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13. ABSTRACT (Maximum 200 words)

This project is concerned with signal processing and coding techniques, which can improve the performance of spread-spectrum multiple-access systems. Specific topics investigated during the course of this project include: (1) Reduced-rank interference suppression; (2) Combined coding and interference suppression, (3) Joint transmitter-receiver optimization in the presence of multiple-access interference; and (4) The effect of limited feedback on the performance of joint transmitter-receiver optimization schemes. The theory of large random matrices has been used to analyze the performance of both interference suppression and interference avoidance schemes. For example, we have used these techniques to analyze the performance of adaptive reduced- and full-rank least squares filtering for interference suppression with limited training. This analysis shows the effects of algorithm parameters, which determine the initialization and data windowing, along with system load and noise level. Other contributions include optimization of the ratio of pilot-to-data power and code rate with adaptive linear interference suppression, and signature optimization for combined interference avoidance and pre-equalization of multi-path. Transmitter optimization with limited feedback has also been considered, and bounds on the achievable performance as a function of feedback bits per dimension have been obtained. This project has resulted in a patent application for an adaptive reduced-rank filter, a paper award (for work on reduced-rank filtering), and numerous journal and conference publications on the preceding topics.

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Problem Statement

One of the main limitations on achievable data rates in multi-user wireless networks is interference. The source of the interference may be from other users or systems, and can vary according to channel conditions and mobility rates. This project has investigated signal processing and coding techniques, which can mitigate interference in spread spectrum systems. Our emphasis has been on Direct-Sequence spread spectrum, although many of the techniques proposed and analyzed have wider applicability. We have focused primarily on linear interference suppression, and interference avoidance. Linear interference suppression at the receiver can be implemented with low-complexity adaptive filters. Adaptability is important for mobile wireless applications, in which the user channels and interference vary with time. A fundamental challenge is how to improve the performance of adaptive linear interference suppression filters with limited training, and with acceptable complexity. Interference avoidance can be achieved by changing user signatures at the transmitter, and requires feedback from the receiver about interference and channel conditions. In what follows, we highlight some of our main results obtained during the course of this project. Citations refer to the list of journal and conference publications listed at the end of this report.

Summary of Results

Reduced-Rank Interference Suppression

A reduced-rank filter projects the input signal onto a lower dimensional subspace for further processing. This has the advantage of potentially reducing complexity, and reducing the amount of training required to achieve a given target performance. In [6], the output Signal-to-Interference Plus Noise Ratio (SINR) is evaluated for a few different reduced-rank filters as a function of the filter rank, or the (reduced) dimension of the signal subspace. The results are asymptotic as the number of users and processing gain tend to infinity with fixed ratio, and uses results from the theory of large random matrices. This analysis shows that a low-rank Multi-Stage Wiener Filter (MSWF) can achieve near full-rank performance independent of the system size (i.e., number of users). We also show that the signal subspace associated with the MSWF is a Krylov subspace. Namely, each basis vector can be obtained by multiplying the preceding basis vector by the (estimated) covariance matrix. The initial basis vector is the (estimated) steering vector. This technique does not require an explicit estimate of the signal subspace, and performs well under heavy loads. We have also shown that the optimal rank can be adaptively estimated. A patent application has been filed for this reduced-rank filtering technique. The paper [6] received the IEEE Communications Society and Information Theory Society Joint Paper award.

Adaptive versions of the MSWF have been presented in [8], which require only a training sequence for filter estimation. In [22] a simple rank-order-recursive method is presented for updating the reduced-rank filter coefficients. Namely, the filter for rank D+1 is recursively determined from the rank-D filter. This enables a scheme for adaptively selecting the rank to optimize performance for any training length. This method is applied to reduced-rank space-time equalization in [27].

