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13. ABSTRACT *(Maximum 200 words)*
This project is concerned with the applicability of adaptive linear interference suppression for DS-CDMA in a peer--to--peer network. This technique is robust with respect to extreme near-far power variations. The following topics have been studied. (1) performance in the presence of time- and frequency-selective fading, (2) reduced-rank methods for faster convergence and tracking, (3) adaptive transmitter pre--processing for interference avoidance, (4) combined coding and interference suppression, and (5) performance in the presence of mixed rate traffic. Overall, our results indicate that adaptive linear interference suppression can be made robust with respect to time-varying channels and interference. Algorithmic enhancements which improve upon the performance in a dynamically changing environment have been proposed and evaluated.

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DS-CDMA, interference suppression, wirelss communications

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ADAPTIVE INTERFERENCE SUPPRESSION FOR DS-CDMA

Final Report

Michael L. Honig

November 12, 1999

U.S. ARMY RESEARCH OFFICE

GRANT DAAH04-96-1-0378

NORTHWESTERN UNIVERSITY

1 Problem Statement

This project is concerned with the performance of adaptive linear interference suppression for wireless Direct-Sequence (DS)-Code-Division Multiple-Access (CDMA). Linear interference suppression can potentially solve the near-far problem, which may be especially troublesome in a peer-to-peer environment characteristic of battlefield communications. Adaptive algorithms based on the Minimum Mean Squared Error (MMSE) criterion can be used to adjust the filter coefficients. These algorithms have the attractive property that little side information is required. Namely, they require either a training sequence, or alternatively, knowledge of the desired user's timing, spreading code and an associated channel estimate.

The following topics and problems associated with adaptive linear interference suppression have been studied during the course of this project:

1. Reduced-rank adaptation with large processing gains.
2. Performance variability over the user population due to the use of short spreading codes.
3. Performance with mixed-rate services.
4. Performance in the presence of dynamic fading, bursty interference, and associated algorithmic enhancements.
5. Combined coding and interference suppression.

In what follows, we highlight our results in each of these areas.

2 Reduced-Rank Interference Suppression

For covert communications, the processing gain must be very large, which adversely affects the convergence and tracking performance of an adaptive algorithm. One approach to solving this problem is to project the received CDMA signal onto a lower-dimensional signal subspace. This reduces the number of filter coefficients to be estimated, and can thereby improve tracking and convergence. A comparison of subspace, or "reduced-rank", adaptive algorithms was presented in [6]. (All citations refer to the appended list of publications supported by this grant.) The results show that these methods make the adaptive filter insensitive to near-far transients caused by bursty interference. By carefully selecting the subspace onto which the received signal is projected, this remains true even when the subspace dimension is less than the dimension of the signal subspace.

A sample set of results is shown in Figure 1. Uncoded error rate is shown as a function of the power of the interferers for different adaptive reduced-rank algorithms. Interference transients are created by gating the users on and off. These results show

