Multidisciplinary University Research Initiative

Space-Time Processing for Tactical Mobile Ad Hoc Networks

Interim Report

August, 2009

Submitted to U.S. Army Research Office

Grant No. W911NF-04-1-0224

PI: James R. Zeidler

Co-PIs: J.J. Garcia-Luna, Yingbo Hua, Simon Haykin, Hamid Jafarkhani,
Tara Javidi, Michael Jensen, Srikanth Krisnamurthy, Laurence Milstein,
John Proakis, Bhaskar Rao, A. Lee Swindlehurst, Michele Zorzi

Contact: Dr. James R Zeidler, University of California, San Diego, Department of Electrical and Computer Engineering, 9500 Gilman Dr. #0407, La Jolla, CA 92093-0407. Tel: (858)534-5369

Email: Zeidler@ece.ucsd.edu

Table of Contents

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED August 1, 2008 to July 31, 2009

4. TITLE AND SUBTITLE
Space-Time Processing For Tactical Mobile Ad Hoc Networks

5. FUNDING NUMBERS
W911NF0410224

6. AUTHOR(S) James Zeidler (PI), J.J. Garcia-Luna, Simon Haykin, Yingbo Hua, Hamid Jafarkhani, Tara Javidi, Michael Jensen, Srikanth Krisnamurthy, Laurence Milstein, John Proakis, Bhaskar Rao, A. Lee Swindlehurst, Michele Zorzi

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California - San Diego
Office of Contract and Grant Administration
9500 Gilman Drive, Mail Code 0934 La Jolla, CA 92093-0436

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
46637CIMUR

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Recent developments in communication systems technology promise to greatly improve the performance of point-to-point communications for both commercial and tactical networks. These developments include the use of electronically steerable antenna arrays, space-time multiple input multiple output (MIMO) signal processing techniques, and improved techniques for error correction. In this project we will address the challenging question of how these technological developments can best be exploited in a tactical networking context, where signal interference and channel uncertainty issues have a tremendous impact on end-to-end system performance.

Tactical applications pose unique requirements for the network, including decentralized control to eliminate single points-of-failure, vulnerability to jamming and electronic warfare, and mission critical latency bounds for end-to-end data delivery. Moreover, a tactical network is generally composed of mobile nodes and the routing protocols must deal with a range of node mobilities and time varying channel conditions. Consequently this project is focused on the design of ad hoc networking architectures that utilize MIMO transmitters and receivers at each node. The goal of this program is to define the best way to utilize multiple transmit and receive antennas at each node to improve the robustness, capacity, and quality of service of the network.

14. SUBJECT TERMS
ad hoc networks, wireless networks, MIMO, tactical networks, mobile networks, channel estimation, channel measurements, directional antennas, space-time coding

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT **UNCLASSIFIED**	18. SECURITY CLASSIFICATION ON THIS PAGE **UNCLASSIFIED**	19. SECURITY CLASSIFICATION OF ABSTRACT **UNCLASSIFIED**	20. LIMITATION OF ABSTRACT **U**

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

Enclosure 1

Abstract

Recent developments in communication systems technology promise to greatly improve the performance of point-to-point communications for both commercial and tactical networks. These developments include the use of electronically steerable antenna arrays, space-time multiple input multiple output (MIMO) signal processing techniques, and improved techniques for error correction. In this project we will address the challenging question of how these technological developments can best be exploited in a tactical networking context, where signal interference and channel uncertainty issues have a tremendous impact on end-to-end system performance.

Tactical applications pose unique requirements for the network, including decentralized control to eliminate single points-of-failure, vulnerability to jamming and electronic warfare, and mission critical latency bounds for end-to-end data delivery. Moreover, a tactical network is generally composed of mobile nodes and the routing protocols must deal with a range of node mobilities and time varying channel conditions. Consequently this project is focused on the design of ad hoc networking architectures that utilize MIMO transmitters and receivers at each node. The goal of this program is to define the best way to utilize multiple transmit and receive antennas at each node to improve the robustness, capacity, and quality of service of the network.

1. Introduction

The project team consists of fourteen faculty members from four campuses of the University of California (San Diego, Irvine, Santa Cruz, and Riverside); Brigham Young University, Provo, Utah; and McMaster University, Hamilton, Ontario, Canada. The individual faculty members were selected for specific areas of expertise that together spanned the wide ranging research concentration areas defined in the initial BAA for the topic area. The specified concentration areas spanned "the physics of RF propagation and signal processing; the electrical engineering of antenna array design and electronics; computer science of networking; and the mathematics of information and control theory".

The specified objective of this MURI topic was to "create network protocols and signal processing algorithms necessary to implement adaptive beam steering and spatial channel reuse in mobile wireless communication networks with the specific objective of enabling reuse of radio channels to double network capacity and improve protection for military communications. The research should also result in the science that will allow for the decision of which spatial reuse technique to use (space-time coding (STC) or transmit beam forming), if any, based on topology and network load.

A series of project meetings have been held at UCSD and UC, Irvine over the course of this project. The goal of these meetings was to first define a hierarchy of problems that require resolution and then outline the approaches to solve these problems so that robust and reliable mobile ad hoc networks can be developed for tactical applications. These group meetings have led to joint work between PIs, joint publications, co-advising of graduate students, and numerous visits between subgroups of PIs to identify viable approaches for solving cross-layer networking problems.

The problem definition, research issues and the overall project research goals were defined in the previous interim annual reports and the work during the past year has focused on satisfying these established goals.

This report describes the specific accomplishments for the current year from August 1, 2008 through July 31, 2009. During this period we have made significant progress in meeting the objectives of "providing cross-layer, energy efficient MIMO signal processing algorithms for mobile multiuser ad hoc networks employing directional antenna arrays and space time coding (STC) for tactical applications." We have successfully developed techniques for exploiting beamforming (BF) and STC for improved collision avoidance. Our results clearly indicate however, that the full potential for the integration of the physical layer information from MIMO antennas into the routing and scheduling protocols for a tactical ad hoc network will only be achieved by developing a fundamentally new approach to the protocol development that utilizes the antennas to enable multiple simultaneous transmissions from multiple nodes to provide multi-packet reception capablilities at each node. The results show that the network performance will be optimized by utilizing the spatial processing gains afforded by the antennas to manage the interference in a controlled fashion rather than simply trying to improve existing network routing and scheduling protocols to reduce the number of collisions.

In addition, the results clearly show the advantages of cooperative communications between nodes using either relay nodes and/or virtual MIMO nodes. These approaches provide energy efficient utilization of the network resources and enable the development of protocols with significant spatial spreading gain even for nodes with limited antenna resources. Such cooperation has also been shown to provide improved space-time scheduling in terms of fairness and quality of service.

The utilization of MIMO assets forces the entire question of channel capacity in MIMO ad hoc networks to be reexamined as a function of how the information is disseminated. The use of unicast, multicast, broadcast and various forms on one-to-one, one-to-many and many-to-many routing can be done more efficiently with multiple antennas at the nodes. The optimization of the routing protocols depends fundamentally on the quality of the channel state information (CSI) that is available at the nodes of the network however, and significant effort has been made to define the best transmission strategies as a function of the available CSI. A testbed has been developed and tested to evaluate end-to-end performance of different topologies in multi-hop ad hoc networks.

The relations between MIMO signal processing and network coding have been explored and novel rate adaptation techniques that can trade off rate for coding and diversity gain have been developed. In addition network metrics such as information efficiency and throughput have been defined in terms of physical layer parameters such as the modulation and coding schemes, the channel statistics, the Doppler rate and the spatial diversity order. The selection of the appropriate number of training symbols to assure given levels of throughput, delay and efficiency were also evaluated. The dependence of the information efficiency and network throughput on the underlying physical parameters of the network was also extended to random multi-hop networks.

One of the initial barriers to crosslayer integration of the physical layer information into the routing and scheduling protocols was the significant differences between the time scales associated with the relative time scales of channel variations at the physical layer that occur at the symbol rate and the temporal stability (nominally a packet interval) that is deemed necessary for reliable routing and scheduling. Stable subspaces in the channel impulse response have been identified for which stable transmission can be sustained without instantaneous channel state information at the transmitter. This was accomplished using channel distribution information instead of CSI. The reduction in the required feedback requirements for CDI vs CSI have been quantified. The effect of quantized noisy feedback in the CSI estimates was also investigated and the concepts of network beamforming and distributed beamforming have been examined.

A number of methods to minimize the impact of mutual interference in a multi-user network have been examined. In addition to the use of beamsteering to avoid nodes that are generating interference in the network, the use of interference cancellation techniques based on multi-user detection has been investigated.

The overall performance attainable by a mobile ad hoc network depends fundamentally on the MIMO channel characteristics. During the past year the previous models were refined using several different modeling approaches for time varying MIMO channels

During this period the project team has written a total of 40 journal papers that have been published or accepted for publication. We have also presented 35 conference papers and completed 17 manuscripts that have been submitted to peer reviewed journals and are currently under review. In addition, a book *Modeling MIMO Channel Models* was co-authored by one of the PIs and his graduate student and accepted for publication by Wiley Press in 2009. Also, a chapter “Interference Rejection and Management” was co-authored by three of the PIs on the project and published in the book *New Directions in Wireless Communications Research* by Springer-Verlag in 2009. The lists of the papers published and submitted for publication under this project is provided in Appendix 3.

A summary of the major research activities conducted and results that were obtained is provided below. Detailed descriptions of the overall results are provided in the papers listed in the Appendicees. In addition these papers are posted on the ARO website and also on the project website at http://zeidler.ucsd.edu/~muri

2.0 Scientific Progress and Accomplishments

2.1 Antenna Design and Multi-User Feedback Reduction for MIMO Communications in Mobile Ad Hoc Networks

PI: Michael A. Jensen

GSR: Yan Shi, Daniel Evans

Prior work in optimal MIMO antenna design had not constrained the solution to result in physically realizable antennas. We extended the prior work to incorporate a constraint of physical realizability in order to design optimal MIMO antennas that are practically implementable.

Feedback Complexity Reduction for CDI-based Signaling: Our joint work with UCSD has focused on the use of covariance-based transmission for time-variant channels which reduces the feedback of the frequency but increases the complexity of each feedback event. This work demonstrates the application of matrix compression techniques for dramatically reducing the feedback complexity for CDI-based signaling.

In the following sections, we summarize our progress in these areas.

Optimal MIMO Antenna Design

Recent work has shown how to specify antenna radiation patterns which maximize the diversity gain given the stochastic power angular spectrum (PAS) of a multipath propagation environment and an aperture within which the antennas must reside [1]. However, achieving these characteristics is difficult if not impossible, since they require that the current distributions for the different elements overlap in the aperture. This work presents several variants of the approach which can determine near-optimal radiation patterns under the constraint that the apertures (and therefore currents) for the elements do not overlap. Computational examples show that some of the methods can consistently provide performance which rivals that achievable with the optimal results for overlapping currents.

Theoretical Framework

We assume that the vector incident field $\overline{\mathbf{p}}_{\text{inc}}(\theta,\phi)$ impinging on the antenna array is a zero-mean complex Gaussian stochastic process with the field arriving at one angle uncorrelated with that arriving at another angle. The dyadic PAS, or the average impinging power per unit angle, is $\overline{\overline{\mathbf{P}}}(\theta,\phi)=\mathrm{E}\{\overline{\mathbf{p}}_{\mathrm{inc}}(\theta,\phi)\overline{\mathbf{p}}_{\mathrm{inc}}^{*}(\theta,\phi)\}$, where $\{\cdot\}^{*}$ is a conjugate and $\mathrm{E}\{\cdot\}$ denotes an expectation. If $\overline{\mathbf{e}}_{m}(\theta,\phi)$ represents the open-circuit radiation pattern of the *m*th antenna, the covariance matrix for the open-circuit antenna voltages has elements [1]

$$R_{mp}=\int_{\Omega}\overline{\mathbf{e}}_{m}(\theta,\phi)\cdot\overline{\overline{\mathbf{P}}}(\theta,\phi)\cdot\overline{\mathbf{e}}_{p}^{*}(\theta,\phi)d\Omega\,.$$

The diversity gain may be computed by creating an equivalent system of uncorrelated antennas with the branch gains given by the eigenvalues of the covariance matrix [2]. Therefore, antennas which maximize these eigenvalues will maximize the system diversity gain.

The synthesis of the optimal antenna patterns begins by using standard electromagnetic analysis to relate the *m*th radiation pattern to a vector current function $\overline{\mathbf{j}}_{m}(\overline{\mathbf{r}})$ confined to an aperture. If the currents for different elements (values of *m*) are allowed to overlap within the same aperture, we expand the current functions using orthogonal vector basis functions using

$$\overline{\mathbf{j}}_{m}(\overline{\mathbf{r}})=\sum_{n}B_{nm}\overline{\mathbf{f}}_{n}(\overline{\mathbf{r}}),$$

where B_{nm} represents an unknown weighting coefficient. With this expansion, the covariance becomes $\mathbf{R}=\mathbf{B}^{T}\mathbf{C}\mathbf{B}^{*}$, where $\{\cdot\}^{T}$ is a transpose and **C** can be computed from known quantities. Additionally, constraints are placed on the coefficients such that 1) each pattern has unit radiated power and 2) antenna superdirectivity is limited. These constraints produce a modified version of the matrix **C**, and the dominant eigenvectors of this modified matrix are used to construct the current coefficients which maximize the diversity gain [1]. Unfortunately, the resulting antennas are difficult if not impossible to synthesize since the specified currents overlap in the aperture. Our goal is therefore to determine non-overlapping currents (antennas) whose performance comes close to that of the optimal elements.

Covariance Method: Consider first applying the eigen-analysis to each aperture individually and selecting the dominant eigenvector as the coefficients for each antenna. This maximizes the power received by each aperture but neglects cross-correlation, and therefore the approach should work well only for reasonably-spaced apertures.

Modified Covariance Method: In this case, we determine the current distribution of Aperture 1 using the Covariance Method and compute the diversity gain obtained using the radiation characteristics of Aperture 1 coupled with the current distribution associated with each of the possible eigenvectors for Aperture 2. The eigenvector producing the maximum diversity gain is then selected. For each subsequent aperture, this procedure is repeated based upon the already-selected currents. This helps to incorporate the impact of correlation in the computation.

Current Method: Let $\mathbf{b}_m$ represent the *m*th column of **B** representing the optimal coefficients for the *m*th current distribution, with $\mathbf{b}_m^i$ corresponding to the elements of $\mathbf{b}_m$ representing the currents in Aperture *i* (this assumes each basis function has support in only a single aperture). Furthermore, let $\mathbf{w}^i$ represent the unknown coefficients describing the currents in Aperture *i*. To find the vectors $\mathbf{w}^i$ that form a good basis for $\mathbf{b}_m^i$, we solve

$$\mathbf{w}^i = \arg\max_{\mathbf{w}} \sum_m \Gamma_m \cos^2\theta_m^i$$

where θ_m^i is the angle between $\mathbf{b}_m^i$ and $\mathbf{w}$. The weight Γ_m allows placing emphasis on dominant modes and is selected according to $\Gamma_m = \Lambda_m \left\|\mathbf{b}_m^i\right\|^2$, where Λ_m is the eigenvalue of the covariance matrix corresponding to the current weight $\mathbf{b}_m$. Since $\cos^2\theta_m^i = \mathbf{w}^H \mathbf{b}_m^i \mathbf{b}_m^{iH} \mathbf{w} / \left(\left\|\mathbf{b}_m^i\right\|^2 \mathbf{w}^H \mathbf{w} \right)$, we can write

$$\mathbf{w}^i = \arg\max_{\mathbf{w}} \frac{\mathbf{w}^H \tilde{\mathbf{B}}^i \mathbf{w}}{\mathbf{w}^H \mathbf{w}}$$

where $\tilde{\mathbf{B}}^i = \sum_m \Lambda_m \mathbf{b}_m^i \mathbf{b}_m^{iH}$. The optimal value of $\mathbf{w}^i$ is the dominant eigenvector of $\tilde{\mathbf{B}}^i$.

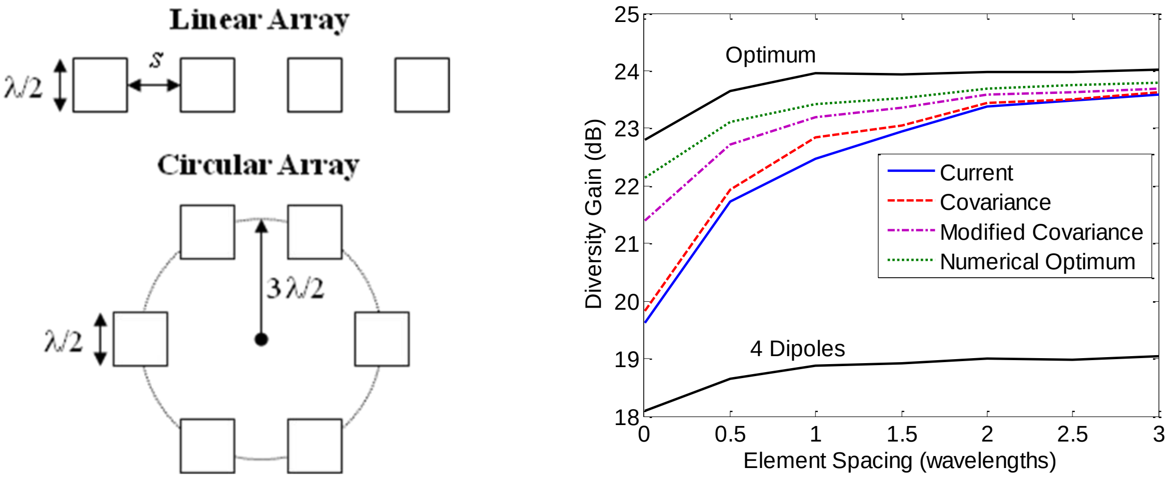
Numerical Optimization: Starting with the currents from the Modified Covariance Method, we apply a simplex optimization to refine the currents to maximize the system diversity gain. While this does not guarantee a global maximum, it does demonstrate the scale of improvement that can be expected from numerical optimization.

Results

For the computations used in evaluating these techniques, we restrict ourselves to a two-dimensional scenario, where the basis functions are two-dimensional square pulse functions. These two-dimensional representations are suitable for environments where the propagation has a single polarization and is confined to the horizontal plane. The PAS consists of multiple clusters each characterized by a Laplacian function defined by a mean angle in the azimuthal plane computed as a random variable uniformly distributed on $[0, 360^\circ)$, a relative strength computed as a random variable uniformly distributed on [1, 10], and an angle spread (width of the Laplacian). For each computation, 1000 different statistical realizations of the PAS are constructed, and the diversity gain results represent average values. The diversity gains are computed at the 1% probability level assuming maximal ratio combining with an isolated dipole used as the reference [2].

Figure 1(a) shows the geometry of the aperture arrays used in the computations. Each array consists of a set of square apertures, □/2 on a side, and configured either in a linear array of four apertures or a circular array of six apertures. In each aperture, 25 pulse functions arranged in a 5 by 5 grid are used to represent the currents. The diversity gain obtained using the radiation characteristics computed using the methods outlined above is compared with that obtained from Hertzian dipole antennas placed at the centers of the apertures.

Figure 1(b) plots the average diversity gain for the linear array of apertures computed with the different methods as a function of the spacing s between the aperture edges. The number of PAS clusters is uniformly drawn from a discrete set of integers between one and four, while the angle spread of each cluster is a uniformly distributed random variable on $\left[15^\circ, 50^\circ\right]$. These results show that as the spacing increases, the diversity gain for the three approximate methods converges to the same value. This is because much of the diversity is created by the wide array spacing, and therefore the techniques must only create radiation patterns which maximize the gain. Furthermore, the performance of the approximate techniques approaches that of the optimal radiation characteristics (overlapping currents) for the same reason. All of the techniques produce radiation characteristics which significantly outperform those of the dipole array, emphasizing the fact that shaping the element response can provide significant benefit. Finally, it is interesting to recognize that the performance of the optimal elements and the dipoles remain relatively constant for spacings larger than a wavelength.



(a)

(b)

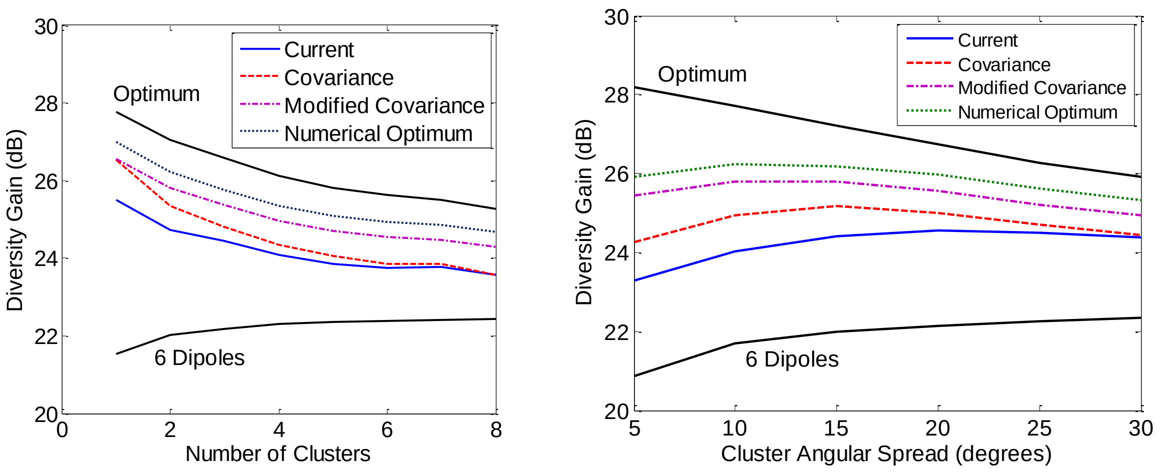
Figure 1: (a) Geometry of the apertures used for the computational examples. (b) Average diversity gain versus s for the four-element linear array.

Next, we consider the case of the circular array of apertures and the corresponding array of dipoles. Figure 2(a) plots the average diversity gain as a function of the number of clusters in the PAS when the angle spread is chosen randomly as outlined above. These results show that increasing multipath creates a reduction in diversity gain for all methods, since the apertures are no longer able to effectively increase performance by focusing the radiation pattern in specific directions. In contrast, the diversity gain of the dipoles increases as the increased multipath richness creates a better environment for diversity processing. These curves also demonstrate that the Modified Covariance Method is on average best able to determine the radiation characteristics appropriate for the environment. Figure 2(b) shows the diversity gain versus the cluster angle spread when four clusters are used in the PAS. These results reinforce the observations concerning multipath richness and performance, and further show that the performance degrades when the angle spread becomes too narrow.

Table I: Diversity Gain Performance Relative to those of the Optimal Radiation Characteristics

	Single PAS (dB)	Average over 1000 PAS (dB)
Numerically Optimized	-0.59	-
Covariance	-3.69	-3.50
Modified Covariance	-1.35	-1.39
Current	-3.02	-2.89

Table I shows the values of diversity gain in dB relative to the performance of the optimal overlapping antennas for a single representative PAS as well as the average taken over 1000 random PAS shapes. The average numerically optimized results are not shown due to the large computation time for this method. These results show that the numerically-optimized results can nearly achieve the performance of the ideal radiation characteristics and confirm that the Modified Covariance Method is superior to the other methods.



(a) (b)

Figure 2: (a) Average diversity gain versus the number of clusters in the PAS for the six-element circular array. (b) Average diversity gain versus the angle spread of the four clusters in the PAS for the six-element circular array.

Feedback Reduction for the MIMO Broadcast Channel

The use of MIMO technology in the multi-user broadcast channel is an intriguing possibility, as it enables dramatic increase in network throughput over single-antenna implementations. However, when the transmit precoding is performed based on the channel state information (CSI) at the transmitter [3], [4], the performance is highly sensitive to CSI errors due to inaccurate channel estimation, stale CSI due to channel time variations, or inadequate knowledge of the channel frequency response in frequency-selective channels [5]-[7]. This has motivated the development of a precoding strategy based on channel distribution information (CDI) at the transmitter, in the form of spatial correlation matrices, that offers stable performance in the time-varying and frequency-selective MIMO broadcast channel [6], [7]. While the multi-user sum rate of such an approach is suboptimal compared to the case of non-linear dirty paper coding (DPC) or linear capacity optimal beamforming techniques with perfect CSI, the fact that the CDI remains more constant in time and frequency enables the approach to offer superior average throughput with infrequent feedback events.

The cost of using CDI-based techniques, however, is that the complexity of each feedback event can be very high. For example, given a MIMO system with N_t transmit and N_r receive antennas, CSI- and CDI-based schemes respectively require feedback of an $N_\mathrm{r} \times N_\mathrm{t}$ channel matrix and $N_\mathrm{r} N_\mathrm{t} \times N_\mathrm{r} N_\mathrm{t}$ covariance matrix for each user. This dramatic difference in feedback complexity motivates the development of new methods for reducing the feedback communication requirements. Recently, it has been shown that by using simple models – such as the well-known Kronecker model – for the covariance structure, the volume of required feedback data can be reduced to a level similar to that required for CSI-based precoding [6]. However, further research focused on additional reductions in the required feedback and detailed comparisons showing how reduced-feedback CDI-based precoding performs relative to CSI-based precoding for the MIMO broadcast channel has yet to be completed.

The goal of this work is to demonstrate use of the Karhunen-Loeve (KL) Transform to compress the amount of information that must be fed back to the transmitter when using CDI signaling. The performance of the approach is assessed using long channel time series created with a clustered physical channel model based on experimental measurements. The results show that excellent results can be obtained with significant reduction in feedback complexity.

System Description and Channel Model

The MIMO broadcast channel consists of a single transmitting node with N_t antennas and N_u receiving nodes each with N_r antennas. We represent the $N_\mathrm{r} \times N_\mathrm{t}$ channel matrix from the transmitter to the *j*th user and at the *k*th sample time as $\mathbf{H}_j^{(k)}$. Assuming that transmit precoding (non-linear or linear) has been applied such that $\mathbf{x}_j^{(k)}$ represents the $N_\mathrm{t} \times 1$ precoded vector destined for the *j*th user at the *k*th sample time, the $N_\mathrm{r} \times 1$ received vector for the *j*th user at the *k*th sample time can be expressed as

$$\mathbf{y}_j^{(k)} = \mathbf{H}_j^{(k)}\mathbf{x}_j^{(k)} + \sum_{i=1,i\neq j}^{N_\mathrm{u}} \mathbf{H}_j^{(k)}\mathbf{x}_i^{(k)} + \boldsymbol{\eta}_j^{(k)}$$

where $\boldsymbol{\eta}_j^{(k)}$ is an $N_\mathrm{r} \times 1$ vector of zero-mean unit-variance additive white Gaussian noise. Note that this model can be extended to frequency-selective channels by adding a frequency index, although this is not included here as our focus is on narrowband time-varying channels.

Transmit Precoding

Given this system description, we turn our attention to the precoding methods used for the MIMO broadcast channel. While dirty paper coding represents the optimal communication strategy [5], prior research has clearly demonstrated that its performance is highly sensitive to accuracy of the transmit CSI, resulting in rapid throughput degradation as the CSI becomes stale [6]. Since the behavior of dirty paper coding with error in the CSI is similar to that encountered with linear beamforming, such as the capacity optimal regularized channel inversion (CO-RCI) [6], we keep the comparison simple and use CO-RCI as the benchmark technique for CSI-based beamforming (CSI-BF). This approach derives the multi-user beamforming vectors at the transmitter directly from the CSI which must be fed back from each receiver to the transmitter. From a practical perspective, since feedback cannot occur for data transmission at all sample times, the beamforming vectors are derived from the channel $\mathbf{H}_j^{(k_0)}$ and are used for some finite time window characterized by a finite set of samples $k_0 \le k < k_0 + K$.

For CDI-based beamforming (CDI-BF), we estimate the covariance of the channel as $\mathbf{R}_j = \mathbf{E}\left\{\mathbf{h}_j^{(k)}\mathbf{h}_j^{(k)H}\right\}$, where $\mathbf{h}_j^{(k)}$ is a vector formed from column-wise stacking of $\mathbf{H}_j^{(k)}$, and the expectation is performed over time (with index *k*). We use the algorithm developed in [6] to construct beamforming vectors from the matrices $\mathbf{R}_j$, $1 \le j \le N_\mathrm{u}$. As demonstrated by the results obtained with measured channel data assuming the receiving nodes are mobile [6], we can assume that this covariance matrix remains relatively constant over some reasonable time window.

As we consider the construction of the beamforming vectors for these two signaling methods, we immediately see that CSI-BF and CDI-BF respectively require feedback of N_u matrices of size $N_\mathrm{r} \times N_\mathrm{t}$ and $N_\mathrm{r} N_\mathrm{t} \times N_\mathrm{r} N_\mathrm{t}$. While CDI-BF requires less frequent feedback, to be competetive either the feedback frequency must be reduced by a factor of $N_\mathrm{r} N_\mathrm{t}$ or the amount of data must be dramatically reduced. For systems where $N_\mathrm{r} \approx N_\mathrm{t}$, this can be effectively accomplished by parameterizing the covariance matrices using a physical model such as the Kronecker model. However, for situations where N_r is small, use of CDI-BF with these parameterizations still requires feedback of larger matrices than would be required for CSI-BF in the same situation. This observation motivates the work presented in this paper.

In comparing these beamforming methods, we quantify their performance using the sum rate of the multi-user channel. Specifically, let $C_\chi^{(k_0,k)}$ represent the sum mutual information achieved by a specific precoder χ, where χ is selected from the set {CSI-BF, CDI-BF}, at the time index *k* when the precoding is constructed from CSI or CDI at time index $k_0 < k$. The sample expected throughput (SET) is then defined by averaging this mutual information over different starting times for the same time offset using

$$S_\chi(\Delta_k) = \frac{1}{K - \Delta_k} \sum_{m=1}^{K-\Delta_k} C_\chi^{(m, m+\Delta_k)}$$

where, as a reminder, *K* is the total number of time samples. We also use the average SET (ASET) defined by

$$\bar{S}_\chi(M) = \frac{1}{M} \sum_{\Delta=0}^{M-1} S_\chi(\Delta)$$

where *M* represents the time displacement.

The CO-RCI algorithm considered in this paper assumes a single data stream per user, such that the symbol $\mathbf{x}_j^{(k)}$ destined for the *j*th user is transmitted using the beamforming weights $\mathbf{b}_j^{(k_0)}$ constructed from the CSI $\mathbf{H}_j^{(k_0)}$. Beamforming weights $\mathbf{w}_j^{(k)}$ constructed from the CSI $\mathbf{H}_j^{(k)}$ are applied at the receiver. The signal-to-interference-plus-noise ratio (SINR) for the *j*th user under this scenario and assuming phase synchronization at the receiver becomes [6]

$$\rho_j = \frac{\left|\mathbf{w}_j^{kH}\mathbf{H}_j^k\mathbf{b}_j^{k_0}\right|^2}{1+\sum_{i\neq j}\left|\mathbf{w}_j^{kH}\mathbf{H}_j^k\mathbf{b}_i^{k_0}\right|^2}$$

It is possible that the beamforming weight determination excludes a user from the channel [8], in which case $\mathbf{b}_j^{(k_0)}$ such that $\rho_j = 0$. The sum mutual information obtained by summing the mutual information values for the N_u users is given by

$$C_{\mathrm{CSI-BF}}^{(k_0,k)} = \sum_{j=1}^{N_\mathrm{u}} \log_2\left(1+\rho_j\right).$$

The goal of the CDI-based beamforming approach considered in this work is to maximize the throughput averaged over a specified time window [6]. Once the beamforming weights are constructed from the algorithm, the sum mutual information $C_{\mathrm{CDI-BF}}^{(k_0,k)}$ can be constructed by using the appropriate weights in the formulation above. The results in [6] demonstrate that these beamforming weights provide a stable throughput in a time-varying channel.

Channel Model

Evaluations of the CSI-BF and CDI-BF algorithms considered here using time-varying channels measured in several different environments reveal that while the CSI-BF technique has high initial SET (when the CSI is of high quality), its performance degrades rapidly with time offset Δ_k. In contrast, the CDI-BF technique provides stable sum rate performance over a relatively long time period. The problem with this analysis, however, is that the temporal extent of each measured channel time series available for this study is inadequate for determining the temporal extent over which the CDI-BF vectors remain valid.

As a result of this limitation in the measured data, in this paper we resort to the use of a physics-based channel model [9]. This recently developed model extracts the dominant multipath clusters from measured data and uses an auto-regressive model to simulate the time variation in the key cluster parameters (angle of departure or arrival and channel gain). The model includes a mechanism for allowing new clusters to appear and existing clusters to disappear based on the probability distributions observed in real measurements. Analysis of the channel matrices obtained with this model show that they exhibit behaviors very consistent with the behaviors observed in the measured data. We therefore use this model in our analyses. In the implementation, each multipath cluster consists of 50 components or *rays*, with the angle of departure (or arrival) for each ray relative to the cluster mean angle specified as a random variable satisfying a truncated Laplacian distribution with an angle spread of 30°. The model implementation assumes that each time sample represents a physical spacing of 0.0086 wavelengths, which matches the sampling of the underlying measured data.

It is important to also emphasize that, as in the analyses performed previously, channel variation is created in this study as the receiving nodes move. Therefore, while this is manifest as a time-variation in the channel, the key physical phenomenon that creates the variation is node spatial displacement. Therefore, the results shown in this paper are all given as a function of node displacement in wavelengths at the center frequency of the simulation. Given a velocity for the nodes, it is a simple matter to convert the displacement independent variable to time.

KL Transform for Feedback Reduction

Methodology

We emphasize at this point that CDI-BF is designed to maximize the *average* sum rate of the broadcast channel communication, which implies that each beamforming vector provides good average signal strength to the intended user while controlling the average interference to the other users in the network. If we define the effective null space of $\mathbf{R}_j$ as the subspace characterized by eigenvalues smaller than some threshold (since in most multipath channels a true null space of the covariance will not exist), then good CDI-BF performance implies we can find a beamforming vector for user *j* which lies in the effective range space of $\mathbf{R}_j$ and the effective null space of $\mathbf{R}_i$, $i \neq j$. Practically speaking, if this is to work for a reasonable number of users, it implies that each covariance matrix is characterized by a few dominant eigenvectors.

It is therefore intuitive to try to use this property to reduce the feedback complexity, which naturally motivates an evaluation the KL Transform for feedback data compression. Specifically, let $\mathbf{R}_j = \mathbf{\Sigma}_j \mathbf{\Lambda}_j \mathbf{\Sigma}_j^H$ represent the eigenvector decomposition of $\mathbf{R}_j$, where because $\mathbf{R}_j$ is Hermitian we know that $\mathbf{\Sigma}_j$ is the unitary matrix of eigenvectors and $\mathbf{\Lambda}_j$ is the diagonal matrix of real, non-negative eigenvalues constructed so that the eigenvalues fall in order of decreasing value. The feedback reduction comes by feeding back only the dominant eigenvectors and the corresponding eigenvalues for each user.

