Multidisciplinary University Research Initiative

Space-Time Processing for Tactical Mobile Ad-Hoc Networks

Interim Report

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ABSTRACT

Recent developments in communication systems technology promise to greatly improve the performance of point-to-point communications for both commercial and tactical networks. 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. This project is focused on the design of ad-hoc networking architectures that utilize MIMO transmitters and receivers at each node. This program will evaluate tradeoffs in waveform design, beamforming, space-time coding, channel state estimation, and receiver design in order to define the best way to utilize time-frequency-and spatial diversity to improve the robustness, capacity, and quality of service of a tactical mobile ad-hoc network.

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Scientific Progress and Accomplishments

Army Research Office FY04-FY09 Multi-University Research Initiative (MURI) Project on
"Space-Time Processing for Mobile Ad-Hoc Networks"

1. Background:

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 FY04 MURI topic was to "create network protocols and signal processing algorithms necessary to implement adaptive beam steering and spatial channel reuse in mobile wireless communication networks with the specific objective of enabling reuse of radio channels to double network capacity and improve protection for military communications. The research should also result in the science that will allow for the decision of which spatial reuse technique to use (space-time coding (STC) or transmit beam forming), if any, based on topology, network load, etc."

The kickoff meeting was held at the University of California, San Diego on 15 June, 2004 and the first annual review of the project was held at UCSD on July 28, 2005. The presentations from both meetings are provided on the MURI website at http://zeidler.ucsd.edu/~muri
The website also provides background information and relevant publications from each researcher that will supplement the information in this report..

At the conclusion of the kickoff meeting in June 2004, the government evaluation team made a request that since the initial funding for the project did not allow a full start until fall 2004, we should utilize the summer to coordinate the activities at the various universities and prepare a research coordination plan that defines the key technical issues that the project team plans to address and the relation of each of the individual PI's work to the overall project goals.

The project team met again at UCSD on August 5 to prepare the plan and also to define specific areas where research collaborations between PIs would be productive. All PIs were in attendance with the exception of Professor Haykin who is in a unique position since his funding must be provided separately by the

Canadian government and his tasks are still in the proposal stage. The results of the meeting are summarized below.

2. Results of the Research Coordination Meetings:

2.1. Problem Definition

The goal of the meeting was to define a hierarchy of problems that require resolution if mobile ad-hoc networks are to become a viable possibility in tactical scenarios where hostile forces may be actively attempting to degrade network performance through jamming or to discover the location of the nodes in the network by intercepting transmissions. The key research issue is to define how to best utilize multiple transmit and receive antennas at each node to improve the robustness, capacity, and quality of service for the network. The group agreed to select two scenarios to define the critical research issues for such a network.

The primary difference in the two scenarios is the mobility of the nodes, with one scenario restricted to pedestrian velocities and the second including nodes moving at vehicular speeds. In both scenarios the number of nodes will be sufficiently large to provide a rich possibility of possible routing paths (nominally 30 to 100 nodes with up to four antennas per node in a typical scenario) and the range of node velocities sufficiently large to study topologies that must operate with a realistic range of temporal stabilities for the channel state information. The system will be a wideband voice/data network operating at a nominal center frequency of 2.4 GHz. The channels considered will include terrestrial models typical of rural and urban areas with both flat fading and frequency selective fading channels with a variable number of resolvable paths on each antenna. The practical limitations on antenna orientations associated with combat operations (e.g. operation close to the ground and non-ideal element location) will be evaluated. In both cases the impact of jamming and hostile intercept will be considered.

The possibility of hostile action to deny services or exploit the transmissions has an immediate impact on the choice of waveforms since a wideband spread spectrum waveform is required to mitigate jamming. In addition, the difficulty of achieving power control in ad-hoc networks makes it desirable to consider alternatives to direct sequence Code-Division Multiple Access (CDMA). Consequently, variations of spread spectrum waveforms such as multicarrier CDMA and orthogonal frequency division multiplexing (OFDM) that utilize different approaches (such as frequency hopping) to spread the transmitted information will be considered. Multicarrier waveforms will also provide spectrum flexibility by allowing the nodes to utilize whatever spectrum is available to increase network capacity and to avoid interferers. Time division and frequency division duplexing will both be considered and the conditions for which scheduling can provide improved performance over contention based channel access protocols will be determined. The specific traffic models considered will include bursty and high density many-to-one, point-to-point and multicasting scenarios that incorporate relays to provide end to end data/voice services. The ability of the network to smoothly transition from low data rate to high data rate operation will be evaluated. The general network architecture will be a multi-hop ad-hoc network without centralized control or single points of failure.

A primary objective is to develop new radio network technologies that provide an extended coverage range without the use of centralized control. Accordingly, a key research goal is to develop new routing and scheduling protocols that incorporate spatial information from the physical layer to improve performance at the higher layers of the network. Key metrics that will be used to evaluate the performance of the network include channel capacity in bits/sec/Hz and outage probability. Quality of service measures such as fairness, latency, bit-error rate, and energy consumption will also be determined. It was agreed that the robustness of the network and its associated outage probability are generally the most important metric for defining system performance in tactical applications and that raw bit rate would be less important than reliability over an extended coverage range. The research will develop routing algorithms that support neighbor discovery and reliable end-to-end data delivery in a network that must smoothly transition between different data rates.

2.2. Research Issues

The group unanimously agreed that the central research issue is to define how the physical layer information provided by the multiple transmit and receive elements at each node of the network can be utilized to improve the robustness of a tactical mobile ad-hoc network that has no centralized control and no single points of failure. It was agreed that the use of multi-input multi-output (MIMO) transmit/receive diversity can potentially provide significant gains in network performance but those gains come at the expense of a closed feedback loop between the physical, MAC and networking layers. The best approach to define this cross-layer processing is a critical research issue since the time scale for the feedback process must be compatible with the stability of the channel estimates.

The key research issue associated with this type of network is thus the need to define the refresh rate for the channel state information (CSI) estimates used in the network routing and scheduling. The temporal variations of the CSI estimates must be determined as a function of the signal-to-noise ratio and Doppler dependence of various antenna processing and STC algorithms. The temporal stability of the CSI estimates will be evaluated and utilized to determine how frequently information must be exchanged between nodes for data delivery and also for the neighbor discovery process for various network topologies, node velocities, and channel conditions. It was generally agreed that the use of beamforming should increase the temporal stability of the network and potentially decrease the probability of hostile intercept, but that this gain would come at the expense of requiring node tracking and the increased possibility of hidden nodes.

Consequently the signaling architecture that is used to establish the locations of all the nodes and the data rates that are achievable on each link in a tactical network is a key research issue. Protocols that ensure that the measurements done during the signaling portion remain valid during the data transmission period are required.

It was agreed that the contention based scheduling protocols that are currently used can provide a baseline for network performance, but the goal is to provide enhanced performance though the use of beamforming and/or space-time coding. The work will focus on the development of distributed receiver oriented multiple access scheduling protocols for ad-hoc networks with directional antennas that can form multiple beams and maintain several independent communication links. A key research issue will be the development of dynamic scheduling algorithms that exploit space-time coding and beam steered antennas to support unicast, multicast, and broadcast transmissions based on flow aware scheduling of transmissions. The channel state conditions that are required to provide performance gain over contention based network protocols is a research issue that will be addressed in this project.

The stability of the CSI estimates over the transmission paths is also dependent on the routing protocol selected and the manner the information is relayed between nodes. Consequently the determination of the type of feedback to employ, the number of bits allocated to the CSI feedback loops, and the number of nodes used to relay information between destinations are all important research issues. A number of open and closed loop feedback algorithms will be evaluated. A fundamental issue that will be addressed is the accuracy with which the channel gain matrix (**H**) must be determined to support the MAC layer and routing protocols. We have previously shown that partial CSI can provide significant gains and it is possible that highly accurate complete channel gain matrix determination could result in a more temporal variability, thus requiring more frequent updates on the channel state in the routing and scheduling protocols. One of the research issues to be addressed is the development of hybrid space-time coding and beamforming architectures that optimize tradeoffs in performance and complexity with varying amounts of CSI. Multistage processes that would first locate the neighbors and then refine the **H** matrix computations will also be investigated. Other fundamental issues inherent to resolving the above questions are the role of local vs distributed information and relaying in the routing and scheduling protocols.

Since the use of antenna diversity provides improved BER at lower SNR, the issues of initial acquisition and synchronization must be addressed. This is a research issue in this project because the acquisition is typically achieved using pilot tones in commercial systems and this constitutes a potential source of vulnerability in a tactical network where low probability of intercept must be considered.

2.3. Role of Each Principal Investigator in Overall Research Objective

The team was selected to provide some overlap in critical technology areas and collaboration between individual PIs is currently being developed. Professors Luna-Garcia, Krishnamurthy, Cruz, Hua and Zorzi are addressing various aspects of the scheduling and routing protocols at the network and MAC layers. Professor Luna-Garcia's work is focused on developing MAC protocols that provide higher data rates through the use of STC, beamforming and any other available node location information from the physical layer. His research will evaluate the rates that CSI must be updated for both data delivery and neighbor discovery in various network topologies. Scheduling and routing protocols will be developed and evaluated to define their reliability as a function of the variations in the CSI estimates and refresh rates for channel conditions that include variable link quality over the available paths. Professor Krisnamurthy will design MAC and routing protocols that are tightly intertwined with what is possible at the physical layer, specifically to use the CSI information to improve network performance using the reception of multiple simultaneous beams from a MIMO transceiver. Protocols that use directional transmissions for neighbor discovery with full and partial state CSI for data delivery will be evaluated. Professors Cruz, Krishnamuthy, and Zorzi plan to collaborate on providing a comparison of open loop protocols that exploit coding and end-to-end transmissions with forward error correction relative to closed loop techniques that require retransmissions. In addition they will design a distributed MAC layer protocol that effectively schedules transmissions simultaneously in spite of the fact that the concurrent transmissions may also produce mutual interference. The use of geographical information in routing will also be evaluated. Professor Zorzi will also focus on the issues of how to be integrate cross-layer information in the MAC and routing algorithms. Professor Cruz will design and evaluate joint MAC/routing/scheduling protocols using only limited information from a MIMO based physical layer and integrate the results obtained with his prior work that required full knowledge of physical layer parameters. Professor Hua's work will focus on developing reliable relaying algorithms that exploit the MIMO channel information at each node and provide end-to-end data delivery in a large network by efficient multi-hop relaying.

Professors Swindlehurst, Jensen and Zeidler will focus on determining the accuracy and temporal stability of the CSI estimates for a MIMO based physical layer using a combination of analysis, simulation and experimental measurements. Professor Swindlehurst will also focus on developing algorithms for channel state estimation and prediction and also on developing beamforming and coding algorithms that allow multiple users to communicate simultaneously with high throughput and minimal interference. Professor Jensen will utilize his expertise in RF antenna design to assess MIMO system performance for realistic tactical environments and provide channel data models appropriate for realistic system simulation. Professors Jensen and Swindlehurst will work jointly to obtain experimental validation of multiuser MIMO channel models using the BYU testbed. Professor Zeidler will collaborate with them on the analysis and validation of models that define the temporal stability of the channel state estimates.

Professors Rao and Jafarkhani will evaluate open and closed loop feedback algorithms to provide CSI estimates to multiuser MIMO networks. Feedback based methods promise better utilization of the spectrum thereby supporting higher overall system throughput, and lower power communication suitable for low probability of detection (LPD) as well as design of simpler receiver structures. However for these benefits to be realized in space-time ad-hoc networks, many interesting questions have to be addressed. In order to support a wide range of node mobilities, Professor Rao will develop a flexible class of quantization techniques and evaluate their effectiveness and robustness. This study will explore effective parameters to be fed back, alternate efficient parameterization of the information being fed back, and the trade offs between complexity and performance. In connection with feedback issues there are also the associated problem of channel estimation and transceiver design to maximally exploit the feedback information. Professor Jarfarkhani will design STC structures that are flexible enough to be used in an ad-hoc network and will consider the use of partial CSI and a combination of STC and beamforming. He will also evaluate meaningful measures of connectivity for ad-hoc networks, such as symbol error rate and capacity using multiple antennas.

Professors Milstein, Proakis and Zeidler will evaluate a number of signal and waveform issues involving the stability and accuracy of the CSI estimates from mobile multi-user MIMO transceivers. Professor Milstein will define the best modulation approaches for the underlying waveforms and evaluate the acquisition, synchronization and performance properties for a number of alternative frequency-hopped multicarrier spread spectrum waveforms, including CDMA and OFDM. He will also address the problem of optimizing the cross-layer interactions in a stressed mobile tactical environment, emphasizing spatial processing wherever feasible and define the channel conditions that are required to support scheduling in an ad-hoc network. Professor Proakis will focus on the signal design and equalization approaches for a mobile multiuser MIMO network and the use of CSI estimates in the physical and network layer optimization. Professor Zeidler will evaluate the reliability of CSI information for frequency hopped spread spectrum waveforms in a mobile multiuser OFDM MIMO network.

2.4. Collaborative Research Initiatives in Progress

Following the research meeting in August, a number of subgroups have met to initiate collaborative research efforts on some of the key research initiatives identified above. Professors Cruz, Krishnamurthy, and Zorzi held a number of joint meetings regarding the MAC and routing issues. Professors Rao and Jarfarkani are also collaborating on a related project funded by the California Institute of Telecommunications and Information Technology (CAL(IT)^2) and have continued to refine their research objectives to ensure that they jointly cover a range of potential open and closed loop feedback scenarios for channel state information and coding. Professors Swindlehurst, Jensen, and Zeidler are initiating a joint research effort on the temporal variations of the channel state estimates.

A series of technical seminars were held at UCSD during the academic year with technical lectures provided by Professors Swindlehurst, Luna-Garcia, Jafarkhani, and Krishnamurthy. These allowed interaction between the students and professors on the current research initiatives described below. These technical seminars were very useful and will be continued throughout the coming year to foster continuing interaction between the PIs and their graduate students and postdocs.

2.5. Canadian Participation in MURI Project

As stated earlier, Professor Haykin is in the unique position that his research must be funded separately by the Canadian government. He met with officials of the Canadian Department of National Defense (DND) when our award was announced and was directed to the National Science and Engineering Research Council (NSAERC) where he has applied to two different programs. The first avenue is a corporate matching program that did receive support from Nortel, but in the area of cognitive radio instead of the work in channel state estimation for multiuser MIMO radio networks that he had originally proposed to do with the MURI team. His graduate student presented this research at the kickoff meeting in June, but it was agreed that the cognitive radio work did not fit in with the rest of the MURI effort. Professor Haykin has subsequently received funding from the Special Research Opportunities (SRO) program at NSAERC. This proposal focuses on research in channel state estimation for multiuser MIMO radio networks that could, in part, be done in collaboration with the planned experimental work at BYU, and the other initiatives in the use of CSI information in scheduling and routing discussed above. His research plans are summarized below.