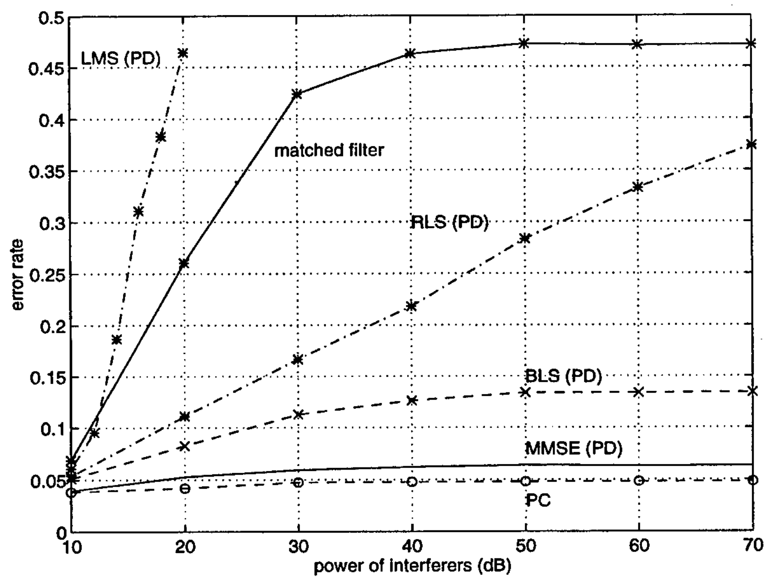

Figure 1: Uncoded error rate vs. relative power of interferers (dB) for reduced-rank adaptive adaptive algorithms. (RLS= "Recursive Least Squares", BLS= "Block Least Squares", PD= "Partial Despreading", MMSE= "Minimum Mean Squared Error", PC= "Principal Components", LMS= "Least Mean Square" (stochastic gradient algorithm)).

that the performance of the reduced-rank techniques is insensitive to these transients.

A new class of adaptive reduced-rank algorithms was presented in [11]. These algorithms are based on the multi-stage Wiener filter presented by Goldstein and Reed, in which the outputs of each successive stage are computed via "Residual Correlation" of the outputs of the preceding stage. An important property of this technique is that near full-rank Minimum Mean Squared Error (MMSE) performance is achieved with subspace dimension much less than the number of users. Furthermore, the algorithms are less complex than other reduced-rank techniques that require estimation of the signal subspace.

Figure 2, taken from [11], shows probability of error vs. subspace dimension D after training with 200 symbols. The processing gain N is 128 and there are 40 asynchronous users. The Residual Correlation (ResCor) technique achieves a minimum value at $D = 8$, which is far below the dimension of the signal subspace. The other curves correspond to other reduced-rank techniques that have been proposed. These results show that the ResCor technique can achieve near-optimal (MMSE) performance with less than $2N$ training symbols. This is a significant improvement over conventional (full-rank) least squares adaptation.

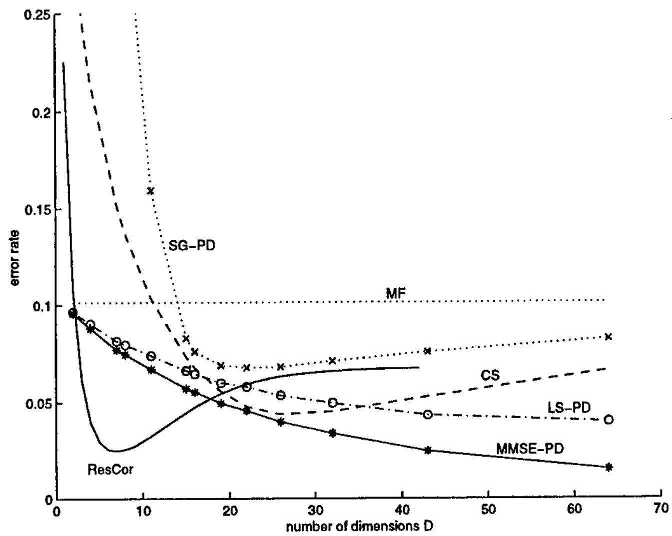

Figure 2: Error rate vs. dimension D for different reduced-rank algorithms after training with 200 symbols. $N = 128$, 40 users. "ResCor"= Residual Correlation method, "MF"= Matched-filter, "CS"= Cross-spectral method, "PD"= Partial Despreading, "SG"= Stochastic Gradient, "LS"= Least Squares.

3 Transmitter Pre-Processing

Pre-processing at the transmitter, in addition to receiver adaptation, can reduce multiple-access interference and associated near-far problems. We propose a scheme in which the spreading code for each user is expressed as a linear combination of D orthgonal basis vectors. (The basis vectors are different from user to user.) The D combining coefficients are selected to minimize Mean Squared Error at the output of the receiver filter. By varying D, steady-state performance can be traded off with the amount of feedback bandwidth required for transmitter adaptation. This technique, reported in [18], can be viewed as a generalization of "one-dimensional" power control. The additional feedback for transmitter updates can be carried by a pilot channel, which has been included in both forward and reverse links of Third Generation Wideband CDMA standards.