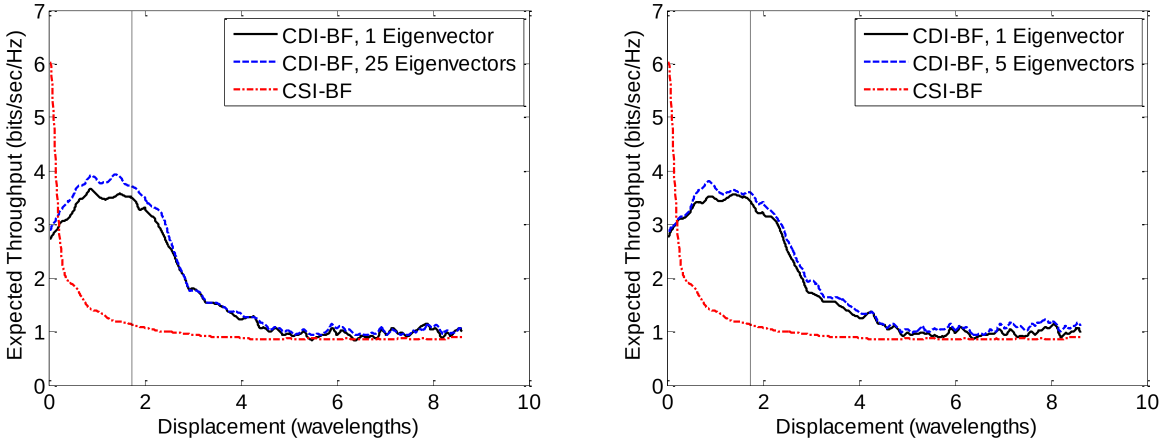
SET vs. Node Displacement

Consider the case where $N_{\mathrm{u}} = N_{\mathrm{t}} = N_{\mathrm{r}} = 5$ and the total allocated transmit power for the beamforming methods is set at $P = 10$ [6]. Figure 3(a) plots the SET as a function of the receiver displacement assuming that only one or all 25 eigenvectors and eigenvalues are fed back to the transmitter at the initial location (displacement = 0). The values represent averages taken over 50 random channel realizations from the stochastic model. The vertical line in the plot shows the time window over which the covariance is estimated, which means that the portion of the curve representing true communication throughput for CDI-BF is that to the right of this solid line. It is noteworthy that feedback of a single eigenvector provides performance close to that obtained using full covariance feedback (25 eigenvectors). The SET for the case of CSI-BF assuming the CSI at the receiver is known perfectly at all times but the CSI at the transmitter is fed back only at the initial location is also shown for comparison. In terms of feedback complexity, CSI-BF requires feedback of 25 complex numbers, which is the same as that required for CDI-BF with a single eigenvector. The difference, however, is that the CDI remains useful for a longer duration, demonstrating the effectiveness of the technique.

Figure 3(b) repeats the plot of Fig. 3(a) for the case where the covariance matrix fed back is modeled using a Kronecker product approximation with the one-sided covariance matrices computed using the Rank-1 approximation [6]. In this case, each one-sided covariance is 5×5, and feedback of a single eigenvector for each of the two one-sided covariance matrices results in feedback of two vectors each with five complex numbers (along with two real eigenvalues). The performance in this case is similar to that in Fig. 3(a) despite the additional reduction in feedback complexity.

Achievable System Throughput

We can further manipulate these metrics to represent achievable performance in a practical implementation. Conceptually, if a receiver possesses either CSI or CDI at a point in time and must feed that information back to the transmitter, and if the receiver (or transmitter) is mobile, then by the time the receiver has fed back the information to the transmitter, that information is stale, resulting in performance degradation relative to the case of perfect CSI or CDI. Based on the fact that degradation with displacement is less for CDI-BF than for CSI-BF (as shown in Fig. 3(a)), we expect that a system using CDI will suffer less relative degradation, although the actual throughput performance depends on the capabilities of the feedback channel.



(a)

(b)

Figure 3: SET Curves for a 5×5 MIMO network with $N_u = 5$ and $P = 10$ with different numbers of covariance matrix eigenvectors fed back to the transmitter. The KL Transform of the (a) full covariance matrix or (b) rank-1 approximation to the Kronecker product of the covariance matrix is used.

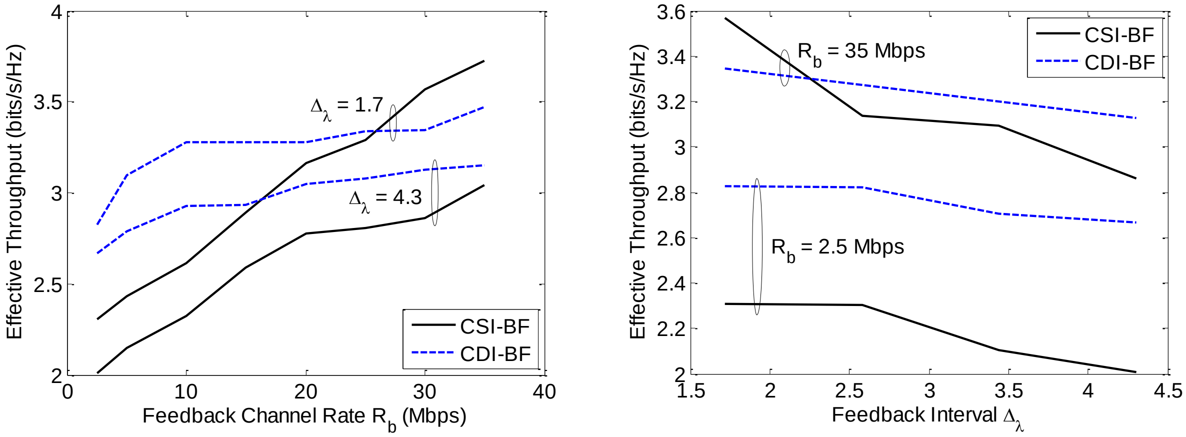
To get a more accurate understanding of the throughput behavior, we assume that at zero displacement, the receivers have estimates of either their CSI or their CDI as appropriate and that the nodes are capable of full duplex communication. Each receiving node quantizes the required feedback information into *B* bits assuming 64 bits are used for each real number and subsequently feeds the information back over the channel with a bit rate R_b (which incorporates feedback channel bandwidth, modulation, and coding). With each receiver node moving at a velocity *v*, the maximum Doppler frequency is $f_{D.,\max} = 2v / \lambda$, where □ is the wavelength at the communication center frequency. We refer to the distance moved (in wavelengths) by the nodes over the time during which the feedback is taking place as the *latency* (consistent with the horizontal axis in Fig. 3(a)), which can be computed using

$$L_\lambda = \frac{f_{D.,\max}}{2R_b} B.$$

We then compute the ASET for the communication assuming feedback occurs at an interval (in wavelengths) of Δ_λ, where the window over which the covariance information is estimated is that shown in Fig. 3(a) (which corresponds to 200 samples at 0.0086 wavelengths per sample).

In the following computations, we assume the receiving nodes move at vehicular speeds of 72 km/hour and communication occurs at a center frequency of 2.4 GHz, resulting in $f_{D.,\max} = 3.2$ Hz. ASET is computed over a window of 1000 samples (node displacement of 8.6 wavelengths), where the number of feedback events within that window is determined by the feedback interval Δ_λ. For CDI-BF, feedback uses a single eigenvector for each of the one-sided covariance matrices computed using the Rank-1 approximation with the Kronecker model. The system again uses $N_\mathrm{u} = N_\mathrm{t} = N_\mathrm{r} = 5$.

Figure 4(a) plots the ASET for this system as a function of the feedback rate R_b for two different values of the feedback interval Δ_λ for both CSI-BF and CDI-BF. These results show that the performance of both beamforming strategies increases with the feedback rate because of the reduced latency between the time of estimation and time of use of the CSI or CDI. The impact of rate on CSI-BF is particularly significant, which can be explained by the rapid degradation in performance with receiver motion shown in Fig. 3(a) for CSI-BF. In other words, for CSI-BF, increased latency in the feedback results in less accurate CSI at the outset of its use, and therefore the system cannot achieve the high performance obtainable for small displacements in Fig. 3(a). In contrast, CDI-BF is more forgiving of stale CDI, resulting in reduced sensitivity to feedback rate in Fig. 4(a). More importantly, these results show that unless the feedback rate is high and the feedback interval is small, CDI-BF outperforms CSI-BF in terms of average system throughput.



(a) (b)

Figure 4: Effective system throughput (ASET) of CSI-BF and CDI-BF (a) versus the feedback rate R_b for two different values of the feedback interval Δ_λ and (b) versus the feedback interval Δ_λ for two different values of the feedback rate R_b.

These observations are reinforced by the results in Fig. 4(b) which plots the ASET for the system as a function of the feedback interval Δ_λ for two different values of the feedback rate R_b. Once again, we see that CSI-BF outperforms CDI-BF only when the feedback interval is small and the feedback rate is high. These results further highlight that the improvement offered by CDI-BF is particularly enhanced when the feedback rate is low, since the increased latency significantly degrades the performance of the CSI-BF approach. Finally, the curves emphasize that CSI-BF experiences increased sensitivity to the feedback interval.

References

[1] B. T. Quist and M. A. Jensen, “Optimal antenna pattern design for MIMO systems,” in Proc. 2007 IEEE Antennas and Propag. Society Intl. Symp., Honolulu, HI, Jun. 10-15 2007, pp. 1905-1908.

[2] O. Norklit, P. D. Teal, and R. G. Vaughan, “Measurement and evaluation of multi-antenna handsets in indoor mobile communication,” IEEE Trans. Antennas Propagat., vol. 49, pp. 429-437, Mar. 2001.

[3] J. Lee and N. Jindal, “High SNR analysis for MIMO broadcast channels: dirty paper coding versus linear precoding,” *IEEE Trans. Inf. Theory*, vol. 53, pp. 4787-4792, Dec. 2007.

[4] G. Caire and S. Shamai, “On the achievable throughput of a multiantenna Gaussian broadcast channel,” *IEEE Trans. Inf. Theory,* vol. 49, pp. 1691-1706, Jul. 2003.

[5] A. Goldsmith, S. A. Jafar, N. Jindal, and S. Vishwanath, “Capacity limits of MIMO channels,” *IEEE Trans. Inf. Theory*, vol. 21, pp. 684-702, Jun. 2003.

[6] A. L. Anderson, J. R. Zeidler, and M. A. Jensen, “Reduced-feedback linear precoding with stable performance for the time-varying MIMO broadcast channel,” *IEEE J. Selected Areas Commun*., vol. 26, pp. 1483-1493, 2008.

[7] Y. Shi and M. A. Jensen, “Stable transmission in the frequency-selective MIMO broadcast channel,” in *Proc. 2008 IEEE 68th Veh. Technol. Conf.*, Calgary, Alberta, Canada, Sep. 21-24 2008, pp. 1-5.

[8] Q. H. Spencer, J. W. Wallace, C. B. Peel, T. Svantesson, A. L. Swindlehurst, and A. Gummalla, “Performance of multi-user spatial multiplexing with measured channel data,” in *MIMO System Technology and Wireless Communications*, CRC Press, 2006.

[9] C. Chen and M. A. Jensen, “A stochastic model of the time-variant MIMO channel based on experimental observations,” *IEEE. Trans. Vehicular Technology*, vol. 58, no. 6, pp. 2618-2625, Jul. 2009.

2.2 Cross-Layer Design and Analysis of MAC and Routing Protocols for Ad Hoc Networks with Multiple Antennas

PI: Prof. Michele Zorzi

Introduction

During the past year, Dr. Zorzi's research efforts have been focused on different issues concerning the PHY. MAC and routing protocol layers. Novel results, as well as wrap-up research completing the activities carried out during the last year, include:

1) The proposal of a novel practical system for decode-and-forward physical layer network coding, a topic to which increasing effort has been devoted by the research community in the past four years. While remarkable improvements have been carried out from a theoretical point of view, the definition of practical architectures have not yet received as much attention. In this field, we have virtually solved all issues that would hinder implementation by mixing some well-known techniques (such as OFDM) and new ideas (network demodulation) in the right context
2) The routing problem in MIMO ad hoc networks has been addressed again in relation to MAC issues and PHY issues such as imperfect channel estimation. The main objective here is to wrap up the results of the previous years concerning packet forwarding strategies for MIMO ad hoc networks yet provide new theoretical results explaining some behaviors and projecting the evolution of these behaviors as such usual assumptions as perfect channel estimation are removed; checking whether previous results hold or not is key to a correct protocol design.
3) The cooperative paradigm for ad hoc networking, which exploits diversity, Hybrid ARQ, and MIMO techniques, has been explored further. Routing protocols have been designed that take explicit advantage of these advanced PHY techniques in a multi-hop network setting. We have shown that this approach has the potential to significantly improve the networking performance, and is deeply cross-layer as it couples routing choices and opportunistic networking behaviors with PHY and MAC mechanisms.

In this document, we provide an overview of the main technical issues and contributions, as well as some sample performance results, in these three areas, referring to the specific papers for a detailed description and for an extensive set of results.

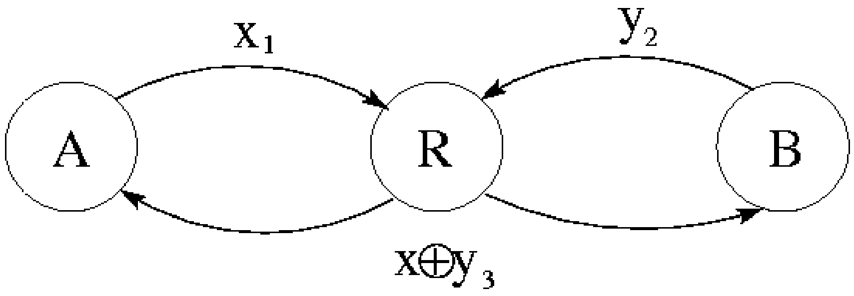
MIMO, Network Coding, and PHY integration

During the year 2008, Prof. Zorzi's efforts on network coding have focused on designing new techniques that better integrate this technique with the physical layer. In the last months new work has been carried out in this area, especially around physical layer network coding (PNC). This concept has lately attracted a certain interest in the network coding community [1]-[7]. The basic idea can be illustrated in the two-way relay channel (TWRC, Fig. 1). Two nodes (A and B) must exchange two packets (A's X and B's Y) through an intermediate relay R. In classic Network Coding (NC), A would send X in time slot 0, B would transmit Y in slot 1 and R would broadcast $X \oplus Y$ in slot 2 (Fig. 1 a). In physical layer network coding, A and B would simultaneously send X and Y, while R would relay a function of X and Y, which is invertible in X or Y as soon as the other variable is known (Fig. 1b). Given that A and B know their own packets, they can each potentially decode the other node's frame. This method reduces the number of required slots from 3 to 2. Note that R need not decode X and Y separately, but it is enough to directly decode a linear combination Z. This can potentially reduce the error rate because less information needs to be extracted from the received signal [1], [3], [4].

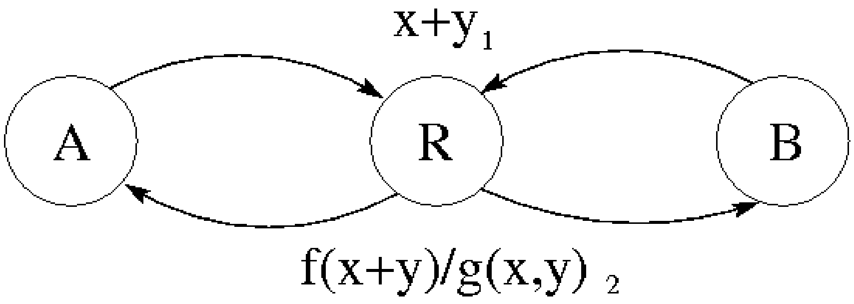
At least two main ideas have been developed in this context. The first one is called amplify-and-forward physical layer network coding (AF-PNC, also called analog network coding [3], [6]). The relay amplifies the analog superposition of X and Y and broadcasts this signal, that will be called S. The end-user terminals A and B can recover the signal sent by the other node by subtracting their own waveform out of the received signal sent by R. The resulting signal depends only on the intended packet, under the hypothesis of perfect cancellation. On the other hand, in decode-and-forward physical layer network coding (DF-PNC [3],[4]), R decodes a linear combination L of X and Y directly from the analog superposition. This packet L is broadcast and A and B can remove their own frame from L to recover the desired data unit.

Such systems are of interest in the context of ad hoc MIMO wireless networks for a variety of reasons. First of all, the presence of multiple antennas at the terminals is not precluded, although most of the current studies focus on single antenna terminals. We note that even in the presence of single-antenna terminals, the processing at the receiver is inherently MIMO, where the multiple input/output relationships are generated by the network coding technique rather than by multi-element antennas. Actually, the introduction of multiple antennas at R can dramatically improve the performance of DF-PNC: DF-PNC suppresses the noise at every decoding step. Hence, it is able to work at higher SNR than AF-PNC. Clearly, the higher the diversity, the smaller the bit error rate. Hence, the introduction of multiple antennas at least at the relay can significantly enhance the performance of DF-PNC over AF-PNC. It is thus of great interest to explore practical architectures for DF-PNC, since they would benefit more than other competing systems from the properties of MIMO techniques. Prof. Zorzi's efforts have focused on SISO nodes as a necessary and preliminary step towards MIMO nodes, but studies of MIMO centric DF-PNC are a natural extension.

Furthermore, physical layer network coding is especially suited for bidirectional traffic. Such type of traffic is of special importance in military or emergency ad hoc networks, where VoIP or video sessions are necessary among the participants. Moreover, NC is well known to be beneficial also for multicast packets, and these frames are again very commonplace for wireless ad hoc networks.



a) Digital Network Coding



b) Physical layer Network Coding

Figure 1: Comparison of Digital and Physical Layer Network Coding

While AF-PNC has been implemented in a real-world testbed [6], no actual implementation of DF-PNC has yet been built (or at least disclosed). Some of the biggest problems in this field are the necessity of having symbol synchronous signals at R and flat fading channels. Such a symbol synchronization induces a certain structure in the received signals that eases the decoding process, for instance enabling the usage of sophisticated lattice-based schemes [4]. In addition, the demodulation is rather different from the conventional one and nobody has yet defined how this process would yield soft values for the channel decoder. So far, only hard detection has been designed and this can be a relevant hindrance for modern channel codes.

Prof. Zorzi's effort in this area has aimed to solve the aforementioned practical issues for DF-PNC (namely, design a DF-PNC system that makes no assumptions on symbol synchronization and multipath fading and can work with modern channel codes). The main result has been the proposal of a transceiver architecture (depicted in Fig. 2). The main elements of this system are the following, while the details can be found in [7]. First of all, data is channel encoded by a potentially non binary channel code. The resulting Galois symbols are mapped into a set of OFDM-modulated QAM symbols which are pulse shaped and sent into the wireless medium. The receiver will collect the superposition of potentially different quasi-simultaneous waveforms (i.e., roughly frame synchronized but not necessarily symbol synchronized) from multiple transmitters. The receiver will first estimate the channel, perform OFDM demodulation, map the resulting samples into soft values by means of so called “network demodulation” and finally decode these values into information bits.

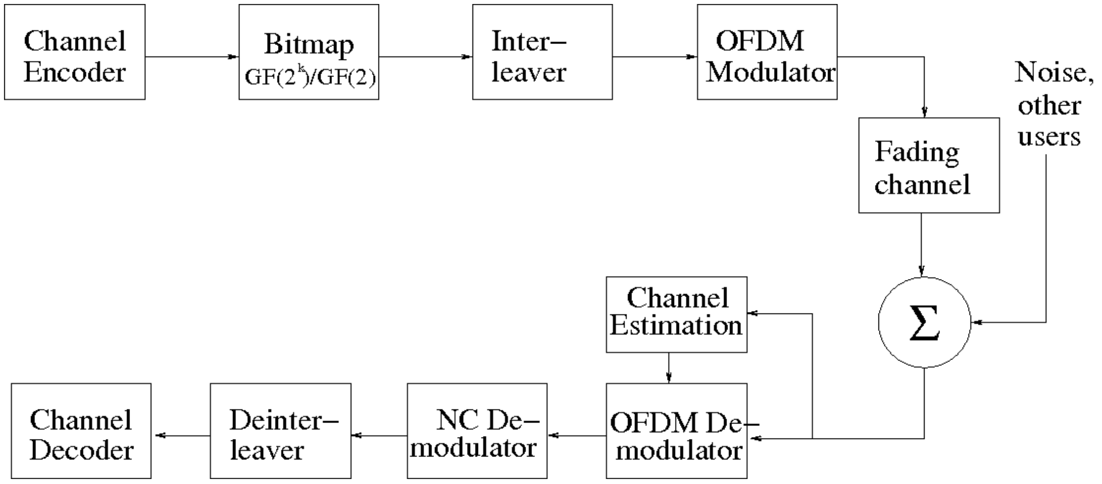


Figure 2: System block architecture

The network demodulation block is a signal processing algorithm that takes as an input symbols that are symbol synchronous (thanks to OFDM) and yields the soft values of the Galois symbols for an arbitrary linear combination of the collided packets. The network demodulator works on a symbol-by-symbol basis and lists all most likely sets of modulated symbols sent by the transmitters. The key property is that different sets of transmitted symbols lead to the same linear combination. Hence, the probability that one element of the resulting linear combination assumed a certain value can be computed by marginalization, i.e., by summing up the probabilities of all pairs of transmitted symbols that yield the same output. This enumeration and summation can be performed efficiently by sphere decoding.

Some brief remarks are in order so as to fully appreciate the benefits of this architecture:

- ✓ Usage of nonbinary codes: Network Coding requires a potentially large Galois field to properly work in a generic network. In order to do it, it is necessary to work with nonbinary channel codes.
- ✓ OFDM: OFDM is a necessary block in our architecture, since it allows to compensate for a relative delay between the users up to the cyclic prefix. This is in stark contrast with single carrier DF-PNC, where the relative delay can be up to a small fraction of the symbol duration; hence the system robustness has increased by 2-3 orders of magnitude. In addition, frequency selective channels are naturally handled by OFDM and no special provision must be taken for it.
- ✓ Network demodulation: network demodulation is the core and novel element of our architecture. It yields an arbitrary linear combination of the colliding packets by listing all most likely sets of received symbols. In addition, it is flexible enough to compute the soft values of the decoded symbols, hence enabling the usage of modern channel decoders (such as LDPC or turbo codes).

The performance of AF-PNC and our proposed scheme have been compared in the TWRC for Rayleigh fading channel. As shown in Fig. 3, the proposed scheme (blue line called “Heuristic Digital”) performs very close to the synchronous case (i.e., the signals arrive simultaneously to the relay), In addition, a gain of about 2.5 dB is possible with respect to AF-PNC.

The simulation results have shown that even a suboptimal implementation of our DF-PNC system concept is able to outperform AF-PNC. In addition to the performance improvements, other advantages are brought by this technique. For example, we expect DF-PNC to be more robust to channel estimation errors, since in AF-PNC the interference cancellation process is subject to these errors; instead DF-PNC is not affected, because A and B subtract their own digital packet (X and Y, respectively), rather than the estimate of the amplified analog signal at R. Moreover, AF-PNC needs oversampling to yield satisfactory performance, whereas our architecture still achieves good results without it. Furthermore, AF-PNC can transmit only a signal proportional to the sum of the colliding packets. Instead, DF-PNC can potentially yield any linear combination, and this flexibility is beneficial for NC in realistic topologies. Finally, AF-

PNC does not work in frequency selective channels, while our proposal naturally accommodates these environments because of OFDM. All these points encourage additional investigation on this technique.

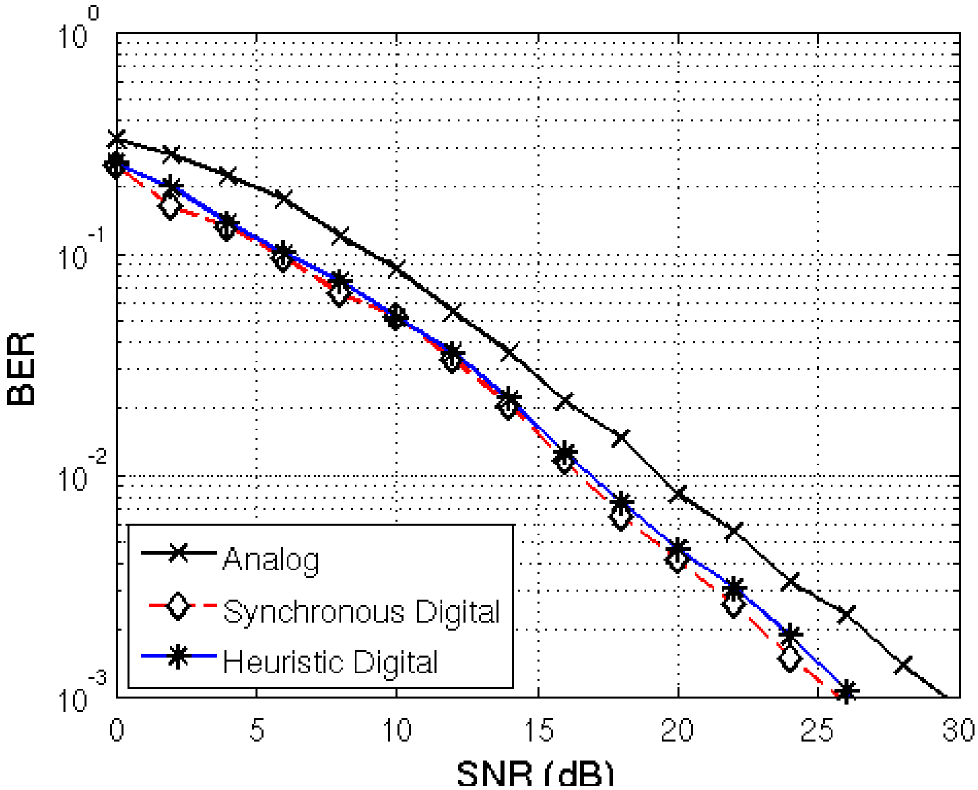


Figure 3: AF- vs DF-PNC in the two way relay channel

MIMO MANETs with Decision-Feedback Multiuser Detection

1) Integrated Multiuser detection / MAC protocol / routing

Dr. Zorzi's main line of efforts has been directed toward integrating PHY, MAC and, ultimately, routing design. Designing a MAC layer helps understand the interaction between network protocols and PHY, giving insight on how the spatial de-multiplexing algorithm should be "driven" in order to achieve transmission effectiveness. The main problem to face here is to answer the following questions: how should the nodes decide what to transmit and to which receiver? How much should transmission parallelism be encouraged? What is the impact of the underlying policies and protocols on routing? The studies carried out during the previous years led to the design of a MAC protocol that tries to address these problems. This year, this protocol has been the subject of further investigations aimed at assessing its actual capabilities and at substantiating the assumptions behind it. This has led to a journal paper that has been submitted to the *IEEE Transactions on Wireless Communications* and is currently being reviewed for publication.

In order to fix ideas, let us describe shortly the basics of the MAC protocol and the routing protocol working on top of it. Our MAC exploits multiuser detection as offered by advanced MIMO-BLAST signal processing to support multiple access in a different way than in standard CSMA/CA networks. Namely, the concept of collision is softer, and nodes are encouraged to access the channel simultaneously, leaving it to signal processing to decouple superimposed signals. This access paradigm bears the potential to boost network performance; however, it requires some distributed control on the nodes' part so that simultaneous transmissions do not exceed the decoupling capabilities of PHY-level signal processing. To reach this objective, the MAC protocol works in frames. Each frame is composed of 4 slots, which are used to transmit Request-To-Send (RTS), Clear-To-Send (CTS), data and ACKnowledgment packets, respectively. RTSs and CTSs do not carry the same meaning as in standard CSMA/CA: they are not employed to stop neighbors from transmitting, but only to advertise transmit intentions, inform receivers, and get back instructions as to controllable transmission parameters (namely, the number of antennas that should be used to transmit, which directly affects the achievable bit rate as well as the receiver load). However, traffic control does not take place only at the receivers: transmitters control the injected traffic by limiting both the number of receivers they call upon in the CTSs and the overall number of antennas used. In particular, nodes are divided into classes; the class of a node conveys information about the maximum number of antennas to be used when transmitting to a set of neighbors which includes that node. RTSs are formed so as never to exceed a neighbor's class [8]. We usually indicate classes within curly brackets: for example, {2, 4, 6, 8} means that a node can only take a class value equal to one of the numbers in the brackets. Upon receiving (possibly many) RTSs the receivers decide whether to grant transmissions or not by applying a so-called CTS policy. The policy takes into account how many packets represent wanted traffic and how many represent interference, decides whether some of this interference should be detected and canceled to improve the reception of wanted packets, and correspondingly compiles instructions in CTS packets according to a balance between these two factors. This is the concept behind the Follow Traffic (FT) policy [8].

After CTS reception, data transmissions follow, using as many antennas as indicated in the CTS, and sending one Packet Data Unit (PDU) of fixed length, through each antenna. Finally, ACKs are sent back by receivers to provide feedback. Transmitters receiving no CTS in response to a sent RTS back off for a random amount of time, chosen within an exponentially-increasing window. Two backoff policies are considered, Dest-Lock (that blocks attempts toward the node that denied the transmission) and Node-Lock (that blocks transmissions toward all nodes, and thus conservatively blocks excess traffic). Nodes need not be strictly symbol-synchronous to work in accordance with this MAC protocol: only frame-synchronization is required, as the actual performance decrease due to the absence of symbol synchronization can be obviated by oversampling the receive antenna inputs and running the de-multiplexing algorithm on a larger set of samples. This turns the synchronization problem into a receiver hardware complexity problem.

MAC and routing are tightly related in MIMO ad hoc networks. Take for example our protocol above: shortest path routing is not necessarily the best choice. In fact, short paths tend to rely on longer links; in a MIMO network, long-reach links may require transmissions with few antennas in order to keep the transmit power high and transmit signals effectively. Therefore a shortest path is also a lower bit rate end-to-end connection. On the other hand, adaptive routing policies could show improved communication performance by choosing locally optimal relays over a multihop path in a dynamic fashion. The comparison below shows the apparent benefits yielded by dynamic relay selection. On the left (Figure 4), we considered a typical Poisson traffic model, whereby packets are generated randomly at given rate by all nodes: in this very simple case dynamic selection outperforms even a pre-computed set of shortest paths, obtained through the Djikstra algorithm and optimized for the minimum number of hops. On the right (Figure 5), we have set up a more complex scenario involving a more realistic type of traffic, more bursty in nature and whose generation is correlated in time. According to the model in [10], traffic is decomposed in sessions, each originating flows; each flow is composed of a random number of packets. The number of flows within a session is also random. In time, packets and flows are generated according to a Poisson process of given rate. In the correlated traffic case, the dynamic relay selection policy outperforms shortest path routing more than with uniform traffic, and increases throughput by about 25%. With either traffic type, dynamic relay selection accounts for many node parameters, such as current queue backlog level, advancement provided, class of the neighbor and backoff timer. A specifically designed weighing function yields a synthetic utility number between 0 and 1: the available node bearing the largest utility is chosen.

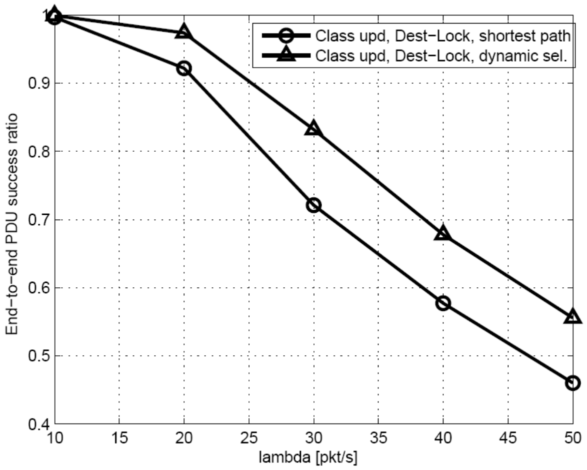


Figure 4: End-to-end throughput as a function of traffic generation rate, Poisson model.

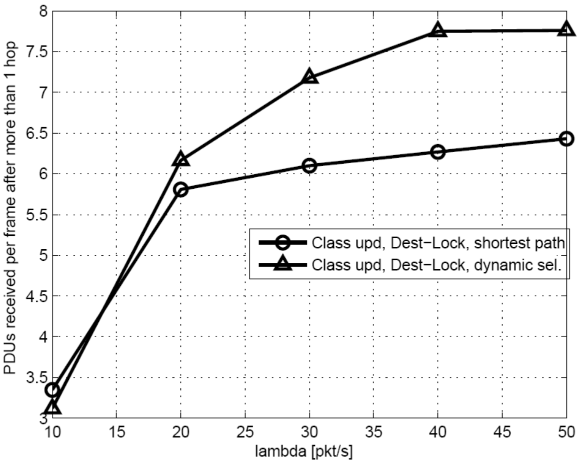


Figure 5: End-to-end throughput as a function of traffic generation rate, correlated model.

We recall that routing protocols require a means to measure not only the overall quality of a node, but also of the link over which the communication is to take place. In our protocol, we are inherently provided with such a measure, which is the class of the node. We have previously noted [10] that a fixed class is however not a good choice, as it does not keep track of a node's actual capability to exploit concurrent access as allowed by the MAC. To this end, we deployed a class update policy that allows to convey more precise information about the amount of spatial multiplexing the node can support. This is key in MAC operations: only by knowing the exact limits of its receiver does a node make correct decisions as to the traffic to inject. Correct MAC operations then reflect on routing (through correct transmissions and through more correct information to add up to the relay utility). To this end, we restricted the class of a node to within the set {2, 4, 6, 8}, chose the success ratio as a measure of the reliability of a link, and considered the following link class updating algorithm:

$$r_{new} = a\frac{N_{ACK}}{N_{SENT}} + (1-a)\, r_{old} ,$$

where r_{old} and r_{new} are the old and new reliability measures, respectively, and a is a weight used to tune the reaction speed of the algorithm to link reliability changes. The new reliability is then compared to different *increasing* and a *decreasing* thresholds. If either is exceeded, the class of the link is respectively increased or decreased, though always allowed to have values in the set {2, 4, 6, 8}. Every time the class is changed, the link reliability variable is reinitialized. In terms of routing, the choice of updating the class dynamically yields apparent benefits. We investigated more deeply in this direction to yield such results as those in Figures 7 and 6, which depict end-to-end throughput and success ratio for different class update and MAC-level backoff policies. The first observation in order here is that the more aggressive Dest-Lock policy achieves a better throughput too. In a multihop network, this result is easily explained:

as a node fails to contact a node for routing, it is allowed to try another one in the following frame. Node lock does not allow so, and leaves the node in backoff for a while before retrying. However, regardless of the specific backoff policy (which in the end only affects the general throughput trend), we see from the figures that updating the class indeed yields a benefit, and a more apparent one in terms of success ratio. Being able to maintain higher levels of throughput at higher success ratio indicates that fewer resources are wasted and that only transmissions with a chance to succeed actually take place. This is very important in an ad hoc network, where resources may be limited and thus must be carefully exploited.

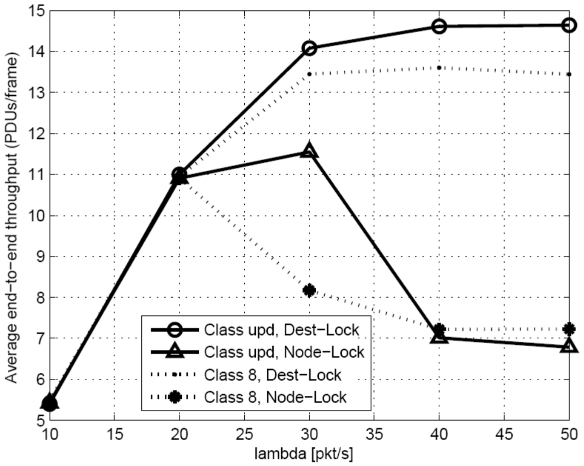


Figure 7: End-to-end throughput as a function of traffic generation rate, for the class update and fixed class policies .