2.6. Research Space in the New CAL(IT)^2 Buildings at UCSD and UCI

The California Institute for Telecommunications and Information Technology CAL(IT)2 promised support to the MURI project for research spaces in the new building that is currently under construction at UCSD. CAL(IT)2In addition, Professor Jarfarkhani has requested project space for the MURI project in the new CAL(IT)2 building at UCI. The move-in dates for the new buildings on both campuses are November 2004 in Irvine and October 2005 in San Diego. Space has been requested for MURI faculty, graduate students, and visitors in the new buildings. The spaces requested for visitors will facilitate coordination and collaboration between the faculty at different campuses by providing office and research spaces in San Diego and Irvine for the faculty and students working on the MURI project at the other campuses.

3. Technical Inputs from the Review Team

Following the research coordination meetings in August 2004, inputs from the Army Research Laboratory (ARO) and the Army Research Lab (ARL) on the waveforms and traffic models to be utilized in the analysis were solicited by Professors Milstein and Zeidler. The recommendations provided by Dr. Swami and Dr. Sadler from ARL are summarized below.

Dr. Swami indicated a general preference for Frequency Hopped (FH) over direct sequence (DS) spread spectrum waveforms particularly because the power control requirements for DS are much more stringent than that for FH (as articulated clearly in papers by Torrieri of ARL). In addition both expressed an interest to emphasize FH in this project simply because there is tremendous industry and NSF investment in DS (but not in FH). Dr. Swami also cited reasons to favor FH that are related to to Low Probability of intercept (LPI), low probability of detection (LPD) and partial band interference (PBI) considerations that are important for tactical networks.

Dr. Swami did note however that there are situations where DS may have advantages and gave examples such as a high-rate LOS scenario (e.g., ground to air, with directional antennas). In addition he felt that orthogonal frequency division multiplexed (OFDM)modulation offers advantages including "(a) the ability to hop a subset of sub-carriers within the band, and (b) the ability to provide users with varying number of sub-carriers, based on their priority/QoS needs". He noted that the current Lucent MIMO DARPA project will field both DS and OFDM waveforms. Dr. Swami stated that they do not yet have specific recommendations on the variants of OFDM that would be most useful in an ad hoc setting, but indicated that features (a) and (b) would be desirable. Synchronization becomes another critical issue in the ad hoc scenario, where due to lack of beaconing, users would have to contend with both time and frequency offsets.

Dr. Sadler agreed with the recommendations that Dr. Swami had provided and added that FH can be used as an overlay for almost any system. The traditional FH sysems have been narrow band, but he felt that multi-carrier was a logical wide band extension of current narrowband FH systems, which may occupy non-contiguous spectrum (which he deemed very important for military of the future, given the desire to be adaptive to spectrum occupancy yet wideband). In addition he stated that generally we can apply all the spreading ideas in multi-carrier, now across time and/or frequency. On the other hand, with conventional DS, all the bits (and all the users) take a hit in the presence of a single narrow band interferer.

As a result of this feedback from ARL research was initiated to provide fundamental performance tradeoffs between multi-carrier FH and DS modulations for the waveforms transmitted at each node of our tactical network.

Following the first annual review of this MURI, additional feedback was solicited from ARO and ARL on the channel models that the Army felt were most representative of tactical environments. In general the channel models have to be separated into two categories: ones that are analytically tractable and ones that are empirically based. Analytical models include Rayleigh, Jakes, Nakagami, Rician, and others. Empirical models include the GSM and COST 259 models that are used for commercial systems. In addition there is a set of JTRS maritime models that are used for the evaluation of candidate JTRS radios. The JTRS maritime model was based on a set of experiments conducted at SSC, San Diego. The test involved three sets of measurements: ship to ship at sea; a ground based transmitter to a ship in port at the 32nd St. Naval Station, and from a ship to a HUMVEE as the ship was entering San Diego Bay and the HUMVEE was driving from Point Loma to the 32nd St. Naval Station along Harbor Drive, Pacific Coast Highway, and through downtown San Diego. These measurements were reported in SSC technical reports and also in MILCOM papers. We confirmed in conversations with Dr. Swami and Dr. Sadler from ARL and Dr. Rich North, the Technical Director for the PEO C4I & Space at SPAWAR that there is no validated empirical channel model for the Army tactical operations. Dr. North had been the program manager of the channel measurement effort for the Navy Digital Modular Radio and the JTRS maritime channel model and has followed the development of representative channel models for the JTRS radio development. It was agreed that there presently is not a validated channel model for Army tactical operations, especially for the MIMO case. There is also not a validated commercial model for MIMO networks at this time. The COST 259 model does provide improvements over the GSM model since it adds direction of arrival statistics to the omni-directional antennas that characterize the GSM models.

Dr. Swami and Dr. Sadler have both indicated a great interest in utilizing the measurement capabilities that are part of this project to help provide more information on realistic MIMO channel models for our applications. They specifically have contacted Drs. Jensen and Swindlehurst at BYU and Dr. Zeidler at UCSD to encourage us to focus part of our effort on providing more definitive channel modeling information in the next year of the project.

3.1. MURI Related Technology Transfer with DoD

Dr. Stephan Lapic, SPAWAR Systems Center (SSC), San Diego has invited Professors Cruz, Krishnamurthy and Zeidler to collaborate with his group at SSC in the development of a prototype Naval ad-hoc mobile network based on steerable antenna arrays.

Other DoD interactions include collaboration with Professors Proakis and Zeidler with Vincent McDonald (PI) of the SPAWAR Systems Center in San Diego on an ILIR SPAWAR project entitled: “Enhanced Underwater Communication Using MIMO Systems”. Their work on this project involves the design of reduced complexity MIMO receivers and the design of space-time codes for underwater communications.

Professors Proakis has also been a co-investigator on a SSC project entitled “UHF SATCOM Adaptive Filtering”, where his work involves the development of a channel model for signal scatter off the sea surface and applications of adaptive filtering algorithms to mitigate signal distortion and narrowband interference.

Dr. Zeidler has also been a co-investigator of a SSC project entitled “Composable Antenna System Signal Processing for GPS” that
involves interference suppression in GPS arrays using a composable array of randomly located elements. He is also involved in an ONR and SSC project on adaptive interference suppression in tactical communications systems.

In addition Professor Jensen has applied space-time coding allow dual-antenna transmission from maneuvering air vehicles. 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.

This technology has produced 3 provisional patents, and commercialization funding has been awarded by the State of Utah and the US Department of Defense through the Central Test and Evaluation Investment Program (CTEIP). After creation of the prototype, a new start up will be created (early 2007) to market the technology.

In addition, Professor Jafarkhani has submitted a provisional patent application: UC Case No. 2005-087, "NEW METHOD FOR CODE DESIGN IN WIRELESS COMMUNICATION SYSTEMS" based on his work in this project.

4. Scientific Progress and Accomplishments

4.1. Baseline Systems Model

As discussed above the decision was made by the MURI team to focus our analysis on a baseline system model that consisted of a heterogeneous terrestrial ad-hoc network with 30-100 nodes and up to four antennas/node. Any or all of the nodes could be mobile. There is no centralized control and jamming and physical destruction of nodes is always possible. The nodes may be shadowed from each other, creating network topologies where the nearest nodes are not necessarily connected to their neighbors and multi-hop routing is necessary to ensure network connectivity. Multi-casting and uni-casting of wideband data and voice is a network requirement as is the necessity to reduce vulnerability to hostile interception.

4.2. Research Goals

The overall 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 in the presence of the tactical impairments defined above.

The development of improved antenna, signal processing and coding technologies provide many forms of diversity to increase network capacity. The types of diversity available to the system designer include space, time, frequency, polarization, and network diversity. Diversity is critical to improve the reliability and minimize the need for retransmission and to reduce the latency in the network. Exploitation of the available time, frequency and spatial diversity on a link is useful in maximizing the link capacity, but for multi-user systems it becomes essential in order to minimize the amount of multi-user interference. Proper selection of waveforms, modulation, coding and spatial filtering is essential. In addition, cross layer optimization required to exploit physical layer diversity at the network level. The chosen waveforms must be resistant to jamming and intercept and the antenna configurations adaptable to combat conditions. Multihop transmissions are required to overcome shadowing and allow network reconfigurability, and real time channel state information is required for time varying mobile channels required. The time variability of the channel will depend strongly on the node velocities, which will also introduce Doppler spreading that will limit the coherence bandwidths of the channel.

The goal of the cross layer design is to use feedback from the lower layers to discover and maintain appropriate routes and define the network topology and at the MAC layer to support scheduling based on interference zones and generated traffic. At the physical layer, adaptive antennas could be adjusted based on the needs of the network layer to provide feedback to higher layers to define the interference zones and minimize co-channel interference. In order to accomplish these goals it is essential to utilize the available diversity provided by the system parameters.

Diversity is inherent in the physical layer and includes time, frequency, space and polarization diversity. At the physical layer these parameters can be optimized to stabilize the fading in the channel. Diversity can also be achieved in the MAC or higher layer. Network diversity includes multiuser diversity (by scheduling or routing) and cooperative diversity (by cooperative transmission). In principle network diversity could be utilized to exploit the channel fluctuation to choose the best links to use at a given time, provided that the temporal fluctuations are slow enough. The fundamental challenge for this project is to utilize combinations of physical and network diversity to maximize network capacity and robustness in an optimal fashion.

One key research issue in utilizing combinations of network and physical layer diversity is the way to best utilize channel state information (CSI). Optimizing network capacity will depend on *where, when,* and *how accurately* the CSI can be obtained. CSI may be available at the destination node only, source and destination node, or across the network. The time-scale of available CSI is especially important. It must be known whether knowledge about the channel can be expected to remain stable over a symbol interval, a packet interval, or over multiple packets.

The ratio of the coherence time relative to the data rate is an especially important parameter to define in order to evaluate what physical layer parameters can be used to increase network capacity. The use of STC or beamforming in conjunction with ad-hoc routing and scheduling remains an open research issue especially because the channel statistics are not yet known for mobile MIMO networks. Physical and network diversity could be exploited simultaneously in some scenarios, e.g. physical layer diversity could be used to combat fast fading effects, while network diversity can be used against slow fading. The key question is under what conditions one can shift between different forms of diversity.

During the past year we have made significant advances at the network, MAC and PHY layers of our baseline tactical ad-hoc network. Details are provided below.

4.2.1. Network Layer: (Overall Goal is to Discover and Maintain Appropriate Routes and Provide Feedback to Lower Layers on Topology Construction)

During this reporting period, Professor Garcia-Luna has obtained results in two key areas related to the orchestration of the physical layer with the medium-access control layer:

(a) Analyzing the capacity of wireless networks with MIMO nodes under a cooperative approach for resource sharing.

(b) Refining the interference matrix model that we developed recently to take into account the impact of fading, directional antennas, and MIMO nodes.

For the reporting period, Professor Cruz's papers were published in the area of beamforming for MIMO networks. He investigated the efficacy of cooperative relaying schemes in a network context. In addditon, Professor Krishmamurthy has evaluated power efficient broadcasting methods for cooperative diversity in ad-hoc networks. Professors Cruz and Krisnamurthy are also working at the

MAC layer as discussed below.

Professor Tara Javidi was appointed as an Assistant Professor of ECE at UCSD and moved to San Diego in January 2005. She was invited to affiliate with this project due to her expertise in ad-hoc wireless networks. Her work is focused on the development of a formal approach to the analysis and design of self-configuring wireless ad-hoc networks as described below.

4.2.1.1. Beamforming for MIMO Networks:

In [SCR], Song, Cruz, and Rao found that for any multiple-input and multiple-output (MIMO) network with linear beamformers, there exists a dual network that attains the same signal to interference plus noise ratio (SINR) performance. This network duality is a generalization of the virtual uplink concept in the context of cellular networks to reduce a MISO problems to a SIMO problem. They developed network duality which is applicable to arbitrary multi-user MIMO networks with a generalized cost function. More importantly, they provide an optimization theoretic perspective of network duality which naturally leads to the construction of a dual network. They considered the joint MIMO beamforming and power control problem with individual SINR constraints. They applied network duality to this problem and proposed a high performance algorithm which compared to past approaches has improved convergence behavior.

4.2.1.2. Cooperative Transmission in Wireless Networks:

In [NC], Nebat and Cruz, investigated the effectiveness of relaying based cooperative transmission, as compared with pure routing. It was shown that with channel state information available at the transmitters (CSI-T) and multi-user diversity leveraged in the form of optimal power allocation and relay selection, the advantage of general relay based cooperative schemes over pure routing is negligible when the performance of a single link is considered. In terms of total network throughput, we developed insight that suggests why pure routing might be the prevailing protocol. Cheap relay (relays that cannot transmit and receive at the same time) based 2-hop routing performs close to the bound at the most common spectral efficiencies, given that the terminal density is sufficiently high. Closed form optimal power allocations for several relay based cooperative protocols were also derived.

4.2.1.3. Opportunistic Cooperation:

The capacity of MIMO systems has received considerable attention [foschini], [telatar], [jafar]; however, all these studies concentrate on the concept of one-to-one communication among nodes. Even the work by Jovicic et al [jovicic] studies the capacity of wireless ad hoc networks by assuming that the entire network is a single MIMO system in which some nodes are part of the transmitter and the remaining nodes in the network are part of the receiver, and where all the nodes have only one antenna. A random line is used to cut the network into two parts for senders and receivers. While this work [jovicic] was the first attempt to compute the capacity of networks based on MIMO systems, the results are rather optimistic by assuming all the receiving nodes in the network are capable of cooperating with each other, to decode the data. Furthermore, Chen and Gans [gans] showed that the node capacity of a MIMO ad hoc network goes to zero as the number of nodes increases.

Professor Garcia-Luna has completed work based on the limitations of the above results. He has noted that the protocol stacks of wireless ad hoc networks implemented or proposed to date have been designed to support the communication among senders and receivers that are competing with one another for the use of the shared bandwidth. This ``competition-driven'' view of bandwidth sharing has had profound implications on network architectures and methods used to access the channel and disseminate information. For example, because all transmissions compete with one another, medium access control (MAC) protocols attempt to avoid or react to ``collisions'' of packets, given that a receiver can decode a single transmission at a time, and a single copy of a data packet is forwarded at each relay from source to destination, given that additional copies would increase the destructive-interference effect.

During this reporting period, we developed the first integrated approach to cooperative bandwidth sharing in MANETs and proposed opportunistic cooperation. The term ``opportunistic'' indicates the fact that the number of nodes cooperating with one another in a cell at each communication session is a random variable. With opportunistic cooperation, 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. Our cell size limits the number of nodes in each cell, on average, even as the number of nodes grows to infinity, 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. Clearly, a consequence of such a strategy is an increase in the receiver complexity of all the nodes in the network. The two main questions that we address in our research are: (a) what cross-layer protocol mechanisms are suitable to attain opportunistic cooperation in MANETs? and (b) what are the fundamental performance limits of a MANET with opportunistic cooperation?

