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Space-Time Processing for Tactical Mobile Ad Hoc Networks

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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.

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Abstract

Recent developments in communication systems technology are providing significant improvements in 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.

1.0 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 beamforming), 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, 2007 through July 31, 2008. During this period we have made significant progress in meeting and exceeding the original 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 capabilities 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 of 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. An 802.11n testbed has been developed and tested to evaluate different configurations and OPNET has been used to evaluate end-to-end performance in multi-hop ad hoc networks.

During the past year 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 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. Selection of the appropriate number of training symbols to assure given levels of throughput, delay and efficiency was 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 cross-layer integration of the physical layer information into the routing and scheduling protocols is the significant differences between the time scales associated with the channel variations at the physical layer, 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 (CDI) 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 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 two different modeling approaches for time varying MIMO channels

During this period, the project team has written a total of 46 journal papers that have been published or accepted for publication. We have also presented 53 conference papers and completed 13 manuscripts that have been submitted to peer reviewed journals and are currently under review. The lists of the papers published and submitted for publication under this project is provided in Appendix 3.

Bhaskar Rao, Rene Cruz and Bongyong Song received the Stephen O. Rice Prize Paper Award in the field of Communication Systems for the paper “Network Duality for Multiuser MIMO Beamforming Networks and Applications” IEEE Transactions on Communications, March 2007. This paper presented results obtained on this project. Bhaskar Rao also received the Ericsson Endowed Chair in Wireless Access Networks in May 2008. Michael Jensen was elected to Fellow of the IEEE, raising the number of project PIs who are IEEE Fellows to eleven. The PIs on the project have received a number of best paper awards at technical conferences, given numerous keynote addresses, organized conferences, sessions, special journal issues and played a significant role in advancing the understanding of mobile MIMO tactical ad hoc networks. Michele Zorzi was elected Editor-in-Chief of the IEEE Transactions on Communications in January 2008. A list of the honors and awards for the year is provided in Appendix 1.

A summary of the major research activities conducted and results that were obtained is provided below. Detailed descriptions of the results are provided in the papers listed in Appendix 3. 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 Many-to-Many Communication in MANETs

PI: J.J. Garcia-Luna-Aceves

GSRs: Shrisih Karande, Hyunchul Kim, Xin Wang, Zheng Wang, Xianren Wu, Hui Xu

Technical Accomplishments

The protocols and architectures of today's ad hoc networks are derivatives of those developed in the past for the Internet, which in turn date back to the ARPANET design in the 1960s. These protocols and architectures reflect the severe memory and processing constraints imposed on computing equipment dedicated to communication tasks 40 years ago, and the fact that the communication links used at the time were point-to-point. The legacy of this development is twofold. First, processing and storage ``inside'' wireless ad hoc networks is kept to a minimum, even though gigabytes of storage are easily available today in nomadic nodes. Second, the wireless links of ad hoc networks are shared using one-to-one communication schemes, which have been developed for point-to-point links or broadcast links subject to centralized control (e.g., a base station controlling mobiles).

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

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

1. Approaches for Many-to-Many Communication in MANETs

We have developed architectures and protocols to take advantage of multipacket reception (MPR) and multipacket transmission (MPT) in MANETs.

A. An Architecture for Many to Many Communication in MANETs

In a nutshell, under a many-to-many communicaiton paradigm, senders and receivers collaborate rather than compete with one another to access the channel and to relay information. Each transmitting node either relays a message to all close nodes or delivers a packet to one of the neighbor nodes if it is the destination. Using a many-to-many communication approach to design the communication protocols can substantially increase the capacity of an ad hoc network compared to the capacity attained under the one-to-one communication paradigm used to date. Many-to-many communication is a vision for multiple concurrent communication settings, i.e., a many-to-many framework where multi-packet transmissions (MPTs) and multi-packet receptions (MPRs) occur simultaneously. In this scheme, nodes access the available channel(s) and forward information across a MANET in such a way that concurrent transmissions become useful at destinations or relays. We have assumed that the cell size limits the number of nodes in each cell, on average, making it feasible to decode the dominant interference using multiuser detection. Hence, sender-receiver pairs *collaborate*, rather than compete, and the adjacent transmitting nodes with strong interference to each other are no longer an impediment to scaling laws but rather an acceptable communication by all receiving nodes for detection and relaying purposes. MPT and MPR per node are attained through a CDMA-SIC scheme enabling nodes to relay each other packets with the possibility of multi-copy forwarding to reduce delay and no capacity loss [13]. A consequence of such a strategy is an increase in the receiver complexity of all the nodes in the network.

We have shown that, by utilizing mobility, multiuser diversity[1] [14], SIC, cognition[2] and bandwidth expansion, the link's Shannon capacity and the per source-destination throughput attain an upper-bound of $O(n^{\frac{\alpha}{2}})$ and a lower-bound of $\Omega[f(n)]$, for n total nodes in the network, a path loss parameter $\alpha > 2$, and $1 \le f(n) < n^{\frac{\alpha}{2}}$.

We have published an extended version of our findings in [1].

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[1] i.e., a node transmits a packet to all its nearest neighbors, and those relays deliver the packets to the destinations when each destination becomes a close neighbor of each relay.

[2] To allow a node to know where it is and who the nodes in the same cell are.

B. Joint Routing and Scheduling with Multiple Packet Reception

We formulated [2], [3], [4] an approach to take advantage of multipacket reception (MPR) at the link and network levels. The motivation for this work is that, for MPR to really help ad hoc networks scale, the protocols used in such networks have to be redesigned from the ground up to *embrace*, not combat, multiple access interference (MAI). We present an approach to the joint routing and scheduling problem in ad hoc networks in which nodes are endowed with MPR. Our joint routing and scheduling solution takes advantage of multiple concurrent transmissions around receivers that are part of routes from sources to destinations. The main contribution of this part of our work consists of deriving the formulation of the joint routing scheduling optimization in ad hoc networks using MPR, and proposing a novel heuristic that approximates the upper bound on performance. Additional weok is needed to make this approach practical for MANETs.

C. ORCHESTRA

We developed ORCHESTRA [9], [5], a channel access protocol that uses reservations and virtual MIMO to provide high throughput and bounded channel access delays. Channel access process is divided into a contention-based access period and a scheduled access period. To attain high throughput, nodes build the channel schedule using the contention-based access period, and utilize the spatial multiplexing gain of virtual MIMO links in the scheduled access period. To attain bounded channel access delays, nodes reserve time slots through opportunistic reservations. We evaluated the performance of ORCHESTRA through numerical analysis and simulations, and showed that it results in much better throughput, delay, and jitter characteristics than simply using MIMO nodes together with scheduled access (i.e., NAMA) or contention-based access (i.e., IEEE 802.11 DCF).

2 Fundamental Limits of Wireless Networks

The seminal work by Gupta and Kumar [15] on the capacity of wireless networks focused on the traditional view of ad hoc networking in which protocols are based on a one-to-one communication paradigm aimed at avoiding multiple access interference (MAI). This work has sparked a growing amount of interest in the understanding of the fundamental capacity limits of wireless ad hoc networks. This prior work falls into three main areas. The first research area has focused on extending the results by Gupta and Kumar (e.g., [16]). The second area consists of developing and analyzing schemes capable of increasing the capacity of wireless networks for unicast applications (e.g., [17], [18], [19], [20], [21], [22], [23], [24],

[25], [26], [27]). The third area of research has addressed the fact that Gupta and Kumar's results apply only to wireless networks subject to multi-pair unicasts, and includes a number of studies on the capacity of ad hoc networks subject to broadcasting (e.g., [28], [29], [30]) and multicasting (e.g., [31], [32], [33]).

Interstingly, there has been no unified treatment on the capacity of wireless networks subject to different types of forwarding disciplines, and all prior research has focused on what is attainable with specific approaches to handle MAI. All prior work focuses on one type of information dissemination, and no prior work has 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. Our research over the past year has made fundamental contributions in this respect, which we summarize below.

A. Unified modelling framework of capacity-delay tradeoffs

We have introduced the first unified modeling framework for the computation of fundamental limits of capacity-delay tradeoffs in wireless ad hoc networks in which information is disseminated by means of unicast routing, multicast routing, broadcasting, or different forms of anycasting, and in which receivers are capable of transmitting or receiving a single packet at a time [12].

We define (n, m, k)-casting as a generalization of all forms of one-to-one, one-to-many and many-to-many information dissemination in wireless networks. In the context of (n, m, k)-casting, n, m, and k denote the number of nodes in the network, the number of destinations for each communication group, and the actual number of communication-group members that receive information (i.e., $k \leq m$), respectively.

We computed the upper and lower bounds for the capacity of (n, m, m)-casting ($C_{m,m}(n)$), and show that: (a) $\Theta\left(1/(\sqrt{mn \log n})\right)$ bits per second is a tight bound for the capacity of multicasting (i.e., $m = k < n$) when $m \leq \Theta\left(n/(\log n)\right)$; (b) the multicast capacity of a wireless network equals its order capacity for multi-pair unicasting when the number of destinations for each multicast source is not a function of n; and (c) and the multicast capacity of a random wireless ad hoc network is ($\Theta\left(1/n\right)$), which is the broadcast capacity of the network, when $m \geq \Theta\left(n/(\log n)\right)$.

We showed that the capacity of (n, m, k)-casting ($C_{m,k}(n)$) has tight bounds equal to $\Theta\left(\sqrt{m}(nkr(n))^{-1}\right)$, $\Theta\left(\left(nkr^2(n)\right)^{-1}\right)$ and $\Theta\left(n^{-1}\right)$ when $\Theta(1) \leq m \leq \Theta\left(r^{-2}(n)\right)$, $k \leq \Theta\left(r^{-2}(n)\right) \leq m \leq n$, and $\Theta\left(r^{-2}(n)\right) \leq k \leq m \leq n$. This result generalizes prior results on the throughput capacity of ad hoc networks for unicasting, multicasting and broadcasting. When $m = k = \Theta(1)$, the resulting capacity equals the well-known capacity result for multi-pair unicasting by Gupta and Kumar. For $k = 1$, this constitutes the first capacity result for anycasting. Furthermore, this is the first result for the capacity of ``manycasting" $(1 < k < m)$ in wireless ad hoc networks, where k out of m members of a communication group receive information from a source.

We obtained the first unified delay computation and capacity-delay tradeoff analysis for wireless ad hoc networks. Our results extend previous results on the delay for unicasting $(m = k = 1)$ [34] to the more general cases when $\Theta(1) \leq m \leq \Theta\left(r^{-2}(n)\right)$, $k \leq \Theta\left(r^{-2}(n)\right) \leq m \leq n$, and $\Theta\left(r^{-2}(n)\right) \leq k \leq m \leq n$, for which we show that the delay of a random wireless ad hoc network, which we denote by $D_{m,k}(n)$, equals $\Theta\left(k\left(\sqrt{m}r(n)\right)^{-1}\right)$, $\Theta(k)$ and $\Theta\left(r^{-2}(n)\right)$, respectively. Based on this analysis, we obtained the unifying capacity-delay tradeoff for wireless ad hoc networks to be $C_{m,k}(n)D_{m,k}(n) = \Theta(\left(nr^2(n)\right)^{-1})$.

B. Scaling laws of information dissemination modalities in wireless networks with multi-packet reception

We have extended our modelling framework to account for the use of multi-packet reception (MPR) or multi-packet transmission (MPT) [7], [8], [9], ?.

We have obtained the first results on the capacity of ad hoc networks with MPT under different forms of information dissemination, and the first results for the capacity of networks with MPR for dissemination modalities other than unicast traffic. We show that the per source-destination (n, m, k)-cast throughput capacity $C_{m,k}(n)$ of a wireless random ad hoc network with MPT or MPR is tight bounded (upper and lower bounds) by $\Theta\left(T(n)\sqrt{m}/k\right)$, $\Theta(1/k)$ and $\Theta\left(T^2(n)\right)$ w.h.p.[3] when $k \leq m \leq \Theta\left(T^{-2}(n)\right)$, $k \leq \Theta\left(T^{-2}(n)\right) \leq m$, and $\Theta\left(T^{-2}(n)\right) \leq k \leq m$, respectively. In these results, the transceiver range $T(n)$ in MPT or MPR is different from the transmission range $r(n)$ used in the capacity results for networks with point-to-point communication ?. For comparison purposes, we also show the (n, m, k)-cast capacity result for point-to-point communication.

We have also characterized the capacity-delay tradeoff of wireless ad hoc networks with MPT, MPR, and point-to-point communication. We show that MPT and MPR have similar throughput capacity and delay behavior in wireless ad hoc networks. We modelled the behavior of the capacity of an ad hoc network with MPT, MPR, or point-to-point schemes as a function of the (n, m, k)-cast parameters and as a function of the transceiver range. For the minimum value of $T(n) = r(n) \geq \Theta\left(\sqrt{\log n/n}\right)$ for the

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[3] An event occurs with high probability (w.h.p.) if its probability tends to one as n goes to infinity. Θ, Ω and O are the standard order bounds.

transceiver range to guarantee network connectivity ?, the (n,m,k)-cast throughput capacity of MPT or MPR is shown to have a gain of $\Theta(\log n)$ compared to that of point-to-point communication. When $T(n) > \Theta\left(\sqrt{\log n/n}\right)$, the (n,m,k)-cast with MPT or MPR can achieve higher throughput capacity gains than that of point-to-point communication. Furthermore, the capacity-delay tradeoff for MPT or MPR is fundamentally different from point-to-point communications tradeoff.

C. Optimal capacity of wireless networks

We have been able to characterize the optimal interference-free capacity of a wireless network, and also showed how it can be attained in the presence of interference [6].

As we have stated, no prior work has 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. We model 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 define 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 introduce a protocol model in which nodes have the ability to decode correctly multiple packets transmitted concurrently from different nodes, and transmit concurrently multiple packets to different nodes. We refer to this as the multi-packet transmission and reception (MPTR) protocol model.

The task of concurrently maximizing the data-rate for k S-D pairs is an instance of the multi-commodity flow problem. Hence, the *maximum concurrent multi-commodity flow-rate* (MCF) in a RGG equals the interference free capacity (i.e., the optimal capacity) of the network. To derive upper bounds on the optimal network capacity, we have used the fact that the MCF is less than the minimum capacity of a multi-commodity cut for any arbitrary graph. The max-flow min-cut theorem by Ford and Fulkerson establishes that this bound is tight for a single commodity. However, in general, the min-cut does not provide a tight bound on the max-flow [36]. The bound is known to be tight only for special cases [35], and in general can exhibit a gap of $\Theta(\log n)$ [36]. Accordingly, we have established a tight max-flow min-cut theorem for RGGs for the first time, and showed that $\Theta\left(n^2 r^3(n)/k\right)$ is a tight bound on the optimal capacity of a wireless network.

We have generalized prior results by Gupta and Kumar and our own results for wireless networks with MPR, and have shown that the optimal capacity of wireless networks is attainable in the presence of MAI. We deduce tight order bounds for the capacity of random networks under various interference models, and show that the per-commodity capacity, under the protocol model suggested by Gupta and Kumar, exhibits a tight order bound of $\Theta(1/r(n)k)$. This result generalizes Gupta and Kumar's result to any $k \geq \Theta(n)$ S-D pairs. Similarly, we generalize our own prior analysis for the MPR protocol model. We show that, under the MPR model, the per-commodity capacity of the network scales as $\Theta(nr(n)/k)$, which means that it is bounded away from the optimal capacity by a factor of $\Theta\left(nr^2(n)\right)$.

We show that MPTR achieves the optimal capacity of $\Theta\left(n^2 r^3(n)/k\right)$. Hence, MPTR provides a gain of $\Theta\left(nr^2(n)\right)$ over MPR and any previously reported feasible capacity. What is just as striking is that MPTR can achieve the dual objective of increasing capacity and decreasing the transmission range as n increases. This is in stark contrast to the commonly held view that the capacity of multihop wireless networks cannot increase as the number of nodes increases. Indeed, our results demonstrate that the capacity of ad-hoc networks can actually *increase* with n while the communication range tends to zero!

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2.2 The Cubature Kalman Filter: A New Generation of Nonlinear Filters for Sequential State Estimation

PI: Simon Haykin
GSRs: Haran Arasaratnam and Nelson Costa

Problem statement:

> Given a nonlinear dynamic system, estimate the hidden state of the system in a recursive manner by processing a sequence of noisy observations dependent on the state.

The Bayesian filter provides a unifying framework for the optimal solution of this problem, at least in a conceptual sense. Unfortunately, except in a few special cases, the Bayesian filter is not implementable in practice -- hence the need for approximation.

The celebrated Kalman filter is a special case of the Bayesian filter, assuming that the dynamic system is linear and both the dynamic noise and measurement noise are statistically independent processes. Except for this special cases, exact implementation of the Bayesian filter is not computationally feasible. We therefore have to abandon optimality and be content with a sub-optimal nonlinear filtering algorithm that is computationally tractable.

There are two Approaches for approximate nonlinear filtering

1. Direct numerical approximation of the posterior in a local sense, exemplified by the extended Kalman filter.

2. Indirect numerical approximation of the posterior in a global sense, exemplified by particle filters.

The cubature Kalman filter, belongs to the first family. It builds on the cubature rule, (rooted in numerical methods), thereby providing a new nonlinear filtering algorithm that is endowed with the following properties:

1: The cubature Kalman filter (CKF) is a derivative-free on-line sequential-state estimator: It relies on integration for its operation.

2: Approximations of the moment integrals are all linear in the number of adjustable parameters.

3: Computational complexity of the cubature Kalman filter as a whole, grows as n^3, where n is the dimensionality of the state space.

4: The cubature Kalman filter completely preserves second-order information about the state that is contained in the observations.

5: The cubature Kalman filter inherits properties of the linear Kalman filter, including square-root filtering for improved accuracy and reliability.

6: The cubature Kalman filter is the closest known direct approximation to the Bayesian filter, outperforming all other presently known nonlinear filters.

Simply put, the CKF eases the curse-of-dimensionality problem
but, by itself, does not overcome it.

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

PI: Tara Javidi

GSR: Somsak Kittipiyakul

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 cover 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.

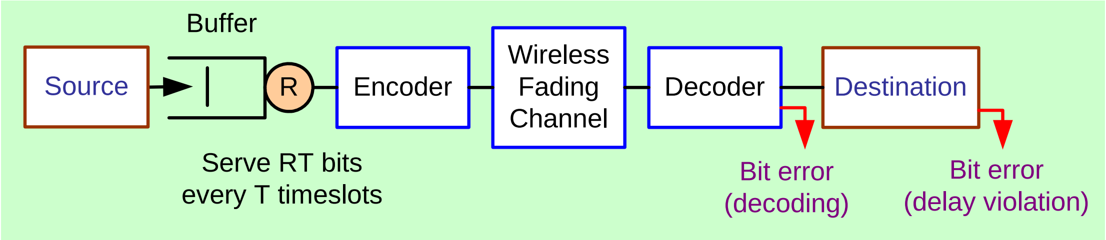

Fig. 1. System model

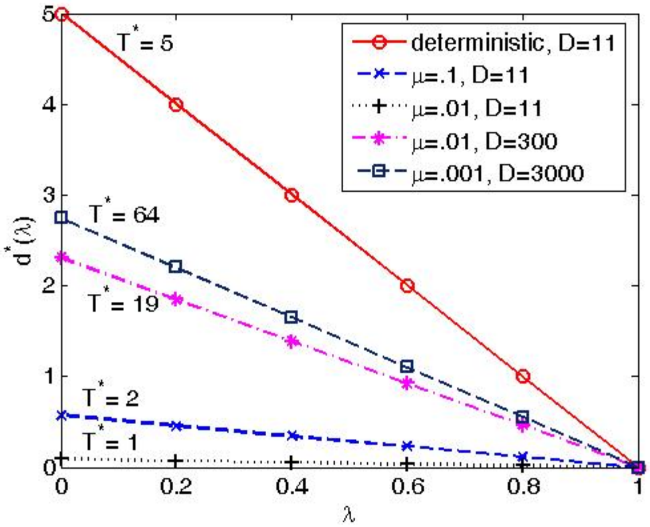

Fig. 2. Exponent of the total error probability for SISO fast fading channel and compound Poisson bit-arrival process

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.

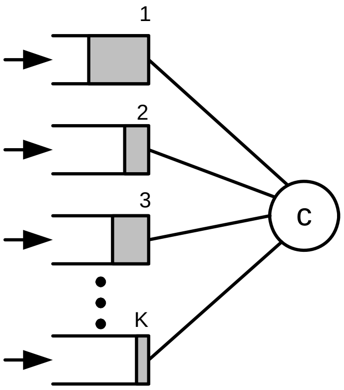

Fig. 3. Multiple-queue, single-server model

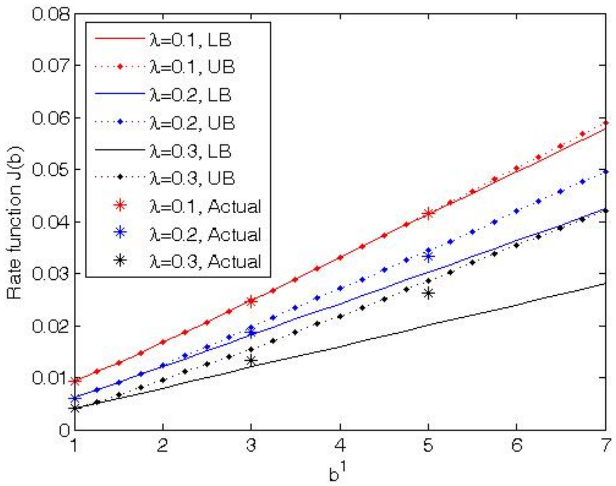

Fig. 4. Example of the actual and the lower and upper bounds of the exponents of the buffer overflow probability where the threshold is (b^1, b^2=1), for compound Poisson bit-arrival process (at various arrival rates) and for two users.

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

PI: Srikanth Krishnamurthy

GSRs: Ece Gelal, Konstantinos Pelechrinis

SUMMARY OF ACCOMPLISHMENTS

During this period we have primarily focused on understanding the performance of MIMO links in practice. Towards this, we have conducted measurements on an 802.11n testbed and have developed an understanding of MIMO STBC behavior. We are in the final phases of the design of our topology control mechanism for facilitating multi-user MIMO communications. We summarize our achievements below.

1. **Studying MIMO's Medium Access Control protocol (802.11n)**: Our goal is to study both (a) the differences between a SISO and a MIMO link in isolation in a realistic environment, and (b) the performance of a MIMO link in the presence of multiple links with the currently employed 802.11 DCF MAC protocol for MIMO communications. We have conducted an extensive set of experiments on our indoor wireless testbed which, is equipped with the RT2860 mini PCI cards that support 2x2 MIMO communications. Our experimental results indicate that the benefits of using MIMO over SISO on an isolated link is not directly applicable in a multi-user scenario. CSMA/CA significantly degrades the performance since it does not take into account the interference cancellation capability of the MIMO PHY layer; the PHY can support multiple simultaneous transmissions and a new MAC design is necessary to exploit this capability.
2. **Constructing High Fidelity Abstractions of MIMO Diversity:** We assess the fidelity of a plurality of MIMO PHY layer abstractions by comparing the performance (with the abstractions) to that with benchmark link-level measurements on our testbed. We also perform multi-hop network simulations that are based (at the physical layer) on the abstractions and the measurements; we compare end-to-end metrics to evaluate the impact of the physical layer abstraction on the performance perceived at the higher layers.
3. **Medium access control for Multi-User MIMO Communications**: Our goal is to utilize the interference cancellation capability using MIMO systems and to increase the spatial reuse in the ad hoc network by allowing multiple concurrent communications in a region. Towards this goal we have designed a scheme that divides communication links into groups; the groups then access the channel in a TDMA fashion. In a given time slot, the

concurrent communications are successful with high probability. We have examined the time complexity of this approach; we also analyze its efficiency in terms of spatial reuse.

1. EXPERIMENTAL STUDY OF A 802.11n REAL TESTBED

The current medium access protocol of MIMO is IEEE 802.11n. 802.11n is essentially an extension of previous 802.11 protocols and it is based on CSMA/CA access policy. MIMO PHY layer provides an opportunity to support more than one concurrent transmission. However, CSMA/CA allows only for one transmission at a time. We perform experiments of both MIMO links in isolation and when operating in conjunction with other MIMO and/or SISO links. Our objective is to understand the implications of using the CSMA/CA protocol for MIMO operations. In a nutshell our main findings can be summarized as follows:

a) MIMO links indeed provide benefits on an isolated link. In order to show this we demonstrate experimental results that are related with the Packet Delivery Ratio (PDR) versus RSSI (Received Signal Strength Indication), connectivity between nodes and energy savings.

b) When MIMO links compete for the medium using 802.11n the achieved throughputs are much lower than the ones advertised by this technology. The main cause for this has to do with the inherent characteristics of CSMA/CA. CSMA/CA provides max-min fairness by providing equal probabilities of accessing the medium to all users. This in turn, causes good MIMO links to suffer in the presence of poor quality links.

c) The channel-bonding feature may lead to even higher performance degradations due to increased levels of interference.

In the following we elaborate on our experimental assessments.

A. Performance of an Isolated MIMO Link:

In order to show the benefits of a MIMO link in isolation over the corresponding SISO link we perform the following set of experiments:

i) We measure the PDR as a function of RSSI on the same links when using MIMO and SISO.

ii) We measure the number of feasible links (out of the total number of possible links) on our testbed when nodes are using MIMO and when they are using SISO.

iii) We measure the transmission power needed for achieving the same throughput on a link when using MIMO and when using SISO.

