PIPELINED ADAPTIVE CDMA MOBILE RECEIVERS

Ramin Baghaie and Stefan Werner

Helsinki University of Technology
Laboratory of Telecommunications Technology
P.O. BOX 3000, 02015 HUT, FINLAND
Email: {ramin.baghaie, stefan.werner}@hut.fi

ABSTRACT

Adaptive multiple-antenna receivers can provide insensitivity to the interfering powers and room for more users or they require smaller number of antennas compared to the matched filter solution. In this paper, pipelined implementation of an adaptive Direct-Sequence Code Division Multiple Access receiver is proposed when multiple antennas are utilized for mobile communications. A number of approximation techniques are utilized to pipeline the Recursive Least-Squares (RLS) algorithm used for the receiver. The resulting pipelined structure achieves a higher throughput or requires lower power as compared to the receiver using the conventional serial RLS algorithm. As a result of pipelining, the hardware overhead is only 2*M* extra latches. For different number of antennas and different levels of pipelining the signal-to-interference versus the relative interfering power are illustrated.

1. INTRODUCTION

Pipelined DSP algorithms allow us to tradeoff speed, power and area during the course of VLSI implementation. Reductions in power or area are of great importance when implementing mobile communication systems. Although applying pipelining to algorithms without feedback is rather simple, pipelining of DSP algorithms having a feedback loop is not a trivial task. Inserting latches to pipeline the recursive loop of such algorithms is only useful when execution of multiple interleaved independent data is of interest. This however, will not improve the iteration bound of such algorithms. That is why various algorithm transformation techniques such as the Look-Ahead (LA) and the Relaxed Look-Ahead (RLA) have already been proposed for the pipelining of recursive DSP [1-5]. These transformations introduce additional concurrency in a serial algorithm at the expense of hardware overhead.

The look-ahead technique has been successfully applied to a number of such algorithms [1]. The LA technique, however, results in a large hardware overhead as it transforms a serial algorithm into an equivalent pipelined algorithm. This equivalency is in terms of the input-output behavior [1-3]. The RLA technique involves in approximating the algorithms obtained via the look-ahead technique. Through these approximations, this technique maintains functionality of the algorithm rather than the input-output behavior.

A number of approximations such as sum, product and delay relaxation are possible and each result in a different algorithm. Depending on the approximations, there may be a performance degradation. Despite this fact, in many applications the performance loss can be rather insignificant [1,5].

Unlike the LA technique, application of the RLA technique modifies the original algorithm. Therefore, convergence analysis of the new pipelined algorithm is necessary. Sometimes, this analysis can be cumbersome. Despite of this, hardware overhead of the resulting pipelined algorithm is considerably less as compared to the conventional LA technique. In addition to this, it has also a higher throughput compared to the serial algorithm [1]. This increase of throughput can be exchanged for either reducing power or reducing the chip area. Area reduction can be achieved in combination with the folding transformation [1]. Power reduction, however, can be done in combination with power supply scaling [6,7].

In [5], pipelined implementation of an adaptive Direct-Sequence Code Division Multiple Access (DS-CDMA) receiver with multiple antennas for downlink was reported. In that work, pipelined implementation of the Least-Mean-Square (LMS) algorithm was investigated. It was shown that due to the higher misadjustment, as the number of pipelining stages increases the signal-to-interference ratio (SIR) will decrease.

In this paper, we investigate the implementation of the pipelined Recursive Least-Squares algorithm by utilizing the Relaxed Look-Ahead technique and compare the result with the conventional serial algorithm. This paper is organized as follows. In Section 2, multiple-antenna CDMA receivers are discussed. Section 3 deals with different aspects of the pipelined implementation of the adaptive receiver. In Section 4, simulation results are reported, and conclusions are given in the last section.

2. MULTIPLE-ANTENNA CDMA RECEIVER

Downlink receivers in DS-CDMA communication systems were studied in [8]. In that work, by including multiple antennas and also employing adaptive algorithms the idea in [9] was generalized. Figure 1 illustrates the structure of their linear receiver equipped with N antennas [8].

In the receiver of Figure 1, each of the N antenna branches contains a linear filter whose coefficients are to be optimized. The filtered signals from each antenna are then added together to form a decision variable.