We analyzed a specific instantiation of opportunistic cooperation in the context of MIMO systems using an FDMA/MIMO approach. Nodes transmit and receive simultaneously using different portions of the available spectrum. During transmission, a node sends packets from only one of its antennas, and uses all of its antennas to receive and decode packets from multiple nodes simultaneously. Therefore, each MIMO system in this scheme consists of multiple transmitting nodes acting as a single-array of multiple antennas, and a single receiver node with multiple antennas in a cell. This approach does not require any coordination among receiving nodes for decoding the received packets. A node is assumed to know its own location, and a "bandwidth allocation map" that partitions the available bandwidth according to cells, such that interference among nodes located in different cells is eliminated by using different frequency bands, and nodes within the same cell use their antennas to cooperate in a way that their concurrent transmissions can be decoded by the intended receivers.

We have shown that, with the proposed approach, the per-node ergodic capacity does not depend on the total number of nodes; however, it is a function of such other network parameters as the number of receiving antennas, cell area, average node density, noise spectral density, and the path loss parameter. Surprisingly, we also demonstrate that each node capacity grows as the transmit power of each node in the network increases. This result proves that increasing interference does not reduce each node capacity if the interference is properly treated. It is also shown that the total bandwidth required is finite for the proposed FDMA/MIMO system.

4.2.1.4. Power Efficient Broadcasting with Cooperative Diversity in Ad hoc Networks

The increased reliability provided by the spatio-temporal communications allows for nodes to use lower transmission power levels and yet, achieve the transmission range possible with traditional single-input single-output (SISO) communications. We explore our ability to reduce energy consumption by exploiting space-time communications; in particular we consider a broadcasting application. Broadcasting by its nature, is a transmission intense operation and hence, results in the consumption of significant power. Due to the importance of broadcasting, there have been significant efforts [3] towards the design of energy efficient broadcast methods; however, these are not within the context of cooperative diversity.

Specifically, our objective during the reporting period has been to translate the gains due to cooperative diversity, when applied to broadcasting, to savings in power consumption. Toward this objective, we have designed appropriate modifications to existing SISO based broadcast protocols to facilitate the new technology. For the purpose of this study, we choose to incorporate cooperative diversity in a counter-based broadcast scheme. We chose this scheme because it is efficient and requires only local information.

Khandani et al. [4] have computed the optimal power assignment for every cooperating node in order to minimize the power consumption of a cooperative transmission. However, that computation assumes ideal channel conditions, knowledge of the channel state information (CSI) at the transmitter and global knowledge of the topology. Obviously, this information is not available in a distributed setting (as in ad hoc networks). Therefore, we choose to have the nodes transmit at various fixed power levels, and measure the performance based on metrics such as coverage and consumed power. This method is effective in demonstrating the significance of the power savings when our broadcasting scheme with cooperative diversity is used. As shown by the results (Fig.2), the power consumed with the use of our protocol (using cooperative diversity) is about eight times lower as compared to what is achieved with the non-cooperative method (SISO).

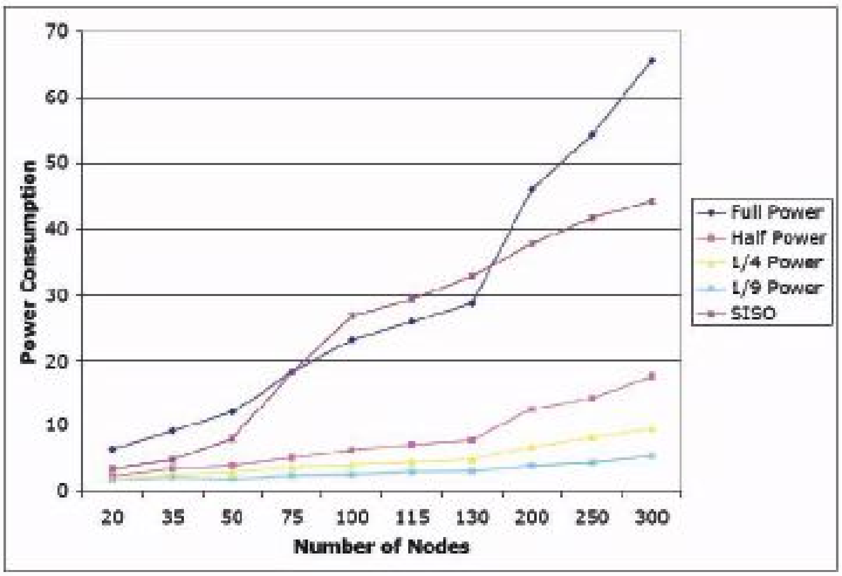

Fig. 2

4.2.1.5. Performance Evaluation of MIMO Space-Time Coded Ad Hoc Networks

A number of protocols for wireless ad hoc networks with directional antennas have been proposed, mostly on the medium access control (MAC) layer. The evaluation of the performance of these protocols has been done mostkly by simulation, and very few works have attempted to model ad hoc networks with directional antennas analytically. These analytical models, however, have been very limited, in that they have assumed over-simplified antenna gain patterns, like the ``pie-slice'' and ``cone-plus-ball'' antenna models. In these models, all directions within a certain angle sector have constant gain, while no power is radiated/absorbed along the other directions (``pie-slice''), or a lower constant gain is assumed for the directions outside the angle sector to represent the back and side lobes of the antenna pattern (``cone-plus-ball''). In reality, no physical antenna can provide such constant gain for a given angle sector, and real antenna patterns are far more complex than ``pie-slices'' or ``cone-plus-ball'' models. In fact, real antenna patterns have non-negligible gains in all directions, and often have significant side and back lobes that can contribute considerably to the amount of perceived noise, leading to performance degradations such as the ones observed by Ramanathan et al [jsac05] in a real-life ad hoc network testbed. Consequently, conclusions about capacity improvements based on such over-simplified antenna models may not necessarily reflect the true potentials or limitations of the use of directional antennas in ad hoc networks.

During the past year, Professor Garcia- Luna has developed the first analytical model of wireless ad hoc networks that considers the impact of realistic antenna gain patterns on network performance. In particular, we focus on the modeling of wireless ad hoc networks with directional antennas. For this purpose, we use our previous work [mobicom04], which allows a comprehensive treatment of ad hoc networks at the physical (PHY) and medium access control (MAC) layers. A key feature of our model is the fact that it captures the interactions between both layers and takes into account the radio connectivity among nodes, all conveniently conveyed through the use of interference matrices. We attain a linear approximation for the probabilities of successful handshakes among transmitters and receivers by taking advantage of the fact that any MAC protocol must attempt to avoid having interfering transmissions around the recipient of a frame transmission. The extensions we developed over the past year include: (a) taking into account the impact of packet flow distribution among multiple receivers; (b) expressing the impact of frame size distribution; (c) modeling the impact of the carrier sensing mechanism in carrier-sensing MAC protocols; and (d) providing richer interference matrices that explicitly model the impact of a node's transmission on the SINR degradation of every other node, i.e., the effect of capture with respect to every potential interferer is treated individually.

The key benefit of his model is that it relates the bit error probabilities obtained for specific choices at the physical layer (e.g., modulation) and channel characteristics (e.g., multipath fading) with the transmission rates attained by the MAC protocol. Over the next year, Professor Garcia-Luna will be able to take into account different assumptions about MIMO STC wireless links and their effect on contention-based and schedule-based MAC protocols.

4.2.1.6. A Formal Approach to the Analysis and Design of Self-Configuring Wireless Ad-Hoc Networks

As the technologies fueling wireless communications become more and more advanced, we are seeing demand for new, widespread, and diverse applications. Ad-hoc networks, in particular, are being used for everything from coordinating underwater robotics, to supporting communication in remote and/or hostile environments, to space exploration. For these applications, traditional communication schemes using centralized control are typically cost-prohibitive, and may actually be impossible to deploy. In such scenarios, the ability of a group of nodes to self-configure into a feasible and stable network configuration is critical. The goal is for individual nodes to use locally available information and rules to self-configure into a stable and feasible network configuration that supports both the communication and functional goals of the system.

For this project, Professor Javidi is interested in quasi-static scenarios where significant changes in the environment occur slowly over time. This allows us to increase the efficiency of the network by using some level of scheduling and/or synchronization at a macro level, while continually tracking small changes in environment at a micro level. She is interested in a decentralized selection of MAC and physical layer parameters (i.e. transmit power, transmission rate, time-slot assignment, beam and directional antenna angle, etc) that guarantee certain desirable network properties.

Initial results have been generated for a network that uses both time and code division multiple access. The use of CDMA allows for simultaneous reception, and provides a natural way to manage network interference by adapting transmission rates in response to changes in the environment. This interference management, however, requires some notion of scheduling and infrastructure (provided by the time-division structure). Such a configuration is appropriate when traffic is heavy on all links because it increases the bandwidth efficiency. We have shown that the configuration of this type of network consists of three basic components: neighbor discovery, time-slot assignment, and rate assignment. By decomposing the network configuration problem into separate logical components, we are able to design rules that generate stable, feasible network architectures in a finite amount of time. We have also shown the existence of practical signaling mechanism that allow for truly decentralized implementation of these rules.

Over the next year, the goal of Professor Javidi's effort on this project is to expand the framework described above to include numerous types of network configuration. The incorporation of results from other MURI projects is critical to this process, as the self-configuration problem in general is highly dependent not only on the particular application, but upon elements from nearly every layer of the protocol stack. Of particular interest is the incorporation of various physical layer technologies into the model. It will be important to examine the pros and cons of incorporating physical layer parameters such as modulation techniques and antenna directionality into the MAC layer. In addition, it is important to understand the impact of these MAC layer schemes on the higher-level performance of the network. The rules developed for the time and code division scheme described above attempt to maximize MAC layer capacity, but this does not necessarily translate into maximizing the overall network capacity. Since even the definition of network capacity can be application specific, it will be important to understand the relationship between the notions of MAC and network capacity and incorporate that relationship into the design of local rules.

4.2.1.7. Design of Wireless MIMO Relays and Data forwarding Policies

Professor Hua has focused on the problem of networking of MIMO nodes. Three major discoveries were made.

The first is that two clusters of neighboring nodes may form a virtual MIMO channel and data packets can be relayed through routes of parallel relays. A route of parallel relays is found to have a much longer lifetime than traditional routes of serial relays, and a normalized routing overhead of parallel relays is found to be much smaller than that of serial relays.

The second is that each MIMO node in a large ad hoc network should be able to perform as regenerative relay as well as non-regenerative relay. The regenerative relay mode provides robustness in packet recovery while the non-regenerative relay mode allows fast packet transmission. Optimal design of non-regenerative MIMO relays has been discovered.

The third is that efficient transmissions of large volumes of packets through ad hoc networks can be done through route-guided data forwarding protocols. Route-guided data forwarding protocols take the advantage of the broadcast nature of radio signals and a pre-established route with random link qualities with respect to a stream of packets in a highly dynamic environment.

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4.2.2. **MAC Layer Results**: (Overall Research Goal is Support Scheduling based on Interference Zones and Generated Traffic Models)

Professor Cruz has also focused on the development of specific distributed MAC protocols which incorporate coarse channel state estimates as well as QoS requirements, and examination of the tradeoff between channel measurement cost and benefit (joint work with L. Milstein).

Professor Zorzi has focused on the implications of layered space-time multiuser detection on the design of MAC protocols for ad-hoc networks. One of the key objectives of his research effort is to provide effective means to couple promising physical layer technologies (related to the use of multiple antennas at both the transmitter and the receiver) with networking technologies and protocols in a tactical ad hoc network scenario. This goal is ambitious and challenging for a number of reasons. In particular, it implies a solid understanding of both PHY MIMO technologies and networking protocol design, and requires the use of realistic PHY models able to capture the essential behavior of the receiver and of the propagation/interference environment while being sufficiently simple so as to make it possible to use them in network layer studies (e.g., by network level simulation).

Professor Krishnamurthy has completed work during the reporting period that focused on two orthogonal but complimentary directions: MAC/ROUTING solutions for directional antennas and MAC/ROUTING solutions for virtual MIMO links. His goal is to explore, design and build every part of a complete space-time based communication system, following a bottom-up approach.

More specifically, during the reported period Professor Krishnamurthy has:

1. Built centralized and distributed protocols for unicasting and broadcasting that enable and exploit virtual MIMO/MISO (links formed with cooperative diversity) in ad hoc networks. The motivation for starting out with virtual MIMO instead of actual MIMO links was that it provided backward compatibility with legacy systems.

2. Designed a polling based MAC protocol that exploits the capabilities of directional antennas. We have also designed a new topology control algorithm. Topology control is critical towards building a routing protocol that is closely knit with the MAC protocol. Our design includes both centralized and distributed versions and provides bounded node degree, while guaranteeing connectivity and bounded path stretch factor. The methods that we have designed can be, with minor modifications, used with MIMO based networks.

4.2.2.1. MAC/ROUTING SOLUTIONS FOR DISTRIBUTED MIMO LINKS

Space-time communications can help combat fading and hence can significantly increase the capacity of ad hoc networks. Virtual MIMO links facilitate spatial-temporal communications without actually requiring the deployment of physical antenna arrays. Professor Krisnamurthy's motivation for investigating the deployment of virtual MIMO within the current project comes from the belief that the provision of a framework for space-time communications for already deployable networks can be crucial for the success of real MIMO based systems. Furthermore, investigating virtual MIMO links first fits within their general bottom-up approach. Virtual MIMO links allow for an easier and cheaper implementation - no additional hardware is required. Many challenges that arise while building a framework to use virtual MIMO links are very similar to those that arise when real MIMO links are to be employed. However, there exist some differences; we will further investigate these in future efforts.

Professor Krishnamurthy has two main objectives: to increase the throughput of ad hoc networks, and to minimize energy consumption beyond the level that is possible with SISO links.

a) A Framework for Distributed Spatio-Temporal Communications in Mobile Ad hoc Networks

During the reporting period Professor Krishnamurthy has designed and implemented in OPNET, a multi-layer approach to exploit virtual MISO links in mobile ad hoc networks. Our approach is based on the development of a synergy between the layers of the protocol stack; lower layers export appropriate information and optimization "handles" to higher layers, while higher layers allow for the refinement of the performance parameters of lower layers. In particular, we take advantage of the extended range possible with virtual MISO links to establish shorter paths, which in turn, leads to an increase in throughput and a reduction in latency. First, we develop a new MAC protocol that closely ties in with the underlying physical layer to enable virtual MISO links. In particular, the MAC layer facilitates coordination between the collaborating nodes that transmit jointly on a virtual MISO link. Second, we design a routing protocol that can construct a path with virtual MISO links. Our approach has two attractive properties: (a) it is completely decentralized and nodes do not need more than local (one-hop) information, and (b) it provides robustness to link failures due to both mobility and interference effects. The latter property is facilitated via a dynamic anycast mechanism for establishing virtual MISO links.

Professor Krishnamurthy has performed extensive simulations with physical layer models that include fading effects to evaluate our approach. We observe that our schemes can successfully help form and exploit virtual MISO links. They provide significant improvements in higher-layer performance in terms of the observed end-to-end throughput. In particular, in mobile scenarios, the throughput (Fig. 1, virtual MISO denoted with VMISO) increases by as much as 150%.