Our results are presented in figures 1, 2 and 3. As we observe in Figure 1, MIMO achieves better performance in terms of PDR. We set the transmission rate to fixed values (54Mbps for SISO and 65Mbps for MIMO) and we measure the PDR with different RSSI values. We are using high transmission rates since we expect that the performance of SISO will exhibit high variations in these scenarios. What we observe is that the performance benefits with MIMO are significant. The performance is much more stable and predictable. For a fixed RSSI, MIMO achieves higher PDR.

We are also interested in examining the percentage of the links on our testbed that are feasible with SISO and MIMO. There are 21 potential links on our testbed (since we have 7 MIMO nodes). In order to examine the feasibility of a link the sender tranmits “echo requests” to all the other nodes with the maximum transmission power. Upon not receiving “echo reply” messages we conclude that the corresponding link is not feasible. As we notice in figure 2, all the links on our testbed are feasible with MIMO while 14% of the links are not feasible with SISO. Note here that our testbed consists of 7 nodes only. We expect that in more dense deployments the benefits from using MIMO will be even larger.

Finally, we seek to examine whether the use of MIMO can save energy (by using lower transmission power) in order to achieve the same throughput on a link as with SISO. We pick a target throughput on a link (that it is achievable with SISO) and we measure the transmission power we set on the wireless NIC when operates at the MIMO and at the SISO modes, respectively. The results are presented in figure 3. We observe that the transmission power we need to set with the MIMO mode of operation is much lower than the corresponding SISO mode.

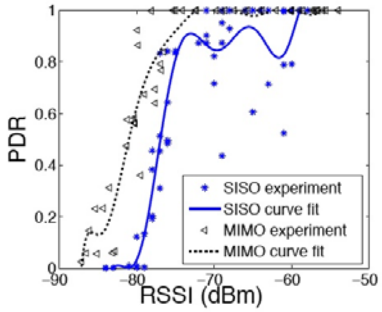

Figure 1: For fixed RSSI, PDR is always higher with MIMO

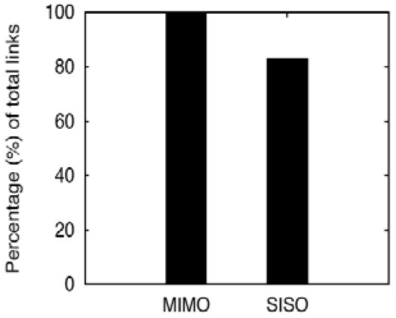

Figure 2: The number of feasible links with MIMO is much larger

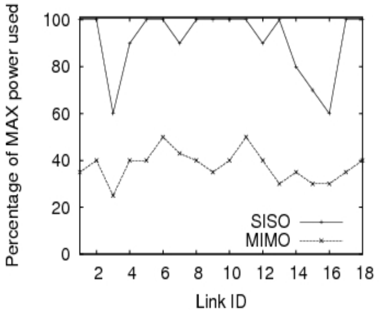

Figure 3: MIMO requires less transmission power to achieve the same throughput as SISO

B. Performance in multi-user setting:

In order to examine the behavior of a MIMO link in multi user setting we performed the following experiments:

i) We activate simultaneously two links (one is always MIMO) that compete with each other and we observe the corresponding performance.

ii) We use channel bonding on a MIMO link and we quantify the performance degradation in terms of throughput when another link is active on a different channel (e.g. channel bonding MIMO link on channel 6 and the interfering link on channel 1 or 11).

Our results are presented in figures 4-7.

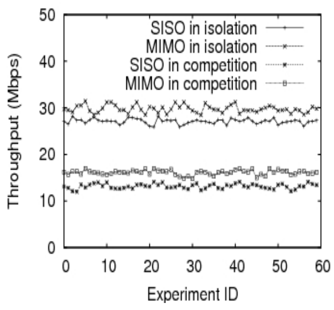

Figure 4: Interaction between a "good" MIMO link and a "good" SISO link

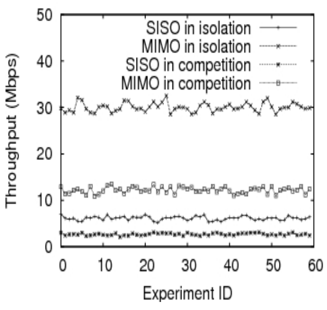

Figure 5:Interaction between a "good" MIMO link and a "bad" SISO link

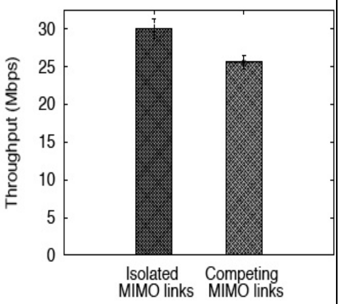

Figure 6: Interaction between two "good" MIMO links

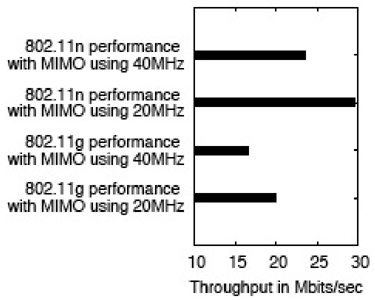

Figure 7: Channel bonding can degrade performance due to higher adjacent channel interference

In figures 4-6 we present the results of our experiments when a MIMO link competes for the medium with (i) a high quality SISO link, (ii) a low quality SISO link and (iii) a MIMO link. In all cases we use the rate adaptation algorithm of our cards. When we refer to a SISO link as high quality we mean that the achievable throughput on it is more than 20Mbps, while a low quality link is one that cannot achieve more than 8Mbps. We observe that in all cases the performance is significantly degraded for the MIMO link as compared to the isolated case. We have to note here that when the MIMO link is in isolation we are able to observe throughputs at the order of 31-33 Mbps (higher than the corresponding maximum achievable throughput with SISO). However the machines we are using for our experiments (Soekris net4826) are not powerful enough and as a result we cannot explicitly observe the throughputs advertised from this technology. The limitation has to do with the processing capabilities of these machines, which is not enough to process the packets as fast as they are sent and this results in many losses in the kernel space. However we are currently in the process of building a new MIMO testbed in order to be able to observe the correct throughput gains (with new hardware). In any case the degradation due to the presence of another competing link is obvious. The DCF function of 802.11n does not effectively exploit the capabilities of MIMO at the PHY layer.

In the following we conduct experiments in order to see the effect of channel bonding. Channel bonding is a technique that combines two or more adjacent channels in order to create a wider one that can sustain higher transmission rates. However this can impose higher levels of interference even from links that operate on different bands. In order to see if this is indeed true we used a MIMO link on channel X ($X \in \{1,6,11\}$) which employs channel bonding (40 MHz bandwidth) and we activate (concurrently) another SISO link (20 MHz bandwidth) on channel Y, with $Y \in \{1,6,11\}$ and $|X-Y|=5$; we seek to measure the corresponding throughput. Our experimental results are presented in figures 7. As we notice from this figure when we employ channel bonding the interference from/to the adjacent channel is high enough to degrade the performance on both links. We also observed using the same experimental set up (but when Y was such that $|X-Y|=10$) that the interference between the two links is negligible and there is no performance degradation.

2. EVALUATING THE ABSTRACTIONS OF MIMO DIVERSITY

We seek to evaluate the fidelity of various *abstractions* of the MIMO gain due to spatial diversity (*diversity gain*). An abstraction characterizes MIMO diversity gain either in terms of an SNR benefit or in terms of a mapping between the SNR and the achievable BER (or PER, *i.e.*, packet error rate); this is a high-level representation of the PHY layer behavior. Its use is inevitable, since a full-fledged simulation with both PHY and the higher layers can be prohibitive in terms of simulation time and memory. Thus, a trade-off emerges between the complexity of an abstraction and the conformance of the characterization to the “real” behaviors. The more detailed the abstraction, the better the fidelity.

Previously, higher layer protocols that were designed to exploit MIMO spatial diversity were evaluated with simplistic abstractions. These abstractions assumed that the PHY layer gains are directly exported to the higher layers. In our work, we show that this may not always be the case. We identify the physical layer components that are neglected or are incorrectly specified by these abstractions. These components include the error correction coding and modulation schemes that are used with space-time codes, and the channel characteristics. A high-fidelity link abstraction (in terms of conformance to the practical system) considers the modulation and coding schemes that are used in the 802.11g/n specification, and a channel model that represents the propagation characteristics in the practical deployments. We progressively incorporate these components in the MIMO (and SISO) abstraction, and evaluate their impact on both the link level and the higher level behavior.

A. Building New Abstractions:

First, we have built new, higher-fidelity MIMO link abstractions that characterize packet success probability on an 802.11g/n link at a certain transmission rate. In order to build these abstractions, we first re-visited the physical layer components of the IEEE 802.11g/n communication links. We implemented on MATLAB, a transmitter-receiver system that incorporates these components, and we performed bit-level simulations for various noise powers. From this we obtained the probability of reception success (in terms of bit error rate or packet error rate) as a function of the SNR. Below is a list of the abstractions we considered in this project:

i) A-1: This is the most commonly used abstraction in prior studies. It simply assumes that diversity gain is a constant decrease in the required SNR for achieving a target BER at a certain rate. This decrease is quantified for a MIMO system using Alamouti codes with BPSK, Q-PSK and 8-PSK modulation schemes on a quasi-static flat Rayleigh fading channel. (Error correction codes are not considered.) However, diversity gain must be quantified as a function of the reception SNR. The next abstraction addresses this feature.

ii) A-2: The system in this abstraction is similar to the one used in A-1; however, diversity gain is determined based on the SNR upon reception, as opposed to assuming all MIMO links achieve the same constant diversity gain. The BER in the received packet is determined based on its SNR; this relation is characterized by the curves in Figure 8.

iii) A-3 (FF): This abstraction specifies the PHY system differently from the previous two abstractions. It incorporates the error correction codes and the modulation schemes that are specified in the IEEE 802.11g/n standards. In particular, the system uses 4-, 16, and 64-QAM modulation schemes with R=3/4 punctured convolutional codes, and a Viterbi decoder is employed at the receiver for decoding. "*FF*" refers to a fast Rayleigh fading channel. Fast fading channel models were also used in the previous two abstractions; in this channel model it is assumed that the fading characteristics change *per-bit* in the transmitted data packet. The next abstraction incorporates a Slow Fading channel model; this is motivated by our observations from testbed measurements, which will be described later in the report.

iv) A-3 (SF): The only difference of this abstraction from A-3 (FF) is the incorporated channel model. In this abstraction, the Rayleigh fading is time-correlated; in other words, the fade lasts for the duration of a packet.

v) A-3P (FF) and A-3P (SF): All four abstractions *(i)-(iv)* characterized the link behavior in terms of the SNR-BER relation. However, in practice evaluation of link success is performed based on packet delivery ratios (or in terms of a complimentary metric, packet error rate). Thus, we derive from A-3(FF) and A-3(SF) new abstractions that quantify the PER for a given SNR. These relations are generated for 1500-byte packets; this is the size of packets that are used in our testbed measurements, which we describe later.

Figures 8-11 depict the link abstractions described above. In these figures, diversity gain is observed in the change of slope and range of the BER (or PER) vs. SNR curves on SISO and MIMO communications.

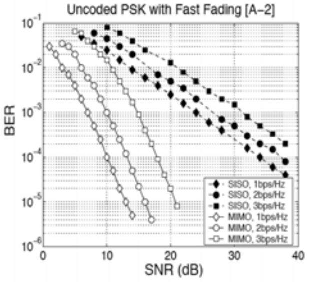

Figure 8: BER vs. SNR on MIMO and SISO links with Abstraction A-2

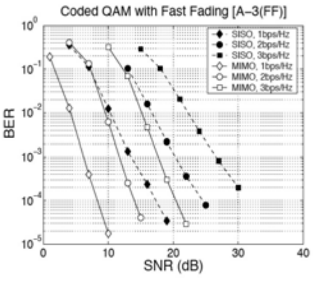

Figure 9: BER vs. SNR on MIMO and SISO links with Abstraction A-3 (FF)

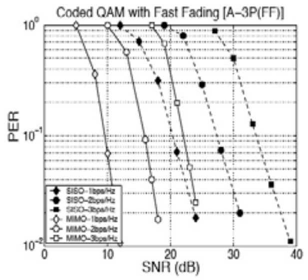

Figure 10: PER vs. SNR on MIMO and SISO links with Abstraction A-3P (FF)

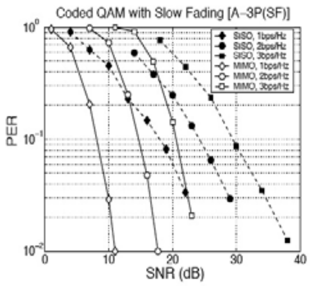

Figure 11: PER vs. SNR on MIMO and SISO links with Abstraction A-3P (SF)

B. Link-Level Measurements on 802.11g/n Links:

In order to evaluate the created abstractions in terms of their fidelity to the practical system, we measured packet delivery statistics on 802.11g/n links in our testbed. We use a set of 15 links; this set contains both line-of-sight (LoS) and non-line-of-sight (NLoS) links. The same set of links is used in SISO (802.11g) and MIMO (802.11n) modes. By repeating the experiments with different transmission power levels we obtain a range of SNR values and the average PER at each SNR. We repeat the measurements at 1bps/Hz, 2bps/Hz and 3bps/Hz bit rates; these rates correspond to 18, 36, 54 Mbps rates offered with the 802.11g standard, and to 19.5, 39, 58.5 Mbps with 802.11n. The SNR-PER relation observed in our measurements is shown in Figure 13. It is seen in the figure that the most significant diversity gain is observed at the highest rate of 3bps/Hz.

As described before, we have studied *bit-level* and *packet-level* abstractions (*i.e.*, abstractions that characterize the success probability of a bit or a packet for a given SNR). In order to understand the relation between these behaviors, we examine the occurrence of bit errors in a packet, using a different set of measurements. In these measurements, in order to collect all corrupted packets (including the ones that fail the CRC check and are dropped before the MAC layer), we disable the CRC check in the wireless card. Our observations suggest that bit errors in practice happen in bursts. We show the distribution of the bit error burst length in Figure 12.

Finally, a comparison of the most advanced abstraction we considered (A-3P(SF) in Figure 11) and the link behavior observed in measurements (Figure 13) reveals that there are still subtle differences between the SNR-PER curves belonging to each system (*e.g.* the curves from practice have a sharper slope). We believe that this is due to the use of OFDM in the practical system.

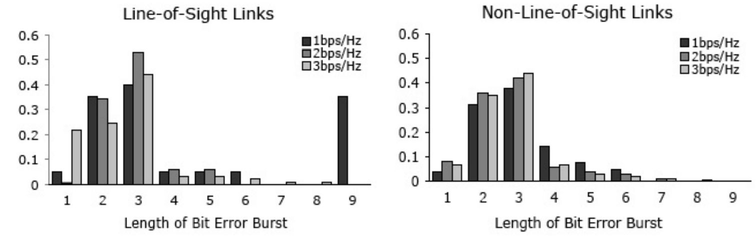

Figure 12: The distribution of burst length on Line-of-Sight and Non-Line-of-Sight links.

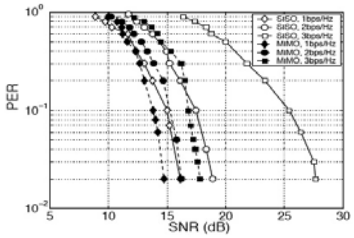

Figure 13: PER vs. SNR on MIMO and SISO links observed in testbed measurements.

C. End-To-End Performance Evaluation on Multi-Hop Networks:

Having observed the link behavior projected with each abstraction, we perform network simulations using each abstraction at the physical layer; the goal is to observe the impact of the physical layer abstraction on higher layer performance metrics. Using OPNET, we simulate ad hoc networks with various topologies and channel conditions. In figures 14-16 we show how end-to-end (E2E) behaviors compare with each other, with the different abstractions. Figure 14 shows the ratio of E2E throughputs in the network using SISO versus MIMO communications. It is seen that the bit-level abstractions over-estimate the performance improvement with MIMO over SISO. We also see that the E2E behavior with the most advanced abstraction we considered (A-3P(SF)) conforms well with that of the Measurement-Driven Abstraction (MDA)[4]. In Figures 15, 16 we show the CDF of this ratio at the lowest and highest rates considered. We again observe that A-3P(SF) has satisfactory fidelity to MDA.

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[4] MDA is an abstraction created based on our link layer measurements.

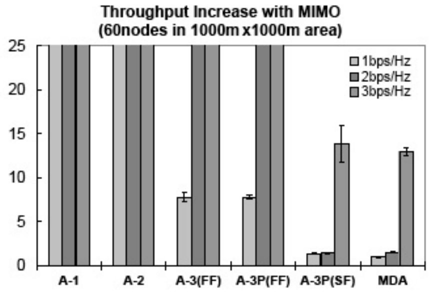


Figure 14: Simplistic abstractions overestimate achievable performance improvement with MIMO.

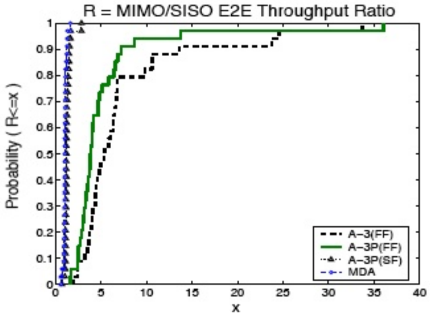


Figure 15: Cumulative distribution of per-flow throughput ratio on MIMO vs SISO links (at 1bps/Hz)

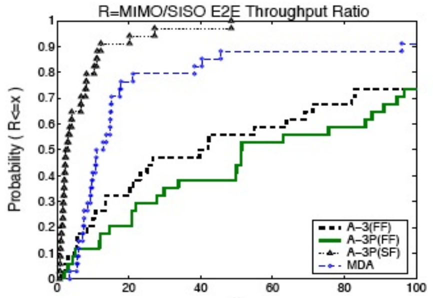


Figure 16: Cumulative distribution of per-flow throughput ratio on MIMO vs SISO links (at 3bps/Hz)

3. 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 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 ad hoc network.

A. Motivation for Topology Control in a MIMO Ad Hoc Network:

First, we briefly re-visit the physical layer system used in our model. Transmissions are performed using a single antenna; the choice of the antenna element is dictated by the feedback of channel state from the receiver node. Nodes receive using all antenna elements; thus, they receive a superimposed signal comprising the transmitted streams. Upon reception, nodes use *Successive Interference Cancellation (SIC)* to detect and remove strong interference components from this signal and then they detect their target data stream.

The constraint of the above-mentioned system is that 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 interference is determined based on its SINR, which itself depends on the strength of all signals in the received compound signal. To ensure that SIC can successfully be used at the receivers to remove unwanted interference, there is need for a higher-level mechanism that regulates which links can be active at the same time. This mechanism would allow concurrent communications on only the links whose receivers *can* use SIC to eliminate strong interference. In other words, the mechanism should group the communication links such that in each group links can co-exist.

In a multi-hop network, every transmitter needs to acquire medium access as frequently as possible, so that delay is kept low. To provide frequent channel access to all links, the mechanism we design for grouping the links must create as few groups as possible (this is because links in different groups cannot be active at the same time due to physical layer constraints). In last year's report, we have explained that this tradeoff can be formulated as a *set cover problem*. In this problem, the goal is to cover all elements of a larger set, using as few smaller sets as possible. We have also discussed that the *set cover* problem is NP-hard, and that it can be reduced to our problem in polynomial time; thus, our problem is NP-hard.

We design a greedy heuristic algorithm to solve our problem. (Note that we cannot use the existing approximation algorithms for the Set Cover problem, because these algorithms assume that the *sets* are defined. In our problem, defining the feasible link sets is not straightforward.)

B. Problem Formulation:

We divide *E*, the set of *communication links*[5] in the given ad hoc network into as few groups as possible, such that in each group the links can coexist without obstructing each other's reception. The grouping is based on the mean reception powers at the nodes. Note that at a receiver, the mean power from a transmitter is inversely proportional to the distance from this transmitter and directly proportional to the square of a Rayleigh distributed random variable representing the instantaneous multipath fading effect on the transmitted signal. We assume that the mean of this random variable is the same on all links; we thus perform grouping based on inter-node distances.

In every group, following two criteria must be met for every ordered pair (*T*,*R*) in order to ensure that the communication between them is successful.

1. At the receiver *R* of a link *(T,R)*, the **total power** of the *weaker interference* terms must not exceed the power from the transmitter *T* of this link, scaled by 1/β. (β: SINR threshold for successful reception on a link.) Here "weaker interference terms" refers to the concurrent transmitters that are farther (from the receiver) than transmitter of this link. Equation (1) below formulates this constraint. In the equation, P_{TR} denotes the power received at node *R* when node *T* transmits.

$$\sum_{X\in V: P_{XR}<P_{TR}} P_{XR} \le \frac{P_{TR}}{\beta} \quad (P_{XR} < P_{TR} \text{ when } d_{TR} > d_{XR},\ d_{XR} \text{ is the distance between nodes X and R}).$$

$$\sum_{X\in V: d_{XR}>d_{TR}} \frac{1}{d_{XR}^{\alpha}} \le \frac{1}{d_{TR}^{\alpha}\cdot\beta} \qquad (1)$$

2. Each of the *stronger interference* components that affect a link *(T,R)* (i.e., from every concurrent transmitter *Y* such that link *(Y,R)* ∈ E and $P_{YR}>P_{TR}$) must satisfy*:*

---

[5] For a node pair *T*, *R* in the network, if the reception power (or SNR) at *R* when *T* transmits is greater than a threshold γ, then there is a directional communication link from *T* to *R*, and the grouping needs to ensure that link *(T,R)* can operate successfully in its group. For two nodes *T′*,*R′* such that the power or SNR does not exceed a specified threshold, the directional link (*T′*,*R′*) will not be used for data communication, and the interference at *R′* (when *T′* transmits) is negligible.

$$\forall\, Y \in V : P_{YR} > P_{TR}\ , \quad P_{YR} \geq P_{TR} \cdot (\beta+1)^k \ \ , \ \ k \in [1, A-1].$$

$$\text{i.e., if } \ d_{YR} < d_{TR}\ \text{, then} \quad d_{YR} \leq \frac{d_{TR}}{(\beta+1)^{k/\alpha}} \qquad (2)$$

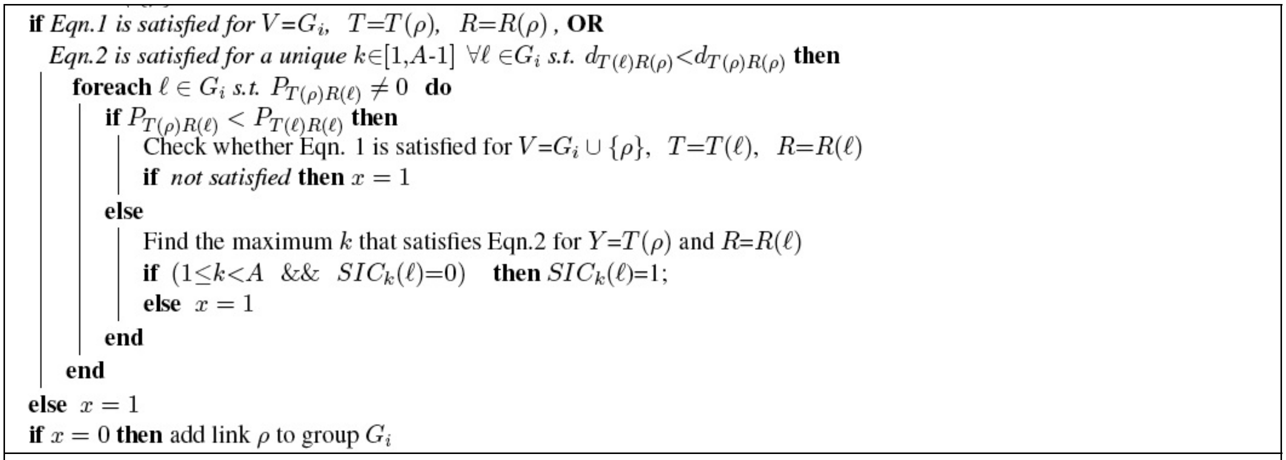
Eqn. (2) follows from Eqn. (3) below. In absence of strong interference, Eqn. (3) must be satisfied for successful communication on link *(T,R)*. However, in existence of a strong interfering transmitter *Y*, Eqn. (4) must **first** be satisfied, so that *Y*'s signal is correctly detected and removed from the compound signal. By writing the interference term *I* (from Eqn. (3)) in terms of P_{TR} and substituting in Eqn. (4), we obtain Eqn. (2) for *k*=1. If there is a second strongly interfering transmitter present, then one can iteratively proceed similarly to obtain Eqn. (2) for *k*=2, and so on.

$$\frac{P_{TR}}{N + \underbrace{\sum_{L \neq T} P_{LR}}_{I}} > \beta \qquad (3)$$

$$\frac{P_{YR}}{N + P_{TR} + \underbrace{\sum_{L \neq \{T,Y\}} P_{LR}}_{I}} > \beta \qquad (4)$$

C. Greedy Heuristic for Grouping the Links:

Our greedy approach visits all links, iterating by picking the longest link in the network, using equations (1) and (2) to check whether it can coexist with existing links in the group, adding this link to the same group if positive, proceeding to the next link otherwise. This approach is demonstrated below.



