Performance of Iterative Multiuser Decoding and Channel Estimation in WCDMA systems

Srikrishna Bhashyam
ECE Department, Rice University,
6100, S. Main, Houston, Texas 77005, USA.
skrishna@rice.edu

Ari Hottinen
Nokia Research Center,
P.O. Box 407 Nokia Group 00045 Finland.
hottinen@research.nokia.com

ABSTRACT

This paper studies the performance of iterative multiuser decoding, interference cancellation, and channel estimation techniques applicable to third generation WCDMA systems. The concept uses *a posteriori* probabilities of code symbols to enhance detection, decoding and channel estimation in an iterative fashion. Performance is analyzed in a multi-path channel with simulations. It is seen that the proposed concept combats multiuser interference effectively and performs almost as well as single user systems.

1 Introduction

Code division multiple access (CDMA) systems are inherently limited by multiple access interference (MAI). Families of "low-complexity" multiuser receivers have been proposed to combat this problem of MAI. The focus in the paper is the FDD/WCDMA system employing random codes. It is well known linear receivers e.g. (MMSE and decorrelator) are difficult to implement in a system employing random/long codes and these receiver structures are not considered in this paper. On the other hand, we can improve the conventional receivers by using interference cancellation techniques with soft (or hard) decisions rather efficiently.

Conventionally interference cancellation is done prior to channel decoding e.g. by exploiting techniques proposed in [13, 8]. However, with sufficient delay and memory tolerance, we can improve these by deriving optimum soft output from the channel decoder and exchanging soft information between the interference canceller and channel decoder. This latter option is exercised in this paper in connection with Turbo codes. In particular, we extend the results obtained in [6] to multipath channels and incorporate channel estimation to the iterative (Turbo) receiver. The resulting receiver has relatively low complexity and it can be considered as an add-on feature to conventional multi-user detection receivers, where the output of the channel decoder is not used in enhancing interference cancellation.

Recently, many such nonlinear centralized multiuser decoders have been proposed with different complexity reduction techniques [2, 12, 5, 4, 7, 9, 3, 10, 11]. In this paper, we derive the a posteriori probabilities (APPs) for each coded bit from K log-MAP Turbo decoders [9, 1] and use the *a posteriori mean* of each channel (coded) bit to weight interference cancellation. This is similar to [2], except that we use symbol-by-symbol MAP decisions instead of codeword MAP decisions. The complexity of the K-user MMSE channel estimator in [11] is too high for general use and simplifications are necessary. However, it is used to illustrate the general effects of channel estimation errors on iterative decoding in this paper. Other channel estimation schemes can also be updated iteratively in a similar manner to provide improved performance.

2 System Model

We consider an asynchronous CDMA system over a multipath fading channel. The received signal, $r(t)$, can be expressed as

$$r(t) = \sum_{k=1}^{K}\sum_{l=1}^{L} A_{k,l}(t) s_k(t-\tau_{k,l}) b_k(t) + n(t) \qquad (1)$$

where K is the number of users in the system, L is the number of paths in the channel, $b_k(t)$ is the information signal (± 1) of the k^{th} user, $s_k(t)$ is the spreading sequence of the k^{th} user, $\tau_{k,l}$ is the delay of the l^{th} path of the k^{th} user, $A_{k,l}(t)$ is the time-varying fading amplitude of the l^{th} path of the k^{th} user and $n(t)$ is the additive white Gaussian noise. The spreading sequences $s_k(t)$ are chosen to have periods much larger than a bit duration and is chosen to be composed of rectangular pulses.

