{BS}$,

- Compute $K_{d}^{(i)}$(dB)
- Evaluate $P_{NLOS}^{(i)}$ and $P_{LOS}^{(i)}$
- Evaluate $d_{i} = P_{LOS}^{(i)} - P_{NLOS}^{(i)}$

if $d_{i} > 0$, then LOS component is present from BS, with probability $P_{LOS}^{(i)}$.
else, LOS component is absent from BS, with probability $P_{NLOS}^{(i)}$.

5. SIMULATION RESULTS

The EKF-based estimation was simulated in tracking mode. We assume that the initial multipath delay estimates are within $N_{init}$ samples away from the true delays, where $N_{init} = N_{r}$. The acquisition of the closely spaced multipath delays can be done with a separate feed-forward acquisition based on correlation and additional signal processing such as the nonlinear Teager Kaiser (TK) operator-based estimation [24], the iterative LS-based algorithms, projection onto convex sets (POCS) [9, 10, 25], or the pulse subtraction (PS)-based algorithms [26, 27]. The simulation results showed that the most promising algorithms are TK and POCS. Figure 1 shows the block diagram of the acquisition model including the additional signal processing.

The discrete-time TK operator applied to a complex signal $x(n)$ is given by [27, 28]

$$
\Psi_{d}(x(n)) = x(n-1)x(n-1)^{*} - 0.5[x(n-2)x(n-2)^{*}].
$$

TK exploits the structure of the cross-correlation function to estimate the subchip-spaced multipath components [24, 28].

The POCS algorithm is a constrained deconvolution approach, originally proposed in [9, 25] for delay estimation in Rake receivers, under the assumption of rectangular pulse shapes. If we reformulate (2) into a vectorial form, it is possible to write the following expression:

$$
y_{u}(n) = G_{u}h_{u}(n) + v_{\eta}(n),
$$

where $y_{u}(n)$ is the vector of correlation outputs corresponding to the $u$th BS, at different time lags between 0 and maximum channel delay spread $\tau_{max}T_{s}$. It is defined as $y_{u}(n) = [y_{u}(n,0), \ldots, y_{u}(n,\tau_{max}T_{s})]^{T} \in \mathbb{C}^{(\tau_{max}+1) \times 1}$. The matrix $G_{u}$ is the pulse shape deconvolution matrix with element $g_{i,j} = \sqrt{E_{\eta}}g_{i,j}(i-j)$, for $i, j = 0, \ldots, \tau_{max}$. $v_{\eta}(n)$ is the sum of Inter-Channel-Interference (ICI), Inter symbol Interference (ISI), MAI, and AWGN noises after the despreading operation. The vector $h_{u}(n)$ of elements $h_{i,u}$ is defined such that
The channel from each BS has 3 closely-spaced paths, the first one being either Rayleigh or Rician. The channel is supposed to be Rayleigh with probability \( \frac{L}{N} \) and Rician with probability \( 1 - \frac{L}{N} \). The delay separation between successive paths are uniformly distributed in \([T_c/N_s; T_c] (N_s = 8)\).

In Figure 3, we show the tracking trajectory of both delays and channel coefficients of the first arriving path for \( L = 4 \), with tracking delay error initialized at \( N_{\text{init}} = \tau - \hat{\tau} = 0.5T_c \).

The matrix of the average path powers is

\[
P_{\text{BS}} = \begin{bmatrix} 0 & -2 & -2 & -3 \\
-1 & -1 & -4 & -5 \\
-2 & -1 & -4 & -6 \\
-2 & -2 & -4 & -5 \end{bmatrix} \text{ dB.} \tag{27}
\]

The first row corresponds to the average path powers of the desired BS. The simulation shows that EKF is able to track quite accurately the delays and the complex channel coefficients by using the IC scheme. In Figure 4, we show the probability of acquiring correctly the delay of the first arriving path within an error of 1 sample (1/N_s, chip) with and without IC algorithm. The channel from each BS has 3 closely-spaced paths. The corresponding average powers are

\[
P_{\text{BS}} = \begin{bmatrix} 0 & -1 & -4 \\
-3 & -2 & -4 \\
-1 & -2 & -4 \\
-2 & -2 & -4 \end{bmatrix} \text{ dB.} \tag{28}
\]
The channel profile from the desired BS is Rayleigh with probability $p_R = 0.9$ and it is Rician with probability 0.1. The Rician factor is exponentially distributed with mean $\mu_R = 4$. The acquisition probability is computed over $N_{\text{rand}}$ random realizations of the channel, $N_{\text{rand}} = 200$. We can see that it is possible to achieve 20% to 30% gain in the probability of first-arriving path acquisition by using the IC algorithm at low NFR values. The tracking of the first-arriving path can be achieved in up to 80% of the cases with IC. However, at high NFR, the feedback propagation error in EKF, when the interference is strong, prevents the correct tracking of the delay. The initial delay and covariance errors have a major effect on the convergence of the EKF, that is, bad initialization may lead to divergence of the algorithm.