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if Eqn.1 is satisfied for $V{=}G_i$,  $T{=}T(\rho)$,  $R{=}R(\rho)$ , OR
  Eqn.2 is satisfied for a unique $k \in [1,A\text{-}1]$ $\forall \ell \in G_i$ s.t. $d_{T(\ell)R(\rho)} < d_{T(\rho)R(\rho)}$ then
    foreach $\ell \in G_i$ s.t. $P_{T(\rho)R(\ell)} \neq 0$ do
        if $P_{T(\rho)R(\ell)} < P_{T(\ell)R(\ell)}$ then
            Check whether Eqn. 1 is satisfied for $V{=}G_i \cup \{\rho\}$,  $T{=}T(\ell)$,  $R{=}R(\ell)$
            if not satisfied then $x = 1$
        else
            Find the maximum $k$ that satisfies Eqn.2 for $Y{=}T(\rho)$ and $R{=}R(\ell)$
            if ($1 \leq k < A$ && $SIC_k(\ell){=}0$)  then $SIC_k(\ell){=}1$;
            else $x = 1$
        end
    end
else $x = 1$
if $x = 0$ then add link $\rho$ to group $G_i$
```

Figure 17: Demonstrating how every link is visited and evaluated before the decision whether it must be added to a group.

We show that this approach has a complexity of O(|V||*E*|I) where I is the number of groups that are formed, and in the worst case it forms O (g^{α}) times more groups than could be formed with an optimal algorithm; α is the path loss exponent and g is the maximum ratio (among all nodes) of a node’s distance with its farthest neighbor considered for addition to this group, to the distance with the farthest neighbor that is added to this group.

2.5 Space-Time Power Scheduling - From Wireless Intranet to Wireless Internet

PI: Yingbo Hua

Students: Yi Huang, Ting Kong, and Yuan Yu

Summary of Achievements:

We have researched on the space-time power scheduling issues of ad hoc wireless networks. In [J1], we have developed a distributed and cooperative link scheduling (DCLS) algorithm for large-scale ad hoc networks. Under the DCLS algorithm, each participating link in a large network chooses a time (or frequency) slot for data transmission after it follows an iterative, distributed and cooperative interference calibration process. This process involves exchanges of small control packets between neighboring links until convergence. The DCLS algorithm can yield a desired spacing between concurrent co-channel data transmissions in a large network, and hence produce a high throughput of intranet traffic. The DCLS algorithm appears to be the first of its kind.

In [J2], we have developed a space-time power scheduling scheme for multiple distributed MIMO links where the channel state information is unknown to transmitters. In the absence of channel state information at source nodes, the ergodic channel capacity is achievable (approximately) via temporal coding over multiple coherence intervals. Applying the ergodic channel capacity and the projected gradient search method, we have evaluated the throughput of distributed MIMO links and established a major advantage of space-time power scheduling over space-only power scheduling. Before our contribution, the space-only power scheduling approach had dominated the discussions in the literature on distributed MIMO links.

In [J3], we have further established the importance of space-time power scheduling by considering the fairness and quality-of-service issues. Instead of maximizing the sum throughput of all MIMO links, we have considered proportional-fair criterion and rate-constrained power minimization problems. Although the problem is non-convex, the gradient projection method has consistently produced better results than all other existing schemes. The work in [J5] was the first of our series on distributed MIMO links, where we have firmly established that space-time power scheduling is still highly beneficial even if the channel state information remains constant. In [C3], the cooperative space-time power scheduling method is shown to have a much higher throughput than a game theory based algorithm.

In [J4], we have studied an opportunistic synchronous array method (O-SAM) as a medium access control protocol for a large-scale wireless network of routers. We have shown that the network throughput can be significantly improved if each receiver selects from its neighboring nodes the best transmitter. We have also shown that the packet spectral efficiency, among several other key parameters, is very important for network throughput. The packet spectral efficiency is governed by symbol constellation size and coding redundancy. This study provides an important guideline for designing transceivers to be deployed in ad hoc wireless networks.

In [J6] and [C2], we have provided a further development of the synchronous array method (SAM) and investigated the impact of traffic load on network throughput. Among the new versions of SAM, we have developed a distributed SAM, which schedules data transmissions via a randomized, localized and coordinated access. The D-SAM differs from the DCLS algorithm in that the former does not need to perform any iterative process between nodes and any node can be a potential receiver within each time frame. The D-SAM captures an essence of the MSH-DSCH proposed in IEEE 802.16. Our study shows that if the network is fully loaded and the network topology is regular, the best spacing between a receiver and its nearest interfering transmitting node should be about two hops, which supports the rule used in MSH-DSCH. However, for partially loaded network, the situation is different. By examining ALOHA, we have shown that if the traffic is under 1% of the full load, the transmissions between nearest neighbors are no longer the most efficient. Yet, this number also indicates that unless the traffic load is very low, transmissions between nearest neighbors are the most efficient for intra-network traffic.

All the work shown above is about wireless intranet, which is concerned with the intra-network traffic in a large-scale wireless network. Yet, the inter-network traffic that goes through gateways to connect to the Internet is also important. We refer to this problem as wireless internet. To some degree, all of our previous studies are applicable to wireless internet. However, a unique problem with wireless internet is the fairness of the requirements imposed onto all nodes. If all nodes in a large network are required to communicate directly with an access point, the far away nodes are severely disadvantaged. If all nodes are required to relay their neighbors' data, the nodes nearest to the access point are severely disadvantaged. How to best balance the traffic load among all nodes is a unique issue for wireless internet. Our preliminary study has suggested that a good traffic balance is possible by splitting the flows between each transmitter and its receivers. The physical layer technique known as successive interference cancellation (SIC) is especially useful for this networking purpose. For a network of three nodes (including the access point), an analytical solution has been found. For a larger network, efficient optimization algorithms are currently under investigation. Like SIC at a receiver, the dirty paper coding (DPC) at a transmitter is also applicable for splitting flows from each transmitter. But our preliminary results have shown that DPC is not as efficient as SIC for traffic balancing in wireless internet.

Research Plan for the Coming Year:

We will continue our investigation of space-time power scheduling for tactical wireless internet.

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

PI: Prof. Michele Zorzi

SUMMARY OF ACCOMPLISHMENTS:

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

Introduction

During the past year, Dr. Zorzi's research efforts have dealt with a variety of issues at the PHY, MAC and routing protocol layers. In particular, three main areas have been studied:

1) The integration of MIMO signal processing and Network Coding has been explored for the first time, leading to important performance improvements. This research line has established fundamental parallels between MIMO and Network Coding and has shed some light on limits of classic Network Coding for wireless networks. Starting from this point, novel rate adaptation techniques that can trade off rate for coding and diversity gain have been developed. Moreover, cooperative protocols based on these ideas have been successfully developed.
2) The effects of imperfect channel estimation on MAC protocols for MIMO ad hoc networks have been carefully modeled and evaluated, highlighting some relevant tradeoffs that arise among different network metrics, mainly throughput, efficiency, delivery delay and success ratio
3) The previously proposed cooperative MAC protocol has been integrated with a routing scheme, in which paths are updated based on link conditions, and PHY cooperation and relay election are dynamically selected in an opportunistic fashion. The behavior of the scheme in terms of path characterization as well as end-to-end performance has been studied.

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 a more extensive set of results.

Integrating MIMO and Network Coding

Network Coding (NC) is a decade-old technique that enables to achieve significant performance improvements in wired, multihop networks. Its main feature is to allow intermediate nodes not only to forward received packets, but also to transmit functions of these packets. Any node can recover the original packets (called Information Units) as long as a sufficient number of their combinations (called Coded Packets) has been received. If the Coded Packets are linear combinations of a set of Information Units, the receiver has to solve a linear system to decode the original packets:

$$\mathbf{s} = \mathbf{G}\mathbf{x} \tag{1}$$

This mechanism was proved to be very efficient for networks whose links are error-free, where it achieves the cut-set upper bound on network throughput. However, wireless communications by no means satisfy this property, and network coding in wireless environments does yield some improvement, but they are not yet a match for the wired counterpart. One of the key problems is that conventional NC can use only packets that have been correctly decoded by PHY. However, if too many Coded Packets are lost, (1) may be underdetermined, in which case decoding becomes impossible.

On the other hand, a similar problem to (1) is solved in MIMO systems: in a V-BLAST based communication scheme, the receiver tries to decode a vector of transmitted symbols out of a vector of received samples, and these two quantities are linked by means of a matrix. However, one of the critical features of MIMO is its resilience to channel fading. The aim of this research has been to draw a parallel between MIMO detection and NC decoding, with the final goal of improving NC robustness to wireless channel impairments. This goal is supported by Eq. (1), which suggests that since every Information Unit is embedded in potentially all Coded Packet, a high diversity order may be achievable in this setting, because every received packet has information about the original frames.

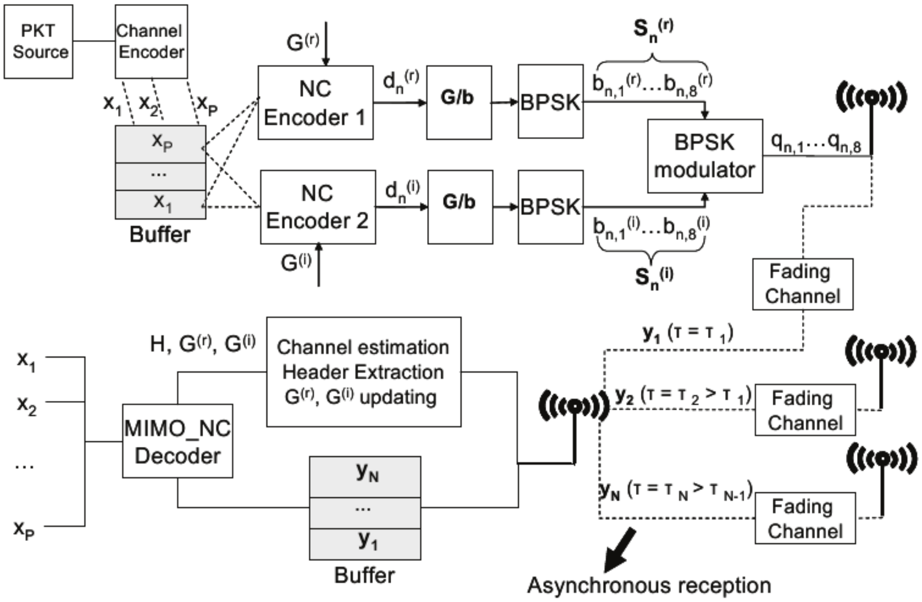

Figure 1: MIMO_NC architecture.

The first and main product of this research has been the creation of a PHY technique called MIMO_NC based on MIMO signal processing for the reliable recovery of information in wireless NC [C1]. Figure 1 shows the overall architecture. At the transmitters, new Coded Packets are created as linear combinations of correctly decoded Information Units. All these packets are expressed by symbols in the Galois field $GF(2^B)$, the linear combinations are performed within this finite field, and each Coded Packet includes in its header the coefficients of the linear combination. These frames are turned into BPSK symbols and sent on the wireless channel and each receiver stores the received soft samples in a buffer. This buffer gathers all packets that refer to the same generation, i.e., the same set of Information Units. Let us call the generation size *P* and the number of received Coded Packets *N*. The *n*th Coded Packet is a linear combination of the *P* Information Units according to the coefficients g_{1n}, g_{2n}, …, g_{Pn}. This

Coded Packet is subject to Rayleigh fading (flat fading is assumed) and the complex channel coefficient is denoted as h_n. The resulting system is:

$$\begin{pmatrix} y_{11} \\ \ldots \\ y_{NB} \end{pmatrix} = \begin{pmatrix} h_1 & \ldots & 0 \\ \ldots & \ldots & \ldots \\ 0 & \ldots & h_N \end{pmatrix} \begin{pmatrix} g_{11} & \ldots & g_{P1} \\ \ldots & \ldots & \ldots \\ g_{N1} & \ldots & g_{NP} \end{pmatrix} \begin{pmatrix} x_1 \\ \ldots \\ x_P \end{pmatrix} + \begin{pmatrix} n_{11} \\ \ldots \\ n_{NB} \end{pmatrix} \tag{2}$$

which can also be written as:

$$\mathbf{Y} = \mathbf{HGx} + \mathbf{n} \tag{3}$$

where $\mathbf{H} = diag(\mathbf{H}_1, \cdots, \mathbf{H}_n)$, $\mathbf{H}_n$ is the $B \times B$ identity matrix multiplied by h_n, $\mathbf{G}$ is the matrix of Galois numbers used to combine the Information Units, $\mathbf{x} = (x_1, \cdots x_P)$ and x_p is a symbol of the *p*-th Information Unit. Note that in MIMO the mixing of transmitted symbols is due to the propagation through the wireless channel. In NC this mixing is due to the combination of different Information Units due to the $\mathbf{G}$ matrix. This has a significant impact on the achievable diversity, as will be later shown. Also note that all nodes are assumed to be equipped with just one antenna, while an antenna array is useful but not necessary. The MIMO feature of MIMO_NC (and the consequent need for MIMO signal processing at the receiver) comes from the fact that multiple inputs (the original Information Units) are coded together by the NC matrix $\mathbf{G}$ to create the multiple outputs (the Coded Packets) that further result in multiple received packets at the destinations.

MIMO_NC performs Maximum Likelihood detection on (3). This problem can be efficiently solved by means of the Sphere Decoding algorithm, which is able to significantly reduce the computationally complexity. Eq. (3) can be written as:

$$\mathbf{Y} = \mathbf{HLUx} + \mathbf{n} = \mathbf{HLz} + \mathbf{n} \tag{4}$$

where $\mathbf{LU}$ is the lower upper decomposition of $\mathbf{G}$ and $\mathbf{z} = (z_1, \cdots, z_P)$ is $\mathbf{Ux}$. The system $\mathbf{Y} = \mathbf{HLz} + \mathbf{n}$ can be efficiently solved by Sphere Decoding, since the first equation depends only on z_1, the second only on z_1, z_2, and the *p*-th equation depends only on the first *p* elements of $\mathbf{z}$. Hence, this enables the recursive solution of the system. Once the value of $\mathbf{z}$ that minimizes $\|\mathbf{Y} - \mathbf{HLz}\|^2$ is found, $\mathbf{x}$ can be computed by back-substitution from $\mathbf{z} = \mathbf{Ux}$.

The main advantage of MIMO_NC over conventional NC is the possibility to use packets that would be discarded by NC. For instance, redundant packets (that do not increase the rank of G) or corrupted frames are not employed by traditional NC, while they can be used by MIMO_NC to improve the success probability of the detection phase.

One of the main results of this research has been the evaluation of some fundamental limits of NC and MIMO_NC. In particular, it has been possible to explicitly compute the diversity order of the packet error probability on receiving *N* Coded Packets which are combinations of *P* Information Units. In both cases, the diversity order is *N*-*P*+1. This is due to the fact that $\mathbf{G}$'s elements are chosen in the same Galois field as the symbols of the Information Units. Instead, in a MIMO system, the channel matrix's elements are complex Gaussian random variables. This turns out to be the key factor to achieve full diversity N when Maximum Likelihood detection is used for V-BLAST.

In order to overcome this problem, a modified version of MIMO_NC, called Super MIMO_NC, has been devised [C2]. The key property of Super MIMO_NC is the modification of both encoding and decoding phases with respect to standard NC, while MIMO_NC modifies only the latter. In Super MIMO_NC, each Coded Packet includes two linear combinations of the Information Units, rather than only one. This increases the achievable diversity order from *N*-*P*+1 to $\mathrm{N} - \lfloor (\mathrm{P}-1)/2 \rfloor$. Hence, Super MIMO_NC trades off rate for diversity. Moreover, in a third version of MIMO_NC, called Adaptive MIMO_NC, the number of linear combinations per Coded Packet is a function of the SINRs of the received packets. This enables to adapt the level of redundancy to the channel state, and hence achieve different degrees of the diversity-rate tradeoff.

Two sample results are given in Figures 2 and 3. The former tests the performance of all these systems in the "Star topology," where N nodes are deployed around a central terminal, and all these N nodes have the same set of P Information Units. Each node sends to the central receiver one or two linear combinations of the Information Units, according to the adopted wireless scheme. The metric of interest is the probability that the receiver may correctly recover all the original packets. Figure 2 shows the performance for different protocols against the average SNR between one of the N external nodes and the central terminal. First of all, the diversity order is N-P+1 as predicted. Moreover, the larger the gap between N and P, the larger the gain of MIMO_NC and Super MIMO_NC over standard NC.

Moreover, another interesting scenario is a network composed by a set of randomly located nodes, where some terminals must transfer their data to everyone else. Figure 3 shows the probability that all nodes receive all packets in a 10 node network with two sources. As is clear, standard NC is significantly outperformed by MIMO_NC based protocols. The ability of MIMO_NC to withstand losses due to channel fading leads to a gain of over 4 dB against standard NC, and hence MIMO_NC allows much higher reliability for broadcast traffic. This work has been summarized into a submitted journal paper [J1].

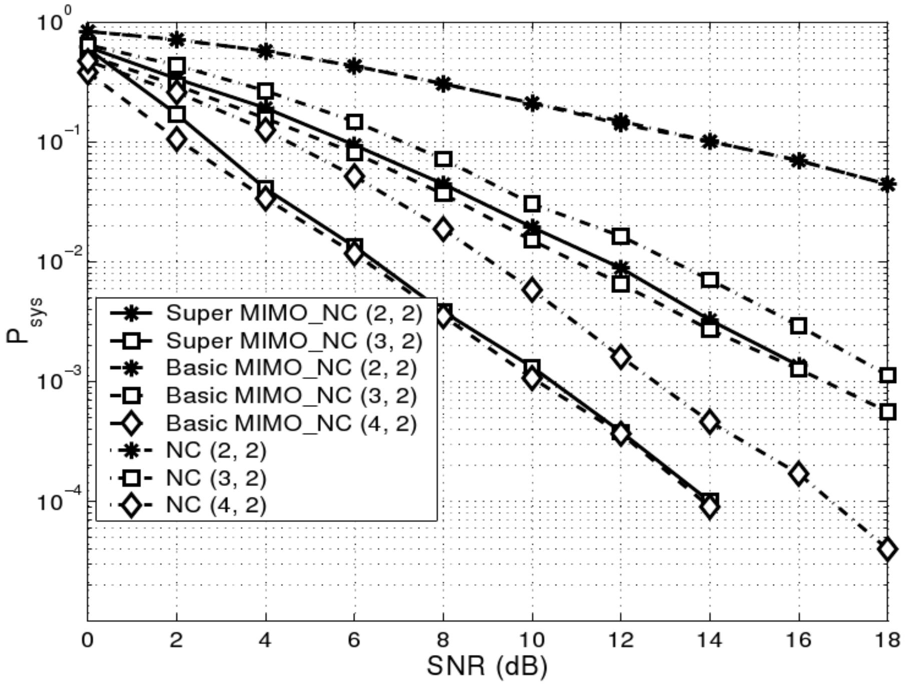

Figure 2: Outage probability in the star network.

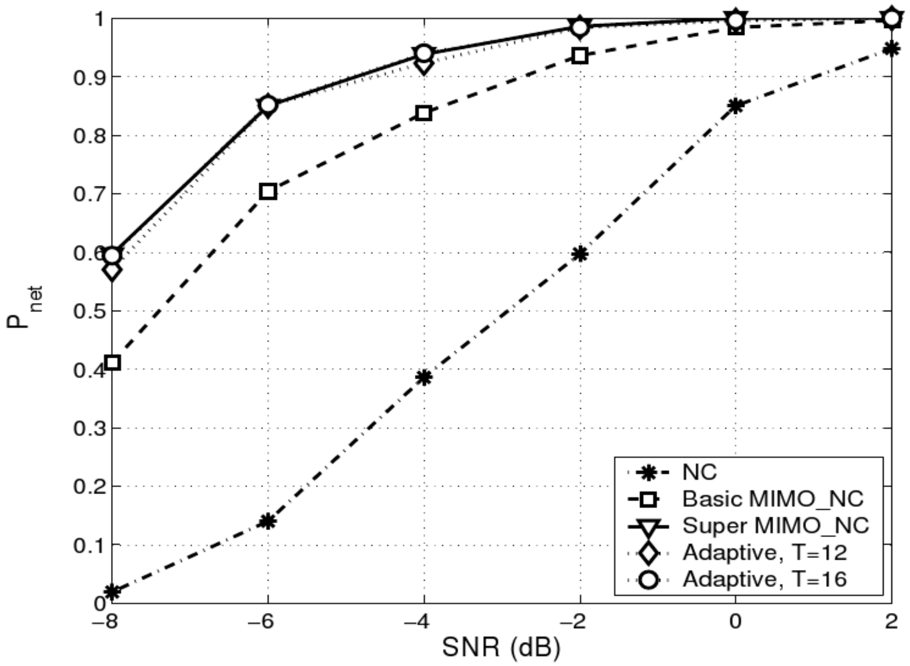

Figure 3: Probability of delivering all packets to the whole network.

Finally, a cooperative protocol based on MIMO_NC has been devised to overcome a basic problem of many cooperative schemes. In many of these protocols, if a source node transmits without success a packet to the intended destination, a relay is expected to retransmit the data of the source without receiving a direct benefit (in fact, suffering some penalty, as it may have to delay its own traffic). If the destination employs MIMO_NC, the cooperator can transmit the combination of the corrupted packet plus a new frame drawn from its own queue. This implies that a relay can pursue its own interest when performing a cooperative retransmission. A protocol called Phoenix that uses this idea and MIMO_NC has been proposed in [C3]. A sample result is shown in Figure 4, which compares the throughputs achieved by standard CSMA, a realistic decode-and-forward protocol and Phoenix for an ad hoc network. Phoenix can gain as much as 17% with respect to CSMA and 13% with respect to simple cooperation in terms of throughput. Other results can be found in [C3].

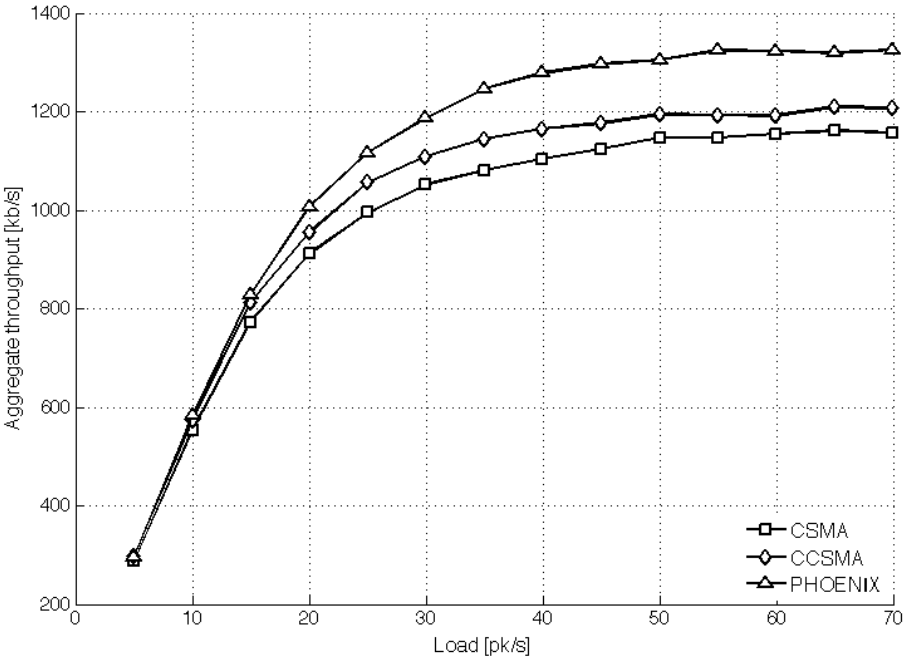

Figure 4: Delay for Phoenix.

On the impact of channel estimation on MAC protocols for MIMO ad hoc networks

The past three years have been partly devoted to the design and detailed evaluation of a novel MAC protocol for MIMO MANETs employing decision-feedback multiuser detection *à la* V-BLAST. The protocol was developed with adaptability and reliability concepts in mind ever since the early stages of the design. Dr. Zorzi's main objective has been to create a solution that could gather information on local network conditions (required traffic, congestion levels, etc.) and modulate its behavior so as to match these conditions without worsening congestion but yet encouraging some degree of parallelism and spatial reuse among the nodes in the same network area.

The protocol proved itself to be a valid solution that encompassed both a means of coping with interference and an adaptation mechanism to direct traffic injection so that certain prescribed quality indices (such as SNR) and constraints (such as the maximum number of trackable channels) could be matched at the receiver. Along with (and in support to) the performance evaluation, an analytical tool was developed with the aim to improve simulations from a computational complexity point of view: this tool relies on the computation of the SNR at each step of the V-BLAST detection process, by taking into account channel effects, as well as the power of interfering signals, detection and canceling errors, and the residual power stemming from over-constrained zero-forcing procedures. This analytical approximation of the SNR incurred during the V-BLAST detection has been of great use in both evaluation efforts (to explore the design space and find the best combinations of protocol parameters) and further design efforts (to improve the aspects of the protocol that could be optimized to gather additional performance improvements).

The investigations carried out about V-BLAST based MIMO ad hoc networks during this fourth year have been concentrated on the analysis of channel estimation errors and of their impact on the performance of MAC protocols. A thorough model has been deployed in order to find the variance of channel samples obtained by training the receiver through a known preamble sequence. While channel estimation through training sequence correlation is a fairly well known approach, the novelty of the investigation is to consider that incoming signals usually bear different average incoming powers, but these powers can be group-wise equal. In other words, it is very likely that some signals, perhaps transmitted by the same node, arrive at the receiver with the same average power, and that this power can vary significantly among all transmit nodes, depending on their distance. This is especially true in a MIMO ad hoc networks, where nodes are encouraged to perform parallel transmissions, and can thus send multiple signals at once: in this scenario, multipath fading-related fluctuations aside, all antennas employed by the same sender will bear equal average power, whereas this power will be different, in general, from sender to sender. Since this has a direct impact on the cross-correlation of all received powers, it is very important to understand how this affects channel estimation.

We now summarize the relevant analysis steps about the effects of channel estimation. The reader is referred to [C4] for a more complete discussion. Assume that every node has N_A antennas. All antennas are used during reception, whereas in general only $n_i < N_A$ antennas might be used during transmission. Our goal is to find the statistics of the channel coefficient $h_{j\ell}^{(i)}$ between antenna j of node i and antenna ℓ at the receiver, in terms of its mean and variance depending on the average received power, as well as on the cross-correlation between channel coefficients related to different transmitters. For channel estimation purposes, antenna j

of user i sends a training sequence $s_{ij}(t)$ of N binary symbols $\{-1,+1\}$, each of duration T. The signal received at antenna ℓ of the receiver can be expressed as

$$r_\ell(t) = \sum_{i=1}^{M}\sum_{j=1}^{n_i} h_{j\ell}^{(i)} s_{ij}(t-\tau_i) + z_\ell(t) \ , \tag{5}$$

where M is the number of transmitting nodes, and $z_\ell(t)$ is a circularly complex random variable with zero mean and constant power spectral density equal to $N_0/2$ (per dimension) modeling noise at the antenna input, whereas $\tau_i \approx U[0,T]$ is the timing offset of user i due to its propagation delay to the receiving node. Channel estimation is performed by calculating the following quantity

$$\hat{h}_{k\ell}^{(m)} = \frac{1}{NT}\int_0^{NT} r_\ell(t) s_{mk}(t)\, dt \quad = \quad h_{k\ell}^{(m)} + \sum_{i\neq m}\sum_{j=1}^{n_i} h_{j\ell}^{(i)} J_{jk}^{(i,m)} + Z_\ell \quad = \quad h_{k\ell}^{(m)} + \Delta h_{k\ell}^{(m)} \tag{6}$$

where Z_ℓ is the noise at antenna ℓ of the receiver, whereas $J_{jk}^{(i,m)}$ is the matched filter output corresponding to antenna j of user i. This last term can be shown to have zero mean and variance

$$\mathrm{Var}\left(J_{jk}^{(i,m)}\right) = \frac{1}{6N} \tag{7}$$

whereas the filtered noise term is circularly complex Gaussian with zero mean and variance $\mathrm{E}\left[| Z_\ell |^2\right] = N_0/(NT)$. By proceeding with the computation of the statistics of $J_{jk}^{(i,m)}$s, one can also show that these quantities can be modeled as a set of independent random variables with approximately Gaussian distribution, zero mean, and variance $1/(6N)$. Finally, it is possible to write the channel estimation equations in an overall matrix form as

$$\hat{\mathbf{H}} = \mathbf{H} + \mathbf{JH} + \mathbf{Z}'' = \mathbf{H} + \Delta\mathbf{H} \tag{8}$$

where the last term highlights the source of uncertainty in the channel estimation procedure, and in particular that, besides noise, one of the additive terms, $\mathbf{JH}$, is directly proportional to the channel matrix, and represents the mutual dependence between different transmissions and the actual estimation error caused to one another.

By varying the number of training symbols in the preamble sequence sent before a packet, it is possible to strike a balance between key network metrics such as throughput, delay, efficiency, and so forth. Before delving more into this topic, we briefly recall how our MAC protocol works. Basically, all transmissions are organized in frames. Each frame is composed of 4 slots, that are used to transmit a Request-To-Send (RTS), Clear-To-Send (CTS), data and ACKnowledgment packets, respectively. Since concurrent transmissions are possible and encouraged, the packets of the same type usually need be de-multiplexed using the multiuser detection algorithm. After having received RTSs this way, the receivers apply a policy to decide whether to grant transmissions or not with the aim to guarantee some protection from interference and a sufficient throughput performance, under the constraint that no more than a certain number of channels per antenna can be estimated, and thus the estimation resources need be allocated to the most convenient signals. 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. Unheard CTSs cause random backoffs of exponentially-increasing duration. 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). These access rules are expected to have different impacts on the way the network reacts to estimation errors, and have been carefully explored. Before proceeding, we recall that training sequences are transmitted before the packet for which channel estimation is required. Since RTSs and CTSs are sent using one antenna each, they require a single training sequence. Data PDUs, however, are sent through multiple antennas: therefore, all additional antennas that are employed during the data phase (besides the one used for transmitting the RTS, if we assume that the coherence time of the channel is longer than the duration of a frame) need channel estimation. The ACK phase is the only one that does not require training, because the ACK can be sent with the same antenna used for the CTS, whose channel is hence already known.