Figure 3 shows a plot of averaged SINR at the output of a matched filter vs. dimension D for a synchronous CDMA system with processing gain $N = 32$ and background SNR of 8 dB. The D transmitter combining coefficients are chosen to minimize Mean Squared Error. These results show that the single-user bound is achieved for D much less than the number of users. Results with log-normal shadowing are included, and show that the scheme is robust with respect to received power variations.

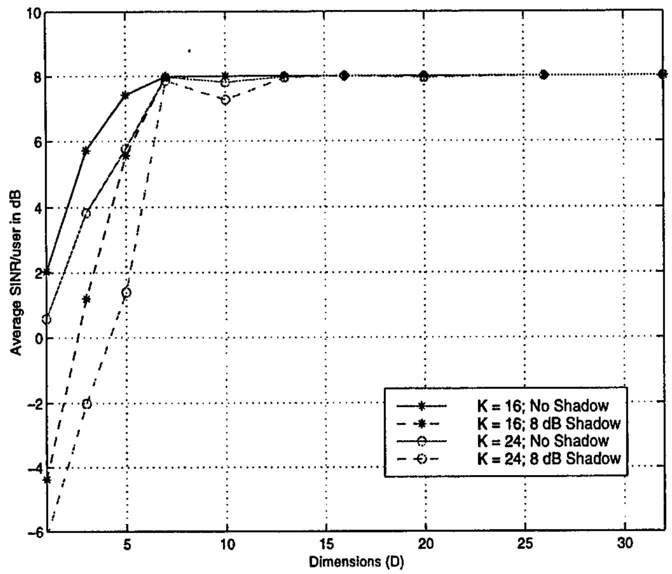

Figure 3: Averaged output SINR vs. D with transmitter pre-processing and a matched filter receiver. K is the number of users.

4 Combined Coding and Interference Suppression

Error control coding is a necessary component of a wireless communications system. We have investigated the performance of combined coding and interference suppression in the presence of strong interference transients, characteristic of packet CDMA with little or no power control. Our results show that coding effectively reduces the error rate due to these transients. Furthermore, the use of a weighted decoding metric, which assigns low reliability to decoder inputs at the onset of the transient, can greatly improve performance. Figure 4 compares the error rates obtained using optimally weighted and unweighted decoding metrics. A single interference transient (new user) is assumed which causes a transient rise in background interference plus noise of 10 dB. The figure shows that the weighted metric gives a dramatic improvement in power savings relative to the unweighted metric at low error rates. In addition to these results, we have also investigated the performance of combined coding and interference suppression in the presence of dynamic fading.

When error control coding is combined with interference suppression, the code rate is an important system parameter. For fixed bandwidth expansion factor (processing gain), a low code rate implies a smaller number of chips per coded bit, and hence fewer adaptive coefficients for interference suppression. That is, there is a tradeoff between the error correction capability of the code and the interference suppression capability of the linear receiver. We have analyzed this tradeoff by computing upper bounds on coded performance with punctured convolutional codes, and by computing cutoff rates. Both large system analysis (number of users K and processing gain N become large with fixed K/N) and computer simulation were used to generate performance

