INTERFERENCE CANCELLATION WITH BAYESIAN CHANNEL MODELS AND APPLICATION TO TDOA/IPDL MOBILE POSITIONING

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ABSTRACT

In wireless communications, dealing with multiple access interference is a common problem. Interference, like the signal of interest, is characterized by a transmitted signal and a channel response. In recent years, improved channel estimation techniques have been proposed based on Bayesian channel estimation. The exploitation of priori knowledge such as the power delay profile allows to reduce the effective number of channel parameters. Whereas the direct use of the Bayesian channel estimate for the user of interest may lead to bias problems, its use for an interfering signal allows to better suppress interference. In this paper we introduce the concept of Component-wise Conditionally Unbiased (CCU-) LMMSE channel estimation and consider its application to the problem of TDOA-based mobile positioning in 3G systems exploiting IPDL frames.

1. INTRODUCTION

Mobile positioning systems have received significant attention in both research and industry over the past few years and finding the location of the mobile phone become one of the important feature of communication system due its various potential applications (effective intra and inter-system handoff, location of emergency caller...). The basic function of location system is to collect information about the position of a mobile station (MS) and to study that information to get a location estimate. The conventional methods for wireless positioning are based on the estimation of direction of-arrival (DOA), time-of-arrival (TOA) or time-difference-of-arrival (TDOA) at a convenient number of base stations. The fundamental problem with all location techniques is the non ability to hear distant Base stations (BS's) which transmit on the same frequency (CDMA systems). One suggestion for UMTS is to include idle periods in the downlink of the BS. In these periods timing measurements can be made for more distant BS's. To exploit this idle periods, we require a good knowledge on the channel impulse response (CIR), which can be provided by a good channel estimator.

Estimation of the transmission channel has a crucial role in the location algorithms in communications systems. Channel parameters which are embedded in white Gaussian noise are observed indirectly by the received data. Usually the channel estimation is based on the known sequence of bits, which is unique for a certain transmitter and which is repeated in every transmission burst. Thus, the channel estimator is able to estimate CIR for each burst separately by exploiting the known transmitted bits and the corresponding received samples. In the majority of mobile positioning techniques, CIR estimates are performed using a simple matched filtering [1, 2], or the BLUE (Best Linear Unbiased Estimator) estimation [3]. However, such approaches can provide an acceptable estimation performance only if the observations (equations) is much more numerous than CIR parameters (unknown). The fact that lead to a capacity loss (if the Idle period is too long), or position estimation error (if the CIR is not long enough). On the other hand, unlike the channel impulse response, the Time Delay Profile change very slowly; and can be estimated with a good accuracy. Tacking into account this prior information can lead to a better tradeoff between capacity loss and mobility tracking.

This paper is organized as follows. In section 2, we introduce the IPDL positioning method . The Component-wise Conditional Unbiased Linear Minimum Mean Square Error (CCULMMSE) estimator will, then, be derived in section 3. The performance, and a SIC implementation of the CCULMMSE estimator will, also, be discussed. The adaptive EM estimation of the Power Delay Profile is investigated in section 4; and finally a discussion and concluding remarks are provided in section 5.

2. THE IPDL POSITIONING METHOD

The downlink positioning is based on detecting the Time-Of-Arrival (TOA) of signals from different BSs. In CDMA

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the fundamental problem is that because of the near-far problem it is difficult to hear other BSs. In downlink transmission, the received signal strength, when coming from a remote BS can be quite weak, especially when the mobile terminal is close to the serving BS . This situation is usually referred to as the hearability problem. In order to improve the hearability of neighboring BSs, the serving BS provides idle periods in continuous or burst mode. This technique is known as Idle Period-Down Link transmission (IPDL). The idle periods are short and arranged in a pseudo random way made known to all MSs in advance. The pseudo randomness assures that the effect of simultaneous idle periods in adjacent BSs is minimized. The length of the idle periods is a parameter, which the operator can change to trade off positioning response time and accuracy against capacity loss in the DL. With longer idle periods, the achievable accuracy would be better because of longer integration time at the MS, but the system capacity would be reduced and some assumptions about the channel model can't take the way. During these periods the serving BS completely ceases its transmission and the MS is scheduled to make the needed measurements from the neighbour BSs now hearable. By supporting the IPDL, the localization performance in MS will improve, as there will be less interference present during idle periods.

