A HYBRID SIC/PIC DETECTOR BASED ON A REDUCED NETWORK OF KALMAN FILTERS FOR DS-CDMA SYSTEMS OVER MULTIPATH FADING CHANNELS

Bessem SAYADI, Sylvie MARCOS

Laboratoire des Signaux et Systèmes - LSS-CNRS-Supélec
Plateau de Moulon, 91192 Gif sur Yvette, FRANCE
email : {sayadi, marcos}@lss.supelec.fr

ABSTRACT

A Network of Kalman Filters (NKF)-based detector has recently been proposed for joint Multiple Access Interference (MAI) and Inter-Symbols Interference (ISI) compensation in DS-CDMA systems [1][2][3]. It is based on a symbol state space representation of the DS-CDMA system. The NKF-based detector presents an exponential complexity in term of the Kalman filters (Q^K where Q represents the number of points in the symbol constellation and K represents the number of active users in the system). In this paper, we propose to linearize the number of Kalman filters used in the aformentioned structure by combining a hybrid SIC/PIC structure and a reduced Network of Kalman Filters-based on a reduced state space representation of the DS-CDMA system. The proposed structure involves two steps. The first, called *forward* step, decodes the users in a serial approach using a SIC structure. The second, called *backward* step, is based on a hybrid SIC/PIC structure in order to produce better estimates of the transmitted symbols. The new resulting structure based on a reduced *forward-backward* NKF detector employs $2(K-1)Q$ Kalman filters. It exhibits better performances than the well known existing SIC-RAKE receiver especially in channels with a large delay spread.

1. INTRODUCTION

The new generation of wireless systems based on the CDMA technique employs short length spreading codes and allows more mobile users with simultaneous access in order to increase the capacity in terms of the number of users per cell and to allow high data rate multi-media services. Shorter codes, when subjected to a large delay-spread multi-path channels, look more frequency selective, loose their orthogonality and lead to a significant ISI interference. This point, coupled with the growth of the users simultaneously accessing the system, leads to a large MAI interference. In such a case, the conventional RAKE-based receiver suffers a significant performance degradation. This why there is an increasing interest in MUD receivers that mitigate both, MAI and ISI, interferences in order to obtain reliable estimates of transmitted symbols.

Several multiuser receivers with different complexity and performance have been proposed. The optimum multiuser receiver [4] presents a complexity that grows exponentially with the number of users. So, several suboptimal schemes have been investigated. Multi-stage Interference Cancellation (MIC) techniques [5][6][7][8] have been studied extensively due to their low implementational complexity. Linear multiuser receivers [4][9] are another important class of suboptimal receivers that suppress MAI. Recently, a new multiuser detector was proposed in [1][2]. It is based on a state-space estimation techniques used for both uplink or downlink link in frequency selective fading channels. State-space estimation techniques via the application of the classical Kalman filter have been suggested in the past as CDMA multiuser detection [10][11]. Due to the recursive nature of these techniques, they outperform the FIR (Finite Impulse Response) filtering techniques [10][1]. The application of the Kalman filtering approach is based on the assumption of Gaussianity of the observation and state noises [12]. This is not valid, in our case, since the state noise is related to the transmitted symbols of the users. In [1][2][3], it is shown that by approximating the *a posteriori* pdf by a Weighted Sum of Gaussian (WSG) density functions [13][1], where each Gaussian term parameters are adjusted using one Kalman filter, the resulted MUD detector is structured into a Network of Kalman Filters (NKF). The NKF detector cancels jointly the MAI and ISI interferences and it is near far resistant [1][3]. However, the NKF-based detector decodes all the users jointly and therefore its complexity grows exponentially with the number of users.

In this paper, we propose, a novel approach that we call the hybrid structure based on a reduced Network of Kalman Filters. The new proposed algorithm, first, decodes the users in a serial approach. The SIC structure is chosen because of its relatively low complexity and suitability for hardware implementation. The most difference between the well known SIC-RAKE structure [7][8] consists of the nature of the used Interference Cancellation Unit (ICU). Therefore, it is clear that to obtain better performances, careful attention must be taken in the dealing of the ICU. Here, a reduced Network of Kalman filters is used as ICU because it is able to cancel jointly the MAI and ISI interferences. Second, we also propose to use a feedback based on a hybrid PIC/SIC structure in order to optimize further the estimates of the transmitted symbols. The proposed hybrid approach can incorporate, instead of a reduced NKF, the classical Kalman filter ignoring the numeric character of the transmitted symbols or a FIR-MMSE detector [6]. The resulted structure called *forward backward* structure presents two principals advantages. First, it improves the performances over the SIC-RAKE structure [7][8]. Second, it reduces the complexity of the NKF detector published in [1] and linearizes the number of Kalman filters employed in the structure.