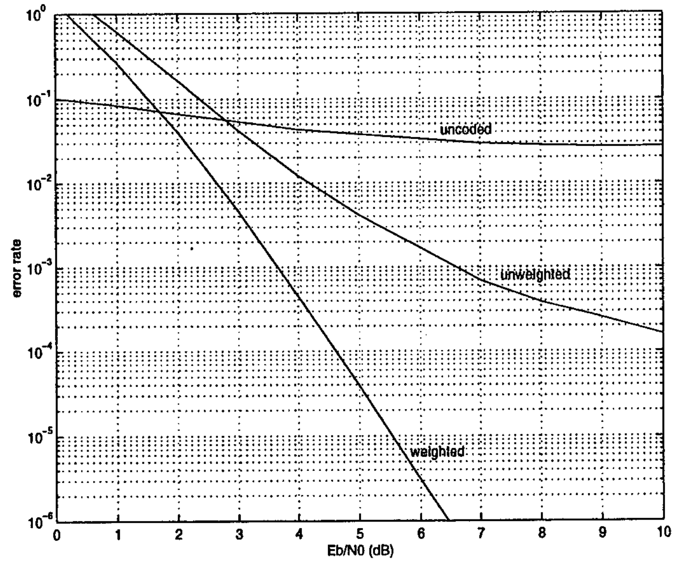

Figure 4: Error rate vs. SNR for an adaptive filter in the presence of a strong interference transient. The interferer causes an initial rise of 10 dB in effective noise variance (noise plus interference). Curves for uncoded transmission, coded transmission with an optimally weighted decoding metric, and coded transmission with an unweighted decoding metric are shown.

results with and without Rayleigh fading.

Figure 5a, taken from [17], shows the union bound on bit error rate vs. load (number users/bandwidth expansion) for convolutional codes with different rates. The constraint length is 8 in each case. Results with and without flat Rayleigh fading are shown. These results show that without fading a high-rate code (3/4) performs the best, whereas with fading the low-rate (1/4) code performs the best. Figure 5b was generated by computing the cutoff rate and shows minimum required E_b/N_0 for reliable communications vs. code rate for different loads. For each case shown, the optimal code rate occurs at the minimum of the curve. These results show that as the load increases, the optimal code rate increases along with the minimum E_b/N_0. Ongoing work includes extending this to multipath fading channels.

5 Performance in the Presence of Fading

In the presence of dynamic (time-selective) fading, the optimal (MMSE) filter coefficients are time-varying. An important issue is whether or not an adaptive algorithm is able to track this optimal solution, and how much performance degradation is caused by tracking error. Adaptive algorithms have been presented which exploit available knowledge of the channel for the desired user (for example, path delays and path gains). The performance of these algorithms has been evaluated by both analysis and computer simulation in [4, 5, 15, 16].

