Adaptive Channel Equalizer for WCDMA Downlink

Kari Hooli, Matti Latva-aho, and Markku Juntti

University of Oulu, Centre for Wireless Communications
P.O. Box 4500 FIN-90014 University of Oulu
FINLAND
email: kari.hooli@ee.oulu.fi

ABSTRACT

The main 3rd generation cellular communications standard is based on wideband code-division multiple-access (WCDMA). For WCDMA downlink, receivers based on channel equalization at chip level have been proposed to ensure adequate performance even with a high number of active users. These receivers equalize the channel prior to the despreading, thus restoring the orthogonality of users and resulting multiple access interference (MAI) suppression. In this paper, ideas of generalized side-lobe canceler (GSC) and minimum output energy (MOE) are applied to the adaptation of downlink channel equalizer. The performance of the adaptation scheme is compared to the performance of conventional Rake receiver as well as to the performance of equalizer adapted with Griffiths' algorithm. Numerical results show significant performance gain over Rake receiver and some performance gain over the Griffiths' algorithm in a fading channel.

1. INTRODUCTION

Wideband code-division multiple-access is the main air interface of the 3rd generation cellular mobile communications standards. The downlink capacity is expected to be more crucial than the capacity of the uplink due to the asymmetric capacity requirements, i.e., the downlink direction should offer higher capacity than the uplink [1]. Therefore the employment of efficient downlink receivers is important. In order to avoid performance degradation near-far resistant (or multiuser) receivers can be used. Several suboptimal receivers feasible for practical implementations have been proposed, including linear minimum mean squared error (LMMSE) receivers [2]. The adaptive versions of the symbol level LMMSE receivers rely on cyclostationary of multiple access interference (MAI), and thus require periodic spreading sequences with a very short period. Hence they can not be applied on the WCDMA downlink, which uses spreading sequences with 1 radio frame (10 ms) period.

In a synchronously transmitted downlink employing orthogonal spreading codes MAI is mainly caused by multipath propagation. Due to the non-zero cross-correlations between the spreading sequences with arbitrary time shifts, there is interference between propagation paths (or Rake fingers) after the despreading causing multiple access interference. If the received chip waveform, distorted by the multipath channel, is equalized prior to the correlation by the spreading code or matched filtering, there is only a single path in the despreading. With orthogonal spreading sequences the equalization effectively retains, to some extent, the orthogonality of users lost due to the multipath propagation, thus suppressing MAI. Since the signal is equalized on the chip level, not on the symbol level, they can also be applied in systems using long spreading sequences. Such a receiver, discussed e.g. in [3]-[6], consists of a linear equalizer followed by a single correlator and a decision device, as depicted in Fig. 1.

Several adaptive versions of chip-level channel equalizers have been presented, e.g., in references in [6]-[7]. In this paper the ideas of generalized side-lobe canceler and minimum output energy are applied, resulting a novel adaptation scheme, channel-response MOE (CR-MOE). The bit error rate (BER) in a Rayleigh fading multipath channel was numerically evaluated for CR-MOE equalizer and compared to the performance of conventional Rake receiver and equalizer adapted with Griffiths' algorithm, suggested in [8]. Comparison between CR-MOE and Griffiths' algorithm [9] is quite natural due to the similarities of the schemes.

2. SYSTEM MODEL

Since the downlink is considered, synchronous transmission of all signals through the same multipath channel is assumed. The discrete-time received signal at user terminal can be written as

$$\boldsymbol{r} = \sum_{k=1}^{K} \boldsymbol{D}\boldsymbol{C}\boldsymbol{A}_k\boldsymbol{S}_k\boldsymbol{b}_k + \boldsymbol{n}, \tag{1}$$

where K is the number of users, $\boldsymbol{D}$ is a path delay and chip waveform matrix whose columns contain samples from appropriately delayed chip waveforms, and $\boldsymbol{C}$ is a block diagonal channel matrix containing channel coefficients for L propagation paths. Diagonal matrix $\boldsymbol{A}_k$ contains the average received amplitudes and $\boldsymbol{S}_k$ is a block diagonal matrix

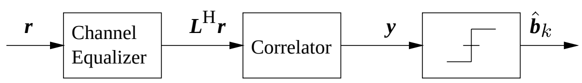

Fig. 1. Conceptual structure of chip-level channel equalizer.

