Multiuser Detection in TDMA and CDMA Systems

Anders Ahlén
Signals and Systems, Uppsala University,
PO Box 528, SE-75120, Uppsala, Sweden.
E-mail: Anders.Ahlen@signal.uu.se URL: www.signal.uu.se

Abstract

Multiuser detection in TDMA and CDMA systems is considered based on multi-variable DFEs. In the TDMA case the performance is evaluated on both simulated and real measurement data. It is shown that the proposed DFEs can improve the performance considerably. The proposed DFEs are also used in a downlink W-CDMA case. The achievable performance in such a case is not sensitive to the structure of the multiuser detector. Also, contrary to what is known from uplink scenarios, the conventional detector performs rather well, particularly when the signal to noise ratio is low.

I. Introduction

Multiuser detection has been studied extensively over the last decade. The primary focus has been on CDMA systems. See, for example, [7]-[11],[15],[16]. To obtain adequate performance in such systems orthogonality among the received signature sequences has to be preserved. In practice, however, this is virtually impossible to achieve with conventional receivers, particularly if the system is asynchronous and the discrepancy in power is large among the users. Improved results can be obtained if power control is used. An alternative would be to use more advanced detectors with less sensitivity to near-far effects.

Multiuser detectors can also be used in FDMA and TDMA systems. An efficient way to increase capacity in such systems is to decrease the reuse factor. Multiple receivers or *antenna arrays* are indispensable tools in this context due to their ability to enhance the desired signals while suppressing cochannel interference. When all available frequencies are used in every cell, a system with reuse factor one is obtained. However, capacity can be further increased if several users within a cell share all the available frequencies and time slots. Such systems will however be subject to severe cochannel interference. Multiuser detection would then be an attractive alternative to retrieve the user sequences. Multiuser detection within a cell was first proposed in [4] and [5] where frequency non-selective channels and linear detectors were used.

Interference rejection [1], [2], [3] can also be used for this purpose by detecting one signal at a time while treating the others as interference. If the class of detectors are constrained to be linear, then it can be shown that an MSE optimal linear multiuser detector is the same as a set of interference cancelers [18]. This is however not true for nonlinear detectors, such as DFEs and MLSEs.

If complexity would not be an issue, then an MLSE detector would be the preferred choice. However, MLSE detectors would in most applications be deemed too complex when the number of users grow. In such situations the use of multi-variable DFEs would be an interesting alternative. Multi-variable DFEs have been used previously in the literature, see, for example, [10], [12], [13]. In this paper we will use a multi-variable DFE as a means to perform multiuser detection in both TDMA and CDMA systems. The results discussed here is a short summary of more elaborate investigations presented in [18], and [14].

II. Channel Models

The performance of model based detectors depend critically on the quality of the channel estimates. It is therefore essential that we use an appropriate model structure and a reliable and accurate channel estimation algorithm. Channel estimation based on training sequences with few data has been thoroughly investigated in [19].

In this paper we shall, in the TDMA case, use linear baseband models which include pulse shaping and analog modulation, and which are sampled at the symbol rate. We consider a scenario with M users and N receiver antennas. This means that the uplink scenario presupposes M users, each transmitting with a single antenna and the base station receiving all messages with N antennas. In the downlink we assume the base station to have M antennas, each of which transmits a separate message, whereas each mobile uses N receiver antennas for the detection. In the CDMA case the received signal is sampled at the chip rate and antenna arrays are not assumed.

Let the received signal at antenna i, and the symbol sequence transmitted from user j be denoted $y_i(k)$ and $d_j(k)$ respectively. Furthermore, let the discrete time baseband channel between user j and receiver antenna i be represented by

$$B_{ij}(q^{-1}) = B_{ij} + B_{ij}q^{-1} + \ldots + B_{ij}q^{-L} \tag{1}$$

where B_{ij}^n are complex-valued constants, L is the order, and where q^{-1} is the unit delay operator, $q^{-1}y(k) = y(k-1)$. The sampled signal at antenna i can then be expressed as

$$y_i(k) = \sum_{j=1}^{M} B_{ij}(q^{-1})d_j(k) + v_i(k) \ , \tag{2}$$

where we assume that $d_j(k)$ and $v_i(k)$ are mutually uncorrelated, zero mean, and stationary stochastic sequences. By collecting the received signals, the user sequences, and the noises in vectors

$$y(k) = (y_1(k) \ \ldots y_N(k))^T \ ; \quad d(k) = (d_1(k) \ \ldots \ d_M(k))^T \ ; \quad v(k) = (v_1(k) \ \ldots \ v_N(k))^T \ ,$$

we obtain a multiple input multiple output model

$$y(k) \quad = \quad \boldsymbol{B}(q^{-1})d(k) + v(k) \tag{3}$$

with $\boldsymbol{B}(q^{-1})$ given by

$$\boldsymbol{B}(q^{-1}) = \begin{pmatrix} B_{11}(q^{-1}) & \ldots & B_{1M}(q^{-1}) \\ \vdots & \ddots & \vdots \\ B_{N1}(q^{-1}) & \ldots & B_{NM}(q^{-1}) \end{pmatrix} \tag{4}$$

In (3) we have assumed that all users are located in the same cell. Out of cell users will then be included in the noise $v(k)$. Adjacent cell users can also be included in $\boldsymbol{B}(q^{-1})$ if the base stations are synchronized and if the training sequences are all different and known.

