# Turbo Coding and Adaptive Channel Equalization for WCDMA Downlink

Dejan Drajic[1], Kari Hooli[2], Markku Juntti[2]

*Abstract* – **Receivers based on channel equalization have proven to be one of the most promising candidates for terminal receivers in wideband code-division multiple-access (WCDMA) downlink. The channel equalizers provide multiple access interference (MAI) suppression, and thus ensure adequate receiver performance even with a high nnumber of active users. However, the performance improvement provided by the equalizers in conjunction with a powerful forward error control (FEC) coding has been unclear. In this paper, the performance of adaptive equalizers is numerically evaluated with 1/3-rate turbo coding, and compared to the performance of the conventional Rake receiver. The numerical results show significant performance improvement over the Rake receiver in a Rayleigh fading multipath channel.**

*Keywords*: **WCDMA downlink, multiple access interference, equalization, turbo coding**

## I. INTRODUCTION

The air interface of the Universal Terrestrial Radio Access (UTRA), the most important 3rd generation cellular mobile communications standard, is based on wideband code-division multiple-access (WCDMA). In the 3rd generation cellular networks 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 use of efficient downlink receivers is important. To achieve an efficient performance, multiuser receivers [2] can be used. However, the multiuser receivers suitable for terminals typically rely on cyclostationarity of multiple access interference (MAI), and, thus, require periodic spreading sequences with a very short period. Hence, they can not be applied in the frequency division duplex (FDD) mode of WCDMA downlink, which uses spreading sequences with one radio frame (10 ms) period.

In a synchronously transmitted downlink employing orthogonal spreading codes, multipath propagation is a significant source of MAI. Due to the non-zero cross-correlations between the spreading sequences with arbitrary time shifts, there is interference between propagation paths causing multiple access interference. If the received chip waveform, distorted by the multipath channel, is equalized, the signal effectively experiences a single-path propagation. With orthogonal spreading sequences the equalization retains, to some extent, the orthogonality of users lost due to the multipath propagation, thus suppressing MAI. Since the equalization does not resort to the cyclostationarity of MAI, it can also be applied in systems using long spreading sequences.

The channel equalizer has proven to be one of the most promising terminal receivers for WCDMA/FDD downlink. Thus it has drawn attention and inspired numerous publications in the recent years. The equalization at chip-level has been treated e.g. in [3-6]. Also a large variety of adaptive equalizers suitable for WCDMA downlink have been presented, and for in-depth discussion the reader is instructed to [7], [8] and references therein. The equalization is performed prior to the spreading sequence matched filtering in the aforementioned references, but the equalization can also be done at symbol level, as shown in [9]. Performance of chip-level equalizer with channel coding was presented in [10] but the considered equalizer was an ideal linear equalizer, thus providing performance bounds for adaptive equalizers. In [11] some results were presented with channel coding for the adaptation method introduced in the paper. In this paper, two adaptive chip-level equalizers are studied, and their performance is numerically evaluated with 1/3-rate turbo coding in a Rayleigh fading frequency-selective channel. The effects of interleaving depth and 2nd receive antenna are also addressed.

The rest of the paper is organized as follows. System model is defined in Section II the receivers are defined in short in Section III and the employed turbo coding is described in Section IV. The performance of the equalizers is evaluated and compared to the conventional Rake receiver in Section V followed by concluding remarks in Section VI.

## II. SYSTEM MODEL

Since the downlink is considered, synchronous transmission of signals from a base station through the same multipath channel is assumed. The received signal $\boldsymbol{r}$ after down-conversion, low-pass filtering, and sampling can be written as

$$\boldsymbol{r} = \sum_{k+1}^{K} \boldsymbol{DCS}_k \boldsymbol{A}_k \boldsymbol{b}_k + \boldsymbol{n} \in \mathbb{C}^{N_c N_s}, \qquad (1)$$

where $K$ is the number of active users assigned to the base station, $N_s$ is the number of samples per chip, $N_c$ is the number of chips and $M_k$ is the number of symbols for the $k$th user in the observation window ($N_c$=$G_k M_k$, where $G_k$ is the spreading factor for $k$th user, product $G_k M_k$ is constant for all users). The