The outline of this paper is as follows. Section 2 presents the reduced state-space description of the multiple-access system as a multiple-input multiple-output linear system. Section 3 presents the structure of the proposed detector. Section 4 gives some Monte Carlo simulation results for the analysis of the performance of the proposed structure. Finally, section 5 draws some concluding remarks.

2. REDUCED STATE-SPACE MODEL OF THE MULTIUSER CDMA SYSTEM

The CDMA system can fit the Kalman model exactly or approximately in terms of the measurement equation and the state transition equation. In this section, we reduce the state space model of the CDMA system presented in [1] which allows us to highlight the impact of ISI on the received signal and also to have an estimate of the user's symbols at the symbol rate.

Consider a baseband digital DS-CDMA system of K active users. Let us denote by $d_k(m)$ the symbol of the k^{th} user belonging to a finite set $\Omega = \{d_i, i = 1, \ldots, Q\}$ where Q is the number of points in the signal constellation ($Q = 2$ for BPSK modulation) and transmitted in the time interval $[mT_s, (m+1)T_s[$ where T_s represents the symbol period. Let us introduce $\mathbf{c}_l = [c_l(0), \ldots, c_l(L-1)]^T$ as the spreading code of user l. L is the processing gain.

In [1], we show that by concatenating the received signal sampled at the chip rate, $r(k)$, in a vector $\mathbf{r}(k) = [r(kL), \ldots, r(kL+L-1]^T$, we can write,

$$\begin{aligned}
\mathbf{r}(k) &= \mathbf{A}(k)\mathbf{d}(k) + \mathbf{b}(k) \qquad (1)\\
\mathbf{A}(k) &= [\mathbf{G}(0), \ldots, \mathbf{G}(\tilde{k}-1)]\\
\mathbf{G}(p) &= [\mathbf{g}_1(p), \ldots, \mathbf{g}_K(p)]\\
\mathbf{g}_i(p) &= [\tilde{g}_i(pL), \ldots, \tilde{g}_i(pL+L-1)]^T, i = 1, \ldots, K\\
\mathbf{d}(k) &= [\mathbf{x}(k)^T, \ldots, \mathbf{x}(k-\tilde{k}+1)^T]^T\\
\mathbf{x}(k) &= [d_1(k), \ldots, d_K(k)]^T\\
\mathbf{b}(k) &= [b(kL), \ldots, b(kL+L-1)]^T
\end{aligned}$$

where $\tilde{g}_i(p), i = 1, \ldots, K$, is the result of the convolution between the code sequence $\mathbf{c}_k$ and the i^{th} user channel coefficients taken at the chip rate. $b(k)$ is a white Gaussian noise with zero mean and power spectral density σ_n^2. $\tilde{k} = \lceil \frac{P+L-1}{L} \rceil$, where P is the maximum delay of the paths of the channel, is the number of interfering symbols in the system.

By applying a permutation matrix over the column of matrix $\mathbf{A}(k)$ and over the line of the global vector $\mathbf{d}(k)$ in order to bring together the symbol of the same user l in the same sub-vector, the received signal $\mathbf{r}(k)$ can be written as follows:

$$\begin{aligned}
\mathbf{r}(k) &= \mathbf{A}_p(k)\mathbf{d}_p(k) + \mathbf{b}(k) \qquad (2)\\
&= \sum_{l=1}^{K} \mathbf{A}_{p,l}(k)\mathbf{x}_{p,l}(k) + \mathbf{b}(k) \qquad (3)
\end{aligned}$$