Our first objective is to assess the impact of the training sequence length, N, on the throughput of our system. Intuition suggests that a greater N provides better channel estimates (the variance of the terms in the $\mathbf{JH}$ component of $\Delta\mathbf{H}$ decreases proportionally to the inverse of N); however, a greater N has the detrimental effect of decreasing communication efficiency, by wasting bandwidth for non-data-bearing signals. Our first objective is then to understand the tradeoff between N and the achieved efficiency and throughput. Figure 5 quantifies this tradeoff by showing how these two metrics vary as a function of N, for a network of 25 nodes, deployed in a 5 x 5 grid, with nearest neighbors 25 m apart. With this configuration, all nodes may receive a significant amount of interference from any other node, so that the MAC protocol and the impact of channel estimation can be tested under stress conditions. We set the traffic generation rate to $\lambda = 600$ packets per second..

First of all we observe that the throughput, for this first comparison, is expressed in Packet Data Units (PDUs) that are correctly received per frame. That is, we assume any data packet is split in blocks that are suitable to be transmitted through one antenna: for example, each block has a length of 1000 bits. During the handshake procedures, the MAC protocol decides how many PDU transmissions should take place. We assumed the use of the Node-Lock backoff policy, with a window parameter of $W = 16$. In more detail, this requires any user that did not receive a CTS in response to an RTS to delay the next transmission attempt by a random amount of frames, whose maximum value increases exponentially as a function of the subsequent failures f, according to the law $B_{\max} = W \cdot 2^{f-1}$. The throughput that could be theoretically achieved in this scenario, in case of perfect channel estimation, is slightly more than 8 PDUs/frame [C5]. By looking at the first graph in Figure 5, we see that the throughput increases for increasing N as expected, asymptotically reaching the highest value. The values considered for N span all powers of 2 from 1 to 1024: while the lowest and highest values are clearly infeasible, they allow nevertheless to gather a detailed picture of imperfect channel estimation effects. In particular, we observe that efficiency (defined as the ratio of data symbols sent over all transmitted symbols) is actually maximum for very low N: in this case, however, we achieve so little throughput to make the configuration undesirable. For higher N, instead, the network experiences better throughput performance and almost constant efficiency (very close to the maximum value indeed) until $N = 32, 64$, that allow the best efficiency as well as reasonable throughput. From this analysis, we observe that a value such as $N = 64$ achieves the best tradeoff between throughput and efficiency

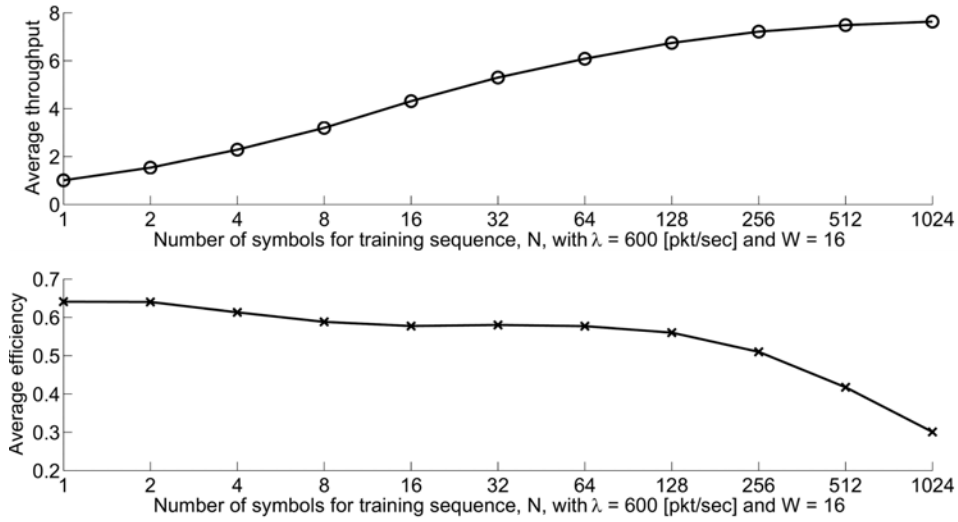

Figure 5: Comparison between throughput and efficiency as a function of traffic for Node-Lock, $W = 16$ and $\lambda = 600$.

In our next comparison, we consider again throughput and efficiency, but define throughput as the aggregate bit rate (in Mbps) that is achieved in the network. This definition makes it possible to highlight a further negative effect of longer training sequences, that improve the number of PDUs per frame that get through, but yet increase the duration of the frame itself, thus actually decreasing throughput for too high a value of N. Furthermore, we extended the comparison by allowing signaling packets (RTSs, CTSs, and ACKs) and data PDUs to be preceded by training sequences of different length, N_{sig} and N_{data}, respectively. The results of this comparison can be seen in Figure 5, that shows two contour plots, for efficiency (dotted) and throughput (solid, colored). While this is just a sample of many similar results that we derived, it allows to strike a balance between throughput and efficiency by setting the values of N_{sig} and N_{data} that best fit some prescribed constraints. For example, if we want to ensure a prescribed throughput of no less than 25 Mbps while achieving an efficiency of at least 0.5, we can choose any pair of values of $N_{sig} \in \{32, 64\}$ and $N_{data} \in \{64, 128, 256\}$. A second effect is also brought to evidence by Figure 6: namely the traffic transport limitation caused by a low N_{sig}. Namely, a low N_{sig} determines a low success ratio for RTSs: in case RTSs are lost due to detection errors (ultimately caused by wrong channel estimation), CTSs are not sent, thus causing transmitters to back off and limiting network traffic. For example, this explains why, for $N_{sig} = 4$, increasing N_{data} does not improve throughput, and ultimately worsens it for high N_{data}, because traffic is limited by N_{sig}, and the net effect of a greater N_{data} is to increase the frame duration, rather than offering more protection to the few PDUs actually sent. On the contrary, fixing, e.g., $N_{data} = 64$ and varying N_{sig} allows to increase throughput, at least until the estimation offered by this N_{data} is good enough.

The same kind of analysis has been carried out for other relevant metrics such as delivery delay and success ratio (for both signaling and data packets), allowing to choose the best set of values of such metrics according to prescribed constraints.

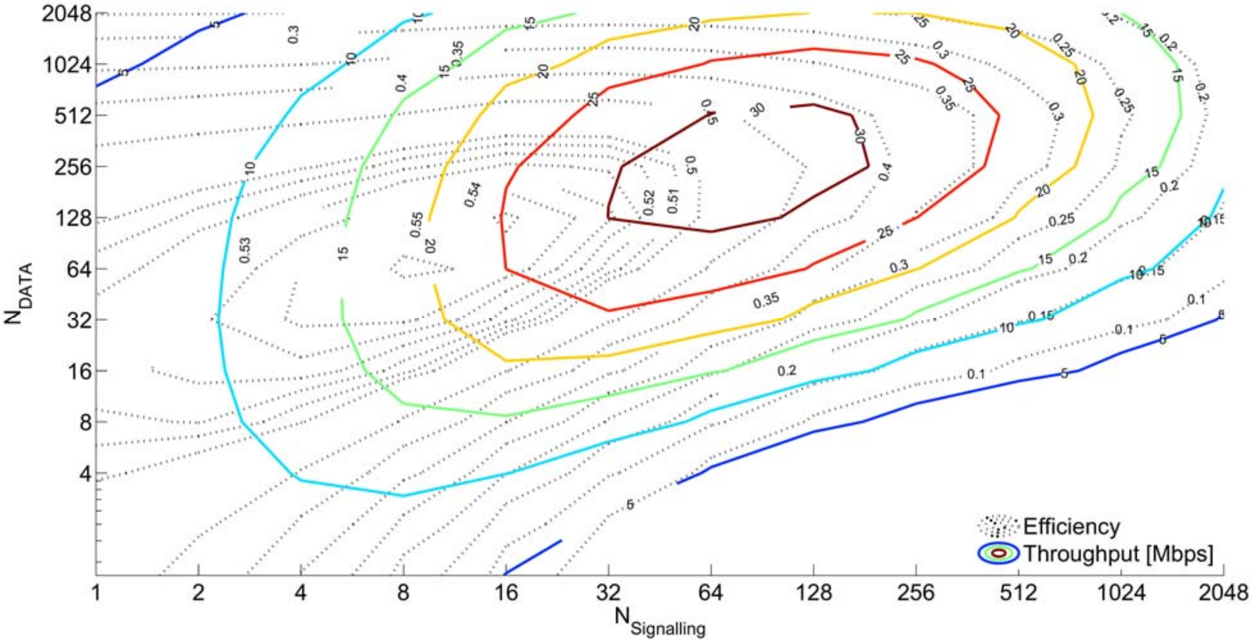

Figure 6: Contour curves of efficiency and throughput for different values of N_{sig} and N_{data}. Node-Lock, $W = 16$, $\lambda = 600$.

Cooperative packet forwarding in MIMO ad hoc networks

In [J3][C7][C8], we proposed and investigated a cooperative protocol aiming at the improvement of the performance of MIMO networks with simultaneous and asynchronous node access. In our system, cooperating nodes realize a distributed hybrid automatic retransmission request (HARQ) error control scheme. Packets are encoded with a low-rate error correction code, and the obtained codeword is split in several fragments. After an initial handshake phase, the data transmission is divided into phases. In the first phase, the source sends a fragment of the codeword to the intended destination, that replies with a feedback packet indicating the correct/erroneous reception of the packet. If erroneous reception is reported, the source sends a further fragment, followed by a feedback packet from the destination. The communication continues until the destination reports correct reception or the maximum number of phases is reached. Note that the destination collects all received fragments, obtaining in each new phase a code with lower rate, thus increasing correct decoding probability. The HARQ protocol described before adapts the code-rate to the current channel and interference conditions of the channel. Adaptability is proven to be a critical issue in highly variable channels. In a MIMO system with asynchronous communications, interference variations, due to the start and the end of simultaneous communications, cause fast variations of channel conditions. HARQ not only provides adaptability to channel variations, but also reduces the level of interference in the network with respect to conventional error control protocols, such as pure ARQ and forward error correction (FEC). If cooperation is enabled, idle nodes that correctly decoded the packet at previous phases, re-encode it and send fragments of the obtained codeword. MIMO is particularly suited to cooperation, since all nodes involved in sending fragments can transmit simultaneously, thanks to the multiuser detection capabilities of the receiver, without the need for setting a TDMA access schedule for the various transmissions of cooperating nodes. Moreover, the transmissions by simultaneous cooperating nodes and the ability to select among a number of candidates enables a significant overhead reduction. In [J3][C7][C8], we addressed fundamental issues, such as, for instance, availability and selection of the cooperating nodes, and interaction of cooperation with the level of interference in the network.

During the fourth year, we further extended our approach exploiting the adaptability and flexibility of MIMO networks in a multi-hop scenario. The system we proposed in [J2]0 integrates the distributed HARQ described before with an opportunistic routing protocol. When considering multi-hop networks, single-hop cooperation can be used to extend coverage range and, thus, to reach the final destination in a lower number of hops. Conversely, in our work, cooperation is used to dynamically select high efficiency routing paths providing geographical advancement towards the final destination, and to reinforce already activated links incurring fading and interference impairments. This is, in our opinion, a fundamental aspect of our work, connected to the MIMO architecture and to the simultaneous access scenario, where the interference in the network is a critical issue. Moreover, a MIMO PHY layer allows the effective deployment of protocols requiring signaling exchange. We describe in the following the proposed system.

We assume that nodes have a predefined routing table to any destination of the network. In particular, routing paths are formed with a shortest path policy. In this manner, it is possible to define a metric specifying the distance between each pair of nodes in the network. More precisely, each node knows its distance towards each possible destination in terms of number of hops.

Before the data transmission, the source and the destination perform a handshake phase, meant to check destination availability and channel conditions. If the SNR perceived at the receiver is lower than a threshold t the communication is dropped and a further attempt is scheduled after a random backoff interval. The threshold t avoids the deployment of communications likely to involve many phases and yet to fail due to adverse channel conditions. In this system, even if the nodes of the network are allowed to access the channel simultaneously, a long communication, potentially ending with a failure, generates a significant interference and reduces the performance of other ongoing communications.

If on the contrary the SNR is above threshold, then the communication proceeds following the HARQ mechanism previously described. If cooperation is active, however, it is used not only to realize the aforementioned distributed HARQ scheme, but also to provide dynamic path selection.

In this new scheme, the main idea is that cooperators can, under specific conditions, become instead relays, taking charge of the packet forwarding on a path different from the predefined one. The new path selection can be performed in two ways, at the beginning of the transmission or after the first transmission phase.

When transmission begins, if after the RTS-CTS handshake the perceived SNR is below threshold, idle nodes which have good channels towards the source and the destination can send a cooperative CTS (cCTS). After receiving at least one cCTS, the source starts the transmission, since the presence of cooperators is likely to improve the success probability. However, if one or more idle nodes which send the cCTS are closer to the final destination than the source, according to the predefined routes, they notify in the cCTS their availability to become instead relays. The source can then select one of them, which becomes the new destination, as in Figure 7. This technique is also known as Opportunistic Routing.

A similar scheme can be used after the first transmission phase. If the feedback packet from the destination declares decoding failure, nodes which have decoded the missing part of the packet send a cooperative ACK, and replace the source in delivering the packet, thus acting as cooperators. If, however, one of these cooperators decoded the entire packet, and is closer to the final destination, it can declare decoding success and become a relay, hence starting to forward the packet along a different route.

A similar scheme, which takes into account also the availability of some geographical information at the nodes, thus improving the quality of the metric used to switch from the static route to a different one, is also being studied.

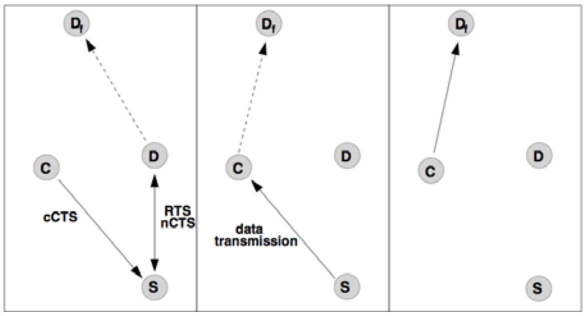

Figure 7: Example of cooperative relaying, where the idle node C takes charge of packet forwarding.

In the following we show some results obtained through extensive simulations of the proposed scheme. We assume the MIMO-BLAST transmitter and receiver architecture described in [J4], whose performance is approximated as [J5]. Packets are encoded with a linear erasure block code, whereas signaling packets are protected with a convolutional code. The results are averaged over twenty random topologies in a fixed area of 500x500 m, for each number of nodes. In Figure 8 the average distance of successful links is plotted. The longer links used by the non cooperative protocol can be explained since a Shortest Path algorithm was used to define the static routes. When using Opportunistic Routing, on the contrary, the links are shorter, since there is a high probability that at each hop an idle node closer to the source, but still having a shorter path towards the final destination, has the possibility to volunteer as relay. When also coded cooperation, which strengthens the long links, is used, then the two effects are both present, and the average link length is higher. We report in Figure 9 the average aggregated end-to-end throughput as a function of the number of nodes. Although Opportunistic Routing requires a higher amount of signaling packets, it grants a higher throughput, due to the lower delay achieved by avoiding long backoff periods. Even better performance is reached if cooperation is also used, despite the higher interference generated by the transmissions from the cooperators. This is also the reason that causes a throughput degradation when the number of nodes increases. This effect is highlighted also in Figure 11, where results on networks where nodes are equipped with two antennas are added. The use of spatial multiplexing grants an additional throughput improvement. Nonetheless, for a large number of nodes the additional interference due to the presence of cooperators limits the achievable throughput of the cooperative protocol. Better performance, in this situation, is offered by the simple Opportunistic Routing.

Finally, in Figure 10 the end-to-end delivery success ratio is reported, for paths with different number of hops. For one-hop paths, the improvement is granted by the HARQ scheme. Therefore, Opportunistic Routing gives no advantage, since routing is unnecessary, whereas the additional redundancy sent by the cooperators can increase the success probability. For multi-hop paths, instead, the improvement is more pronounced, and even the use of Opportunistic Routing alone gives some advantage, since links with bad conditions are often avoided.

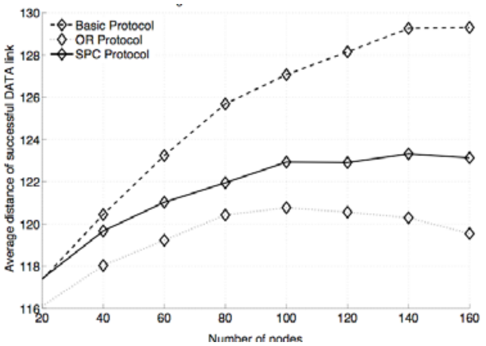

Figure 8: Average distance of the successful links (one hop links) as a function of the number of nodes in the network for the considered protocols.

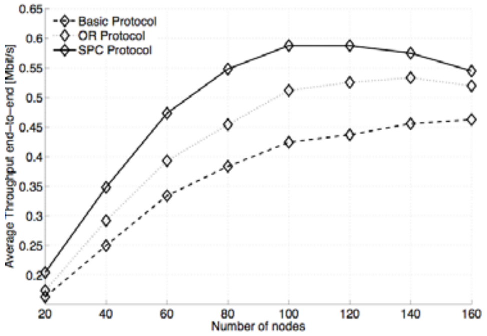

Figure 9: Average end-to-end throughput as a function of the number of nodes in the network for the considered protocols.

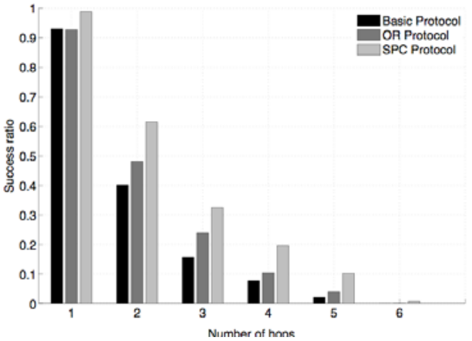

Figure 10: End-to-end success delivery ratio on path with a different number of hops, for a 40 nodes network.

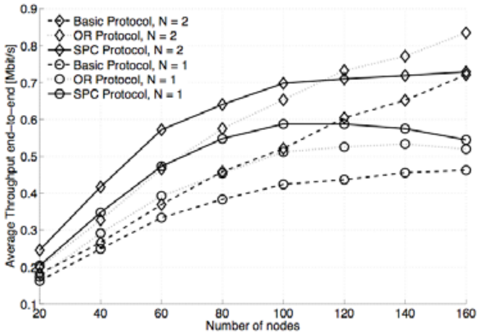

Figure 11: Average end-to-end throughput as a function of the number of nodes, and for different numbers of antennas used at each node.

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2.7 Cognitive Radio for Ad Hoc Networks

PI: Laurence Milstein

GSRs: Patrick Amihood, Andrew Ling, and Qi Qu

A. Summary of Research Result

1. Cooperative Virtual MIMO - Qi Qu

Following our preliminary work from the previous year, we investigate the issue of cooperative node selection in cooperative MIMO communications for wireless ad hoc networks, where a source node is surrounded by multiple neighbors and all of them are equipped with a single antenna. Our problem is as follows: Given power, delay and data rate constraints, how does a source node dynamically choose its cooperative nodes from its neighbors to form a virtual MIMO system with a destination node which has multiple antennas, as well as adaptively allocate the power level and adjust the constellation size for each of the selected cooperative nodes. We consider the optimization of all these parameters, given the system constraints, by judiciously considering both the local information distribution and the long-haul transmission involved with cooperative MIMO, and the delay/power consumptions involved in each of the two procedures.

Specifically, we consider a cooperative MIMO system with spatial multiplexing, and we jointly consider the selection of cooperative nodes and the power/rate allocation among the selected nodes in order to minimize the bit-error-rate performance of the system. We first quantify the energy and delay induced during the local distribution stage; then, for the long haul transmission stage, given a subset of cooperating nodes, we express the system performance as a function of that subset of nodes, and the power/data rate allocated to each node; after that, we form a multi-variable optimization problem to maximize the performance at the destination node, taking into account both stages and the energy/delay/rate constraints.

Initially, we investigate how to select the cooperative nodes and how to solve the optimization problem where the source node has full instantaneous channel state information (CSI). Then for systems where instantaneous CSI is not available, we propose algorithms based upon channel correlation information. Finally, we briefly describe a simple cooperation procedure based on which the cooperation can be realized in an actual system.

Our studies showed that the system performance can be greatly affected by delay and energy constraints. When the delay and energy constraints become stringent, the system performance degrades substantially. For example, when the SNR is 21 dB, the BER when there is no delay constraint is roughly three orders of magnitude better than when delay constraint is on the order of one-third of a second. This demonstrates that in a cooperative MIMO system for an ad hoc network, the local distribution and long haul transmission stages should be jointly considered in order to obtain acceptable performance.

Our results also indicate that when instantaneous CSI is not available, the system can still function by making use of only channel correlation information, but there is a degradation of performance. For example, when channel correlation information is the only information available, an extra 2 dB of SNR is required to achieve a BER of 10^{-4} as compared to the required SNR when instantaneous CSI is available.

2. Effects of Spatial Diversity and Imperfect Channel Estimation on Wideband Multi-Carrier CDMA Systems - Andrew Ling

Our research focused on the comparison of two multi-carrier signaling schemes: multi-carrier direct sequence code division multiple access (MC-DS-CDMA) and multi-carrier code division multiple access (MC-CDMA). When viewed in the frequency domain, these two multi-carrier schemes differ in the widths of their sub-bands---MC-DS-CDMA uses direct sequence spreading at each sub-carrier, while each sub-carrier in MC-CDMA is unspread. Thus, over a given bandwidth, MC-CDMA employs a larger number of sub-carriers than MC-DS-CDMA. If both schemes transmit at the same information rate, then each data symbol is repeated across a larger number of sub-carriers in MC-CDMA than in MC-DS-CDMA. While this implies that MC-CDMA potentially has higher frequency diversity than MC-DS-CDMA, it also means that if both schemes use the same energy-per-bit, then the energy per sub-carrier is lower in MC-CDMA than in MC-DS-CDMA. In other words, each MC-CDMA sub-carrier operates at a lower signal-to-noise ratio (SNR), which implies that the receiver's estimate of the channel gain at each sub-carrier frequency in MC-CDMA is more prone to error. Therefore, when MC-DS-CDMA and MC-CDMA are compared under equal bandwidth, information rate, and energy-per-bit constraints, there exists between these two schemes a possible trade-off between diversity and channel estimation errors.

Initially, we studied this trade-off by comparing the theoretical bit error rates of MC-DS-CDMA and MC-CDMA for a single-input single-output (SISO) system. We employed bandlimited non-overlapping sub-bands in both multi-carrier schemes by using waveform shaping and wider sub-carrier spacing. In both schemes, we also used the same combining scheme at the receiver (i.e., maximal ratio combining), as well as the same pilot-based scheme to estimate the channel gains at each sub-carrier frequency. Two different channel scenarios were considered; the coherence bandwidth of the channel was assumed to equal the bandwidth of one MC-CDMA sub-band in Scenario #1, and the bandwidth of one MC-DS-CDMA sub-band in Scenario #2. We derived closed-form expressions for the bit error probabilities of both schemes under both scenarios, and we compared these error probabilities for different information rates, number of users, and number of pilot symbols per channel estimate. Our results showed that a performance trade-off between the two multi-carrier schemes in the single-user case exists in Scenario #2 when the number of parallel data symbols, M, is such that M>1. In the multi-user case, however, a performance trade-off between the two schemes exists in Scenario #2 when M>1 only if the number of pilot symbols per channel estimate is large enough.

We extended this previous work by comparing MC-DS-CDMA and MC-CDMA for a multiple-input multiple-output (MIMO) system with two transmit and two receive antennas. We employed Alamouti space-time block coding at each sub-carrier frequency to achieve full transmit diversity in the absence of channel state information at the transmitter. By assuming (1) the coherence bandwidth is equal to the bandwidth of one MC-DS-CDMA sub-band, and (2) the number of data symbols transmitted in parallel, M, is such that M>1, we examined only those cases where MC-CDMA has higher frequency diversity than MC-DS-CDMA, because these are the only instances in which there is a performance trade-off between the two schemes. Given that increases in diversity yield diminishing gains, we expected the addition of spatial diversity to the multi-carrier comparison to benefit MC-DS-CDMA more than MC-CDMA. To determine whether these gains for MC-DS-CDMA are enough to offset the difference in frequency diversity between the two schemes, we applied a quadratic-form based technique to derive closed-form expressions for the bit error probabilities of both schemes, and we compared the numerical results of the MIMO system against those of the SISO system for different information rates, number of users, and number of pilot symbols per channel estimate. Our results showed that for the single-user case, the aforementioned gains for MC-DS-CDMA are enough to overcome the difference in frequency diversity between the two multi-carrier schemes when M is small, but not when M is large. Also, when matched-filter-based detection is used for the case of multiple users, our results showed that the additional diversity increases the number of pilot symbols required to force a performance trade-off between the two schemes.

2.8 Instantaneous and Average Rate Maximization in Multi-User, MIMO Channels with Linear Processing

PI: Zeidler

GSR: Adam Anderson and Sagnik Gnosh

SUMMARY OF ACCOMPLISHMENTS

The general focus of our work for the MURI is to provide information to both the physical (PHY) and medium access control (MAC) layers that remains applicable over long durations of time allowing for cross-layer optimization in the protocol stack. In previous years, we have shown that channel state information (CSI) is affected by the channel *coherence time* and becomes outdated in highly mobile channels resulting in severe loss in performance for both linear and nonlinear PHY algorithms. Such instability in CSI at the PHY layer will be exacerbated in the MAC and direct CSI seems impractical for optimization in the network layers. Channel distribution information (CDI), however, is stable over the statistical *stationarity time* of the channel meaning CDI remains constant over a much larger timeframe than CSI and may be shared between layers. With our "bottom-up" approach to the problem we derive transmit precoding methods that use CDI in the PHY in order to provide links with stable performance that ultimately can be utilized by the MAC.

The specific focus of this year's work was to completely derive the instantaneous and average rate maximizing beamformers for both the broadcast (BC) and multiple-access (MAC) channels using either CSI or CDI at either transmitter or receiver. The form of these beamformers is labeled as a regularized inversion and thus beamforming with CSI is called RCI while beamforming with CDI is referred to as RCDI. This work was a straightforward and insightful continuation of the previous year's work and can be summarized as the following:

1) *RCDI beamforming in the broadcast channel (RCDI-BC)*. For extremely high mobility or delay, it may be impossible to achieve accurate CSI even at the receiver (CSIR) let alone the transmitter. In this scenario the performance of RCDI beamforming would help alleviate the loss in performance when using receive beamforming with outdated CSIR.
2) *Channel distribution parameterization*. Though stable for a longer timeframe than CSI, the amount of information required for RCDI processing is much larger than that of standard RCI beamforming. Thus, we focus research on possible ways of parameterizing the spatial correlation matrices in order to reduce their size while maintaining the simulated performance shown with RCDI.
3) *RCDI beamforming in the multiple-access channel (RCDI-MAC)*. Finally, the dual of the broadcast channel is the multiple-access channel which is another possible multi-user link

in an ad hoc network. The performance of RCI beamforming for these channels is not fully explored and needed to be derived prior to the RCDI-MAC beamformer. Similar results and advantages are seen with RCDI-MAC as shown with RCDI-BC.

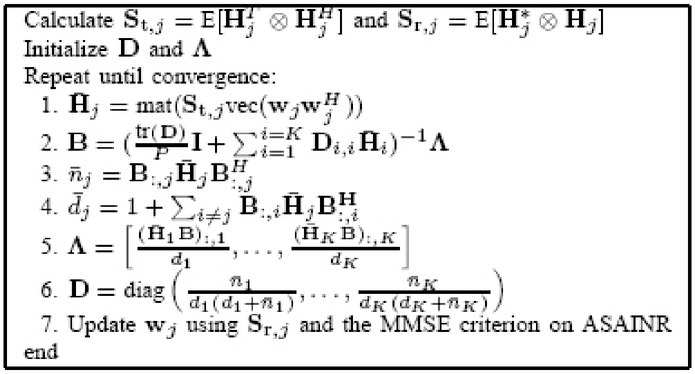
4. RCDI Beamforming in the Broadcast Channel (RCDI-BC)

Providing accurate CSI to the transmitter in a time-varying channel is a difficult task and results in significant performance loss when not done correctly [1]. Work done in previous years has shown that when CDI is used at the transmitting node in a BC, the decay seen by outdated CSI can be mitigated at the expense of initial throughput loss. For extremely high velocity or interfence-rich environments, accurate CSIR may also be difficult to obtain. This error at the receiver results in even more loss in data rate when coupled with outdated CSIT. We explore the possibility of using CDI and both transmitters and receivers in the multi-user BC.

A. RCDI-BC Beamforming at the Receiver

Regularized channel distribution inversion in the broadcast channel (RCDI-BC) beamforming follows the general procedure defined in [2] for RCI-BC beamforming with the ideal rate bound found in [1]. Using the combination of these two approaches results in the iterative beamforming algorithm found in Table 1.

Table 1: RCDI-BC ALGORITHM FOR AVERAGE RATE MAXIMIZATION IN THE BC