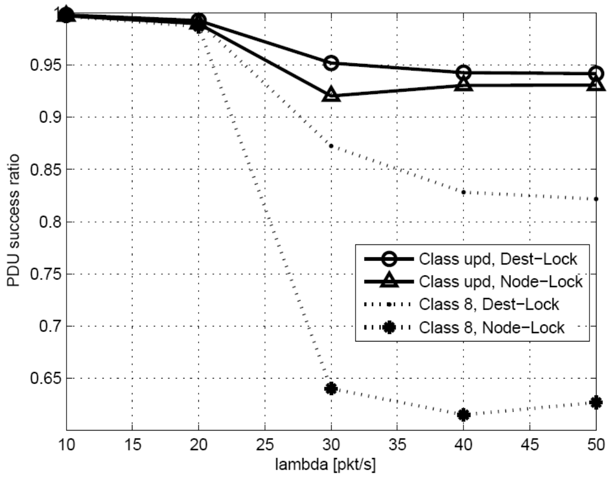


Figure 6: End-to-end success ratio as a function of traffic generation rate, for the class update and fixed class policies .

While the observations above make very important points towards the development of increasingly effective routing protocols, special attention should be posed to PHY-originated impairments such as those due to imperfect channel estimation. A significant fraction of Prof. Zorzi efforts, last year, was devoted to the characterization of imperfect channel knowledge through the statistics of the matrix describing the deviation of channel estimates from the actual realization. In ad hoc networks, this was shown to be different than in studies of point-to-point links, which form the largest part of the available literature. In particular, it was shown that the channel matrix can be written as

$$\hat{\mathbf{H}} = \mathbf{H} + \mathbf{J}\mathbf{H} + \mathbf{Z}'' = \mathbf{H} + \Delta\mathbf{H} \qquad (1)$$

where the last term highlights the source of uncertainty in the channel estimation procedure: this term contains both noise, through the matrix **Z”**, and a component related to the instantaneous channel realization, **JH**. The matrix **J**, in this term, describes the effect of simultaneous transmissions between other node pairs, which cause a “footprint” of the signal to appear in the matched filter output of the current receiver. This output depends on the channel between the different transmitters and the receiver, which explains the term **JH**. The wrong channel estimates in (1) can easily be simulated as it can be shown that the variance of the elements of **J** is $1/6N$, where N is the length of the training sequence employed for channel estimation. The elements of **Z”** also have a close-form variance, which is expressed as N_o/NT, where $N_o/2$ is the double-sided noise power spectral density, and T is the symbol time. Last year, it was highlighted that acting on N allows to drive different kinds of tradeoffs. More specifically, by calling *Nsig* the length of the training sequence associated to signaling messages, and *Ndata* the length of the sequence used for data packets, then one can choose whether to move the system working point on a better throughput, better efficiency, better success ratio mode, or to a combination of those. This year, these tradeoffs have been studied to a larger extent, yielding such results as those in Figure 9, which shows the contour curves of average transmission efficiency (the ratio of purely information bits sent per frame over all bits sent in a frame), success ratio (the ratio of correctly transmitted packet data units, i.e., data chunks suitable to be sent over one antenna, to all packet data units sent) and delivery delay (time in ms required to deliver one packet to its destination).

The superposition of these curves allows to understand which metrics are competing and which can be optimized almost simultaneously. For example, from Figure 9, we infer that success ratio and efficiency are competing metrics: to opt for a high success ratio (e.g., to reduce retransmissions) means to accept a limited transmission efficiency, because the large *Ndata* required to support the wanted success ratio will exceedingly increase the frame time duration. With the help of tradeoff curves such as those in Figure 8, one can also determine the sensitivity of network metrics to local variations on the choice of *Nsig* and *Ndata*. In this figure, which compares the performance in terms of throughput and transmission efficiency for varying *Nsig* and *Ndata*, the most desirable operating point is as close as possible to the top-right corner. In this case we see that increasing or decreasing *Nsig* for fixed *Ndata* around the point of optimality, corresponding to traveling the bold black lines) yields worse results than varying *Ndata* for fixed *Nsig* (which corresponds to traveling dashed grey lines). In fact [12], decreasing *Nsig* below the optimality point makes the detection of RTS messages more prone to errors: if this happens, links cannot be set up. On the other hand, if *Nsig* is too high, RTSs are given too much protection, and thus their detection will likely end successfully. Therefore, more links will be set up, more data packets transmitted, and the channel estimation accuracy offered by *Ndata* turns out to be too low to support the increased amount of data transmissions.

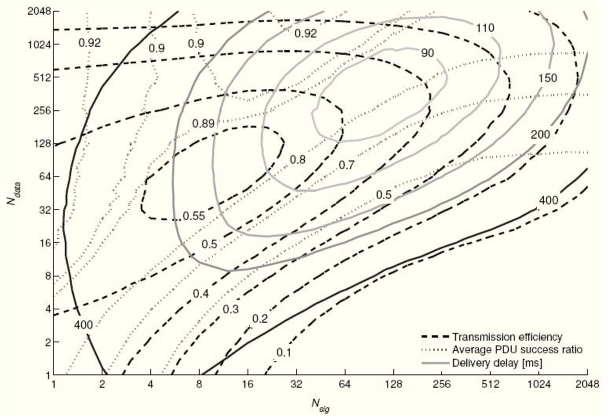


Figure 9: Contour curves of transmission efficiency, PDU success ratio, and Delivery delay (in ms) as a function of *Nsig* and *Ndata*. Each curve is obtained by cutting the surface plot of each metric with a plane corresponding to the metric value indicated on the curve.

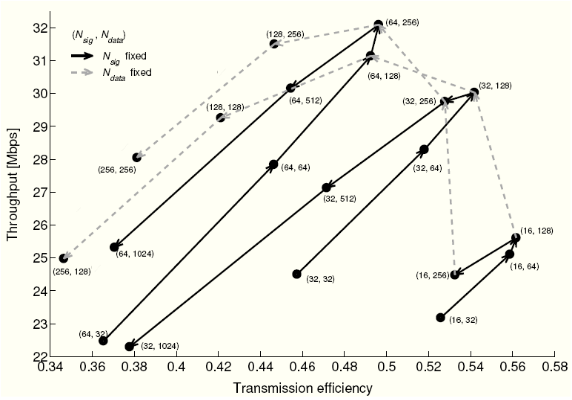


Figure 8: Tradeoff curves between of transmission efficiency and throughput. Black arrows correspond to variations in *Ndata* for fixed *Nsig*, vice-versa for grey arrows.

Another extension to last year's work includes the investigation of the following question, which directly arises from the previous evaluation: since the number of packet data units sent in a frame is the most important variable, and perhaps the most difficult to support through a proper choice of the PHY parameters, does any artificial bound on the number of PDUs sent on a link help at all? To see this, we plot throughput against traffic in Figure 10, and limit the number of antennas to be used in a transmission by limiting the maximum class of a node. So while in the previous years we almost always used a {2, 4, 8} configuration (meaning that a node can be transmitted to using at most either 2, 4, or 8 antennas), now we reduce that to {2, 4, 7}, {2, 4, 6} and {2, 4, 5}. These configurations limit to at most 7, 6, or 5 antennas the maximum spatial multiplexing that a transmit node is ever allowed. As we see from the Figure, though, this hardly yields any advantage. Although there is a slight throughput improvement, this does not justify the operation of limiting the number of transmit antennas. For comparison, we also put in the picture the {1, 2, 4} and {3, 6, 12} configuration, which assumes that the number of physically available antennas equipped at each node changes from 8 to 4 and 12, respectively. The results expectedly show worse performance for the {1, 2, 4} configuration (4 antennas equipped at each node) and better performance for the {3, 6, 12} configuration (12 antennas at each node). From this comparison and previous results, we infer that playing on the tradeoff arising between physical-level parameters and higher-level performance indicators (while allowing the upper layers to automatically manage communications) is a much better way to increase performance than to empirical limit transmission parallelism. While these are just examples of the performance investigations carried out by Prof. Zorzi, the reader is referred to [11], [12] and [13] for a more in-depth discussion.

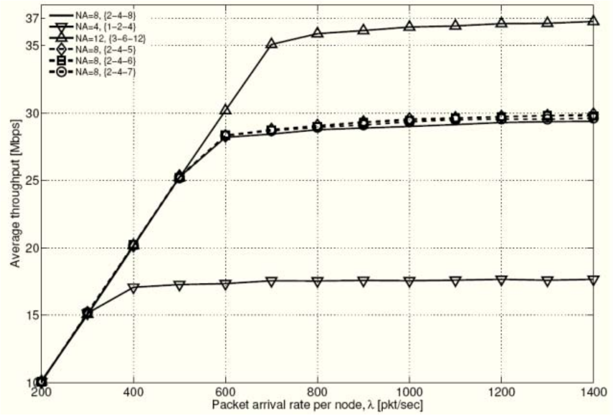


Figure 10: Throughput as a function of traffic for different number of antennas and class configurations.

Routing in Cooperative MIMO Ad Hoc Networks

In the recent literature, cooperation has been envisioned to increase the capacity of wireless networks. The cooperative rationale provides the transmission of information content by nodes that overheard the transmission by the original source. The goal may be either to increase the capacity of the original communication or to decrease its outage probability.

Most of the previous work looks at cooperation from a single-link perspective. In general, simple topologies with few nodes are analyzed, often disregarding practical issues such as nodes availability for cooperation, packet arrivals and interference.

The single-link perspective not only biases the performance evaluation, but also fails to enlighten some aspects of cooperation that may be extremely relevant in networking, thus potentially limiting the effectiveness of the design. We therefore look at cooperation from a network-wide perspective.

In particular, we consider a MIMO ad hoc network where the potential of the physical layer is exploited to improve the parallelism of the network, rather than to increase the capacity of each single link and the interference rejection capabilities granted by the MIMO technology is used to let multiple transmitters to concurrently access the channel. Thus, the access protocol does not follow a collision avoidance rationale, and the outage probability of a transmission strongly depends on the interference coming from the other transmissions taking place at the same time.

In our previous work, we addressed the design of cooperation in such a network, considering single-hop communications only. We proposed a cooperative protocol that integrates error control and cooperation in order to increase the efficiency of the communications.

Due to the start and the end of interfering transmissions, the conditions of the channel during a communication may significantly vary. Therefore, the capabilities of the communication protocol to adapt the transmission rate to the instantaneous conditions of the channel and the evolution of the interference is a key design goal. Hybrid Automatic Retransmission reQuest (HARQ), by providing packet encoding, retransmission and combining, has been shown to grant adaptiveness and efficiency to wireless communications in time varying channels. We focus in particular on Incremental Redundancy HARQ, where in each retransmission of a packet, the source transmits a different fragment of a long codeword obtained by encoding the original packet. The receiver collects the different fragments and combines them in order to get a code with lower rate, thereby increasing the probability of successful decoding.

The proposed cooperative protocol allows the neighbors of a transmitting source that decoded the packet sent by the latter to transmit redundancy in its place. This increases the channel diversity of the communication and allows an improved efficiency.

In the considered multiple simultaneous access scenario, cooperation has also a beneficial effect on other ongoing communications. In fact, shorter and more effective communications result in a lower per packet interference. Moreover, the possibility for simultaneous transmissions considerably reduces the overhead needed to set up cooperation.

The cooperative HARQ protocol described above has been shown to significantly improve the performance of the network. However, by shifting the design from single link to the entire network perspective (Fig. **11**), it is possible to achieve a deeper integration of cooperation in the system.

In particular, cooperation may be intended as a means to improve packet forwarding in the network, rather than to improve the efficiency of a single link. Herein, we propose an effective protocol that integrates error control and cooperation with multi-hop routing in order to more effectively face channel impairments due to interference.

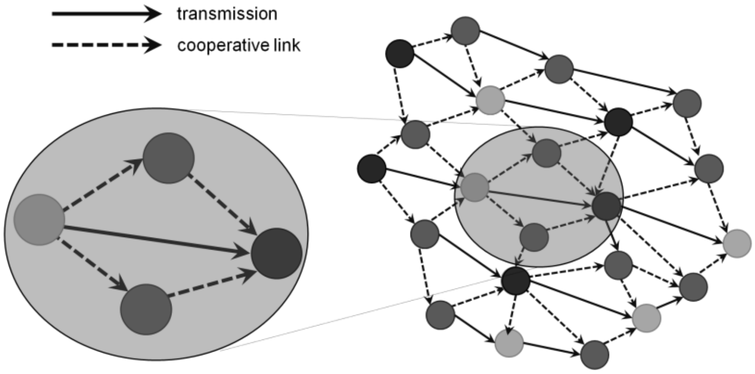


Figure 11: Cooperative communications need to be considered in a network-wide perspective.

It can be observed that traditional routing protocols may not be effective in a network where channel conditions quickly and unpredictably vary. In fact, route formation cannot deal with the quick oscillations of the channel quality, and may fail to select an efficient sequence of relays to reach the destination.

In order to cope with these issues, we propose a cooperative protocol, referred to as cooperative HARQ and opportunistic routing (CHOR) protocol in the following, that manages packet forwarding by adaptively and opportunistically selecting an efficient route to the destination. We underscore again that an inefficient route, where each hop requires long delivery attempts, i.e., attempts with many transmission phases, may increase the interference load of the network and damage other communications by increasing both their failure rate and their waiting time before packet transmission.

The CHOR protocol adds two main features to the basic communication protocol:

it enables other nodes that overheard the transmission by the source to send fragments of the codeword obtained by re-encoding the received packet

it opportunistically switches to a different next hop relay in order to minimize the amount of redundancy sent and to guarantee a geographical advancement to each packet.

In the cooperative error control we previously proposed the cooperators only transmit incremental redundancy to strengthen the chosen route to the destination. In the cooperative integrated error control and routing protocol those nodes may opportunistically take charge of packet forwarding in order to grant an efficient advancement of the packet toward the destination (see Fig. **12**).

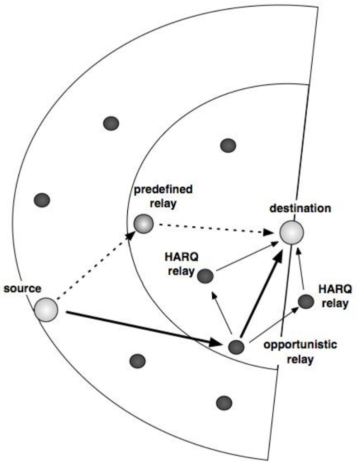


Figure 12: Cooperative rationale plainly applied to multi-hop communications.

As in the cooperative error control protocol, the possibility for simultaneous channel access granted by the MIMO physical layer allows an efficient deployment of the cooperative relay selection.

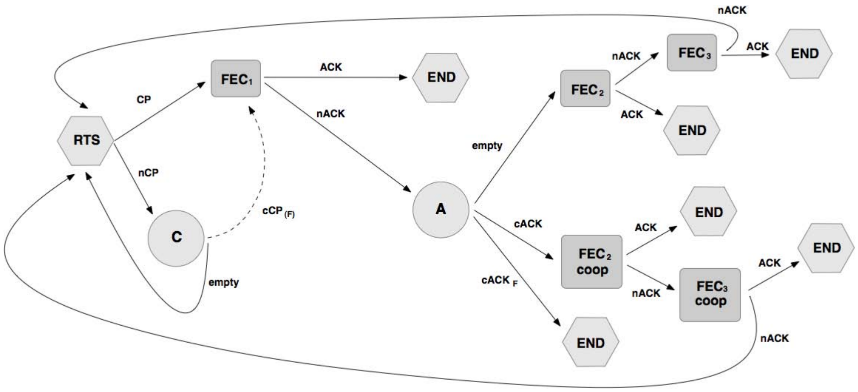


Figure 13: State diagram of the proposed cooperative packet forwarding protocol.

A state diagram of the protocol is shown in Fig. **13**. The original transmitter quits the communication if the destination reports bad channel conditions and there are no available cooperators. Otherwise, the original transmitter performs transmission of adaptive incremental redundancy possibly helped by its neighbors. If a nodes with a smaller number of hops decodes the packet, then the original communication is quit and the new node takes charge of packet forwarding.

We developed a simulator which describes the network from the physical to the routing level. Performance is averaged over random topologies, where nodes are uniformly placed in a fixed square area of side 500m. Packet arrivals in the buffer of each node are generated according to a Poisson process, and the destination of each packet is randomly chosen among all the other nodes in the network. We assume that a fixed fraction of the queue is left for packets received from other nodes which must be forwarded to their final destinations. A timeout is also set, and packets which have not yet been delivered when it expires are dropped. Finally, each node, as previously explained, has a routing table, generated via Shortest Path algorithm, in which the routes towards every possible destination are stored.

The physical layer is based on a Minimum Mean Square Error (MMSE) version of the layered space-time multiuser detection (LASTMUD) architecture previously considered in this research line.

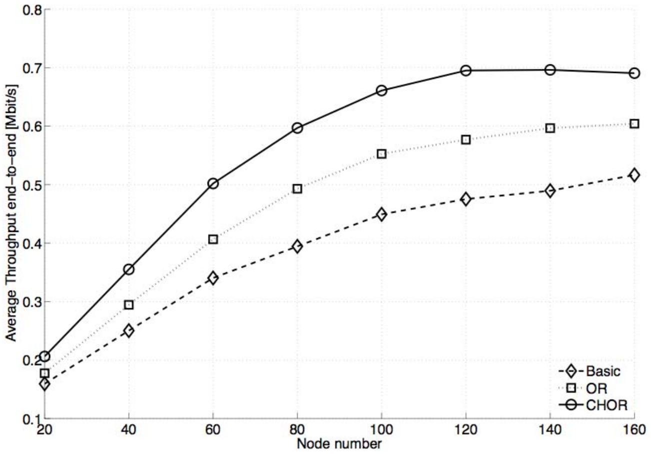


Figure 14: End to end throughput for the considered scheme.

Fig **14** depicts the end--to--end throughput for the basic, OR and CHOR protocols as a function of the number of nodes in the network, each equipped with only one antenna. As can be seen, the throughput grows for all the protocols as the number of nodes increases, until it reaches a floor.

In fact, as the number of nodes is increased, the network is initially able to support the greater traffic generated by the transmissions, whereas beyond a certain value the level of parallelism that the network can sustain saturates. This is due to the effect of interference, that does not allow other communications to start (the intended receiver reports bad channel conditions) and results in an increased failure rate of the delivery attempts.

The OR protocol achieves an improved throughput with respect to that of the basic protocol. In fact, although a slightly larger signaling overhead is required, the capability of choosing opportunistically the path improves the probability that the packet is eventually delivered to its destination. Moreover, the avoidance of bad links enables more efficient communications, and thus the interference load decreases and each packet is delivered in a shorter time. The CHOR protocol outperforms both the OR protocol and the basic communication scheme. The possibility for the neighbors with a good channel to the next hop relay to help the HARQ process by sending HARQ packets on behalf of the source speeds up the delivery process and reduces the probability that nodes enter backoff. However, cooperative HARQ may result in bursty transmissions if the number of HARQ relays is large, an event that may happen in densely populated networks. The burst of cooperative transmissions may generate short-term interference congestion conditions, that may be harmful for the other ongoing communications. The effectiveness at the intended receiver depends on the tradeoff between the amount of collected redundancy and the quality of the channel experienced by each HARQ packet.

As a final remark, we underscore the importance to extend the cooperative rationale to a wider network perspective, and to consider the effect of the surrounding network on each single cooperative communication, that are distinctive features of our work

References

[1] S. Zhang, S. C. Liew and P. P. Lam; “Physical-Layer Network Coding”, in *ACM MOBICOM*, Los Angeles (CA, USA), Sep. 2006.

[2] P. Popovski and H. Yomo; “Bi-directional Amplification of Throughput in a Wireless Multi-Hop Network”, in *IEEE VTC Spring*, Melbourne (Australia), May 2006.

[3] P. Popovski and H. Yomo; “Physical Network Coding in Two Way Wireless Relay Channels”, in *IEEE ICC*, Glasgow (UK), June 2007.

[4] B. Nazer and M. Gastpar; “Compute-and-forward: Harnessing interference with structured codes”, in *IEEE ISIT*, Toronto (Ontario, Canada), July 2008.

[5] L. Xiao, T. E. Fuja, J. Kliewer and D. J. Costello Jr.; “A network coding approach to cooperative diversity”, *IEEE Transactions on Information Theory*, vol. 53, no. 10, pp. 3714?3722, Oct. 2007.

[6] S. Katti, S. Gollakota and D. Katabi; “Embracing wireless interference: Analog network coding”, in *ACM SIGCOMM*, Kyoto (Japan), 27-31 Aug. 2007.

[7] F. Rossetto and M. Zorzi; “On the Design of practical Asynchronous Physical Layer Network Coding”, *IEEE SPAWC*, Perugia (Italy), 21-24 June 2009

[8] Paolo Casari, Marco Levorato and Michele Zorzi, “MAC/PHY Cross-Layer Design of MIMO Ad Hoc Networks with Layered Multiuser Detection,” *IEEE Transactions on Wireless Communications*, vol. 7, num. 11, pp. 4596-4607, Nov. 2008.

[9] L. Muscariello, M. Mellia, M. Meo, M. A. Marsan, and R. L. Cigno, “Markov models of internet traffic and a new hierarchical MMPP model,” *Computer Communications*, vol. 28, no. 16, pp. 1835–1851, Sep. 2005.

[10] MURI on Space Time Processing for Tactical Mobile Ad-Hoc Networks, Interim Report 2008, http://zeidler.ucsd.edu/~muri/pages/publications/AnnualReport2008.pdf

[11] Davide Chiarotto, Paolo Casari, and Michele Zorzi, “On the Statistics and MAC Implications of Channel Estimation Errors in MIMO Ad Hoc Networks,” *IEEE Transactions on Wireless Communications*, submitted.

[12] Davide Chiarotto, Paolo Casari, and Michele Zorzi, “On the Statistics and MAC Implications of Channel Estimation Errors in MIMO Ad Hoc Networks,” *Proc. of IEEE GlobeCom*, New Orleans, LA, 2008.

[13] Davide Chiarotto, Paolo Casari, and Michele Zorzi, "On the Tradeoff between MAC-level Performance Metrics in MIMO Ad Hoc Networks with Imperfect Channel Estimation," *Proc. of IEEE Second International Workshop on Cross-Layer Design, IWCLD 2009*, Palma de Mallorca, Spain, 2009.

2.3 Cross Layer Design for Enabling and Exploiting Space-Time Communications in Ad Hoc Networks

PI: Srikanth Krishnamurthy

GSRs: Ioannis Broustis, Ece Gelal, Konstantinos Pelechrinis

SUMMARY OF ACCOMPLISHMENTS

Our primary focus is on exploiting the PHY-layer gains due to MIMO at the higher layers. In line with this, we have two research projects. These projects target the exploitation of MIMO spatial diversity and MIMO spatial multiplexing, respectively. In the following we summarize our achievements in these projects.

1. Abstractions of MIMO Diversity Gain: Our purpose in this project is to assess the fidelity of previously considered abstractions (or models) of MIMO diversity, by comparing the performance predicted by these models with the practical performance observed on our testbed. In the previous report we have included the description of the models we have investigated, and some of our observations. In this report, we include our additional experiments and results with regards to: (i) assessing the fidelity of network simulations (ii) evaluating how the routing layer decisions interact with each model when diversity gain is examined on multi-hop flows. For (i), we include our observations on single-link flows, and for (ii) we include our observations when different routing metrics are used.
2. Medium access control for Multi-User MIMO Communications: Our purpose in this project is to utilize the interference cancellation capability using MIMO systems and to increase the spatial reuse in a multi-hop network by allowing multiple concurrent communications in a region. Towards this goal we have designed centralized and distributed algorithms that divide the communication links into separate sub-topologies, which are then activated in a TDMA fashion. In a given sub-topology, the concurrent communications are successful with high probability. We also show that previously employed models for multi-user MIMO communications yield significantly low probabilities of successful decoding in multi-hop settings.

1. CAPTURING THE PERFORMANCE GAINS DUE TO MIMO DIVERSITY

In this project, we focus on the modeling of MIMO diversity gain. We have explained the details of this project in the previous progress report. Briefly, we examine the cross layer interactions between the PHY, link and routing layers in networks with MIMO links operating in the *diversity* mode. Towards this, we **first** create models that represent the MIMO diversity gain in terms of a mapping between the SNR and the achievable BER (or PER, *i.e.*, packet error rate). In parallel, we also take measurements on an indoor 802.11n testbed. **Second,** we examine the goodness of each model by comparing their performance with the performance driven by measurements, on multihop networks via simulations. Our work brings to light the following cross-layer dependencies that affect the gains due to MIMO diversity: (1) PHY layer gains due to MIMO diversity do not always carry over to the higher layers, (2) the use of other PHY layer features such as FEC codes significantly influence the gains due to MIMO diversity, and (3) the choice of the routing metric can impact the gains possible with MIMO.

In the previous progress report, we have shown results with regards to the observations (1) and (2) above. During this period, we have added more results that validate the fidelity of our simulations for assessing a model in terms of representing the MIMO diversity gain. These results are presented in part A below. We have also evaluated these models using different routing metrics in multi-hop networks. Our observations are presented in part B.

A. Results on Single-Hop Flows:

In order to assess our multi-hop network simulations in terms of how good they are for comparing the end-to-end performance of each model to that with the measurement-driven model (MDM), we compare the throughput results in our simulations directly with those obtained via measurements. Towards this, we first measure the link throughput with SISO and MIMO on different links in our testbed at all three rates. Then, we simulate several single-hop topologies and obtain the throughput with SISO and MIMO for a range of SNR values. We present the results in Fig. 1 for two sample SNR values. We observe that the simulated throughput with MDM differs by at most 11% from what we measure on our testbed. This result suggests that MDM is an effective indicator of throughput; thus, MDM is considered to be a good benchmark to quantify the throughput in multi-hop settings. We also observe that the throughput with M-3P (SF) differs by at most 21% from the throughput with MDM, and 24% from the throughput on the testbed (at 3 bps/Hz data rate). On the other hand, the use of simplistic models can lead to a drastic overestimation in the performance improvement with MIMO. For instance, with M-2, the absolute throughput is much lower (77% lower with MIMO and 3,000 times lower with SISO) than what is observed on the testbed. Since M-2 does not account for FEC codes, the packet transmissions with this model experience higher losses leading to poor throughput. This effect is more pronounced with SISO than MIMO (in fact the throughput is close to zero, see Figures 3 and 4) and thus, the diversity gain is extremely high. With the fast fading models, M-3(FF) and M-3P(FF), again the improvements with MIMO over SISO are much higher than what is observed on the testbed. This is because the errors are less bursty. While the FEC codes are more effective than they are in practice, the errors tend to be spread over many more packets, leading to poorer throughputs with these models. With M-3P (SF), the impact of the environment in the indoor setting (bursty errors) is better captured; thus, the behavioral results are similar to what is observed on the testbed.

Note: however that, the throughput behavior with the models are not exactly identical to that with measurements, because the wireless channel could be different in reality from what is implemented in the simulator.

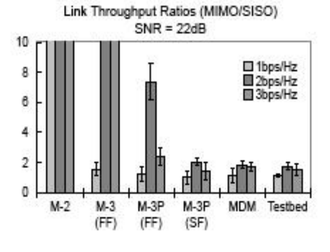


Figure 1: Throughput Ratio at 22dB

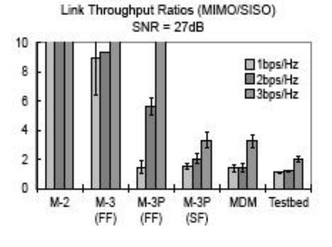


Figure 2: Throughput Ratio at 27dB

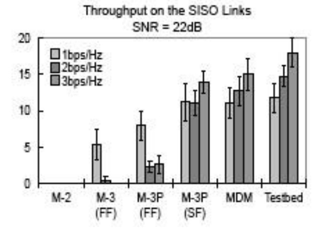


Figure 3: SISO Throughput at 22dB

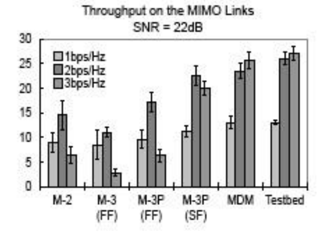


Figure 4: MIMO Throughput at 22dB

B. Results on Multi-Hop Flows Using Different Routing Metrics

Next, we perform simulations on multi-hop networks using each abstraction at the physical layer; we do so on multi-hop flows where the routing protocol (DSR in our work) chooses the shortest *or* the minimum-ETX route for packet delivery. The first policy refers to the DSR version that uses hop count as the routing metric. In this policy, DSR chooses the minimum hop route from among those that are discovered. When this route fails, other cached routes may be used. With the second policy, we compute the ETX metric to be the inverse of the link’s reliability. In particular, ETX is quantified in terms of the packet delivery rate (PDR) on the link for the corresponding rate. Intermediate nodes are not allowed to report cached routes to the source as in the default ETX implementation.

We examine the ratio of the achievable end-to-end network throughput using MIMO links to that using SISO links, with ETX-based routing. We observe that with ETX, this ratio decreases as compared to the minimum hop routing considered earlier. We define D to be the reduction in this ratio compared to minimum hop routing (Fig. 7). We consider the same 50-node topologies for evaluating both cases. As seen in the figure, the gains due to MIMO decrease with the use of ETX by as much as 20%. With ETX, the use of the more stable (albeit longer) routes with more reliable links (higher average SNR) improves the SISO performance as compared to minimum-hop routes. With the higher average SNRs on the SISO links, the FEC codes are more effective and MIMO does not provide significant additional benefits. Similarly, we observe that the conformance of the M-3P (SF) to MDM in terms of the delay performance increases; the two curves (corresponding to M-3P(SF) and MDM) are closer to each other in Fig. 6 than in Fig. 5. This is because ETX links operate at relatively high SNRs where the PER with M-3P (SF) is closer to that with measurements.

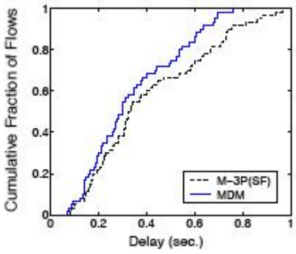


Figure 5: DSR with minimum-hop routing. Delay at 3 bps/Hz

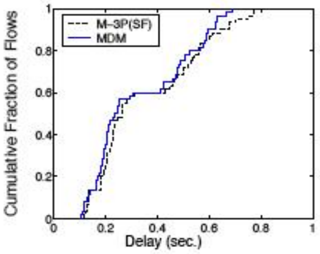


Figure 6: DSR with ETX routing metric, Delay at 3 bps/Hz

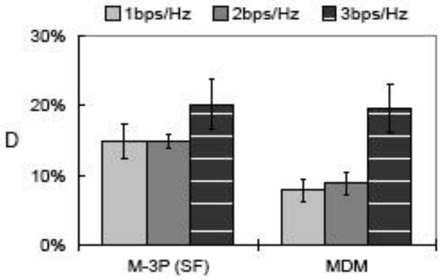


Figure 7: Performance improvements due to MIMO relative to SISO decrease with ETX-based routing

This work is currently under submission to ACM CONEXT 2009.

2. MULTI-USER MIMO COMMUNICATIONS

Space division multiplexing with MIMO systems allows nodes to transmit or receive multiple streams at a time. In this project, our goal is to efficiently utilize spatial multiplexing in multi-hop multi-user MIMO networks. We have stated our goal and approach in detail in last year's report. In brief, we design a topology control mechanism that enables successful multi-stream *receptions* in a multi-user MIMO network.

A. Re-visiting the Problem

First, we briefly re-state our problem. In multi-hop MIMO networks, wherein the nodes transmit using *one* of their antennas (this choice being facilitated by *selective diversity*) and utilize *Successive Interference Cancellation* (SIC) for receiving their target signals in presence of interference, the MU-SIC (Successive Interference Cancellation in Multi-User MIMO networks) problem seeks to find a maximal number of communications that can be simultaneously active, while each active receiver can extract its target signal successfully.

There are two challenges towards realizing the above-mentioned system. First, a receiver can afford no more than A-1 strongly interfering concurrent transmissions with its intended transmission (where A is the size of the antenna array). Furthermore, the success of the detection of each strong interfereing signal is determined based on its SINR, which itself depends on the strength of all signals in the received compound signal. To address these challenges, or specifically, to ensure that SIC can successfully be used at the receivers to remove unwanted interference, a higher layer mechanism must control which links can be active at the same time. Finally, this mechanism must allow every transmitter to acquire medium access as frequently as possible, in order to limit medium access delays.

We show that the MU-SIC problem is in the NP-hard class.

B. Centralized Solution Approach to the MU-SIC Problem: C-MUSIC

We design C-MUSIC, a centralized heuristic algorithm that groups the communication links in a given multi-hop network into a minimal number of groups, such that in each group SIC can be carried out successfully with an arbitrarily small error probability, δ.

C-MUSIC takes as input the interference graph G' (V', E') of the network, in which there is a vertex in V' for every directional communication in the network and there is a directional edge in E' between each node pair that interferes with each other. (We have described the construction of the interference graph in detail in prior progress reports; therefore, we skip the details here.) It maintains a dynamically changing set of nodes R' which, initially contains the nodes in G' (i.e., V'). It executes in steps; in the first step it finds a maximal subset R_1' of R', a maximal subset of G', whose elements can be active concurrently. R_1' is subtracted from R' and in the subsequent iterations, a maximal subset of R'- R_1' is found. C-MUSIC terminates when R' is empty. This construction is depicted in pseudocode in Figure 8 below.

QuickTime™ and a
decompressor
are needed to see this picture.

Figure 8: Demonstrating how every link is visited and evaluated before the decision whether it must be added to a group.

We show that C-MUSIC has a performance efficiency of Ω, where Ω is the maximum opportunity cost in the network. (The opportunity cost O_e for link *e* is the maximum number of links that interfere with *e*, which can be active simultaneously if *e* is deactivated. From among the opportunity costs of all the links in the network, Ω is the maximum opportunity cost.)

C. Distributed Solution Approach for MU-SIC Problem: D-MUSIC

We also propose a distributed variant of the C-MUSIC algorithm. With D-MUSIC, nodes exchange local messages and determine the links that can be activated concurrently in their neighborhood. Thus, while the sub-topologies are determined on a global scale, the process of determination is performed in a distributed manner, in parallel, and locally in the different parts of the network.

Each node associates itself with one of the Transmitter, Receiver, and Overhearer functionalities in each sub-topology. Each node aims to become a transmitter for each of its neighbors, in at least one sub-topology. The link construction is initiated at the Transmitter nodes (as shown in Figure 9 below). Upon hearing a link request from a neighbor *u*, the target node *v* computes whether the candidate transmitter (*u)* can be decoded *given* the accumulated level of interference in the network; the accumulated interference is caused by the communications that have already become part of this sub-topology. Towards this calculation, *v* considers existing transmitters in terms of whether they are received with a stronger or weaker power compared to *u*. If link *(u,v)* can be formed, *v* becomes a Receiver and acknowledges the link request; otherwise it remains an overhearer and sends a negative-acknowledgement to *u*. These steps are shown in Figures 10 and 11 below.

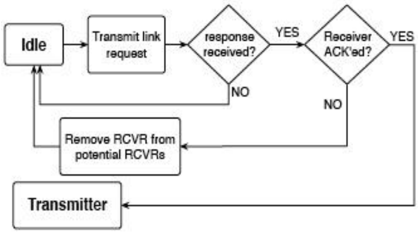
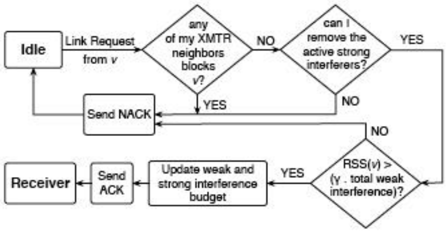
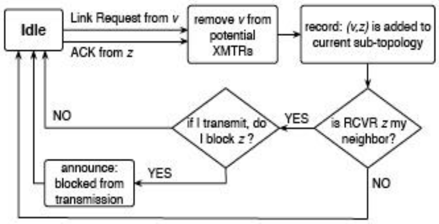
		

Figure 9: DSR with minimum-hop routing. Delay at 3 bps/Hz	**Figure 10: DSR with ETX routing metric, Delay at 3 bps/Hz**	**Figure 11: Performance improvements due to MIMO relative to SISO decrease with ETX-based routing**

D. Performance of C-MUSIC and D-MUSIC

We evaluate the performances of C-MUSIC and D-MUSIC in various settings using OPNET network simulator. We also compare the performance of our approaches with an approach where, A-1 other links are allowed to be simultaneously active in a neighborhood of a receiver; as discussed earlier, many MAC protocols are based on allowing these many concurrently active links [2]. We call this the degree of freedom based approach or simply DoF-based topology control.