where $\mathbf{A}_p(k) = \begin{bmatrix} \mathbf{A}_{p,1}(k) & \mathbf{A}_{p,2}(k) & \cdots & \mathbf{A}_{p,K}(k) \end{bmatrix}$ is $L \times K\widetilde{k}$ matrix, $\mathbf{d}_p(k) = \left[\mathbf{x}_{p,1}^T(k)\ \mathbf{x}_{p,2}^T(k)\ \ldots\ \mathbf{x}_{p,K}^T(k)\right]^T$ is $K\widetilde{k} \times 1$ vector, and $\mathbf{x}_{p,l}(k) = \left[d_l(k)\ d_l(k-1)\ \ldots\ d_l(k-\widetilde{k}+1)\right]^T$ is $K \times 1$ vector with $l = 1, \ldots, K$. $\{\mathbf{A}_{p,l}(k)\}_{l=1,\ldots,K}$ are matrices of dimension $L \times \widetilde{k}$, obtained by selecting the columns from the matrix $\mathbf{A}(k)$ corresponding to the l^{th} user symbols. We denote $\mathbf{d}_p(k)$ the permuted $\mathbf{d}(k)$ vector.

The idea, now, is to run a reduced NKF detector in order to estimate the l^{th} user symbols, i.e. $\mathbf{x}_{p,l}(k)$, instead of estimating the global state vector $\mathbf{d}_p(k)$ as is done in [1]. So we propose to modify the Interference Cancellation Unit used in the RAKE-SIC or in the hyrid MMSE-SIC schemes by incorporating a reduced NKF detector based on Q Kalman filters working in parallel. So we propose the following proposed reduced state-space representation,

$$\left\{ \begin{array}{l} \mathbf{x}_{p,l}(k) = \mathbf{F}_p\mathbf{x}_{p,l}(k-1) + \mathbf{g}_p d_l(k) \\ \mathbf{r}(k) = \mathbf{A}_{p,l}(k)\mathbf{x}_{p,l}(k) + \sum\limits_{i=1, i\neq l}^{K} \mathbf{A}_{p,i}(k)\mathbf{x}_{p,i}(k) + \mathbf{b}(k) \end{array} \right. \qquad (4)$$

where $\mathbf{F}_p$ is a one shift matrix,

$$\mathbf{F}_p = \begin{pmatrix} 0 & 0 & \cdots & \cdots & 0 \\ 1 & 0 & \ddots & \ddots & \vdots \\ \vdots & \ddots & 0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & \cdots & 1 & 0 \end{pmatrix}_{\widetilde{k} \times \widetilde{k}} \quad \text{and} \quad \mathbf{g}_p = \begin{pmatrix} 1 \\ 0 \\ \vdots \\ \vdots \\ 0 \end{pmatrix}_{\widetilde{k} \times 1}$$

Equation (4) represents a reduced state-space of the CDMA system where the state vector, now, contains the symbols of the desired user, l, where $l = 1 \ldots K$.

3. PROPOSED DETECTOR

In this section, we introduce our proposed hybrid detector that involves two steps.

3.1. *Forward* step

The NKF detector presents many advantages [1]. It is a recursive algorithm and it performs much better than the RAKE detector, the classical FIR-MMSE, the Decision Feedback Equalizer (DFE) detector and the Kalman detector [3]. For these reasons, we have chosen the reduced NKF detector as ICU. The *forward* step employs a SIC structure as is proposed in [6]. Suppose that $(i-1)$ users have been decoded. So we suppose to have the estimation of the sub-vectors $\mathbf{x}_{p,1}(k|k), \cdots, \mathbf{x}_{p,i-1}(k|k)$. For further readings, please refer to [3][1] for more details on the NKF algorithm and all the related developments. By applying the SIC approach, we will generate the interference caused by the last decoded (1,..., $i-1$) users in order to substract it from the received signal in order to decode the i^{th} user,

$$\begin{aligned}
\widehat{\mathbf{r}}_i(k) &= \mathbf{r}(k) - \underbrace{\sum_{l=1}^{i-1} \mathbf{A}_{p,l}(k)\mathbf{x}_{p,l}(k|k)}_{\text{regenerated interference}} \qquad (5)\\
&= \mathbf{A}_{p,i}(k)\mathbf{x}_{p,i}(k) + \underbrace{\sum_{l=i+1}^{K} \mathbf{A}_{p,l}(k)\mathbf{x}_{p,l}(k) + \mathbf{b}(k)}_{\mathcal{D}(k)}
\end{aligned}$$