The research described in the paper has been supported by Nokia and Texas Instruments. The contents of the paper have been presented in COST 262 workshop in Ulm, Germany, on 17.-18.1. 2001.

containing the spreading sequence for the kth user. The cell specific scrambling sequence is included to the spreading sequence, and the sequences are normalized so that $\boldsymbol{S}_k^{\mathrm{H}}\boldsymbol{S}_k = \boldsymbol{I}$. Vector $\boldsymbol{b}_k$ contains the transmitted symbols of the kth user, and vector $\boldsymbol{n}$ contains samples from white complex Gaussian noise process with variance σ_n^2. A more detailed description of the system model is given e.g. in [6].

3. RECEIVERS

In this section, the conventional Rake receiver as well as the adaptive equalizers are discussed. First, the Rake receiver, the linear minimum mean square error (LMMSE) chip-level channel equalizer, and Griffiths' algorithm are shortly defined, followed by discussion of the channel-response MOE equalizer.

In the Rake receiver, the received signal is filtered by the chip waveform, appropriately time-aligned and despread by correlation with the spreading sequence in the each of the Rake fingers. To obtain the decision variable, the Rake fingers are weighted by the channel coefficient estimates and combined in the maximal ratio combining (MRC).

The chip-level LMMSE equalizer is obtained by minimizing the mean square error between the equalizer output and the total transmitted signal, i.e., by solving

$$\boldsymbol{w}_L = \arg\min_{\boldsymbol{w}} \mathrm{E}\left[|\boldsymbol{w}^{\mathrm{H}}\boldsymbol{r} - \sum_{k=1}^{K}\boldsymbol{A}_k\boldsymbol{S}_k\boldsymbol{b}_k|^2\right], \qquad (2)$$

where minimization is carried out elementwise. The optimization problem in (2) can be easily solved. However, the exact LMMSE solution depends on the spreading sequences of all users following from the dependency between consecutive chips to be estimated. In [6] it was shown that the chip dependency has only minor effect on the performance, and the LMMSE solution can be approximated as

$$\boldsymbol{w}_L \approx \left(s^2\sum_{k=1}^{K}A_k^2\boldsymbol{D}\boldsymbol{C}\boldsymbol{C}^{\mathrm{H}}\boldsymbol{D}^{\mathrm{H}} + \sigma_n^2\boldsymbol{I}\right)^{-1}\boldsymbol{D}\boldsymbol{C}. \qquad (3)$$

The decision variable of the chip-level LMMSE equalizer after the correlation with a spreading sequence is

$$\begin{aligned}\boldsymbol{y} &= \boldsymbol{S}_1^{\mathrm{H}}\boldsymbol{w}_L^{\mathrm{H}}\boldsymbol{r}\\ &= \boldsymbol{S}_1^{\mathrm{H}}\boldsymbol{C}^{\mathrm{H}}\boldsymbol{D}^{\mathrm{H}}\left(s^2\sum_{k=1}^{K}A_k^2\boldsymbol{D}\boldsymbol{C}\boldsymbol{C}^{\mathrm{H}}\boldsymbol{D}^{\mathrm{H}} + \sigma_n^2\boldsymbol{I}\right)^{-1}\boldsymbol{r}. \qquad (4)\end{aligned}$$