As an alternative to detect all users jointly we can detect one at a time while regarding the others as interference. A suitable model would then be

$$y(k) = \boldsymbol{B}_1(q^{-1})d_1(k) + V(k) \tag{5}$$

where $\boldsymbol{B}_1(q^{-1})$ is now the first column of (4). In this model all users, except user one, are regarded as cochannel interference and included in the noise term $V(k)$. Evidently $V(k)$

in (5) will be both spatially and temporally colored. Estimation of the matrix valued covariance function of $V(k)$ is then crucial if a detector is to be based on (5). This might be a major problem if the training sequence is short. In the sequel we shall refer to (3)(4) and (5) as the MU-channel model and SU-channel model respectively. These models were used in [18] and [14] as a basis for detector design and they will also be our basis here.

III. Detector Structure

We shall use a multi-variable DFE as detector. It will be constrained to have FIR filters in both the feedforward and feedback links[1]:

$$\begin{aligned} \hat{d}(k-\ell|k) &= \boldsymbol{S}(q^{-1})y(k) - \boldsymbol{Q}(q^{-1})\tilde{d}(k-\ell-1|k) \\ \tilde{d}(k-\ell|k) &= f(\hat{d}(k-\ell|k)) \ . \end{aligned} \tag{6}$$

Here $y(k)$ is the received sampled signal vector while $\tilde{d}(k-\ell-1|k)$ is the vector of most recent decisions. The feedforward filter $\boldsymbol{S}(q^{-1})$, of order ns, and the feedback filter $\boldsymbol{Q}(q^{-1})$, of order nq, have dimensions $N|M$ and $M|M$ respectively. If the channel model (3), (4) is used, then $\boldsymbol{Q}(q^{-1})$ will be a full matrix whereas if (5) is used then $\boldsymbol{Q}(q^{-1})$ will be constrained to be a diagonal matrix. This constraint is natural since we have required the interference canceler to detect one user at a time. The parameter ℓ, which is a user choice, is known as the smoothing lag or the decision delay. In general ℓ will determine the degree of the feedforward filter. To simplify the design we adopt the usual assumption that all previous decision are correct, that is, $\tilde{d}(k-\ell|k) = d(k-\ell)$.

Now we can use Theorem 1 in [14] or Theorem 3.4 in [18] to design both the multiuser detection and interference rejection DFEs.

IV. Experimental results

A. The TDMA Case

To compare and evaluate the proposed detectors, described by (6), under fairly realistic conditions extensive simulations have been conducted. For a thorough investigation see [18] and [14]. We shall here present only two scenarios:

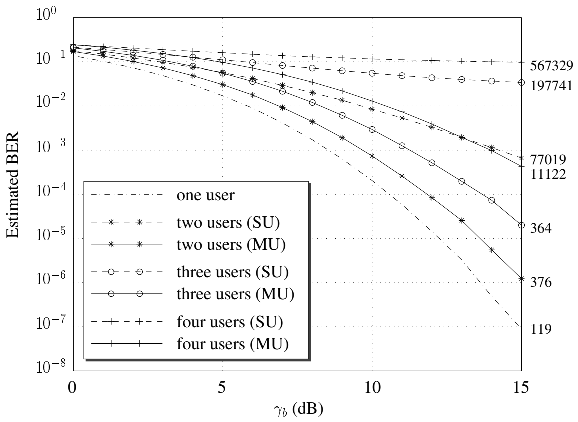
- Monte Carlo simulations with estimated channel parameters, uncorrelated antennas and equal transmitter powers.
- A case with real data acquired from uplink measurements of a DCS 1800 test bed[2].

From the left diagram of Figure 1 it is clear that a considerable performance improvement can be obtained by detecting the users jointly instead of one at a time. The reason is the following: First, the multiuser detector (6), based on a full $\boldsymbol{Q}(q^{-1})$ matrix and the MU-channel model (3), (4), has more degrees of freedom than the interference rejection detector (6) based on a diagonal $\boldsymbol{Q}(q^{-1})$ matrix and the SU-channel model (5). Second, it is difficult to estimate the covariance matrix of $V(k)$ in (5) based on few data. To alleviate this effect we have in Figure 1 used both the training sequence and the detected symbols in the estimation.