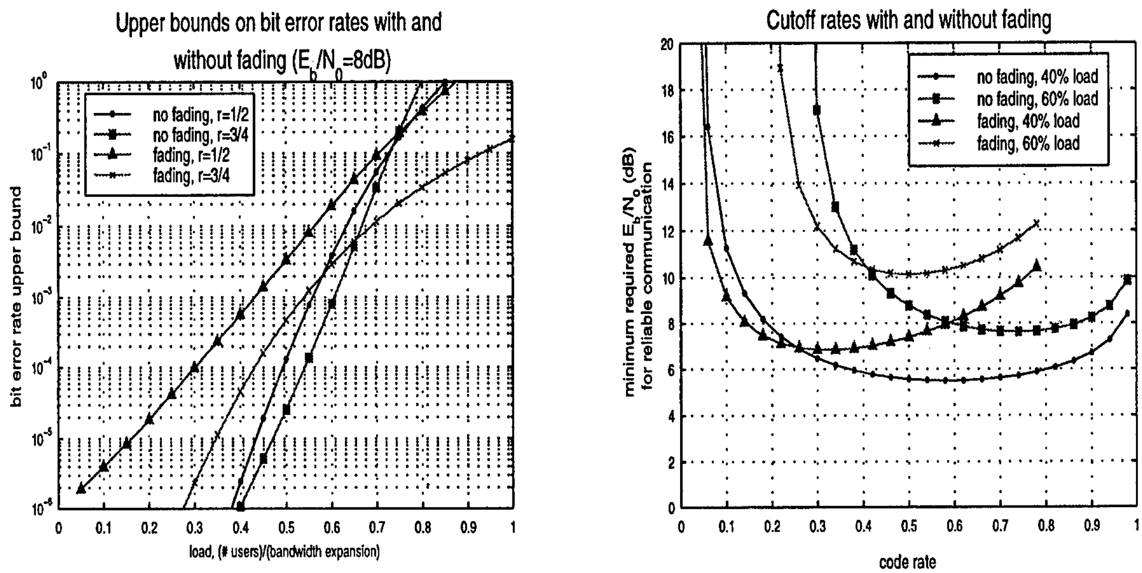

Figure 5: (a) BER vs. load for different rate convolutional codes with and without flat Rayleigh fading. (b) Minimum E_b/N_0 vs. cutoff rate R_0 for different loads.

Our results indicate that the algorithms considered maintain their performance advantage relative to the matched filter in the presence of flat, or non-frequency-selective fading. However, frequency-selective fading can potentially degrade the performance of adaptive algorithms. It is shown that if the interferers are subject to moderate to fast fading, then the adaptive algorithm tends to treat each path as an additional interferer, thereby increasing the dimension of the space spanned by the interference. This compromises the ability of the filter to suppress interference. Even so, the adaptive filter still exhibits robustness to near-far power variations, in contrast to the conventional matched filter.

The performance of adaptive interference suppression in the presence of bursty interference is considered in [14]. A model is considered in which the users are widely distributed over a geographic area, and are subject to log-normal shadowing. "Users" in this case are packets, which arrive according to a stochastic (Poisson) process, and have an exponentially distributed duration. The results show that least squares adaptive algorithms provide a significant gain in capacity relative to the conventional matched-filter, and are insensitive to power variations across the user population.

6 Performance Variability

Because adaptive linear interference suppression requires short spreading codes (say, spanning one symbol), the performance (i.e., Signal-to-Interference-Plus-Noise Ratio (SINR) or error rate) depends on the particular assignment of spreading codes to various users. That is, the performance depends on the cross-correlations between the spreading waveform for the user of interest and other users. With a random assignment of spreading codes, the performance will therefore vary from user to user.

Figure 6, taken from [1], shows distributions for SINR associated with the conventional matched-filter and MMSE linear receivers for a multiple-access CDMA channel with additive white Gaussian noise and a log-normal received power distribution. The processing gain is 32. Two curves, marked "1 dB" and "6 dB" (indicating the standard deviation of the log-normal distribution), are shown for the MMSE detector, corresponding to tight and loose power control, respectively. For the MMSE detector, the distribution shown is with respect to the user population. Although the analogous distribution is shown for the matched filter receiver, each user receives the same performance (the mean of the distribution), provided that the spreading code for each user changes from symbol to symbol.

Figure 6 shows that the spread in SINR over the user population can be significant (e.g., 10 dB). The system operating point (target SINR) for the MMSE detector is chosen so that nearly all users have an SINR which is greater than the mean SINR for the matched-filter receiver. The number of users corresponding to the MMSE detector is twice the number of users corresponding to the matched-filter detector. Also, tight power control is assumed for the matched filter. As power variations over the user population increase (as in a peer-to-peer environment) the relative performance improvement obtained with the MMSE detector increases. This work indicates that in some cases it may be necessary to reassign spreading codes in order to achieve a desired performance.