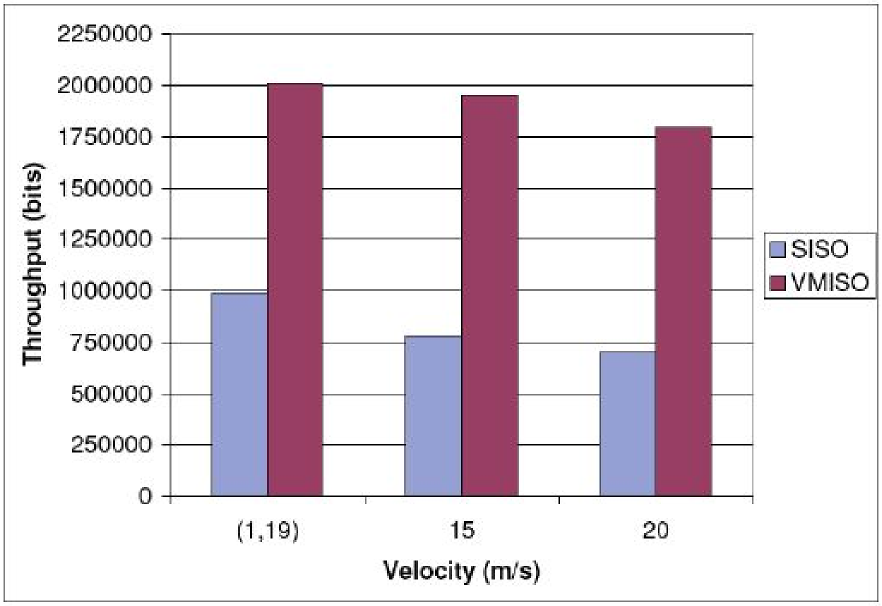

Fig. 1: Benefits of using Virtual MISO in terms of throughput

4.2.2.2. MAC/ROUTING SOLUTIONS FOR DIRECTIONAL ANTENNAS

Professor Krishnamurthy's work in this approach is pursued in two related directions:

a. Design of a MAC protocol for the full exploitation of the properties of directional antennas;
b. Design of a topology control algorithm that facilitate the performance enhancements possible PMAC in a given network, by reducing the polling overhead. The algorithm controls the topology, guaranteeing a maximum node degree of 6.

During the reporting period, he designed PMAC -- a MAC protocol that integrates a neighbor discovery and tracking mechanism along with the medium access control. PMAC is the first MAC protocol that uses only directional communications. As such, it overcomes the problems due to asymmetry in range and deafness – two major problems faced by all the previous MAC protocol designed for directional antennas. The key idea that forms the basis for our protocol is the use of a polling strategy wherein a node polls its discovered neighbors periodically; this would enable the node adjust its antenna weighting coefficients so as to continuously track its neighbors. The protocol design allows for modifications to facilitate its use when space-time codes or more sophisticated antenna arrays are used.

The major intricacy of the integration between the routing protocol and PMAC is t topology control. This is because PMAC performs best when each node maintains links only with a minimal number of selected neighbors; other neighbors are to be reached via these chosen direct neighbors. By thus imposing a limit on node degree, we impose a bound on the polling overhead. On the other hand, in terms of routing, the effect of reducing the node degree can result in a disconnected network, or can boost the lengths of paths between nodes. We have designed centralized and distributed topology control algorithms that provide bounded node degree, while guaranteeing connectivity and bounded path stretch. While in our current work, we focus on unit disk graphs (suitable for circular transmissions with sectorized beam directional antennas), we plan to use more realistic channel models and design better topology control schemes in the forthcoming year.

The centralized algorithm (LDS) allowed Professor Krishnamurthy to derive the desired properties; in particular, the maximum degree of the topology output by LDS is 6. Note here that the theoretical minimum value that the maximum node degree can have is 5 in order that the graph stay connected. Furthermore, LDS also guarantees that, for each pair of nodes that were connected in the input topology, they will be connected in the output topology by a path with hop count P', such that, $P'=O(P+\log(\Delta))$,where P and Δ respectively denote the length (hop count) of the shortest path between the same nodes in the input topology, and the maximum node degree in the input topology. These results improve the most relevant previous results in [1], [2].

His distributed version (D-LDS) makes the algorithm practically applicable to ad hoc networks, and has the attractive properties of (i) scalability, (ii) obviating the need for synchronization, (iii) being based on local decisions of individual nodes, and (iv) using O(n) messages in the worst case (where n is the number of nodes in the network). Through simulations and analysis of D-LDS in moderate to large size networks, we show that the communication requirement is low, the resulting network has average node degree close to 3, and the hop stretch in practice is much lower than the theoretical bound and is close to 3 on average. (Figures 3 and 4).

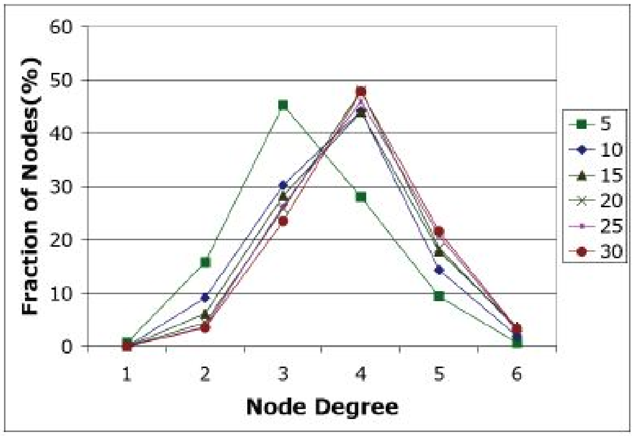

Fig. 3

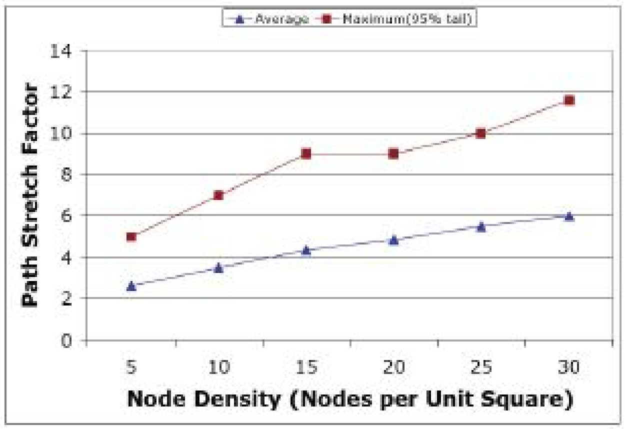

Fig. 4

Current work proposes an implementation of these algorithms in unit disk graphs, which renders them applicable only to omni-directional antennas or directional antennas with circular transmissions. However, Professor Krishnamuthy's target for future development of this work is to satisfy the same attractive properties in ad hoc networks equipped with MIMO antennas, where the unit-disk graph assumption does not hold.

4.2.2.3. On the Implications of Layered Space--Time Multiuser Detection on the Design of MAC Protocols for Ad Hoc Networks

During the first year, Dr. Zorzi has produced results on MAC layer design tightly coupled with the PHY features of the system we are studying. In particular, the interference cancellation capabilities of a recently proposed scheme have been incorporated in a MAC simulation study, and some initial protocol design and optimization has been carried out, showing good potential for improvement, and pointing out a few promising directions for further work.

Dr. Zorzi has a unique blend of expertise spanning both PHY and networking, and has been instrumental in promoting discussions within the networking team (especially Drs. Rene Cruz and Tara Javidi of UCSD, and to some extent Dr. Srikanth Krishnamurthy of UCR), leading an effort to try and integrate the various activities in a unifying framework, in which various aspects (e.g., MAC, routing, resource management, network organization) are jointly studied and their effects on each other are considered. Also, his understanding on PHY issues and of capabilities and requirements of MIMO PHY technology has been very useful in discussing what can or cannot be done within the MURI framework, and in pointing out possible directions in which to develop new ideas. He has also been discussing with Dr. Jafarkhani of UCI issues related to protocol design using space-time codes, and they are going to start soon some collaboration on this topic. Even though Dr. Michele Zorzi's support on this project is limited to one summer month, two of his Italian Ph.D. students (not funded directly on the MURI) have been working on MURI-related issues to the overall benefit of this project.

Dr. Zorzi's main goal was to analyze the implications of using a recent layered space--time multiuser detection technique in MAC protocol design for ad hoc networks with multiple antennas. From this point of view, this work relates to both physical layer and network layer studies.

Traditional MIMO studies, including the seminal work by Foschini, usually assume that all transmit and receive antennas are used to implement high-data-rate links. In the scenario we are considering, achieving a high rate on a single link is not by itself the objective, rather we would like to maximize the network performance in a multi-user context. This means that maximizing the single link rate is not necessarily the best choice, and it is not obvious how many antennas should be used for each transmission in a scenario where multiple users should transmit simultaneously. The considered model, therefore, is one in which each node has multiple antennas, and uses some of them to transmit (the selection of the exact number of antennas is part of the protocol), and all of them to receive. In addition, each antenna transmits an independent stream of bits, so that at the receiver signals coming from the same node or from different nodes are treated similarly. The goal is to design a proper channel access mechanism where, in a distributed way, each node decides when to transmit and with how many antennas, and how to receive intended signals and to cancel interfering signals, in such a way that the throughput of the network is maximized.

To this aim, we need to clearly understand the PHY performance of the MIMO technique in such a multi-user scenario, and from this understanding to draw conclusions and derive design recommendations for the development of appropriate access schemes. In this context, during the reporting period we have focused on two technical objectives: i) develop models and gain understanding of MIMO behavior in ad hoc networks via detailed PHY studies in a multi-user scenario, in order to characterize the achievable performance; and ii) provide initial design and performance evaluation of MAC protocols tailored to the multi-user MIMO environment. These objectives are fully in line with the overall thrust of the project, where one of the main goals is to come up with effective protocol design criteria for ad hoc networks in the presence of MIMO technology.

4.2.2.4. PHY characterization and performance study

Professor Zorzi 's first study relevant to the general problem has to do with PHY performance of the simple networking model considered. He used an interference cancellation scheme proposed by Sfad et al. (IEEE Transactions on Wireless Communications, Jul. 2003) as the receiving algorithm, and we investigate its multi-user capabilities in the presence of multiple transmissions. In general, three terms are identified in the received signal, namely the signals that are detected (and, if necessary, canceled), the interference that cannot be estimated (and is therefore considered as unknown), and the receiver thermal noise. He studied the BER performance and the statistics of the number of errors in the transmission of a block of bits, as a function of the noise level and the number of interferers. Full detail of the receiver algorithm at the PHY layer is accounted for and bit-level simulation is used to generate those results (an approximate analytical approach is also being pursued). These results make it possible for us to understand what are the achievable performance within such a network, and to provide guidance in making decisions about how many transmissions can be supported and in accurately assessing the benefits of using interference cancellation.

It is worth noting that so far in the networking research community no detailed PHY model has been used towards evaluating networking performance at higher layers (this is in fact one of the main limitations of the current literature on the topic), whereas detailed approaches in the PHY research community have rarely been targeted towards networking issues, and therefore do not address some of the scenarios that are most relevant in our context. On the other hand, Professor Zorzi's study is much more detailed than what exists, and is expected to provide much better results when applied to networking protocol design and performance evaluation.

The main conclusion of such a study is that the probability of successful reception is high even in the presence of a significant number of parallel transmissions, as long as the noise level is not too high. The presence of unknown interference in seen to significantly impact the performance. Finally, the effect of packet length as well as some preliminary results on the use of coding are also investigated. While many other results need to be generated in order to make this study complete (this is part of our planned work for the future), the insight gained so far is very important and useful.

The results of this study have direct implications about the design of MAC protocols, in which, e.g., it turns out to be convenient to be aggressive in allowing multiple transmissions from nodes close to each other. Although many of the obtained results are very much in agreement with what one might have intuitively expected, the contribution of our study is to make it possible to quantitatively characterize this behavior and to formulate effective access rule for the considered scenario.

4.2.2.5. PHY-aware MAC cross-layer design and performance study

Based on the characterization of the PHY behavior and on the corresponding performance results, a second important objective that Professor Zorzi has pursued relates to the design of access rules for MIMO ad hoc networks. Typical access protocols for ad hoc networks are based on CSMA/CA technology, whose main representative is IEEE 802.11. In these protocols, one tries to avoid simultaneous transmissions in the same area, which cannot be sustained in a traditional narrowband system. Following a Request-to-send (RTS) packet, issued by the sender, the desired receiver responds with a Clear-to-send (CTS) packet, which grants the sender an opportunity to transmit the data packet. This mechanism, coupled with a physical carrier sensing mechanism, is meant to avoid that two packet transmissions overlap in the same network area, leading to a collision and the resulting loss of all packets involved.

On the other hand, in the presence of interference-tolerant transmission technologies (including MUD, MIMO, and interference cancellation), this approach is too conservative and leads to poor throughput performance. In the presence of these capabilities, it is better to adopt a more aggressive approach where multiple transmission requests can be issued and served simultaneously, while relying on PHY processing to separate the signals. If this capability is to be exploited, one needs to design new MAC mechanisms which incorporate it in the access rules.

As a first step towards addressing the problem of multiple access in MIMO ad hoc networks, we consider an 802.11-like scheme, modified to allow for multiple transmissions in a controlled way, based on the capture results of our previous study. More specifically, we assume that the access mechanism is still based on RTS/CTS signaling exchange, but the use of these signaling packets is different from that in the traditional 802.11 version. For ease of explanation and of study, we first referred to a scheme where transmissions are packet synchronous. This makes it easier to fully exploit interference cancellation capabilities, since the combination of interfering signals can be estimated during a first training phase so that interference protection is maximized during the data transfer portion of the schedule. Extension to asynchronous schemes is under study.

First of all, nodes issue RTSs according to the status of their queues. These RTSs are typically sent simultaneously, and can be jointly received by all nodes within range. This makes it possible for all nodes involved to know the network traffic, and this information is important in order to i) decide whether or not to grant permission to transmit (thereby controlling the level of interference so as to make interference cancellation successful); ii) decide how many antennas to use in transmission (thereby implementing some implicit rate and admission control); iii) decide how to best employ the degrees of freedom at the receiver according to the algorithms detailed below; iv) keep an estimate of the networking activity, which is useful in deciding medium-term transmission policies.

In order to understand how this kind of approach may be effective, we have considered three policies at the receiver. In all cases, a receiving node has the ability to track the channel conditions of a limited number of signals (one degree of freedom is used per transmit antenna) so that there is a limit to how many antennas the receiver can listen to. The first policy completely ignores the possibility of interference cancellation, and issues CTSs based on intended signals only, ignoring the interference, which is then included in the unknown noise term in the detection process. This can be seen as a baseline case which corresponds to a naïve extension of 802.11. The other schemes, on the other hand, have the ability to track interfering signals and to cancel them at the receiver. In the presence of many incoming signals (more than the receiver can handle) a choice must be made about which ones are to be detected, and which ones are left as unknown interference. The two policies differ from each other in how a receiver prioritizes in allocating its degrees of freedom to incoming signals. In one policy, the receiver first focuses on all signals meant for it, and with any degrees of freedom left deals with some of the interferers (typically the strongest). In the other policy, the receiver focuses on the strongest of the intended signals, and then on the remaining signals in decreasing order of received power. By doing so, the receiver may neglect some of the intended signals, in order to be able to cancel strong interferers. In other words, the receiver focuses on purpose on fewer intended signals while providing a much higher reliability to their detection, whereas in the first policy it tried to maximize the number of intended signals received while sacrificing reliability. Our results show that the policy that privileges the reliability of the cancellation process over the number of intended signals has a significantly better performance, in terms of throughput, queue length, and protocol efficiency. This demonstrates that careful design of MAC protocols in this environment may lead to significantly better schemes, and encourages a deeper investigation of this class of access schemes.