The MMSE estimate of the i^{th} user symbol, $E(\mathbf{x}_{p,i}(k)|\mathbf{x}_{p,1}(k|k), \cdots, \mathbf{x}_{p,i-1}(k|k), \mathbf{R}^k)$, where $\mathbf{R}^k$ is the collected observation until time k, is obtained from a reduced Network of Kalman Filters based on Q Kalman filters working in parallel, which takes into account the non Gaussianity of the state noise (see equation (4)). It approximates the *a posteriori* pdf $p(\mathbf{x}_{p,i}(k)|\mathbf{R}^k)$ by a WSG as is described in [1]. We note that it is reasonable to approximate the $\mathcal{D}(k)$ term as a white Gaussian noise. The output of the i^{th} ICU, denoted by $\mathbf{x}_{p,i}(k|k)$, is a convex combination of the output of Q

Kalman filters. It can be written as,

$$\begin{aligned}\mathbf{x}_{p,i}(k|k) &= \sum_{q=1}^{Q}\alpha_{i,q}(k)\left[\mathbf{x}_{p,i}^{q}(k|k-1)\right. \quad (6)\\ &\left. +\mathbf{K}_q(k)\widehat{\mathbf{e}}_{p,i}^{q}(k|k-1)\right]\\ \widehat{\mathbf{e}}_{p,i}^{q}(k|k-1) &= \widehat{\mathbf{r}}_i(k)-\mathbf{A}_{p,i}(k)\mathbf{x}_{p,i}^{q}(k|k-1) \quad (7)\\ \mathbf{x}_{p,i}^{q}(k|k-1) &= \mathbf{F}_p\mathbf{x}_{p,i}(k-1|k-1)+\mathbf{g}_p d_q \quad (8)\end{aligned}$$

where the subscript i denotes the user index and the subscript p denotes the permuted vector.
The weight coefficients $\alpha_{i,q}(k)$ are obtained as follows,

$$\alpha_{i,q}(k) \propto \exp\left(-\frac{1}{2}\left(\widehat{\mathbf{e}}_{p,i}^{q}(k|k-1)\right)\mathbf{\Omega}_i^q(k|k-1)^{-1}\left(\widehat{\mathbf{e}}_{p,i}^{q}(k|k-1)\right)^T\right)$$

where $\mathbf{\Omega}_i^q(k|k-1)$, given by equation (9), is the predicted error covariance matrix. By supposing the independency between the symbols and the noise and by supposing, also, that the symbols are i.i.d, $\mathbf{\Omega}_i^q(k|k-1)$ can be written as follows,

$$\begin{aligned}\mathbf{\Omega}_i^q(k|k-1) &= \mathbf{A}_{p,i}(k)\mathbf{P}_i^q(k|k-1)\mathbf{A}_{p,i}(k)^T \quad (9)\\ &+\textstyle\sum_{l=1}^{i-1}\mathbf{A}_{p,l}(k)\mathbf{P}^l(k|k)\mathbf{A}_{p,l}(k)^T+\\ &\textstyle\sum_{l=1,j=1,\, j\neq l}^{i}\mathbf{A}_{p,l}(k)\mathbf{P}^{l,j}(k|k)\mathbf{A}_{p,j}(k)^T\\ &+\textstyle\sum_{l=i+1}^{K}\mathbf{A}_{p,l}(k)\mathbf{A}_{p,l}(k)^T+\sigma^2\mathbf{I}_L\end{aligned}$$

where
$\mathbf{P}_i^q(k|k-1) =$
$E[\left(\mathbf{x}_{p,i}(k)-\mathbf{x}_{p,i}^q(k|k-1)\right)\left(\mathbf{x}_{p,i}(k)-\mathbf{x}_{p,i}^q(k|k-1)\right)^T|\mathbf{R}^{k-1}]$ presents the prediction error covariance matrix of the reduced state vector $\mathbf{x}_{p,i}(k)$. The estimation covariance matrix is denoted by $\mathbf{P}^l(k|k)=E[\left(\mathbf{x}_{p,l}(k)-\mathbf{x}_{p,l}(k|k)\right)\left(\mathbf{x}_{p,l}(k)-\mathbf{x}_{p,l}(k|k)\right)^T|\mathbf{R}^k]$.
And, $\mathbf{P}^{l,j}(k|k) =$
$E[\left(\mathbf{x}_{p,l}(k)-\mathbf{x}_{p,l}(k|k)\right)\left(\mathbf{x}_{p,j}(k)-\mathbf{x}_{p,j}(k|k)\right)^T|\mathbf{R}^k]$ presents the inter-covariance of the error on the estimation of $\mathbf{x}_{p,l}(k)$ and $\mathbf{x}_{p,j}(k)$.
Since the global state vector, $\mathbf{d}_p(k)$, contains independents components (the symbols are i.i.d.), it is then reasonable to expect that the estimation covariance matrix is a diagonal matrix [3]. Therefore, the off-diagonal terms can be neglected, i.e. $\mathbf{P}^{l,j}(k|k)\simeq\mathbf{0}_{\tilde{k}}$, $l\neq j$. So, $\mathbf{\Omega}_i^q(k|k-1)$ can be approximated as follows,