This received signal is discretized at the receiver by chip-matched filtering. The chip-matched filtered received signal is then processed for channel estimation, detection and decoding. This chip-matched filter output signal over a window of length DN_c chips can be represented as

$$\mathbf{r} = \mathbf{SAb} + \mathbf{n} \qquad (2)$$

where $\mathbf{r}$ is a $DN_c \times 1$ vector of chip-matched filter outputs, $\mathbf{b}$ is a $M \times 1$ vector of bits in the window ($M =$

0-7803-5718-3/00/$10.00 ©2000 IEEE.

total number of bits of all users in the window × number of paths), $\mathbf{A}$ is a $M \times M$ diagonal matrix of the fading coefficients corresponding to each bit of each user in the window and $\mathbf{S}$ is the $DN_c \times M$ spreading matrix whose columns are the spreading vectors corresponding to the bits of all the users in the window. The spreading vectors are assumed to be long pseudo random sequences of period much larger than symbol duration. Therefore, the $\mathbf{S}$ matrix changes from one window to the next. This is not explicitly shown in equation (2) to simplify the notation. A processing window larger than one symbol duration is used to account for the asynchronous nature of the channel. One simplifying assumption made is that the delays of all the users and paths are multiples of the chip duration. However, the techniques used in this paper are general and can be extended to include all arbitrary delays.

3 Iterative Multiuser Detection and Decoding

In this section, we will describe iterative multiuser receivers based on parallel interference cancellation (PIC). In iterative PIC, the estimated multiple access interference for each user is removed from the received signal during each iteration. The estimated interference signal during each iteration is obtained using the knowledge of the spreading codes, channel fading amplitude estimates and symbol estimates of the interfering users in the previous iteration. The reduced interference signal is then processed for detection and decoding. The reduced interference signal during the l^{th} iteration is obtained as

$$\mathbf{r}^{(l)} = \mathbf{r} - \mathbf{S_I}\hat{\mathbf{A}}_\mathbf{I}\hat{\mathbf{b}}_\mathbf{I}^{(l-1)} \tag{3}$$

where $\mathbf{S_I}$ is the spreading code matrix of the interfering users, $\hat{\mathbf{A}}_\mathbf{I}$ is the estimated fading coefficient matrix of the interfering users and $\hat{\mathbf{b}}_\mathbf{I}^{(l-1)}$ is the estimate of the transmitted bits of the interfering users in the $(l-1)^{th}$ iteration.

In iterative multiuser detection, the estimate of the bits $\hat{\mathbf{b}}_\mathbf{I}^{(l-1)}$ is made using conventional matched filter detection. Either hard decisions or soft decisions from the output of the matched filter are used. However, this decision assumes that the different bits in the vector are independent. While this assumption is valid for uncoded communication systems, it is not satisfied for coded communication systems. In a coded system, the symbol vector $\mathbf{b_I}$ is constrained to be in the code space. This constraint can be imposed by determining the feedback bits for interference cancellation from the decoded output of the decoder. In the particular case of turbo decoding, it is easy to obtain the the *aposteriori* mean estimate of $\mathbf{b_I}$ from the iterative log-MAP decoder. By incurring the additional delay involved in waiting for the decoding to be complete, we can use the aposteriori mean estimate of $\mathbf{b_I}$ from the decoder. In the case of turbo coded systems, it can be more effective to combine a few PIC iterations with turbo decoding iterations as opposed to increasing the number of turbo decoding iterations. This gives the iterative multiuser decoding scheme. The performance of these two different PIC techniques (iterative multiuser detection and multiuser decoding) are compared in Section 5 using simulations. As expected, multiuser decoding provides gains over multiuser detection.

In our work, we also consider the effect of errors in channel $(\hat{\mathbf{A}}_\mathbf{I})$ estimation. In addition to considering the estimation process in the iterative decoding scheme, we update the channel estimate also iteratively. The next section discusses the specific estimation scheme studied in this paper.

4 Iterative Channel Estimation

The channel fading coefficient matrix required for interference cancellation and RAKE reception is estimated using a linear MMSE filter with the knowledge of the transmitted pilot symbols. Although an MMSE estimate is used in this paper, the idea of updating the estimate iteratively is applicable equally well to most other channel estimation techniques. This specific implementation just demonstrates how the soft estimates of the symbols can be effectively used for channel estimation in addition to detection and decoding. The initial MMSE channel estimate using pilot symbols is then iteratively updated using the decisions for the data bits obtained after each decoding iteration.

