KALMAN-FILTER BASED CHIP ESTIMATOR FOR WCDMA DOWNLINK DETECTION

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ABSTRACT

In the WCDMA downlink, the multipath channel destroys orthogonality between users and causes multiple access interference (MAI). This channel-induced MAI can be combated by channel equalization to approximately restore orthogonality. This paper presents a chip-estimator method based on Kalman filtering suitable for WCDMA downlink. The method does not require a training sequence or the knowledge of other-users' spreading codes. Simulation results show considerable performance improvement using the proposed estimator compared with that of the RAKE receiver.

1. INTRODUCTION

WCDMA has been chosen as the standard for the third generation mobile communication systems in Europe and Japan. The demand on high data rates and flexible data services expected in the downlink channel increases the demand on the mobile receivers.

In the downlink, the user signals are synchronous and the users of possible different data rates are separated by orthogonal codes. Due to multipath propagation, inter-path interference (IPI) will cause multiple-access interference (MAI). It is known that the conventional RAKE receiver is incapable of suppressing inter-path interference [1]. Adaptive multiuser detection, see for example [2]-[4], has shown to be a promising technique for interference suppression in DS-CDMA systems. The adaptive implementations are especially attractive if implemented in a mobile terminal due to the low computational complexity and relaxed requirement for knowledge of the interfering signal parameters. However, the approaches taken in [2]-[4] require cyclostationary interference on symbol level in order for the adaptation algorithm to converge to a solution. A multiuser detector suitable for long code system is presented in [5], where a Kalman filter is used as a symbol detector. The detector require knowledge of all user codes and as a consequence it is more suitable for implementation at the base station.

In downlink WCDMA, the user signals are separated by orthogonal Walsh codes and thereafter scrambled by a cell-specific long code spanning a whole frame of data. Applying the methods in [2]-[4] to WCDMA downlink would require several parallel adaptive structures updated only once per frame. In general, this causes convergence problems since it will take several hundreds of iterations for each adaptive filter to converge, i.e., several hundreds of frames for a total convergence [1]. Therefore, other approaches are needed to suppress MAI. It is shown in [6] that in the special case of downlink transmission, channel induced MAI can be efficiently suppressed by channel equalization. There are many ways to perform equalization or chip decorrelation through adaptive methods, see, e.g., [6] -[8] for interesting approaches.

In this paper, Kalman filter is used to estimate the transmitted chips based on the observation of the received chips and knowledge of the channel. The solution of the Ricatti equations yields a sequence of estimated chips that, once fed to the conventional matched filter detector, results in the estimated transmitted symbol.

The paper is organized as follows. In Section 2 we describe the downlink signal model used. In Section 3 we present the state-space description of the system and the Kalman filter equations. In Section 4 we show simulation results and in Section 5 we present conclusions.

2. DOWNLINK SIGNAL MODEL

In a K-user system, the transmitted chip sequence from user k can be written as

$$x_k(n) = \sum_{m=1}^{M} A_k(m) b_k(m) c(n) s_k(n - mG_k) \qquad (1)$$

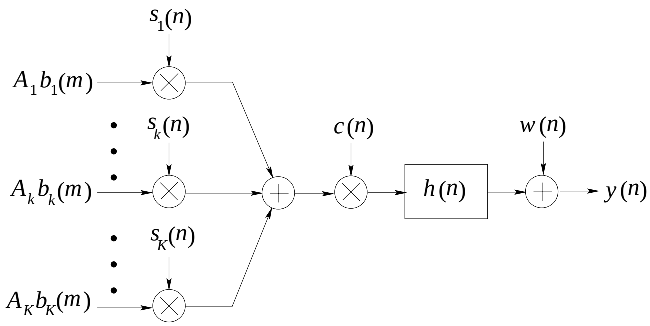

Figure 1: Block diagram of the system.

where for the mth symbol $A_k(m)$ is the amplitude due to power control, $b_k(m)$ is the transmitted symbol, s_k is the orthogonal variable-length Walsh code used for channelization with $s_k(n) \in \pm 1$ for $n = 0, \ldots, G_k - 1$ and zero otherwise, where G_k denotes the number of chips per symbol. Finally, $c(n)$ denotes the cell-specific scrambling sequence spanning one data frame. The transmitted sequence of chips composed by the K simultaneously active users of possibly different data rates is given by

$$x(n) = \sum_{k=1}^{K} x_k(n) \tag{2}$$

The transmitted signal propagates through an L-path channel and is received at the mobile