4.2.2.6 References:

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3. Paolo Casari, Marco Levorato, Michele Zorzi, "On the Implications of Layered Space--Time Multiuser Detection on the Design of MAC Protocols for Ad Hoc Networks," IEEE Personal, Indoor, and Mobile Radio Communications (PIMRC) conference, Sep. 2005.
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4.2.3 Physical Layer Results:

The overall research goals at the physical layer are to optimize space/time/frequency diversity to minimize mutual interference between the mobile nodes and maximize bit-error rate (BER) performance. In addition the PHY layer must provide channel estimation statistics for MIMO nodes to the MAC and networking layers, and respond to requests from the networking and MAC layers on desired input parameters to those layers. The PIs specifically focused on this goal are Professors Milstein, Proakis, Rao, Zeidler, Swindlehurst, Jensen, Jafarkhani, and Haykin.

4.2.3.1 Theoretical Performance Limits of Time-Varying MIMO Channels

Node mobility is the most significant factor that limits the performance gain offered by multiple antennas in a communications network, be it cellular or ad hoc. In order to understand how MIMO systems perform under mobility, the MURI team has undertaken an analytical performance analysis of space-time modulation techniques under a wide variety of conditions.

Using a simple innovations model for the time-variations of the MIMO channel, Professor Swindlehurst has conducted a detailed performance analysis of pilot-symbol assisted modulation (PSAM) and differential modulation MIMO techniques. His analysis is general enough to apply to both line-of-sight and Rayleigh fading environments (or combinations of the two), and includes the effects of channel estimation error. This work is reported in [3]. Professor Swindlehurst has been able to accurately predict the high-SNR error floor that results due to the use of stale channel estimates in mobile systems. In addition, he was able to use his analysis to predict the optimal (in terms of capacity) amount of training to use for each data block, the optimal length of a data block before re-training is necessary, the optimal allocation of power between the training and data portions of the transmitted block, and also under what conditions it is better to use non-coherent (e.g. differential) modulation rather than PSAM. While PSAM techniques generally outperform differential modulation, they require an appropriate choice of training parameters to do so. To date, this effort has focused on PSAM architectures where the training data is front-loaded in each data block. Professor Swindlehurst is planning to extend this research to situations where the training data is embedded along with the data.

4.2.3.2 Experimental Evaluation of Spatial Multiplexing Performance

Multiple antennas allow for the possibility of "spatial multiplexing" (sometimes referred to as "multipacket reception") in ad hoc networks. While a number of algorithms have been proposed to achieve this goal, they have only been tested with simulated data under very simplistic channel modeling assumptions. BYU has a major effort to experimentally study the feasibility of spatial multiplexing in real networked MIMO scenarios. This work is reported in [1]. In this context, "spatial multiplexing" refers to the ability of one node in a network to communicate with two nodes simultaneously in broadcast mode using only spatial (beamforming) techniques for transmit discrimination. Using both indoor and outdoor MIMO channel measurements taken in rich scattering environments, we have demonstrated that users separated by as little as 5-10 wavelengths (1-1.5 meters at 2.4 GHz) possess independent enough channels to permit spatial multiplexing. We have also shown that capacity growth is quite slow as the network attempts to spatially multiplex more and more users, indicating that interference soon becomes a limiting factor. For nodes equipped with a typically small number (less than 4) antennas, it appears that multiplexing only two users is realistic under real conditions. Our next step is to study the effect of mobility on spatial multiplexing, and how to effectively update the channel parameters in order to maintain a minimum QoS level (e.g.,SINR) to all multiplexed users. We have been investigating a simple LMS technique for tracking the mean value of the channel.

Professor Jensen has developed a new channel sounder for MIMO wideband systems. He have developed a new system capable of measuring the MIMO channel for up to 8 transmit and receive antennas over bandwidths of up to 100 MHz. The system, capable of obtaining a full 8 x 8 channel matrix in 3.2 ms, uses a switched antenna architecture which uses only a single transmit and receive chain to connect sequentially to the different antennas. The device is being used to analyze the frequency and time-dependent nature of MIMO channels in environments typical of military ad-hoc networks.

Professor Jenson has initiated an effort to assess MIMO channel characteristics in multi-user networks. Clearly the performance is critically dependent on the characteristics of the available communication channels. For example, the ability of MIMO algorithms to increase link efficiency while suppressing interference to other users can be limited if the channels from a transmit node to different receiving nodes are similar. Furthermore, the temporal (or spatial) variability of these channels dictates how frequently channel state information must be acquired and, in some implementations, shared within the network. Professor Jenson has examined the properties of MIMO channels as a function of the physical proximity of multiple users and have explored the effect of channel similarity on the performance of multi-user MIMO algorithms. His initial analysis suggests that good multi-user MIMO communication is possible in rich multipath environments even as the physical separation between nodes gets as small as 10 wavelengths. Similarly, he has carefully assessed the temporal variability of the channel through the use of new metrics that quantify the degradation in performance resulting from outdated channel estimates. This analysis reveals that channel state information (CSI) must be estimated at the receiver every time one of the nodes moves 0.1~0.2 wavelengths. The transmitter requires an update of the CSI every time one of the nodes moves ~10 wavelengths.

Based on measured data, Professor Jenson has generated two different models for describing the temporal behavior of MIMO channels: a stochastic matrix approach and a stochastic description of the multipath characteristics. Each of these two models has distinct advantages in terms of complexity and accuracy. Based on the time-variation channel models developed, he has investigated the temporal variation in the MIMO channel coefficients for different array topologies. Professor Jenson's analysis suggests that arrays of directive elements (arranged to cover the full communication space in angle) achieve the same capacity but produce significantly reduced temporal variation as an identical array with omnidirectional elements. He has generated an arrangement with a manufacturer of a vest antenna array to conduct measurements to substantiate (quantify) this finding in typical tactical environments.

4.2.3.3 MIMO Channel Prediction

In mobility-limited situations where channel estimates become stale when the nodes of the network move more than a fraction of a wavelength, it is natural to wonder if channel prediction or tracking techniques could be used to extend the "horizon" of usefulness over which a channel estimate may be useful. In this effort (reported in [2]), Professor Swindlehurst has been studying the theoretical performance limits of MIMO channel prediction. He have been able to demonstrate that, at least theoretically, MIMO scenarios should allow one to predict the channel much farther into the future than single-input single-output scenarios. His CRB analysis shows that the "prediction length" (a normalized quantity that measures how far in the future a channel can be accurately predicted) for a 3x3 MIMO system is two orders of magnitude greater than a corresponding 1x1 SISO system (from a few hundredths of a wavelength to several wavelengths). The reason for these remarkable gains is that a series of MIMO channel measurements (obtained, for example, using training data) provide multiple measurements of the space-time channel parameters rather than just one. Professor Swindlehurst has devised a simple channel prediction scheme that achieves a small degree of the promised MIMO prediction gain, but the gap between theory and performance is still large. We are continuing to focus on algorithms that allow one to better realize this gain.

4.2.3.4 Channel Equalization for MIMO Systems

Low complexity and reduced power consumption are primary considerations in receiver design for ad hoc communication networks. These requirements are complicated by the fact that receivers operate in fading mutipath channels. Professor Proakis has considered the design of MIMO systems for ad hoc networks in which joint spatial and temporal equalization, usually called precoding, is performed at the transmitter. Precoding at the transmitter reduces the receiver complexity significantly and provides a degree of interference suppression from the signals intended for different receivers. We are evaluating the performance characteristics of three nonlinear proceeding techniques. One approach is based on the QR decomposition of the MIMO channel matrix; the second is based on the zero-forcing criterion for designing the precoder; the third method is based on the minimum-mean-square-error criterion for designing the precoder. Performance results on the QR decomposition approach for a two-multipath component Rayleigh fading MIMO channel were presented at the Annual Review on July 28, 2005 and are available on the MURI website.

4.2.3.5 Quantifying Performance Improvements Due to Spatial-Temporal Diversity in Mobile MIMO Spread-Spectrum Ad-Hoc Networks With Partial Band Interference

Dr. Zeidler has investigated the effect of the spatial diversity due to multiple antennas and the temporal diversity due to interleaving and coding for mobile ad-hoc networks with spread-spectrum. The effects of Doppler spreading in a time-varying fading channel were analyzed for a DS-CDMA system. The tradeoffs in channel estimation accuracy that are realizable at low Doppler rates and the effects of increased time diversity at high Doppler rates are evaluated. The gains associated with the use of finite depth interleaved convolutional codes at high Doppler rates are derived. For a DS-CDMA two-branch transmit diversity system, the performance of Alamouti's space-time code in time-varying channels with noisy channel estimates is derived. It is shown that the Alamouti space-time code with a maximum likelihood symbol detector and linear combining is outperformed by a system with no transmit diversity at high Doppler rates or low pilot SNR. Comparisons of analytical results with experimentally measured channel data from BYU are provided.

In order to obviate channel time variability without excessive pilot power, non-coherent codes, such as differential space-time codes (DSTC), have also been analyzed by Dr Zeidler and Dr. Jensen to provide robustness in mobile ad-hoc networks. Dr. Zeidler evaluated a frequency-hopped CDMA (FH-CDMA)system was evaluated with DSTC and error-correction codes to provide improved performance in tactical multiuser ad-hoc networks. The use of erasure insertion in such a system was evaluated. The results show that substantial improvement in performance can be achieved over a system without erasure insertion, especially when the partial band interference in the system is significant. In addition, a DSTC that is effective with offset modulations is developed in order to provide improved spectral performance in the presence of amplifier nonlinearities. It was shown that while traditional DSTC operates at a reduced transmission rate relative to other STC, the combination of DSTC with offset modulation allows full rate transmission at the expense of greater detector complexity.

4.2.3.6 The Effect of Channel Estimation Errors on System Performance

Professor Milstein has considered the effect of imperfect channel state information (CSI) on both waveform design and scheduling protocols. Regarding the former topic, a tradeoff between the use of multicarrier CDMA and direct sequence multicarrier CDMA is studied. With respect to the latter topic, the influence of mobility on the accuracy of CSI is illustrated by considering the performance of a multiuser diversity system. The selection of waveforms is dictated by the feedback from the Army Research Lab discussed above in Section 3.0.

Professor Milstein has considered the tradeoff between multi-carrier direct-sequence CDMA (MC-DS-CDMA) and multi-carrier CDMA (MC-CDMA)[1]. To make a fair side-by-side comparison between the two schemes, both systems were set up to match each other as closely as possible, and it was assumed that they operated under equal bandwidth, information rate, and transmitted power constraints. Waveform shaping was used in both systems to bandlimit the signal at each sub-carrier, and the sub-carriers were spaced in such a way that adjacent sub-bands did not overlap. Frequency diversity was achieved by using repetition coding to send a bit over multiple sub-carriers, and maximal-ratio combining was used at the receiver to combine the energy from these different channels. Since direct-sequence spreading is performed at each sub-carrier in MC-DS-CDMA, resulting in wider sub-bands when compared with those of MC-CDMA (in MC-CDMA, the data at each sub-carrier is modulated by only a single chip in the spreading sequence, with different sub-carriers modulated by different chips), over a given bandwidth, the MC-CDMA system has a larger number of sub-carriers. And since the information rate is kept constant between the two systems, a bit is repeated across a larger number of sub-carriers in MC-CDMA than in MC-DS-CDMA, potentially giving MC-CDMA greater frequency diversity. On the other hand, the energy for a given bit is distributed across a larger number of sub-carriers in MC-CDMA than in MC-DS-CDMA, such that the energy-per-repetition in MC-CDMA is lower than in MC-DS-CDMA. As a result, MC-CDMA suffers from noisier channel estimation, because the signal-to-noise ratio (SNR) upon which the channel estimates are made is lower in MC-CDMA than in MC-DS-CDMA. Therefore, a trade-off with regards to frequency diversity and channel estimation errors may exist between the two systems.

Regarding the effect of channel estimation errors on scheduling protocols, the key consideration there is the Doppler spread of the channel. In Professor Milstein's work ([2]), he analyzed the performance of a multiuser diversity system taking into account the feedback errors due to channel variability. Based upon a block fading model, he derived an expression for throughput as a function of system parameters, such as packet length and data rate thresholds, and channel characteristics, such as Doppler spread. His results indicate that there is a tradeoff between multiuser diversity and mobility, with higher mobility resulting in a decrease in average throughput.

The key conclusions that were established from Professor Milstein's work are the following:

1. If the coherence bandwidth of the channel equals the bandwidth of one of the MC-DS-CDMA subcarriers, and if there is more than a single user active in the system, then with the same data symbol transmitted across all the subcarriers, MS-DS-CDMA outperforms MC-CDMA for all values of Eb/No. If multiple symbols are transmitted in parallel, MC-DS-CDMA yields better performance unless a sufficiently large number of pilot symbols are employed, in which case MC-CDMA has an advantage.

2. If the coherence bandwidth of the channel equals the bandwidth of one of the MC-CDMA subcarriers, the two systems perform the same if the multipath intensity profile is rectangular. If the

multipath intensity profile is a decaying function of delay, then the MC-CDMA system outperforms the MC-DS-CDMA system.

3. Regarding the use of scheduling to provide multiuser diversity in a mobile environment, the desirable effects of multiuser diversity tend to disappear as the relative velocity between the transmitter and the receiver becomes large.

4.2.3.7 Quantization Algorithms and their Analysis in Feedback MIMO systems.

Professor Rao has investigated the use of feedback of channel state information to the transmitter by the receiver. It is known that this can greatly enhance the throughput of a communication network provided that the delay in the channel feedback does not exceed the stability of the channel estimates. There are significant issues such as limited feedback, errors in feedback, delay in feedback etc that can significantly compromise the performance of feedback based multiple input multiple output (MIMO) systems. The goal of Professor Rao's work is to determine how to best employ feedback in MIMO ad-hoc networks. To that end, the performance of Multiple Input Multiple Output (MIMO) systems with limited feedback is studied in this work. In particular, we examine the capacity loss resulting from the use of finite number of bits for quantizing the channel state information. For effective feedback, we consider vector quantization (VQ) based techniques. For multiple input single output (MISO) systems, we introduce a new design criterion and develop the corresponding iterative design algorithm for quantization of the beamforming vector. For complexity-limited systems, tree-structured VQ is also examined and compared with the full-search VQ method. The performance of systems with VQ-based quantized beamforming is analyzed for the independent Rayleigh fading case. This requires finding the density of the squared innerproduct between the optimum and the quantized beamforming vector, which is obtained by considering a simple approximation of the quantization cell. The approximate density function is used to lower bound the capacity loss due to quantization, the outage probability and the bit error probability.