In order to estimate the channel, the received vector is reformulated as a function of the unknown channel and the known spreading and symbol matrices. The received vector $\mathbf{r}$ in equation 2 is rewritten as

$$\mathbf{r} = \mathbf{S}\mathbf{B}\mathbf{a} + \mathbf{n} \tag{4}$$

where $\mathbf{B}$ is a diagonal matrix of the bits of all the users (repeated for all paths) and $\mathbf{a}$ is a vector of the fading coefficients.

The linear MMSE estimate of the channel fading coefficients in the l^{th} iteration is obtained as

$$\hat{\mathbf{a}}^{(l)} = \mathbf{R_a}^\top \mathbf{B}^{(l-1)^\top} \mathbf{S}^\top (\mathbf{S}\mathbf{B}^{(l-1)}\mathbf{R_a}\mathbf{B}^{(l-1)^\top}\mathbf{S}^\top + \sigma^2\mathbf{I})^{-1}\mathbf{r} \tag{5}$$

where $\mathbf{R_a}$ is the fading correlation matrix of the fading coefficient vector $\mathbf{a}$. In the first iteration, at least one symbol must be known to get the initial estimate of the channel. This is achieved by using pilot symbols. In the following iterations, the data decisions are also used along with the pilot symbols to improve the estimate. The correlation structure of the fading process is also incorporated by the fading correlation matrix. The time correlation, $R_a(\tau)$, of the fading process is assumed to be

$$R_a(\tau) = \sigma_a^2 J_0(w_d \tau) \tag{6}$$

where J_0 is the Bessel function of zeroth order, w_d is the Doppler spread of the channel and σ_a^2 is the variance of the fading coefficient.

5 Simulation Results

The performance of the iterative joint decoding and channel estimation scheme in an asynchronous turbo coded CDMA system is analyzed using simulations. Initially, we show the performance of the iterative multiuser detection and decoding schemes in the presence of perfect channel knowledge. This is shown in Figures 1 and 2 for a system with the following parameters. The performance improvement in PIC due to decoded soft decisions is clearly seen in the comparison of the channel bit error rate (before decoding) of the iterative multiuser detection and decoding schemes in Figure 1. Similar gains are then observed in the decoded information bit error rate also in Figure 2. Thus, when perfect knowledge of the channel is available at the receiver, the joint iterative decoding scheme performs almost as well as a single user system over the same channel. However, only noisy estimates are available in practice and this mainly affects the performance in two different ways. There are performance losses due to imperfect multipath RAKE combining (for detection) and imperfect interference cancellation. Therefore, the performance of iterative joint decoding is studied along with channel estimation. The iterative channel estimation technique discussed in Section 4, which uses the *a posteriori* mean estimates of the code symbols to improve the channel estimates during each iteration, is employed.

Channel	Two path Rayleigh fading
Mobile speed	30 km/h
Modulation	BPSK spreading, BPSK symbols
Codes	Random, length 16
Chip rate	4.096 Mcps
Number of users	16
Encoding	Rate 1/3 PCCC, with generators 7_8 and 5_8
Turbo interleaving	Random interleaver
Log MAP decoder iterations (final stage)	6
Log MAP decoder iterations	3
Frame duration	10 ms
Number of bits in frame (data + pilot)	2560
Power	Equal average power
Asynchronous	

Table 1: Simulation Parameters

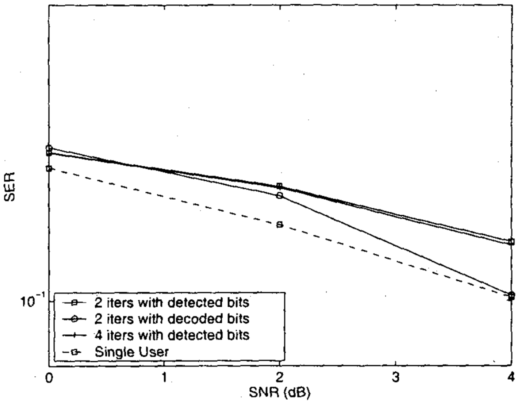

Figure 1: Performance (channel bit error rate) of iterative multiuser detection and iterative multiuser decoding