$$\begin{aligned} y(n) &= \sum_{l=1}^{L} h_l(n)x(n-l+1) + w(n) \\ &= \mathbf{h}^{\mathrm{T}}(n)\mathbf{x}(n) + w(n) \end{aligned} \tag{3}$$

where $h_l(n)$ is the lth path channel coefficient during chip interval n, $w(n)$ is an additive white Gaussian noise sequence with variance σ_w^2, and $\mathbf{x}(n)$ and $\mathbf{h}(n)$ are given by

$$\begin{aligned} \mathbf{x}(n) &= [x(n)\, x(n-1)\, \ldots\, x(n-L+1)]^T \\ \mathbf{h}(n) &= [h_1(n)\, h_2(n)\, \ldots\, h_L(n)]^T \end{aligned} \tag{4}$$

respectively. Figure 1 shows the block diagram over the system considered.

Assuming orthogonal multiuser signals generated at the transmitter and that a suitable strategy can be employed to estimate the chips at the receiver, then symbol detection can be accurately performed via a matched filter. In the next section we describe a state-space model for equations (1)–(4) and how a Kalman filter can be used to estimate the transmitted chip sequence, $\{x(n)\}$.

3. THE KALMAN FILTER MODEL

For a channel with L paths, we may define a state-space model as follows:

$$\mathbf{x}(n) = \mathbf{\Phi}\mathbf{x}(n-1) + \mathbf{u}(n) \tag{5}$$

where the state vector contains the present and past chips, and $\mathbf{\Phi}$ and $\mathbf{u}(n)$ are given by

$$\mathbf{\Phi} = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ 1 & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & 0 \\ \vdots & 0 & 1 & 0 \end{bmatrix} \tag{6}$$

and

$$\mathbf{u}(n) = [u\, 0, \ldots, 0]^{\mathrm{T}} \tag{7}$$

with u being $x(k)$ such that we have $\mathbf{Q} = E[\mathbf{u}(n)\mathbf{u}^{\mathrm{T}}(n)]$ as $\mathrm{diag}(\sigma_u^2, 0, \ldots, 0)$ and $\sigma_u^2 = \sum_{k=1}^{K} A_k^2$.

As remarked in [9], in order to deal with nonminimum phase channels, a fixed lag smoothing form of the Kalman filter can be used. For a fixed lag d, this smoother can be carried out by increasing the dimension of the state vector (initially equal to L) to $d+1$ and augmenting (zero padding) $\mathbf{h}(n)$ as in

$$\begin{aligned} \mathbf{x}(n) &= [x(n)\, \ldots\, x(n-L+1)\, \ldots x(n-d)]^T \\ \mathbf{h}(n) &= [h_1(n)\, \ldots\, h_L(n)\, 0\, \ldots\, 0\,]^T \end{aligned} \tag{8}$$

Yet, the observation $y(n)$ is given by $\mathbf{h}^{\mathrm{T}}(n)\mathbf{x}(n) + w(n)$.

The chip estimates, $\hat{x}(n)$, can be obtained via the solution of the Ricatti equations, i.e.,

$$\hat{\mathbf{x}}(n|n-1) = \mathbf{\Phi}\hat{\mathbf{x}}(n-1|n-1) \tag{9}$$

$$\mathbf{M}(n|n-1) = \mathbf{\Phi}\mathbf{M}(n-1|n-1)\mathbf{\Phi}^T + \mathbf{Q} \tag{10}$$

$$\mathbf{K}(n) = \frac{\mathbf{M}(n|n-1)\mathbf{h}(n)}{\sigma_w^2 + \mathbf{h}^T(n)\mathbf{M}(n|n-1)\mathbf{h}(n)} \tag{11}$$

$$\begin{aligned} \hat{\mathbf{x}}(n|n) &= \hat{\mathbf{x}}(n|n-1) \\ &\quad + \mathbf{K}(n)[y(n) - \mathbf{h}^T(n)\hat{\mathbf{x}}(n|n-1)] \end{aligned} \tag{12}$$

$$\mathbf{M}(n|n) = [\mathbf{I} - \mathbf{K}(n)\mathbf{h}^T(n)]\mathbf{M}(n|n-1) \tag{13}$$

The final chip estimate $\hat{x}(n-d)$ is obtained by averaging the $d+1$ estimates related to the current chip value

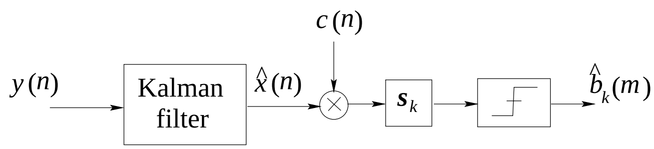

Figure 2: Block diagram of the receiver.

from the state vector at $d+1$ different time instants. The estimated chip sequence is descrambled with the cell specific long code $c(n)$ and fed to the symbol detector which in case of orthogonal user signals is the matched filter. Figure 2 shows the structure of the receiver.