In the adaptive chip-level channel equalizers, the received signal is filtered by chip waveform, equalized and correlated with the spreading sequence. The decision variable for arbitrary selected user 1 after the correlation with spreading sequence is given by $\boldsymbol{y} = \boldsymbol{S}_1^{\mathrm{H}}\boldsymbol{z}$, where vector $\boldsymbol{z}$ contains equalizer outputs for corresponding chip intervals. The nth element of $\boldsymbol{z}$ is defined by $\boldsymbol{w}(n)^{\mathrm{H}}\bar{\boldsymbol{r}}(n)$, where $\boldsymbol{w}(n) \in \mathbb{C}^{(2D+1)N_s}$ contains the equalizer taps and $\bar{\boldsymbol{r}}(n) = [r((n-D)N_s)\dots r(nN_s),\dots r((n+D+1)N_s-1)]^{\mathrm{T}}$ is a vector of output samples from the chip waveform matched filter within equalizer at nth chip interval. N_s is the number of samples per chip.

Several adaptation algorithms are obtained through different approximations of gradient vector

$$\frac{\nabla J}{\nabla \boldsymbol{w}} = -2\mathrm{E}[d^*\bar{\boldsymbol{r}}] + 2\mathrm{E}[\bar{\boldsymbol{r}}\bar{\boldsymbol{r}}^{\mathrm{H}}]\boldsymbol{w}, \qquad (5)$$

where $J = \mathrm{E}[|d - \boldsymbol{w}^{\mathrm{H}}\bar{\boldsymbol{r}}|^2]$ is the mean square error and d^* is the desired equalizer output's complex conjugate [10]. For example, the standard LMS algorithm is obtained by replacing expectations with instantaneous estimates, i.e., signal vectors $\bar{\boldsymbol{r}}(n)$. In [8], the Griffiths' algorithm is used for the adaptation of chip-level channel equalizer. The algorithm is obtained from (5) by replacing $\mathrm{E}[d^*\bar{\boldsymbol{r}}]$ with $\tilde{\boldsymbol{p}}$, the channel response matched filter. The resulting adaptation becomes

$$\boldsymbol{w}(n+1) = \boldsymbol{w}(n) - \mu(z^*(n)\bar{\boldsymbol{r}}(n) - \tilde{\boldsymbol{p}}), \qquad (6)$$

where μ is the adaptation step size and $z(n)$ is the equalizer output at nth chip interval.

In the channel-response constrained minimum-output-energy (CR-MOE) equalizer, the equalizer is decomposed into a constraint (or non-adaptive) component and to an adaptive component. This is the well known idea of generalized side-lobe canceler, described, e.g., in [10, chap. 5]. The same approach has been applied in blind MOE multiuser receivers, in which the spreading sequence of a desired user is used as the constraint [11]–[12]. As mentioned, the equalizer is decomposed into two parts, i.e., $\boldsymbol{w} = \tilde{\boldsymbol{p}} + \boldsymbol{x}$. The channel response matched filter $\tilde{\boldsymbol{p}}$ is used as the non-adaptive part, and the adaptive part $\boldsymbol{x}$ is constrained onto subspace orthogonal to $\tilde{\boldsymbol{p}}$ to avoid suppression of the desired signal. Now the mean square error J can be written as

$$J = \mathrm{E}[d^2] - 2\tilde{\boldsymbol{p}}^{\mathrm{H}}\tilde{\boldsymbol{p}} + (\tilde{\boldsymbol{p}} + \boldsymbol{x})^{\mathrm{H}}\mathrm{E}[\bar{\boldsymbol{r}}\bar{\boldsymbol{r}}^{\mathrm{H}}](\tilde{\boldsymbol{p}} + \boldsymbol{x}). \qquad (7)$$