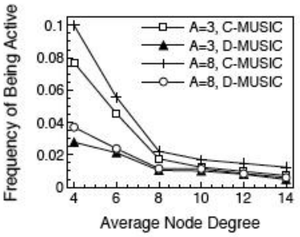
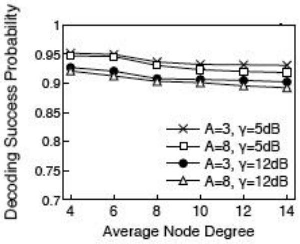
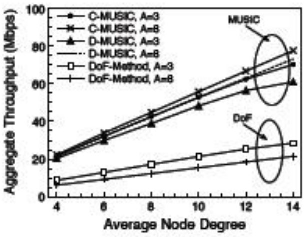
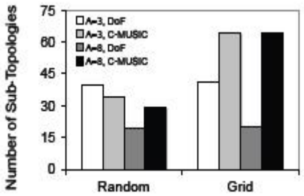
			

Figure 12: Throughput Ratio at 22dB	**Figure 13: Throughput Ratio at 27dB**	**Figure 14: SISO Throughput at 22dB**	**Figure 15: MIMO Throughput at 22dB**

In Figure 12, we show that the frequency with which sub-topologies are activated with D-MUSIC is high at moderate densities. In Figure 13, show that topology control with D-MUSIC in dense multi-user MIMO networks effectively bounds the probability of decoding error. In Figure 14, we compare C-MUSIC and D-MUSIC with the DoF-based topology control. We find that, although the DoF-based topology control finds fewer sub-topologies (since it only considers the number of interferers), the throughput is much lower compared to what is achieved with both our algorithms. This is because the decoding error probability in each sub-topology is as high as 0.7, whereas it is 0.04 with MUSIC. Finally, in Figure 15 we show that in grid topologies, C-MUSIC is coerced into constructing a significantly larger number of sub-topologies (2.2 times more than with random topologies for A=8), each consisting of much fewer links. This is because in a grid topology each node is equi-distant from its neighbors, and the signals of neighbors arrive at a receiver with similar powers. Unlike C-MUSIC however, we observe that DoF constructs a similar number of sub-topologies with both the random and the grid deployments. This is because DoF takes into account the node degree (which is 7 on average in all simulated topologies) and not the SINR.

This work is currently under submission to IEEE Infocom, 2010.

REFERENCES:

[1] D. Tse and P. Viswanath, “Fundamentals of wireless communication” Cambridge University Press, 2005.

[2] K. Sundaresan, R. Sivakumar, M. A. Ingram, and T.-Y. Chang, “A fair medium access control protocol for ad-hoc networks with MIMO links”. In Proceedings of IEEE Infocom, 2004.

2.4 Opportunistic Multi-hop Routing, Adaptation, and Congestion

PI: Tara Javidi

GSRs: Hairou Zhuang and
Somsak Kittipiyakul

As a part of the MURI project, PIs Javidi, Milstein and Cruz have used sophisticated methods from stochastic optimization and approximation to investigate and propose optimal cross layer (PHY, MAC, and Routing) and distributed mechanisms for MIMO ad hoc networks [12], [13], [14]. The outcome of these analytic studies resulted in the design of a family of scalable schedulers which, asymptotically, use minimum total power to transfer the information bits for all the end-to-end connections at the requested rates. To this end, we decomposed the multi-hop MIMO network into multiple “decoupled” MIMO broadcast subsystems. In each time slot, each subsystem independently decides the transmit power, the antenna weights, the transmission rates and the forwarding rules of information bits based on the channel state information and previous decisions of other neighboring subsystems. Given a decomposition of the network into MIMO “decoupled” sub-blocks, the proposed algorithms are shown to converge asymptotically to the optimal solution. Even though asymptotic in nature, these algorithms have significant implications for the design of MIMO networks as they 1) established a promising benchmark, predicting significant improvements for many network scenarios, and 2) provide insight in the design of cross-layer optimal resource allocation at the MIMO-MAC and routing layers.

Lott and Teneketzis [8]-[9] were among the first researchers who introduced opportunism in the context of wireless multi-hop routing. Independently, Larssen proposed a fully implemented protocol suite for Selection Diversity Forwarding (SDF) in [10]. In both of these papers, the source identifies a set of potential forwarders and multicasts the message to them. The successful recipients respond with ACKs in the order in which they were listed in the original message header, so that a collision between ACKs is avoided. The source identifies the best amongst these receivers, according to some predefined criteria, and sends a forwarding order to it. Hence, the actual routing decision is made after transmission of data. While [1] suggests time-invariant critera such as hop-count, transmission rate, and transmission energy for making the final forwarding decision, [10] suggests various time-varying criteria, like forward progress, cost progress, queue backlogs etc, for making the final forwarding decision. Extremely Opportunistic Routing (ExOR) [11] is based on the same idea, with differences in the selection metrics.

With a slight twist, [19] considers the issue of diversity routing from the perspective of traffic stability, i.e., guaranteeing a certain vector of flow rates between given source-destination pairs. We would also like to point out that our work in [14] philosophically coincides with formulation in [19], with the main point of difference in our approaches and methodologies: Our work [14] relies on constrained convex optimization and stochastic approximation frameworks to minimize (asymptotically) the expected sum power subject to a constraints on the minimum long-term average rate at the flow level, while [19] uses a Lyapunov-type penalty function as the cost of violating the QoS requirements to establish stability. The Lyapunov drift analysis is, then, applied to prove the stability, while working within a stochastic approximation framework, our formulation allows for a more general optimization setting. The price of this more powerful methodology is the asymptotic nature of the result. However our more recent work [20] uses the insight obtained from [14] to combine the benefits of [8] and [19] vis-à-vis a congestion diversity measure. Such successful merging of cross-layer diversity routing schemes underlines the significance and promise of the work.

The decision per hop approach raises a number of protocol issues [20]-[21]:

Queuing Delay and Protocol Dynamics: In order to make a local decision on the best next hop node, the queue backlogs as well as channel quality at the receiving nodes needs to be fed back to the transmitting node. In other words, the next “best” hop a dynamically changing option, not only based on channel characteristics and variations but also based on traffic matrix. This can potentially cause oscillatory behavior, whose long-term impacts might be negligible but cause undesirable short term behavior. In other words, while these oscillatory effects tend to smooth out for long flows, they significantly disturb the behavior of short flows.

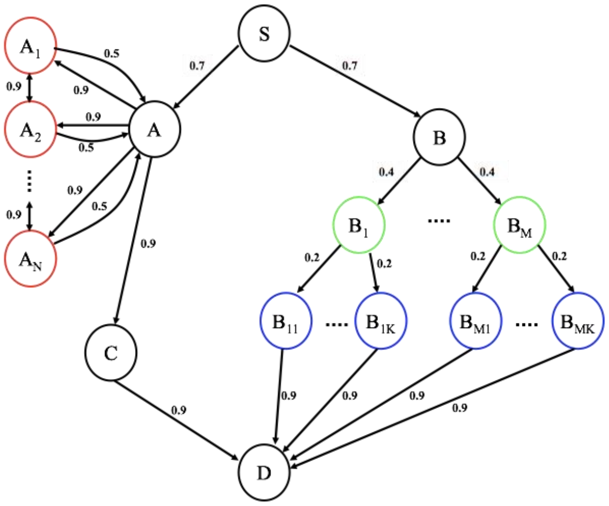


Fig. 1. A multi-hop wireless network

Congestion Problems and Delay-Throughput Trade-off: In many cases, there is an inherent trade-off between packets finding the "shortest" route to the destination and the least congested one. We have been able to show examples, where choosing "shortest" routes can substantially decrease the delay [15]. We have shown that including queuing delay as well as channel quality (both instantaneous state as well as Baysian models) in determining the "distance" to a node is necessary to guarantee an overall desirable behavior. In this, our primary results [15] combine results on backpressure routing [17]-[19] with appropriate concepts from opportunistic routing to improve the delay performance in SISO networks. Our work attempts at taking advantage of diversity in congestion levels across the network without creating unnecessary balancing.

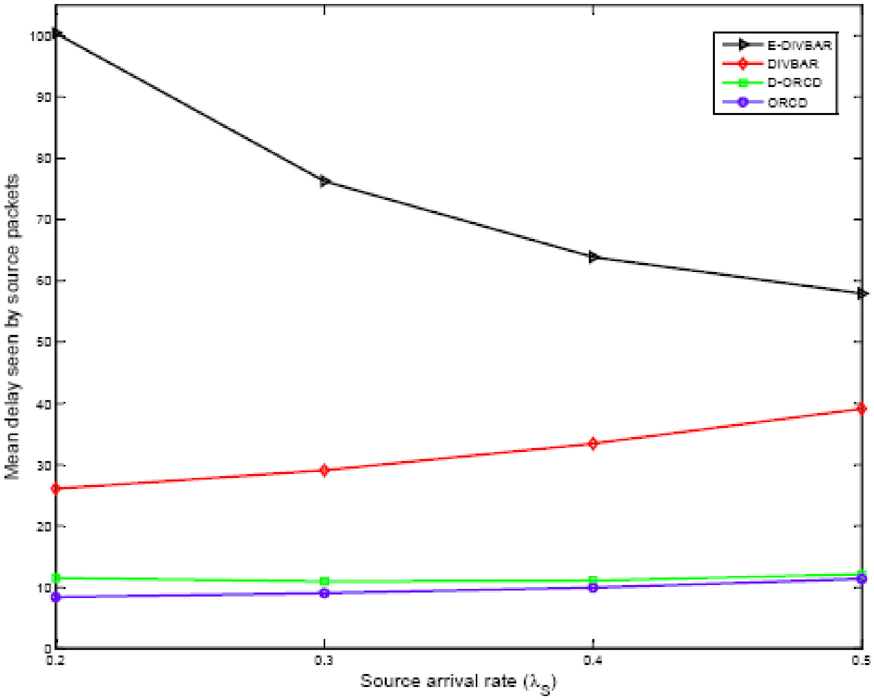


Fig. 2. Delay versus traffic rate (intensity) in the example given in Fig. 1.

Channel Quality Indicator (CQI) and MIMO scheduling: Our work in cross-layer MIMO networking relies heavily on the notion of channel quality to coordinate MAC and routing layer functionalities. In particular, we have relied heavily on the simplicity of our MIMO-BC sub-blocks to identify and adapt instantaneous rate and power schedules. The choice of sub-gradient in this setting was key to obtaining the result.

Channel Quality Distribution (CQD): In order to make a local decision on the best next hop node, the channel quality information is needed. This potentially includes short term indicator (CQI) as well as the channel radio characteristics. While the opportunism reduces the impact of channel estimation error in CQI, the performance of opportunistic algorithms shows a large degree of sensitivity to CQD [7]. An important extension, our work [22] addresses the question of how to account for temporal variation in channel quality as well as effective schemes to construct useful probabilistic models to capture the impact of diversity. In other words, given the stationarity of CQI, one can devise many algorithms to account for receiver diversity in the long term.

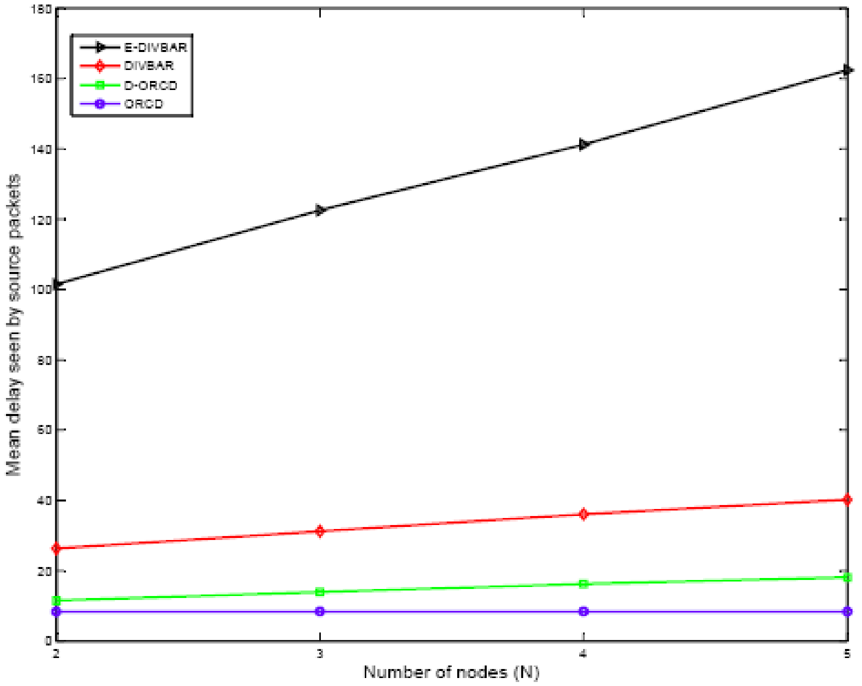


Fig. 3. Delay versus the size of the “hole” A-A, hence, network size.

High-SNR Cross-Layer Optimization for Delay-Limited Data Transmission in Outage-Limited Wireless Systems

In our previous work [7], we studied the optimal operating point in point-to-point (quasi-static) MIMO channel and the asymptotic expression of the total probability of bit error, where errors occur either due to delay or due to erroneous decoding. The problem setting focused on the case where there is no channel state information at the transmitter (no CSIT) and no feedback, and on the static case of fixed operating parameters. In our recent work [2], we generalize this study to include other outage-limited communication settings, such as cooperative relay [4,5] and fast-fading channels [3]. In these settings, we are interested in the asymptotic high-SNR error performance when the delay bound requirement, D, is finite and small. Given that the asymptotic expression of the total probability of bit error is valid without requiring asymptotically large D, it is then meaningful to ask about the optimal coding block duration, a question which is not answered in our previous studies with asymptotic D. To have a valid expression of the delay violation probability at finite and small D, we assume a class of smoothly scaling (with SNR) bit-arrival processes. This class of processes covers many interesting processes used for traffic modeling.

Our analysis provides closed-form expressions for the error performance, as a function of the channel and source statistics. These expressions identify the scaling regime of the source and channel statistics in which either delay or decoding errors are the dominant cause of errors, and the scaling regime in which a prudent choice of the coding duration and rate manages to balance and minimize these errors. That is, in this latter regime, such optimal choice manages to balance the effect of channel atypicality and burstiness atypicality. We apply the results in the different communication settings discussed above.

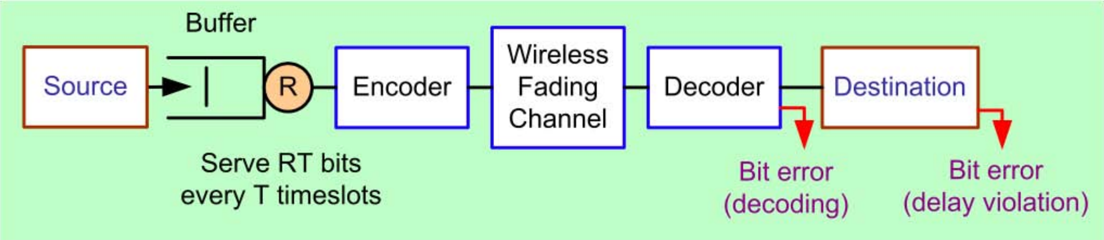


Fig. 4. System model

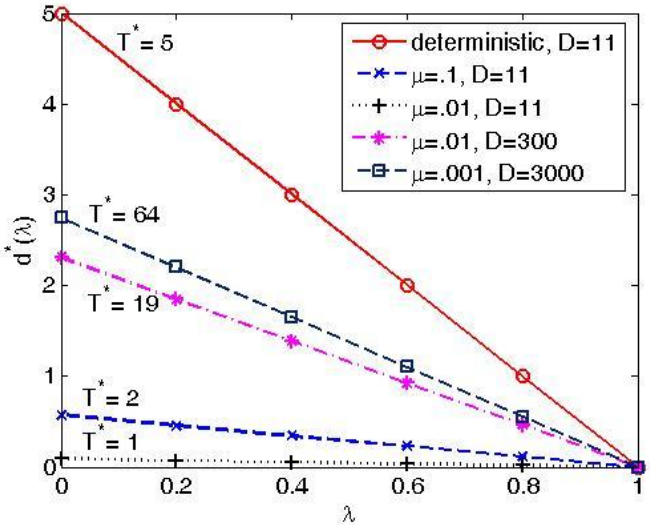


Fig. 5. Exponent of the total error probability for SISO fast fading channel and compound Poisson bit-arrival process

Many-Sources Large Deviations for Max-Weight Scheduling

This work is an extension of our previous study for MIMO multiple access channel [6] and our recent work described earlier. In [6], we studied the joint optimization of the MAC layer and the physical layer. We formulated and analytically derived bounds on the optimal operating point and the asymptotic (high-SNR and large delay bound D) error performance of MIMO-MAC channel for bursty sources with delay constraints. The adopted system model brings together the four types of gains: diversity, spatial multiplexing, space-division multiple-access, and statistical-multiplexing gains.

To extend the work in [6] to the case when the delay bound D is not asymptotically large, in [1] we look at the queuing performance of the dynamic queue-based (Max-Weight) scheduling policy of a single fixed-capacity server, when the arrival processes are an aggregation of multiple i.i.d. flows. We study a particular scaling of the traffic, known as many-sources scaling, where the number of flows scales with the channel capacity. The interested queuing performance is the asymptotic buffer overflow probability. Assuming a many-sources sample path large-deviation principle (LDP) for the arrival processes, we establish an LDP for the queue length process by employing Garcia's extended contraction principle that is applicable to quasi-continuous mappings. In the future, we hope to use this result [1] and the result in [2] to extend the work in [6] to multiple access channels.

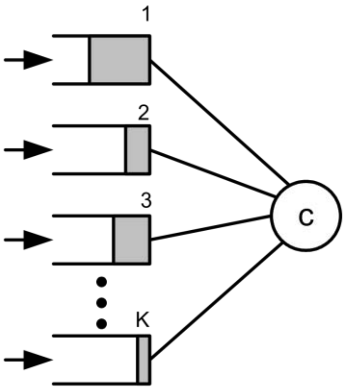


Fig. 6. Multiple-queue, single-server model

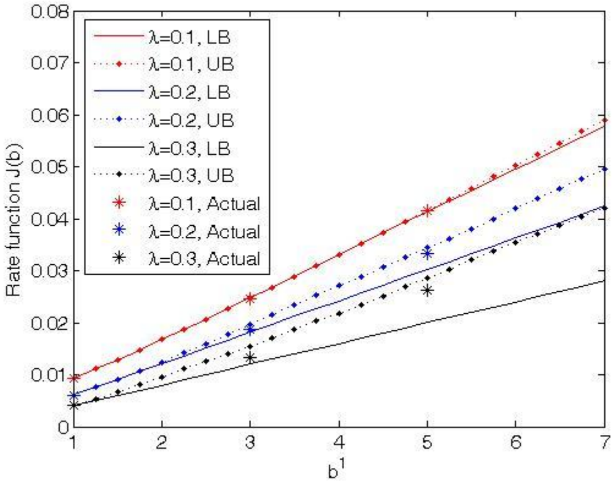


Fig. 7. Example of the actual and the lower and upper bounds of the exponents of the buffer overflow probability where the threshold is (b^1, b^2=1), for compound Poisson bit-arrival process (at various arrival rates) and for two users.

References:

[1] S. Kittipiyakul, T. Javidi, and V. G. Subramanian, ``Many-sources large deviations for max-weight scheduling," submitted to *46th Annual Allerton Conference on Communication, Control, and Computing (Allerton'08)*.

[2] S. Kittipiyakul, P. Elia, and T. Javidi, ``High-SNR analysis of outage-limited communications with bursty and delay-limited information," Vol. 55, Issue 2, pp. 746–763, Feb. 2009

[3] S. Kittipiyakul and T. Javidi, ``Relay scheduling and cooperative diversity for delay-sensitive and bursty traffic," in *45th Annual Allerton Conference on Communication, Control, and Computing*, Monticello, Illinois, USA, Sep. 2007.

[4] P. Elia, S. Kittipiyakul, and T. Javidi, ``Cooperative diversity in wireless networks with stochastic and bursty traffic," in *IEEE Int. Symp. Information Theory*, Nice, France, Jun. 2007.

[5] P. Elia, S. Kittipiyakul, and T. Javidi, ``On the Responsiveness-Diversity-Multiplexing tradeoff," in *5th Intl. Symp. on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks*, Apr. 2007.

[6] S. Kittipiyakul and T. Javidi, ``Optimal operating point for MIMO multiple access channel with bursty traffic," *IEEE Trans. Wireless Commun.*, vol. 6, no. 12, pp. 4464-4474, Dec. 2007.

[7] S. Kittipiyakul and T. Javidi, ``Optimal operating point in MIMO channel for delay-sensitive and bursty traffic," in *IEEE Int. Symp. Information Theory*, Seattle, Washington, USA, Jul. 2006.

[8] C. G. Lott and D. Teneketzis, ``Stochastic routing in ad hoc wireless networks", Proceedings of the 39th IEEE Conference on Decision and Control, 2000

[9] C. Lott and D. Teneketzis, ``Stochastic routing in ad-hoc networks", IEEE Transactions on Automatic Control, Jan. 2006, Vol. 51, No. 1, pp. 52- 70

[10] P. Larsson, "Selection Diversity Forwarding in a Multihop Packet Radio Network with fading channel and capture", in Proceedings of SIGMOBILE Mob. Comput. Commun. Rev. 5(4):47-54, 2001

[11] S. Biswas and R. Morris, "ExOR: Opportunistic MultiHop Routing for Wireless Networks", Proc. SIGCOMM 2005

[12] Y.-H. Lin and R. Cruz, "Opportunistic link scheduling, power control, and routing for multi-hop wireless networks over time varying channels." Prodeedings of Annual Allerton Conference on Communication, Control, and Computing, 2005

[13] Y. Lin, T. Javidi, R. Cruz and L. Milstein, "Distributed Link Scheduling, Power Control and Routing for Multi-hop Wireless MIMO Networks," Proceedings of the Fortieth Asilomar Conference on Signals, Systems and Computers (ACSSC '06), pp. 122-126, Pacific Grove, Calif, USA, 2006

[14] Y. Lin, T. Javidi, R. Cruz and L. Milstein, "Stochastic Optimization and Approximation with an Application in Cross-layer Design of MIMO Ad hoc Networks," Submitted to IEEE Transactions on Information Theory

[15] P. Gupta and T. Javidi, "Towards Delay Optimal Routing in Multi-hop Networks", Proceedings of Asilomar Conference on Signals Systems and Computers, 2007

[16] T. Javidi and D. Teneketzis, "Sensitivity analysis of an optimal routing policy in an ad hoc wireless network", IEEE Transactions on Automatic Control, Volume 49, Aug. 2004

[17] L. Tassiulas and A. Ephremides. "Dynamic Server Allocation To Parallel Queues With Randomly Varying Connectivity." IEEE Trans. on Informations Theory, vol. 39, pp. 466-478, March 1993

[18] L. Tassiulas and A. Ephremides. "Stability Properties Of Constrained Queueing Systems And Scheduling Policies For Maximum Throughput In Multihop Radio Networks." IEEE Transactions on Automatic Control, Vol. 37, no. 12, Dec. 1992

[19] Michael J. Neely, "Optimal Backpressure Routing for Wireless Networks with Multi-Receiver Diversity," Conference On Information Sciences And Systems (CISS), Invited Paper On Optimization Of Comm. Networks, March 2006

[20] M. Naghshvar, H. Zhuang, and T. Javidi, "A General Class of Throughput Optimal Routing Policies in Multi-hop Wireless Networks", to be presented at Allerton Conference, 2009.

[21] M. Naghshvar, and T. Javidi, "Opportunistic Routing with Congestion Diversity in Wireless Multi-hop Networks", submitted to IEEE Infocom 2010.

[22] A. Bhorkar, M. Naghshvar, T. Javidi, B. Rao, An Adaptive Opportunistic Routing Scheme for Wireless Ad-hoc Networks, to appear in Proceedings of IEEE International Symposium on Information Theory, 2009

2.5 Fast Power Allocation for MIMO Relays

PI: Yingbo Hua

Student: Yuan Yu

Highlights of Research

MIMO relays are useful building blocks for tactical wireless mobile ad hoc networks. Power allocations in space, time and frequency are essential for MIMO relays to perform efficiently. Fast computation of power allocation in response to fast changing environment such as channel state information and network topology is critically important for network performance. Our achievements in the past year include: a) the proof of the optimality of diagonalization of multihop non-regenerative MIMO relays for any Schur convex or Schur concave cost functions, b) the establishment of a generalized water filling theorem for MIMO link power allocation with multiple power constraints, and c) the development of a class of power allocation algorithms for uplink and downlink of a non-regenerative MIMO relay system with multiple users.

a) Optimality of Diagonalization

We consider a multiple-hop MIMO relay system where each relay performs waveform amplification and transformation without digital decoding and re-encoding. Such a relay is also called non-regenerative relay. Comparing to regenerative relays, non-regenerative relays are much simpler and have much less end-to-end delay. However, a disadvantage of non-regenerative relays is the effect of noise accumulation. To minimize the effect of noise accumulation, the design of the relay matrix for each relay is critical.

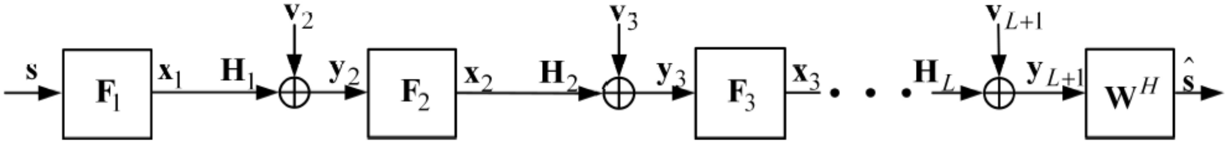


Figure 1: A multi-hop MIMO relay system

As shown in Figure 1, the output waveform vector of the source node is $\mathbf{x}_1 = \mathbf{F}_1\mathbf{s}$ where $\mathbf{s}$ is the vector of independent source symbols and $\mathbf{F}_1$ is the precoding matrix at the source. The waveform vector received by the first relay node is $\mathbf{y}_2 = \mathbf{H}_1\mathbf{x}_1 + \mathbf{v}_2$ where $\mathbf{H}_1$ is the channel matrix of the first link and $\mathbf{v}_2$ is the noise. The relay matrix of the first relay is $\mathbf{F}_2$, i.e., $\mathbf{x}_2 = \mathbf{F}_2\mathbf{y}_2$. Similar expressions hold for all other relays. At the destination, the recovered symbol vector is $\hat{\mathbf{s}} = \mathbf{W}^H\mathbf{y}_{L+1}$ where $\mathbf{y}_{L+1}$ is the waveform vector received by the destination node and $\mathbf{W}^H$ is the minimum mean square error (MMSE) equalization matrix. Here, we assume that interferences between nodes that are two or more hops apart are negligible.

One important question is how we should choose the matrices $\mathbf{F}_1$, $\mathbf{F}_2$, …, $\mathbf{F}_L$ where L is any positive integer. The answer to this question in general depends on the criterion of interest. Such criteria may include the maximization of the end-to-end mutual information (i.e., capacity), the minimization of the averaged mean squared errors in $\hat{\mathbf{s}}$, or the minimization of the maximum mean square errors in $\hat{\mathbf{s}}$. It turns out that all these criteria belong to a much larger class of functions called Schur convex functions or Schur concave functions in majorization theory [1]. After several attempts over several years, we finally succeeded to prove in [2] that the optimal structures of all the relay matrices under the Schur convex or Schur concave criterion subject to power constraints at all relays are such that the effective channels between $\mathbf{s}$ and $\hat{\mathbf{s}}$ are diagonalized and the singular values of all channel matrices are aligned with each other according to their values. This fundamental result is a multi-hop generalization of many previously published results for two-hop MIMO relays, e.g., see references in [3]. It is also a result that other researchers have not been able to establish in their studies of multi-hop MIMO relays. The optimality of diagonalization implies that the singular vectors of each of the unknowns $\mathbf{F}_1$, $\mathbf{F}_2$, …, $\mathbf{F}_L$ should be constructed from the singular vectors of the corresponding channel matrix, and the only remaining unknowns are the singular values of each of $\mathbf{F}_1$, $\mathbf{F}_2$, …, $\mathbf{F}_L$. This simplifies the computation tremendously. The singular values of $\mathbf{F}_1$, $\mathbf{F}_2$, …, $\mathbf{F}_L$ can be found via cyclic water filling search.

b) Generalized Water Filling

Water filling is a very useful concept and algorithm for allocating power for a MIMO (and/or multi-carrier) link with a conventional power constraint. But for tactical MIMO networks, multiple power constraints may be required for a MIMO link for purposes such as controlled interferences to other nodes in the network. This generalized problem can be formulated as follows:

$$\max_{\mathbf{Q}\geq 0} \log\left|\mathbf{I} + \mathbf{H}\mathbf{Q}\mathbf{H}^H\right| \qquad (1)$$

$$\text{s.t., } tr\left(\mathbf{B}_i\mathbf{Q}\mathbf{B}_i^{\ H}\right) \leq P_i \text{ for } i = 1,2,\cdots,m$$

where $\mathbf{H}$ is the channel matrix of the link under consideration, $\mathbf{Q}$ the source covariance matrix, $\mathbf{B}_i$ the constraint matrices depending on applications. For the conventional problem where $m = 1$, the conventional water filling algorithm is the most efficient method. But when $m > 1$, the common method to solve (1) is the general-purpose convex problem solver known as CVX in Matlab. In [4], we established the following theorem:

Theorem (Generalized Water Filling): The solution to (1) is given by:

$$\mathbf{Q} = \mathbf{K}^{-H}\mathbf{V}(\mathbf{I} - \mathbf{\Sigma}^{-2})^{+}\mathbf{V}^{H}\mathbf{K}^{-1} \qquad (1)$$

where $\mathbf{K} = (\sum_{i=1}^{m}\mu_i\mathbf{B}_i^H\mathbf{B}_i)^{1/2}$ (assumed to be non-singular), $\mathbf{V}$ and $\mathbf{\Sigma}$ are determined from the SVD $\mathbf{H}\mathbf{K}^{-H} = \mathbf{U}\mathbf{\Sigma}\mathrm{V}^{H}$, $(\cdot)^{+}$ replaces all negative diagonal elements by zeros and leaves all non-negative diagonal elements unchanged, and $\boldsymbol{\mu} = (\mu_1,\ldots,\mu_m)$ are the solution to the following dual problem:

$$\max_{\boldsymbol{\mu}\geq 0} -\log|\mathbf{I}+\mathbf{HQH}^H| + \sum_{i=1}^{m}\mu_i(tr(\mathbf{B}_i\mathbf{QB}_i^H)-P_i) \qquad (2)$$

$$s.t. \quad \mathbf{Q}=\mathbf{K}^{-H}\mathbf{V}(\mathbf{I}-\boldsymbol{\Sigma}^{-2})^{+}\mathbf{VK}^{-1}.$$

The dual problem is convex and can be solved efficiently using the Newton's method. Furthermore, when the parameter space of the dual problem is much smaller than that of the primal problem, which is a typical case, the dual problem can be solved with much less time than the primal problem. The resulting algorithm is much faster than CVX.

c) Power Scheduling for a MIMO Relay System with Multiple Users

Also shown in [4], we have developed several power scheduling algorithms for uplink as well as downlink of a MIMO relay system with multiple multi-antenna users. The relay node performs waveform amplification and transformation without digital decoding and re-encoding, which is hence non-regenerative.

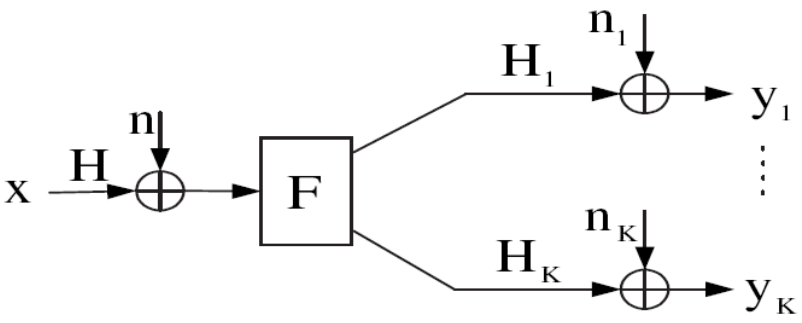


Figure 2: Downlink of multiuser MIMO relay

For downlink, our algorithms search for the optimal source covariance matrix and the optimal relay matrix to either maximize the users' sum rate subject to a power constraint or minimize the total power consumption subject to users' rate constraints.

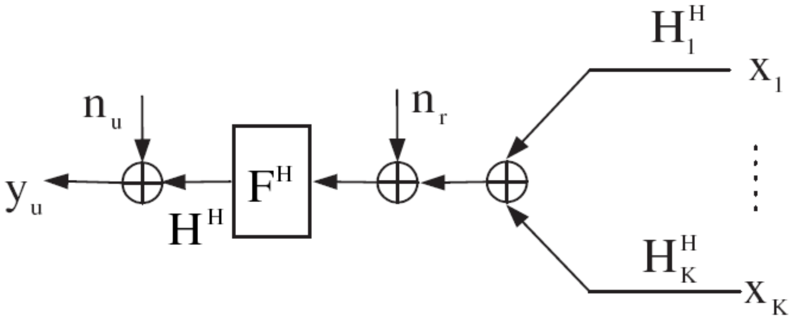


Figure 3: Uplink of multiuser MIMO relay

For uplink, our algorithms optimize the source covariance matrices of multiple users and the relay matrix. Several cost functions are considered depending on the choices such as dirty paper coding (DPC) or zero forcing dirty paper coding (ZFDPC) at the sources. The source covariance matrices and the relay matrix can be searched by a joint gradient search or a cyclic search. In all cases except for an algorithm based on high-SNR approximation and geometric programming, the algorithms obtain locally optimal results of the original problems. To increase the likelihood of finding the global optimal, we considered multiple random initializations. This strategy is naturally suitable for parallel computations with multi-core microprocessors. One important observation from [4] is that approximating a non-convex problem by a convex problem is not necessarily the best strategy. Multiple gradient searches with multiple random initializations can achieve much better results than a convex approximation based approach.

References:

[1] A. W. Marshall and I. Olkin, *Inequalities: Theory of Majorization and Its Applications*. Academic Press, 1979.
[2] Y. Rong and Y. Hua, "Optimality of diagonalization of multi-hop MIMO relays," *IEEE Transactions on Wireless Communications*, submitted March 2009, revised June 2009.
[3] Y. Rong, X. Tang and Y. Hua, "A unified framework for optimizing linear non-regenerative multicarrier MIMO relay communication systems," *IEEE Transactions on Signal Processing*, accepted June 2009.
[4] Y. Yu and Y. Hua "Power scheduling for a MIMO relay system with multiple-antenna users", *IEEE Transactions on Signal Processing*, submitted April 2009, revised July 2009.