The method above require that channel estimates are fed to the Kalman filter. In WCDMA downlink the estimates could be based on either the dedicated pilot symbols available in each frame or the common pilot channel provided in each cell.

4. SIMULATION RESULTS

In order to test the performance of the Kalman filter as chip estimator, bit-error-rate (BER) curves were generated through simulations, and the results were compared with those of the conventional RAKE receiver.

The downlink WCDMA system under consideration contained K synchronous users of equal rate using Walsh codes of length $G_k = 16$ or $G_k = 4$. The scrambling code was taken as part of a long Gold code as given in [10]. The performance of the proposed method was evaluated in a Rayleigh fading channel with three resolvable paths. Carrier frequency 2 GHz, chip rate 3.84 MHz, and mobile speed of 5 km/h were used. The BER performance of the proposed method was evaluated for signal-to-noise ratio (SNR) values ranging from 5 dB to 15 dB. In the simulations the base station transmits with same power to all the users. Perfect channel estimates were assumed in the simulations. The length of the state-vector was chosen to $d+1=6$.

Figure 3 shows the BER as a function of the SNR in the case of $G_k = 16$ for $K = 4$, 8, and 16 users. The results clearly show a substatial increase in performace obtained by using the Kalman chip estimator.

In Figure 4 the system consists of $K = 1$, 2, or 4 users with $G_k = 4$. In the single user case, the RAKE receiver is still suffering from inter path interference and a performance improvement is still possible by using the chip estimator.

In both figures it can be observed that the gain by using the Kalman receiver is increasing with increasing number of users. This is due to the fact that the Kalman receiver utilizes the power from all the users in the chip estimation.

So far we have assumed perfect knowledge of the parameters σ_w^2 and σ_u^2. In practice these parameters are unknown and estimates are needed. To verify the impact these values have on the performance, curves were generated assuming incorrect values. Figure 5 shows the results from a system with $K = 8$ users with spreading factor $G_k = 16$. In Figure 5 the solid line corresponds to the true values of σ_u^2 and σ_w^2, the dashed line uses values σ_u^2 and $2\sigma_w^2$, the dotted line uses values $10\sigma_u^2$ and $4\sigma_w^2$, and the dashdotted line uses $5\sigma_u^2$ and $3\sigma_w^2$.

As can be seen from the figure, errors in the values σ_u^2 and σ_w^2 have almost no impact on the final results, and as a consequence no accurate estimation of these parameters are needed.

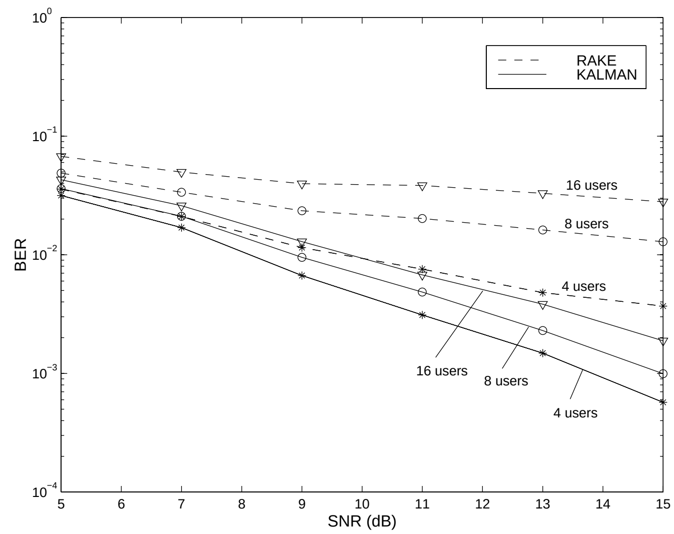

Figure 3: BER as a function of SNR for the Kalman receiver (solid) and the RAKE receiver (dashed) in a 3-path Rayleigh fading channel, spreading factor $G_k = 16$

5. CONCLUSIONS

Kalman filtering equalization was successfully applied to WCDMA chip sequence estimation. This method was found to be particularly suitable for mitigating MAI in downlink communications, for orthogonality between users is restored leading to a simple symbol-detection scheme.

The method does not require a training sequence or the knowledge of other-users' spreading codes, and the estimation is based on the chip sequence corresponding to all active users in the system. Simulations confirming the good performance of the method in different scenarios when compared to the conventional RAKE receiver were presented. Robustness of unknown initialization parameters was also addressed.