An example of IPDL method has been shown in figure 1. When BS#1 entered in idle period i, The MSs in BS#1 could detect other BS (i.e. from BS#2 to BS#n, where n is an uncertain number and the number of neighbor BSs) signal. In that time the other BSs did not anything else but just transmit their CPICH and other downlink channels.
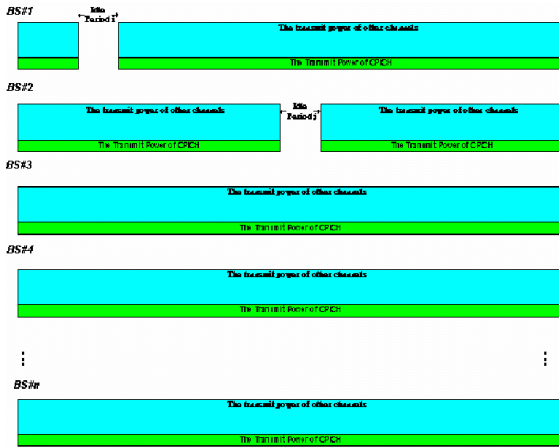

Fig. 1. IPDL Method

3. THE CHANNEL CCULMMSE ESTIMATOR

3.1. Problem statement

The estimation of the transmission channel has a crucial role in the location algorithms in communications systems.

Channel parameters are observed indirectly by the received data : convolved with a known training sequence and embedded in a white Gaussian noise.

$$y = \sum_{k=1}^{M} X_k h_k + v \qquad (1)$$

where

- $y = [y_1 \cdots y_N]^T$ denotes received data on a given idle period. N is the idle period length.
- $v = [v_1 \cdots v_N]^T$ represents the additive white gaussian noise.
- M is the number of detected base stations.
- $h_k = [h_{k,1} \cdots h_{k,L_k}]^T$ denotes the channel impulse response between the MS and the kth base station. L_k is k^{th} CIR length.
- $X_k = \begin{bmatrix} x_1 & \cdots & x_{L_k} \\ \vdots & & \vdots \\ x_N & \cdots & x_{N+L_k-1} \end{bmatrix}$ is an $N \times L_k$ matrix characterizing the training sequence of the kth base station.

Using a compact notation, received data can be written as:

$$y = Xh + v \qquad (2)$$

where $X = [X_1 \cdots X_M]$, and $h = [h_1^T \cdots h_M^T]^T$.

Generally, the estimation problem leads to a tradeoff between "the capacity loss" and "the estimation noise". In fact, the length of the idle period should be as short as possible to ensure that the FL capacity loss is minimized. On the other hand, the channel length must be enough to allow the estimation of the right Time of Arrival. The channel length depends on the uncertainty associated with the Mobile Station (MS) position. If there is a prior estimation of the MS position, the uncertainty can be considerably reduced. However, if this prior information is inexistent (initialization), or not reliable (fast movement), longer CIR must be considered. Additionally, the more BS's taking into account, the better the position estimate will be; but the more coefficients need to be estimated.

If the training sequence is much longer than the channel impulse response, and/or the channel energies are comparables; the quantity $X^H X$ will be approximately spherical, and the matched filter approximates the LMMSE estimator (under unbiasness constraint). However, if these assumptions are not valid, taking into account the prior power delay profile can advantageous; and can lead to a better "capacity loss" vs. "estimation noise" tradeoff.

On the other hand, whereas the direct use of the Bayesian channel estimate for an interfering signal allows to better

suppress of interference, its use for the user of interest may lead to bias problem. The fact that can lead to a poor position accuracy, as the ToA estimate is based on a fitting between the estimated CIR and the pulse-ship. That motivates us to introduce the concept of Component-wise Conditionally Unbiased (CCU-) LMMSE channel estimation, in order to exploit the prior knowledge about the power delay profile, while ensuring the estimator unbiasness (in the component-wise sense).