2.6 Interference Cancellations in Multiuser and Wireless Relay Networks

PI: Hamid Jafarkhani

Students:

Erdem Koyuncu: Partially supported by MURI (PhD student)

Feng Li: Partially supported by MURI (PhD student)

We have had contributions in three research projects:

1. Interference cancellation in multiuser networks
2. MIMO Multi-Hop Channels
3. Canceling interference in wireless relay networks

In the following we briefly summarize our progress in each project:

(1) Interference cancellation in multiuser networks

The issue of interference in wireless networks has recently attracted a lot of attention. We had proposed interference cancellation methods for any number of users and any number of antennas at the users and the receiver. We continued our contribution by:

A. Performance Analysis of Multiple Antenna Multi-User Detection

We derive the diversity order of our previously proposed multiple antenna multi-user cancellation and detection schemes. The common property of our detection methods is the usage of Alamouti and quasi-orthogonal space-time block codes. For detecting J users each having N transmit antennas, these schemes require only J antennas at the receiver. Our analysis shows that when having M receive antennas, the array-processing schemes provide the diversity order of $N(M - J + 1)$. In addition, our results prove that regardless of the number of users or receive antennas, when using maximum-likelihood decoding we get the full transmit and receive diversities, i.e. NM, similar to the no-interference scenario. [33]

B. Multiple-Antenna Interference Cancellation and Detection for Two Users Using Precoders

Also, we consider interference cancellation for a system with two users when users know each other channels. The goal is to utilize multiple antennas to cancel the interference without sacrificing the diversity or the complexity of the system. Before, in the literature, it was shown how a receiver with 2 receive antennas can completely cancel the interference of two users and provide a diversity of 2 for users with 2 transmit antennas. We propose a system to achieve the maximum possible diversity of 4 with low complexity. Our main idea is to design precoders, using the channel information, to make it possible for different users to transmit over orthogonal spaces. Then, using the orthogonality of the transmitted signals, the receiver can separate them and decode the signals independently. We analytically prove that the system provides full diversity to both users. In addition, we provide simulation results that confirm our analytical proof. [35], [36]

(2) MIMO Multi-Hop Channels

MIMO multi-hop channel plays an important role in wireless ad hoc networks. In this work, we investigate the resource allocation optimization problem in order to achieve throughput maximization with given resource constraints. We propose algorithms with low complexity to achieve maximum capacity. The main idea is to determine the rank of the optimal transmit covariance matrix and the optimal power allocation of each node separately using our low-complexity algorithm. Further, we reduce the complexity of our algorithm by adding another pre-processing algorithm. Using our algorithms, we find that while dynamical allocation of time and power could increase channel capacity, equal time and power allocation among different nodes may not cause much capacity loss. [32]

(3) Canceling interference in wireless relay networks

In another effort, we consider the problem of interference in wireless relay networks. There have been many cooperative schemes proposed for relay networks. Most of these schemes are designed for a single user. We consider a relay network that allows multiple users transmit simultaneously. Our main contributions are:

A. Interference Cancellation in Distributed Space-Time Coded Wireless Relay Networks

We consider the interference cancellation (IC) problem in multi-user wireless relay networks. First, it is shown that using distributed space-time coding (DSTC), the multiple antenna IC scheme that we had proposed for systems with direct transmissions can be applied to relay networks. The ML decoding after full IC can be performed symbol by symbol. Then, by allowing IC at relays, a new degree of freedom in relay network design is discovered. With this new idea, the required number of antennas at the receiver for full IC can be reduced and a balance between diversity and delay can be obtained. [34]

B. Beamforming in Wireless Relay-Interference Networks with Quantized Feedback

We consider quantized beamforming in wireless amplify-and-forward (AF) relay networks. We use the Generalized Lloyd Algorithm (GLA) to design the quantizer of the feedback information and specifically to optimize the bit error rate (BER) performance of the system. Achievable bounds for different performance measures are derived. First, we analytically show that a simple feedback scheme based on relay selection can achieve full diversity. Unlike the previous diversity analysis on the relay selection scheme, our analysis is not aided by any approximations or modified forwarding schemes. Then, for high-rate feedback, we find an upper bound on the average signal-to-noise ratio (SNR) loss and show that it decays at least exponentially with the number of feedback bits, B. Using this result, we also demonstrate that the capacity loss also decays at least exponentially with B. In addition, we provide approximate upper and lower bounds on the BER, which can be calculated numerically. Simulations are also provided, which confirm our analytical results. We observe that, for R relays, our designs achieve full diversity when $B \geq \log R$ and a few extra feedback bits are sufficient for a satisfactory performance in terms of the array gain. Simulations also show that our approximate BER is a reliable estimation on the actual BER for even moderate values of B. [37]

References:

[30] S. Ekbatani, F. Etemadi, and H. Jafarkhani, "Throughput maximization over slowly fading channels using erroneous quantized feedback," to appear in IEEE Transactions on Communications.

[31] Y. Jing and H. Jafarkhani, "Network Beamforming Using Relays with Perfect Channel Information," IEEE Transactions on Information Theory, June 2009.

[32] F. Li and H. Jafarkhani, "Resource Allocation Algorithms with Reduced Complexity in MIMO Multi-Hop Fading Channels," IEEE Wireless Communications and Networking Conference (WCNC-09), Apr. 2009.

[33] J. Kazemitabar and H. Jafarkhani, "Performance Analysis of Multiple Antenna Multi-User Detection," Information Theory and Applications Workshop, Jan. 2009.

[34] Y. Jing and H. Jafarkhani, "Interference Cancellation in Distributed Space-Time Coded Wireless Relay Networks," IEEE International Conference on Communications (ICC-09), June 2009.

[35] F. Li and H. Jafarkhani, "Interference Cancellation and Detection Using Precoders," IEEE International Conference on Communications (ICC-09), June 2009.

[36] F. Li and H. Jafarkhani, "Multiple-Antenna Interference Cancellation and Detection for Two Users Using Precoders," submitted to IEEE Journal of Selected Topics in Signal Processing.

[37] E. Koyuncu and H. Jafarkhani, ``Beamforming in Wireless Relay-Interference Networks with Quantized Feedback," IEEE Global Communications Conference (Globecom-09), Nov. 2009.

2.7 Feedback MIMO Systems

PI: Bhaskar D. Rao

GSRs: Yogananda Isukapalli

SUMMARY OF RESEARCH

Our work is concerned with feedback in MIMO based Ad Hoc networks; development of effective quantization methods, analysis of feedback systems with finite rate feedback, analysis of feedback systems with imperfect channel state information, and developing protocols that support multiple simultaneous transmissions.

a) Average SEP/BEP analysis with Channel Estimation Errors and Feedback Delay

In this work, we analyze average symbol error probability and bit error probability performances of M-PSK and M-ary rectangular QAM constellations with Gray code mapping.

This was the work was mainly carried out in the first two years of MURI project and the journal paper related to this work appeared in *IEEE transactions on communications* Jan. 2009 issue [1].

b) Optimum Codebook Design for Minimizing the Average SEP Loss and Analysis of Loss Due to Channel Quantization

In this work, we focused on Multiple Input Single Output (MISO) systems where channel state information (CSI) is conveyed from the receiver to the transmitter through a finite-rate feedback link. The importance of the choice of performance metric and the effect of mismatch in the channel statistics assumptions are the main focus of this work.

Some of the ideas related to this work were discussed in last year's report, and the journal paper with complete details, appeared in *IEEE transactions on signal processing* May 2009 issue [2].

c) Modeling of Feedback Imperfections: Distinction between Feedback Delay and Estimation Error

This work was initiated last year and constitutes a major portion of our work this year. The motivation for this work is to address some of the shortcomings of existing work. In particular, to develop models of feedback systems that more closely reflect real communication systems and to provide analytical results for appropriate and meaningful metrics. We made significant improvements on the modeling of imperfections and identified the proper metric namely Packer Error Probability (PEP). On the analytical side, we have clearly pushed the boundary and developed new tools. The expressions are complex but simple enough to compute and so are still useful in that they can obviate the need for computer simulations that are time consuming. A journal paper related to this work was submitted to *IEEE transactions on signal processing* in May 2009 and revised in Jul. 2009 [3].]. A conference paper related to this work also appeared in Globecom'08 [4]. Another journal paper related to developing an analytically tractable approximation for the Gaussian Q-function also appeared in *IEEE communications letters* Sep. 2008 issue [5]. We now briefly discuss the main ideas related to this work.

Multiplicative fading is a major source of performance degradation in multipath wireless environment. Channel coding and interleaving can offer some protection from the negative effects of fading. However, in some wireless systems data has to be organized into small packets, which are confined to fixed time slots, with or without interleaving. One popular example of such a system is the slotted multiple access scheme. It is important for the system designers to know the impact of fading on the performance. An important metric for studying the performance of a non-interleaved wireless packet data transmission is the average packet error probability (PEP). Packet error probability is also increasingly becoming an important quality-of-service parameter for the wireless networking community since it determines how frequently the information packet has to be re-transmitted.

Extensive analytical results quantifying the impact of fading on average symbol and error probability (SEP/BEP) are available for various modulation schemes. However, in slow fading situations, there is no mapping between the average SEP/BEP and the average PEP. Consequently knowing average SEP/BEP does not help in understanding the average PEP. Analysis of average PEP is a more complicated problem compared to the analysis of average SEP/BEP. Analytical quantification of packet error probability has received considerable attention in the literature. Closed-form expressions for PEP have been derived for the non-coherent FSK modulation. The non-coherent FSK's SEP, conditioned on the channel, is an exponential function and taking expectation of the higher powers of conditional SEP w.r.t. the fading random variable is analytically tractable. However, closed-form expressions are not available for coherent BPSK and other constellations. Conditional PEP (conditioned on a function of the wireless channel) for a scheme such as coherent BPSK results in integer powers of the Gaussian-Q function. This makes the analysis challenging because in order to derive the average PEP expression, one has to integrate the integer powers of the Gaussian-Q function w.r.t. the random variable that captures the fading environment, an analytically difficult exercise. We also note that, to the best of our knowledge, the effect of channel estimation errors on PEP has not been considered in the literature.

In this work we consider the problem of deriving analytical expressions for PEP of a multiple input single output system with various forms of practical imperfections. We later show that this problem captures various commonly interested performance analysis of wireless systems as special cases. The first form of feedback imperfection considered is channel estimation error. It is now a common practice to model the actual channel and its estimate as a jointly Gaussian random process, with an error term that is orthogonal to the channel estimate. The error term associated with a particular channel estimate is unknown to the receiver and hence it becomes part of noise when the performance analysis is carried out. If the channel under consideration is varying at symbol level, or if the performance criteria is average symbol/bit error probability, then the variance of the error term will be simply added (along with the symbol dependency) to the variance of the receiver noise resulting in an effective noise term with variance equaling the sum of variance of receiver noise and the variance of the estimation error term. In this part of the work, we also follow the standard model of joint Gaussianity between the channel and its estimate, but adapt it to the packet fading model. An important difference is that in a packet fading model the error term is constant for the entire packet while each symbol experiences a different noise sample requiring new analytical tools.

The second form of feedback imperfection we address is the delay between constructing the beamforming vector at the receiver and using it at the transmitter. Another well accepted formulation is to treat the impact of feedback delay in a manner similar to estimation errors, i.e., actual channel and its delayed version are assumed to be jointly Gaussian with an unknown (to the receiver) error term that is orthogonal to the delayed version. Since the delay related error term is unknown to the receiver, similar to estimation related error term, during performance analysis it becomes part of noise thus removing any conceptual distinction between the mismatch in beamforming due to feedback delay and estimation errors. Though much of the past work on feedback delay effectively make the delay related error term part of receiver noise, alternate options were considered (primarily in the context of adaptive modulation). However, it is important to note that much of the work treated estimation errors and feedback delay in a similar manner, i.e., either both the error terms are assumed to be known or unknown to the receiver. In this work, based on feedback system considerations we feel it is appropriate to treat the errors due to feedback delay to be known at the receiver, while the errors due to estimation errors are un-known at the receiver. This modeling approach is adopted in this work and it shows that the impact of feedback delay on beamforming MISO system performance can be less severe and is also conceptually quite different from channel estimation errors.

The third form of feedback imperfection considered in this work is finite-rate quantization of the channel. To summarize, the contributions presented in this work are threefold: an accurate characterization of estimation errors in a packet fading context, a new modeling of feedback delay which shows improved performance for a beamforming MISO system and conceptually distinguishes it from estimation errors, and derivation of an analytical expression quantifying the impact of channel estimation errors, feedback delay and channel quantization on the average packet error probability. All these contributions further the understanding of feedback communication systems. As a side benefit, the analytical tools developed promise to be of general interest with broad applicability.

d) Wireless Channel Modeling and Prediction

In this work, we turn our attention to the issue of minimizing the negative impact of feedback delay on the performance of the system. An obvious solution to the problem of feedback delay is to predict the channel and then quantize the predicted channel. In this chapter we study the role of ergodicity in wireless channel prediction. With an eye on developing a better wireless channel simulator we first begin with a general, but non-linear and non-tractable, form of wireless channel model. Under certain assumptions we then consider a simplified and well accepted linear sinusoidal channel model. Following the sinusoidal channel model, conditions under which the ergodic assumption is valid are presented. This sheds insight into when statistical channel models that employ ensemble averaging are appropriate.

Due to the lack of ergodicity in a typical real world wireless channel, Least Squares prediction, an approach based on time averages is motivated as opposed to linear minimum mean squared error channel prediction, an approach based on ensemble averaging. We then study methods such as Forward-Backward and rank reduction for high quality channel prediction. Simulation results are presented to complement the analytical expressions. Simulation results also illustrate the improvement in channel prediction quality [6].

e) MIMO Ad Hoc Networks

Last year we proposed a novel asynchronous Media Access Control (MAC) protocol, Opportunistic MAC (OMAC), for MIMO ad-hoc networks [10]. The proposed solution is based on closed loop minimal feedback antenna selection diversity scheme and optimums receive combining. The use of antenna selection diversity contributes to a reduction in the feedback information and in the effective interference produced. To utilize the spatial degrees of freedom offered by MIMO, we propose the use of a novel rank based metric to obtain interference information as well to to enable multiple simultaneous transmissions and to make MAC decisions. The rank of the interference matrix, R_I is used as a metric. Through analysis and simulation, we found that the proposed protocol significantly outperforms 802.11 MIMO and obtained high spatial degree of freedom utilization.

The performance evaluation in our work had assumed that the rank estimation mechanism was error-free (i.e., it would always correctly estimate the number of concurrent communications). In our current work [7], we develop a robust method to estimate this quantity, based on a rank estimation algorithm resilient to noise and interference. Our key contribution is the design and performance evaluation of a novel carrier sense scheme tailored to MIMO that exploits the spatial structure of MIMO waveforms. The proposed carrier sense system used here is by no means specific to OMAC, and could also be adopted by other MIMO ad hoc protocols. The

other MIMO MAC protocols based on carrier sense may use the conventional approach (i.e., compare the average received power across the antennas against a certain threshold) that does not exploit this structure or may propose ad hoc techniques that work only when transmissions are slot synchronous, while our scheme works also for asynchronous communications. We show that this carrier sense mechanism can help realize the communication parallelism inherent in MIMO at a limited cost in computational complexity.

References:

[1]. Y. Isukapalli, R. Annavajjala, and B. D. Rao, “Performance analysis of transmit beamforming for MISO systems with imperfect feedback,” *IEEE Transactions on Communications*, vol. 57, issue. 1, pages: 222-231, Jan. 2009

[2]. Y. Isukapalli, J. Zheng, and B. D. Rao, “Optimum codebook design and average SEP loss analysis of spatially independent and correlated feedback based MISO systems with rectangular QAM constellation,” *IEEE Transactions on Signal Processing*, vol. 57, issue. 5, pages: 2017-2024, May 2009

[3]. Y. Isukapalli and B. D. Rao, “Packet error probability of a transmit beamforming system with imperfect feedback,” submitted, May 2009, revised, Jul. 2009, *IEEE Transactions on Signal Processing*

[4]. Y. Isukapalli and B.D. Rao, "Analyzing the Effect of Channel Estimation Errors on the Average Block Error Probability of a MISO Transmit Beamforming System," IEEE Global Telecommunications Conference, New Orleans, LA, USA, pages: 1-6, Dec - 2008

[5]. Y. Isukapalli and B. D. Rao, “An analytically tractable approximation for the Gaussian Q-function,” *IEEE Communications Letters*, vol. 12, issue. 9, pages: 669-671, Sep. 2008.

[6]. Y. Isukapalli and B. D. Rao, “Multi-antenna wireless channel modeling: statistical properties and prediction,” in preparation, *IEEE Transactions on Signal Processing*

[7]. E. Coviello, A. Bhorkar, F. Rossetto, B. D. Rao, and M. Zorzi, “A Robust Approach to Carrier Sense for MIMO Ad Hoc Networks*”* International conference on communications, Jun. 2009

2.8 Hierarchical modulation for jointly combined space-time coding and spatial multiplexing in MIMO system

PI: Laurence Milstein

GSR: Seok-Ho Chang

I. Introduction

We are interested in the cross-layer design of a tactical communications system to support real-time video transmissions. The basic element of the design is the use of MIMO technology to achieve unequal error protection (UEP) among the different components of a scalable video waveform. As will be discussed below, scalable video signals are designed so that different parts of the waveform have different levels of importance. Thus, UEP is a natural way of protecting the more important components more heavily than the less important components. The goal of the research is to jointly use the key properties of the physical layer and application layer to enhance system performance through the use of MIMO designs.

Scalable video has both a base layer and an enhancement layer. Successful reception of only the base layer provides relatively poor reproduction of the video, but the quality improves monotonically as more of the enhancement layer is successfully received. However, if the base layer is not correctly received, the enhancement layer is useless. Thus, the base layer should be protected more strongly than the enhancement layer.

Since the base layer of scalable video should be transmitted more reliably than the enhancement layer, space-time coding can be employed for the base layer, while spatial multiplexing can be used for the enhancement layer. In this research, we combine the UEP that arises with the use of a hierarchical constellation, with the UEP that can be achieved through the use of MIMO.

II. Proposed scheme

We regard the hierarchical constellation as the superposition of two subconstellations, a basic subconstellation and a secondary subconstellation, where the Euclidian distance between the signal points of the basic subconstellation is greater than that of the secondary subconstellation. As an example, for 2 by 2 MIMO systems, the constellation symbols of our scheme are given by

$$\begin{bmatrix} S_A[2n] & S_A[2n+1] \\ S_B[2n] & S_B[2n+1] \end{bmatrix} = \begin{bmatrix} x_1[2n] + x_{2A}[2n] & -x_1^*[2n+1] + x_{2A}[2n+1] \\ x_1[2n+1] + x_{2B}[2n] & x_1^*[2n] + x_{2B}[2n+1] \end{bmatrix} \quad (1)$$

where each row corresponds to a transmit antenna, each column corresponds to a time symbol, and other notation is defined as follows:

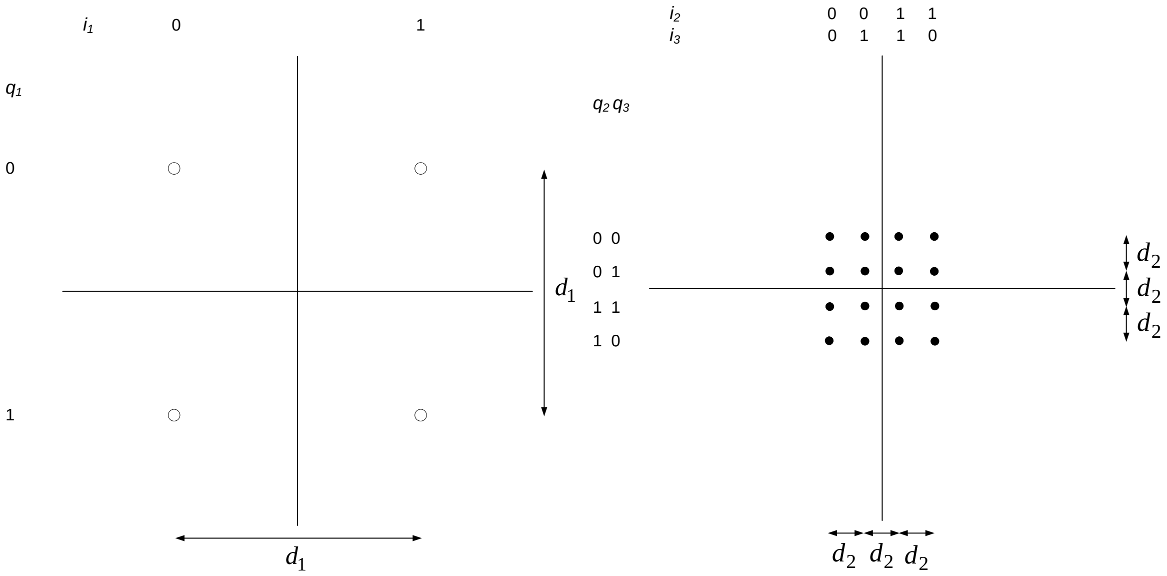
$S_A[n]$, $S_B[n]$: hierarchical constellation symbols which are transmitted on antennas A and B, respectively.

$x_1[n]$: basic subconstellation symbol which is transmitted using an Alamouti code.

$x_{2A}[n]$, $x_{2B}[n]$: secondary subconstellation symbols which are transmitted using spatial multiplexing on antennas A and B, respectively.

Note that the basic and secondary subconstellations can have an arbitrary alphabet size. As an example, Fig. 1 (a) uses QPSK for the basic subconstellation, where the minimum Euclidian distance between signal points is given by d_1 (note that the average power, $P_1 = d_1^2 / 2$). Fig. 1 (b) shows the secondary subconstellation using 16 QAM whose minimum Euclidian distance is given by d_2 (note that the average power, $P_2 = 5d_2^2 / 2$). Lastly, Fig. 2 shows hierarchical 4/64 QAM which is the superposition of the basic and the secondary subconstellations shown in Figs. 1 (a) and (b).

Note that from (1), we are effectively using fourth order diversity for the two base layer bits of each 64 QAM symbol, and using spatial multiplexing for the four enhancement layer bits of each 64 QAM symbol.



(a) QPSK (Almouti coding) (b) 16 QAM (Spatial multiplexing)

Fig. 1. Basic and secondary subconstellations.

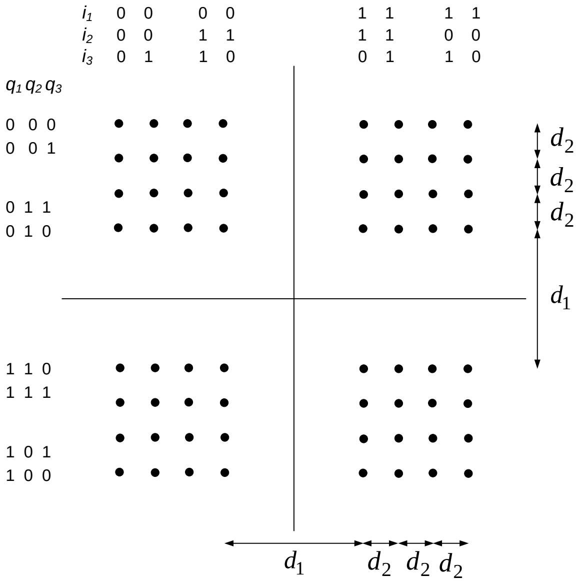


Fig. 2. Hierarchical 4/64 QAM.

III. Simulation results

We evaluate the performance of the proposed hierarchical 4/64 QAM scheme using the mapping of (1). Note that for each symbol duration, the proposed scheme transmits 2 bits and 8 bits for the base layer and the enhancement layer, respectively. For comparison purposes, we also evaluate the performance of a hierarchical 2/32 QAM scheme which employs just spatial multiplexing, and a hierarchical 4/1024 QAM scheme which employs just space-time coding. Note that both schemes also transmit 2 bits and 8 bits for the base and enhancement layers, respectively, for each symbol duration. In other words, the above three schemes all have the same data rate.

We use the progressive source coder SPIHT [2] as an example, and provide the results for the standard 8 bits per pixel (bpp) 512×512 Lena image [3] with a transmission rate of 0.375 bpp. To compare the image quality, we use peak-signal-to-noise ratio (PSNR), defined as

$$\mathrm{PSNR} = 10 \log \frac{255^2}{E[D]} \quad \text{(dB)} \tag{2}$$

where 255 is due to the 8 bpp image, and $E[D]$ is the expected distortion of the image. For this analysis, we used mean-squared error as the distortion measure, D. All the three schemes are decoded using maximum likelihood decoding [1]. Fig. 3 shows the PSNR performance. It is seen that the proposed hierarchical modulation which combines space-time coding and spatial multiplexing outperforms the two conventional schemes.

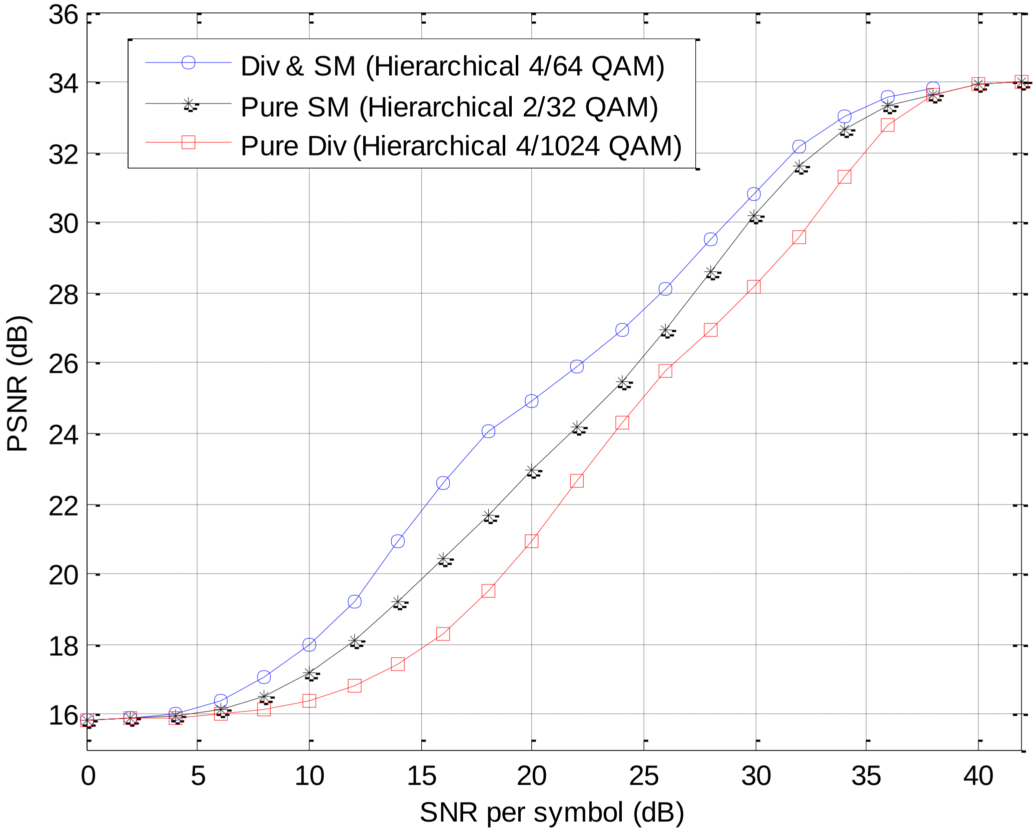
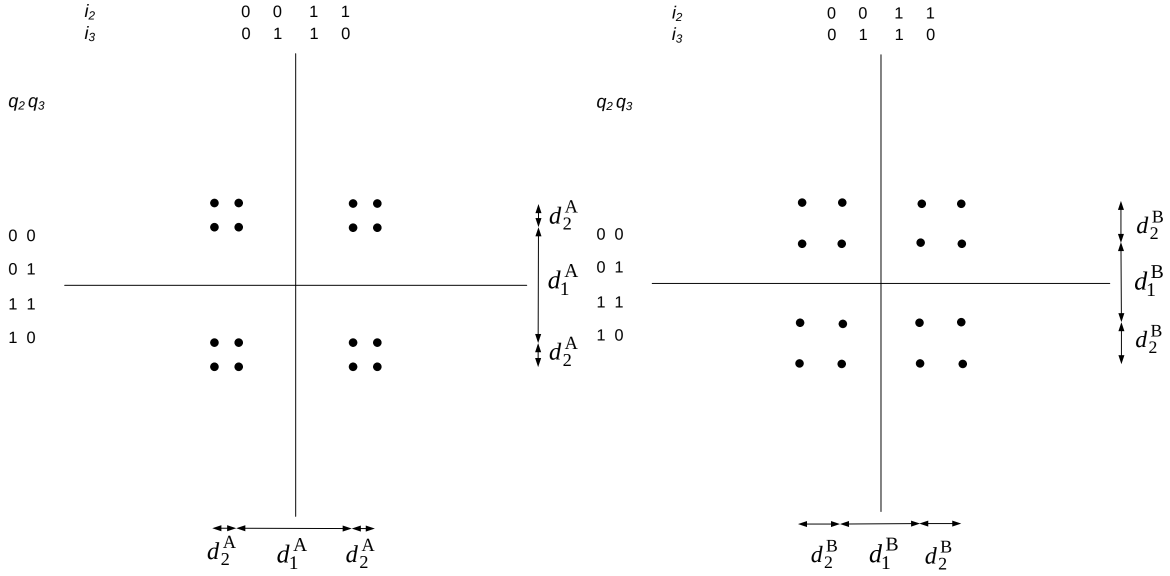


Fig. 3. PSNR performance of the proposed scheme.

III. Conclusion and future research

In this report, we proposed a specific scheme for hierarchical modulation which combines two different MIMO techniques to minimize the expected distortion for either progressive images or scalable video by employing uniform QAM constellations for the basic and the secondary subconstellations. However, subconstellations themselves can be hierarchical QAM constellations. As an example, for hierarchical 256 QAM, the basic subconstellation can be 4/16 QAM and the secondary subconstellation also can be 4/16 QAM. Further, when we employ hierarchical constellations for $x_{2A}[n]$ and $x_{2B}[n]$ of (1), the secondary subconstellation symbols which are transmitted using spatial multiplexing on antennas A and B can have distinct minimum Euclidian distances. In [2], specific methods of multiplexing hierarchical constellations which have distinct minimum Euclidian distances was proposed to achieve multiple levels of UEP. We are now considering using the techniques of [2] in conjunction with spatial multiplexing. As an example, Fig. 4 shows hierarchical 4/16 QAM constellations having different minimum Euclidian distances for the secondary subconstellations. Note that Alamouti coding is still used for the base layer of the scalable video.



(a) Secondary subconstellation on antenna A (b) Secondary subconstellation on antenna B

Fig. 4. Hierarchical 4/16 QAM constellations having different minimum Euclidian distances for secondary subconstellations.

References

[1 A. Paulraj, R. Nabar, and D. Gore, *Introduction to Space–TimeWireless Communications*. Cambridge, U.K.: Cambridge Univ. Press, 2003.

[2] S.-H. Chang, M. Rim, P. C. Cosman and L. B. Milstein, “Optimal Multiplexed Hierarchical Modulation for Unequal Error Protection of Progressive Bit streams,” *IEEE Globecom’09,* Honolulu, Hawaii, USA, Nov. – Dec. 27–1, 2009.

2.9 Channel Diversity and Delay Characterization in Random Wireless Networks

John G. Proakis, Principal Investigator

James R. Zeidler, Principal Investigator

Kostas Stamatiou, Graduate Student

1. Publications

[1] K. Stamatiou, J.G. Proakis and J.R. Zeidler, "Channel Diversity in Random Wireless Networks", submitted to *IEEE Transactions on Wireless Communications*.

[2] K. Stamatiou, F. Rosssetto, M. Haenggi, T. Javidi, J. Zeidler and M. Zorzi, "Delay Characterization of Random Multi-hop Networks", submitted to *IEEE Transactions* on *Wireless Communications*

2. Introduction

In one aspect of our work, we consider a network composed of an infinite number of routes on an infinite plane. The first approach we take is to assume that each route simply consists of only one link, i.e., a transmitter (TX) and receiver (RX) at distance R. This single-hop model can be considered as a snapshot of an actual multi-hop network and allows us to evaluate the performance in terms of *single-hop metrics,* that reflect the performance benefit at the multi-hop level. Such metrics are the *network throughput,* defined as the product (spatial density of TXs) x (link throughput), which addresses the need to pack as many transmissions as possible in space; and the *information efficiency,* defined as the product (transmission distance) x (link throughput), which captures the trade-off present in a multi-hop network where, transmitting farther means a packet needs fewer hops to reach its final destination. However, for a fixed TX power, the RX signal-to-interference (SIR) ratio is lower. The single-hop approach allows the analytical evaluation of the aforementioned metrics, as a function of various physical layer parameters, such as the multiple-access (MA) scheme, e.g. frequency hopping (FH), the coding scheme, e.g., convolutional coding, and, in case the nodes have more than one antenna, the multiple-input multiple-output (MIMO) technique, e.g., space-time coding or spatial-multiplexing

Although it provides useful insight on how physical layer choices affect the link performance, the above approach has its shortcomings. It implicitly assumes that the source of communication and its respective final destination lie at an infinite distance from each other and focuses on optimizing the performance of a single link, with the hope of providing a benefit at the end-to-end level. Since the distance of the final destination or the number of hops are not specified, there are no guarantees in terms of end-to-end delay and throughput. The second part of our work assumes a simplified – but still realistic – physical layer and focuses on evaluating the end-to-end delay and throughput over a typical network route, when the source and final destination are at a specified distance R, and a number of relays are placed on the line between them, in order to forward the packets that originate at the source. A simple link-layer protocol is considered, where, if a packet is not received correctly by a node, it is stored at the head of the queue of the previous node in the route and retransmitted at the next available opportunity. Central to our analysis is the notion of stability of the relay queues, i.e., making sure that their lengths do not become unbounded over time, and, as a result, the end-to-end delay becomes infinite. We address issues such as: determining the optimal number of relays and their placements, so that the delay is minimized and/or the throughput is maximized; the impact of imperfect relay placement on the delay; the maximum allowable MAC probability for backlogged sources and the maximum allowable packet arrival probability for non-backlogged sources such that all queues in the network are stable.

With regard to the network topology, we assume that the locations of the sources (TXs in the first model) are drawn independently according to a spatially homogeneous Poisson process of density λ and the orientation of the destinations (RXs in the first model) is random. The topology, thus the interference experienced over a link, can actually change due to mobility or, effectively, due to random access, if the network is static. In both cases, a link is characterized by its packet success probability, which is an average measure of performance, over different network topologies and channel realizations. We assume that the channel between any two nodes at distance r includes Rayleigh fading and path-loss according to the law, r^{-b}, where $b>2$ is the path-loss exponent. All nodes have the same transmit power – normalized to one – and additive Gaussian noise is disregarded, i.e., we are considering an interference-limited environment.

3. Summary of Achievements.

In the journal paper [1], we explore the benefits of channel diversity in wireless ad hoc networks. Our model is that of a Poisson point process of transmitters, each with a receiver at a given distance. A packet is divided into blocks which are transmitted over different subbands that are determined by random frequency hopping (FH). At the receiver, a maximum-likelihood decoder is employed to estimate the transmitted packet/codeword.

We demonstrate that large gains in terms of network capacity are possible, by combining FH during packet transmission and error correction coding of modest complexity. If L is the Hamming distance of the convolutional code employed at the TX, λ is the density of TXs and M

is the number of subbands, we show that, as $\lambda / M \rightarrow 0$, the codeword error probability scales as O ($(\lambda / M)^L$). This implies that the transmission capacity scales as

$\varepsilon^{1/L}$ for $\varepsilon \rightarrow 0$, where ε is the constraint placed on the codeword error probability. The pre-constant depends on the geometry of the symbol constellation and is also approximately proportional to N^{α} where N is the number of antennas at the RX and

$\alpha = 2/b$, where $b > 2$, is the propagation exponent. We also derive upper and lower bounds on the ergodic capacity C of the typical TX-RX link.