$$\begin{aligned}\mathbf{\Omega}_i^q(k|k-1) &\simeq \mathbf{A}_{p,i}(k)\mathbf{P}_i^q(k|k-1)\mathbf{A}_{p,i}(k)^T+ \quad (10)\\ &\textstyle\sum_{l=1}^{i-1}\mathbf{A}_{p,l}(k)\mathbf{P}^l(k|k)\mathbf{A}_{p,l}(k)^T+\\ &\textstyle\sum_{l=i+1}^{K}\mathbf{A}_{p,l}(k)\mathbf{A}_{p,l}(k)^T+\sigma^2\mathbf{I}_L\end{aligned}$$

It is clear that $\mathbf{\Omega}_i^q(k|k-1)$ depends on the estimation covariance matrices of the last decoded users since the reduced state vector, $\mathbf{x}_{p,i}(k)$, is estimated from a signal partially cleaned from the $(i-1)$ previous decoded users. Therefore, it is obvious that this procedure takes into account the error propagation phenomenon.
In the same manner, the corresponding Kalman gain can be approximated as follows

$$\mathbf{K}_q(k)\simeq\mathbf{P}_i^q(k|k-1)\mathbf{A}_{p,i}(k)^T\mathbf{\Omega}_i^q(k|k-1)^{-1} \quad (11)$$

and the estimation error covariance matrix for every Kalman filter in the NKF detector is approximated as follows,

$$\begin{aligned}\mathbf{P}_i^q(k|k) &\simeq \left(\mathbf{I}_{\tilde{k}}-\mathbf{K}_q(k)\mathbf{A}_{p,i}(k)\right)\mathbf{P}_i^q(k|k-1) \quad (12)\\ \mathbf{P}_i^q(k|k-1) &= \mathbf{F}_q\hat{\mathbf{P}}(k-1|k-1)\mathbf{F}_q^T+\mathbf{Q}_q \quad (13)\end{aligned}$$

where $\mathbf{Q}_q=\varepsilon\mathbf{I}_{\tilde{k}}$, $\varepsilon\ll 1$.

3.2. *Backward* step

After the first step, it is clear that the last decoded user, user K, benefits from a strong interference cancellation since its estimation is obtained from a signal cleaned from the interference of all the other users, for 1 to $K-1$. So, we propose in order to further optimize the estimates of the transmitted symbols obtained from the first step (or stage) to incorporate a second stage based on a hybrid PIC/SIC structure which uses the most up-to-date symbol estimate. This constrasts with the standard PIC detector, which only uses the previous stage's estimation.
Since we have the estimation of all the symbol's users, we propose to exploit the last decoded symbol, $\mathbf{x}_{p,K}(k|k)$, to improve the last symbol estimate of the $(K-1)^{th}$ user, $\mathbf{x}_{p,K-1}(k|k)$ and so on in a *backward* manner. First, the *backward* step reestimates the symbol of user $(K-1)$. We regenerate the interference caused by all the interfering users: for 1 to $K-2$ and K. Second we substract it from the received signal as follows,

$$\widehat{\mathbf{r}}_{K-1}(k)=\mathbf{r}(k)-\Upsilon_{1,\ldots,K-2,K}$$

where
$\Upsilon_{1,\ldots,K-2,K}=\sum_{l=1}^{K-2}\mathbf{A}_{p,l}(k)\mathbf{x}_{p,l}(k|k)-\mathbf{A}_{p,K}(k)\mathbf{x}_{p,K}(k|k)$ is the regenerated interference. The new symbol estimate of the $(K-1)$ user is obtained from a reduced NKF presented in the last section. The only difference, now, is that the prediction covariance matrix $\mathbf{\Omega}_{K-1,q}(k|k-1)$ takes into account all the estimated covariance matrices. So, $\mathbf{\Omega}_{K-1,q}(k|k-1)$ can be approximated by,