3.2. The CCULMSE estimator

The Linear Minimum Mean Square Error (LMMSE) estimator is given by:

$$\widehat{h}_{LMMSE} = \left(C_{hh}^{-1} + \frac{1}{\sigma_v^2} X^H X \right)^{-1} \frac{1}{\sigma_v^2} X^H y$$

$$= \underbrace{\left(\sigma_v^2 \left(X^H X \right)^{-1} C_{hh}^{-1} + I \right)^{-1}}_{A} \left(X^H X \right)^{-1} X^H y$$

$$= A \; \widehat{h}_{BLUE} \qquad (3)$$

where $\widehat{h}_{BLUE}$ denotes the Best Linear Unbiased Estimator. The main problem of the LMMSE estimate is that it is biased. This bias may lead to position estimation error when path parameters are extracted from the biased channel estimate. The type of bias considered here should be conditional, treating the channel as deterministic. However, it is not required to force joint unbiasedness between all channel impulse response coefficients, which would prevent the exploitation of any prior knowledge on the channel distribution. That is why we impose a Component-wise Conditionally Unbiasedness (CCU) constraint:

$$E\left[\widehat{h}_{k,j}/h_{k,j} \right] = h_{k,j} \qquad k = 1 : M \, , \; j = 1 : L_k \qquad (4)$$

By minimizing the MSE, subject to the CCU constraint, one can show that the CCU-LMMSE estimate can be written as:

$$\widehat{h}_{CCULMMSE} = D \; \widehat{h}_{LMMSE} \qquad (5)$$

where D is a diagonal matrix that forces the component-wise unbiasedness constraint.
Thus,

$$\widehat{h}_{CCULMMSE} = (diag(A))^{-1} A \; \widehat{h}_{BLUE} \qquad (6)$$

As localization, and CIR estimation performances are strongly related, position accuracy are evaluated by evaluating the MSE of the CIR estimation. The MSE is performed using a Monte Carlo simulation for a basic scenario. The received signal is assumed to be the superposition of the contribution of 5 distinct base stations, and embedded in a white Gaussian noise. The relative received signals power are respectively 0, -5, -10, -15, -20 dB. The power delay profile is
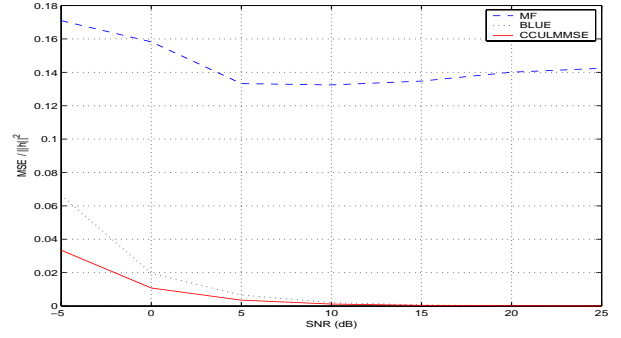
Fig. 2. CIR estimation accuracy using MF, BLUE, and CCULMMSE estimators

generated according to the channel model "vehicular B". Figure 2 plots the curves of the estimation of the MSE of the 5th (the weakest) using respectively a simple matched filter, a BLUE, and a CCULMMSE estimators. As it was expected, curves show that the CCULMMSE outperforms the two other approaches. Moreover, for high SNR, the BLUE converge to the CCULMMSE estimator (as they become optimal).

3.3. SIC implementation of the CCULMMSE estimator

In previous, we have proposed a CCULMMSE scheme to improve the CIR estimation. The inherent complexity, however, is cubic on $L = \sum_k L_k$ (as the technique requires the inversion of a, non necessarily Toeplitz, matrix). For practical implementation, Successive Interference Cancellation (SIC) approach can been used to approximate the CCULMMSE estimator; with lower complexity.

Successive Interference Cancellation is a nonlinear type of multi-channel estimation scheme in which CIR's are estimated successively. The approach successively cancels strongest channels. Assume that channels have been ordered in order of decreasing $SNR_k = \frac{\sigma_x^2 \|h_k\|}{\sigma_v^2}$ at the channel estimator input. The first (strongest) channel impulse response estimation is produced by a simple matched filter,

$$\widehat{h}_1 = X_1^H y \qquad (7)$$

After making an umbiased estimate of the CIR, the LMMSE estimator is derived, the interfering signal is recreated at the receiver, and subtracted from the received waveform.

$$\widehat{h}_1^{LMMSE} = \left(\sigma_v^2 C_{hh}^{-1} + diag\left(X_1^H X_1 \right) \right)^{-1} \widehat{h}_1$$
$$\widehat{y}_1 = X_1 \widehat{h}_1^{LMMSE}$$
$$y \leftarrow y - \widehat{y}_1$$

Note that, even if $X^H X$ can not be approximated as diagonal, non-diagonal elements of $X_1^H X_1$ can be neglected (as the number of unkown is M times less).