[1]Dejan Drajic is with Ericsson d.o.o.,V.Popovica 6, 11070 Belgrade, Yugoslavia, dejan.drajic@eyu.ericsson.se

[2]Kari Hooli and Markku Juntti are with the University of Oulu, Centre for Wireless Communications, P.O. Box 4500 FIN-90014 University of Oulu, Finland, kari.hooli@ee.oulu.fi

samples from multiple receive antennas are interleaved into a single vector $\boldsymbol{r}$ and thus $N_s$ is the product of number of antennas $N_a$, and samples per chip on each of the antenna branches. In Eq. (1), $\boldsymbol{D}=\ddot{\boldsymbol{D}}\otimes\boldsymbol{I}_{N_a}$ (the distance between antennas is assumed to be small enough so that the path delays are the same for all antennas), where $\otimes$ is Kronecker product, $\ddot{\boldsymbol{D}}=\left[\boldsymbol{d}_1^{(1)},\ldots,\boldsymbol{d}_L^{(N_c)}\right]\in\Re^{N_cN_s/N_a\times LN_c}$ is a path delay and chip waveform matrix where column vector $\boldsymbol{d}_l^{(n)}$ contains samples from appropriately delayed chip waveform for the $l$th path of $n$th chip, $\boldsymbol{C}\in\mathbb{C}^{N_aLN_c\times N_c}$ is a block diagonal channel matrix with column vectors containing the time-variant channel coefficients for $L$ paths of $N_a$ antennas. Term $\boldsymbol{DC}$ models the combination of chip waveform and multipath channel, and is common for all users on the same base station. $\boldsymbol{S}_k\in\Xi_c^{N_c\times M_k}$, where $\Xi_c$ is the chip alphabet, is a block diagonal spreading sequence matrix where column vectors contain the spreading sequences for the $k$th user with a spreading factor $G_k$. The spreading sequence consists of the cell specific scrambling sequence and the user specific channelization sequence, and the sequences are normalized so that $\boldsymbol{S}_k^{\mathrm{H}}\boldsymbol{S}_k=\boldsymbol{I}$. The average received amplitude for the $k$th user is contained in a diagonal matrix $\boldsymbol{A}_k+A_k\boldsymbol{I}_{Mk}$, and vector $\boldsymbol{b}_k=[b_k^{(1)},\ldots,b_k^{(Mk)}]^{\mathrm{T}}\in\Xi_b^{(Mk)}$, $\Xi_b$ is the symbol alphabet, contains the encoded symbols of the $k$th user. The noise vector $\boldsymbol{n}\in\mathbb{C}^{N_cN_s}$ contains samples from the white complex Gaussian noise process with covariance $\boldsymbol{C}_{nn}=\sigma_n^2\boldsymbol{I}_{NcNs}$.

## III. Adaptive Channel Equalizers

In this section, the receivers are briefly presented. With the introduced system model, the decision variable of the Rake receiver for user 1 is given by

$$\boldsymbol{y}=\boldsymbol{S}_1^{\mathrm{H}}\boldsymbol{C}^{\mathrm{H}}\boldsymbol{D}^{\mathrm{H}}\boldsymbol{r}, \tag{2}$$

i.e., the received signal is filtered by the chip waveform, appropriately time-aligned and weighted with channel coefficients in the Rake fingers, coherently combined and finally despread.

*CPICH-trained equalizer*. In both adaptive equalizers, the appropriately sampled received signal is filtered by chip waveform, equalized and correlated with the spreading sequence. The most straightforward solution to the adaptation of chip-level equalizer is to use the normalized LMS (NLMS) algorithm with the common (or dedicated) pilot channel as reference signal [7], [4]. It is straightforward to extend the CPICH-trained equalizer, depicted in Fig. 1, for multiple receive antennas by interleaving the samples from the antennas into one vector $\ddot{\boldsymbol{r}}$ (for two antennas, for example, the samples from the first antenna are inserted as odd samples in $\ddot{\boldsymbol{r}}$, and the samples from the second antenna as even samples). To limit the overall complexity of the equalizer, the output of chip waveform filter is sampled at chip rate with two receive antennas, whereas two samples per chip are used with one receive antenna. Otherwise the equalization remains unchanged.