$$\begin{aligned}\mathbf{\Omega}_{K-1,q}(k|k-1) &\simeq \mathbf{A}_{p,K-1}(k)\mathbf{P}_{K-1}^q(k|k-1)\mathbf{A}_{p,K-1}(k)^T+ \quad (14)\\ &\textstyle\sum_{l=1}^{K-2}\mathbf{A}_{p,l}(k)\mathbf{P}^l(k|k)\mathbf{A}_{p,l}(k)^T+\\ &\mathbf{A}_{p,K}(k)\mathbf{P}_K^q(k|k)\mathbf{A}_{p,K}(k)^T+\sigma^2\mathbf{I}_L\end{aligned}$$

The new estimate of the symbol of the $(K-1)^{th}$ user is the output of the reduced NKF detector denoted by $\mathbf{x}_{p,2}^{K-1}(k|k)$. The new estimation error covariance matrix is denoted $\mathbf{P}_K^2(k|k)$. In a serial approach, we transpose the same mechanism to reestimate the other users: $K-2$ to 1. It is clear that the proposed *feedback* employs a PIC structure since we regenerate the interference caused by all the users and a SIC structure since we reestimate the user successively $(K-1, K-2,\ldots 1)$.
The detailed structure is shown in Figure 1 where the ICU, chosen here as a reduced NKF detector, can be replaced by a classical Kalman filter ignoring the numeric character of the transmitted symbol or a FIR-MMSE detector as is proposed in [6]. We remark that the number of the employed Kalman filters is $(2K-1)Q$. It is obvious that the proposed structure simplifies the NKF-based detector published in [1].

4. SIMULATION RESULTS

We consider a synchronous DS-CDMA system transmitting over a frequency selective Rayleigh fading channel. It is chosen to be the simplified $BRAN\ A$ channel generally employed in the Hyperlan2 norm. We present some simple numerical results which illustrate the potential of the proposed approach as an effective tool for improving the performance of the well known SIC-RAKE structure [7][8] over a multipath channel. We consider the performance of a system with 3 users, $K=3$. The users signatures are

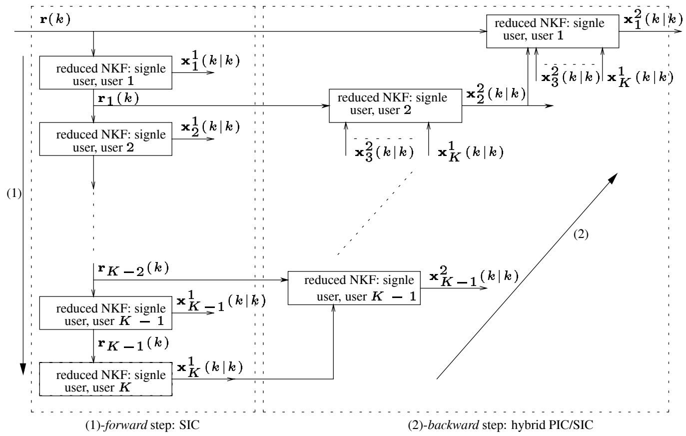

Fig. 1. Block scheme of the proposed hybrid SIC/PIC structure based on a reduced NKF.

Gold sequences of length $L = 7$. It is assumed that the channel do not changes during the transmission of bursts of 256 symbols. A BPSK modulation is employed, so, $Q = 2$. The channel has 9 Rayleigh paths. So we have a severe ISI interference since we have 3 interfering symbols on a symbol window. We employ a delay of 2 symbols for the estimation.