Clearly the mean square error for given $\tilde{\boldsymbol{p}}$ is optimized by minimizing the last term of J, i.e., equalizer output energy. To obtain adaptive algorithm for $\boldsymbol{x}$, stochastic approximation is applied to the gradient of output energy $\boldsymbol{w}^{\mathrm{H}}\mathrm{E}[\bar{\boldsymbol{r}}\bar{\boldsymbol{r}}^{\mathrm{H}}]\boldsymbol{w}$. The orthogonality condition is maintained at each iteration by projecting the gradient onto the subspace orthogonal to $\tilde{\boldsymbol{p}}$. The orthogonal component of gradient is given by

$$\nabla\tilde{J}_{\perp\tilde{\boldsymbol{p}}} = \left(\bar{\boldsymbol{r}} - \tilde{\boldsymbol{p}}\frac{\tilde{\boldsymbol{p}}^{\mathrm{H}}\bar{\boldsymbol{r}}}{\tilde{\boldsymbol{p}}^{\mathrm{H}}\tilde{\boldsymbol{p}}}\right)\bar{\boldsymbol{r}}^{\mathrm{H}}\boldsymbol{w}. \qquad (8)$$

The resulting adaptation algorithm is given by

$$\boldsymbol{x}(n+1) = \boldsymbol{x}(n) - \mu z^*(n)(\bar{\boldsymbol{r}}(n) - z_p(n)\tilde{\boldsymbol{p}}), \qquad (9)$$

where $z_p(n) = \tilde{\boldsymbol{p}}^{\mathrm{H}}\bar{\boldsymbol{r}}(n)/(\tilde{\boldsymbol{p}}^{\mathrm{H}}\tilde{\boldsymbol{p}})$ is the output of channel response matched filter normalized with the energy of channel response. The CR-MOE equalizer is depicted in Fig. 2.

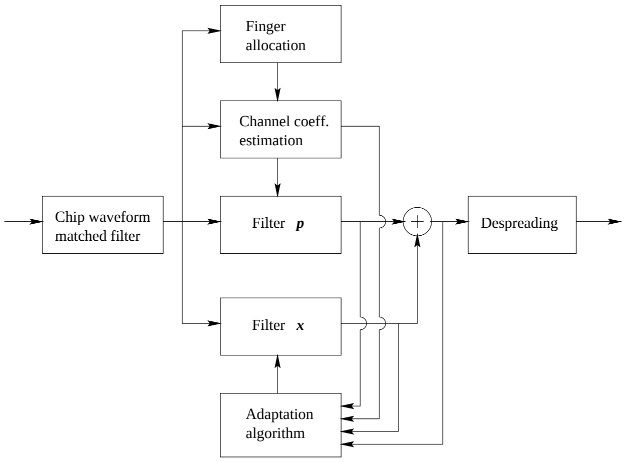

Fig. 2. Structure of CR-MOE equalizer.

The CR-MOE has the typical weaknesses of MOE adaptation [12]. The orthogonality between $\boldsymbol{x}$ and $\tilde{\boldsymbol{p}}$ is lost when the channel response estimate is updated. Thus periodical re-orthogonalization of $\boldsymbol{x}$ is required, given by

$$\boldsymbol{x}_{\perp\tilde{\boldsymbol{p}}} = \boldsymbol{x} - \frac{\tilde{\boldsymbol{p}}^{\mathrm{H}}\boldsymbol{x}}{\tilde{\boldsymbol{p}}^{\mathrm{H}}\tilde{\boldsymbol{p}}}\tilde{\boldsymbol{p}}. \tag{10}$$

The second problem of the MOE adaptation is the unavoidable estimation error in $\tilde{\boldsymbol{p}}$. Due to the estimation error, $\boldsymbol{x}$ has small projection on true $\boldsymbol{p}$ while maintaining orthogonality with $\tilde{\boldsymbol{p}}$. Since $\boldsymbol{x}$ is adapted to minimize output energy, the projection on $\boldsymbol{p}$ translates to partial suppression of the desired signal component. Since the channel estimation error is usually relatively small, suppression of the desired signal means large $||\boldsymbol{x}||^2$ values[1] and significant noise enhancement. Therefore, in noisy environments the suppression remains at acceptable levels. However, to avoid the desired signal suppression at high SNR, $||\boldsymbol{x}||^2$ values must be restricted. One solution is to introduce tap leakage [12]

$$\boldsymbol{x}(n+1) = (1-\mu\alpha)\boldsymbol{x}(n) - \mu z^*(n)(\bar{\boldsymbol{r}}(n) - z_p(n)\tilde{\boldsymbol{p}}), \tag{11}$$

where α, a small positive constant, controls the tap leakage. On the other hand, too low $||\boldsymbol{x}||^2$ values prevent efficient channel equalization. Therefore α must be adjusted to changing conditions. This can be achieved by periodically observing $||\boldsymbol{x}||^2/||\tilde{\boldsymbol{p}}||^2$ ratio and adjusting α if necessary.