```
Calculate $\mathbf{S}_{t,j} = \mathrm{E}[\mathbf{H}_j^T \otimes \mathbf{H}_j^H]$ and $\mathbf{S}_{r,j} = \mathrm{E}[\mathbf{H}_j^* \otimes \mathbf{H}_j]$
Initialize $\mathbf{D}$ and $\mathbf{\Lambda}$
Repeat until convergence:
  1. $\bar{\mathbf{H}}_j = \mathrm{mat}(\mathbf{S}_{t,j}\mathrm{vec}(\mathbf{w}_j\mathbf{w}_j^H))$
  2. $\mathbf{B} = (\frac{\mathrm{tr}(\mathbf{D})}{P}\mathbf{I} + \sum_{i=1}^{i=K} \mathbf{D}_{i,i}\bar{\mathbf{H}}_i)^{-1}\mathbf{\Lambda}$
  3. $\bar{n}_j = \mathbf{B}_{:,j}\bar{\mathbf{H}}_j\mathbf{B}_{:,j}^H$
  4. $\bar{d}_j = 1 + \sum_{i \neq j} \mathbf{B}_{:,i}\bar{\mathbf{H}}_j\mathbf{B}_{:,i}^{\mathbf{H}}$
  5. $\mathbf{\Lambda} = \left[\frac{(\bar{\mathbf{H}}_1\mathbf{B})_{:,1}}{d_1}, \ldots, \frac{(\bar{\mathbf{H}}_K\mathbf{B})_{:,K}}{d_K}\right]$
  6. $\mathbf{D} = \mathrm{diag}\left(\frac{n_1}{d_1(d_1+n_1)}, \ldots, \frac{n_K}{d_K(d_K+n_K)}\right)$
  7. Update $\mathbf{w}_j$ using $\mathbf{S}_{r,j}$ and the MMSE criterion on ASAINR
end
```

Definitions for each of the specific parameters can be found in [1]; however, it is most significant to note that the only input parameters required to the RCDI-BC algorithm are nonlinear permutations on the spatial correlation matrices $\mathbf{S_t}$ and $\mathbf{S_r}$.

For simulation purposes, measurements taken with the BYU test equipment from three different environments will be shown here. The “Urban” dataset was acquired in a locale with large buildings and other mobile and stationary obstructions while “Indoor” contains channels measured inside the fourth floor of the Brigham Young University engineering building. “Outdoor” refers to a typical university campus where the transmitter was specifically located in an area surrounded by trees.

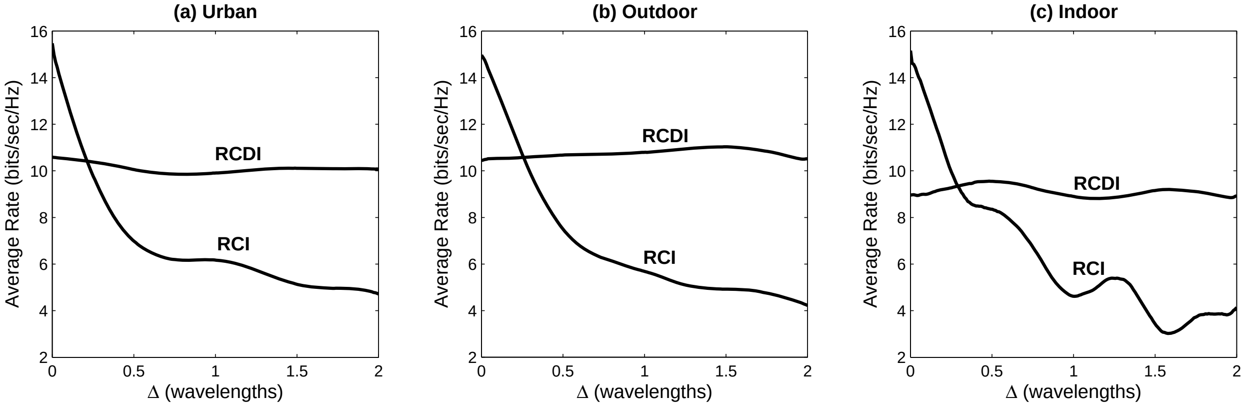


Figure 12: Average sum-rate of RCI and RCDI versus displacement for M=K=4 and P=10. The receiver and transmitter share equally delayed knowledge of that channel given by Δ(wavelengths) from the current channel. Shown are the (a) Urban, (b) Outdoor, and (c) Indoor environments.

For each dataset, the required input parameters are calculated for either the RCI or RCDI algorithms. For RCI, the individual channel realizations are fed directly into the algorithm to calculate the necessary beamformers. The system parameters are fixed such that each node has M=4 antennas and there are a total of K=4 users and a total power constraint of P=10. For RCDI, an average was taken over all channel realizations in order to calculate $\mathbf{S_t}$, $\mathbf{S_r}$, and the beamformer as derived in Table 1.

The stability of RCDI implies that the feedback frequency for the RCDI algorithm is much lower than that required by the RCI approach to maintain a specified throughput. Furthermore, as shown in Figure 1 for the Indoor environment, spatial structures introduced on the channel due to the environment directly affect the possibility of effectively using CDI as a precoding resource. For a spatially-white channel, the RCDI algorithm could not make any distinction between users and no gains would be possible over outdated CSI.

5. Channel Distribution Parameterization

The prior section demonstrated that in this past year we found a solution for the RCDI-BC algorithm that enables good throughput performance with reduced feedback frequency in the time-varying broadcast channel. However, because the algorithm computation requires the full spatial correlation matrix the amount of data that must be fed back is significant. In fact, assuming M antennas per node, each user must feedback an M^2xM^2 matrix, or M^4 complex values, in contrast to the M^2 numbers that must be fed back for RCI-BC implementation using the channel matrix.

One of the goals of our work this past year was to consider ways to parameterize the large spatial correlation matrix to reduce the required volume of feedback data. The approach finally taken is to explore the use of popular channel models, namely the Kronecker and Weichselberger models, which impose structure on the correlation matrix to allow its representation using smaller matrices with the final result being feedback quantity that is on par with CSI while feedback frequency is significantly reduced.

A. Kronecker Model Parameterization

The Kronecker model [3] assumes separability between transmit and receive spatial correlation matrices. Assuming that $\mathbf{H}_w$ is an M ×M matrix with zero-mean, unit variance, i.i.d. complex Gaussian entries, the correlated channel matrices can be realized using

$$\begin{aligned}
\mathbf{H}^{\mathrm{Kron}} &= \sqrt{\mathbf{R}_r}\mathbf{H}_w\sqrt{\mathbf{R}_t} \\
\mathbf{S}_t^{\mathrm{Kron}} &= \left(\sqrt{\mathbf{R}_t}^T \otimes \sqrt{\mathbf{R}_t}^H\right)\mathbf{I}_t\left(\sqrt{\mathbf{R}_r}^T \otimes \sqrt{\mathbf{R}_r}^H\right) \\
\mathbf{S}_r^{\mathrm{Kron}} &= \left(\sqrt{\mathbf{R}_r}^* \otimes \sqrt{\mathbf{R}_r}\right)\mathbf{I}_r\left(\sqrt{\mathbf{R}_t}^* \otimes \sqrt{\mathbf{R}_t}\right)
\end{aligned}$$

These results demonstrate that the necessary feedback information for RCDI-BC is reduced to two MxM matrices for a total of $2M^2$ complex numbers.

B. Rank-1 Approximation Parameterization

Computing the one-sided correlation matrices directly from the channel matrices and then using the Kronecker products to estimate the full correlation matrix can result in substantial modeling error. An alternate approach is to impose the Kronecker structure of the correlation matrix but compute one-sided estimates from the optimization

$$\min_{\mathbf{R}_r, \hat{\mathbf{R}}_t} ||[\mathbf{R} - \hat{\mathbf{R}}_t \otimes \hat{\mathbf{R}}_r||^2$$

These estimates can be obtained using the solution discussed in [4], which is referred to as the rank-1 approximation. This approach also results in a feedback complexity of $2M^2$ complex numbers.

C. Weichselberger Model Parameterization

The Weichselberger model [5] was introduced in an effort to overcome some of the deficiencies discovered with the Kronecker model. The Kronecker model deficiencies arise from imposing one-sided correlations on the spatial structure of the channel which result in underestimation of the channel capacity. Under the Weichselberger model, channel matrix realizations are represented as

$$\begin{aligned}
\mathbf{H}^{\mathrm{Welchs}} &= \sqrt{\mathbf{U}_r}(\tilde{\boldsymbol{\Omega}} \odot \mathbf{H}_w)\sqrt{\mathbf{U}_t}^T \\
\mathbf{S}_t^{\mathrm{Welchs}} &= (\mathbf{U}_t \otimes \mathbf{U}_t^*)\left\{(\tilde{\boldsymbol{\Omega}}^T \otimes \tilde{\boldsymbol{\Omega}}) \odot \mathbf{I}_t\right\}\left(\mathbf{U}_r^T \otimes \mathbf{U}_r^H\right) \\
\mathbf{S}_r^{\mathrm{Welchs}} &= (\mathbf{U}_r^* \otimes \mathbf{U}_r)\left\{(\tilde{\boldsymbol{\Omega}}^* \otimes \tilde{\boldsymbol{\Omega}}) \odot \mathbf{I}_r\right\}\left(\mathbf{U}_t^H \otimes \mathbf{U}_t^T\right)
\end{aligned}$$

where matrix quantities are defined as in [5]. This result indicates that the RCDI implementation requires feedback of three MxM matrices for a feedback complexity of $3M^2$ complex numbers.

The performance of the RCDI implementation for the different parameterizations is examined in Figure 2 for various measured environments. For this plot, the power is held constant at P=10 while the number of antennas and users was swept assuming M=K. The “boxed” region

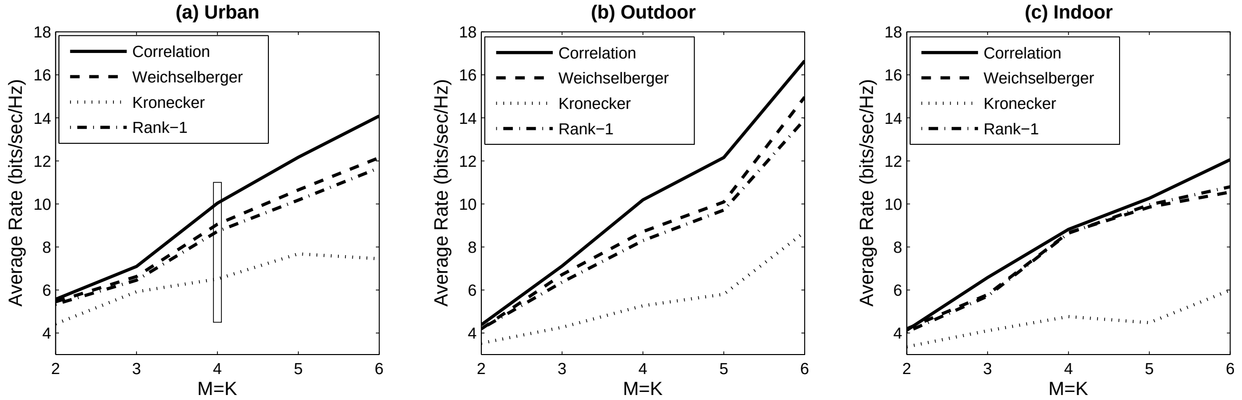


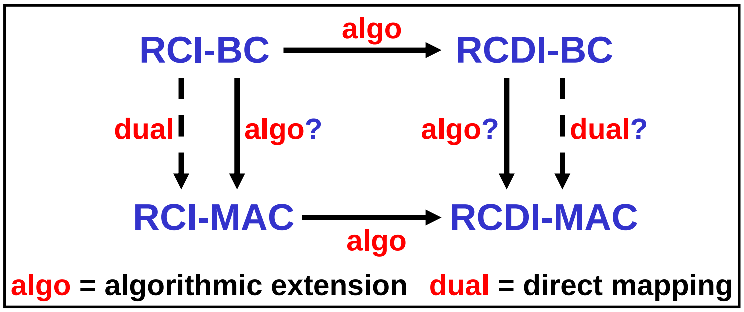
Figure 13: Average sum-rate versus system size when the matrices S_t and S_r are generated by using: the full correlation matrix, the Weichselberger model, the Kronecker model, and a rank-1 approximation. Shown are the (a) Urban, (b) Outdoor, and (c) Indoor environments.

These results also show that while the Kronecker structure for the correlation matrix is reasonable (as evidenced by the performance for the rank-1 model), it is critical that the input matrices be properly estimated.

6. RCI/RCDI Beamforming in Multiple-Access Channels (RC(D)I-MAC)

The previous sections have provided a description of the RCI and RCDI algorithms in time-varying, MIMO BC channels. This past year we also set goals in order to derive similar beamforming algorithms for the MAC. To this end, different approaches can be taken as mapped out in Table 2.

Table 2: Dualities and Algorithmic Extensions of MAC/BC Beamformers



As an example, the RCI-BC algorithm for the MISO channel was first shown in [2]. Using an algorithmic extension, the RCDI-BC algorithm was derived as explained previously and is shown as a connection in Table 2. Since our ultimate goal is to create the RCDI-MAC beamformer (lower-right side of Table 2) there are different possible routes we can take:

1) The easiest would be to invoke duality between the BC and MAC with CDI. For nonlinear precoding, there is a direct mapping between optimal input covariance matrices for dirty-paper coding (DPC) in the BC and successive interference cancellation (SIC) in the MAC which results in equal throughput [6]. There is no proof that this same duality holds for beamforming and CDI.
2) Though not true for CDI, a duality does exist between BC and MAC beamforming that allows one to go from RCI-BC to RCI-MAC directly. However, there is no obvious method of transforming the RCI-MAC beamformer into RCDI-MAC.
3) The final path we chose, as shown in Table 2, is to first create an RCI-MAC algorithm directly using CSI and then use the algorithmic extension we invoked on the BC to arrive and RCDI-MAC.

Since RCI-MAC did not exist, we must first calculate this beamforming algorithm and then use similar steps as taken in the BC to finally find RCDI-MAC.

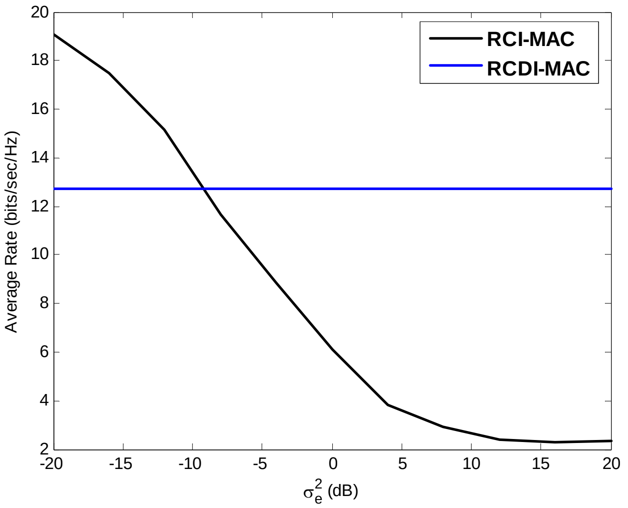


Figure 3: Loss in average rate versus channel error for the RCI-MAC and RCDI-MAC beamformers for M=K=4 and P=10. The error is assumed Gaussian and additive to the CSI while CDI is considered error-free.

Figure 3 shows the performance of RCDI-MAC as well as the degradation of RCI-MAC when erroneous CSI is used to calculate the beamforming weights. For this simulation, the feedback channel is assumed instantaneous and perfect while the transmitters and receiver possess equally-erroneous CSI as quantified by σ_e while CDI is perfect for all users.

3. Summary

The results presented this past year are an exciting new method of transmitting information between PHY layer links in an ad hoc network. By using CDI in order to calculate beamforming weights, performance loss due to channel coherence time is removed which could allow the MAC layer and PHY layer to share information that is stable over both applicable timeframes. Additionally, by parameterizing the spatial correlation matrices needed for RCDI beamforming, we have successfully reduced both the quantity *and* frequency of necessary feedback in multi-user MIMO links.

The final extension of this work is to analyze similar beamforming techniques in more complex multi-user channels:

a. *RCI/RCDI beamforming in hybrid channels (RC(D)I-HC)*. It may be possible to apply the model used for RCI/RCDI beamforming to more complex channels. For example, a network consisting of multiple nodes may have both MAC and BC channels occurring simultaneously resulting in increased interference. An RC(D)I-HC beamformer becomes of special interest in these cases and allows the MAC layer further options in optimizing the network.

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2.9 Using Feedback in Ad Hoc Networks

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GSRs**:** Siavash Ekbatani: Partially supported by MURI; Graduated (PhD),

Javad Kazemitabar: Partially supported by MURI; Graduated (PhD),

Erdem Koyuncu: full GSR (49%) for the entire year,

Postdoc: Yindi Jing: Partially supported by MURI

We have had contributions in three research projects:

(1) MIMO systems using finite-rate noisy feedback
(2) Network Beamforming
(3) Cross-layer design in the presence of interference

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

(1) Combining the benefits of the diversity/coding gain from space-time coding and the array gain from beamforming has recently attracted a lot of attention. From a practical point of view, the transmitter channel state information is degraded by several factors in the feedback channel, e.g. the bandwidth limitation, the delay, and the noise. We consider the effects of a finite-rate feedback and the noise in the feedback link. The main contributions are:

A. Combining Beamforming and Space-Time Coding Using Noisy Quantized Feedback

The goal of combining beamforming and space-time coding is to obtain full-diversity order and to provide additional received power (array gain) compared to conventional space-time codes. In this work, a previously proposed class of code constellations, called generalized partly orthogonal designs (PODs), is utilized. Both high-rate and low-rate feedback information is incorporated with possible feedback errors. A binary symmetric channel (BSC) model characterizes feedback errors and two cases are studied: first, when the BSC bit error probability is known a priori to the transmission ends and second, when it is not known exactly. Based on a minimum pairwise error probability (PEP) design criterion, we design a channel optimized vector quantizer (COVQ) and a precoder matrix codebook. The attractive property of our combining scheme is that it converges to conventional space-time coding with low-rate and erroneous feedback and to directional beamforming with high-rate and error-free feedback. This scheme also shows desirable robustness against feedback channel modeling mismatch. [27]

B. Rate and Power Adaptation over Slow Fading Channels with Noisy Quantized Feedback

Also, we consider the objective of maximizing the expected transmission rate over slow fading channels when quantized channel feedback is available for rate and power control. This problem has been recently studied in the literature assuming noiseless feedback. We consider a more realistic model, where the feedback indices are subject to errors. Our scheme considers a binary symmetric channel (BSC) model for every feedback bit. A channel optimized scalar quantizer (COSQ) is designed to utilize noisy feedback in our system. The impact of noisy quantized feedback is studied when multi-layer coding is employed to combat the uncertainty about the channel state information (CSI) at the transmitter. We also study temporal power adaptation in this system. We show that a noisy feedback system based on COSQ design never performs worse than a no-feedback system and its performance approaches a noiseless feedback scenario as the feedback link quality improves. [21]

(2) We introduce the concept of beamforming in wireless relay networks. For a network with any number of relays and no direct link, the optimal power control is solved analytically. The complexity of finding the exact solution is linear in the number of relays. Our results show that the transmitter should always use its maximal power, but surprisingly, the optimal power used at a relay can take any value between zero and its maximum transmit power. We also consider the more practical cases in which partial channel information is available. The main contributions are:

A. Beamforming in Wireless Relay Networks

This work is on relay beamforming in wireless networks, in which the receiver has perfect information of all channels and each relay knows its own channels. Instead of the commonly used total power constraint on relays and the transmitter, we use a more practical assumption that every node in the network has its own power constraint. A two-step amplify-and-forward protocol with beamforming is used, in which the transmitter and relays are allowed to adaptively adjust their transmit power and directions according to available channel information. The optimal beamforming problem is solved analytically. The complexity of finding the exact solution is linear in the number of relays. Our results show that the transmitter should always use its maximal power and the optimal power used at a relay is not a binary function. It can take any value between zero and the maximum transmit power. Also, interestingly, this value depends on the quality of all other channels in addition to the quality of the relay’s channels. Despite this coupling fact, distributive strategies are proposed in which, with the aid of a low-rate broadcast from the receiver, a relay needs only its own channel information to implement the optimal power control. Simulated performance shows that network beamforming achieves full diversity and outperforms other existing schemes. [23]

B. Distributed Beamforming in Wireless Relay Networks with Limited Feedback

First, we consider beamforming in networks whose relays know the channel means and covariances. The question we answer is: To optimize the network performance, how much power should each relay use? Two short-term power constraints are considered: an aggregate power constraint on all relays and a separate power constraint on each relay. We generalize the distributed space-time coding scheme so that each relay can adapt its transmit power according to the partial channel information it has. When the transmit power is high, we analytically solve the relay power control problems in two-relay networks based on the pairwise error probability minimization. Simulation shows that appropriate relay power control can largely improve the network reliability, especially when the qualities of the two transmission paths are far apart. In some scenarios, lack of relay power control may cause diversity loss. [22]

Then, we consider the case of the quantized beamforming in wireless 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. [25]

C. Single and Multiple Relay Selection Schemes and Their Diversity Orders

This work is on relay selection (RS) schemes for wireless relay networks. First, we derive the diversity of many single RS schemes in the literature. Then, we generalize the idea of RS by allowing more than one relay to cooperate. Several multiple RS schemes are proposed, which are proved to achieve full diversity. Simulation results show that they perform much better than the corresponding single RS methods and very close to the optimal multiple RS scheme. However, the computational complexity of the suboptimal schemes is linear in the number of relays, far superior to the optimal selection, which has exponential complexity. In addition, when the number of relays is large, the multiple RS schemes require the same amount of feedback bits from the receiver as single RS schemes. [24],[29]

(3) In another effort, we consider the problem of cross-layer design in the presence of interference. Currently, we are in the process of designing a cross-layer approach that incorporates our new physical layer methods into the MAC layer protocols. The ultimate goal is to cancel the interference in the physical layer instead of avoiding it in the MAC layer. As a first step to achieve our ultimate goal, we have studied the effects of interference in existing scenarios. The main contributions are:

A. Global Optimal Routing, Scheduling and Power Control for Multi-hop Wireless Networks with Interference

We consider the problem of joint routing, scheduling and power control in multi-hop wireless networks. We use a linear relation between link capacity and signal to interference noise ratio in our formulation. In a previous work, using a duality approach, the optimal link scheduling and power control that minimizes the total average transmission power is found. We formulate this problem as a linear programming problem with exponential number of constraints. To cope with the exponential number of constraints, we propose an iterative algorithm based on the cutting plane method. The separation Oracle for the cutting plane algorithm turns out to be an element-wise concave optimization problem that can be effectively solved using the branch and bound algorithm. We extend the same method to find the optimal routing scheduling and power control. Simulation results show that this methodology is more efficient and scalable compare to the previously proposed algorithm. [28]

B. A Study of Connectivity in MIMO Fading Ad-Hoc Networks

We investigate the connectivity of fading wireless ad-hoc networks with a pair of novel connectivity metrics. Our first metric looks at the problem of connectivity relying on the outage capacity of MIMO channels. Our second metric relies on a probabilistic treatment of the symbol error rates for such channels. We relate both capacity and symbol error rates to the characteristics of the underlying communication system such as antenna configuration, modulation, coding, and signal strength measured in terms of Signal-to-Interference-Noise-Ratio (SINR). For each metric of connectivity, we also provide a simplified treatment in the case of ergodic fading channels. In each case, we assume a pair of nodes is connected if their bi-directional measure of connectivity is better than a given threshold. Our analysis relies on the central limit theorem to approximate the distribution of the combined undesired signal affecting each link of an ad-hoc network as Gaussian. Supported by our simulation results, our analysis shows that (i) a measure of connectivity purely based on signal strength is not capable of accurately capturing the connectivity phenomenon, and (ii) employing multiple antenna mobile nodes improves the connectivity of fading ad-hoc networks. [26]