Figure 2 shows the BER performance of user 2 assuming the same Signal to Noise Ratio for all users. We plot the performance of the proposed approach, the SIC-RAKE structure , the original NKF published in [1] and the proposed hybrid structure employing a classical Kalman filter. We remark, that the performance of the

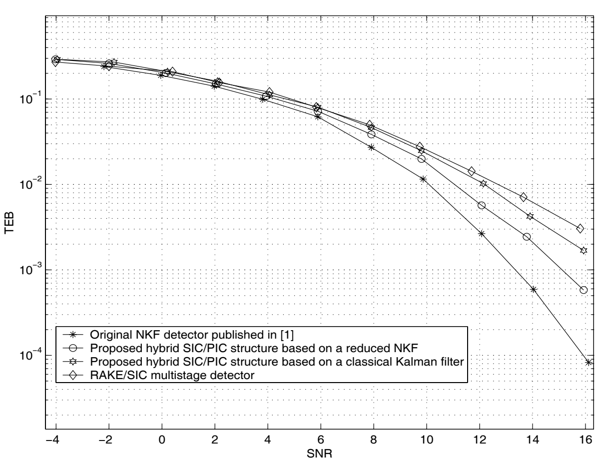

Fig. 2. Performances of the proposed hybrid structure based on a reduced NKF compared to the RAKE/SIC multistage structure [7][8], the proposed hybrid structure based on a classical Kalman filter and the original NKF proposed in [1].

system are improved compared to the performance obtained from the SIC-RAKE receiver. Also, we show that the good modelization of the state noise, $\mathbf{g}_p d_l(k)$, by a Weighted Sum of Gaussian terms improves the performances of the classical Kalman filter ignoring the numeric character of the state noise.

5. CONCLUSION

In this paper, we have shown that the proposed hybrid structure reduces the complexity of the NKF-based detector proposed in [1] and alleviates efficiently the MAI and ISI interferences for a transmission over a multipath fading channel with long spread delay. A significant system capacity improvement can be achieved compared to the conventional DS-CDMA system receiver or to the SIC-RAKE cancellation strategy which exploits the diversity introduced by the multipath channel. The proposed structure can be optimized for real time implementation since the Interference Cancellation Unit is based on a recursive algorithm.

6. REFERENCES

[1] B. Sayadi and S. Marcos, “A network of Kalman filters based detector for joint MAI and ISI suppression in asynchronous DS-CDMA systems,” *IEEE International Symposium on Spread Spectrum Techniques and Applications, ISSSTA02*, vol. 2, pp. 511–515, Prague, Sept 2002.

[2] B. Sayadi and S. Marcos, “Robust equalization based on a network of Kalman filters in impulsive noise environments,” *ICASSP 03*, vol. 5, pp. 37–40, Hong Kong, May 2003.

[3] B. Sayadi, *A Network of Kalman Filters as multiuser detector for DS-CDMA systems*, Ph.D. thesis, Paris Sud university, France, Dec 2003.

[4] S. Verdu, *Multiuser Detection*, Cambridge, 1998.

[5] S. Moshavi, “Multi-user detection for DS-CDMA communications,” *IEEE communications magazine*, pp. 124–136, October 1996.

[6] C. Tsai, W. Fang, and J. Chen, “Hybrid MMSE and SIC for multiuser detection,” *Vehicular Technology Conference*, vol. 3, pp. 1779–1783, May 2001.

[7] M. Ammar, T. Chonavel, and S. Saoudi, “Multi-stage SIC structure for uplink UMTS multiuser receiver over multipath Rayleigh channels,” *Vehicular Technology Conference, VTC spring*, vol. 4, pp. 2514–2518, May 2001.

[8] M. Ammar, T. Chonavel, and S. Saoudi, “Asynchronous multi-stage SIC detector for DS-CDMA systems over multipath fading channels,” *IEEE third workshop on Signal Processing Advances in Wireless Communications*, pp. 190–193, March 2001.

[9] R. Lupas and S. Verdu, “Linear multiuser detector for synchronous code-division multiple-access channels,” *IEEE trans on information theory*, vol. 35, pp. 123–136, January 1989.

[10] T.J. Lim and Y. Ma, “The Kalman filter as the optimal minimum mean-squared error multiuser CDMA detector,” *IEEE Transactions on information theory*, vol. 46, No 7, pp. 2561–2566, November 2000.

[11] J. Thielecke, “A state-space multiuser detector for CDMA systems,” *IEEE International Conference on communications*, vol. 3, pp. 1762 –1767, May 1993.

[12] E.W. Kalman and J.K. Su, *Introduction to Optimal Estimation*, Springer, Sept 1999.

[13] D.L. Alspach and H.W. Sorenson, “Nonlinear Bayesian estimation using gaussian sum approximation,” *IEEE Trans. on Automatic Control*, vol. 17, Aug. 1972.