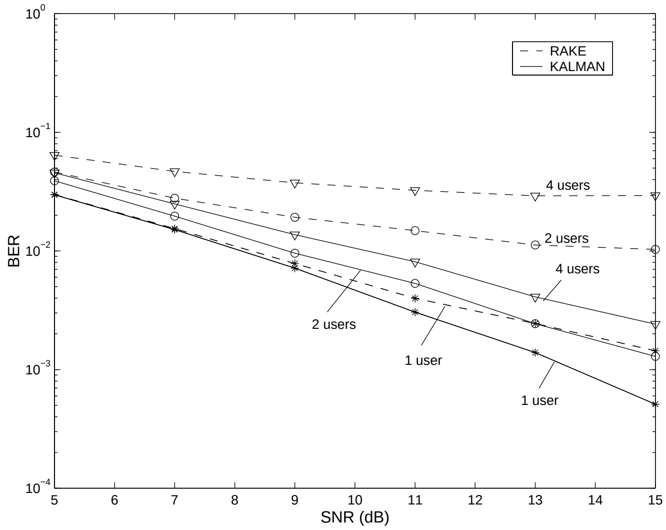

Figure 4: BER as a function of SNR for the Kalman receiver (solid) and the RAKE receiver (dashed) in a 3-path Rayleigh fading channel, spreading factor $G_k = 4$.

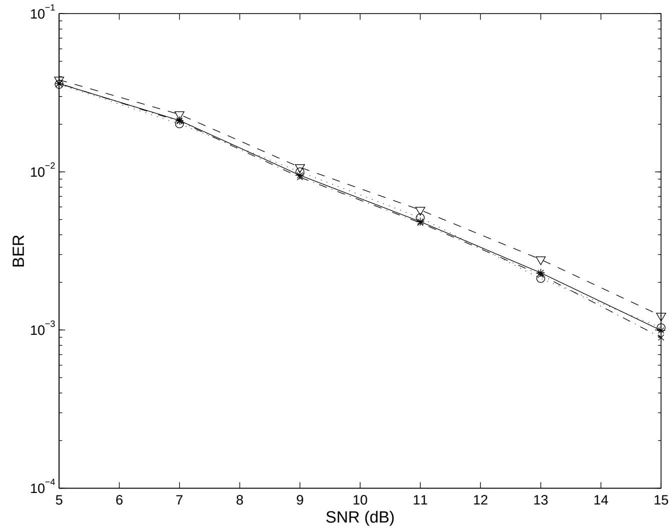

Figure 5: BER as a function of SNR for the Kalman receiver in a 3-path Rayleigh fading channel with incorrect values of σ_u^2 and σ_w^2, spreading factor $G_k = 16$.

6. REFERENCES

[1] M. Latva-aho, *Advanced receivers for wideband CDMA system*, Doctoral thesis, Department of Electrical Engineering, University of Oulu, Finland, 1998.

[2] M. L. Honig, U. Madhow, S. Verdú, "Blind adaptive multiuser detection," *IEEE Transactions on Information Theory*, vol. 41, pp. 944-960, July 1995.

[3] S. L. Miller, "An adaptive direct-sequence code-division multiple access receiver for multiuser interference rejection," *IEEE Transactions on Communications*, vol. 43, pp. 1745-1755, February-April 1995.

[4] G. Woodward, B. S. Vucetic, "Adaptive detection for DS-CDMA," *Proceedings of the IEEE*, vol. 86, no). 7., pp. 1413-1434, July 1998.

[5] T. J. Lim, L. K. Rasmussen, H. Sugimoto, "An asynchronous multiuser CDMA detector based on the Kalman filter," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 9, August 1998.

[6] S. Werner, J. Lilleberg, "Downlink channel decorrelation in CDMA systems with long codes," in *IEEE International Vehicular Technology Conference*, VTC'99, Houston, USA, May 1999.

[7] K. Hooli, M. Juntti, M. Latva-aho, "Inter-path interference suppression in WCDMA systems with low spreading factors," *IEEE International Vehicular Technology Conference*, VTC'99, November 1999.

[8] P. Komulainen, M. Heikkilä, "Adaptive channel equalization based on chip separation for CDMA downlink," *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Vehicular Technology Conference*, PIMRC'99, Osaka, Japan, September 1999.

[9] S. McLaughlin, "Adaptive equalisation via Kalman filtering techniques," *IEE Proceedings F*, vol. 138, no. 4, August 1991.

[10] Third generation partnership project (3GPP), Document 3G TS 25.213 Spreading and modulation (FDD), December 1999.