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2.10 Feedback MIMO Systems

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GSRs: Yogananda Isukapalli

SUMMARY OF RESEARCH

Our work is concerned with feedback based MIMO systems; development of effective quantization methods, analysis of feedback systems with finite rate feedback, analysis of feedback systems with imperfect channel state information.

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

In this work [1]-[3], 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.

The effect of limited feedback on the ergodic capacity is a well studied concept. Average symbol error probability (SEP), another important communication system performance metric, has received much less attention. For a limited set of constellations and for i.i.d fading channels it has been analyzed utilizing an approximation to the statistical distribution of the key random variable that characterizes the system performance. Similar to the capacity analysis, SEP analysis for correlated channels using such statistical methods has not met with much success.

In this work we first design codebooks that are optimum for minimizing the SEP loss assuming perfect channel knowledge at the receiver. For this scenario, we then make use of the source coding based framework to analyze the ASEP loss in correlated Rayleigh fading channels with rectangular QAM constellation. The application of the source coding based framework to this problem is quite involved because of the complicated dependency of the objective function on the random variables involved as well as the nature of the constellation (M1 x M2-QAM). The impact of the performance metric on the performance on the quantizer is highlighted by comparing the performance with past quantizer designs which utilize capacity loss as a metric.

The quantizer design problem in the presence of channel estimation errors is also addressed and compared to the designs that assume perfect channel knowledge at the receiver. More Details can be found in [1]-[3].

b) Refined Modeling of Imperfect Feedback for MISO systems and Performance analysis

In our previous work [4] we studied the effect of all three forms of feedback imperfection on the average symbol and bit error probabilities of various constellations. In this work [5]-[7], under the block fading (channel fixed for the entire block) assumption, we take a closer look at the feedback imperfections and modeling assumptions. For feedback systems to be practically viable, the coherence time of the channel variations has to be comparable to the feedback delay. An important consequence of the slow channel variation assumption is that averaging over the channel variations within a single block is no longer appropriate leading to the consideration of block error probabilities. To the best of our knowledge, the effect of feedback imperfections on the average block error probability, an important and a meaningful system metric, has not received much attention. As will be evident from the analysis of average block error probability (BELP) in this work, conceptually and analytically, handling the channel estimation errors along with feedback delay and finite-rate channel quantization for block fading channel model is quite involved, and is not a simple extension of the results from average symbol and bit error probabilities.

Typically the channel is estimated at the receiver with the help of training symbols. Due to the presence of thermal noise, channel estimation errors are inevitable in any practical system. We considered the issue of channel estimation in detail in [8]. 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. In a block fading channel model, the channel (its estimate and the related estimation error) is assumed to remain constant for the entire block. In this work, we also follow the standard model of joint Gaussianity between the channel and its estimate but adapt it to the block fading model. 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 [4]. In a block fading model, the average BLEP analysis has to consider the fact that error term is constant for the entire block while each symbol experiences a different noise sample.

In any practical system, feedback delay between constructing the beamforming vector at the receiver and using it at the transmitter is an un-avoidable form of feedback imperfection. Compared to our previous work [4], another significant change in this work is the modeling aspect of feedback delay. In [4] following another well accepted formulation, we modeled the behavior of feedback delay to be 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 error related error term, it becomes part of noise thus obliterating any conceptual distinction between the mismatch in beamforming due to feedback delay and estimation errors. In this work we take a closer look at the feedback delay and develop a model that results in improved system performance. The new model shows that the impact of feedback delay on beamforming MISO system performance can be less severe and conceptually it is quite different from channel estimation errors.

The third form of feedback imperfection we address is the finite-rate channel quantization. In principle, the vector quantization method is same as the one considered in [4]. However, since the channel estimation errors and feedback delay are modeled differently, quantization plays an analytically complicated role in the performance analysis.

In the performance analysis, since we are dealing with the average BLEP, it is necessary to carry out the expectation of higher powers of Gaussian Q-function, i.e., assuming a block of N un-coded BPSK symbols we have to carry out the expectation with respect to the Gaussian Q-function raised to powers from 1 to N. In [9] For $N \geq 3$, we proposed an analytically tractable tight approximation to the Gaussian Q-function to evaluate its expectation. In summary, the contributions of this work are threefold: first - an accurate characterization of estimation errors in a block fading context, second - a new modeling of feedback delay which improves the performance of beamforming MISO system and conceptually distinguishes itself from estimation errors, and third - developing tools relevant for deriving analytical expressions quantifying the impact of channel estimation errors, feedback delay and channel quantization on the average block error probability.

c) MAC Protocols for MIMO Ad-Hoc Networks

We have also developed a MAC protocol for MIMO Ad-Hoc Networks. The use of space-time block codes in ad-hoc networks has received some attention. The advantage of such a scheme is that one can benefit from the spatial diversity without significantly impacting the spatial spectral characteristics. The use of feedback has proven to be more complex. To exploit MIMO capabilities with feedback, we propose 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.

OMAC exploits the opportunities of simultaneous transmissions by using a novel rank-based physical layer metric in order to maximize the utilization of the degrees of freedom in MIMO ad hoc wireless networks. Number of active transmitters in the network is an indicator of utilization of degrees of freedom. We chose rank of the correlation Matrix of interference matrix, Rank(R_I), for estimating the number of active transmitters on the channel. A node proceeds with transmission only if estimated Rank(R_I) is less than maximum supported degrees of freedom in MIMO system. The basic Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is at the heart of the proposed OMAC protocol. The protocol transmits RTC/CTS using Space Time Block Codes (STBC) while DATA and ACK are transmitted using antenna selection diversity.

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2.11 Application of Game-Theory to Multi-user Detection in MIMO Ad Hoc Interference Networks

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GSRs: Matt Nokleby (MS Student, 50%), Michael Larsen (PhD Student, 50%)

Summary

We have investigated the use of multi-user detection to improve performance in MIMO interference networks. Unfortunately, while multi-user detection often allows higher data rates, it greatly complicates the problem: in addition to choosing a transmit covariance for each transmitter, we must decide which signals each receiver will detect and which data rates make such detection feasible. We have derived methods to optimize the data rates in two ways: (1)

maximizing the sum throughput of the network, and (2) choosing rates based on the Kalai-Smorodinsky bargaining solution from cooperative game theory. Simulation results suggest that, while sum-rate maximization yields higher average throughput, the Kalai-Smorodinsky solution provides a superior solution in terms of fairness. The simulations also suggest that multi-user detection significantly improves network performance.

Background

Mitigating the effects of mutual interference in ad hoc networks composed of multiple-input multiple output (MIMO) nodes is critical to realizing their potential throughput advantages. In MIMO links, interference can be partially avoided by spatially coordinating users' signals. For example, in [1, 2], nodes spatially "steer" their transmissions to increase the total throughput of the network. However, interference-cancelation techniques based on multi-user detection can further improve the performance of wireless systems [3]. Conceptually, if a receiver can correctly decode an interfering signal, it can "subtract" that interference from the incoming signal, allowing the intended signal to be decoded more easily and at a higher data rate. However, successful multi-user detection imposes limitations on the data rates of the interfering transmitters so that their signals may be detected and subtracted out.

We have studied the information-theoretic advantages of incorporating multi-user detection in optimizing users' data rates in a MIMO interference network. Each transmitter must choose an input covariance matrix, which spatially characterizes the transmitted signal, and each receiver must decide which interfering signals to detect. These decisions define a set of feasible data rates. We therefore choose covariances and detection decisions in order to maximize users' rates.

Of course, in a network of interfering links, it is impossible to simultaneously maximize each user's rate. So, we choose the optimal rates in two different ways. First, we simply maximize the sum of the users' rates, or the total network throughput. However, maximizing throughput often results in solutions where weaker links are forced to transmit at low data rates. Therefore, we also consider the Kalai-Smorodinsky bargaining solution [4] from cooperative game theory. This approach axiomatically defines an efficient solution that explicitly considers individual users' rates. Our simulation results suggest multi-user detection significantly improves the performance in both solutions. They also suggest that the Kalai-Smorodinsky solution significantly improves the fairness of the users' rates, but has lower total throughput than sum-rate maximization.

Simulation Results

To examine the effectiveness of our methods, we have performed simulations on randomly-generated networks. We assume Rayleigh-fading channels and network nodes that are randomly and uniformly located on the unit square. In Figure 1 we plot the average per-user rate for a variety of values of L (number of interfering links) and N (number of antennas at each network node) for both the sum rate and K-S solutions. We choose $N = 2$ when $L < 5$ and $N = 3$ for $L = 5$. As a baseline, we also compute results for single-user detection. Each data point represents the average of 100 independent trials. Naturally, maximizing the sum rate gives the best average rate, while the K-S solution performs somewhat worse. Indeed, in terms of sum rate, it is better to maximize using single-user detection than to use the K-S solution under multi-user detection. Next, in Figure 2 we plot the average of the *worst* user's rate as a partial measure of the fairness of each solution. In terms of fairness, the K-S solution clearly performs better. Although the average rate is lower, users enjoy improved worst-case performance over sum-rate maximization.

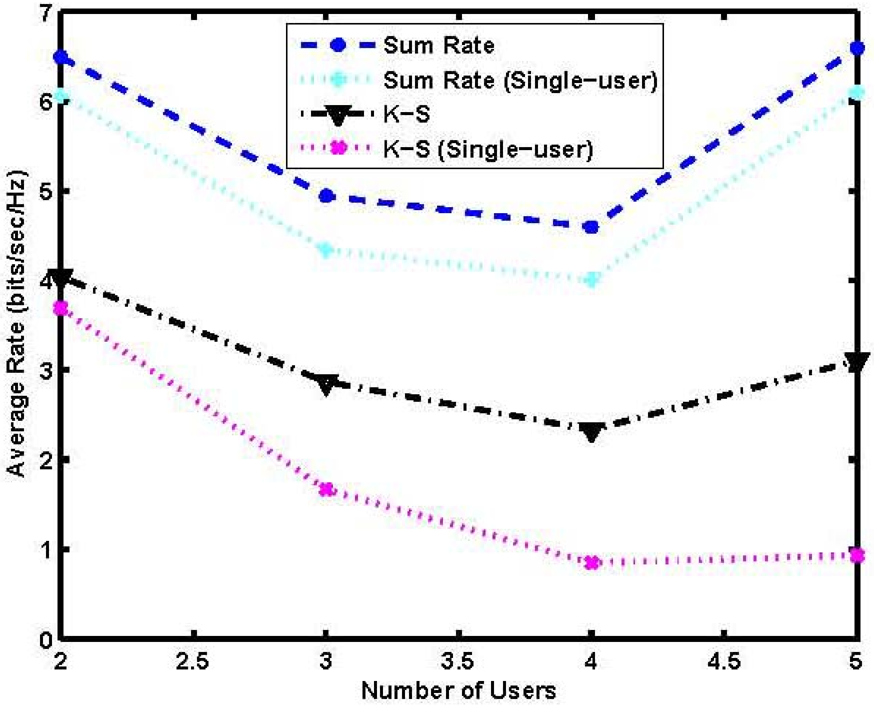

Figure 1: Average rate per user for sum-rate and K-S solutions.

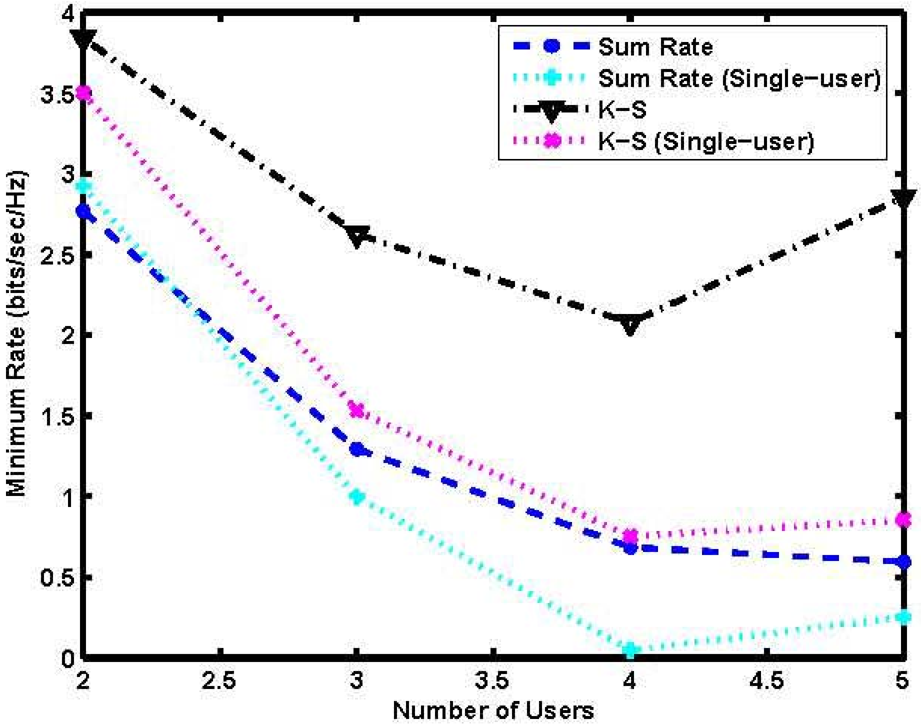

Figure 2: Worst user's rate for sum-rate and K-S solutions

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2.12 Random multi-hop networks: assessing the impact of physical layer techniques and characterizing delay and throughput

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Graduate Student: Kostas Stamatiou

1. Introduction

We consider a network composed of an infinite number of *routes* on an infinite plain. The first approach we take is to assume that each route simply consists of only one link, i.e., a transmitter (TX) and a 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 antennas, the multiple-input multiple-output (MIMO) technique, e.g., space-time coding or spatial-multiplexing (see [1] and [2] in Section 1).

The above single-hop approach, albeit providing useful insight with respect to how physical layer choices affect the link performance, 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 (see [3] in Section 1) 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 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.

Regarding 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.

2. Achievements

In [1] and [2], the single-hop approach is followed in order to evaluate the impact of different MIMO techniques on the network throughput and the information efficiency. These techniques are: maximal-ratio-combining (MRC), orthogonal space-time block coding (OSTBC) and spatial multiplexing via zero-forcing (SM-ZF). FH is selected as the MA scheme, i.e., the carrier frequency is randomly selected from a set of M frequencies every dwell, *during* the transmission of a packet (a dwell is a group of symbols that are transmitted on the same frequency). The fading matrix is estimated in each dwell with the help of pilot symbols, so that the aforementioned MIMO techniques can be applied. Since the fading and the level of interference change within the packet, a convolutional code is employed to harness the available frequency and interference diversity across dwells. A Viterbi decoder at the RX decides what is the most likely packet/codeword to have been transmitted.

Our main results are (all nodes are equipped with the same number of antennas):

- In terms of network throughput, for a small number of antennas (<4), MIMO spatial diversity techniques provide larger gains. Moreover, the performance of OSTBC and MRC is comparable; the former provides a larger spatial diversity order than the latter, at the expense however of increased interference in the network. For a larger number of antennas, SM-ZF can outperform spatial-diversity techniques, provided that an appropriate number of streams is activated. Our analysis provides a good approximation to this number, that depends on the total number of antennas and the path-loss exponent.
- In terms of information efficiency, SM-ZF with any number of streams outperforms spatial diversity techniques. Once again, the gain can be maximized by appropriately selecting the number of activated streams.
- The gain of a coded over an uncoded system in terms of throughput and information efficiency is substantial and most of it is obtained for relatively low code diversity orders, i.e., moderate complexity.

In [3], the multi-hop system described in Section 2 is considered. In more detail, each route comprises a source, a destination at distance R and N-1 relays on the line defined by the source-destination pair. The distance of the n-th relay, n = 1,...,N-1, from its source is the same for all routes. Time is divided into packet slots and the following synchronous protocol is observed: all nodes at the same distance from their source, transmit the packet at the head of their queue, then wait for N slots till they can transmit again (in this manner intra-route interference is avoided). If a packet is successfully received by the next node, it is appended at the end of its queue, otherwise it remains at the head of the queue of the transmitting node, waiting for the next attempt. A packet is successfully received, provided that the SIR at the given hop is above a certain threshold, β. This physical layer model implies that all symbols in the packet are transmitted over the same band, facing the same interference and fading conditions, which is quite different from the model considered in [1] and [2]. However, it allows the derivation of a compact expression for the packet error, or *outage*, probability, which in turns facilitates the computation of the end-to-end delay and the throughput.

Each relay in the route introduces a *queueing* and a *head-of-line* delay, which are functions of the packet success probabilities over the hops preceding and following that relay. The sum of these constituent delays yields the end-to-end delay. It also turns out that, provided all queues are stable, the throughput of a typical route is the success probability in the first hop, divided by the number of hops, N. The network throughput is evaluated by simply multiplying the route throughout, with the density of sources λ.

We now provide an indicative list of results of the multi-hop model described above. Fig.1 shows the delay for a two-hop system as a function of the relay placement. Note that there is a relay placement that minimizes the delay. Moreover, the delay becomes very large as the relay is placed closer to the half-point. In fact, it can be proved that the relay queue becomes unstable when the relay is placed at or below the half-point. Fig.2 shows the delay - optimized over all possible relay positions - as a function of R, for different numbers of hops. Note that, for each R, an optimal number of hops exists that provides the smallest delay. Also, the lower envelope of these curves is approximately linear, which agrees with the intuition that the minimum time to traverse a network should linearly increase with the network radius. In Fig.3, the respective network throughput curves are shown. It is seen that, approximately, the same number of hops that minimizes delay also maximizes the network throughput.

3. Future Work

We would like to extend our recent results for the multi-hop scenario, when the nodes in a route have MIMO capabilities. Is it preferable to use the multiple antennas in order to empty the queues faster (spatial multiplexing) or to provide larger link success probabilities (spatial diversity)? We would like to have design insights as to what MIMO techniques are more beneficial in terms of end-to-end delay and throughput. We believe that, such an extension to our current analysis, demands the derivation of simple formulas for the outage probability, in the presence of spatial diversity. This will be the subject of future work.

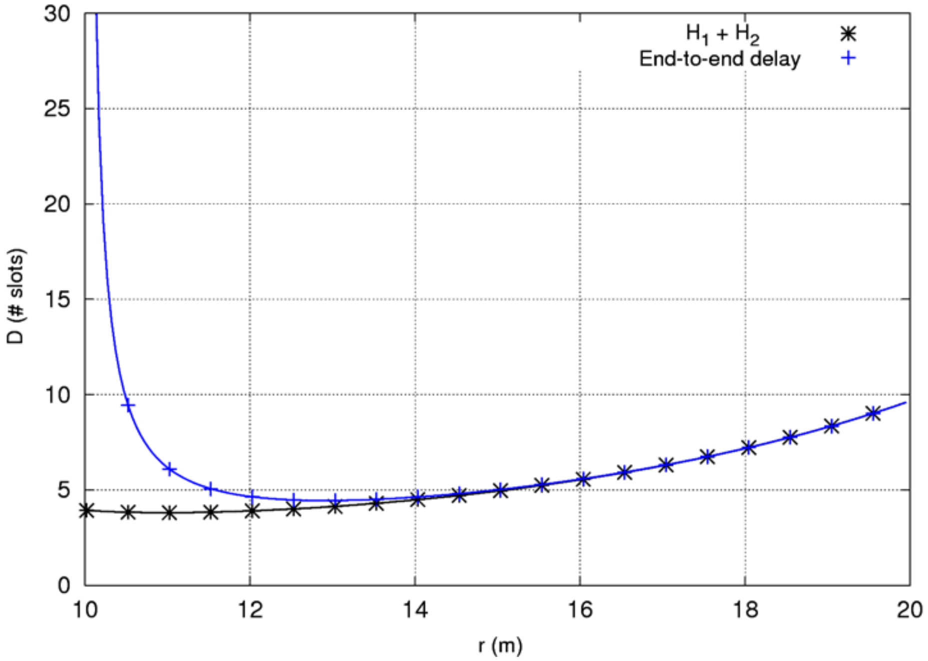

Fig.1 - Delay vs. relay position (N = 2, R = 20m, b = 4, λ = 0.0004, β = 6dB).

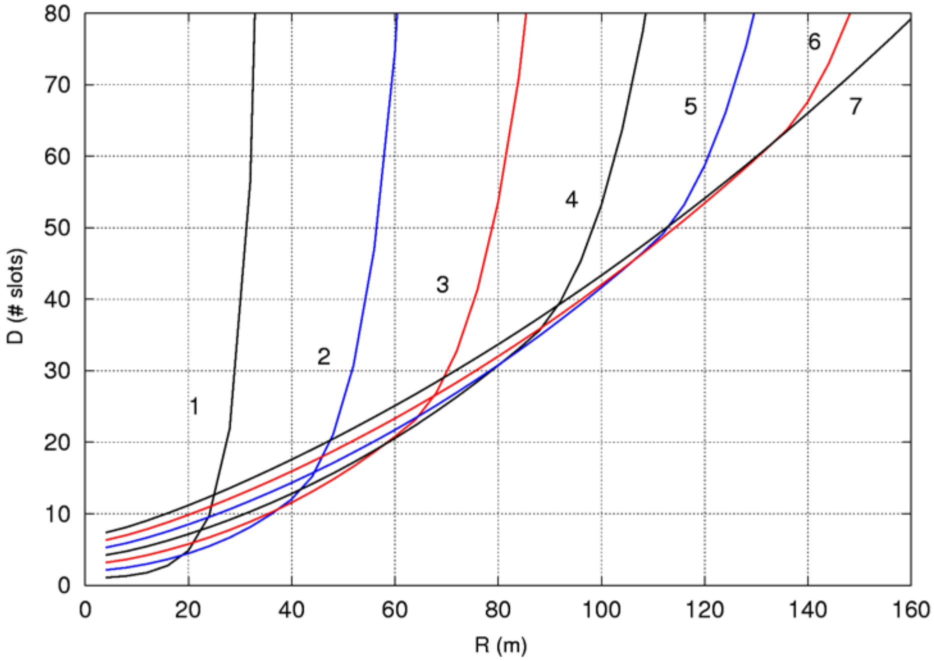

Fig.2 - Delay vs. R (b = 4, λ = 0.0004, β = 6dB).

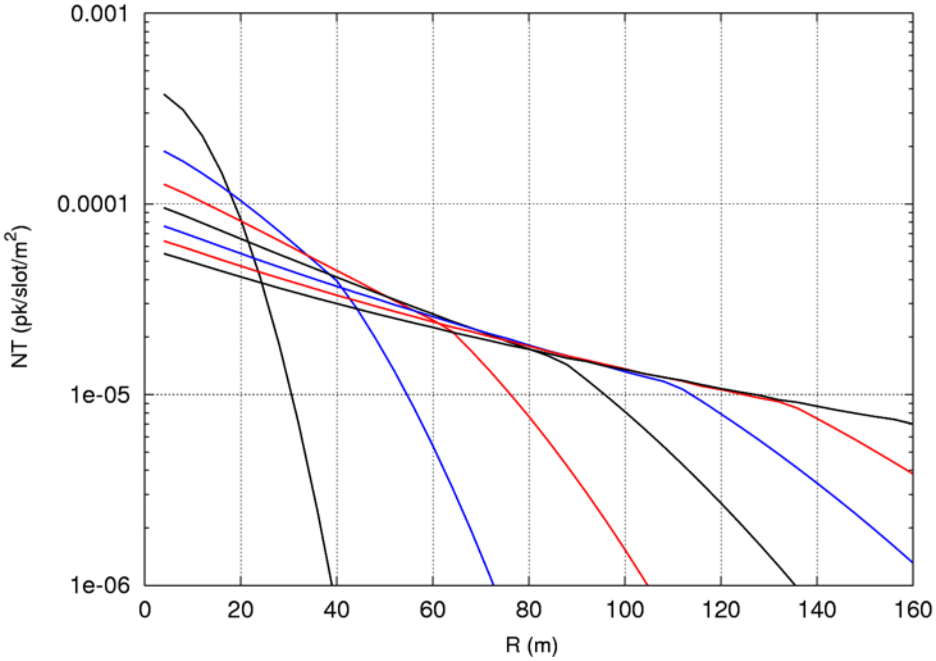

Fig.3 – Network throughput vs. R (b = 4, λ = 0.0004, β = 6dB).

2.13 Propagation Modeling and Stable Signaling for MIMO Communications in Mobile Ad Hoc Networks

PIs: Michael A. Jensen

GSR: Chan Chen, Daniel Evans

Summary of Accomplishments

During this period we have primarily emphasized two research projects relevant to the overall focus of channel characterization for MIMO communications in mobile ad hoc networks:

1. *Modeling of the Time-Variant MIMO Channel:* During the prior year, we developed two different modeling approaches for the time-variant MIMO channel for mobile radios. We have expanded this work, creating a stochastic model for the multipath parameters which is then used to create an accurate and physically-realistic model for time-varying channel responses.