In Figure 1, $\mathbf{r}_i$ denotes the received signal after chip-matched filtering at antenna i, $\mathbf{h}_i$ contains the complex filter coefficients for the ith antenna, and z is the decision variable formed by adding the filtered outputs from each antenna. The filter coefficients and the received sequences from the antennas are collected in vectors as:

$$\mathbf{h} = \left[\mathbf{h}_1^{\mathrm{T}} \ldots \mathbf{h}_N^{\mathrm{T}}\right]^{\mathrm{T}} \tag{1}$$

$$\mathbf{r} = \left[\mathbf{r}_1^{\mathrm{T}}\ \mathbf{r}_2^{\mathrm{T}} \ldots \mathbf{r}_N^{\mathrm{T}}\right]^{\mathrm{T}} \tag{2}$$

By using Eqs. (1) and (2), the output from the receiver can be written as:

$$z = \mathbf{h}^{\mathrm{H}}\mathbf{r} \tag{3}$$

The goal is to find the filter $\mathbf{h}$ such that the output is minimized under the constraints that the desired user's code sequence in every antenna can pass undistorted. Thus, minimization problem can be formulated as [8]:

$$\hat{\mathbf{h}} = \arg\min_{\mathbf{h}} E\left\{|z|^2\right\} \tag{4}$$

$$\text{subject to:}\quad \mathbf{C}^{\mathrm{H}}\mathbf{h} = \mathbf{u}$$

where matrix $\mathbf{C}$ and vector $\mathbf{u}$ are:

$$\mathbf{C} = \begin{bmatrix} a_1\mathbf{s}_{1,1} & 0 & \cdots & 0 \\ 0 & a_2\mathbf{s}_{1,2} & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & a_N\mathbf{s}_{1,N} \end{bmatrix} \tag{5}$$

$$\mathbf{u} = \left[|a_1|^2\ |a_2|^2 \ldots |a_N|^2\right]^{\mathrm{T}} \tag{6}$$

where $\mathbf{s}_{1,i}$ is the code sequence with length G and a_i is the complex phase factor of the desired user at the antenna element. The solution to this problem is found by the method of Lagrange multipliers, see, e.g., [10]:

$$\mathbf{h}_{\text{opt}} = \mathbf{R}^{-1}\mathbf{C}\left[\mathbf{C}^{\mathrm{H}}\mathbf{R}^{-1}\mathbf{C}\right]^{-1}\mathbf{u} \tag{7}$$

where $\mathbf{R}$ is the correlation matrix. The closed-form solution of Equation (4) is not suitable in practice, as we need to estimate the correlation matrix and perform an inversion. Thus, an adaptive implementation of the detector is considered.

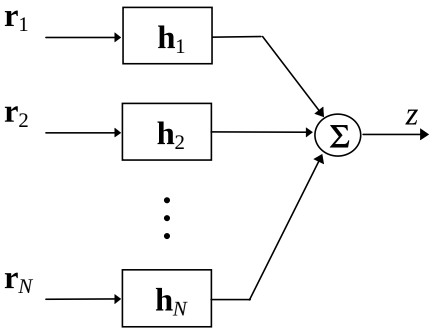

Figure 1. Structure of the linear receiver of [8].

In this paper, the structure of the generalized sidelobe canceler [10] which transforms a constrained problem into an unconstrained problem by means of an orthogonal decomposition of $\mathbf{h}$ is used. The main reason for doing this is that simpler algorithms can be applied. The idea is to divide the weight vector $\mathbf{h}$ into two parts as:

$$\mathbf{h} = \mathbf{h}_q - \mathbf{C}_a\mathbf{h}_a \tag{8}$$

where $\mathbf{h}_q$ is a fixed vector satisfying the constraint equations, $\mathbf{C}_a$ is a GN×(GN-N) matrix and $\mathbf{h}_a$ is an adaptive filter of dimension (GN-N)×1, and it is unaffected by the constraints. By choosing:

$$\mathbf{h}_q = \mathbf{C}(\mathbf{C}^{\mathrm{H}}\mathbf{C})^{-1}\mathbf{u} \tag{9}$$

and finally by defining:

$$\mathbf{x} = \mathbf{C}_a^{\mathrm{H}}\mathbf{r} \tag{10}$$

$$d = \mathbf{h}_q^{\mathrm{H}}\mathbf{r} \tag{11}$$

we can apply the RLS adaptive implementation for the update of the vector $\mathbf{h}_a$ [10].

3. IMPLEMENTATION OF THE PIPELINED RECEIVER

In this section, we investigate implementation of the pipelined receiver by utilizing the RLA technique and results are compared with those obtained from the conventional algorithm.