Figure 3 shows the performance of the iterative multiuser decoding and channel estimation scheme for a CDMA system with the parameters shown in Table 1. The performance of the iterative decoding scheme with iterative channel estimation is shown in comparison to the performance with perfect channel knowledge. The performance loss due to channel estimation error in the RAKE combining and decoding is related to the loss in single user performance in Figure 3 and the loss due to channel estimation error in interference cancellation is related to the loss in multiuser performance in figure 3. The performance loss due to imperfect channel estimation can be significant and is limited in our case by updating the channel estimates using the data decisions in addition to the pilot symbols. A channel estimation window size of 26 symbols was used in this case. Using data decisions reduces the need to transmit pilot symbols and allows more information to be transmitted. The pilot symbols are needed only to guarantee a good initial channel estimate which can be improved iteratively.

Figure 4 shows the mean squared error in channel estimates after each channel estimation iteration. The channel estimates are improved significantly by feeding back the *a posteriori* mean estimates of the code symbols.

Finally, we show the improvement in bit error rate after each iteration in iterative multiuser decoding and channel estimation. The improvement in each iteration is due to improved interference cancellation and improved channel estimation due to decision feedback. In this case a channel estimation window size of 11 was used. With a larger window size, the performance can be improved. For example, the improved performance with a window size of 26 was shown in Figure 3.

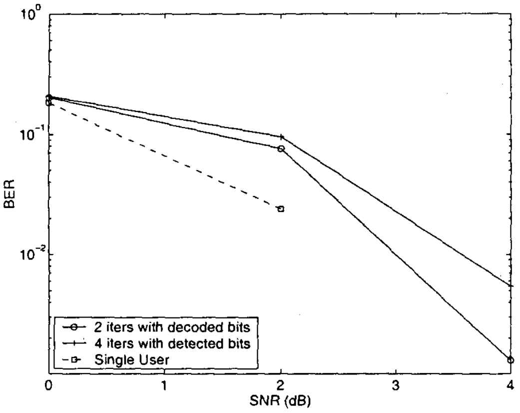

Figure 2: Performance (information bit error rate) of iterative multiuser detection and iterative multiuser decoding

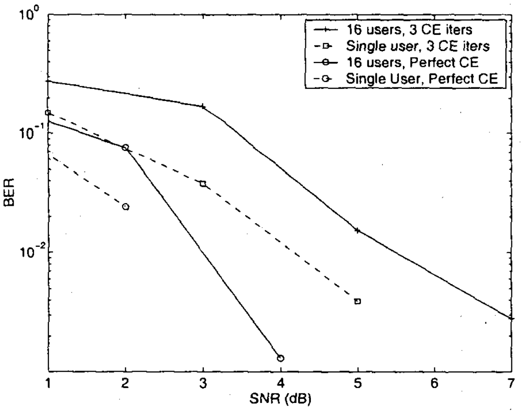

Figure 3: Performance of iterative multiuser decoding with perfect channel estimates (CE) and iterative channel estimation