An analysis of both reduced- and full-rank adaptive filters with finite training is presented in [10],[12],[19]. Convergence analysis of adaptive Least Squares estimators is a notoriously difficult problem. Our approach again uses the theory of large random matrices to compute the asymptotic output SINR as a function of time. Asymptotic in this case refers to the limit as the number of users, processing gain, *and training length* all tend to infinity with fixed ratio. Numerical results show that this analysis accurately predicts the performance of finite-size systems of interest. We also observe that the reduced-rank filter generally requires less training than the analogous full-rank filter.

Interference Suppression with Coding and Channel Estimation

Interference suppression can be facilitated through the use of a pilot channel, which can be used to estimate the channel of the desired user. In that case, the ratio of pilot-to-data power is a parameter, which can be optimized. In [9],[15], the output SINR of the receiver filter is computed as a function of the pilot-to-data power ratio, and other system parameters, such as load and noise level. This is used to optimize the pilot-to-data power ratio in different scenarios. We also studied the performance with convolutional coding, and optimized the code rate using the cutoff-rate as our performance objective. Our results show that a Minimum Mean Squared Error (MMSE) detector is more robust with respect to the selection of a suboptimal code rate than is the conventional matched filter.

Iterative Coding and Interference Cancellation

In general, nonlinear interference cancellation, or decision-feedback techniques may perform better than linear filtering in some situations. Papers [13],[14], and [21] describe nonlinear adaptive decision-feedback detectors (DFDs) with iterative (turbo) decoding. The iterative receiver exchanges information between a soft-in/soft-output MAP decoder for a convolutional code, and the multi-user DFD. Our results show that the adaptive algorithm improves the performance relative to a conventional canceller by exploiting the joint input and output statistics of the MAP decoder. This receiver gives a dramatic performance improvement relative to a linear (noniterative) MMSE receiver.

Signature Optimization

The objective of signature optimization is to avoid interference while pre-combining multipath. The performance of optimized signatures in the presence of multipath is studied in [7] and [17]. Adaptive algorithms for signature estimation have been proposed for both a peer-to-peer and (reverse-link) cellular networks. Performance has been evaluated in the latter scenario in the presence of multipath, and shows that signature optimization can provide substantial performance gains relative to receiver adaptation alone.

To reduce the amount of feedback required, and to reduce the complexity of signature estimation, a reduced-rank scheme is proposed in which the signature is constrained to lie in a lower dimensional subspace. It is shown that low-rank optimization of the signature still gives a substantial performance improvement relative to random signature selection. The performance of this reduced-rank scheme with limited feedback is evaluated in [25]. Given a small number of feedback bits for signature quantization, this scheme gives a substantial improvement in performance relative to scalar quantization of the optimized signature.

We have studied signature optimization for a data service in which multiple signatures can be assigned to each user [23]. This leads to an approach analogous to multi-carrier signaling in which power and bits are allocated across a set of carriers to maximize the total rate. For the multi-code CDMA case considered, the "carriers" are eigenvectors of the appropriate interference plus noise covariance matrix. We have shown that multi-carrier signaling also maximizes the information rate for downlink CDMA, assuming that each user has a linear receiver and a single-user decoder [24]. Downlink signature optimization with multiple transmitter antennas is considered in [33]. Multi-carrier signaling again maximizes capacity, and we derive the rate at which the capacity grows as a function of the number of antennas, users, and background noise.

Multi-Carrier CDMA

Multi-carrier (MC)-CDMA assigns spreading signatures in the frequency domain, rather than the time domain. We have analyzed the performance of MC-CDMA in the presence of frequency-selective Rayleigh fading with multiple users, and multiple signatures per user in [11,26,28,32]. Our results apply in the large system limit as signatures and processing tend to infinity with fixed ratio, and enable the computation of performance measures as a function of system parameters such as data rates per user, noise level, and number of users. We have analyzed both output SINR and the capacity of MC-CDMA with the optimal receiver, and with an optimal linear receiver. This analysis enables us to determine the code rate that maximizes the sum capacity over all users.