The methodology is extended to deal with the problem of transmit beamforming in MIMO spatial multiplexing (SM) systems with a finite-rate feedback channel. Assuming a fixed number of spatial channels and equal power allocation, we extend the capacity loss based design criterion for designing the codebook of beamforming matrices. Using the criterion, we develop an iterative design algorithm that converges to an optimum codebook. Under the i.i.d. channel and high SNR assumption, the effect on channel capacity of the finite-bit representation of beamforming matrix is analyzed. Central to this analysis is the complex multivariate beta distribution and tractable approximations to the Voronoi regions associated with the code points. Furthermore, to compensate for the degradation due to the equal power allocation assumption, we propose a multimode SM transmission strategy wherein the number of data streams is determined based on the average SNR. This approach is shown to allow for effective utilization of the feedback bits.

Based on the insights gained from the codebook design and analysis work, we are now developing a general framework based on high resolution techniques from source coding to address dependence on number of bits, spatial correlation, mis-matched quantizers etc. The VQ based quantizer design based on non-quadratic cost functions along with the analytical framework being developed should play an important role in understanding the issue of qunatized feedback MIMO systems.

4.2.3.8 Beamforming and Space-Time Coding for Ad-Hoc Mobile Networks

Professor Jafarkhani has addressed the tradeoffs in performance between the use of beamforming and space-time coding (STC) in mobile ad-hoc networks. His contributions can be delineated into three specific results.

(1) Professor Jafarkhani has invented a new adaptive structure that combines the advantages of super-orthogonal space-time coding (SOSTTC) and co-phase beamforming. The new design has the following properties:

- Low complexity
- Good performance
- Identical to optimal beamforming for perfect channel feedback and identical to space-time coding for no channel feedback

The design strategy works for any constellation, any rate, any number of states, and any number of feedback bits

(2) We have proposed two new connectivity measures:

- Capacity measure
- Symbol error rate (SER) measure

A classic connectivity measure based on signal strength is not capable of accurately capturing the connectivity phenomenon in an adhoc network. Professor Jafarkhani has studied the effects of modulation, coding, and number of antennas in the connectivity of adhoc networks. For example, he shows how employing multiple antenna mobile nodes enhances the connectivity of fading ad-hoc networks. Specific results obtained include:

(1) Space Time Trellis Codes Based on Channel Phase Feedback:

Space-time coding has been proposed recently for the MIMO wireless communication systems. Most of the proposed space-time coding schemes use the assumption that either no channel state information, or the channel mean / covariance information, is available at the transmitter. In Professor Jafarkhani's work, a new space-time coding scheme was proposed for a closed-loop transmission system, where quantized channel phase information is available at the transmitter. A new performance criterion is derived for the quasi-static fading channel. This design criterion is then used to construct a new class of space-time trellis codes.

The proposed code construction is based on the concatenation of a standard M-TCM outer code with an inner code. The inner code is selected from a series of inner codes using the channel phase feedback. The series of inner codes are constructed based on the systematic set partitioning of several classes of space-time signal designs. Simulation results show significant performance improvement over the other space-time trellis codes in the literature. In addition, the proposed coding scheme enjoys low peak to average power ratio, simple decoding, and easy implementation without complicated eigen-analysis.

(2) Power Loading for Space-Time Trellis Codes Based on Channel Magnitude Feedback:

Professor Jafarkhani has also presented a novel power loading scheme for several existing space-time trellis codes (STTCs). These STTCs are originally designed for the open-loop systems where no channel state information is available at the transmitter. To further enhance the performance of these STTCs, he assumes that the scalar quantized channel magnitude information is available at the transmitter through a feedback channel. Therefore, the error performance of these STTCs is improved through proper power loading on the different transmit antennas. To calculate the power loading parameters, he derives the distance spectrum of these STTCs based on the channel magnitude information. He also uses a novel transfer function analysis to optimize the overall distance spectrum. The proposed power loading algorithm is flexible enough to be applied for various kinds of existing STTCs and it also enjoys easy implementation at the transmitter. Finally, numerical simulations show that the new power loading scheme accomplishes superior performance compared to several widely used open-loop algorithms as well as some popular closed-loop algorithms in the literature.

(3) Outage Probability Metrics of Connectivity for MIMO Fading Ad-Hoc Networks:

Professor Jafarkhani has investigated the connectivity of fading wireless ad-hoc networks with a pair of novel connectivity metrics. His first metric looks at the problem of connectivity relying on the outage capacity of MIMO channels. His second metric relies on a probabilistic treatment of the symbol error rates for such channels. He relates both capacity and symbol error rates to the characteristics of the underlying communication system such as antenna configuration, signal strength, and modulation. He assumes that a pair of nodes are connected if their bi-directional probabilistic measure of connectivity exceeds a given threshold. For each metric of connectivity, he also provides a simplified treatment in the case of ergodic fading channels. In the ergodic case, he assumes a pair of nodes are connected if a their bi-directional deterministic measure of connectivity exceeds another given threshold. Further, he attempts to capture the time correlation of ergodic channels by modeling the fading channel with finite state Markov chains. His simulation results show that (1) a pure measure of connectivity based on signal strength is not capable of accurately capturing the connectivity phenomenon, and (2) employing multiple antenna mobile nodes enhances the connectivity of fading ad-hoc networks.

(4) Rate Constrained Power Control in Space-Time Coded Fading Ad-Hoc Networks:

Under aggregate data rate and loss constraints, Professor Jafarkahani has studied the problem of power control for fading wireless ad-hoc networks accommodating space-time coded mobile nodes. His study relies on modeling the underlying wireless channel with finite-state Markov chains and using Reed-Solomon channel coders to compensate for the temporally correlated loss observed in such networks. His study shows that utilizing space-time coding techniques can reduce power consumption of ad-hoc networks under the given constraints. Further, he investigates the tradeoff between practicality and optimality by means of introducing centralized and decentralized power control schemes. He quantifies the tradeoff by comparing different schemes together.

4.2.3.9 The McMaster University, Canada Contribution to the MURI

Principal investigator (PI): Simon Haykin Ph.D. students: Nelson Costa and Tao (Stephen) Feng

The received signal at the output of a wireless communication channel contains information about both the channel state and the transmitted signal. For the receiver to recover the transmitted signal in an optimum manner, the receiver needs to perform coherent detection on the received signal, which, in turn, means that the receiver must have channel state information. Moreover, the receiver should avoid hard decisions to preserve the full information content of the received signal. To this end, a research program has been established at McMaster University (the Canadian node of the MURI project), which builds on closely related work that has been (until recently) supported by the PI's Discovery Grant awarded by NSERC. The original purpose of this Grant is to study Cognitive Radio and Radar.

Having attended the first MURI Meeting that was held on July 28, 2005, at San Diego, the decision has been made to focus the above-mentioned work on rapidly changing wireless channels. This is not only topical but particularly challenging in the context of MIMO wireless communications, which is a major point of focus for the MURI project. Simply put, if we are to exploit the potential of MIMO techniques for improved spectral efficiency, then a proper understanding of the influence of "mobility" on CSI is a necessary requirement.

1. Wideband MIMO Software-defined Radio (WMSDR): Nelson Costa A four-by-four WMSDR system has been completed. The system is mounted on two racks, one housing the transmitter and the other housing the receiver. Initial tests have validated the satisfactory working condition of the GPS-based system. The primary purpose of the system is provide experimental data for channel state estimation.

   Presently, the system is limited in its portability. In order to be able to collect experimental data on rapidly changing wireless channels, we have to extend the design of of the system to provide its own power supply.

2. Stochastic Differential Equation (SDE) Theory Applied to Wireless Channels (Stephen Feng) Modeling wireless channels is essential to the design of wireless communication systems. An autoregressive (AR) process of order one for wireless channels has long been assumed in the literature, but without a rigorous mathematical/physical basis. In [1], a first-order stochastic AR model is derived for a flat wireless channel; the derivation follows SDE theory applied to the multipath phenomenon. The AR model derived in [1] provides more channel information than currently available AR models for wireless channels.

Simulated data lend strong support to the new SDE-based AR model.The essential features of this work are summarized as follows:

It can model Rayleigh distributed fading channels effectively . it can efficiently generate synthetic Rayleigh distributed channel data . it is an instance of a first-order Markov chain . the model follows from SDE theory concerning the nature of the multipath fading channels, and most importantly, the AR parameters express physical meanings.

3. Improved Bayesian MIMO Channel tracking for wireless communications, incorporating a dynamic model : Kris Huber The AR model studied under point 2 assumes that the AR parameters are static in nature and are estimated prior to any transmission. Thus if the channel conditions change as they would in a rapidly changing wireless environment, then a model mismatch occurs and system performance could be seriously degraded. In [2}. a dynamic channel model is described, which allows for time-varying channel statistics by modelling the AR model parameters themselves as a Markov random walk, thereby allowing the channel model to assume a time-varying behavior. Through realistic simulations, it is demonstrated that the incorporation of dynamic modeling of rapidly channel conditions not only offers significantly improved MIMO performance, but most important at high SNR conditions, the error floor commonly seen in wireless systems using static first order AR models is eliminated.

4. Oversampled Receiver incorporating multiple Kalman tracking for improved performance (stephen Feng) In [3], a novel receiver for wireless communciations is described, which distinguishes itself form a tarditional receiver in two important respects:

   The received signal is oversampled on a symbol by symbol basis, thereby generating multiple time series realizations of the received signal, and . the multiple time series so generated make it possible to build a multiple set of Kalman filters that track the wireless channel, thereby providing reliable CSI.The important point to note here is since these two operations are performed on the channel output after reception, there is no increase in channel bandwidth. Rather, increased system complexity is used to preserve the information content of each channel-corrupted symbol of the received signal. The results of detailed computer simulations show that the receiver performance is progressively increased with increased sampling rate.

   The current work assumes that the measurement noise is additive white Gaussian noise, which, in turn, means that the multiple time series are statistically iindependent.

Work is on progress to deal with the more realistic situation of colored noise. Moreover, it is intended to extend the work to make the channel model dynamic, building on the successful results reported in [2].

With MIMO being a primary mission of the MURI project, the intention is also to expand this novel receiver to encompass MIMO wireless communications under rapidly changing wireless conditions.

Professor Haykin's intention to integrate theory and experimental work as closely as possible in this MURI project.

4.2.3.10 References:

J. Jootar, J. R. Zeidler, and J. G. Proakis, "Performance of Alamouti Space-Time Code in Time Varying Channels with Noisy Channel Estimates," in Proceedings of the IEEE WCNC (New Orleans), pp 498-503, Mar. 2005.

J. Jootar, J. R. Zeidler, and J. G. Proakis, "Performance of Finite-Depth Interleaved Convolutional Codes in a Rayleigh Fading Channel with Noisy Channel Estimates," in Proceedings of the IEEE 61st Vehicular Technology Conference (Stockholm), June 2005.

A. Anderson, J. R. Zeidler, and M. A. Jensen, "Differential Space-Time Coding with Offset Quadrature Phase-Shift Keying", Proceedings of the IEEE Workshop on Signal Processing Advances in Wireless Communications (New York, N. Y.), June 2005

H. Sui and J.R. Zeidler, "Erasure Insertion for Coded MIMO Slow Frequency-Hopping Systems in the Presence of Partial Band Interference", submitted to IEEE Globecom, December 2005

H. Sui and J. R. Zeidler, "An explicit and Unified Error Probability Analysis of Two Detection Schemes for Differential Unitary Space-Time Modulation", submitted to the IEEE Asilomar Conference, November 2005

J. Jootar, J. R. Zeidler, and J. G. Proakis, "Performance of Convolutional Codes with Finite-Depth Interleaving and Noisy Channel Estimates," submitted to IEEE Transactions on Communications, April 2005.

P. Amihood, E. Masry, L. B. Milstein, J. G. Proakis, “Asymptotic Performance of Multicode MIMO Systems in Frequency Selective Fading Channels”, Proc. MILCOM’05, Atlantic City, Oct. 2005

P. Amihood, E. Masry, L. B. Milstein, J. G. Proakis, “Performance Analysis of High Data Rate MIMO Systems in Frequency Selective Fading”, submitted for publication to the IEEE Trans. on Information Theory.

A. S. Ling and L. B. Milstein, "Comparison of Multi-Carrier Modulation Techniques”. To appear in 2005 IEEE Conference on Military Communications.

D. Piazza and L. B. Milstein, “Impact of Feedback Errors in Multiuser Diversity Systems”. To appear in 2005 IEEE Conference on Vehicular Technology.

T. Feng, T. Field, and S. Haykin, "Stochastic differential equation theory applied to wireless channels," submitted to IEEE Trans. Communications

K. Huber and S. Haykin, "Improved Bayesian MIMO channel tracking for wireless communications: incoropräting a dynamic model," Final revision, IEEE J. Wireless communications

T. Feng ans S. Haykin, "Novel procedure for reliable detection in an unknown wireless environment," IEEE Conference on Radio and Wireless, San Diego, CA, January 2006 (invited).

Conclusions

The scientific and technical progress made during the first year of this project has been significant. It has resulted two published journal papers, 31 published conference papers and 41 submitted journal and conference papers. In addition the PIs on the project have completed textbooks in ad-hoc networks, space-time coding, wireless communications and digital signal processing. The PIs have been asked to serve on many conference organizing committees, act as technical chair, and provide invited papers at many of the leading conferences in the field.

It is difficult to provide a summary of the large body of work completed during the year, but it can be noted that we obtained capacity results for networks with MIMO nodes and developed the first analytical models for ad hoc networks that can take into account realistic antenna gain patterns, and considers STC technology. Network topologies & protocols to integrate CSI parameters into the MAC and higher layers are under development and beamforming vs STC comparisons are in progress. MAC/Routing protocols using spatial re-use that incorporate antenna arrays, STC &

MUD are under development and channel access protocols for collaborative MIMO nodes are being defined. Data forwarding policies using wireless relays to reduce power consumption, transmission delay and packet loss rate in progress.

We have quantified the effects of imperfect CSI on waveform design and routing protocols for mobile multiuser systems and evaluated tradeoffs in spatial and temporal diversity for coherent and incoherent MIMO modulations for time varying channels. Interference suppression through channel equalization (precoding) at the transmitter and the use of frequency hopped differential unitary space-time codes have been developed. The effects of quantization of the CSI information and the training and pilot signal parameters being evaluated for open loop transmission systems and differential modulation and decision feedback equalization techniques have been developed for closed loop systems. The channel prediction distance of a 3x3 MIMO system was shown to be significantly greater than a SISO system. In additional a detailed experimental channel characterization of realistic time variations in the MIMO channels has been initiated. Further, an assessment of time-variation and superdirectivity in MIMO antennas has been completed. A contribution by Professor Simon Haykin at McMaster University, Canada was funded by the National Science and Engineering Research Council to expand current wideband MIMO channel measurement capabilities at BYU using MIMO radio hardware developed at McMaster.