### 5.2. LOS detection

First, we show the performance of PTS-based LOS detection. Then, we show the performance of Rician factor-based algorithm. We consider a relatively fast fading channel with mobile velocity $v = 80$ km/h (22.22 m/s). In the statistical test, the decision is made on $N_{\text{slots}}$ slots basis, with $N_{\text{slots}} \in \{50, 100, 500, 1000, 1500, 2000, 4000\}$. Independent points spaced at $\Delta_{\text{coh}}$ apart are taken within the decision interval. In WCDMA, 1 slot is $t_{\text{slot}} = 0.6667$ milliseconds and for $S_F = 256$, there are 10 symbols per slot. The confidence level in the decision was 99.99% [23]. Table 1 shows the comparison of the measured data distribution of the first path against several distributions: Rayleigh, Rician, Gaussian, and Lognormal.
Table 1: Probabilities of accepting a certain distribution with a confidence level of 99.99%. Rayleigh and Rician channels ($K_r = 15.5 \, \text{dB}$) and $v = 22.22 \, \text{m/s}$.

| Rayleigh channel | $N_{\text{slots}}$ | $P_{\text{Rayleigh}}$ | $P_{\text{Rician}}$ | $P_{\text{Normal}}$ | $P_{\text{Lognormal}}$ | Decision |
|------------------|---------------------|------------------------|----------------------|---------------------|-------------------------|----------|
|                  | 50                  | 0.993                  | 1                    | 1                   | 0.83                    | None     |
|                  | 100                 | 0.993                  | 1                    | 0.98                | 0.76                    | None     |
|                  | 500                 | 1                      | 1                    | 0.86                | 0                       | None     |
|                  | 1000                | 1                      | 1                    | 0.40                | 0                       | None     |
|                  | 1500                | 1                      | 1                    | 0.10                | 0                       | NLOS     |
|                  | 2000                | 1                      | 1                    | 0                   | 0                       | NLOS     |

| Rician channel  | $N_{\text{slots}}$ | $P_{\text{Rayleigh}}$ | $P_{\text{Rician}}$ | $P_{\text{Normal}}$ | $P_{\text{Lognormal}}$ | Decision |
|-----------------|-------------------|------------------------|----------------------|---------------------|-------------------------|----------|
|                 | 50                | 1                      | 1                    | 1                   | 0.04                    | None     |
|                 | 100               | 1                      | 1                    | 1                   | 0                       | None     |
|                 | 500               | 1                      | 1                    | 0                   | 0                       | NLOS     |
|                 | 1000              | 1                      | 1                    | 0                   | 0                       | NLOS     |
|                 | 1500              | 0                      | 1                    | 0                   | 0                       | LOS      |
|                 | 2000              | 0                      | 1                    | 0                   | 0                       | LOS      |

Figure 5: Estimated and theoretical Rayleigh and Rician pdfs for $N_{\text{slots}} = 500$ (plot (a)) and $N_{\text{slots}} = 1500$ (plot (b)). Rician channel profile ($K_r = 15.5 \, \text{dB}$), $v = 22.22 \, \text{m/s}$.

When the channel is Rayleigh distributed (i.e., NLOS case), we see that at least 1500 slots are needed to decide Rayleigh and Rician. This is not contradictory as the Rayleigh distribution is a particular case of Rician. Hence, the overall decision will be Rayleigh and the LOS component will be absent. If we use a lower number of slots (e.g., 100 slots), the distribution cannot be established, as we also detect normal distribution with probability 0.98, and Lognormal distribution with probability 0.76. Also, in the case of Rician channel profile (i.e., LOS case), at least 1500 slots are needed to decide Rician distribution. We point out that for LOS case, the statistical test for Rayleigh distribution should provide $P_{\text{Rayleigh}} = 0$. In this case, the number of independent points needed for the decision is $N = 880$, which is obtained from

$$N = t_{\text{slot}} N_{\text{slots}} / \Delta t_{\text{coh}}$$

(29)

In Figure 5, we show the similarities between estimated pdf, theoretical Rayleigh, and theoretical Rician pdfs when the channel is Rician with $N_{\text{slots}} = 500$ and $N_{\text{slots}} = 1500$. We can see that the measured data curve and Rician curve have good fitting for the later case. This technique can be used efficiently in continuous time measurement mode when the mobile can keep track of the channel estimates over several
Table 2: Probabilities of accepting a certain distribution using Rician factor-based algorithm. Rayleigh and Rician channel (Kr = 15 dB) and v = 22.22 m/s.