Joint Transmitter-Receiver Optimization with Limited Feedback

Joint transmitter-receiver optimization in general assumes that a feedback channel is available to relay channel information back to the transmitter. We have studied the performance of joint transmitter-receiver optimization with finite feedback in [25,29-31,34]. That is, the receiver is allowed to relay a fixed number of bits back to the transmitter. In [25] and [30], we study signature optimization for Direct-Sequence CDMA. The same analytical approach is applied to Multi-Input/Multi-Output (MIMO) channels in [31]. In [29] and [34] we study multi-carrier transmitter optimization. Using the theory of extreme order statistics, we compute an upper bound on the achievable SINR of DS-CDMA with signature optimization as a function of the number of feedback bits per dimension (processing gain). We have compared this performance with that of reduced-rank signature optimization with scalar quantization of filter coefficients described earlier. Although the reduced-rank signature scheme is relatively simple, it still performs relatively close to the upper bound for the cases examined.

We have also characterized the growth in achievable data rate for single-user multi-carrier transmission as a function of the number of feedback bits per sub-channel [29]. Specifically, we have shown that in the presence of independent Rayleigh fading sub-channels, a capacity increase of $O(\log N)$ can be achieved with $O(\log^3 N)$ feedback bits, where N is the number of sub-channels. Furthermore, $O(\log N)$ is the growth in capacity achieved with perfect channel knowledge at the transmitter (i.e., water pouring). This work is generalized in [34] to the case where the sub-channels are correlated. In that case, the amount of feedback required to achieve the $O(\log N)$ growth depends on the correlation among sub-channels, but is generally much less than that required for independent sub-channels.

Performance of Linear Interference Suppression with Fading

In a mobile wireless environment the channels are time-varying, which causes the optimal linear interference suppression filter to vary with time. The filter must be adaptive in order to track the optimal solution, and the performance depends on the particular algorithm and the rate at which the channel varies. In [3],[5], adaptive filtering algorithms are presented and evaluated, which exploit available channel knowledge for the desired user in order to improve performance.

Journal Papers Published

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11. M. Peacock, I. Collings, and M. L. Honig, “Asymptotic Analysis of LMMSE Multiuser Receivers for Multi-Code Multi-Carrier CDMA in Rayleigh Fading", submitted to *IEEE Transactions on Communications*, August 2002.

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12. W. Xiao and M. L. Honig, "Convergence Analysis of Adaptive Reduced-Rank Linear Filters for DS-CDMA", *Proc. Conf. On Information Sciences and Systems*, Princeton, NJ, March 2000.

13. M. L. Honig, G. Woodward, and P. D. Alexander, "Adaptive Multiuser Parallel Decision-Feedback with Iterative Decoding", *Proc. IEEE Int. Symp. On Information Theory*, p. 995, Sorrento, Italy, June 2000.

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15. W. Phoel and M. L. Honig, "Optimization of the Pilot-to-Data Power Ratio for DS-CDMA with Linear Interference Suppression", *Proc. Wireless Communications and Networking Conference*, Sept 2000, Chicago, IL.

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33. H. Bi and M. L. Honig, "Forward Link Capacity Scaling with Linear Receivers and Multiple Transmit Antennas", *IEEE Globecom Conf.*, San Francisco, Ca., December 2003.

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Scientific Personnel

1. Michael L. Honig, Professor
2. Weimin Xiao, Graduate Research Assistant, Ph.D. awarded June 2001
3. Wiroonsak Santipach, Graduate Research Assistant, M.S. awarded 2002 (continuing for Ph.D.)
4. Yakun Sun, Graduate Research Assistant, M.S. awarded 2002 (continuing for Ph.D.)

Invention and Award

1. Patent Application: *Reduced-Rank Adaptive Filter*, filed Oct 2000.

2. IEEE Communications Society and Information Theory Society Joint Paper Award (for paper [6])