3.1. Previous Work

In [5], pipelined implementation of the LMS algorithm for multiple-antennas adaptive mobile receivers was investigated. It was shown that as the number of pipelining stages increases, the signal-to-interference ratio (SIR) will decrease. This was due to the higher misadjustment as a result of the RLA approximations. However, this decrease of SIR was rather high as the relative powers of interfering users increased. In addition to the above mentioned facts, despite the simplicity of the LMS algorithm, as can be seen from Figure 2, its convergence speed is rather slow as compared to the RLS algorithm. This can not be tolerated in many applications and mobile communications is no exception.

3.2. Pipelined RLS Implementation of the Receiver

In this section, pipelined implementation of the RLS algorithm is discussed. Consider the RLS algorithm of Equations (12) to (15) [10]:

$$\mathbf{k}(k) = \frac{\lambda^{-1}\mathbf{P}(k-1)\mathbf{x}(k)}{1+\lambda^{-1}\mathbf{x}^{\mathrm{H}}(k)\mathbf{P}(k-1)\mathbf{x}(k)} \tag{12}$$

$$\alpha(k) = d(k) - \mathbf{h}_a^{\mathrm{H}}(k-1)\mathbf{x}(k) \tag{13}$$

$$\mathbf{h}_a(k) = \mathbf{h}_a(k-1) + \mathbf{k}(k)\alpha^*(k) \tag{14}$$

$$\mathbf{P}(k) = \lambda^{-1}\Big[\mathbf{P}(k-1) - \mathbf{k}(k)\mathbf{x}^{\mathrm{H}}(k)\mathbf{P}(k-1)\Big] \tag{15}$$

Assuming that input $\mathbf{x}(k)$ varies slowly over M samples and $\lambda \approx 1$, by applying the M-step look-ahead and a series of approximations to Equations (12) - (15) we have [1]:

$$\mathbf{k}(k) = \frac{\lambda^{-1}\mathbf{P}(k-M)\mathbf{x}(k)}{\frac{1}{M}+\lambda^{-1}\mathbf{x}^{\mathrm{H}}(k)\mathbf{P}(k-M)\mathbf{x}(k)} \tag{16}$$

$$\alpha(k) = d(k) - \mathbf{h}_a^{\mathrm{H}}(k-M)\mathbf{x}(k) \tag{17}$$

$$\mathbf{h}_a(k) = \mathbf{h}_a(k-M) + \mathbf{k}(k)\alpha^*(k) \tag{18}$$

$$\mathbf{P}(k) = \lambda^{-1}\Big[\mathbf{P}(k-M) - \mathbf{k}(k)\mathbf{x}^{\mathrm{H}}(k)\mathbf{P}(k-M)\Big] \tag{19}$$

For $M = 1$, Eqs. (16) - (19) represent the conventional serial RLS algorithm of Eqs. (12) - (15). Equations (16) to (19) describe the pipelined-RLS algorithm. Through these approximations, the functionality of the algorithm has been maintained. However, the input-output behavior of the Equations (12) to (15) has been altered. As a result of utilizing these relaxation techniques, both the convergence speed and the misadjustment of the new pipelined RLS algorithm should be analyzed. This problem has been addressed in [1] and it was shown that the misadjustment in the case of the pipelined RLS algorithm is the same as in the serial case. However, the convergence speed is M times slower. Although, the slower convergence rate could be considered as a disadvantage, one can stop the updating process after a certain number of iterations. As a result of this and the approximations used to derive Eqs. (16) to (19), the performance may degrade. Usually this means a slight increase in the mean-squared error. Simulation results of Section 4 illustrate that in the context of our application, for a moderate M the performance loss is rather small.

3.3. Hardware Overhead

By examining Equations (16) to (19), one can easily conclude that the hardware overhead of the pipelined RLS algorithm as a result of the RLA technique is only 2M latches. These extra latches are introduced in the recursive loops of $\mathbf{P}$ and $\mathbf{h}_a$. This is rather good in comparison with [5], in which as a result of applying the RLA to the LMS algorithm, (M-1) extra adders and latches per filter tap were required.