In the forthcoming year, Professor Krishnamurthy expects to (i) design topology control algorithms with realistic channel models, and (ii) design MAC and routing protocols for use with MIMO and space-time codes. He is expected to have a close interaction both with the physical layer PIs from UCSD and Prof. J.J. Garcia-Luna from UCSC. Professor Cruz is already integrated with Professors Rao and Milstein at the PHY layer and plans to expand that interaction. Professor Hua plans to work more closely with Professors Krisnamurthy and Garcia-Luna to investigate the impact of interleaving regenerative relays and non-regenerative relays on the throughput of large ad hoc networks, develop in more detail route-guided data forwarding schemes, and explore more deeply routes of parallel MIMO relays.

The need to couple PHY modelling with networking protocol design requires an intense interdisciplinary effort among different people in the MURI team in order to effectively use the best knowledge and practices at the various layers and to design a system that is optimized throughout the protocol stack. It seems clear that such optimization cannot be achieved by simply patching together good schemes at the various layers, but requires a joint effort to understand the different issues and to come up with a joint process for the design (or at least the joint optimization) of the overall protocol stack.

It is also clear that the lack of definitive information on representative channel models for mobile MIMO networks will impede the cross-layer integration, since the channel models are an essential component of the analysis. The results obtained to date with the experimental measurements completed at BYU and the analytical results of many members of the team illustrate that open loop feedback schemes that utilize coherent detection may impose channel stability requirements that may not be achievable in mobile ad-hoc networks. Consequently we will continue to pursue the use of differential modulation such as differential unitary space-time codes and equalization techniques such as decision feedback that do not require an explicit channel model. Channel state estimation is a key issue in working across the protocol stack, since the network layer PIs have asked the PHY layer PIs to just provide them with the BERs of the various links and then they can design the routing protocols. In reality, however, the BERs of the links are time varying and the time constants of this variation will define the success of various protocols. An emphasis will be placed on integrating the measurement capabilities at BYU and McMaster University with the analytical modelling of the PHY layer MIMO transmitter and receiver architectures. The McMaster program will focus on rapidly changing wireless environments, with emphasis on:

- the collection of real life wideband MIMO data using our 4-by-4 system
- the refinement of Kris Huber's dynamic model, and
- the oversampled approach to receiver design, which will be expanded to the MMO case

The MURI team includes a number of experts on PHY technology as well as on networking protocols. Dr. Zorzi's plans to utilize his expertise in both network protocol design (especially at the MAC and routing layers) and PHY issues (including MIMO signal processing, detection performance, multi-user detection) to aid in the development of MAC protocols that integrate the PHY and networking layers, and to act as an interface between PHY and network layer research issues. Planned extensions of this work include interaction between the PIs to accomplish the following: i) a more detailed PHY investigation, including coding, effect of waveform, and possibly other receiver algorithms; ii) relaxation of some of the assumptions, most notably that of synchronous packet transmission; iii) more extensive performance analysis of our schemes in a more general environment (results obtained so far are rather preliminary); iv) inclusion of multihop operation and the routing layer in the study and in the design; v) development of an analytical approximation for PHY performance (success probability) to avoid bit-level simulation, thereby making it possible to perform more thorough network-level investigations; vi) application of space-time coding to efficient broadcast in ad hoc networks; vii) a more systematic study of the access policies and related optimization.

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

List of papers submitted or published that cite ARO support during this reporting period. List the papers, including journal references, in the following categories:

Number of Peer Reviewed Papers: 2

(a) Papers published in peer-reviewed journals (N/A for none)
Manuscripts are available for downloading on http://zeidler.ucsd.edu/~muri

B. T. Maharaj, J. W. Wallace, L. P. Linde, and M. A. Jensen, "Frequency scaling of spatial correlation from co-located 2.4 GHz and 5.2 GHz wideband indoor MIMO channel measurements," Electronics Lett., vol. 41, pp. 65-66, 17 March, 2005.

B. C. Banister and J. R. Zeidler, ``Feedback Assisted Stochastic Gradient Adaptation of Multiantenna Transmission,'' IEEE Transactions on Wireless Communications, vol. 4, pp. 1121-1135, May 2005.

Number of Non Peer Reviewed Papers: 29

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)
Manuscripts are available for downloading on http://zeidler.ucsd.edu/~muri

Y. Nebat and R. L. Cruz, "Routing, Cooperative Transmission and the Relaying Bound: the Effect of Multi-User Diversity," Proc. 2005 CISS, Princeton, NJ March 2005.

B. Song, R. L. Cruz and B. D. Rao, "Network duality and its application to multi-user MIMO wireless networks with minimum SINR constraints," in Proc. IEEE ICC'05, Seoul, Korea, May 2005.

X. Yu, R. Moraes, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, ``Capacity of MIMO Mobile Wireless Ad hoc Networks,'' Proc. IEEE WirelessCom 2005, Maui, Hawaii, June 13--16, 2005.

Z. Ye and Y. Hua, "Networking by parallel relays – diversity, lifetime and routing overhead," The 38th Annual Asilomar Conference on Signals, Systems and Computers, pp. 1302-1306, Pacific Grove, CA, Nov 7-10, 2004.

Z. Ye and Y. Hua, "Stability of wireless relays in mobile ad hoc networks," IEEE

ICASSP'2005, Philadelphia, PA, March 2005.

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S. Kittipiyakul and T. Javidi, "A Fresh Look at Optimal Subcarrier Allocation in OFDMA Systems," IEEE Conference on Decision and Control (CDC 2004), pp 3289-3294, Dec 2004 [Invited Paper]

T. Javidi, "Rate Stable Resource Allocation in OFDM Systems: From Waterfilling to Queue-Balancing," Proceedings of the Allerton Conference on Communication, Control, and Computing, pp. 90-99, Sept 2004 [Invited Paper]

J. Price and T. Javidi, "Joint Scheduling for Self-Configuring Ad-Hoc CDMA Networks," Proceedings of the Allerton Conference on Communication, Control, and Computing, pp. 734-743, September 2004

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A. L. Anderson, M. A. Jensen, and J. R. Zeidler, "Differential space-time coding with offset quadrature phase-shift keying," 6th IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC 2005), New York, NY, June 5-8, 2005.

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B. T. Maharaj, L. P. Linde, J. W. Wallace, and M. A. Jensen, "A cost-effective wideband MIMO channel sounder and initial co-located 2.4 GHz and 5.2 GHz measurements," Proceedings of the 2005 IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), Philadelphia, PA, Mar. 18-23, 2005.

G. Jakllari, W. Luo, S. V. Krishnamurthy, "An Integrated Neighbor Discovery and MAC Protocol for Ad Hoc Networks Using Directional Antennas", In IEEE WoWMoM 2005, Taormina.

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A. Roy, T. Duman, L. Ghazkhanian, V. McDonald, J. G. Proakis, and J. R. Zeidler, ``Enhanced Underwater Acoustic Communication Performance Using Space-Time Coding and Processing," in Proceedings of the IEEE Oceans Conference, vol. 1, (Kobe, Japan), pp. 26-33, Nov. 2004.

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J. Jootar, J. R. Zeidler, and J. G. Proakis, "Performance of Finite-Depth Interleaved Convolutional Codes in a Rayleigh Fading Channel with Noisy Channel Estimates," in Proceedings of the IEEE 61st Vehicular Technology Conference (Stockholm), June 2005.

J. C. Roh and Bhaskar D. Rao, “Performance Analysis of Multiple Antenna Systems with VQ-Based Feedback,” Thirty Eight Asilomar Conference on Signals, Systems and Computers, Pacific Grove, Nov. 2004.

J. C. Roh and B. D. Rao, "Vector Quantization Techniques for Multiple-Antenna Channel Information Feedback," International Conference on Signal Processing and Communications (SPCOM), Bangalore, India. Dec. 2004.

J. C. Roh and B. D. Rao, “MIMO Spatial Multiplexing Systems with Limited Feedback,” IEEE International Conference on Communications. Seoul, Korea. May, 2005.

June Chul Roh and Bhaskar D. Rao, "Performance Analysis of Multiple Antenna Systems with VQ-Based Feedback," 38th Asilomar Conference on Signals, Systems, and Computers 2004, Pacific Grove, CA, Nov. 2004.

Q. Spencer and A. Swindlehurst, "Channel allocation in multi-user MIMO wireless communications systems," Proc. International Conf. on Communications, June, 2004.

Anderson, J. R. Zeidler, and M. A. Jensen, "Differential Space-Time Coding with Offset Quadrature Phase-Shift Keying", Proceedings of the IEEE Workshop on Signal Processing Advances in Wireless Communications (New York, N. Y.), June 2005

Paolo Casari, Marco Levorato, Michele Zorzi, “On the Implications of Layered Space--Time Multiuser Detection on the Design of MAC Protocols for Ad Hoc Networks,” IEEE Personal, Indoor, and Mobile Radio Communications (PIMRC) conference, Sep. 2005.

Paolo Casari, Marco Levorato, Michele Zorzi, “Some issues concerning MAC Design in Ad Hoc Networks with MIMO communications,” Wireless Personal Multimedia Communications conference, Sep. 2005.

Number of Papers not Published: 0

(c) Papers presented at meetings, but not published in conference proceedings (N/A for none)
N/A

Number of Manuscripts: 42

(d) Manuscripts submitted, but not published (N/A for none)
All manuscripts that are accepted for publication are available for downloading on http://zeidler.ucsd.edu/~muri

R.D. Moraes, H.R. Sadjadpour and JJ. Garcia-Luna, "Mobility-Capacity-Delay Trade-off in Wireless Ad Hoc Networks," Elsevier journal on ad hoc networks (to appear).

R. D. Moraes, H.R. Sadjadpour and JJ. Garcia-Luna-Aceves, "Opportunistic cooperation: A new communication scheme for MANETs," accepted for presentation at Asilomar 2005, Pacific Grove, CA, October 30 - November 2, 2005

R. D. Moraes, H.R. Sadjadpour and J.J. Garcia-Luna-Aceves, "Opportunistic cooperation: A new approach for scalable mobile ad hoc networks", submitted to INFOCOM2006.

R. D. Moraes, H.R. Sadjadpour and J.J. Garcia-Luna-Aceves, "Ergodic capacity of MIMO MANETs with opportunistic cooperation," submitted to INFOCOM2006.

R. D. Moraes, H.R. Sadjadpour and JJ. Garcia-Luna-Aceves, "Opportunistic Cooperation: A new approach for scalable Mobile Ad hoc networks," submitted IEEE Transactions on Information Theory.

R. D. Moraes, H.R. Sadjadpour and JJ. Garcia-Luna-Aceves, "Taking full advantage of Multiuser diversity in Mobile Ad hoc networks," submitted to IEEE Transactions on Communications.

M. Carvalho and J.J. Garcia-Luna-Aceves, "Modeling Ad hoc Networks with Directional Antennas," submitted to IEEE Infocom 2006.

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K. Huber and S. Haykin, "Improved Bayesian MIMO channel tracking for wireless communications: incoroprating a dynamic model," accepted for publication, IEEE J. Wireless communications

T. Feng and S. Haykin, "Novel procedure for reliable detection in an unknown wireless environment," IEEE Conference on Radio and Wireless, San Diego,CA, January 2006 (invited).

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X. Tang and Y. Hua, "Optimal design of non-regenerative MIMO wireless relays", IEEE Transactions on Wireless Communications, submitted July 2005.

Z. Ye and Y. Hua, "A route-guided multicast data forwarding policy for wireless relays," IEEE Transactions on Wireless Communications, submitted July 2005.

H. Yousefi'zadeh, H. Jafarkhani, and J. Kazemitabar, "SER-Based Connectivity of Fading Ad-Hoc Networks," IEEE MILCOM, Oct. 2005.

L. Liu and H. Jafarkhani, "Space-Time Trellis Coded Based on Channel Phase Feedback," IEEE International Conference on Communications (ICC-05), May 2005.

H. Jafarkhani, H. Yousefi'zadeh, and J. Kazemitabar, "Capacity-Based Connectivity of MIMO Fading Ad-Hoc Networks," IEEE Global Communications Conference (Globecom-05), Nov. 2005.

S. Ekbatani, L. Liu, and H. Jafarkhani, "A Power Loading Scheme for Space-Time Trellis Codes Based on Channel Magnitude Feedback," IEEE Global Communications Conference (Globecom-05), Nov. 2005.

J. Price and T. Javidi, “On Dual Methods for Adaptive Distributed Resource Allocation in Wireless Networks: A Taxonomy of Practical Challenges in CDMA,” To appear in Resource Allocation in Next Generation Wireless Networks, Eds. Wei Li and Yi Pan, Nova Science Publishers, 2005

J. Price and T. Javidi, “Jointly Optimal MAC and Transport Layers in CDMA Broadband Networks,” To appear in Procedings of IEEE Conference on Decsion and Control (CDC 2005), Dec 2005 [Invited Paper]

J. W. Wallace, A. Gummalla, and M. A. Jensen, “Characterization of the temporal variation of 2.45 GHz MIMO wireless channels in an outdoor campus environment,” submitted to IEEE Trans. Vehicular Technology, July 2005.

M. A. Jensen, M. D. Rice, and A. L. Anderson, “Aeronautical telemetry using multiple antenna transmitters,” submitted to IEEE Trans. Aerospace and Electronic Systems, July. 2005.

N. W. Bikhazi and M. A. Jensen, “The relationship between antenna loss and superdirectivity in MIMO systems,” submitted to IEEE Trans. Wireless Communications,

June 2005.

M. L. Morris, M. A. Jensen, and J. W. Wallace, “Superdirectivity in MIMO systems,” to appear in IEEE Trans. Antennas Propag., Sept. 2005.

J. W. Wallace, B. T. Maharaj, and M. A. Jensen, “Experimental evaluation of the MIMO wideband channel temporal variation,” to appear in Proceedings of the 27th General Assembly of International Union of Radio Science, New Delhi, India, Oct. 23-29, 2005.

M. A. Jensen and J. W. Wallace, “Recent advances in antennas and propagation for MIMO systems: multi-user networks and channel temporal variation,” to appear in Proceedings of the 2005 International Conference on Electromagnetics in Advanced Applications, Torino, Italy, Sep. 12-16, 2005.

J. W. Wallace and M. A. Jensen, “Measurement and characterization of the time variation of indoor and outdoor MIMO channels,” to appear in 62nd IEEE Vehicular Technology Conference Digest (VTC Fall 2005), Dallas, TX, Sep. 25-28, 2005.

M. L. Morris and M. A. Jensen, “Impact of receive amplifier signal coupling on MIMO system performance,” to appear in IEEE Trans. Vehicular Technology, Sept. 2005.

E. Gelal, G. Jakllari, N. E. Young and S. V. Krishnamurthy, “Construction of a Degree-Six Hop-Spanner for Ad hoc Networks”, submitted to IEEE INFOCOM 2006.

G. Jakllari, S. V. Krishnamurthy, M. Faloutsos, P. Krishnamurthy and Ozgur Ercetin, “A Framework for Distributed Spatio-Temporal Communications in Mobile Ad hoc Networks”, submitted to IEEE INFOCOM 2006.

G. Jakllari, I.Broustis, T.Korakis, S.V. Krishnamurthy and L.Tassiulas, “Handling Asymmetry in Gain in Directional Antenna Equipped Ad hoc Networks”, IEEE PIMRC 2005, Berlin, September 2005.