In the right diagram of Figure 1 the performance of the two detectors is rather similar. The reason for this is that the channel is flat fading and all inter-symbol interference is therefore caused by the partial response modulation. Since we also consider a two user case the additional degrees of freedom provided by the use of a full diagonal matrix $\boldsymbol{Q}(q^{-1})$ can not be fully utilized.

[1]This is in general a suboptimum structure unless the channel and noise are described by moving average and autoregressive processes respectively [14][18][17]. However, the performance loss will be marginal in most cases as compared to what can be obtained with more general structures.

[2]The data were provided by Ericsson Radio Systems AB in Kista, Sweden, which is here gratefully acknowledged.



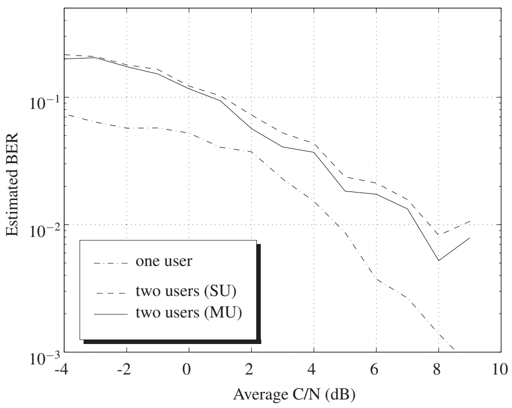


Fig. 1. Left: The MIMO DFE (MU) and MISO DFE (SU) are compared for estimated channels, uncorrelated antennas and equal transmitter power. To to identify the MU-channel model and SU-channel model (3), (4), and (5) both the training sequence and the detected symbols were used. The numbers at the right end of the diagram are the number of errors used to estimate the BER for an SNR per bit of $\bar{\gamma}_b = 15dB$. Right: The MIMO DFE (MU) and MISO DFE (SU) applied to measurement data obtained from a DCS-1800 testbed. Two users ($M = 2$) were transmitting simultaneously. The messages were received by an antenna with eight outputs ($N = 8$).

B. The CDMA Case

By appropriate modeling, on a symbol by symbol basis, the CDMA channel can be described by a MIMO model similar to (3), (4) but with $2N_c$ outputs and $2K$ inputs, where N_c and K represent the processing gain and the number of users respectively. For details on the derivation of this channel model, see [18]. The detector used to separate the users is the same as in (6) but with matrices $\boldsymbol{S}(q^{-1})$ and $\boldsymbol{Q}(q^{-1})$ of dimensions $2N_c|K_1$ and $2K_1|K_2$ respectively. The numbers K_1 and K_2 determines the number of users that should be detected and the number of users that are utilized by the feedback filter respectively. Here, K_1 and K_2 may be smaller but not larger than the number of users K.

To illustrate the utility of the DFE structure as a multiuser detector for CDMA-systems we shall here investigate a downlink W-CDMA scenario which is part of a more elaborate investigation conducted in [18]. The simulation set-up is specified as follows:

- All users have processing gain $N_c = 16$, the codes are so called OVSF-codes and the modulation is QPSK with raised cosine filtering.
- Each frame consists of 160 symbols including 8 pilot symbols. The transmitted power is the same to all users and the propagation delay is estimated with an accuracy of one chip period.
- The channel is Rayleigh fading with three time-invariant taps and it is estimated with the least squares method based on the pilot bits.
- The symbols were detected using the linear MMSE detector, the multiuser DFE and the interference rejection DFE. To design the multiuser DFEs Theorem 5.1 in [18] was used. The BER was compared to that of the conventional RAKE receiver.

In Figure 2, the results from a downlink simulation is presented. It is interesting to note that, from a capacity point of view, the three different multiuser detectors perform equally well. Another interesting observation relates to the conventional detector: At an SNR of 5 dB its performance is rather close to the performance of the multiuser detectors. It is thus tempting to conclude that in downlink scenarios with a lot of noise the use of multiuser detectors may not be worthwhile. This is in contrast to uplink scenarios, where multiuser detectors outperform the conventional detector.

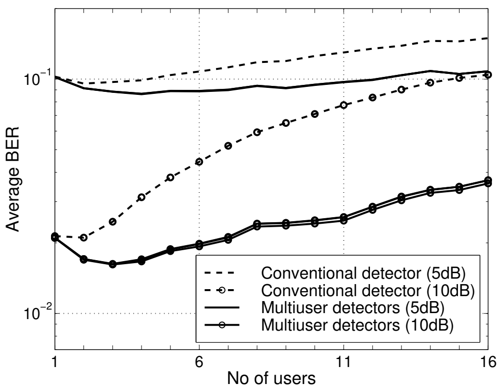


Fig. 2. The performance of three multiuser detectors and the conventional receiver is compared for a downlink W-CDMA scenario. All users have the same power and the processing gain is 16.