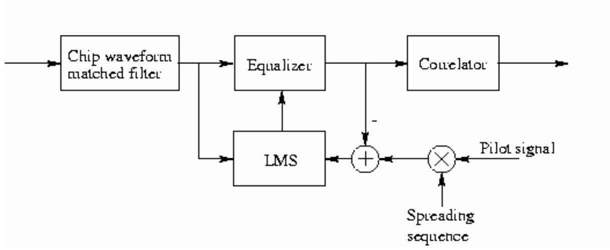


Fig. 1. CPICH-trained LMS equalizer

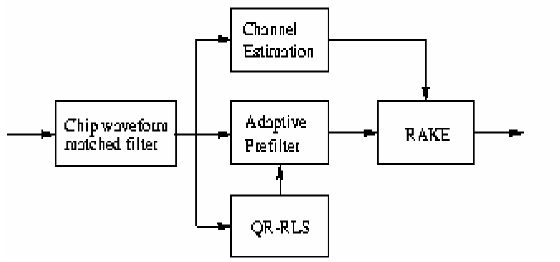


Fig. 2. Prefilter-Rake equalizer

*Prefilter-Rake equalizer.* It is commonly known that an adaptive equalizer can be implemented in two parts, the first part containing the received signal's covariance matrix inverse $\boldsymbol{R}^{-1}$ ($\boldsymbol{R}=\mathrm{E}(\boldsymbol{rr}^{\mathrm{H}})$), and the second part containing the cross-correlation vector between the received signal and desired response [12]. In [13], the approach was suggested for the chip-level equalizers, as well as the use of Rake receiver as the cross-correlation vector estimate. The equalizer was refined in [7] by replacing the matrix multiplication with the inverse estimate by prefiltering. In the prefilter-Rake, a filter matched to the chip waveform is preceding the prefilter, and its output is sampled at chip rate. The structure of prefilter-Rake is depicted in Fig. 2. The prefilter-Rake equalizer is inherently sensitive for an ill-conditioned covariance matrix $\boldsymbol{R}$. To avoid the problem, two separate prefilters are used with two receive antennas. More details on the prefilter-Rake equalizer can be found in [14].

## IV. Channel Coding

Following the WCDMA physical layer specifications [1], the rate 1/3 turbo code [15] was build as a parallel concatenation of two binary 8-state recursive systematic convolutional (RSC) codes with generator polynomials in the binary form [1011;1101]. Turbo encoder contains internal interleaver preceding the other constituent encoder, and the encoder is followed by two additional channel interleavers.

Suboptimal but powerful iterative decoder [15] suitable for low complexity WCDMA terminals was employed at the receiver. Decoder consists of two component log-MAP [16] decoders, one for each constituent RSC encoder. Decoders alternatively improve the log-likelihood information on the input information stream by exchanging their extrinsic information in an iterative fashion. After a few decoding iterations, final bit decision is made.

## V. NUMERICAL RESULTS

In this section, the performance of CPICH-trained and prefilter-Rake equalizers is numerically evaluated in a Rayleigh fading channel, and compared to the performance of conventional Rake receiver. The results address also the effects of interleaving and 2nd receive antenna.

In the simulations, QPSK modulation, Walsh channelization codes, base station specific random scrambling code, and root raised cosine chip waveform with roll-off factor 0.22 were used. Terminal velocity was set to 60 km/h. In all cases, the turbo encoder internal interleaver extended over 10 ms. The encoder was followed by two channel interleavers, with the first one extending over 10 ms and the second spanning over 80 ms [1].

The fading channel profile employed is defined in Table I, which was obtained from the ITU Vehicular A channel by splitting the paths into two paths located at sampling instances. With 2-antenna receivers, the channel profiles were assumed to be the same for both receive antennas, but the fading processes were independent between the antennas.