Practical physical layer issues are discussed such as channel estimation, power control (PC) and channel correlation. We demonstrate via simulation that, with an acceptable rate loss, accurate channel state information (CSI) can be obtained for decoding. With respect to PC, it is shown that channel inversion can actually improve the performance, since the error correction code protects the RX from the deep fades of its nearby interferers. Finally, the impact of the channel correlation is evaluated as the number of subbands and/or the number of dwells is decreased and it is shown that the gains compared to slow FH are still significant.

In journal paper [2], we investigate the end-to-end delay performance of multi-hop random networks. We consider networks where each route consists of a source, a number of relays and a destination at a finite distance, and the locations of the sources and relays are determined according to independent Poisson point processes. Nodes are equipped with queues to accommodate the randomness in the delivery of a packet, which is determined by the level of the SIR over each hop. Given a TDMA/ALOHA MAC protocol, we first study an idealized network model where all routes have the same number of hops, the same distance per hop and their own dedicated relays. Assuming that a stationary regime exists for this network, we analytically evaluate the mean end-to-end delay and the throughput for backlogged and non-backlogged sources. A key point in our analysis is taking into account that the interference level over each hop, i.e., the density of transmitting nodes, depends on the packet success probabilities and vice versa. The derivation of closed-form expressions permits the optimization of the mean end-to-end delay with respect to the number and placement of the relays. The benefits of this relay selection – or routing – strategy are then verified in the original network via simulation.

If the sources are backlogged, we find that the delay is minimized if the first hop is much larger than the remaining hops, e.g., in a delay-optimized three-hop route, the first hop covers half the total distance. On the other hand, in the non-backlogged case, the delay is minimized for equidistant hops. We demonstrate that the respective optimal numbers of hops scale sublinearly and linearly with the source-destination distance. We also discuss stability issues in a multi-hop random network and derive sufficient conditions on the medium access probability (MAP), and the traffic load in the case of non-backlogged sources, for the rate stability of the network.

Simulations show that, when the relays of each route are selected out of a random population, the analytical results are accurate, provided that the density of the relay process is sufficiently large.

2.10 Interference Suppression at the Transmitter in Point-to-Multipoint MIMO Transmission

John G. Proakis, Principal Investigator

James R. Zeidler, Principal Investigator

Laurence B. Milstein, Principal Investigator

Patrick Amihood, Graduate Student

Arun Batra, Graduate Student

1. Publications

[1] P. Amihood, E. Masry, L.B. Milstein and J.G. Proakis, "The Effects of Channel Estimation Errors on a Nonlinear Precoder for Multiple Antenna Downlink Channels", accepted for publications, *IEEE Transactions on Communications*.

[2] A. Batra, J. R. Zeidler, J.G. Proakis and L.B. Milstein", "Interference Rejection and Management", Chapter 9 in *New Directions in Wireless Communications Research*, V. Tarokh (ed.), Springer-Verlag, New York, 2009.

2. Introduction

In this work we have investigated interference mitigation techniques in point-to-multipoint (broadcast) MIMO communication systems, in which the interference mitigation is performed at the transmitter. To mitigate the interference at the transmitter, the transmitter must know the channel characteristics, typically the channel impulse response. This channel state information (CSI) may be obtained from channel measurements performed at each of the receivers by means of received pilot signals sent by the transmitter. Then, the CSI must be sent to the transmitter. In such a scenario, the channel time variations must be relatively slow so that a reliable estimate of the channel characteristics is available at the transmitter. In some systems, the uplink and downlink channels are identical, e.g., the same frequency band is employed for both the uplink and the downlink, but separate time slots are used for transmission. This transmission mode is called time-division duplex (TDD). In TDD systems, the pilot signals for channel measurement may be sent by each of the users in the uplink. In our treatment, we have considered two cases.

In the first case, we assume that the channel characteristics are known perfectly at the transmitter. In the second case, we assume that the channel measurement is corrupted by additive noise, and we evaluate the effect of the noisy estimate on the error rate performance.

3. Summary of Achievements

In journal paper [1], we investigate the effects on the performance, degradation due to channel estimation errors in a point-to-multipoint (downlink) MIMO communication system in which the interference mitigation is performed at the transmitter. In particular, we consider a MIMO system which employs a Tomlinson-Harashima precoder to pre-process the transmitted signal so as to suppress the interference at each of the decentralized receivers. The QR decomposition of the channel matrix is employed to obtain an equivalent channel in which successive interference cancellation at the transmitter can be used to remove the multiuser interference. However, in the presence of estimation errors in the channel matrix, the multiuser interference cannot be perfectly cancelled. We derive the effect of channel estimation errors on the error rate performance of the receivers and assess the performance degradation on the system as a function of the quality of channel estimate. Computer simulations are also performed to corroborate the analytical results.

In Chapter 9 of the book on *New Directions in Wireless Communications Research* [2], we present a tutorial survey of interference suppression techniques in point-to-multipoint MIMO systems in which the interference suppression is performed at the transmitter. More specifically, we consider the downlink of a MIMO system which transmits simultaneously to multiple users that are geographically distributed. The transmitter employs N_T antennas to transmit to K receivers, where $N_T \geq K$. Each user is assumed to have a receiver with one or more receive antennas. The distinguishing feature of the MIMO downlink transmission scenario is that the geographically separated receivers do not employ any coordination in processing the received signals. Consequently, it is desirable to suppress the multiuser interference by pre-processing the signals to the transmitter.

The suppression of the multiuser interference by means of transmitter processing is usually called signal precoding. Signal precoding at the transmitter may take one of several forms, depending on the criterion or the method used to perform the precoding. The precoding techniques described in this chapter include linear processing methods based on the zero-forcing and minimum mean-square-error criteria, and nonlinear processing methods, namely, Tomlinson-Harashima precoding, vector precoding, and a precoding method based on lattice precoding. An assessment of the effectiveness of these linear and nonlinear precoding techniques in suppressing multiuser interference is also provided.

2.11 Distributed Opportunistic Scheduling for Ad-Hoc Communications under Delay Constraints

James R. Zeidler, Principal Investigator

Sheu Sheu Tan, Graduate Student

Channel-aware scheduling has emerged as a promising technique for improving spectrum efficiency in wireless networks. In [1], an ad-hoc network was evaluated that contends for a channel using random access in conjunction with channel-aware distributed opportunistic scheduling (DOS). With DOS, once a successful channel probing has been made (through a successful channel contention), the successful link may decide to continue the data transmission if the observed channel condition is “good”; otherwise, it may skip the transmission, and let all the links re-contend for the channel. For time varying channel conditions, different links experience different channel conditions in different time slots. It is likely that after further probing, the channel can be taken by a link with a better channel condition, resulting in higher network throughput. Hence, the multiuser diversity across links and the time diversity across slots can be exploited in a joint manner.

In a practical system, many wireless applications, such as multimedia traffic, have stringent delay requirements. In this work we have focused on developing channel-aware distributed opportunistic scheduling (DOS) that takes delay into consideration. Without delay constraints, it is possible that the system may spend an arbitrarily long period of time on channel probing, looking for better channel conditions. This may significantly degrade the QoS performance of delay-sensitive applications, for which the delay performance is of critical importance. A main objective of this study is to obtain a rigorous understanding of DOS under delay constraints.

In [1], we study DOS under the average delay constraint from two different perspectives, namely, network-wide average delay constraint and user-specific average delay constraint. Specifically, average delay constraint here refers to an ensemble constraint after averaging over many packet transmissions.

The average delay constraint was first considered from a network-centric point of view, where links cooperate to maximize the overall network throughput subject to the constraint that the **network-wide** average probing and transmission time is no greater than a given time constant, α. Observe that the optimal scheduling under the network-wide average delay constraint is equivalent to a constrained optimal stopping problem. In this work, the ``stochastic" Lagrangian approach is utilized to convert the constrained problem into an unconstrained one. Under the assumption of continuous channel statistics, it is shown that the continuity of channel fading distribution ensures that the channel exhibits sufficient randomization to close the gap between the constrained primal problem and the unconstrained dual problem. We then characterize the corresponding threshold-based optimal scheduling algorithm and its throughput. It was discovered that a sharp transition exists for the optimal threshold tied to a critical time constant, α^*, in the sense that if α is less than α^*, the optimal threshold is upper-bounded by a function of α; otherwise, the imposed delay constraint has no impact on the optimal scheduling, and the optimal threshold is the same as that in the unconstrained case. An iterative algorithm was developed to find the critical time constant, α^*, and show its convergence.

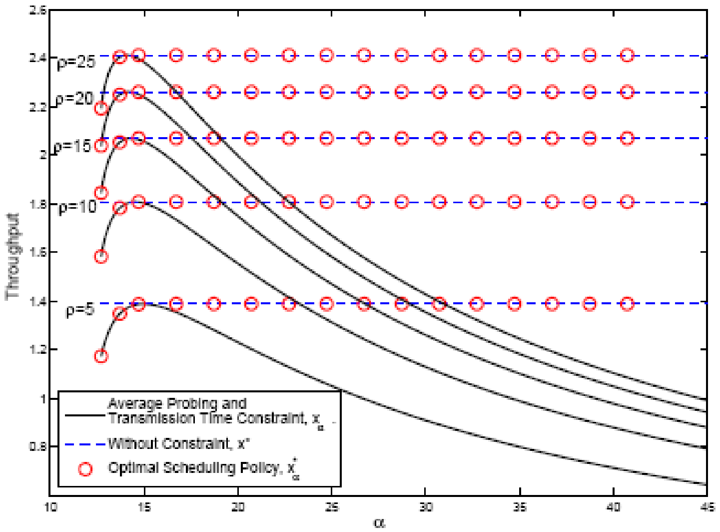


Fig. 3: Maximal throughput for different values of α at different average SNR, ρ

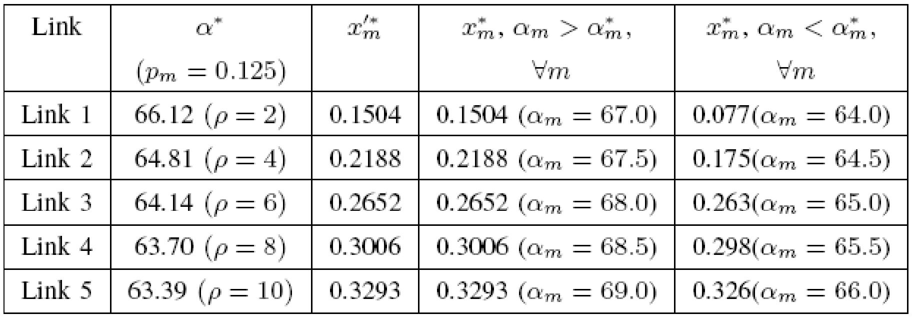
Figure 3 illustrates the maximal throughput under different time constraint values, α at different average SNR, $\rho = 5, 10, 15, 20, 25$. In this figure, the throughput of the threshold policy, x_α is plotted in solid lines and the throughput of the optimal threshold policy for the unconstrained case, x^* is plotted by dashed lines. The circle denotes the maximal throughput corresponding to the optimal scheduling policy under the average delay constraint, x_α^*. We first observe from Fig.3 that in general, $x_\alpha \le x_\alpha^* \le x^*$. Another important observation from Fig. 3 is that x_α

intersects with x^* at its peak point, which is exactly the critical time constant, α^*. Beyond this point, the optimal scheduling policy does not need to take the imposed time constraint into account, i.e. the optimal scheduling policy with time constraint will be the same as that without time constraint when the time constraint α is beyond this critical point. It can also been seen from Fig. 3 that the maximal throughput x_α^* is an increasing function of average SNR, ρ for a given α. This is because when the average SNR increases, the transmission rate becomes higher and yields a higher throughput.

Next, we explore distributed scheduling under the average delay constraint from a **user-centric** perspective, where each link seeks to maximize its own throughput subject to the constraint that the expected user delay should be no greater than its own delay constraint α_m, $m = 1, 2, ...M$. We treat the problem threshold selection under the individual delay constraint as a non-cooperative game. We show that the Nash equilibrium exists for this constrained non-cooperative game. Our results reveal that there exists a vector of critical time constant α_m^*, as the counterpart to that for the network-centric case, such that only when all the delay constraint $\alpha_m \geq \alpha_m^*$, then the delay constraints have no impacts on the optimal threshold in the Nash equilibrium. We further provide an iterative algorithm to find the Nash equilibrium and prove the convergence.

Table 3

OPTIMAL THRESHOLD OF EACH INDIVIDUAL LINK UNDER INDIVIDUAL AVERAGE TIME CONSTRAINT



Link	α^* ($p_m = 0.125$)	$x_m'^*$	x_m^*, $\alpha_m > \alpha_m^*$, $\forall m$	x_m^*, $\alpha_m < \alpha_m^*$, $\forall m$
Link 1	66.12 ($\rho = 2$)	0.1504	0.1504 ($\alpha_m = 67.0$)	0.077($\alpha_m = 64.0$)
Link 2	64.81 ($\rho = 4$)	0.2188	0.2188 ($\alpha_m = 67.5$)	0.175($\alpha_m = 64.5$)
Link 3	64.14 ($\rho = 6$)	0.2652	0.2652 ($\alpha_m = 68.0$)	0.263($\alpha_m = 65.0$)
Link 4	63.70 ($\rho = 8$)	0.3006	0.3006 ($\alpha_m = 68.5$)	0.298($\alpha_m = 65.5$)
Link 5	63.39 ($\rho = 10$)	0.3293	0.3293 ($\alpha_m = 69.0$)	0.326($\alpha_m = 66.0$)

Table 3 is presented to show the optimal threshold of each individual link under individual average time constraint in Nash Equilibrium state. The numerical result in table 3 shows that when the imposed constraint α_m of all the links are bigger than then the critical time constraint of α_m^*, the optimal threshold of all links with time constraint (shown in 4-th column) will be the same as the scenario without time constraint (shown in 3rd column). At the other hand, when the imposed time constraint is less than the α_m^* (shown in 5-th column), the optimal threshold of all the links will be less than the unconstrained threshold, $x_m^{'*}$.

In [1], we only considered the average delay constraint. It would also be of great interest to consider individual packet lifetime constraint. Different from the average delay constraint that specifies an ensemble constraint after taking average over many packet transmissions, the packet lifetime constraint is imposed on scheduling of individual packets and is essentially a constraint on sample-path realizations. We are currently working along this line, and had some initial results.

References

[1] S. S. Tan, D. Zheng, J. Zhang and J. Zeidler, “'Distributed Opportunistic Scheduling for Ad-Hoc Communications under Delay Constraints”, submitted to *IEEE Infocom.*

2.12 Bargaining in the MISO Interference Channel

PI: A. Lee Swindlehurst

GSR: Matt Nokleby

Summary

A common model used for describing wireless ad hoc networks at the physical layer involves assuming a collection of links that are simultaneously active and thus interfering with one another during a given time slot. The problem becomes one of allocating the resources of the network (power, beamformer weights, etc) so that a particular performance metric (e.g., overall throughput, fairness, etc.) is optimized. In this work, we have examined the MISO interference channel using cooperative bargaining theory. Bargaining approaches such as the Nash bargaining solution and the Kalai-Smorodinsky solution have previously been used in wireless networks to strike a balance between max-sum rate efficiency and max-min equity (fairness) in users' rates. However, cooperative bargaining for the MISO interference channel has only been previously studied extensively for the two-user case. We have developed an algorithm that finds the optimal Kalai-Smorodinsky beamformers for an arbitrary number of users in the general MISO

interference channel setting. We also consider joint scheduling and beamformer selection, using gradient ascent to find a stationary point of the Kalai-Smorodinsky objective function. When interference is strong, the flexibility allowed by scheduling compensates for the performance loss due to local optimization. Finally, we have explored the benefits of power control, showing that power control provides non-trivial throughput gains when the number of transmitter/receiver pairs is greater than the number of transmit antennas.

Background

Many of the recent advances in multi-antenna communications systems involve multi-user scenarios, which present a complicated problem partially because performance criteria are difficult to characterize. There is not, for example, a single data rate or bit-error probability to optimize. Instead, we can only maximize composite performance measures such as the network sum rate, max-min fairness, or quality-of-service requirements. Ultimately, the choice of objective function is often somewhat arbitrary.

To meet this challenge, researchers have begun to apply game theory [1], a mathematical idealization of human decision-making, to problems in multi-user communications. Game theory provides a systematic framework for the study of decision-makers with potentially conflicting interests, as well as solutions for such conflicts. Accordingly, a game-theoretic analysis can provide a tractable, structured approach to resource allocation. Researchers have employed game-theoretic ideas to design “fair” power-control schemes, develop decentralized network algorithms, and otherwise solve resource-allocation problems in communications networks [2-8].

In this work, we have focused on the multiple-input single-output (MISO) interference channel. In the MISO interference channel, several communication links, each involving a multi-antenna transmitter and a single-antenna receiver, are simultaneously active. This scenario models, for example, ad hoc networks with multiple antenna nodes where the receivers employ fixed beamformers. Game-theoretic solutions for the MISO interference channel based on bargaining have been considered in [9,10], but only for the two-user case. Our particular focus has been to maximize network performance according to the Kalai-Smorodinsky solution [11], a cooperative bargaining approach closely related to the well-known Nash bargaining solution [12]. For our problem, the fundamental idea of the Kalai-Smorodinsky (K-S) approach is to maximize users’ rates while ensuring that users experience the same fraction of the rate they would achieve without interference. In practice, the K-S solution defines a compromise between efficiency (defined herein in terms of maximizing the sum rate) and equity (maximizing the minimum rate).

Our primary contribution is an algorithm that efficiently finds the K-S solution for an arbitrary number of users, rather than just the two-user case. We transform the rate-maximization problem to a series of convex programming problems, allowing us to find the beamformers that achieve the rates defined by the K-S solution. A drawback of the K-S solution is that, when interference becomes strong for a single user, all users’ bargained rates tend toward zero. To avoid this, we have also investigated the use of joint scheduling and beamformer selection under K-S bargaining, which introduces a temporal degree of freedom for avoiding interference. Scheduling also convexifies the feasible rate region, which is an important consideration in cooperative bargaining. However, the need to jointly address scheduling and beamformer selection complicates the optimization, preventing us from easily finding the K-S solution. We therefore devise a gradient-based algorithm to find a stationary point of the K-S objective function.

While we sacrifice global optimality to include scheduling, the performance advantage of employing time-division multiplexing significantly outweighs the potential loss of optimality when the interference is strong.

Simulation Results

To illustrate the performance of our approach, we use a simulation with 4 transmit antennas and K users. In each simulation, we randomly place K transmitter/receiver pairs on the unit square. The channel coefficients are independently drawn from the zero-mean, unit-variance, complex Gaussian distribution. The channel gains are computed according to a standard path-loss model based on distance. In Figures 1 and 2 we examine algorithm performance in terms of efficiency and equity for K = {2, 4, 6, 8, 10}.

We compare our proposed K-S algorithms with rates obtained by the max-min, max-sum, and TDMA algorithms. The TDMA rates, represent a baseline for the scheduled K-S solutions. Figure 5 shows the average mutual information per user, averaged over 100 realizations for each value of K. Not surprisingly, the average rate is highest under sum rate maximization. Both K-S approaches degrade as we increase the number of users, but eventually the scheduling approach gives a better average rate in spite of the fact that it gives only a stationary point. In Figure 6 we examine the *minimum* mutual information across all links, averaged over the same 100 realizations. Max-min (again unsurprisingly) gives the highest minimum rate, followed by the K-S approaches. Max-sum gives the worst minimum rate, which drops nearly to zero beyond K = 2. The K-S solution allows us to maintain the sum rate while still protecting the weakest links.

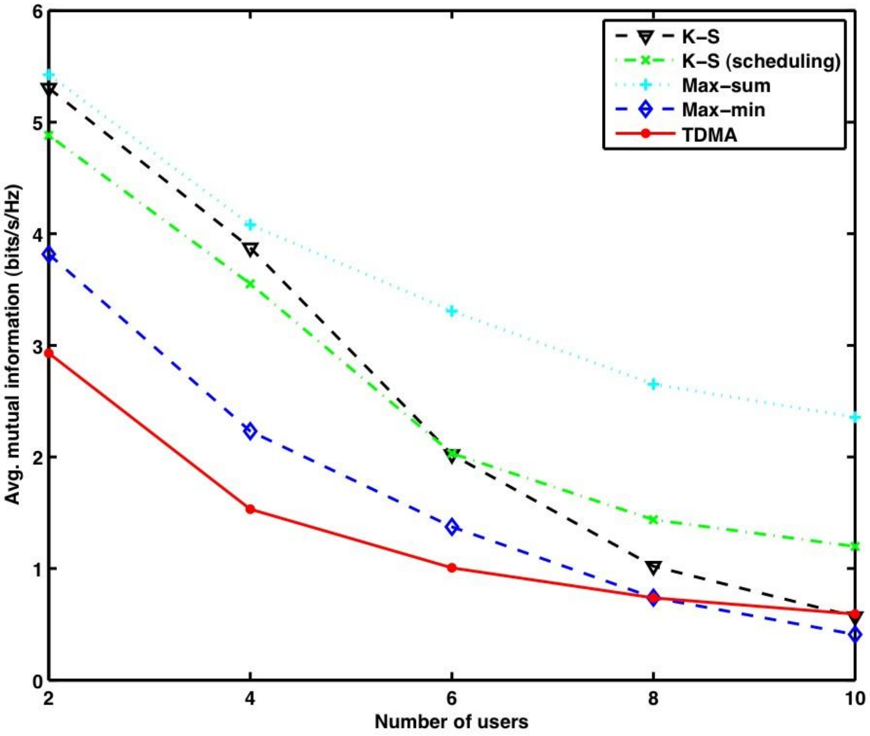


Figure 1: Average mutual information per user.

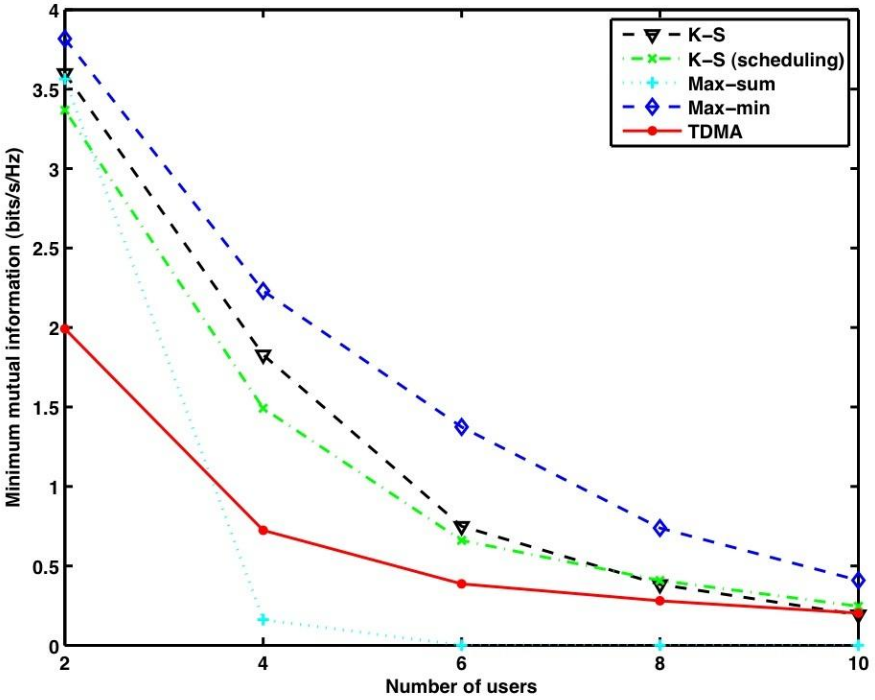


Figure 2: Average mutual information of the worst-case user.

References

[1] D. Fundenberg and J. Tirole, *Game Theory*, 2nd ed. Cambrige, MA: The MIT Press, 1991.

[2] V. Srinivasan, P. Nuggehalli, C. F. Chiasserini, and R. R. Rao, “Cooperation in wireless ad hoc networks.” INFOCOM 2003, 2003, pp. 808–817.

[3] Z. Han, Z. Ju, and K. J. R. Liu, “Fair multiuser channel allocation for OFDMA networks using Nash bargaining solutions and coalitions,” *IEEE Trans. Communications*, vol. 53, no. 8, pp. 1366–1376, August 2005.

[4] R. A. Iltis, S.-J. Kim, and D. A. Hoang, “Noncooperative iterative MMSE beamforming algorithms for ad hoc networks,” *IEEE Trans. Communications*, vol. 54, no. 4, pp. 748–759, April 2006.

[5] G. Arslan, M. F. Demirkol, and Y. Song, “Equilibrium efficiency improvement in MIMO interference systems: A decentralized stream control approach,” *IEEE Trans. Wireless Communications*, vol. 6, no. 8, pp. 2984–2993, August 2007.

[6] J. Ellenbeck, C. Hartmann, and L. Berlemann, “Decentralized inter-cell interference coordination by autonomous spectral reuse decisions,” *14th European Wireless Conference*, pp. 1–7, June 2008.

[7] Y. Chen, K. H. Teo, S. Kishore, and J. Zhang, “Inter-cell interference management in WiMAX downlinks by a Stackelberg game between BSs,” *IEEE International Conference on Communications*, pp. 3442–3446, May 2008.

[8] G. Scutari, D. P. Palomar, and S. Barbarossa, “Competitive design of multiuser MIMO interference systems based on game theory: A unified framework,” *IEEE International Conference on Acoustics, Speech and Signal Processing 2008*, pp. 5376–5379, April 2008.

[9] E. G. Larsson and E. A. Jorswieck, “Competition versus cooperation on the MISO interference channel,” *IEEE Journal on Selected Areas in Communications*, 2008.

[10] E. A. Jorswieck and E. G. Larsson, “The MISO interference channel from a game-theoretic perspective: A combination of selfishness and altruism achieves Pareto optimality,” in *Proc. IEEE ICASSP*, 2008, pp. 5364– 5367.

[11] E. Kalai and M. Smorodinksy, “Other solutions to Nash’s bargaining problem,” *Econometrica*, vol. 43, no. 3, pp. 513–518,May 1975.

[12] J. F. Nash, “The bargaining problem,” *Econometrica*, vol. 18, no. 2, pp. 155–162, April 1950.

2.13 Power Allocation and Bit Loading for Spatial Multiplexing with Imperfect CSI

PI: A. Lee Swindlehurst

GSR: Michael Larsen

Summary

In narrowband multiple-input multiple-output communication systems when the channel state information (CSI) is known perfectly at the transmitter and the receiver, and with no restrictions on codebook design, the well-known water-filling solution maximizes information throughput given a fixed transmission power through use of the singular value decomposition (SVD). In practice, when practical codebooks are used and perfect CSI is unavailable due to mobility and channel estimation errors, adaptations to power levels and bit-loading schemes may need to be made in order to maintain reasonable performance. To analyze this scenario, we have derived simple expressions that detail the impact of imperfect CSI on the signal and interference plus noise powers for subchannels obtained via the SVD-obtained. These expressions are used to derive thresholds on the level of CSI imperfections and noise power tolerable in SVD-based multiplexing systems using M-ary quadrature amplitude modulation. In particular, using our analysis, one can determine in advance whether or not spatial multiplexing will provide any rate performance gain compared with simple beamforming solutions. In addition, approximately optimal subchannel power levels are found for the imperfect CSI scenario.

Background

Given perfect channel state information (CSI) at the transmitter and the receiver of a multiple-input multiple-output (MIMO) communications link, along with no restrictions on codebook design, the well-known water-filling solution maximizes information throughput given a fixed transmission power. The water-filling solution relies on the use of the singular value decomposition (SVD) to separate the MIMO channel into independent single-input single-output subchannels, which separation, in principle, enables interference-free data multiplexing [1-2]. Based on the signal-to-noise ratio (SNR) of the resulting subchannels, bit-loading and coding schemes are then devised to approach the available channel capacity.

In practice, two difficulties arise that must be considered when designing an SVD-based communication scheme. First, it is not possible to obtain perfect CSI since realizable channel estimates are formed from noisy measurements. Mobility in the communication system adds additional complications for CSI estimation, since the MIMO channel changes rapidly when the transmit or receive arrays are in motion. When noisy or outdated CSI is used in conjunction with an SVD-based multiplexing method, the MIMO subchannels become coupled resulting in potentially severe subchannel power loss and mutual interference. As a consequence, subchannel bit-loading levels selected based on the assumption of perfect CSI may no longer meet given error performance constraints. For these constraints to be met, back-off strategies are often employed to reduce the subchannel bit rates and create an error margin that accounts for the CSI mismatch.

However, without knowledge of the levels of the signal loss and interference induced by the subchannel coupling, it is not clear how to systematically carry out such reductions.

A second difficulty arises from the finite nature of the symbol constellations used for bit allocation. In order for the optimality of the water-filling power levels to hold, subchannel bit loading requires an infinite-length codebook with continuous modulation order. The use of discrete codebooks and finite constellations such as quadrature amplitude modulation (QAM) results in additional performance loss when used with the power levels chosen by the water-filling method which were selected assuming idealized symbol constellations [3]–[5]. When practical codebooks are to be used, subchannel power level selection incorporating information about the codebook may help reduce such losses due to mismatches between theory and practice. Capacity-optimal transmission strategies when only imperfect CSI is available have been studied in [6]–[9] and the references therein. Minimum symbol-error-rate (SER) optimization and adaptive modulation have also been studied in [10], [11]. These papers generally advocate multiplexing or beamforming using other information, such as channel covariance information, to guide their design, and, unlike SVD-based schemes, often require complex decoding schemes at the receiver.

Several other studies seeking to retain the elegant structure of MIMO SVD-based solutions have focused on the impact that imperfect CSI and finite modulation have on the SVD-based schemes. The effect of imperfect CSI on the symbol error rate (SER) of MIMO SVD-based multiplexing methods has been examined in [12] for BPSK transmission, and its effect on the bit error rate (BER) using more general constellations including M-ary QAM (M-QAM) has been analyzed in [5], [13]–[16]. With an understanding of the effect of imperfect CSI and finite modulation schemes on SVD-based multiplexing methods, the primary design task becomes the selection of subchannel power and bit-loading levels. For instance, having derived an expression for the BER, [14] proposes an ad-hoc method to select power and bit-loading levels in each subchannel to meet a chosen BER constraint. For the special case of uniform power allocation over all of the MIMO subchannels, [5] develops an expression for an adjusted per-subchannel signal-to-interference-and-noise (SINR) ratio that may be used to select subchannel bit-loading levels [17]. In [4], optimal bit loading using finite symbol constellations assuming perfect CSI is discussed and an ad-hoc method is proposed for approximating that optimum.

We have developed a closed-form expression for the subchannel SINR when using imperfect CSI in SVD-based signaling schemes. This result generalizes the SINR derivation of [5] allowing for non-uniform power allocation and correcting an overestimation of the interference power due to CSI inaccuracies. In addition, this new expression allows for different levels of CSI error at the transmitter and receiver, whereas previous methods typically assume the CSI is identical at both ends of the communications link or that perfect CSI is available at the receiver. Once obtained, our SINR expressions allow us to (1) analyze the impact of imperfect CSI on the MIMO SVD subchannels; (2) find thresholds for the amount of channel uncertainty and measurement noise tolerable when multiplexing over the SVD-based subchannels; and (3) perform robust bit-loading design through the systematic selection of the subchannel power levels. For the special case of identical CSI at both ends of the link, the SINR expression allows us to derive approximately optimal subchannel power levels for M-QAM signaling under a subchannel SER constraint, a result directly applicable to robust bit-loading design.

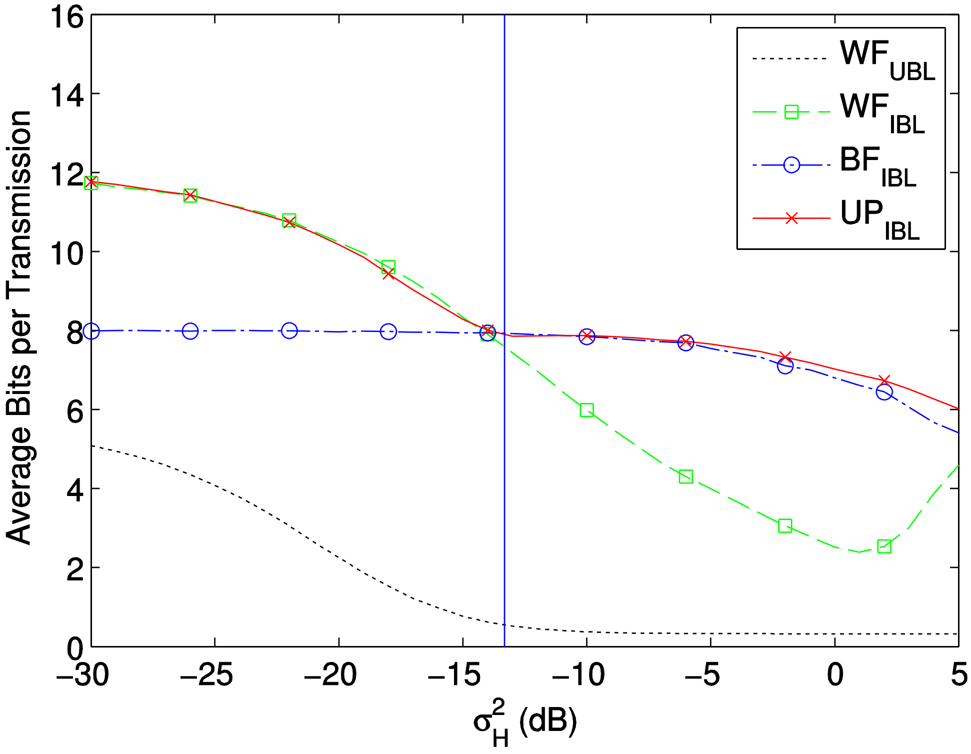


Figure 3 – A comparison of the average bits per transmission achieved using the uniformed and informed bit-loading schemes when accounting

for subchannel outages with confidence level 0.1.

Simulation Results

In Figure 3, we show a sample simulation result to illustrate the validity of our analysis. We assume a four-antenna transmitter and a four-antenna receiver, and we assume that both the transmitter and receiver are using an outdated channel estimate whose coefficients are equal to the true coefficients plus a Gaussian perturbation term of a given variance. Note that our analysis holds for more general scenarios, where the CSI at the transmitter and receiver is not the same, but this example will illustrate the point. We compare the average throughput (capacity x (1 – outage rate)) for four different schemes: (1) WFUBL, which is the standard water-filling solution that ignores the presence of the CSI, (2) WFIBL, which is the approach detailed in [14] that takes the CSI error into account, (3) BFIBL, which is the performance of standard beamforming with transmission power modified to account for the CSI error, and (4) UPIBL, which does optimal power allocation and bit loading taking CSI into account. The average bits per transmission achieved by these schemes are plotted in Figure 3 versus the variance of the CSI error. The vertical blue line is the threshold derived by our analysis showing the level of CSI error above which it is no longer advantageous to perform spatial multiplexing. The threshold accurately predicts the breakpoint, which occurs for perturbations that are about 13dB below the average gain of the channel coefficients. Note that our proposed optimal power allocation/bit allocation scheme (UPIBL) provides the best performance across all levels of CSI error.

References

[1] I. E. Telatar, “Capacity of multi-antenna gaussian channels,” AT&T Bell Labs, Internal Tech. Memo., Jun. 1995.

[2] G. J. Foschini and M. J. Gans, “On limits of wireless communications in a fading environment when using multiple antennas,” *Wireless Pers. Commun.*, vol. 6, pp. 311–335, Mar. 1998.