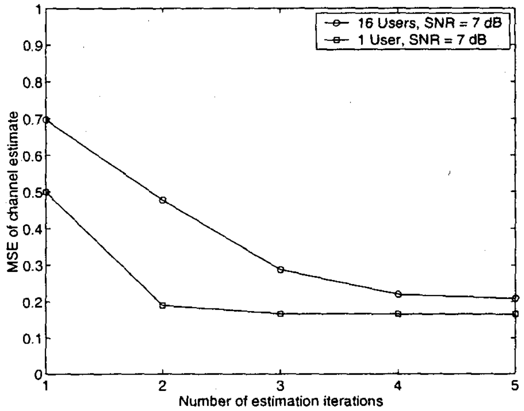

Figure 4: Mean squared error (MSE) of channel estimates after each iteration

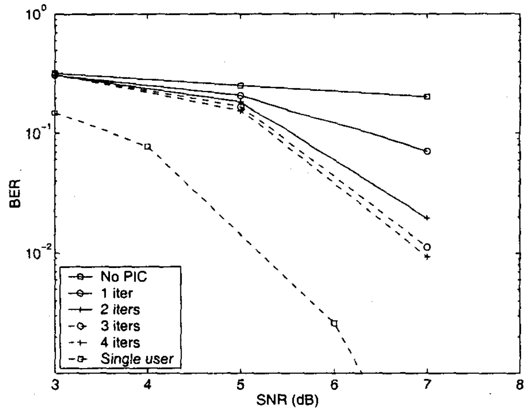

Figure 5: Performance of iterative multiuser decoding and channel estimation after each iteration

6 Conclusions

An iterative multiuser decoding and channel estimation scheme was studied in the context of third generation wideband CDMA systems. The scheme uses the *aposteriori* probabilities of coded symbols to enhance detection, decoding and channel estimation. Iterative multiuser decoding provides significant performance gains over iterative multiuser detection schemes. In the presence of perfect channel knowledge, iterative multiuser decoding schemes perform almost as well as single user systems. Iterative channel estimation that uses the decoded soft decisions in addition to pilot symbols is studied and is shown to effectively limit the losses due to imperfect channel estimation.

References

[1] S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara. A soft-input soft-output APP module for iterative decoding of concatenated codes. *IEEE Communications Letters*, 1(1):22–24, Jan 1997.

[2] S. Das, E. Erkip, J. Cavallaro, and B. Aazhang. Iterative multiuser detection and decoding. In *IEEE Globecom, Communication Theory Miniconference*, pages 1006–1111, Nov 1998.

[3] E. A. Fain and M. K. Varanasi. Group metric decoding for synchronous frequency-selective Rayleigh fading multiple access channels. In *IEEE Globecom, Communication Theory Miniconference*, 1997.

[4] A. Hafeez and W. E. Stark. Combined decision-feedback multiuser/soft-decision decoding for CDMA channels. In *IEEE International Conference on Vehicular Technology*, pages 382–386, Nov 1996.

[5] P. Hoeher. On channel coding multiuser detection for DS-CDMA. In *IEEE International Conference on Universal Personal Communications*, pages 382–386, 1993.

[6] A. Hottinen. Iterative multiuser decoding in WCDMA systems. In *Conference on Information Sciences and Systems*, Mar 1999.

[7] M. Moher. An iterative multiuser decoder for near-capacity communications. *IEEE Transactions on Communications*, 46:870–880, 1998.

[8] L. B. Nelson and H. V. Poor. Iterative multiuser receivers for CDMA channels : An EM-based approach. *IEEE Transactions on Communications*, 44(12):1700–1710, Dec 1996.

[9] M. C. Reed, P. D. Alexander, J. A. Asentorfer, and C. B. Schlegel. Near single user performance using iterative multi-user detection for CDMA with turbo decoders. In *Proceedings IEEE PIMRC*, pages 740–744, 1997.

[10] Y. Shama and B. R. Vojcic. Soft output Viterbi algorithm for maximum likelihood multiuser detection of coded asynchronous communications. In *Conference on Information Sciences and Systems*, pages 730–735, Mar 1997.

[11] J. Thomas and E. Geraniotis. Iterative MMSE multiuser interference cancellation for trellis coded CDMA systems in multipath fading environments. In *Conference on Information Sciences and Systems*, Mar 1999.

[12] M. Valenti and B. Woerner. Iterative multiuser detection for convolutionally coded asynchronous DS-CDMA. In *IEEE International Conference on Vehicular Technology*, 1998.

[13] M. K. Varanasi and B. Aazhang. Multistage detection in asynchronous code-division multiple-access communications. *IEEE Transactions on Communications*, 38(4):509–519, Apr 1990.