TABLE I
CHANNEL PROFILE

| Path | Mean Power [dB] | Delay [ns] |
|---|---|---|
| 1 | 0.0 | 0 |
| 2 | -3.1 | 260 |
| 3 | -5.2 | 391 |
| 4 | -11.6 | 651 |
| 5 | -12.4 | 781 |
| 6 | -12.0 | 1041 |
| 7 | -14.3 | 1172 |
| 8 | -16.5 | 1693 |
| 9 | -20.4 | 1823 |
| 10 | -21.4 | 2474 |
| 11 | -25.6 | 2604 |

At the receiver, the channel coefficients were estimated with a moving average from CPICH. CPICH-trained equalizer contained 16 taps, corresponding to a 2.08 $\mu$s time window, and the length of chip-spaced prefilter was set to 15 taps, corresponding to a 3.91 $\mu$s time window. The log-MAP decoder provided bit decisions after 5 iterations. The decoder had knowledge of average SINR estimated from the pilot symbols once in a radio frame (10 ms). No other channel state information was used in the decoding process.

The transmitted signal contained signals for the desired user with spreading factor 64, and for 4 other users with spreading factor 8. In Fig. 5, the transmitted signal was composed of 63 signals with spreading factor 64. Common pilot channel employing spreading factor 256 was included to the transmitted signal in all cases, and it constituted 10 % from the base station transmission power.

Bit error rate (BER) vs. $E_b/N_0$ (defined for uncoded information bit) is presented in Fig 3 for the CPICH-trained and prefilter-Rake equalizers as well as for the Rake receiver. In the figure, the effect of interleaving depth is studied by presenting results with one interleaver extending over 10 ms, and with two concatenated interleavers extending over 10 ms and 80 ms, respectively. The significant gain of a deeper interleaving is easily seen from the figure. However, the equalizers provide roughly the same performance improvements over the Rake receiver with both interleaving depths. At BER of $10^{-4}$, the gain is about 1.5 dB for the CPICH-trained equalizer while almost a 3 dB gain is achieved with the prefilter-Rake equalizer.

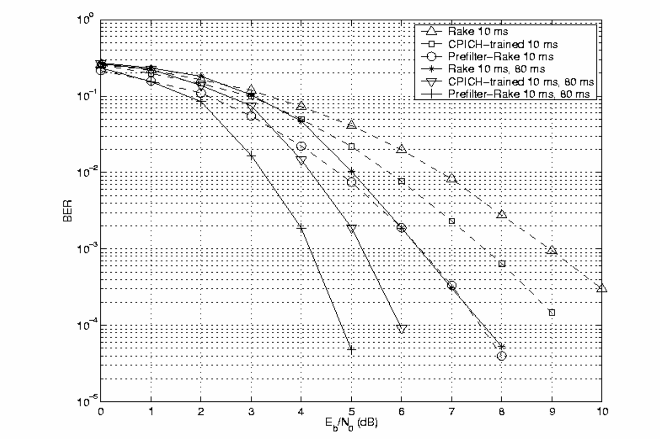


Fig. 3 Bit error rates vs. $E_b/N_0$ for 1-antenna receivers with 10 ms (dashed line) and 80 ms (solid line) interleaving depths

In Fig. 4, BER is presented for 2-antenna receivers with 80 ms interleaving depth. The introduction of the second receive antenna provides diversity gain (the 3 dB antenna gain is incorporated to $E_b/N_0$), which results in an apparent performance improvement with all receivers. The performance gains provided by the equalizers are smaller with the 2-antenna receivers than with the single antenna receivers. However, the prefilter-Rake equalizer provides still a 1.5 dB gain over the Rake receiver, and the CPICH-trained equalizer provides also a gain of 0.5 dB.

In Fig. 5, BER results are presented for the 1-antenna receivers with interleaving depth of 80 ms when a high number of active users, i.e., 63 users with spreading factor 64 together with CPICH, was assigned to the base station. The performance of the Rake receiver is severely degraded when compared to Fig. 3 while the equalizers exhibit only a 1 dB performance degradation. Thus, the equalizers are clearly less sensitive to intra-cell interference than the Rake receiver and provide significant performance gains in situations of severe intra-cell interference.