[3] G. D. Forney Jr. and M. V. Eyuboglu, “Combined equalization and coding using precoding,” *IEEE Commun. Mag.*, vol. 43, pp. 25–34, Dec. 1991.

[4] X. Zhang and B. Ottersten, “Power allocation and bit loading for spatial multiplexing in MIMO systems,” in *Proc. IEEE Int’l Conference on Acoustics, Sound, and Signal Processing (ICASSP ’03),* Honolulu, Hawaii, Apr. 2003, pp. V 53–56.

[5] Z. Zhou, B. Vucetic, M. Dohler, and Y. Li, “MIMO systems with adaptive modulation,” *IEEE Trans. Veh. Technol.*, vol. 54, pp. 1828–1842, Sep. 2005.

[6] E. Visotsky and U. Madhow, “Space-time transmit precoding with imperfect feedback,” *IEEE Trans. Inf. Theory*, vol. 47, pp. 2632–2639, Sep. 2001.

[7] A. Goldsmith, S. A. Jafar, N. Jindal, and S. Vishwanathi, “Capacity limits of MIMO channels,” *IEEE J. Sel. Areas Commun.*, vol. 21, pp. 648–702, Jun. 2003.

[8] S. A. Jafar and A. Goldsmith, “Transmitter optimization and optimality of beamforming for multiple antenna systems,” *IEEE Trans. Wireless Commun.*, vol. 3, pp. 1165–1175, Jul. 2004.

[9] S. H. Simon and A. Moustakas, “Optimizing MIMO antenna systems with channel covariance feedback,” *IEEE J. Sel. Areas Commun.*, vol. 21, pp. 406–417, Apr. 2003.

[10] S. Zhou and G. B. Giannakis, “Optimal transmitter eigen-beamforming and space-time block coding,” *IEEE Trans. Signal Process.*, vol. 50, pp. 2599–2613, Oct. 2002.

[11] ——, “Adaptive modulation for multiantenna transmissions with channel mean feedback,” *IEEE Trans. Wireless Commun.*, vol. 3, pp. 1626–1636, Sep. 2004.

[12] L. M. Garth, P. J. Smith, and M. Shafi, “Exact symbol error probabilities for SVD transmission of BPSK data over fading channels,” in *Proc. IEEE International Conference on Communication (ICC 2005),* Seoul, Korea, May 2005, pp. 2271–2276.

[13] E. K. S. Au *et al.*, “BER analysis of MIMO-SVD systems with channel estimation error and feedback delay,” in *Proc. IEEE International Conference on Communication (ICC 2007),* Glasgow, Scotland, Jun. 2007, pp. 4375–4380.

[14] H. Zhang, D. L. Goeckel, and G. Ananthaswamy, “Adaptive modulation in MIMO eigenbeamforming with outdated channel state information,” in *Proc. IEEE Global Telecommunications Conference (GLOBECOM 2006)*, San Fransisco, CA, USA, Nov. 2006, pp. 1–5.

[15] J. Du *et al.*, “Estimation of performance loss due to delay in channel feedback in MIMO systems,” in *Proc. Vehicular Technology Conference (VTC2004-Fall)*, Los Angeles, CA, USA, Sep. 2004, pp. 1619–1622.

[16] Z. Zhou and B. Vucetic, “The effect of CSI imperfection on the performance of SVD based adaptive modulation in MIMO systems,” in *Proc. IEEE International Symposium on Information Theory (ISIT 2004)*, Chicago, USA, Jul. 2004, p. 317.

[17] ——, “Design of adaptive modulation using imperfect CSI in MIMO systems,” *IEEE Electron. Lett.*, vol. 40, no. 17, pp. 1073–1075, Aug. 2004.

2.14 Instantaneous and Average Sum-Rate Optimizations in Multi-user MIMO Subnetworks

James R. Zeidler, Principal Investigator

Mike Jensen, Principal Investigator

Adam Anderson, Graduate Student

The sum-rate throughput was analyzed with linear processing (beamforming) in multiple-input multiple-output, single- and multi-user wireless links for subnetworks in the context of larger mobile ad-hoc networks (MANET).

The complexity that MANET scheduling algorithms will encounter for various types of PHY layer links was determined. This included point-to-point (P2P) links including the single user channel (SUC), broadcast channel (BC), multiple access channel (MAC), interference channel (IC), and also for more complex topologies generally referred to as hybrid channels (HC) that includes the MIMO X channel. The analysis first derives the number of all possible half-duplex link configurations for a given MANET link topology, and then derives the sum-rate-optimal beamforming for each of the topologies using explicit channel state information for all users. Figure 1 shows the number of possible schedules as a function of the number of nodes in the network. This plot shows that the complexity of scheduling grows significantly as the network size increases.

Maintaining accurate CSI for all users becomes a significant complexity issue for networks with time varying links. When the input information necessary to derive these optimal beamformers becomes outdated or erroneous, significant loss at the PHY layer is seen which would have a cascaded loss effect on the higher network layers. Figure 2 shows the loss in sum-rate for CSI based beamformers when the transmitting nodes

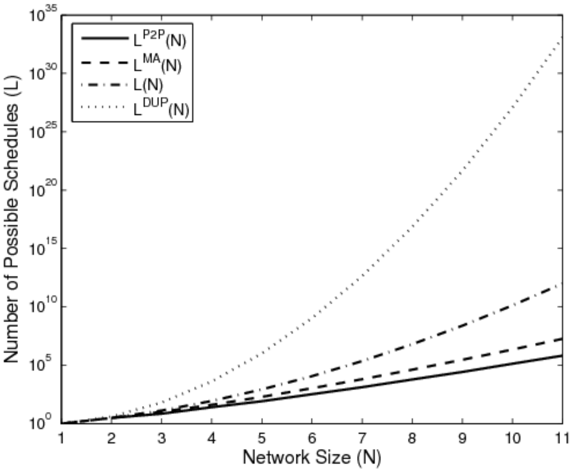


Fig. 1: Number of possible schedules for various links in an N - node ad-hoc network

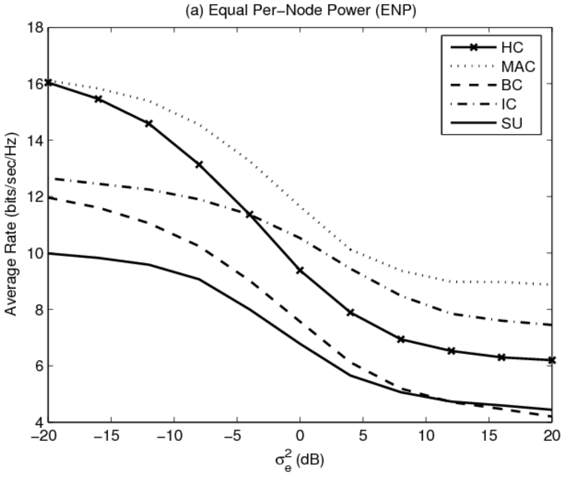


Fig. 2: Instantaneous sum-rate throughputs with erroneous CSI at the transmitter

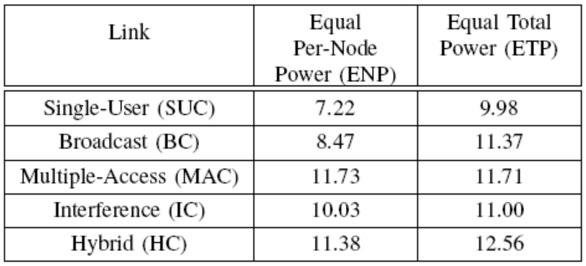
have outdated CSI that is quantified by the channel variance over time, σ_e^2. Measured channel characteristics from the BYU data base are used in the simulations to ensure accurate representation of the channel spatial correlation.

An alternate beamformer (RCDI-HC) that uses channel distribution information in the form of spatial correlation was formulated to provide increased stability for multi-user communication in these. Since the channel distribution will normally remain stable for a longer period than the instantaneous CSI, the required frequency of channel updates is reduced accordingly. This may lead to more robust scheduling performance for tactical networks with routes that can be maintained over longer time intervals. It should be noted however that although the required channel updates are less frequent, they require updates of the channel covariance matrix rather than the instantaneous channel state and are thus more complex. This is discussed in section 1, and methods to reduce the complexity of the covariance matrix updates using simple models such as the Kronecker model are being investigated under this project.

To compare the performance of the two sum-rate beamformers for different link topologies, we first summarize performance results for the perfect CSI (RCI-HC) beamformer in Table 1. Next, we examine the performance of the RCDI-HC sum-rate beamformer that based on channel distribution information in the form of spatial correlation in Table 2. The results show that the relative trends in sum-rate for the different link topologies are similar to those observed in CSI-based beamformer in Table 1. Furthermore, the average sum rate for RCDI-HC beamformers for each link is roughly 70-80% of their RCI-HC counterparts. One of the most important observations regarding the data in Table 2 is that for a statistically stationary channel, the resulting sum-rates are not a function of channel time variations and will not suffer performance loss due to delay in feeding back information to the transmitter. This means that while RCDI-HC offers lower initial sum-rate, it maximizes the duration over which this average sum-rate is valid. Research into the temporal stability of the CDI based beamformers in typical channel conditions is in progress.

Table 1

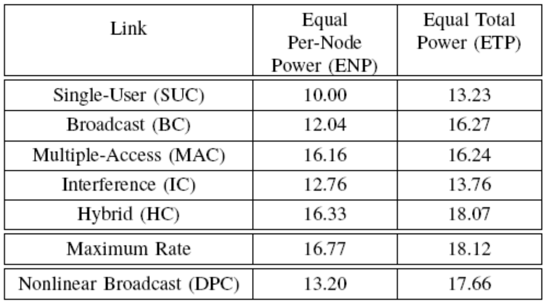
AVERAGE SUM-RATE (BITS/SEC/HZ) FOR VARIOUS LINKS USING RCDI-HC



Link	Equal Per-Node Power (ENP)	Equal Total Power (ETP)
Single-User (SUC)	7.22	9.98
Broadcast (BC)	8.47	11.37
Multiple-Access (MAC)	11.73	11.71
Interference (IC)	10.03	11.00
Hybrid (HC)	11.38	12.56

Table 2

AVERAGE SUM-RATE (BITS/SEC/HZ) FOR VARIOUS LINKS USING CSI-BASED PRECODING



Link	Equal Per-Node Power (ENP)	Equal Total Power (ETP)
Single-User (SUC)	10.00	13.23
Broadcast (BC)	12.04	16.27
Multiple-Access (MAC)	16.16	16.24
Interference (IC)	12.76	13.76
Hybrid (HC)	16.33	18.07
Maximum Rate	16.77	18.12
Nonlinear Broadcast (DPC)	13.20	17.66

References

[1] A. Anderson, J. R. Zeidler and M. Jensen, “Instantaneous and Average Sum-Rate Optimizations in Multi-user MIMO Subnetworks”, submitted to *IEEE Transactions on Wireless Communications*

2.15 Outage Probability Characterization of Multi-User MIMO Networks

James R. Zeidler, Principal Investigator

Bhaskar Rao, Principal Investigator

Sagnik Ghosh, Graduate Student

1. Introduction

In this work, we are interested in providing stable transmission in time-varying multi-user MIMO networks. One of the most compelling problems in rapidly changing networks is the issue of channel feedback to all of the nodes. It is well known that Channel State Information at the Transmitter and Receiver (CSIT and CSIR, respectively) at every node can significantly increase the throughput of the network. However, the amount of feedback required for this is considerable and can consume significant amounts of bandwidth in the system. Furthermore, in networks with high mobility, by the time all of this information has been communicated to every node, that information is already outdated due to the movement of the nodes. In this task we have investigated different types of channel information that are more robust to changes in the channel. Specifically, our work deals with the *channel statistics,* which vary much more slowly than the channel itself. Furthermore, it is possible to attain statistical information *a priori* based on the location of the nodes. Our goal was to determine how Channel Distribution Information (CDI) can be utilized to achieve reliable communication for mobile ad hoc networks.

In previous years, we have studied how to use CDI to maximize the average rate in MIMO Broadcast, MIMO Multiple Access, and MIMO hybrid networks [1]. This year, having explored the average rate maximization problem, we moved to studying the problem from an outage probability perspective. This formulation has many advantages. With CDI, while we can assure some average rate, we can never guarantee that a communication scheme will achieve a certain rate 100% of the time (which would require perfect CSI). In an outage probability framework, we are willing to accept this reality, but we quantify the outage on the links and guarantee a certain rate or SNR the remainder of the time. This framework allows us to have better characterize our network for purposes of design and analysis.

Our work thus far has concerned minimizing the total power consumed by the network while meeting certain communication requirements. This problem is non-trivial, as we cannot simply meet our requirements by blasting power out of all our transmitter nodes. This will cause too much interference in the network to other nodes, so we must intelligently use the spatial characteristics of the channel to minimize this interference. For networks with perfect CSI at all the nodes, this problem has been studied in [2]. We look at this problem if we know the CDI at all the nodes, which brings us much closer to implementing such a system in a practical high-mobility MIMO network.

2. Summary of Achievements

First and foremost, in any discussion about outage probability (the probability that we meet a target SINR on each link), we desire an appropriate closed-form expression to be able to analyze and optimize. In the first part of this work, we consider the popular Rayleigh fading model on the antennas, taking general correlation structures into account. These correlation structures manifest themselves as covariance matrices for each link, and we assume all the nodes have this information (or, equivalently, that a central arbiter has this information and controls all the nodes). We further assume that on each link, we utilize linear transmit and receive beamforming. Under these assumptions, we derive a closed-form expression for the outage probability for both the single-user and multi-user MIMO problems.

Once we have our desired outage expression, we look at minimizing the sum power in the network subject to constraints on the outage. This means we want each link to meet its SINR threshold *x%* of the time, where we are able to set *x*. We first look at the single-user problem, where only the channel statistics are known at both the transmitter and receiver. Such a scenario can occur when the nodes are moving so rapidly that even the receiver has a difficult time capturing the channel. In addition, channel estimation at the receiver usually requires a pilot signal as well as significant computational complexity, which the designer may wish to avoid. In such a setup, when we have CDI, we are able to solve for optimal transmit and receive beamformers and give the power required to meet an outage constraint. See Fig. 1 below. We can see from the plot that most of the CDI outage curves are actually below the CSI curve (assuming perfect channel knowledge at the transmitter and receiver). From this, we can see an additional reason we would want to use such a setup: if we are willing to accept a given outage on the link, we can actually transmit with *lower* power using CDI than if we knew the channel perfectly (using CSI).

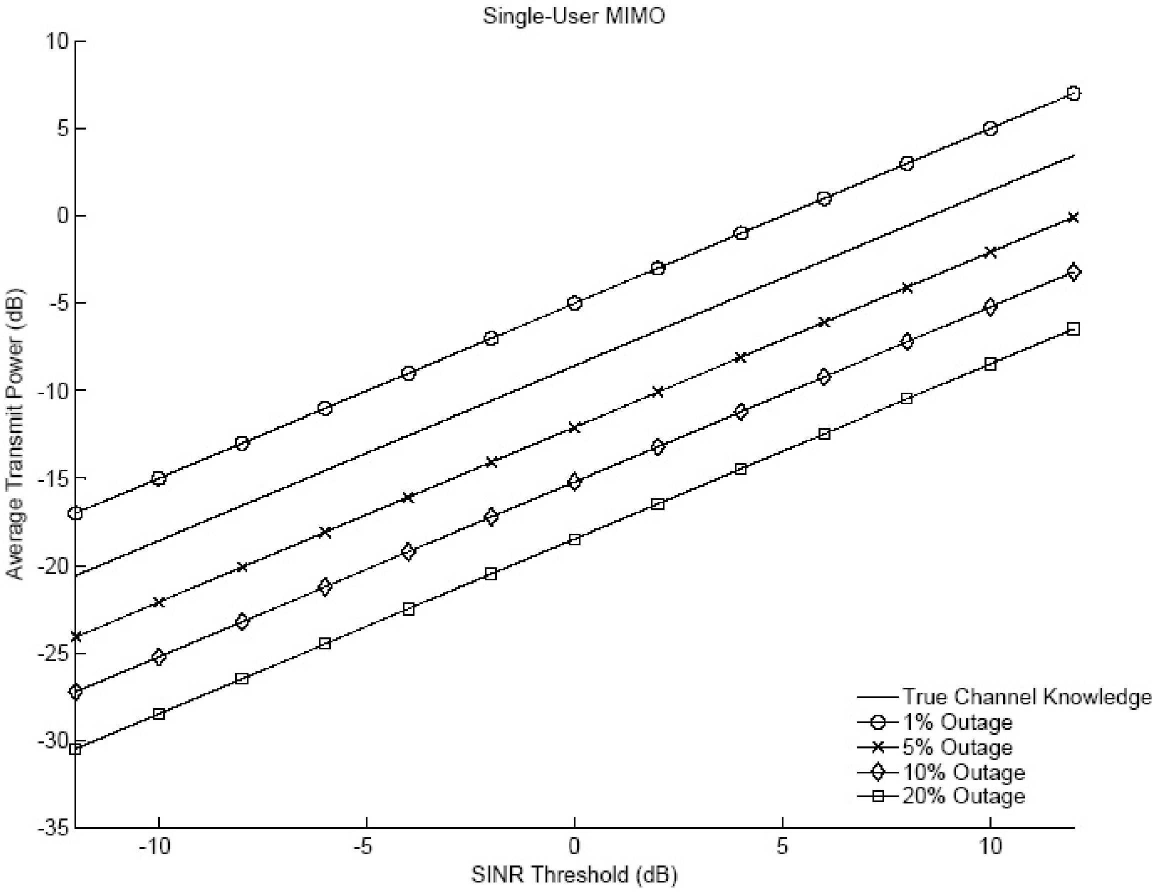


Figure 15

We then moved on to looking at the multi-user MIMO network problem and minimizing the sum power in the entire network. Using some tight bounds, we are able to find “very good” transmit and receive beamformers, and we solve for the optimal power allocation for each node. See Fig. 2 below. We can see that our CDI outage solution gives enormous power savings over the CSI case, even moreso than for single-user MIMO, for low SINR thresholds. The tradeoff here is that if our system requires a higher SINR threshold, our solution becomes infeasible (which can be seen when the curves go to infinity) and we are not able to guarantee the outage constraints. In today’s systems, however, the SINR thresholds on the lower end of the plot are reasonable, showing that if we use CDI information, with some outage we can save a lot of power in our system. This surprising result in both the single-user and multi-user MIMO setups makes the study of the outage probability framework interesting since we can now make a quantifiable tradeoff between outage and power. The two additional benefits of this framework is that all this information must be calculated only once while the channel statistics are valid (compared to the channel itself being valid), yielding huge savings in computational complexity, and as discussed above, the large reduction in feedback.

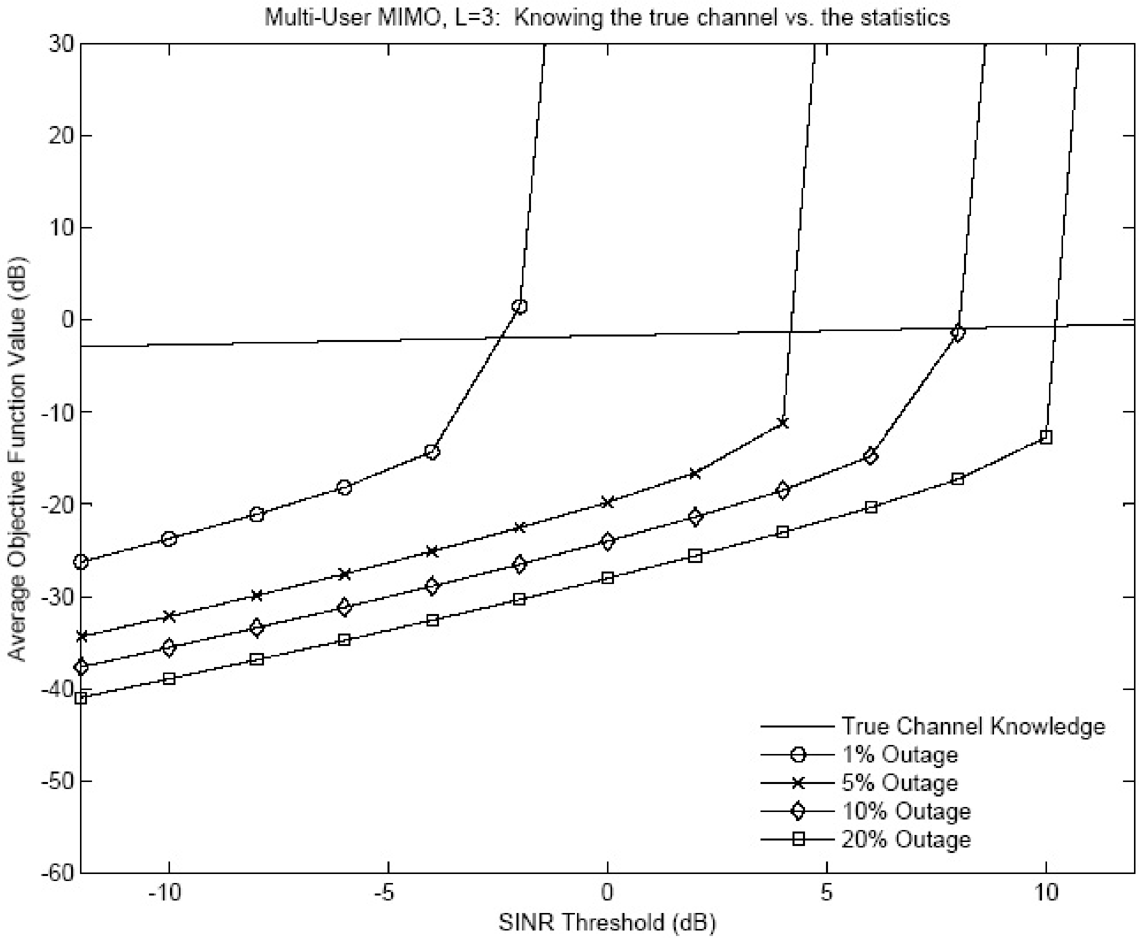


Figure 16

References

[1] A. L. Anderson, J. R. Zeidler, and M. A. Jensen, “Stable transmission in the time-varying MIMO broadcast channel,” *EURASIP Journal on Advances in Signal Processing*, vol. 2008, Article ID 617020, 14 pages, 2008. doi:10.1155/2008/617020.

[2] B. Song, R.L. Cruz, and B.D. Rao, ”Network Duality for Multiuser MIMO Beamforming Networks and Applications,” *IEEE Transactions on Communications*, vol. 55, no. 3, pp. 618–630, Mar. 2007.

2.16 Wideband MIMO Channels and Cubature Kalman Filters

PI: Simon Haykin

Graduate Students: Nelson Costa and I Arasaratnam

Under the Canadian node of the MURI Project, we have made significant contributions to the MURI Project in two areas:

1. MIMO Wideband Channel Models, with three contributions spearheaded by Nelson Costa and Simon Haykin, as highlighted in the material embodied under the following:

(i) Invited Lecture :

N. Costa, and S. Haykin, “A correlation-based wideband MIMO channel model,” Proc. General Assembly of the International Union of Radio Science 2008 (URSI 2008),
7-16 Aug. 2008, Chicago, IL. (invited)

(ii) Invited Tutorial:

N. Costa, " Efficient and Accurate Matrix Channel Models,"
The Annual MURI Meeting, UCSD, October 2008.

(iii) New Book:

N. Costa and S. Haykin, Modeling of Multiple-Input, Multiple-Output Channel Models, accepted for publication, Wiley, 2009.

2. Cubature Kalman Filters, representing a new generation of nonlinear filters, which is the closest approximation to the optimal Bayesian filter in a second-order sense and under the Gaussian assumption, exemplified by the following paper:

I. Arasaratnam and S. Haykin. " Cubature Kalman Filters," IEEE Trans. Automatic Control, June 2009

2.17 Many-to-many Communication in MANETs

PI: J.J. Garcia-Luna-Aceves

Over the past year, we continued our work on many-to-many communication in MANETs. The findings in this project cover two areas:

- The study of fundamental limits for the dissemination of information over MANETs when many-to-many communication is allowed.
- The modeling of approaches that enable many-to-many communication in MANETs by exploiting processing and storage complexity in mobile nodes.

1.1 Fundamental Limits of Wireless Networks

We completed our work on the characterization of the optimal interference-free capacity of a wireless network subject to unicast traffic, and showing how this order capacity can be attained in the presence of interference by means of [1]. The importance of this work is that no prior work had focused on first establishing what is the optimal capacity of a wireless network in the absence of MAI, and then determining whether that capacity is attainable when MAI is present. In stark contrast to the existing literature, our analysis presents the possibility of actually increasing the capacity of ad-hoc networks with the number of nodes, even while the communication range tends to zero.

We modeled a random network with n nodes, a homogeneous communication range of

r(n), and unicast traffic for k source-destination (S-D) pairs. In the absence of interference, such a network corresponds to a random geometric graph (RGG) with an edge between any two nodes separated by a distance less than r(n). We defined a combinatorial interference model based on RGGs, and use it to express all the protocol models used in the past and a model that we later use to show that the optimal capacity of a wireless network is indeed attainable. We generalized prior results by Gupta and Kumar and our own results for wireless networks with MPR, and showed that the optimal capacity of wireless networks is attainable in the presence of MAI. We showed that MPTR achieves the optimal capacity of $\Theta(n^2 r^3 (n)/k)$. This constitutes a gain of $\Theta(nr^2 (n))$ over any previously reported feasible order capacity.

We also completed our work on the order capacity of wireless networks using network coding (NC). We had previously shown that NC used with MPT and MPR renders the same order capacity as simply using MPT and MPR. Our new results [2, 3, 4] show that NC provides no order gain for multicasting and broadcasting compared to what can be attained with traditional multicasting and broadcasting based on store-and-forward routing. Widely cited experiments [5, 6] have been reported recently in which NC has been used successfully in combination with other mechanisms to attain large throughput gains compared to approaches based on conventional protocol stacks. These empirical results have led many to believe that the combination of NC with wireless broadcasting can lead to significant improvements in the multicast order throughput of wireless networks. However, the exact characterization of the multicast order capacity of NC in wireless networks has remained an open problem since its introduction ten years ago, with only limited results having been reported to date on the subject. We undertook the characterization of the multicast and broadcast throughput order of wireless ad-hoc networks in presence of network coding. We considered a network consisting of n nodes distributed randomly in the network space, with each node acting as a multicast source of a group of m randomly chosen nodes in the network. We have shown that, under the protocol model, the per-session multicast capacity of random wireless ad hoc network in the presence of arbitrary NC has a tight bound of $\Theta(1 /\sqrt{mnlog(n)})$ when $m = O(n /log(n))$ and $\Theta(1/n)$ when m =

$\Omega(n / \log(n))$. In addition, we showed that, under the physical model, the per-session multicast capacity of random wireless ad hoc network with arbitrary NC has a tight bound of $\Theta(1/ \sqrt{mn})$ when $m = O (n /\log(n)^3)$, and $\Theta(1/n)$ when $m = \Omega(n/\log(n))$. It has already been established in the literature that the above bounds are achievable on the basis of traditional store-and-forward routing methods. Hence, our results demonstrate conclusively that the throughout gain due to NC for mutlicasting and broadcasting is bounded by a constant factor!

Despite our negative result on the multicast order throughput for NC, the constant-factor gains that can be attained in some cases with NC over store-and-forward routing should not be ignored, and they may be of importance in practical settings. However, our work has also shown that embracing concurrency at the physical layer by means of MPR and MPT provides the same multicast order throughput with or without NC, and that MPR and MPT can be used to attain the optimal unicast capacity in wireless networks [1]. Hence, the effectiveness of using a scheme based on NC to attain higher multicast throughput should be compared against approaches based solely on physical-layer concurrency. In addition, the signaling overhead incurred by the different approaches should be evaluated carefully. Instantiating the necessary NC state at relaying nodes may incur signaling overhead that outweighs any potential throughput gains that NC is intended to provide in the forwarding of data packets.

The last part of our research on the capacity of wireless networks consisted on focusing

on techniques that can attain the benefits of distributed MIMO systems with limited cost.

We developed and studied [7] an interference management technique for the downlink of a wireless cellular network with which D ($D \leq K$) independent data streams can be broadcasted to D out of M mobile stations with single antenna such that these data streams do not interfere with each other. We demonstrated that D can be any number up to the maximum value of K, as long as M is large enough. Therefore, interference management is capable of achieving the maximum multiplexing gain, as long as there is a minimum number of mobile stations in the network. Surprisingly, by taking advantage of fading channels in multiuser environments, the feedback requirement to transmit K independent data streams is proportional to K, and the encoding and decoding scheme is very simple and similar to that of point-to-point communications.

The original multiuser diversity concept was based on searching for the best channels

to use, while our new approach shows that searching simultaneously for the best and worse channels can lead to significant capacity gains. This technique can asymptotically achieve the capacity of dirty paper coding (DPC) when $M \rightarrow \infty$. In general, we can have D mobile stations implementing our interference management scheme, where D depends on the number of mobile stations in the network. If $D < K$, then the rest of K

$- D$ mobile stations require to perform cooperative decoding in order to transmit K independent data streams. Our proposed multiuser diversity scheme provides a tradeoff between multiuser diversity and cooperation among mobile stations. This proposed distributed MIMO scheme does not require mobile stations to cooperate, as long as there are enough mobile stations in the network. It achieves optimal K maximum multiplexing gain in the downlink of cellular systems as long as $K \ll M$. If there are not enough mobile stations in the network, partial cooperation among them is required to achieve the maximum multiplexing gain.

1.2 Modeling of Approaches for Many-to-Many Communication in MANETs

The vast majority of analytical models for medium access control (MAC) protocols (e.g.,

see [8, 9]) have assumed an ideal physical-layer model, in which nodes within a given transmission range receive packets with probability 1 if there are no other concurrent transmissions, and packet transmissions fail with probability 1 if there are any concurrent transmissions. This, of course, is not realistic in most practical situations, especially in mobile ad hoc networks (MANETs), where a packet can be successfully received when the received power is larger than a given threshold, the received power levels may show significant variations around a mean power, and even in the presence of multiple access interference (MAI) caused by concurrent transmissions, receivers can decode packets with probability less than 1. The decoding probability together with MAC protocol behavior determine the performance of MAC protocols in MANETs.

In reality, the received signal is a combination of many replicas arriving over multiple paths between the transmitter and receiver. The signal on these different paths can interfere with each other constructively or destructively; this multi-path effect causes the received signal and power to become variables of space. Especially, if the transmitter or the receiver moves, channel fading causes the received signal and power to become variables of time as well. In addition to above propagation impairments caused by imperfect channel conditions, noise and MAI caused by other concurrent transmissions also impact the probability of correct packet reception. Many MAC protocols employ carrier sensing to mitigate MAI by listening channel status before packet transmissions. As a result, a node transmission probability depends on the channel conditions and is different in carrier-sensing MAC protocols than in MAC protocols without carrier sensing.

While the importance of the physical-layer effects on the performance of MANETs is well recognized, most prior analytical models of MAC protocols operating in MANETs avoid their characterization for the sake of simplicity. For example, Carvalho et al. [10] use linear approximations for the relationship among probabilities of the channel being busy, a node transmitting, and a packet being received successfully, and do not account explicitly for the effect that network density, node mobility and other physical-layer factors have on the performance of MAC protocols.

A few works have attempted to analyze those realistic physical layer factors and incorporate their effect in the modeling of MAC protocols. Pham et al. [11, 12] have tried to take imperfect channel conditions into consideration; however, they only analyze IEEE 802.11 DCF and assume only one specific channel condition, namely Rayleigh channel fading. In addition, they assume that a transmission fails if more than one packet is transmitted concurrently, while in reality a successful packet reception is determined by the signal to interference plus noise ratio (SINR). Zheng et al. [13] generalized the effect of imperfect channel conditions by making the strong assumption that bits are transmitted with a fixed error probability, which provides a wider application area for the model; however, their assumption is also not practical, because there are many network parameters in MANETs that can impact the packet reception probability, such as traffic rate, network density, and mobility.

We have worked on developing a model that takes into account imperfect channel conditions and multiple access interference, and proposed a generalized, parameterized framework for representing the interaction between the physical (PHY) and MAC layers. The focus in this work is not in providing an exact representation of specific MAC protocols. Rather, we aim to model generic MAC protocols in which either an efficient interference prevention scheme is employed or not, and extract common properties of those protocols. We have used two well known examples of those two types of MAC protocols, namely IEEE 802.11 DCF and Aloha, and verify the correctness of our models via simulations. Our first results have been submitted for publication, and our plan is to apply the model to the study of different MIMO schemes. We aim at the analysis via simulation and our analytical framework of specific protocols based on MIMO techniques. More specifically, we are studying the behavior of AMPTR (adaptive multi-packet transmission and reception), which is a MAC protocol aimed at exploiting MPR and MPT.

References

[1] S. Karande, Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, Optimal Unicast Capacity of Random Geometric Graphs: Impact of Multipacket Transmission and Reception, IEEE Journal on Selected Areas in Communications, Special Issue on Stochastic Geometry and Random Graphs for Wireless Networks, Vol. 27, No. 7, Sept. 2009.

[2] S. Karande, Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, Network Coding Does Not Change The Multicast Throughput Order of Wireless Ad Hoc Networks, Proc. IEEE ICC 2009, Dresden, Germany, June 14-18, 2009.

[3] S. Karande, Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, Multicast Throughput Order of Network Coding in Wireless Ad-hoc Networks, Proc. IEEE SECON 2009, June 2226, 2009, Rome, Italy.

[4] S. Karande, Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, On the Multicast Throughput Capacity of Network Coding in Wireless Ad-hoc Networks, Proc. ACM FOWANC 2009: The Second ACM International Workshop on Foundations of Wireless Ad Hoc and Sensor Networking and Computing, New Orleans, LA, May 18, 2009.

[5] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, “Xors in the air: Practical wireless network coding,” in ACM SIGCOMM 2006, Pisa, Italy., Sept. 2006.

[6] S. Chachulski, M. Jennings, S. Katti, and D. Katabi, “Trading structure for randomness in wireless opportunistic routing,” in ACM SIGCOMM 2007, Kyoto, Japan., August 2007.

[7] Z. Wang, M. Ji, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, Cooperation-Multiuser

Diversity Trade- o? in Wireless Cellular Networks, Proc. IEEE Globecom 2009 Wireless Networking Symposium, 30 Nov. - 4 Dec., 2009, Honolulu, HI.

[8] G. Bianchi, “Performance analysis of the ieee 802.11 distributed coordinationfunction,” IEEE Journal on Selected Areas in Communications, vol. 18, pp. 535–547, March 2000.

[9] R. Ma, V. Misra, and D. Rubenstein, “Modeling and analysis of generalized slotted-aloha mac protocols in cooperative, competitive and adversarial environments,” in 26th IEEE International Conference on Distributed Computing Systems, Lisboa, Portugal, July 2006, pp. 62–69.

[10] M. M. Carvalho and J. J. Garcia-Luna-Aceves, “Modeling wireless ad hoc networks with directional antennas,” in IEEE Infocom, Barcelona, Spain, Apr. 2006, pp. 13–26.

[11] P. Pham, S. Perreau, and A. Jayasuriya, “New cross-layer design approach to ad hoc networks under rayleigh fading,” IEEE Journal on Selected Areas in Communications, vol. 23, pp. 28–39, Jan. 2005.

[12] P. P. Pham, “Comprehensive analysis of the ieee 802.11,” Mobile Networks and Applications, vol. 10, pp. 691–703, October 2005.