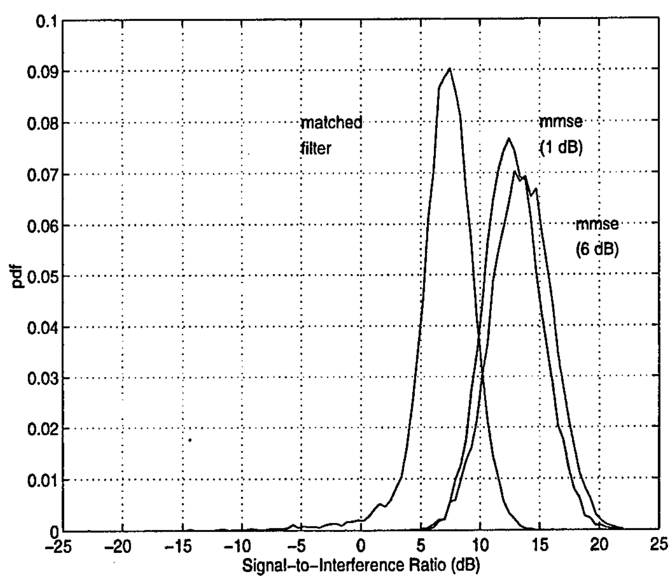

Figure 6: SINR distributions for the matched-filter and MMSE linear detectors.

7 Performance with Mixed-Rate Users

An objective of Third Generation Wideband CDMA systems is to provide variable information rates and Quality of Service. The information rate can be varied by varying the processing gain N and the number of codes. We compare the performance of these two techniques with linear interference suppression in [10]. A disadvantage of the variable spreading gain (single-code) technique is that for high-rate users the output SINR varies periodically with period R_h/R_l symbols where R_h and R_l are the high and low rates, respectively. Consequently, a power control scheme must adjust the power to ensure that the *worst case* Signal-to-Interference-Plus-Noise Ratio (over all symbols) is above the target. An outage occurs if a user must increase the transmitted power above a maximum power limit.

Figure 7, taken from [10], shows achievable regions of SINRs for two classes of users and different receivers, including the matched filter and the linear MMSE receiver. Users in class 2 transmit at four times the rate as users in class 1. For the single-code results shown, the processing gains for the two classes are 64 and 16, respectively. These results show that the MMSE receiver offers a dramatic improvement relative to the matched-filter, and that for the case shown the multi-code scheme offers a significant gain relative to the single-code (variable spreading gain) scheme.

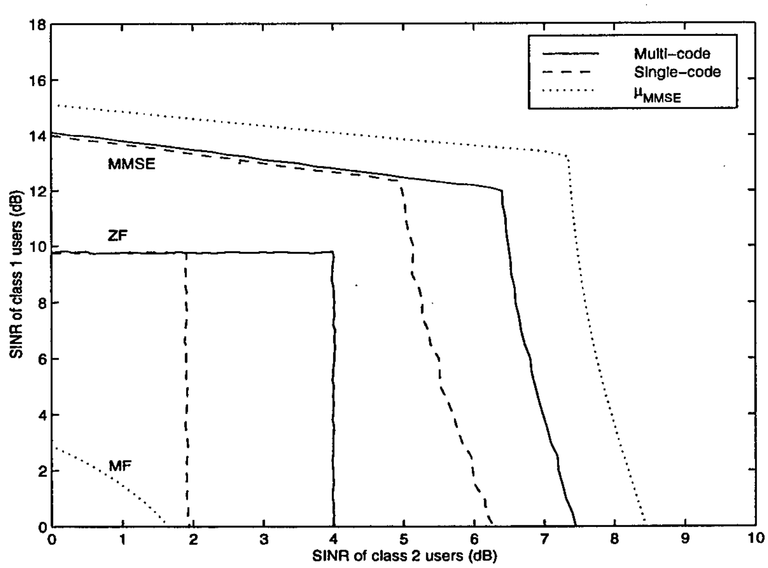

Figure 7: Achievable region of output SINR for two classes of users. Class 2 users transmit at four times the rate as class 1 users. Results for both variable spreading gain (single-code) and multi-code CDMA are shown for the matched filter, zero-forcing, and MMSE receivers.

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9 Participating Scientific Personnel

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- Techaphon Nitisaowaphak, M.S. April 1998
- Aaron Madsen, M.S. May 1998.