It can be easily noted that the considered equalizers have distinctively similar properties. For example the part of adaptation step orthogonal to $\tilde{\boldsymbol{p}}$ in (6) is equal to the adaptation step in (9), assuming the same equalizer taps $\boldsymbol{w}(n)$. However, the estimated channel response is directly inserted to the equalizer in CR-MOE, whereas in Griffiths' algorithm it is gradually introduced through the adaptation. It is clear that both adaptive algorithms rely on the channel response estimate, obtained, e.g., with the help of common or dedicated pilot channel. Also the whole transmitted signal from the desired base-station is utilized in the adaptation instead of, e.g., using only the signal of desired user, thus significantly enhancing the available SNR in the equalizer adaptation. Finally, both equalizers have relatively low complexity with linear dependence on the channel delay spread.

[1] $||\boldsymbol{x}||^2 = \boldsymbol{x}^{\mathrm{H}}\boldsymbol{x}$

4. NUMERICAL RESULTS

To obtain a good understanding and comparison of the presented receivers' performance, BER's were evaluated in a Rayleigh fading channel. The channel had three propagation paths with delays of 0 ns, 521 ns and 1042 ns, and the relative average powers of the paths were 0 dB, -3 dB and -6 dB. QPSK modulation was used employing root raised cosine pulses with roll-off factor of 0.22. Random cell specific scrambling code and Walsh channelization codes were used, and the chip rate was set to 3.84 Mchip/s corresponding to 260 ns chip interval.

The BER's were evaluated for the receivers in a Rayleigh fading channel with 4 users employing spreading factor 8 and common pilot channel (CPICH) using spreading factor 64. The transmission power of pilot channel was scaled to be 11% from the total transmitted power. The terminal velocity was assumed to be 60 km/h. The fingers in the Rake receiver were allocated at correct path delays. For the equalizers, two samples per chip were taken from the output of chip waveform matched filter. The channel response matched filter $\tilde{\boldsymbol{p}}$ had non-zero values at correct path delays as well as on the adjacent samples, due to oversampling of chip waveform. The channel coefficients were estimated with common pilot channel and a moving average filtering.

The BER's are presented in Fig. 3, with the performance of ideal LMMSE equalizer and theoretical single-user bound. From the results it can be seen that both equalizers provide significant performance gain over the Rake receiver. It can be also noted that CR-MOE equalizer provides performance improvement over the equalizer adapted with Griffiths' algorithm in a fading channel.

5. CONCLUSIONS

One approach to improve the performance of WCDMA downlink receivers was studied in this paper, namely channel equalization prior to despreading. The presented receivers restore to some extent the orthogonality of users, and thus suppress the multiple access interference when orthogonal spreading sequences are employed. The filter decomposition idea of generalized side-lobe canceler is applied to the chip-level channel equalization, resulting a novel adaptive equalizer, channel-response MOE equalizer. CR-MOE equalizer consists of two parallel filters. Channel response matched filter is used as the non-adaptive filter, and the other filter minimizes the equalizer output energy.