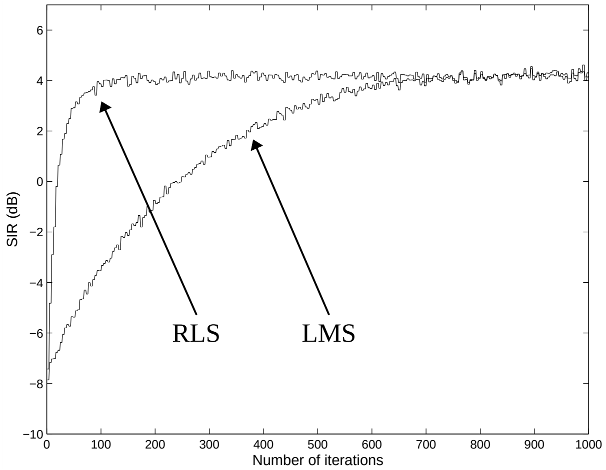

Figure 2. A comparison between convergence speed of the LMS and the RLS algorithms for M=1 and N=1

By proper distribution of these extra delays, the pipelined architecture will operate M times faster. This increase, however, may be traded for either reducing power [6,7] or reducing the chip area by utilizing the folding transformation [1].

4. SIMULATION RESULTS

A number of simulations have been conducted to compare the performance of the conventional serial RLS and the pipelined RLS algorithms for different speedup factors M and different number of antennas N. In these simulations, antennas were structured as a uniform linear array with half the wavelength spacing. The direction of arrival was set to 15°. The spreading sequences were Gold codes of length 7 and the number of users was five. The signal-to-noise ratio at the antennas for the desired user was fixed to 8 dB. The interfering power of all users varied from 0 to 10 dB. The initial condition for the adaptive filter $\mathbf{h}_a$ was the zero vector, and therefore, the output of the filter $\mathbf{h}$ up to M iterations was the same as the output of the $\mathbf{h}_q$. Since the convergence speed of the pipelined RLS algorithm depends on the level of pipelining (see Sec. 3.2), the updating of the coefficient vectors of Figures 3 and 4 were stopped after 300 and 500 iterations (I), respectively. From these figures one can observe that as M increases, the SIR will decrease. This loss of SIR is due to the slower convergence speed of the pipelined RLS algorithm as a result of the RLA approximations. However, this decrease of SIR as a result of fix number of iteration is rather constant for different relative interfering power of different users. Also, the loss of SIR is less as compared to result of [5]. Figure 5 illustrates the SIR versus the relative powers of the interfering users for two antennas (N=2) and when M=1, 3, 5, and 10. In this figure, the coefficient updating is frozen after 500 iterations. It is important to note that in the multiple-antenna case for a large M, the drop of SIR versus the relative interference power is slightly more as compared to receivers using only one antenna. Thus, the level of pipelining *M* should be carefully selected when more antennas are introduced.

5. CONCLUSIONS

Pipelined implementation of a DS-CDMA receiver was proposed when multiple antennas are utilized in mobile receivers. The RLA technique was utilized in order to introduce pipelining and to achieve higher throughput as compared to the receiver using the serial RLS algorithm. Simulations were carried out to illustrate the SIR versus the relative interfering power for different number of antennas and different levels of pipelining. It was shown that as *M* increases the SIR will decrease. This was due to the slower convergence speed as a result of the approximations. However, this decrease of SIR was considerably less than that obtained with the LMS algorithm in [5]. It is important to note that in the multiple-antenna case, the drop of SIR versus the relative interference power is more as compared to the receiver using only one antenna. As a result, the level of pipelining should be carefully selected when more antennas are introduced.

ACKNOWLEDGMENT

This work is part of a research project of the Institute of Radio Communication (IRC) funded by Technology Development Center, NOKIA Research Center, Telecom Finland, and the Helsinki Telephone Company.

REFERENCES

[1] N. Shanbhag and K. Parhi, *Adaptive Digital Filters*, Kluwer Academic Publishers, 1994.

[2] K. Parhi, "Algorithm transformation techniques for concurrent processors," *Proceedings of the IEEE*, vol. 77, pp. 1879-1895, December 1989.

[3] K. Parhi and D. Messerschmitt, "Pipeline interleaving and parallelism in recursive digital filters - Part I: Pipelining using scattered look-ahead and decomposition," *IEEE Trans. on ASSP*, vol. 37, pp. 1099-1117, July 1989.

[4] K. Matsubara, K. Nishikawa, and H. Kiya, "Pipelined LMS adaptive filter using a new look-ahead transformation," in *Proc. IEEE Int. Symp. on Circuits and Systems*, Hong Kong, pp. 2309-2312, June 1997.