| Channel       | N_dots | p_NLOS | p_LOS  | d_mean | Decision |
|---------------|--------|--------|--------|--------|----------|
| Rayleigh      |        |        |        |        |          |
|               | 1      | 0.0917 | 0.9083 | 0.8165 | LOS      |
|               | 10     | 0.5760 | 0.4240 | -0.1520| NLOS     |
|               | 50     | 0.8133 | 0.1867 | -0.6267| NLOS     |
|               | 100    | 0.9000 | 0.1000 | -0.8000| NLOS     |
| Rician        |        |        |        |        |          |
|               | 1      | 0.0975 | 0.9026 | 0.8    | LOS      |
|               | 10     | 0.0272 | 0.9728 | 0.94   | LOS      |
|               | 50     | 0.0433 | 0.9567 | 0.91   | LOS      |
|               | 100    | 0.0918 | 0.9082 | 0.8164 | LOS      |
|               | 500    | 0      | 1      | 1      | LOS      |

milliseconds, for example, the CPICH signal coming from the serving BS.

By applying Algorithm 1 to the same channel profiles tested with the pdf-based technique, we can obtain faster decision on whether the channel is Rayleigh or Rician. The minimum and maximum edges B_min and B_max are -20 and +20 dB, respectively, and the number of subintervals considered is (M + 1) = 10. Figure 6 shows the estimated Rician factor in dB (plot (a)) and the distance d = P_LOS - P_NLOS (plot (b)) when the Rician factor is computed on a slot by slot basis. Table 2 shows the means P_LOS and P_NLOS, respectively, of the probabilities P_LOS and P_NLOS, the mean distance d_mean of d, and the corresponding decision when the Rician factor is computed over N_dots ∈ {1, 10, 50, 100, 500} slots.

For the case of Rayleigh channel, we see that the decision based on 1 slot is not possible, the estimated Rician factor in this case is too high, and the decision will be Rician. At least 10 slots are needed to decide safely that the distribution is Rayleigh. However, in the case of Rician channel, it is quite easy to decide the presence of LOS even on a slot-by-slot basis. To show the performance of Rician factor-based algorithm, we considered a channel with succession of Rayleigh and Rician fading. The estimation of the Rician factor is done on a frame-by-frame basis (1 frame = 15 slots). Figure 7 shows that the true Rician factor versus the estimated Rician factor in dB (plot (a)) and the distance d = P_LOS - P_NLOS (plot (b)). During the first 200 frames and between frames of index 500 and 600, the channel is Rayleigh (Kr [dB] = ∞). The minimum and maximum edges B_min and B_max are -20 and +20 dB, respectively, and the number of subintervals is (M + 1) = 10. We point out that these two edges, B_min and B_max, should be set adaptively, based on the noise level in the system. It is clear that during the first 400 frames, d_mean < 0, where d_mean = mean(d_i, 0 ≤ i ≤ 400), which indicates the absence of LOS component, even if we have Rician distribution during 200 frames. This is due to the fact that for Kr = -6 dB, which is very low, the Rician distribution is very similar to Rayleigh. However, when the Rician factor is 6, 15.5, or 20 dB, it is quite easy to decide the presence of LOS component.

The two presented techniques for LOS detection are making a trade-off between short observation time and noise level estimation. The first technique that is based on pdf estimation does not need any estimation of the noise level, but it requires long observation time, which is not a limitation in continuous time measurement. The second technique which uses much lower observation time needs an estimate of the noise level to set adaptively the thresholds B_min and B_max.

6. CONCLUSIONS

New techniques of LOS/NLOS detection for mobile positioning for WCDMA system have been presented, based on EKF estimation and statistic tests-based decisions. The delays and channel coefficients are jointly estimated using EKF.
with an IC scheme in the context of closely spaced paths in multicell WCDMA transmission. The simulation results showed that the tracking of the first-arriving path can be achieved efficiently with a probability of acquisition varying from 40% to 80% of the cases in good NFR conditions (NFR ≤ 10 dB). The channel coefficient estimates are then used for LOS/NLOS detection. We have presented two statistics-based techniques. The first one is using curve fitting criteria. This method requires the storage of $N$ independent points in the mobile terminal updated at least at coherence time interval ($\Delta_{coh}$) (about 880 points). We showed that this technique can provide quite satisfactory decision on whether the LOS component is present or not. The second technique is based on the estimation of Rician factor and can be used when the measurement interval is constrained in time. We found that in moderate-to-high mobility case, one frame is enough to carry reliable decision on whether the LOS component is present or not. However, the decision parameters should be updated according to the noise level for best performance.

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