The performance was numerically evaluated for CR-MOE equalizer and compared to the performance of conventional

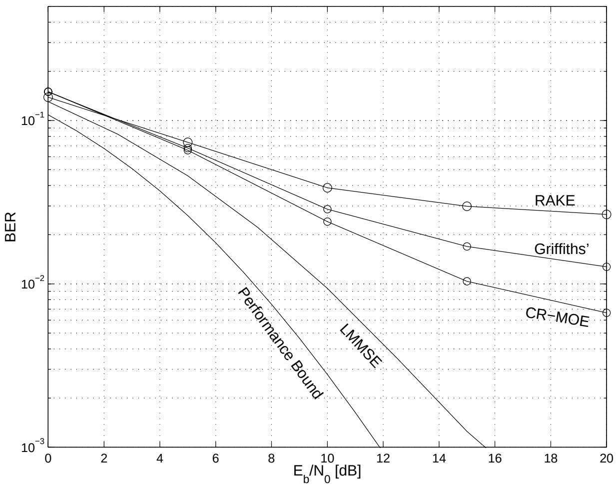

Fig. 3. BER vs. E_b/N_0 in a Rayleigh fading channel for 4 users with spreading factor 8 and CPICH with spreading factor 64.

Rake receiver and an equalizer adapted with Griffiths' algorithm. Results show significant performance gain over the Rake receiver. In a fading channel, CR-MOE equalizer provides performance improvement also over the equalizer adapted with Griffiths' algorithm.

ACKNOWLEDGMENT

Mr E. Corrales is acknowledged for the help with Rake simulations.

REFERENCES

[1] H. Holma and A. Toskala, Eds., *Wideband CDMA for UMTS*, John Wiley and Sons, New York, 2000.

[2] P. B. Rapajic and B. S. Vucetic, "Adaptive receiver structures for asynchronous CDMA systems," *IEEE J. Select. Areas Commun.*, vol. 12, no. 4, pp. 685–697, May 1994.

[3] A. Klein, "Data detection algorithms specially designed for the downlink of CDMA mobile radio systems," in *Proc. IEEE Vehic. Tech. Conf.*, Phoenix, USA, May 4–7 1997, vol. 1, pp. 203–207.

[4] C. D. Frank and E. Visotsky, "Adaptive interference suppression for direct-sequence CDMA systems with long spreading codes," in *Proc. Annual Allerton Conf. Communication Control and Computing*, Allerton House, Monticello, USA, Sept. 23-25 1998.

[5] I. Ghauri and D. T. M. Slock, "Linear receivers for the DS-CDMA downlink exploiting orthogonality of spreading sequences," in *Proc. 32th Asilomar Conf. on Signals, Systems and Comp.*, Asilomar, CA, Nov. 1–4 1998, vol. 1, pp. 650–654.

[6] K. Hooli, M. Latva-aho, and M. Juntti, "Multiple access interference suppression with linear chip equalizers in WCDMA downlink receivers," in *Proc. IEEE Glob. Telecommun. Conf.*, Rio de Janeiro, Brazil, Dec. 5–9 1999, vol. 1, pp. 467–471.

[7] K. Hooli, M. Latva-aho, and M. Juntti, "Performance evaluation of adaptive chip-level channel equalizers in WCDMA downlink," in *Proc. IEEE Int. Conf. Commun., to appear*, Helsinki, Finland, June 11–15 2001.

[8] M. Heikkilä, P. Komulainen, and J. Lilleberg, "Interference suppression in CDMA downlink through adaptive channel equalization," in *Proc. IEEE Vehic. Tech. Conf.*, Amsterdam, The Netherlands, Sept. 19–22 1999, vol. 2, pp. 978–982.

[9] J. R. Treichler, C. R. Johnson, and M. G. Larimore, *Theory and Design of Adaptive Filters*, John Wiley and Sons, New York, USA, 1987.

[10] S. Haykin, *Adaptive Filter Theory*, Prentice Hall, Upper Saddle River, NJ, USA, 3rd edition, 1996.

[11] M. Honig, U. Madhow, and S. Verdú, "Blind adaptive multiuser detection," *IEEE Trans. Inform. Theory*, vol. 41, no. 3, pp. 944–960, July 1995.

[12] S. Verdu, *Multiuser Detection*, Cambridge University Press, Cambridge, UK, 1998.