[5] R. Baghaie, S. Werner, and T. Laakso, "Relaxed look-ahead techniques for pipelined implementation of adaptive multiple-antenna CDMA mobile receivers," in *Proc. IX European Signal Processing Conference*, Island of Rhodes, Greece, September 1998.

[6] M. Chandrakasam, M. Potkonjak, R. Mehra, J. Rabaey, and R. Broderson, "Optimizing power using transformations," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 14, no. 1, pp. 12-31, January 1995.

[7] N. Shanbhag and M. Goel, "Low-Power adaptive filter architectures and their applications to 51.84 Mb/s ATM-LAN," *IEEE Transactions on Signal Processing*, vol. 45, no. 5, pp. 1276-1290, May 1997.

[8] S. Werner, T. Laakso, and J. Lilleberg, "Adaptive multiple-antenna receiver for CDMA mobile reception," to appear in *Proc. ICC'98*, Atlanta, USA, June 1998.

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

[10] S. Haykin, *Adaptive Filter Theory*, Prentice Hall, 1996.

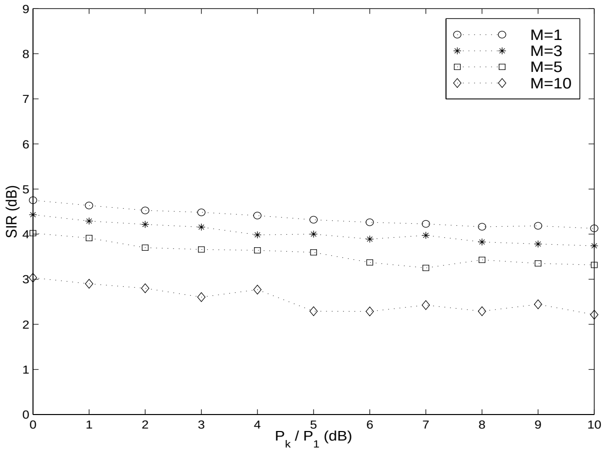

Figure 3. SIR versus the relative powers of the interfering users when *N*=1 and *M*=1, 3, 5 and 10 when *I*=300.

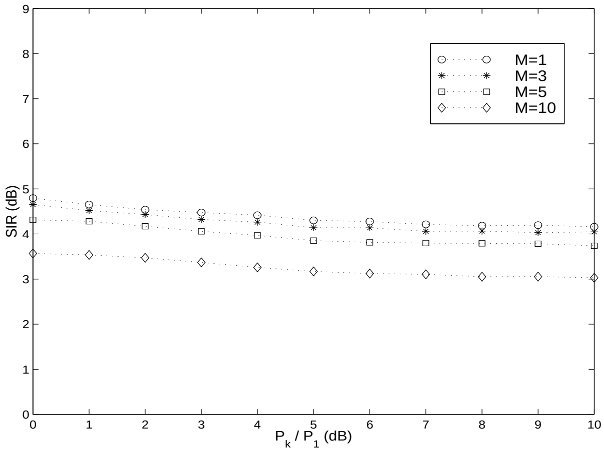

Figure 4. SIR versus the relative powers of the interfering users when *N*=1 and *M*=1, 3, 5 and 10 when *I*=500.

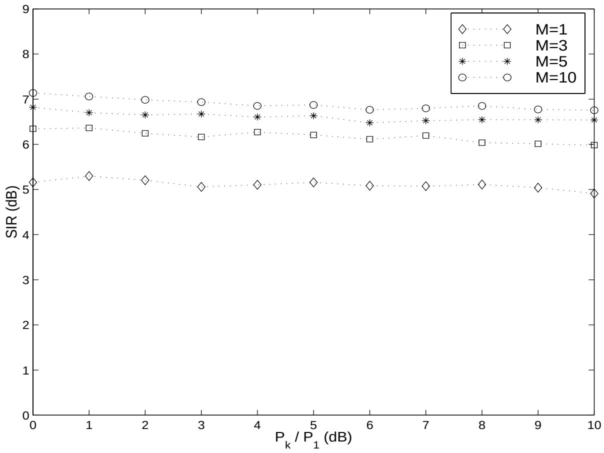

Figure 5. SIR versus the relative powers of the interfering users when *N*=2 and *M*=1, 3, 5 and 10 when *I*=500.