2. *Covariance-Based Signaling for Frequency-Selective Channels*: Our joint work with UCSD has focused on the use of covariance-based transmission for time-variant channels. We have now demonstrated its applicability for frequency selective channels as well, with the result that high performance can be maintained with reduced feedback requirements relative to CSI-based signaling strategies.

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

Modeling the Time-Variant MIMO Channel

Our goal is to explore the extension of conventional MIMO channel modeling techniques to time-varying channels by extracting model parameters from measured data and using information theoretic metrics to determine if the models capture the correct channel behavior. In the past, we have focused on (1) a random matrix model following the multivariate complex normal (MVCN) distribution and (2) a physical time-variant clustering (TVC) model [1]. However, in our prior implementation of the TVC model, we did not identify a stochastic description of the cluster behaviors. In this work, we have extended the TVC model to include an auto-regressive (AR) model for the multipath cluster parameters.

TVC Model

The double-directional channel concept is a powerful technique for system-independent representation of spatial channels, and much research effort has been dedicated to extracting the parameters for individual multipath components from measured data. Alternatively, we can treat the channel as an incoherent process described by a double-directional power spectrum [1]. This method groups multipath components into clusters of arrivals and departures and estimates only the cluster parameters.

Cluster Extraction

The first step is to define the clusters in a measured channel. This is accomplished by the following steps:

1. Estimate the covariance matrix over a moving window from the sampled data and compute the time-variant power angular spectrum (PAS) of the multipath environment from the array configuration and covariance matrix.
2. Extract the set of clusters from the PAS representing 90% of the channel power.
3. Construct waveforms for each cluster representing the time variation of the angle of departure (AOD), angle of arrival (AOA), and power gain. Construct zero-mean unit-variance versions of these waveforms using appropriate transformations. The mean for the AOA and AOD are found to be uniformly distributed on the circle, while the variance is 19.4 degrees for the AOD and 63.6 degrees for the AOA (differences due to the fact that only the receiver is moving). For the power gain, this process also yields a pdf of the mean as well as that of the square root of the variance conditioned on the mean.
4. Generate probability mass functions (pmf) for the number of new clusters that appear at any given time sample and the duration of a cluster.
5. Generate a stochastic description of the waveforms for each type of parameter (AOD, AOA, or gain) consisting of a pdf and power spectral density (PSD).
6. Process the waveforms through a whitening filter to generate a pdf of a temporally white innovation process describing each cluster parameter.

Auto-Regressive Model

The model now consists of a temporally white pdf and PSD for each cluster parameter as well as the auxiliary statistical descriptions (distributions describing the mean and variance of the cluster parameters). To model implementation for the *q*th cluster follows the following steps:

1. We first realize the random variable K_q representing the survival time from the appropriate pmf as well as the random variables $\mu_{\gamma,q}$ representing the mean for the AOD ($\gamma = T$), AOA ($\gamma = R$), and power gain ($\gamma = G$) from the extracted pdfs. We also construct the square root of the variance $\sigma_{\gamma,q}$ for $\gamma = (T, R, G)$ from the appropriate distributions.
2. For each cluster parameter (AOD, AOA, or gain), we generate a temporally white random sequence of length K_q from the innovation pdf extracted previously.
3. This white sequence is passed through a filter with response $H_\gamma(z)$ describing the PSD for the appropriate parameter. The output of this filter is a temporally-correlated sequence whose stochastic parameters (pdf, correlation) match that of the unit-variance zero-mean waveforms extracted from the data.
4. The correlated sequence is scaled by $\sigma_{\gamma,q}$ and then added to $\mu_{\gamma,q}$.

Figure 1 shows a block diagram representing this implementation of the auto-regressive (AR) model.

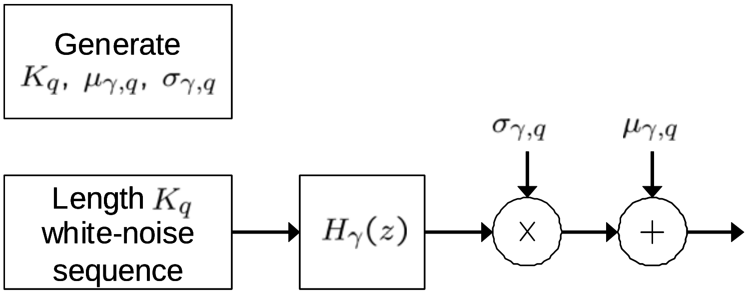

Figure 1: Block diagram describing the AR model used to generate the AOD, AOA, or power gain of an individual cluster in the time-varying stochastic multipath model.

Synthetic Channel Generation

Now that we have developed a mechanism for modeling the time-varying behavior of multipath spatial clusters, we can turn attention to using this framework within a more comprehensive model of the time-varying MIMO channel. We first must determine the number of clusters $Q^{(k)}$ that exist at time sample *k*. For simplicity, we assume that $Q^{(0)} = 4$ and subsequently use the pmf of cluster "births" to determine if a new cluster should be generated at each time step. For each cluster, we generate the AOD, AOA, and power gain as a function of time sample.

We next approximate each cluster with *L* multipath components (rays). AOD $\bar{\phi}_{T,q\ell}$ and AOA $\bar{\phi}_{R,q\ell}$ values for the ℓth ray in the *q*th cluster are each drawn from a zero-mean Laplacian distribution with an angle spread of 26 degrees based on the findings or our prior work, and the model-generated time-varying AOD and AOA waveforms are added to these values to obtain the sequences $\phi_{T,q\ell}^{(k)}$ and $\phi_{R,q\ell}^{(k)}$. Similarly, we compute the voltage gain $\alpha_{q\ell}$ of the ℓth ray in the *q*th cluster as a realization of a zero-mean, unit-variance complex Gaussian random variable which is multiplied by the time-variant voltage gain waveform to obtain the voltage gain sequence $\beta_{q\ell}^{(k)}$. To avoid abrupt changes in the channel, the gain sequence is windowed using a Hamming window. With the multipath parameters described by these time series, the synthetic channel matrix is then realized as

$$H_{mn}^{(k)} = \frac{1}{\sqrt{Q^{(k)}L}} \sum_{q=1}^{Q^{(k)}} \sum_{\ell=1}^{L} \beta_{q\ell}^{(k)} e_{R,m}^{(k)}\left(\phi_{R,q\ell}^{(k)}\right) e_{T,n}^{(k)}\left(\phi_{T,q\ell}^{(k)}\right)$$

where the complex field patterns $e_{R,m}^{(k)}\left(\phi_{R,q\ell}^{(k)}\right)$ for the *m*th receive antenna and $e_{T,n}^{(k)}\left(\phi_{T,q\ell}^{(k)}\right)$ for the *n*th transmit antenna are explicitly functions of time index *k* since their positions may vary in time due to node motion.

Model Comparisons

Figure 2 demonstrates that the cluster data from the model matches that extracted from the experimental data in a statistical sense. However, it is also important that we validate the time evolution of the channel matrices generated from the multipath data. The multivariate nature of the channel matrix complicates efforts to perform this validation. In this work, we will adopt the approach from our prior work of comparing the values of established measures for quantifying the level of MIMO channel time variation generated from the model to those obtained directly from the measured channel matrices. These measures, which are detailed in [1], quantify the information theoretic loss in performance caused by using outdated CSI in the signaling strategy. More explicitly, the transmit capacity delay (TCD) approximates the capacity loss that occurs at time sample *k* when the transmitter forms its signaling strategy using the CSI at time sample 0. Similarly, the receive capacity delay (RCD) approximates the capacity loss that occurs when both the transmitter and receiver use outdated CSI in their signaling strategy.

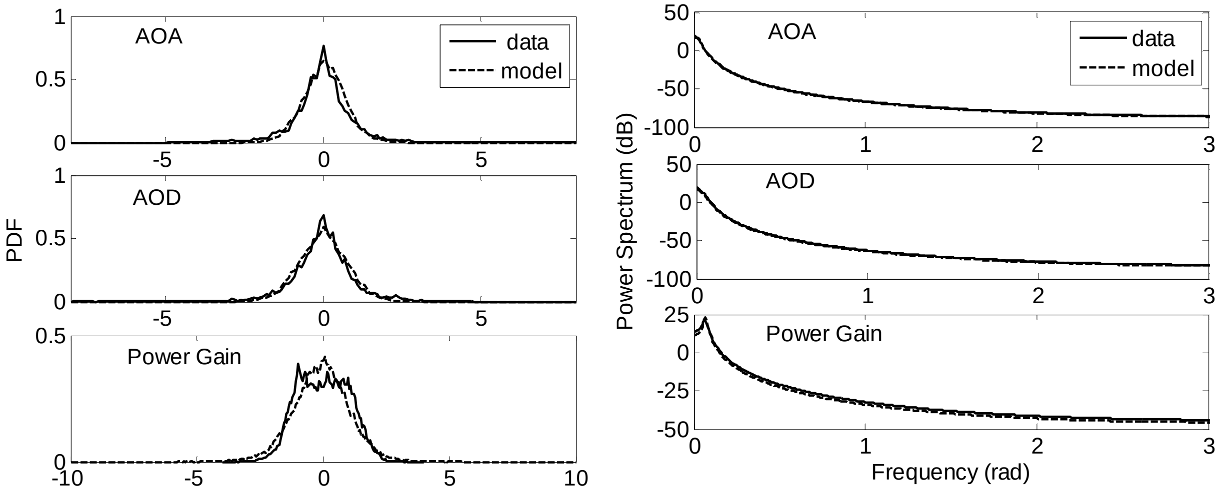

Figure 2: Zero-mean, unit-variance pdfs and power spectra for the AOA, AOD, and power gain for the multipath clusters obtained from the data as well as the stochastic time-varying model.

In the following computations, we assume that the transmit and receive antennas are eight-element UCAs of monopoles identical to those used for the measurements to allow comparisons between the experimental and simulated results. The transmitter remains fixed during the simulation, while the receiver moves in a straight line. The total average transmit power and single-receive average noise power are then computed to produce a single-input single-output signal-to-noise ratio of 10 dB.

Figure 3 plots the TCD normalized to a peak value of unity as a function of receiver node displacement computed from both the measured (averaged over all measurements) and modeled (averaged over 3000 channel realizations) data. This plot is interesting, since it reveals that the model is accurate for short displacements up to about 10 cm even when cluster birth and death is excluded. This suggests that over short displacements, the dominant effect is simply the variation of the cluster angles and gains as well as motion of the node within the environment. However, for larger displacements, cluster birth and death is required for the model to maintain high accuracy, revealing the importance of this process in the channel description.

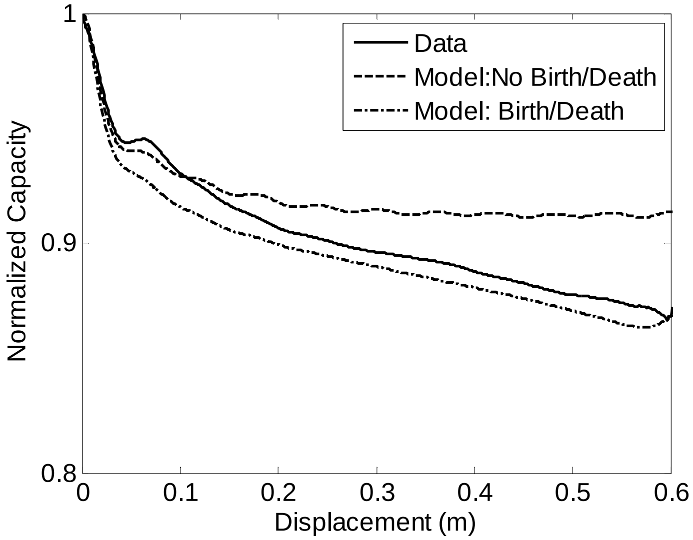

Figure 3: Normalized average TCD metric as a function of receiver displacement computed from the original measured data and the time-variant model.

Figure 4 plots the RCD, plotted versus electrical displacement under the same circumstances outlined in connection with Fig. 3 with the exception that only 1000 channel realizations were necessary to obtain a statistically valid result. In this case where both transmitter and receiver CSI are outdated, the capacity drops dramatically with node displacement, revealing the high sensitivity to accurate receive CSI. The model is able to capture this effect very accurately (with or without cluster birth and death), suggesting that the dominant effect is the change in the CSI due primarily to node motion and secondarily to the cluster variation.

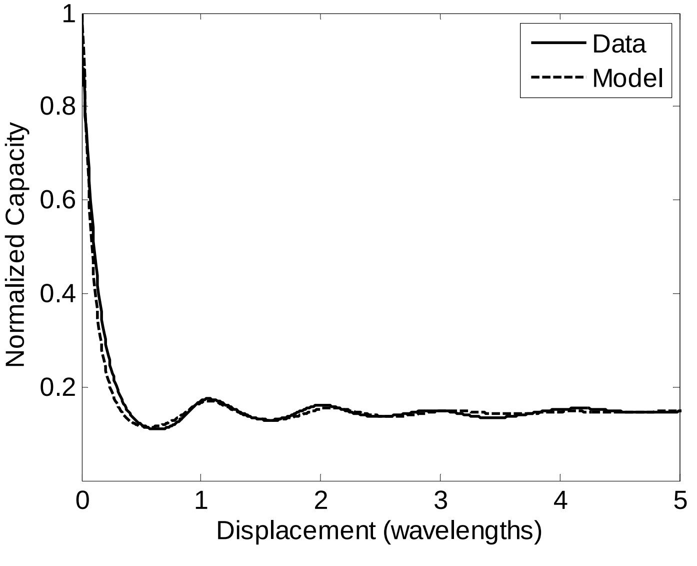

Figure 4: Normalized average RCD metric as a function of receiver displacement computed from the original measured data and the time-variant model.

The multi-user, multiple-input multiple-output (MIMO) broadcast channel has recently been the subject of tremendous interest, resulting in the development of the sum-capacity achieving non-linear dirty paper coding (DPC) as well as linear precoding (beamforming or BF) methods that offer a low complexity but sub-optimal alternative transmission technique capable of transmitting the same number of data streams as that enabled by a DPC-based system. However, these methods show sensitivity to inaccurate or outdated channel state information at the transmitter, and therefore their performance can degrade significantly in realistic operational environments.

Motivated by the performance loss suffered by outdated CSI in time-varying environments, we have recently developed a linear 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 MIMO broadcast channel [2]. Analysis with measured data taken for mobile receiving nodes reveals that this approach provides a multi-user sum rate superior to that offered by DPC or CSI-based beamforming approaches once the nodes have moved 0.25 to 0.50 wavelengths from their initial position (i.e. the position at which the CSI is estimated). Despite all of this analysis for time-varying channels, there currently exists no data which indicates the degradation in CSI-based schemes with frequency offset (i.e. using CSI at one frequency to compute precoding vectors at another) or which studies the stability of CDI-based strategies in the frequency-selective MIMO broadcast channel. Such an analysis is particularly relevant for wideband systems employing multi-frequency signaling schemes such as orthogonal frequency division multiplexing (OFDM). If stable transmission can be found using a single precoding strategy for the entire bandwidth, then this potentially allows a significant reduction in the amount of feedback data required to achieve communication.

The goal of this work is to provide this analysis of different precoding strategies in the frequency selective communications channel. Using measured data, we first explore the degradation in performance for DPC and CSI-based beamforming created by using channel estimates at one frequency to form the precoding strategy at a different frequency. We next compare the sum rate achieved under these conditions with the rate offered by the CDI-based precoding strategy under the same circumstances. The analysis shows that the CSI-based schemes suffer from high sensitivity to frequency variations within the communication band, but that the CDI-based approach offers high stability in realistic measured channels.

System Model, Measured Data, and Transmit Precoding

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 assume a multi-tone signaling strategy such as OFDM, with the N_r x N_t channel matrix from the transmitter to the jth user and at the kth frequency $1 \le k \le K$ denoted as $\mathbf{H}_j^{(k)}$. Assuming that transmit precoding (non-linear or linear) has been applied such that $\mathbf{x}_j^{(k)}$ represents the precoded vector destined for the jth user at the kth frequency bin within the communications bandwidth, the received vector for the *j*th user at the *k*th frequency bin can be expressed as

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

where $\boldsymbol{\eta}_j^{(k)}$ is zero-mean unit-variance additive white Gaussian noise.

One key issue of importance for this work is that any precoding strategy that exploits the MIMO capabilities to allow simultaneous transmissions from the transmitter to multiple receivers requires that the nodes possess some information regarding the channels to the various users. It is not unreasonable to assume that through training, tracking, and prediction techniques, the *j*th receiver can maintain a reasonably accurate estimate of $\mathbf{H}_j^{(k)}$ for all frequencies. However, for systems that have mobile nodes or nodes placed in a time-varying propagation environment, maintaining accurate CSI for all users and frequencies at the transmitter requires frequent feedback of channel coefficients which can be costly in terms of communication resources.

The goal of this work is to extend our prior study to assess the degradation in DPC and CSI-based beamforming strategies under the scenario where the transmitter uses CSI at a single frequency to construct the precoding over the entire bandwidth and to study the potential stability of CDI-based beamforming in this scenario. To perform this analysis, we must be able to determine representations for $\mathbf{H}_j^{(k)}$ whose space-frequency behavior is consistent with that created by realistic propagation environments. We will accomplish this by making use of measured channel data taken within indoor and outdoor environments. The test equipment used allows sampling of a single-user point-to-point MIMO link with $N_r = N_t = 8$ antennas. The indoor and outdoor measurements respectively cover 60 MHz and 8 MHz of bandwidth with 1 MHz spacing at a center frequency of 2.55 GHz. The channel coefficients used in this analysis were measured with a stationary transmitter and a receiver moving at a constant velocity (30 cm/s). Measurements were taken for $N_u = 5$ (indoor) or $N_u = 4$ (outdoor) different receiver locations for a fixed transmitter location, with the resulting channel matrix for the *j*th receiver location and the *k*th frequency bin used to represent the channel matrix $\mathbf{H}_j^{(k)}$. For the results shown in this work, the matrices are reduced to accommodate square systems such that $N_t = N_u$ and $N_r = 1$.

Consistent with our prior work, we will explore three signaling techniques for the MIMO broadcast channel:

1. Dirty paper coding (DPC)
2. CSI-based beamforming (CSI-BF)
3. Channel distribution information (CDI)-based beamforming (CDI-BF).

We will also use the sample expected throughput (SET) as defined in [2] but modified to incorporate variation in frequency as opposed to variation in time.

Results

In this analysis, each receiver is assumed to possess perfect CSI at all frequencies. In contrast, however, the transmitter in the case of DPC or CSI-based beamforming chooses its precoding vectors for all frequency bins based on the CSI at the lowest frequency. In the case of CDI-based beamforming, the correlation matrix is similarly computed based on the data at the lowest frequency bin. In all cases, the SET as a function of frequency offset is averaged over the time series and all starting frequencies in the measurement for fixed network parameters and total transmit power level P (see [2]).

Figures 5 and 6 plot the SET versus frequency offset using two different datasets from the indoor environment for $N_t = 5$ transmit antennas and $N_u = 5$ users. The total allocated power is fixed at $P = 10$. In both cases, the results reveal that DPC has the highest throughput under perfect CSI but is also highly sensitive to changes in CSI as a function of frequency. CSI-based beamforming similarly achieves high performance with perfect CSI, but this performance also falls dramatically with frequency displacement. However, when CDI-based beamforming weights are used, the throughput remains quite stable with frequency variations. As a result, its performance is superior to that offered by either DPC or CSI-based beamforming for frequency offsets beyond 10 MHz. This result, which is consistent with the results observed for channel time variation, suggests that the beamforming weights derived from the channel correlation reside in more stable subspaces within the multi-user frequency-variant channel.

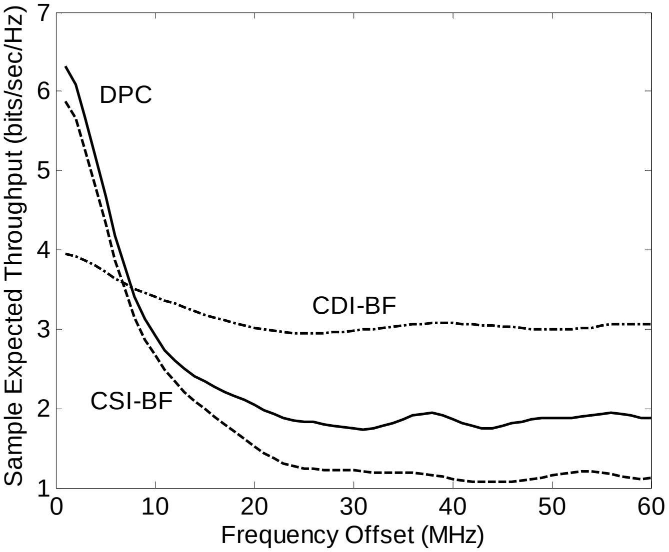

Figure 5: SET as a function of frequency offset for DPC, CSI-based beamforming (CSI-BF), and CDI-based beamforming (CDI-BF) for $N_t = N_u = 5$, $N_r = 1$, and $P = 10$ for one channel measurement in the indoor environment.

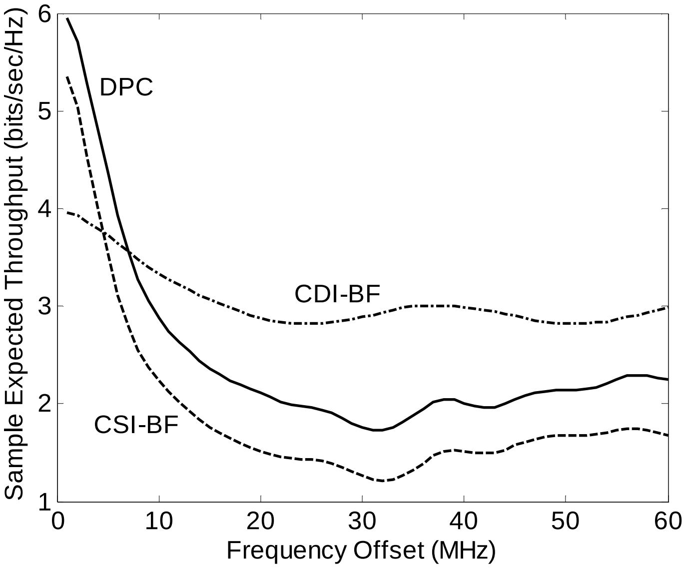

Figure 6: SET as a function of frequency offset for DPC, CSI-based beamforming (CSI-BF), and CDI-based beamforming (CDI-BF) for $N_t = N_u = 5$, $N_r = 1$, and $P = 10$ for one channel measurement in the indoor environment.

The implications of these results are valuable in that they assist in making design choices for networks operating in this type of scenario. For example, if CSI-based techniques are to be employed, the system must feedback CSI at more frequencies if the performance is to remain higher than that achievable with CDI-based beamforming with feedback only at the initial frequency. This effect is quantified more clearly in Figure 7 which plots the SET averaged over the entire frequency band as a function of the number of frequency tones at which CSI or CDI is fed back. This plot reveals that over this 60 MHz channel, if CSI is fed back at only two or three tones, the average performance of DPC is higher than that of CDI-based beamforming computed from CDI at a single tone. From a feedback perspective, DPC only requires a vector of length N_t for each user and frequency tone, while CDI-based beamforming requires a N_t x N_t matrix. Therefore, DPC requires less feedback than CDI-based beamforming for this example. While CSI-based beamforming does not perform as well as DPC, it still can offer improved average performance relative to CDI-based beamforming with reduced feedback requirements.

While this analysis would appear to argue for the implementation of CSI-based techniques, there are several key items that play into an ultimate decision of which signalling technique to use. First, for MIMO links for each user ($N_r > 1$), CSI-based techniques require additional feedback. Second, while the average SET is higher using DPC or CSI-based beamforming, the variation in the SET across the frequencies is much higher for these techniques than it is for the CDI-based beamforming. Therefore, realizing this improved performance requires variable modulation and coding rates in frequency to allow precise loading of bits across the frequency bins. If all bins use the same modulation and coding, then the performance will suffer. In contrast, since the performance remains relatively flat in frequency for CDI-based beamforming, the same modulation and coding could be efficiently applied across all bins in the band for this technique. Third, for mobile systems where the CSI varies rapidly in time, CDI-based beamforming starts to quickly outperform CSI-based techniques since it enables dramatic increases in the time interval between feedback. Therefore, for systems operating in time-varying and frequency-selective environments, CDI-based beamforming enables strong performance with a significant overall decrease in required feedback bandwidth.