In Fig. 6, BERs are presented without any FEC coding, corresponding to Figs. 3 and 4. The performance improvement provided by the channel coding is clearly visible. The good performance of the equalizers as well as the performance differences between the receivers can be noted also from these results.

## VI. CONCLUSIONS

In this paper, the use of a powerful turbo coding performance in conjuction with adaptive channel equalizers was studied in WCDMA downlink, and compared to the performance of conventional Rake receiver. In the performance

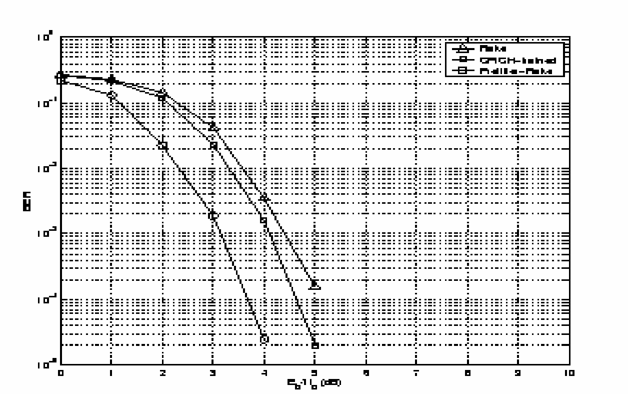

Fig. 4. Bit error rates vs. $E_b/N_0$ for 2-antenna receivers with 80 ms interleaving depth

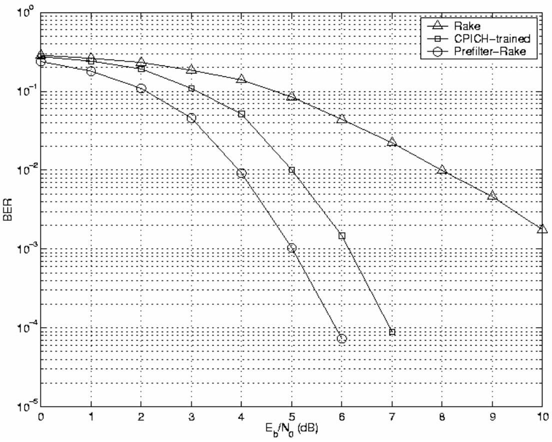


Fig 5. Bit error rates vs. $E_b/N_0$ with a high number of user (63 users with spreading factor 64 and CPICH with spreading factor 256). 1-antenna receivers and 80 ms interleaving depth are employed

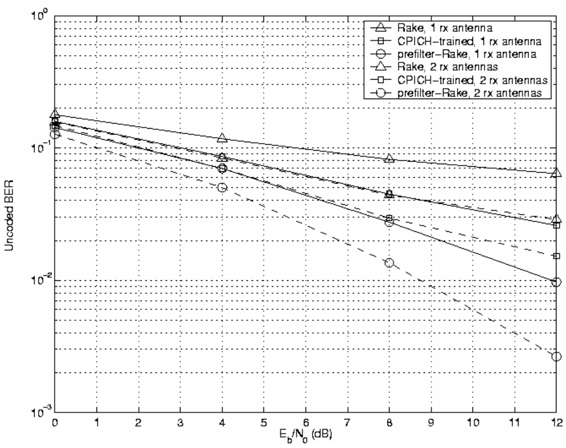


Fig. 6. Bit error rates vs. $E_b/N_0$ without FEC coding for 1-antenna (solid line) and 2-antenna (dashed line) receivers

evaluations various topics, including interleaving depth and second receive antenna, were addressed. In all cases the equalizers, and especially the prefilter-Rake equalizer, provided significant performance gains when compared to the conventional Rake receiver. When the channel equalizers are combined with FEC coding low error rate communications can be efficiently achieved even in situations of severe MAI. Thus the channel equalizers are a viable option for enhancing the receiver performance in WCDMA terminals.

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