A. S. Ling and L. B. Milstein, "Comparison of Multi-Carrier Modulation Techniques”. To appear in 2005 IEEE Conference on Military Communications.

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C. R. Murthy, J. Zheng and B. D. Rao, “Multiple Antenna Systems With Finite Rate Feedback,” Submitted to MILCOM 2005.

June Chul Roh and Bhaskar D. Rao, "Transmit Beamforming in Multiple Antenna Systems with Finite Rate Feedback: A VQ-Based Approach," submitted to IEEE Trans. Information Theory

Q. Spencer, J. Wallace, C. Peel, T. Svantesson, A. Swindlehurst, H. Lee, A. Gummalla, "Performance of Multi-User Spatial Multiplexing with Measured Channel Data," submitted to MIMO Antenna Technology for Wireless Communications, George Tsoulos, editor, CRC Press.

T. Svantesson and A. Swindlehurst, "A Performance Bound for Prediction of MIMO Channels," submitted to IEEE Transactions on Signal Processing.

C. Peel and A. Swindlehurst, "Optimal Trained Space-Time Modulation over a Rician Time-Varying Channel," submitted to IEEE Transactions on Wireless Communications

H. Sui and J.R. Zeidler, "Erasure Insertion for Coded MIMO Slow Frequency-Hopping Systems in the Presence of Partial Band Interference", submitted to IEEE Globecom, December 2005

H. Sui and J. R. Zeidler, "An explicit and Unified Error Probability Analysis of Two Detection Schemes for Differential Unitary Space-Time Modulation", submitted to the IEEE Asilomar Conference, November 2005

J. Jootar, J. R. Zeidler, and J. G. Proakis, "Performance of Convolutional Codes with Finite-Depth Interleaving and Noisy Channel Estimates," submitted to IEEE Transactions on Communications, April 2005.

Honors and Awards

Honors and Awards

Rene Cruz

Editorial Board:
Journal of High Speed Networks
Mobile Networks and Applications (MONET), Springer.

Keynote Speaker:
3rd International Workshop on QoS in Multi-Service IP Networks, QoS IP 2005

Invited Panel Presentation:
Industry Research Symposium, UC Irvine, May 2005.
61st IEEE Vehicular Technology Conference, Stockholm, Sweden, May 2005.
Motorola Scientific Advisory Board Associates Conference, San Diego, April 2005

Program Committee Member:
E-WIND: Workshop on Experimental Approaches to Wireless Network Design and Analysis, ACM SIGCOMM 2005 Workshop, Aug, 2005.
3rd International Workshop on QoS in Multi-Service IP Networks, QoS IP 2005,
25th IEEE International Performance Computing and Communications Conference, (IPCCC) - April 2006 - Phoenix, Arizona
4th Intl. Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, WiOpt 2006, Boston 2006

J.J. Garcia-Luna-Aceves

General Chair:
Second Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, Santa Clara, California, September 2005.

Simon Haykin:
Ellersick Prize Paper Award:
"Turbo-MIMO for Wireless Communications", IEEE Communications Magazine, Vol. 42, No. 10, pp.48-53, October 2004.

Yingbo Hua

Guest editor:
IEEE Signal Processing Magazine, Special Issue on "Signal Processing for Wireless Ad Hoc Communication Networks"
Session Chair:
"Sensor Networks", IEEE International Conference on Acoustics, Speech and Signal Processing, March 2005;
"Relay Networks", Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, Nov, 2004.

Member of Technical Program Committees:
IEEE Workshop on Signal Processing Advances in Wireless Communications, Cannes, France, June 25-28, 2006.
IEEE Workshop on Sensor Array and Multichannel Processing, Waltham, MA, USA, 12-14 July 2006.
IEEE GLOBECOM'05 - Signal Processing for Communications Symposium, St. Louis, MO, USA, Nov 28 - Dec 2, 2005.
IEEE Computational Advances in Multi-Sensor Adaptive Processing, Puerto Vallarta, Mexico, 13-15 December 2005,
International Symposium on Signal Processing and Its Applications (ISSPA), Sydney, Australia, August 2005.
IEEE Workshop on Signal Processing Advances for Wireless Communications, June 5-8, 2005.
IEEE Sensor Array and Multichannel Signal Processing Workshop, Sitges, Barcelona,

Spain, 18-21 July 2004.

Hamid Jafarkhani

TPC co-chair :
Communications Theory Symposium, IEEE Globecom 2006.

Editor:
IEEE Trans on Wireless Communications

Associate Editor:
IEEE Communication letters

Technical Program Committee member:
IEEE International Conference on Communications (ICC), 2006.
IEEE Vehicular Technology Conference (VTC), 2005.
IEEE International Conference on Image Processing (ICIP), 2005.

Tara Javidi

NSF Early Career Award (CAREER):
Cross-layer Integrated Protocol Design for Broadband Wireless Data Networks: A Microeconomic Approach
Invited Papers:
IEEE Conference on Decision and Control, December 2005;
Allerton Conference on Communication, Control and Computing, September 2004

Michael Jensen

Recipient:
Karl G. Maeser Research and Creative Arts Award, BYU, August 2005.

Best Conference Paper Award:
International Telemetry Conference, San Diego, CA October 2004 for paper: M. A. Jensen, M. D. Rice, T. Nelson, A. L. Anderson, “Orthogonal dual-antenna transmit diversity for SOQPSK in aeronautical telemetry channels,”

Srikanth Krishnamurthy

Invited paper:
WPMC 2005.

Technical Program Committees:
INFOCOM 2005, MOBIHOC 2005,
MOBICOM 2005, INFOCOM 2006 and PERCOM 2006.

Panel Co-Chair:
SECON 2005

Finance Co-Chair:
MOBIHOC 2005.

Larry Milstein

Editorial Board:
IEEE Journal on Selected Areas of Communications and the Journal of the Franklin Instititute

Two Invited Papers:
IEEE Military Communications Conference, October 2005.

John Proakis

Education Award of the IEEE Signal Processing Society, May 2004.

Bhaskar Rao

Elected as a member to the IEEE Signal Processing Society's technical committee on Signal Processing for Communications (2004-2007).

Student Best Paper Awards:
"RAKE Finger Placement for CDMA Downlink Equalization," H. Sui, E. Masry and B. D. Rao, 2005 IEEE International Conference on Acoustics, Speech, and Signal Processing, Philadelphia, PA, Mar. 19-23, 2005.

"Lane change intent analysis using robust operators and sparse Bayesian learning" J. McCall, D. Wipf. M. Trivedi and B. D. Rao, Best Student Paper Award at the 2005 CVPR workshop

Lee Swindlehurst

Associate Editor:
EURASIP Journal on Wireless Communications and Networking

Editor:
Special issue of EURASIP Journal on Wireless Communications and Networking entitled "Multi-user MIMO Networks," December, 2004.

Guest editor:
Special issue of the IEEE Signal Processing Magazine entitled "Positioning and Navigation with Applications to Communications," July, 2005.

Technical Program Committee:
MIT Lincoln Labs Adaptive Sensor Array Processing Workshop Secretary & Member,
Board of Governors, IEEE Signal Processing Society

James Zeidler

Technical Program Committee,
IEEE International Communications Conference, 2005.

Guest editor:
IEEE Signal Processing Magazine, Special Issue on "Signal Processing for Wireless Ad Hoc Communication Networks"

Editorial Board:
Journal of the Franklin Institute

Invited Paper:
38th Asilomar Conference on Circuits, Systems and Computers, November 2004

Michele Zorzi

Editor in Chief of the IEEE Wireless Communications Magazine
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,
IEEE Transactions on Mobile Computing,
IEEE Transactions on Communications

Conference organizing committee:
General co-chair, Mobiquitous 2004 (August 2004)

Member of conference technical program committee:
Mobiquitous 2004,
WPMC 2004,
ACM MobiCom 2004,
ACM WMASH 2004,
IEEE ICNP 2004,
IEEE SECON 2004,
IEEE GLOBECOM 2004,
Second European Workshop on Sensor Networks 2005,
IEEE WCNC 2005,
IEEE INFOCOM 2005,
IEEE ICC’05 (NGUS workshop),
WICON 2005,

ACM MobiCom 2005,
IEEE PIMRC 2005,
IEEE SECON 2005,
IEEE LCN 2005,
WiOpt 2006,
IEEE INFOCOM 2006,
WICON 2006,
ICC 2006.

Conference session organizer:
IEEE PIMRC 2005, on “Cross Layer Optimization and Intelligent RRM”

Best paper award:
IEEE MobiWac Workshop, June 2005.

Scientific progress and accomplishments (Description should include significant theoretical or experimental advances)
This accepts plain text only.
See Attachment

Number of Patents Disclosed: 4

List of patent titles disclosed

Number of Patents Awarded: 0

List of patent titles awarded:

Technology Transfer (any specific interactions or developments which would constitute technology transfer of the research results). Examples include interaction with other DOD scientists, interactions with industry, initiation of a start-up company based on research results or transfer of information which might impact the development of products.
Professor Jensen has applied space-time coding allow dual-antenna transmission from maneuvering air vehicles. 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.

This technology has produced 3 provisional patents, and commercialization funding has been awarded by the State of Utah and the US Department of Defense through the Central Test and Evaluation Investment Program (CTEIP). After creation of the prototype, a new start up will be created (early 2007) to market the technology.

Dr. Stephan Lapic, SPAWAR Systems Center (SSC), San Diego has invited Professors Cruz, Krishnamurthy and Zeidler to collaborate with his group at SSC in the development of a prototype Naval ad-hoc mobile network based on steerable antenna arrays over the coming year.

Other DoD interactions include collaboration with Professors Proakis and Zeidler with Vincent McDonald (PI) of the SPAWAR Systems Center in San Diego on an ILIR SPAWAR project entitled: “Enhanced Underwater Communication Using MIMO Systems”. Their work on this project involves the design of reduced complexity MIMO receivers and the design of space-time codes for underwater communications.
Professors Proakis has also been a co-investigator on a SSC project entitled “UHF SATCOM Adaptive Filtering”, where his work involves the development of a channel model for signal scatter off the sea surface and applications of adaptive filtering algorithms to mitigate signal distortion and narrowband interference.
Dr. Zeidler has also been a co-investigator of a SSC project entitled “Composable Antenna System Signal Processing for GPS” that
involves interference suppression in GPS arrays using a composable array of randomly located elements. He is also involved in an ONR and SSC project on adaptive interference suppression in tactical communications systems.
Professor Rao’s work has been applied to generate codebooks for the 802.16 Broadband Wireless Access Working Group “Compact codebooks for transmit beamforming in closed loop MIMO” In particular the work with his June Chul Roh has been adopted to generate codebooks by the 802.16e working group on “Improved Feedback for MIMO Precoder” lead by Intel.

In addition, Professor Jafarkhani has submitted a provisional patent application: University of California Case No. 2005-087, "NEW METHOD FOR CODE DESIGN IN WIRELESS COMMUNICATION SYSTEMS" based on his work in this project.

List of faculty supported by the grant that are National Academy Members

Number of Graduate Students Supported: 23

Names of Graduate Students and percentage each is supported:
Amde, Manish S. 33%
Amihood, Patrick 10%
Anderson, Adam Lane 75 %
Isukapalli, Yogananda 100%
Jootar, Jittra 20%
Lin, Yih-Hao 50%
Ling, Andrew 10%
Liu, Minkui 15%
Song, Bongyong 100%
Spyropoulos, Ioannis 15%
Sui, Haichang 75%

Marcelo Carvalho 100%
Renato Moraes 100%
Xiaohui Yu 100%
Zhenzhen Ye 90%
Xiaojun Tang 10%
Siavash Ekbatani 100%
Javad Kazemitabar 100%
Gentian Jakllari 40%
Ioannis Broustis 25%
Ece Gelal 25%
Nicholas Bikhazi 100%
Michael Larsen 100%

Total of percentages for graduate students above: 13

Number of Post Doctorates Supported: 2

Names of Post Doctorates and percentage each is supported:
Christian Peel 25%
Jon Wallace 20%

Total of percentages for Post Doctorates above: 0

Number of Faculty Supported: 14

Names of Faculty:
James Zeidler
Laurence Milstein
Rene Cruz
John Proakis
Bhaskar Rao
Hamid Jafarkhani
Tara Javidi
Srikanth Krisnamurthy
Yingbo Hua
J.J. Garcia-Luna
Lee Swindlehurst
Mike Jensen
Simon Haykin
Michele Zorzi

Number of Other Research Staff Supported: 1

Names of Other Research Staff Supported:
Jonathan Cheung

Number of Under Graduate Students Supported: 1
Names of Under Graduate Students: Christopher Shaw 30%
Number of PHDs Awarded: 0
Names of personel receiving PHDs:
Number of Master Degrees Awarded: 0
Names of personel receiving Masters:
Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18 298-102

(IMPORTANT! >>> YOU MUST COMPLETE TO RECEIVE ADDITIONAL FUNDING <<<)

The research agreement identified below is under consideration for additional funding. The contemplated funding, resulting in an extension to the performance period of the agreement, is consistent with the terms and conditions of the agreement. Before a decision can be made to provide the additional funding, the following information is needed: (i) an accounting of costs incurred to date and (ii) a projection of financial needs for the period of the agreement extension. Please complete SECTION 2 within 30 days of receipt of this request.

SECTION 1: GENERAL INFORMATION - Provided by ARO

ARO Proposal Number:	46637CIMUR	**Anticipated Total Award:**	$5,249,896.00
Agreement Number:	W911NF0410224	**Amount Funded To Date:**	$1,507,280.00
Agreement Period:	From: 01-Jun-2004 To: 31-Dec-2005	**Currently Funded Through:**	31-Dec-2005
Recipient:	University of California - San Diego	**Planned Extension Funding:**	$1,074,865.00
Principal Investigator:	Dr. James Zeidler	**Planned Extension Period:**	
Principal Investigator's Phone #:	858-534-5369	12 Month(s) beginning 01-Jan-2006	
Principal Investigator's Fax #:	858-534-0415	**ARO Technical Monitor:**	Ulman, Robert
ARO Tech. Monitor's E-mail:	robert.ulman@us.army.mil	**Monitor's Phone #:**	919-549-4330

SECTION 2: ACCOUNTING AND FORECASTING OF EXPENDITURES - Completed by PI

1. Expenditures (cost incurrences from date of contract/grant as of date of receipt of this request or as of most recent cut-off in accounting records:	$950625.00
2. Additional projected expenditures before 01-Jan-2006	$491035.00
3. Forecast expenditures for the proposed period of extension:	$1140485.00

* The projected total funding (sum of lines 1, 2 and 3) cannot exceed the sum of the current and planned extension funding identified in SECTION 1. If the forecast expenditures differ significantly from the budget previously negotiated and included in the research agreement, a new budget must be submitted. A "significantly different" budget is defined as: (i) a decrease in the planned funding level cited above or (ii) a deviation of 10% (plus or minus) to any cost element (direct labor, indirect expense, travel, etc.) included in the budget.

U.S. Army Research Office