Finally, while in these indoor environments the frequency offset at which CDI-based beamforming outperforms DPC is relatively large, in other environments characterized by richer scattering, this cross-over frequency offset may be reduced considerably. Consider, for example, Figure 8 which plots the SET as a function of frequency offset for $N_u = N_t = 4$ and $N_r = 1$ in the outdoor environment. This environment is characterized by several large metal and concrete buildings surrounding the measurement area and many cars parked within the area, resulting in a high scatterer density. In this case, the offset at which DPC and CSI-based beamforming cross the CDI-based beamforming curve is approximately 1 MHz, as compared to the 10 MHz offset for the indoor environments. This example demonstrates the existence of more frequency selective environments in which CDI-based beamforming offers an increased advantage relative to CSI-based techniques

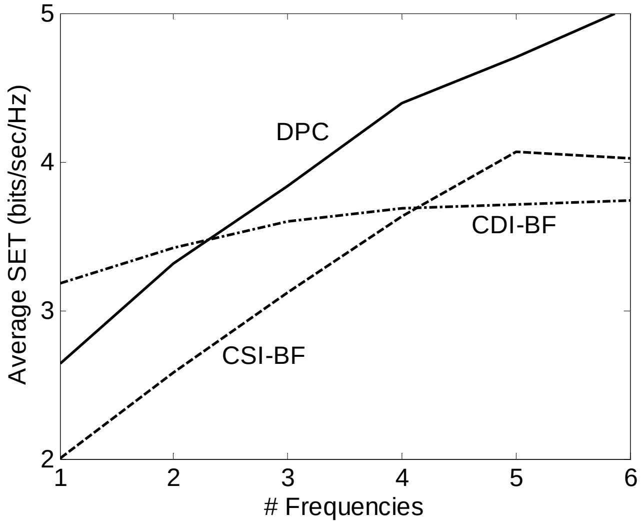

Figure 7: Average SET as a function of the number of frequency tones at which feedback is provided for DPC, CSI-based beamforming (CSI-BF), and CDI-based beamforming (CDI-BF) for $N_t = N_u = 5$, $N_r = 1$, and P = 10 for the environment considered in Figure 5.

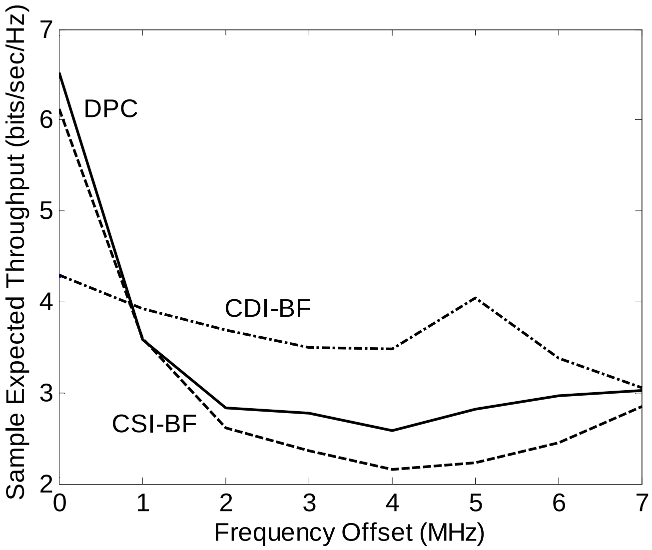

Figure 8: SET as a function of frequency offset for DPC, CSI-based beamforming (CSI-BF), and CDI-based beamforming (CDI-BF) for $N_t = N_u = 4$, $N_r = 1$, and P = 10 for one channel measurement in the outdoor environment.

References

[1] J. W. Wallace and M. A. Jensen, "Time varying MIMO channels: measurement, analysis, and modeling," *IEEE Trans. Antennas Propag., Special Issue on Wireless Communications*, vol. 54, pp. 3265-3273, Nov. 2006.

[2] A. 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, 2008.

3. Conclusions

At the start of this project the focus was on improving point-to-point communications and using the antenna assets at the physical layer to minimize collision to improve overall routing and scheduling performance of tactical mobile ad hoc networks (MANETs). Since that time it has become clear that the best way to satisfy our original goal 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 requires a fundamentally new approach to routing and scheduling that exploits the possibilities provided by the multiple simultaneous data streams between the nodes. These parallel data streams allow multipacket transmission and reception and offer important options for developing more robust routing and scheduling protocols.

During the past year, protocols and architectures to implement unicast, multicast, broadcast and various forms on one-to-one, one-to-many and many-to-many routing in MIMO MANETs have been developed and the improvements in network performance have been demonstrated. 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 net gain that can be realized by the MIMO links and the capacity of the MIMO MANETs are defined by the precoding and detection schemes that are utilized by the transmitter s and receivers at the nodes as well as the link access algorithm employed. We have developed and analyzed both linear and nonlinear precoding and detections approaches and power/rate allocation algorithms. We have also defined the fundamental limits on capacity for various forms of multiple access links and developed rate maximizing beamforming algorithms. The rate maximizing beamforming approaches require accurate CSI at all nodes and hence suffer performance losses due to erroneous CSI that inevitably arises in mobile networks due to limited training, channel estimation errors, feedback delay between nodes, quantization of the feedback information to limit network overhead, and node mobility. Fundamental studies of the impact of the training algorithms, quantization errors, and modulation and coding approaches have been completed. Significant effort has been made to define the best transmission strategies as a function of the available CSI.

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 channel variations at the physical layer and the temporal stability required 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 (CDI) instead of CSI. The results were demonstrated using data collected at BYU. 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.

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 and utilized to examine issues such as the determination of the optimal number of hops that satisfy specified network constraints.

4. Appendices

Appendix 1: Honors and Awards

J.J. Garcia-Luna-Aceves

Marquis Who Is Who in the World, 2008
Marquis Who Is Who in America, 2008

Conference Organization:

General Chair, ACM MobiCom 2008

Member of Technical Program Committee, ACM Mobicom 2008, San Francisco, CA, September 14-19, 2008.

Member of Technical Program Committee, ICCCN '08. 17th International Conference on Computer Communications and Networks, St. Thomas U.S. Virgin Islands, August 4 - 7, 2008.

Member of Technical Program Committee, IEEE SECON 2008, San Francisco Bay Area, June 16-20, 2008.

Yingbo Hua

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

Editor, Signal Processing (EURASIP), 2005-2008.

Guest Editor, IEEE Signal Processing Magazine Special Issue on Signal Processing for Cognitive Radio Networks, 2007-2008.

Member, IEEE Signal Processing Society Technical Committee on Signal Processing for Communications, 2005-2007.

Member, IEEE Signal Processing Society Technical Committee on Sensor Array and Multi-channel Processing, 2005-2007

Member of Technical Committee, IEEE Workshop on Sensor Array and Multi-Channel Signal Processing, Darmstadt, Germany, 21-23 July 2008.

Member of Technical Committee, First International Association for Pattern Recognition Workshop on Cognitive Information Processing, June 9-10, 2008, Santorini, Greece.

Member of Technical Committee, IEEE Workshop on Signal Processing Advances in Wireless Communications, Recife, Brazil, 6-9 July 2008.

Member of Advisory Board, International Conference on Information, Communications and Signal Processing, Singapore, 10-13 December 2007.

Hamid Jafarkhani

Area Editor, IEEE Transactions on Wireless Communications.

Guest Editor, IEEE Journal of Selected Topics in Signal Processing.

Session chair:

IEEE Global Communications Conference (Globecom), 2007, IEEE Data Compression Conference (DCC), 2008, and the Information Theory and Applications Workshop, 2008.

TPC member:

IEEE International Conference on Communications (ICC), 2008, IEEE Wireless Communications and Networking Conference (WCNC), 2008, and the IEEE Data Compression Conference (DCC), 2008.

Michael Jensen
Elevated to Fellow of the IEEE, January 2008

Invited Keynote Address: *2008 International Symposium on Antennas, Propagation, and EM Theory,* Kunming, China, November 2008

Invited Panel Participation: *2008 IEEE Conference on Sensor and Ad Hoc Communications and Networks*, San Francisco, CA, June 2008.

Invited Keynote Address: *2007 International Symposium on Antennas and Propagation,* Niigata, Japan, August 2007

1 Invited Journal Article

6 Invited Conference Presentations

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

Technical Program Committee Member: *2008 IEEE Antennas and Propagation Society International Symposium, 2008 IEEE Fall Vehicular Technology Conference*

IEEE Antennas and Propagation Society Joint Meetings Committee Chair, 2007-Present

Srikanth Krisnamurthy

Editor in Chief of ACM Mobile Computing
and Communications Review (MC2R)

TPC Vice-Chair for ACM MOBICOM in 2007

TPC Co-Chair for IEEE SECON in 2008

Larry Milstein

Senior Editor, IEEE Journal on Selected Areas in Communications
Editorial Board, Journal of the Franklin Institute

TPC, Third Int. Symposium on Communications, Control and Signal Processing
TPC Co-Chair, 2010 Int. Symposium on Ultra-Wideband Communication

Larry Milstein, John Proakis and James Zeidler:

Invited Manuscript: “Interference Mitigation and Management", chapter for the book *New Directions in Wireless Research*, Springer Press, Ed. V Tarokh and I. Blake

John Proakis

Member and Chairman of IEEE Richard W. Hamming Medal Committee

Editor of Book Series in Telecommunications and Signal Processing for Wiley

Academic Advisory Council, Athens Information Technology (AIT)

Seminars at the University of Athens and AIT, Athens, Greece, May 2008 on Interference Suppression in MIMO Broadcast Channels

Keynote address, 15th European Signal Processing Conference, Poznan, Poland, September 2007

Plenary lecture at the Third Western Canadian Summer School on Multiple Antenna Systems, Banff, Canada, August 18-20, 2008

Bhaskar Rao

Stephen O. Rice Prize Paper Award in the Field of Communication Systems for the paper "Network Duality for Multiuser MIMO Beamforming Networks and Applications," by B. Song, R. L. Cruz and B. D. Rao, appeared in the IEEE Transactions on Communications, Vol. 55, No. 3, Mar. 2007, pp. 618-630
http://www.comsoc.org/~awards/rice.html>

Ericsson Endowed Chair in Wireless Access Networks, May 2008
http://www.jacobsschool.ucsd.edu/news/news_releases/release.sfe?id=734

Technical Committee member for the 2008 International Conference on Acoustics, Speech and Signal Processing, April 2008.

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

James Zeidler

IEEE Asilomar Conference on Circuits, Systems and Computers, Organizer of a session on "MultiUser MIMO", October 2008

IEEE Military Communications Conference, Session Chairman, "Communications Signal Processing", November 2008

Michele Zorzi

Best paper awards: IEEE Globecom, Nov. 2007; IEEE COMSOC best tutorial paper, 2007

Editor-in-Chief of the IEEE Transactions on Communications (since Jan. 2008)

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

Member of the editorial board: ACM Journal of Wireless Networks, IEEE Transactions on Wireless Communications, Elsevier's Journal of Ad Hoc Networks

Member of the steering committee: IEEE Transactions on Mobile Computing

Guest editor: "Cognitive wireless networks," IEEE Wireless Communications Magazine (Aug. 2007), "Energy Efficient Design in Wireless Ad Hoc and Sensor Networks," Elsevier's Journal of Ad Hoc Networks (scheduled for 2008); "MIMO-Optimized Transmission Systems for Delivering Data and Rich Content," IEEE JSTSP (Apr. 2008); "Underwater communications and Wireless Networks," IEEE JSAC (scheduled for Dec. 2008).

Conference organizing committee: Technical Program co-Chair, ACM WUWNet 2007 (Sep. 2007).

Appendix 2: Technology Transfers

Michael Jensen

The patent-pending work on the use of space-time coding to allow dual-antenna transmission from maneuvering air vehicles, reported in prior years, continues to move forward. The problem this addresses is the data link loss that occurs when the vehicle-mounted antenna is occluded by the airframe during a maneuver. Use of appropriate space-time codes with dual antennas allows communication to occur for any vehicle attitude. We have constructed a prototype system that is undergoing real-time flight testing by the US Air Force at Edwards AFB. This work enjoys additional funding from the State of Utah and the US Department of Defense through the Central Test and Evaluation Investment Program (CTEIP). It is currently being evaluated for alleviating communication dropouts observed in helicopters flying at low altitudes above tree-canopies and water, with potential funding being allocated during Fall 2008.

In addition to this work, we are working with Rayspan Corporation, a start-up company with venture capital funding, to develop miniature antenna technologies for use in WLAN and cellular systems. These antenna designs include miniature MIMO antennas based on inexpensive printed circuit board technologies. Current studies include inexpensive technologies for decoupling compact arrays on small nodes and physical mechanisms leading to improved radiation efficiencies in small antennas. We are also working with Rayspan to investigate commercialization of innovative reconfigurable antenna technologies for improved MIMO communications in WLAN systems.

Appendix 3: Publications

Appendix 3A: Published Journal Publications

J.J. Garcia-Luna-Aceves

R. Moraes, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, “Many-to-Many Communication for Mobile Ad Hoc Networks,” IEEE Transactions onWireless Communications. Accepted for publication, 2008.

X. Wang and J.J. Garcia-Luna-Aceves, “Embracing Interference in Ad Hoc Networks Using Joint Routing and Scheduling with Multiple Packet Reception,” Ad Hoc Networks, Elsevier. Accepted for publication, May 2008.

X. Wang and J.J. Garcia-Luna-Aceves, “Distributed Joint Channel Assignment, Routing, and Scheduling for Wireless Mesh Networks,” Computer Communications, Elsevier. Accepted for publication, 2008.

Simon Haykin

N. Costa and S. Haykin (2007), “A Novel Wideband MIMO Channel Model and Experimental Validation”, IEEE Trans. Antennas and Propagation, Vol. 56, Iss. 2, pp. 550-562, February 2008.

H. Arasaratnam and S. Haykin, “Cubature Kalman Filters”, IEEE Transactions on Automatic control, accepted for publication, 2008.

Yingbo Hua

HONG, K., HUA, Y., SWAMI, A., "Distributed and cooperative link scheduling for large-scale multi-hop wireless networks," EURASIP Journal on Wireless Communications and Networking, Vol. 2007, Article ID 34716, 9 pages.

RONG, Y., and HUA, Y., "Space-time power scheduling of MIMO links - fairness and QoS considerations", IEEE J. Selected Topics in Signal Processing – Special Issue on MIMO-Optimized Transmission Systems for Delivering Data and Rich Content, Vol. 2, No. 2, pp. 171-180, April 2008.

ZHAO, B., and HUA, Y., "A distributed medium access control scheme for a large network of wireless routers," IEEE Transactions on Wireless Communications, Vol. 7, No. 5, pp. 1614-1622, May 2008.

RONG, Y., and HUA, Y., "Optimal power schedule for distributed MIMO links," IEEE Transactions on Wireless Communications, in press.

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, in press.

Yingbo Hua and Lee Swindlehurst

RONG, Y., HUA, Y., SWAMI, A., and SWINDLEHURST, A. L., "Space-time power schedule for distributed MIMO links without instantaneous channel state information at transmitting nodes," IEEE Transactions on Signal Processing, Vol. 56, No. 2, pp. 686-701, Feb 2008.

Hamid Jafarkhani

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Appendix 3B: Submitted Journal Publications

Srikanth Krishnamurthy

E. Gelal, G. Jakllari, S. V. Krishnamurthy and N. Young, “Topology Management in Directional Antenna Equipped Ad hoc Networks”, submitted to IEEE Transactions on Mobile Computing.

Hamid Jafarkhani

Y. Jing and H. Jafarkhani, "Single and Multiple Relay Selection Schemes and Their Achievable Diversity Orders," submitted to IEEE Transactions on Wireless Communications.

H. Yousefi'zadeh, H. Jafarkhani, and J. Kazemitabar, "A Study of Connectivity in MIMO Fading Ad-Hoc Networks," submitted to IEEE/KICS Journal of Communications and Networks (JCN).

Tara Javidi

S. Kittipiyakul, P. Elia, and T. Javidi, ``High-SNR analysis of outage-limited communications with bursty and delay-limited information," submitted to *IEEE Trans. Inf. Theory*.

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M. A. Jensen and J. W. Wallace, “Antennas for SIMO/MIMO Communication Systems,” to appear in *Modern Antenna Handbook*, C. A. Balanis, Ed., John Wiley & Sons, 2008.N. W. Bikhazi and M. A. Jensen, “Optical MIMO using square-law detection,” submitted to *IEEE Trans. Communications*, Jan. 2007.

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Q. Qu, L. B. Milstein, D. Vaman, “Constrained and Cooperative MIMO Communications in Wireless Ad Hoc/Sensor Networks.” Submitted to IEEE Transactions on Communications

A. S. Ling and L. B. Milstein, “The Effects of Spatial Diversity and Imperfect Channel Estimation on Wideband MC-DS-CDMA and MC-CDMA.” Submitted to IEEE Transactions on Communications.

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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," submitted to IEEE Transactions on Signal Processing, Jun - 2008

Y. Isukapalli and B.D. Rao, "Modeling of Erroneous Feedback for the Block Fading Channel and the Average Block Error Probability Analysis of a Multiple Input Single Output Beamforming System," submitted to IEEE Transactions on Signal Processing, Jul - 2008

Michele Zorzi

Marco Levorato, Federico Librino and Michele Zorzi, "Distributed cooperative routing and hybrid ARQ in MIMO-BLAST ad hoc networks", submitted to *IEEE Transactions on Communications*.

Appendix 3C: Conference Papers

J.J. Garcia-Luna-Aceves

X. Wang and J.J. Garcia-Luna-Aceves, "Collaborative Routing, Scheduling and Frequency Assignment for Wireless Ad Hoc Networks Using Spectrum-Agile Radios," Proc. ICCCN 08: 17th IEEE International Conference on Computer Communications and Networks , August 3–7, 2008, St. Thomas U.S. Virgin Islands.

X. Wang and J.J. Garcia-Luna-Aceves, "Channel Access Using Opportunistic Reservations and Virtual MIMO," Proc. ICCCN 08: 17th IEEE International Conference on Computer Communications and Networks, August 3–7, 2008, St. Thomas U.S. Virgin Islands.

S. Karande, Z. Wang, S. Sadjadpour, and J.J. Garcia-Luna-Aceves, "Optimal Scaling of Multicommodity Flows in Wireless Ad-Hoc Networks: Beyond the Gupta-Kumar Barrier," Proc. IEEE MASS 2008: Fifth IEEE International Conference on Mobile Ad-hoc and Sensor Systems, September 29 - October 2, 2008, Atlanta, Georgia.

Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, "Capacity-Delay Tradeoff for Information Dissemination Modalities in Wireless Networks," Proc. ISIT 08: 2008 IEEE International Symposium on Information Theory, July 6–11, 2008, Toronto, Ontario, Canada.

Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, "The Capacity and Energy Efficiency of Wireless Ad Hoc Networks with Multipacket Reception," Proc. ACM

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Z. Wang, H.R. Sadjadpour, and J.J. Garcia-Luna-Aceves, “Broadcast Throughput Capacity of Wireless Ad Hoc Networks with Multi-Packet Reception,” Proc. IEEE ICC 2008, Beijing, China, May 19–23, 2008.

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Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, “Closing the Capacity Gap in Wireless Ad Hoc Networks Using Multi-packet Reception,” 2008 Information Theory and Applications Workshop, UC San Diego, Jan 27–Feb 1, 2008.

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S. Ekbatani, F. Etemadi, and H. Jafarkhani, "Rate and Power Adaptation Over Slow Fading Channels with Noisy Quantized Feedback," Asilomar Conference on Signals, Systems, and Computers, Nov. 2007.

Y. Jing and H. Jafarkhani, "Beamforming in Wireless Relay Networks," Information Theory and Applications Workshop, Jan. 2008.

Y. Jing and H. Jafarkhani, "Network Beamforming with Channel Means and Covariances at Relays," IEEE International Conference on Communications (ICC-08), May 2008.

Y. Jing and H. Jafarkhani, "Single and Multiple Relay Selection Schemes and Their Diversity Orders," IEEE International Conference on Communications (ICC-08) CoopNet Workshop, May 2008.

J. Kazemitabar, V. Tabatabaee, and H. Jafarkhani, "Global Optimal Routing, Scheduling and Power Control for Multi-hop Wireless Networks with Interference," IEEE Global Communications Conference (Globecom-08), Nov. 2008.

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Y. Shi and M. A. Jensen, “Stable transmission in the frequency-selective MIMO broadcast channel,” *2008 IEEE 68th Vehicular Technology Conference Digest (VTC Fall 2008)*, Calgary, Alberta, CA, Sep. 21-24, 2008

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J. G. Proakis and P. Amihood, “Equalization of MIMO Systems”, *Proc., 15TH European Signal Processing Conference* (EUSIPCO), Poznan, Poland, Sept. 3-7, 2007 (Invited Keynote Address)

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K. Stamatiou, J. G. Proakis and J. R. Zeidler, “Evaluation of MIMO Techniques in FH-MA Ad Hoc Networks”, *Proc. IEEE 2007 Globecom Conference,* Washington, D.C., November 26-30, 2007

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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, Dec - 2008

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M. Nokleby and A. Swindlehurst, "Bargaining and Multi-user Detection in MIMO Interference Networks," In Proc. 2008 International Conference on Computer Communications and Networks, Virgin Islands, August, 2008.

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"On encoding and rate adaptation for MIMO_NC", *IEEE 3rd International Symposium on Communications, Control and Signal Processing 2008*, Malta, 12-14 March 2008.

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Davide Chiarotto, Paolo Casari, and Michele Zorzi, "On the Statistics of Channel Estimation Errors in MIMO Ad Hoc Networks,", accepted at *IEEE GlobeCom* 2008