In this manner successive base stations does not have to encounter interference caused be initial base stations. SIC leads to good performance for all channel estimates: initial CIR estimates improve because the later channels are given less power which means less interference for the initial channels, and later CIR estimate improve because early BS's interference have been cancelled out. Figure 3 shows that the the SIC well approximate the CCULMMSE estimator (specially for low SNR).
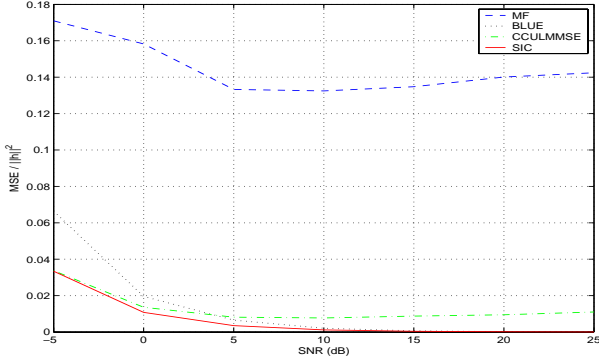

Fig. 3. CIR estimation accuracy using MF, BLUE, CCUL-MMSE, and SIC estimators

4. THE POWER DELAY PROFILE (PDP) ADAPTATION USING EM ALGORITHM

The estimation of the statistical parameter of the transmission channel plays a crucial role in the CIR estimation procedure. Unlike the channel impulse response, the Power Delay Profile change very slowly; and can be estimated with a good accuracy from the received data. In this paper, the identification of the Power Delay Profile model is based on the concept of expectation maximization (EM) and an iterative optimization algorithm to produce maximum-likelihood (ML) estimates under certain conditions. The EM procedure is divided into two steps:

- The expectation step (E-step), computes the conditional expectation of unobserved sufficient information (complete data), under given observed insufficient information (incomplete data) and the current estimation of the parameters.
- The maximization step (M-step), provides the new estimate of parameters by maximizing the conditional expectation over unknown parameters.

As in [4], we propose using an adaptive EM Algorithm to jointly update the LMMSE channel estimates and the power delay profile parameters. The resulting algorithm is listed in the table below (k denotes the idle frame index).

One can show that the power delay profile $\widehat{C}_{hh,k}$ are updated such that:

$$C_{hh,k} = \sum_{j=0} \lambda^j \left(C_{\widetilde{h}\widetilde{h},k} + \widehat{h}_{LMMSE,k} \widehat{h}_{LMMSE,k}^H \right)$$

where in the uncorrelated channel coefficients case $C_{hh,k}$ converges to a diagonal matrix.

PDP Estimation via Adaptive EM Algorithm	
#	**Computation**
Initialization	
1	$\widehat{h}_{0/0} = 0, P_{0/0} = I, C_{hh}^{(0)} = I, M^{(0)} = 0, \gamma^{(0)} = 0$
LMMSE estimation	
2	$C_{\widetilde{h}\widetilde{h},k} = \left(C_{hh,k-1}^{-1} + \frac{1}{\sigma_v^2} X_k^H X_k \right)^{-1}$
3	$\widehat{h}_{LMMSE,k} = C_{\widetilde{h}\widetilde{h},k} \frac{1}{\sigma_v^2} X^H y$
Adaptive EM parameter estimation	
4	$M^{(k)} = \lambda M^{(k-1)} + C_{\widetilde{h}\widetilde{h},k} + \widehat{h}_{LMMSE,k} \widehat{h}_{LMMSE,k}^H$
5	$\gamma^{(k)} = \lambda \gamma^{(k-1)} + 1$
6	$C_{hh,k} = \frac{1}{\gamma^{(k)}} M^{(k)}$

5. CONCLUSIONS

In this paper we have introduced the concept of Component-wise Conditionally Unbiased (CCU-)LMMSE channel estimation and considered its application to the problem of TDOA-based mobile positioning in 3G systems exploiting IPDL frames. The exploitation of priori knowledge about the power delay profile allows reducing the effective number of channel parameters. While component-wise unbiasness constraint allow a good position accuracy (as the ToA is estimated using a pulse-chip fitting). We have, also, proposed a SIC scheme to implement, efficiently, the CCUL-MME with a quadratic complexity.

Although the CCULMMSE estimator, and its SIC implementation, are introduced for mobile positioning application, these concepts are quite general; and can be applied for any CIR estimation problem, as well as for Multi-User detection. They allow a better suppress of interference, while satisfying the component-wise unbiasness constraint; which can be quite important for several applications.

6. REFERENCES

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