[13] Y. Zheng, K. Lu, and D. Fang, “Performance analysis of ieee 802.11 dcf in imperfect channels,” IEEE Transactions on Vehicular Technology, vol. 55, pp. 1648–1656, September 2006.

Conclusions

The primary challenge addressed in this project has been to determine how to best utilize the potential gains of the multiple antennas at the transmitters and receivers to improve the overall performance of the tactical mobile ad hoc network. One of the areas where significant progress has been made is the design of MIMO antennas for conditions where the aperture in which the antennas reside is restricted such that the current distributions for the different elements overlap within the aperture.

Multiple antennas at the nodes of the network have been shown to increase link capacity by allowing multiple parallel radio channels in the same spectral band. This spatial multiplexing gain can provide higher link capacity and facilitate processing of multiple packets, but these gains must be balanced against the increased interference that is generated in a multi-user network. It is possible to limit the interference to other users in the network by utilizing the antennas to provide beamforming gain. Alternatively, the antennas can be utilized to provide diversity and coding gain using space-time coding techniques. Tactical networks may also exploit the spatial selectivity of MIMO equipped nodes to null unwanted interference from jammers.

One of the areas where significant progress has been made is in the area of joint beamforming and space-time coding to improve overall network performance. It has been firmly established that optimal network performance is not achieved simply by maximizing the link throughput since increasing the point-to-point capacity does not exploit the spatial multiplexing gains that can be realized by MIMO equipped nodes. Analytical results are obtained to determine when spatial multiplexing provides performance gains relative to simple beamforming solutions and optimal subchannel power levels are derived as a function of the accuracy of the channel state information available.

The manner in which power is allocated to these MIMO nodes in space, time and frequency has been analyzed to determine the best approach to use in response to changes in the channel state and the network topology. In addition, the feedback schemes required to implement beamforming in these networks has been analyzed for quantized feedback systems as a function of the number of bits of information provided per update. The impact of performance limitations due to both the feedback delay and the channel estimation errors has been evaluated. The impact of channel fading was quantified for a variety of modulation and coding schemes.

The problem of allocating the network resources in a multi-user MIMO network is dependent on the specific performance metric of most interest. The allocation of power to the different channels is defined by the beamformer weights and can be modified to satisfy different network metrics such as the overall throughput, fairness, end-to-end delay, etc. In this project we have examined the use of cooperative bargaining theory to define the tradeoffs between the max-sum rate efficiency (throughput) and max-min equity (fairness) for an arbitrary number of users in MISO interference channels. Power control was shown to provide significant throughput gains when the number of transmitter/receiver pairs is greater than the number of transmit antennas.

MIMO nodes were utilized to achieve unequal error protection among the different components of a scalable video waveform in order to provide a natural way to protect the most important components of the video waveform at the expense of the less important components. This was accomplished by the use of a base layer and an enhancement layer where space-time coding is used to protect the base layer and spatial multiplexing is used for the enhancement layer.

The incorporation of spatial multiplexing gains provided by MIMO equipped nodes into the overall network design results in an inherently crosslayer solution that exploits the physical layer information in the MAC layer for scheduling and routing decisions. This however requires a clear understanding of how the channel state information (CSI) is incorporated into the MAC layer and how the accuracy and temporal stability of the CSI affect the performance of the network protocols used to make scheduling and routing decisions. The accuracy of the CSI obtained is impacted by the temporal variations in the channel that arise in realistic environments, especially in networks with significant mobility of the nodes.

In addition, there is an inherent difference in the time scales over which CSI and routing updates are made. In this project the use of channel statistics in conjunction with, or in place of, channel state information has been evaluated in order to increase the temporal stability of the physical layer information provided to the upper layers of the network.

We have obtained recent results on utilizing channel distribution information (CDI) for beamforming that have been shown to significantly reduce the frequency that channel information must be feedback to the transmitter. When CDI is used in place of CSI on a given link, the network sacrifices some performance in maximum throughput for that specific link relative to that attainable with perfect CSI, but may provide improved performance when there are significant errors in the CSI. In addition, significant reductions in the power required to maintain a given level of performance are achieved. The CDI is based on the channel statistics and changes more slowly than the coherence time of the channel. Reducing the frequency of the updates required has been shown to significantly reduce the overall level of interference created to other users in the network.

During the past year we have developed beamforming algorithms based on channel distribution information (CDI) under a variety of ad hoc networking scenarios (e.g. interference channel, broadcast channels, multi-user, and hybrid channels) and compared the results to those obtained using CSI. The increased temporal stability of the CDI beamformer requires fewer updates of the channel statistics than the channel state, but the feedback update now requires information defining the changes in the channel covariance. In this project we are evaluating various matrix compression techniques to reduce the feedback complexity for CDI –based signaling approaches so that a realistic comparison of the overall system complexity of these techniques can be determined in realistic channel conditions.

Modeling of the wideband MIMO channel has been conducted under this project and various models such as correlation and matrix based channel models have been analyzed. The ability to predict channel variations over time has been evaluated using linear and nonlinear prediction techniques and also by using cubature Kalman Filters. A MIMO system that incorporates a Tomlinson-Harashima precoder was utilized to pre-process the transmitted information so as to suppress the interference at each of the decentralized receivers. A QR-decomposition of the channel matrix was employed to obtain an equivalent channel in which successive interference cancellation at the transmitter can be used to remove the multi-user interference. Analytical results for the error-rate performance were obtained as a function of the channel estimation errors and were verified by computer simulation.

A variety of routing strategies have been evaluated during the past year to incorporate physical layer information into protocols. A cooperative paradigm that exploits diversity, hybrid automatic retransmission requests and MIMO techniques in a multi-hop network scenario has been developed. In addition, decode-and–forward physical layer network coding architectures have been developed.

Testbeds have been developed to evaluate how the routing layer decisions interact with the physical layer model for multi-hop flows. MAC protocols have been developed that utilize the interference cancellation capability of multi-user MIMO systems to increase the spatial reuse in a multi-hop network by allowing multiple concurrent communications in a region. The overall multi-hop network has been decomposed into separate sub-topologies decoupled from each other.

Factors such as the queuing delay have been considered in addition to the channel quality and channel quality distribution to define delay-throughput trade-offs for the network. Opportunistic routing is used to improve delay performance. Closed form expressions for the error performance of the network are provided as a function of the channel and source statistics. In addition, channel aware distributed opportunistic scheduling techniques have been developed for delay constrained networks.

Analytical studies have been made to determine the number of hops that should be used between the source and destination nodes of an ad hoc network. Reducing the number of hops reduces the overall network overhead but this requires increased transmission ranges with a resulting increase in the level of interference to the other nodes. Single hop network metrics such as the network throughput (the product of the spatial density of transmitters and the link throughput) and the information efficiency (the product of the transmission distance and the link throughput) were analyzed to evaluate the impact of space-time coding vs spatial–multiplexing for selected multiple access and coding schemes. The importance of utilizing the channel diversity that can be obtained for the MIMO relays in conjunction with error correction coding is established.

These results were then extended to multi-hop networks where queues are added to each node and the end-to-end delay and throughput performance are evaluated for idealized backlogged and non-backlogged networks. Closed form expressions for these idealized multi-hop networks are obtained that allow the mean end-to-end delay performance to be optimized with respect to the number and placement of relays. The analytic results obtained were verified by network simulation. The rate stability of these networks was also evaluated and the conditions are obtained that ensure that the lengths of the relay queues do not become unbounded over time, thus resulting in an infinite end-to-end delay.

Finally, to address the inherent problem of maintaining channel feedback to all the nodes of a time-varying multi-user network we have evaluated the use of an outage probability (the probability that we meet a target SINR on each link) as a metric that can maintain stable transmission in a rapidly time varying scenario. CSI allows communications for each link to be maintained at the expense of increased power to maintain accurate CSI in poor channel conditions. By accepting a specified outage probability for the links in the network, the undesirable interference that results from the attempts to increase the transmitted power to maintain connectivity on a link with poor channel conditions is avoided.   The channel distribution information (CDI) cannot ensure successful communication at all times for each link in a time-varying fading channel, but it can guarantee a certain signal to interference plus noise ratio (SINR) that will provide a reliable link with a specified outage probability. The use of CSI and CDI information has been analyzed for the outage probability metric. It was shown that the use of CDI results in significant reductions in computational complexity, feedback and transmitted power. The full impact of the use of CDI in mobile ad hoc networks is a topic of current research as discussed above.

Appendices

Appendix 1: Honors and Awards

J.J. Garcia-Luna-Aceves

Elected ACM Fellow ``for contributions to the theory and design of computer communication protocols."

IEEE Fred W. Ellersick 2008 MILCOM Award for Best Unclassified Paper:

Z. Wang, S. Karande, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, ``On

the Capacity Improvement of Multicast Traffic with Network Coding,"

Proc. IEEE MILCOM 2008, San Diego, California, November 17--19,

2008.

Program Co-Chair, 8th International Conference, ADHOC-NOW 2009, Murcia, Spain, September 22-25, 2009

Member of technical program committee for ACM MobiCom 09, IEEE SECON 09, and ACM MobiHoc 09.

Yingbo Hua

Member of Editorial Board, IEEE Signal Processing Magazine, 2007 – 2009

Editor, Signal Processing (EURASIP), 2005

Guest Editor, IEEE Signal Processing Magazine Special Issue on Signal Processing for Cognitive Radio Networks, Vol 25, No. 6, Nov 2008

Member, Technical Program Committee, The Second Cognitive Information Processing workshop (CIP-2010), Tuscan island of Elba (Isola d'Elba), Italy, June 14-15, 2010

Member, Technical Program Committee, Asia-Pacific Signal and Information Processing Association (APSIPA) Annual Summit and Conference, Sapporo Convention Center, Japan, Oct 4-7, 2009

Member, Technical Program Committee, , IEEE Workshop on Digital Signal Processing and Signal Processing Education, Marco Island, Florida, Jan 4-7, 2009

Hamid Jafarkhani

Selected Chancellor's Professor, UCI

Top 10 most-cited researchers in the field of "computer science" during 1997-2007 (Essential Science Indicators from Thomson Scientific)

Keynote Speaker, *World Congress on Computer Science and Information Engineering (CSIE)*, 2009

Area Editor, IEEE Transactions on Wireless Communications

Session Chair in following conferences:

IEEE Wireless Communications and Networking Conference (WCNC), 2009

IEEE Data Compression Conference (DCC), 2009

TPC member in following conferences:

IEEE Global Communications Conference (Globecom), 2009

IEEE International Conference on Communications (ICC), 2009

IEEE Wireless Communications and Networking Conference (WCNC), 2009

IEEE Data Compression Conference (DCC), 2009

Michael Jensen

4 Invited Conference Presentations

Guest Editor, *EURASIP Journal on Wireless Communications and Networking*, Special Issue on Advances in Propagation Modeling for Wireless Systems, 2008-2009

Technical Program Committee Member: *2009 IEEE Antennas and Propagation Society International Symposium, 2009 IEEE Fall Vehicular Technology Conference*

IEEE Antennas and Propagation Society Joint Meetings Committee Chair, 2008-Present

Associate Editor, *IEEE Antennas and Wireless Propag*ation Letters, 2009-present

Symposium Co-Chair, 2010 Intl. Conference on Wireless Information Technology and Systems, Honolulu, HI.

Laurence Milstein

Senior Editor, IEEE Journal on Selected Areas in Communications

Editorial Board, Journal of the Franklin Institute

TPC Co-Chair, 2009 Int. Symp. on Ultra Wideband Communications

Lee Swindlehurst

Conference Organization

Technical Program Chair for 2008 IEEE International Conference on Acoustics, Speech and Signal Processing

IEEE Editorial Assignments:

Editor-in-Chief, IEEE Journal of Selected Topics in Signal Processing Member
Editorial Board, IEEE Signal Processing Magazine Member
Editorial Board, EURASIP Journal of Wireless Communications and Networking

Michele Zorzi

Member-at-Large of the IEEE Communications Society Board of Governors

Editor-in-Chief of the IEEE Transactions on Communications

Editor for Europe of the Wiley Journal on Wireless Communications and Mobile Computing

Member of the editorial board: ACM Journal of Wireless Networks

Member of the steering committee: IEEE Transactions on Mobile Computing

Guest editor: “Energy Efficient Design in Wireless Ad Hoc and Sensor Networks,” Elsevier's Journal of Ad Hoc Networks (Nov. 2008); “Underwater communications and Wireless Networks,” IEEE JSAC (Dec. 2008).

Best paper awards: European Wireless Conference, May 2009, COMSOC best tutorial paper, 2007 (awarded at ICC, May 2008)

Appendix 2: Technology Transfer

Michael Jensen

We continue to work with Rayspan Corporation, a start-up company with venture capital funding, to develop miniature antenna technologies for use in WLAN systems. We have delivered a reconfigurable antenna topology which is currently being evaluated for commercial application. We have also delivered evaluation software to assist in the identification of suitable antenna topologies for MIMO and diversity communication.

Srikanth Krishnamurthy

Professor Krishnamurthy is currently working with CISCO to apply the understanding gained via measurements on Space Time Block Coding and Space Division Multiplexing modes of operation with MIMO from the MURI project to provide improved overall throughput by auto-configuration and management of WLANs.

Appendix 3: Publications

Appendix 3A: Published Journal Publications

J.J. Garcia-Luna-Aceves

H. Sadjadpour, Z. Wang, and J.J. Garcia-Luna-Aceves, The Capacity of Wireless Ad Hoc Networks with Multi-Packet Reception, IEEE Transactions on Communications. Accepted for publication, 2009.

S. Karande, Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, Optimal Unicast Capacity of Random Geometric Graphs: Impact of Multipacket Transmission and Reception, IEEE Journal on Selected Areas in Communications, Special Issue on Stochastic Geometry and Random Graphs for Wireless Networks, Vol. 27, No. 7, Sept. 2009.

Simon Haykin

I. Arasaratnam and S. Haykin. " Cuabture Kalman Filters," IEEE Trans. Automatic Control, June 2009

Yingbo Hua

RONG, Y., and HUA, Y., "Optimal power schedule for distributed MIMO links," *IEEE Transactions on Wireless Communications*, Vol. 7, No. 8, pp. 2896-2900, August 2008.

YU, Y., HUANG, Y., ZHAO, B., HUA, Y., "Further development of synchronous array method for ad hoc wireless networks," *EURASIP Journal on Advances in Signal Processing – Special Issue on Cross-Layer Design for the Physical, MAC, and Link Layer in Wireless Systems*, Vol. 2009, Article ID 873202, 14 pages, September 2008.

RONG, Y., TANG, X., and HUA, Y., “A unified framework for optimizing linear non-regenerative multicarrier MIMO relay communication systems,” *IEEE Transactions on Signal Processing*, accepted June 2009.

Tara Javidi

N. Ehsan and T. Javidi, “Delay optimal transmission policy in a wireless multi-access channel,” *IEEE Trans. Inf. Theory,* Vol. 54, Issue 8, pp. 3745 – 3751, August 2008

J. Price and T. Javidi, “Network coding games with unicast flows,” *IEEE Journal on Selected Areas in Commununications, Volume 26, Issue 7, pp. 1302 – 1316, September 2008*

Hamid Jafarkhani

Y. Jing and H. Jafarkhani “Network Beamforming Using Relays with Perfect Channel Information,” *IEEE Transactions on Information Theory*, vol. 55, pp. 2499--2517, June 2009.

S. Ekbatani and H. Jafarkhani, “Combining Beamforming and Space-Time Coding Using Noisy Quantized Feedback,” *IEEE Transactions on Communications*, vol. 57, pp. 1280--1286, May 2009.

S. Ekbatani, F. Etemadi, and H. Jafarkhani, “Throughput maximization over slowly fading channels using erroneous quantized feedback,” in press *IEEE Transactions on Communications*

Y. Jing and H. Jafarkhani “Single and Multiple Relay Selection Schemes and Their Achievable Diversity Orders,” *IEEE Transactions on Wireless Communications*, vol. 8, pp. 1414--1423, Mar. 2009.

H. Yousefi'zadeh, H. Jafarkhani, and J. Kazemitabar, “A Study of Connectivity in MIMO Fading Ad-Hoc Networks,” *IEEE/KICS Journal of Communications and Networks* (JCN), vol. 11, pp. 47--56, Feb. 2009.

E. Koyuncu, Y. Jing, and H. Jafarkhani "Distributed Beamforming in Wireless Relay Networks with Quantized Feedback," *IEEE Journal on Selected Areas in Communications* (JSAC), vol. 26, pp. 1429--1439, Oct. 2008.

S. Ekbatani, F. Etemadi, and H. Jafarkhani, "Throughput maximization over slowly fading channels using erroneous quantized feedback," In press *IEEE Transactions on Communications*

Michael Jensen

C. Chen and M. A. Jensen, "A stochastic model of the time-variant MIMO channel based on experimental observations," *IEEE. Trans. Vehicular Technology,* vol. 58, no. 6, pp. 2618-2625, Jul. 2009.

N. W. Bikhazi, M. A. Jensen, and A. L. Anderson, "MIMO signaling over the MMF optical broadcast channel with square-law detection," *IEEE Trans. Communications*, vol. 57, no. 3, pp. 614-617, Mar. 2009.

N. W. Bikhazi and M. A. Jensen, "Impact of coupling on MIMO capacity in correlated fast fading environments," *IEEE Trans. Vehicular Technology,* vol. 58, no. 3, pp. 1595-1597, Mar. 2009.

A. L. Anderson, J. R. Zeidler, and M. A. Jensen, "Reduced-feedback linear precoding with stable performance for the time-varying MIMO broadcast channel," *IEEE Journal on Selected Areas in Communications*, vol. 26, pp. 1483-1493, Oct. 2008.

B. T. Maharaj, J. W. Wallace, and M. A. Jensen, "A low-cost open-hardware wideband multiple-input multiple-output (MIMO) wireless channel sounder," *IEEE Trans. Instrum. Meas.*, vol. 57, pp. 2283-2289, Oct. 2008.

M. A. Jensen and J. W. Wallace, "Antenna Design Considerations for MIMO and Diversity Systems," chapter 23 in *Modern Antenna Handbook,* C. A. Balanis, Ed., pp. 1327-1375, John Wiley & Sons: New Jersey, September, 2008.

B. T. Quist and M. A. Jensen, "Optimal antenna radiation characteristics for diversity and MIMO systems," *IEEE Trans. Antennas Propag.*, to appear.

Laurence Milstein

S. Ling and L. B. Milstein, "The Effects of Spatial Diversity and Imperfect Channel Estimation on Wideband MC-DS-CDMA and MC-CDMA," accepted in IEEE Transactions on Communications

P. Amihood, E. Masry, L. B. Milstein, and J. G. Proakis, "The Effects of Channel Estimation Errors on a Nonlinear Precoder for Multiple Antenna Downlink Channels," accepted in IEEE Transactions on Communications.

Q. Qu, L. B. Milstein, and D. R. Vaman, "Cross-Layer Distributed Joint Power Control and Scheduling for Delay-Constrained Applications over CDMA-based Wireless Ad-hoc Networks," accepted in IEEE Transactions on Communications.

John G. Proakis

P. Amihood, E. Masry, L.B. Milstein and J.G. Proakis, “The Effects of Channel Estimation Errors on a Nonlinear Precoder for Multiple Antenna Downlink Channels”, accepted for publications, *IEEE Transactions on Communications*.

Bhaskar Rao

J. Zheng and B. D. Rao, "Capacity Analysis of MIMO Systems Using Limited Feedback Transmit Precoding Schemes," *IEEE Transactions On Signal Processing*, Vol. 56, Issue. 7, Part. 1, Pages: 2886 2901, Jul. 2008

J. Zheng and B. D. Rao, "Analysis of vector quantization using transformed codebooks with application to feedback-based multiple antenna systems," *EURASIP Journal on Wireless Communications and Networking*, Article ID: 125892, 2008

Y. Isukapalli, J. Zheng, and B. D. Rao, “Optimum codebook design and average SEP loss analysis of spatially independent and correlated feedback based MISO systems with rectangular QAM constellation,” *IEEE Transactions on Signal Processing*, vol. 57, issue. 5, pages: 2017-2024, May 2009

Y. Isukapalli, R. Annavajjala, and B. D. Rao, “Performance analysis of transmit beamforming for MISO systems with imperfect feedback,” *IEEE Transactions on Communications*, vol. 57, issue. 1, pages: 222-231, Jan. 2009

Y. Isukapalli and B. D. Rao, “An analytically tractable approximation for the Gaussian Q-function,” *IEEE Communications Letters*, vol. 12, issue. 9, pages: 669-671, Sep. 2008

K. K-Delgado and Y. Isukapalli, “Use of the Newton method for blind adaptive equalization based on the constant modulus algorithm” *IEEE Transactions on Signal Processing*, vol. 56, issue. 8, part. 2, pages: 3983-3995, Aug. 2008

Lee Swindlehurst

M. Nokleby and A. Swindlehurst, "Bargaining and MISO Interference Channel," *EURASIP Journal of Applied Signal Processing*, Volume 2009 (2009), Article ID 368547, 13 pages doi:10.1155/2009/368547

M. Larsen, A. Swindlehurst and T. Svantesson, "Performance Bounds for MIMO-OFDM Channel Estimation," *IEEE Trans. on Signal Processing*, vol. 57, No. 5, pp. 1901-1916, May, 2009

Z. Han, A. Swindlehurst and K. J. R. Liu, "Optimization of MANET Connectivity via Smart Deployment/Movement of Unmanned Air Vehicles,"
IEEE Trans. on Vehicular Technology, 2009 (in press)

M. Nokleby and A. Swindlehurst, "Bargaining and MISO Interference Channel," EURASIP Journal of Applied Signal Processing, 2009 (in press)

James Zeidler

H. Sui and J.R. Zeidler, “Information Efficiency and Transmission Range Optimization for Coded MIMO FH-CDMA Ad Hoc Networks in Time Varying Environments”, IEEE Transactions on Communications, Vol 57, No 2, pp. , February 2009.

Adam L. Anderson, J.R. Zeidler and M.A Jensen, "Reduced-Feedback Linear Precoding with Stable Performance for the Time-Varying MIMO Broadcast Channel", IEEE Journal on Selected Areas of Communications, (*Special Issue on Limited Feedback).* Vol 26, , no 8, pp. 1483-1493, October 2008

Adam L. Anderson, J. R. Zeidler, and M. A. Jensen, ``Stable transmission in the time-varying MIMO broadcast channel," EURASIP Journal on Advances in Signal Processing, (*Special Issue on MIMO Transmission with Limited Feedback),* vol. 2008, Article ID 617020, 14 pages, 2008.

Michele Zorzi

Munari, F. Rossetto, M. Zorzi, "Phoenix: Making Cooperation more Efficient through Network Coding in Wireless Networks", *IEEE Transactions on Wireless Communications,* in press 2009

F. Rossetto and M. Zorzi, "A Low Delay MAC solution for MIMO ad hoc networks", *IEEE Transactions on Wireless Communications*, vol. 8, no. 1, pp. 130-135, Jan. 2009

Paolo Casari, Marco Levorato and Michele Zorzi, “MAC/PHY Cross-Layer Design of MIMO Ad Hoc Networks with Layered Multiuser Detection,” *IEEE Transactions on Wireless Communications*, vol. 7, num. 11, pp. 4596-4607, Nov. 2008

Appendix 3B: Submitted Journal Publications

Yingbo Hua

RONG, Y., and HUA, Y., “Optimality of diagonalization of multi-hop MIMO relays,” *IEEE Transactions on Wireless Communications,* submitted March 2009, revised June 2009.

YU, Y., and HUA, Y., “Power scheduling for a MIMO relay system with multiple-antenna users”, *IEEE Transactions on Signal Processing*, submitted April 2009, revised July 2009.

DONG, X., RONG, Y., HUA, Y., “Cooperative power scheduling for a network of MIMO links,” *IEEE Transactions on Wireless Communications,* submitted May 200

Hamid Jafarkhani

F. Li and H. Jafarkhani, "Multiple-Antenna Interference Cancellation and Detection for Two Users Using Precoders," submitted to *IEEE Journal of Selected Topics in Signal Processing*

Tara Javidi

A. Bhorkar, M. Naghshvar, T. Javidi, B. Rao, "An Adaptive Opportunistic Routing Scheme for Wireless Ad-hoc Networks," submitted to *IEEE/ACM Transactions on Networking*

V. Subramanian, S. Kittipiyakul, T. Javidi, Many-Sources Large Deviations for Max-Weight Scheduling, submitted to *IEEE Trans. on Info. Theory*

Michael Jensen

Y. Shi and M. A. Jensen, "Feedback reduction techniques for the MIMO broadcast channel," *IEEE Trans. Wireless Communications,* submitted Aug. 2009.

D. N. Evans and M. A. Jensen, "Near-optimal radiation patterns for antenna diversity," *IEEE Trans. Antennas Propag.,* submitted May 2009.

C. Chen and M. A. Jensen, "Secret key establishment using the time-variant MIMO channel," *IEEE Trans. Wireless Communications,* submitted Mar. 2009.

A. L. Anderson, J. R. Zeidler, and M. A. Jensen, "Instantaneous and average sum-rate optimizations for multi-user MIMO topologies," *IEEE Trans. Wireless Communications,* submitted Jun. 2009.

J. W. Wallace and M. A. Jensen, "Sparse power azimuth spectrum estimation," *IEEE Trans. Antennas Propag.,* submitted Feb. 2008.

Laurence Milstein

S.- H. Chang, M. Rim, P. C. Cosman, and L. B. Milstein, "Optimized Unequal Error Protection Using Multiplexed Hierarchical Modulation," submitted to *IEEE Transactions on Information Theory*

John G. Proakis

K. Stamatiou, J.G. Proakis and J.R. Zeidler, "Channel Diversity in Random Wireless Networks", submitted to *IEEE Transactions on Wireless Communications*

Bhaskar D. Rao

Y. Isukapalli and B. D. Rao, “Packet error probability of a transmit beamforming system with imperfect feedback,” submitted, May 2009, revised, Jul. 2009, *IEEE Transactions on Signal Processing*

Y. Isukapalli and B. D. Rao, “Multi-antenna wireless channel modeling: statistical properties and prediction,” in preparation, *IEEE Transactions on Signal Processing*

James Zeidler

A. L. Anderson, J. R. Zeidler, and M. A. Jensen, “Instantaneous and average sum-rate optimizations for multi-user MIMO topologies,” *IEEE Trans. Wireless Communications,* submitted Jun. 2009.

K. Stamatiou, F. Rosssetto, M. Haenggi, T. Javidi, J. Zeidler and M. Zorzi, “Delay Characterization of Random Multi-hop Networks”, submitted to *IEEE Transactions* on *Wireless Communications*

K. Stamatiou, J.G. Proakis and J.R. Zeidler, “Channel Diversity in Random Wireless Networks”, submitted to *IEEE Transactions on Wireless Communications*.

Michele Zorzi

Davide Chiarotto, Paolo Casari, and Michele Zorzi, “On the Statistics and MAC Implications of Channel Estimation Errors in MIMO Ad Hoc Networks,” *IEEE Transactions on Wireless Communications*, submitted.

Appendix 3C: Conference Papers

J.J. Garcia-Luna-Aceves

Z. Wang, M. Ji, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, Cooperation-Multiuser Diversity Trade- o? in Wireless Cellular Networks, Proc. IEEE Globecom 2009 Wireless Networking Symposium, 30 Nov. - 4 Dec., 2009, Honolulu, HI.

W. Wang, M. Ji, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, Interference Management: A New Paradigm for Wireless Cellular Networks, Proc. IEEE MILCOM 2009, Boston, MA, October 18-21, 2009.

S. Karande, Z.Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, Multicast Throughput Order of Network Coding in Wireless Ad-hoc Networks, Proc. IEEE SECON 2009, June 2226, 2009, Rome, Italy.

S. Karande, Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, Network Coding Does Not Change The Multicast Throughput Order of Wireless Ad Hoc Networks, Proc. IEEE ICC 2009, Dresden, Germany, June 14-18, 2009.

S. Karande, Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, On the Multicast Throughput Capacity of Network Coding in Wireless Ad-hoc Networks, Proc. ACM FOWANC 2009: The Second ACM InternationalWorkshop on Foundations of Wireless Ad Hoc and Sensor Networking and Computing, New Orleans, LA, May 18, 2009.

Z. Wang, S. Karande, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, On the Capacity Improvement of Multicast Traffic with Network Coding, Proc. IEEE MILCOM 2008, San Diego, California, November 1719, 2008. (IEEE Fred W. Ellersick 2008 MILCOM Award for Best Unclassied Paper).

S. Karande, Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, The Optimal Throughput Order of Wireless Ad Hoc Networks and How to Achieve It, Proc. IEEE MILCOM 2008, San Diego, California, November 1719, 2008.

S. Karande, Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, Capacity of Ad-Hoc Networks under Multipacket Transmission and Reception, (Invited Paper) Proc. 42nd Asilomar Conference on Signals, Systems and Computers, October 26 - October 29, 2008, Asilomar Conference Grounds, Pacific Grove, California.

H. Kim, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, A Closer Look at the Physical and Protocol Models for Wireless Ad Hoc Networks with Multi-Packet Reception, Proc. 42nd Asilomar Conference on Signals, Systems and Computers, October 26 - October 29, 2008, Asilomar Conference Grounds, Pacific Grove, California.

Simon Haykin

N. Costa, and S. Haykin, “A correlation-based wideband MIMO channel model,” Proc. General Assembly of the International Union of Radio Science 2008 (URSI 2008),7-16 Aug. 2008, Chicago, IL. (invited)

Hamid Jafarkhani

J. Kazemitabar and H. Jafarkhani, "Performance Analysis of Multiple Antenna Multi-User Detection," *Information Theory and Applications Workshop*, Jan. 2009.

F. Li and H. Jafarkhani, "Resource Allocation Algorithms with Reduced Complexity in MIMO Multi-Hop Fading Channels," *IEEE Wireless Communications and Networking Conference* (WCNC-09), Apr. 2009.

Y. Jing and H. Jafarkhani, "Interference Cancellation in Distributed Space-Time Coded Wireless Relay Networks," *IEEE International Conference on Communications* (ICC-09), June 2009.

F. Li and H. Jafarkhani, "Interference Cancellation and Detection Using Precoders," *IEEE International Conference on Communications* (ICC-09), June 2009.

E. Koyuncu and H. Jafarkhani, ``Beamforming in Wireless Relay-Interference Networks with Quantized Feedback," *IEEE Global Communications Conference* (Globecom-09), Nov. 2009.

Tara Javidi

A. Bhorkar, M. Naghshvar, T. Javidi, B. Rao, "An Adaptive Opportunistic Routing Scheme for Wireless Ad-hoc Networks," in Proceedings of *IEEE International Symposium on Information Theory*, 2009

M. Naghshvar, H. Zhuang, and T. Javidi, "A General Class of Throughput Optimal Routing Policies in Multi-hop Wireless Networks", to be presented at *Allerton Conference,* 2009.

R. N. Swamy and T. Javidi, "Optimal Code Length for Bursty Sources with Deadlines, IEEE International Symposium on Information Theory, 2009

Michael Jensen

C. Chen and M. A. Jensen, "Secrecy extraction from increased randomness in a time-varying MIMO channel," *Proc. of the 2009 IEEE Global Communications Conference (Globecom)*, Honolulu, HI, Nov. 30-Dec 4, 2009, to appear.

Laurence Milstein

S.- H. Chang, M. Rim, P. C. Cosman, and L. B. Milstein, "Optimal Multiplexed Hierarchical Modulation for Unequal Error Protection of Progressive Bit Streams," accepted in 2009 *IEEE Global Telecommunications Conference*

Bhaskar Rao

Y. Isukapalli and B.D. Rao, "Analyzing the Effect of Channel Estimation Errors on the Average Block Error Probability of a MISO Transmit Beamforming System," IEEE Global Telecommunications Conference, New Orleans, LA, USA, Pages: 1 – 6, Dec - 2008

A. A. Bhorkar, B. S. Manoj and B. D. Rao, "Antenna Selection Diversity based MAC Protocol for MIMO Ad hoc wireless Networks," IEEE Global Telecommunications Conference, New Orleans, Dec. 2008.

E. Coviello, A. Bhorkar, F. Rossetto, B. D. Rao, and M. Zorzi, “A Robust Approach to Carrier Sense for MIMO Ad Hoc Networks” IEEE International Conference on Communications (ICC), Dresden, Germany, Jun. 2009

Lee Swindlehurst

M. Larsen and A. Swindlehurst, "A MIMO Channel Perturbation Analysis for Robust Bit-Loading," in Proc. 2009 *IEEE ICASSP*, Taipei, Taiwan, pp. 2825-2828, April, 2009

James Zeidler

K. Stamatiou, F. Rossetto, M. Haenggi, T. Javidi, J. Zeidler and M. Zorzi,
``A delay-minimizing routing strategy for wireless multi-hop networks," in Proc. IEEE Workshop on Spatial Stochastic Models for Wireless Networks (SPASWIN), Seoul, June 2009

Adam L. Anderson, J. R. Zeidler, and M. Jensen, ``Instantaneous and Average Rate Maximization in MIMO Multiple-Access Channels with Linear Precoding”, IEEE Asilomar Conference on Circuits, Systems and Computers, Oct. 2008

Adam L. Anderson, J. R. Zeidler, and M. Jensen, ``Regularized channel distribution inversion and parameterization in the MIMO broadcast channel," in Proc. 2008 IEEE 68nd Veh. Technol. Conf., Calgary, Canada, Sept. 2008

Adam L. Anderson, J. R. Zeidler, and M. A. Jensen, “Covariance-based signaling and feedback data parameterization for the time-varying MIMO broadcast channel,” Proceedings of the 28th General Assembly of International Union of Radio Science, Chicago, IL, Aug. 7-16, 2008. Invited

Michele Zorzi

F. Rossetto and M. Zorzi; "On the sensitivity of MIMO_NC to channel estimation errors", *EUCAP 2009*, Berlin (Germany), 2009

E. Coviello, A. Bhorkar, F. Rossetto, B. D. Rao and M. Zorzi; "A Robust approach to Carrier Sense for MIMO ad hoc networks", *IEEE ICC 2009*, Dresden (Germany), Jun. 2009

E. Fasolo, A. Munari, F. Rossetto and M. Zorzi; "Phoenix: A Hybrid Cooperative-Network Coding Protocol for Fast Failure Recovery in Ad Hoc Networks", *IEEE SECON 2008*, San Francisco (CA, USA), June 2008

A. Munari, F. Rossetto and M. Zorzi; "On the viability of a Cooperative-Network Coding Protocol in Clustered Networks", *IEEE MILCOM 2008*, San Diego, CA, Nov. 2008

Paolo Casari, Marco Levorato, Daniele Mazzi and Michele Zorzi, “On the Design of Routing Protocols in MIMO Ad Hoc Networks under Uniform and Correlated Traffic,” *Proc. of ACM IWCMC*, Crete Island, Greece, 2008

Davide Chiarotto, Paolo Casari, and Michele Zorzi, “On the Statistics and MAC Implications of Channel Estimation Errors in MIMO Ad Hoc Networks,” *Proc. of IEEE GlobeCom,* New Orleans, LA, 2008

Davide Chiarotto, Paolo Casari, and Michele Zorzi, “On the Tradeoff between MAC-level Performance Metrics in MIMO Ad Hoc Networks with Imperfect Channel Estimation,” *Proc. of IEEE IWCLD,* Palma de Mallorca, Spain, 2009

Appendix 3C: Books

A. Batra, J. R. Zeidler, J.G. Proakis and L.B. Milstein”, “Interference Rejection and Management”, Chapter 9 in New Directions in Wireless Communications Research, V. Tarokh (ed.), Springer-Verlag, New York, 2009.

N. Costa and S. Haykin, Modeling of Multiple-Input, Multiple-Output Channel Models, accepted for publication, Wiley, 2009.