V. Conclusions

Multiuser detection has been considered for TDMA and CDMA systems based on multivariable DFEs. The performance can be considerably improved particularly in uplink scenarios. In downlink CDMA scenarios it is however not immediate that the performance increase obtained with such detectors can motivate the additional complexity.

References

[1] M.V. Clark, L.J. Greenstein, W.K. Kennedy, and M. Shafi, "Optimum linear diversity receivers for mobile communications", *IEEE Trans. Veh. Technol.*, vol. 43, pp. 47-56, Feb. 1994.

[2] P. Monsen, "MMSE equalization of intereference on fading diversity channels", *IEEE Trans. Commun.*, vol. COM-32, pp. 5-12, Jan. 1984.

[3] P. Balaban and J. Salz, "Optimum diversity combining and equalization in digital data transmission with applications to cellular mobile radio – Part I: Theoretical considerations", *IEEE Trans. Commun.*, vol 40, pp. 885-894, May 1992.

[4] J. Winters, "On the capacity of radio communication systems with diversity in a Rayleigh fading environment", *IEEE J. Select. Areas Commun.*, vol. SAC-5, pp. 871-878, June 1987.

[5] J. Winters, "Optimum combining for indoor radio systems with multiple users", *IEEE Trans. Commun.*, vol. COM-35, pp. 1222-1230, Nov. 1987.

[6] S. Verdú, "Minimum probability of error for asynchronous gaussian multiple access channels", *IEEE Trans. Inform. Theory*, vol. IT-32, pp. 85-96, Jan. 1986.

[7] R. Lupas and S. Verdú, "Near-far resistance of multi-user detectors in asynchronous channels", *IEEE Trans. Commun.*, vol. 38, pp. 496-508, Apr. 1990.

[8] M.K. Varanasi and B. Aazhang, "Multistage detection in asynchronous code-division multiple-acces communications", *IEEE Trans. Commun.*, vol. 38, pp. 509-519, Apr. 1990.

[9] Z. Xie, R.T. Short, and C.K. Rushforth, "A family of suboptimum detectors for coherent multiuser communications", *IEEE J. Select. Areas Commun.*, vol. 8, pp. 683-690, May 1990.

[10] A. Duel-Hallen, "A family of multiuser decision-feedback detectors for asynchronous code-division multiple access channels", *IEEE Trans. Commun.*, vol. 43, pp. 421-434, Feb./Mar./Apr. 1995.

[11] C.Tidestav, A. Ahlén, and M. Sternad, "Narrowband and broadband multiuser detection using a multivariable DFE", in *Proc. IEEE Int. Symp. Personal, Indoor, and Mobile Radio Communications*, Toronto, Canada, Sept. 1995, vol. 2, pp. 732-736.

[12] P.A. Voois and J.M. Cioffi, "Multichannel signal processing for multiple-head digital magnetic recording", *IEEE Trans. Magn.*, vol. 30, pp. 5100-5114, Nov. 1994.

[13] A. Duel-Hallen, "Equalizers for multiple input/multiple output channels and PAM systems with cyclostationary input sequences", *IEEE J. Select. Areas Commun.*, vol. 10, pp. 630-639, Apr. 1992.

[14] C. Tidestav, M. Sternad, and A. Ahlén, "Reuse within a cell – Multiuser detection or interference rejection?", *IEEE Trans. Commun.*, vol47, no 10, pp 1511-1522, Oct. 1999.

[15] S. Verdú, "Optimum multiuser asymptotic efficiency", *IEEE Trans. Commun.*, vol. COM-34, pp. 890-897, Sept. 1986.

[16] A. Duel-Hallen, "Decorrelating decision-feedback multi-user detector for synchronous code-division multiple access channel", *IEEE Trans. Commun.*, vol. 41, pp. 285-290, Febr. 1993.

[17] M. Sternad and A. Ahlén, "The structure and design of realizable decision feedback equalizers for IIR channels with colored noise", *IEEE Trans. on Inform. Theory*, vol. 36, pp. 848-858, July 1990.

[18] C. Tidestav, " The Multivariable DFE: Multiuser detection and Interference Rejection", PhD Thesis, Uppsala Univ., Uppsala, Sweden, Dec 1999.

[19] E. Lindskog, " Space-Time Processing and Equalization for Wireless Communications", PhD Thesis, Uppsala Univ., Uppsala, Sweden, June 1999.