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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research 875 North Randolph St. Dr. Robert Bonneau, AFOSR/NL Room 325, Suite 3112 Program Manager, Complex Networks Arlington, VA 22203 Phone: 703-696-9545				10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR/NM	
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13. SUPPLEMENTARY NOTES

N/A

14. ABSTRACT

A key contribution is an Orthogonal Space-Time Block Coding (OSTBC) scheme with max-min precoding is proposed to ensure reliable multicast transmission over MIMO channels. Compared to open-loop OSTBC and max-min beamforming, this scheme achieves universally better performance in terms of the worst-case SNR. Computational complexity reduction was achieved via a diagonal precoding scheme that can be implemented efficiently with linear programming technique and which outperforms the max-min beamforming scheme when the number of users becomes moderately large. The diagonal precoding scheme also provides a good trade-off between the mean performance and the worst-case performance. Another key contribution was a hybrid automatic repeat request (ARQ) scheme for wireless multicast, i.e., common information broadcast, with incremental redundancy channel coding and packet retransmission. With this scheme, one can reliably deliver the same copy of information to different users with minimal delay. In addition, the design of the feedback channel for this scheme can be greatly simplified as no effort is required to combat cross-user interference. This work has been presented at a number of IEEE conferences and in journal papers published in the IEEE Transactions on Signal Processing, and also a book chapter emanating from the IEEE/IEE Waveform Design Workshop.

15. SUBJECT TERMS

Space-Time Coding, Multicasting; MIMO; Dirty Paper Coding

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**Space-Time for MIMO Multicasting and
Full-Rate, Full Diversity Codes with Partial CSI**

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Final Technical Report

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1 SUMMARY OF FIRST AND SECOND YEAR EFFORTS

In today's wireless networks, there has been an increasing demand for applications to send the same copies of information to a group of receivers. For instance, in ad hoc military networks, there are applications where warfighters residing at different locations coordinate through handheld devices and require common data relative to the war zone environment. In cellular communication networks, common broadcast information applications include group-oriented mobile commerce, distance education, and intelligent transportation systems. Multicasting is an appropriate approach for these applications. Unlike unicasting, where the transmitter has to run the routing algorithm for each user separately and duplicate all the transmitting packets, multicasting consumes less network resources and causes less delay by reducing these needs. Generally, the multicasting problem and other traditional broadcast applications such as radio and TV can all be categorized into broadcast channel applications. Compared to radio and television, where the same information is sent to all the users who are tuned in, multicasting has the advantage that with channel state information (CSI), it is possible to adapt the transmitter to a specified subgroup of the mobile units associated with it. As a consequence, a higher data rate and/or lower bit error rate (BER) can be achieved.

The term "multicasting" denotes a scenario where the transmitter sends the same information to a group of users. However, it should be pointed out that this term has a broader definition in the networking literature. A typical wireless multicasting session in a networking context involves two phases. The first phase is the construction of a multicasting tree or a multicasting mesh from the source node to all the destination nodes. In the second phase, each node in the tree/mesh sends out the multicasting data packets to all its one hop children. The first phase may be carried out in wireless channels (e.g. ad hoc networks) or wired channels (e.g. cellular communication networks), for systems with or without wireless backbone, respectively. Nevertheless, the second phase should always be considered in the context of wireless communications.

In a wireless military environment, the requirement for reliable transmission is of utmost importance. To achieve this, one has to deal with the performance degradation caused by multipath fading which is common to all wireless channels. It is known that multiple-input multiple-output (MIMO) schemes provide an efficient means to combat the multipath fading that is present in most wireless networks. Advances in antenna technology have made it possible to practically deploy systems equipped with multiple antennas. Moreover, introducing the spatial dimension into the system eases the design of beamforming/precoding schemes for a specified subgroup of receivers associated with a common transmitter if CSI is available at the transmitter. This CSI can be obtained through the use of feedback from the receiver in frequency division duplexing (FDD) systems or direct channel estimation in time division duplexing (TDD) systems.

In MIMO communication systems, by encoding the transmitted symbol into a matrix with specified structure, open-loop orthogonal space-time block coding (OSTBC) achieves full diversity and a simple decoder at the receiver side. Since it does not require any CSI at the transmitter and treats all the users equally, it is comparable to traditional radio and television applications and can be regarded as a solution to multicasting problems. On the other hand, the benefits of channel adaptation in point-to-point MIMO communication systems have motivated the search for multicasting methods that efficiently incorporate transmit-side CSI into system design. Beamforming methods are often used to optimize the SNR averaged over all receivers. However, the drawback of this scheme is the unfair performance among the receivers, i.e. users with poor channel conditions may be allocated with unacceptably low SNRs. Practical systems, such as future digital video/audio/data applications, often require that each user is able to meet a minimum quality of service (QoS).

Generally, there are two ways to achieve a minimum QoS. The first is to optimize the SNR of the

worst receiver. For example, a max-min beamforming scheme that aims to maximize the worst-case SNR has been developed, and its performance compared to that of the open-loop OSTBC method. Another way to tackle the problem is to minimize the transmit power while keeping the receive SNR at each user above a certain threshold. This method has been studied for CDMA systems where this problem is termed as "selective broadcast." Three categories of transceiver design have been investigated: time only, space-time and space-only designs. A similar technique is also applied to multicasting for ad hoc networks where each node is equipped with multiple antennas.

The optimization problem associated with the beamforming method can be categorized as a non-convex quadratically constrained quadratic programming problem. This problem is strongly NP-hard. However, there exists a category of algorithms that yields, in finite time, a globally ϵ -optimal solution. This is achieved by successively linearizing the objective function and the constraints within the neighboring area of the searched points. In addition, there are also several suboptimal approaches such as iterative least distance programming (ILDLP) and the semidefinite relaxation (SDR) techniques.

This effort focussed on the problem of transmitting the same copies of information over a wireless channel to a specified subgroup of users that are associated with the transmitter. We assumed that the transmitter is equipped with multiple antennas while the users may or may not have multiple antennas. It was observed that when the number of users is small, the max-min beamforming scheme provides some benefit over using OSTBCs. However, as the number of users grows, the performance of this scheme degrades very fast, and at some point, it performs considerably worse than the open-loop OSTBC method. In light of this observation, a MIMO multicasting scheme based on OSTBC precoding is presented. By pre-multiplying the open-loop OSTBC code with a precoding matrix, the transmitter can adapt itself with current CSI to improve performance criteria relating to the users' receive SNRs. The goal is to maximize the receive SNR of the worst-case user. The proposed approach can achieve performance that is universally better than the max-min beamforming or the open-loop OSTBC method. However, the proposed approach suffers from high computational complexity. To this end, a suboptimal max-min diagonal precoding approach is designed. This suboptimal scheme provides a good trade-off between the max-min beamforming and the optimal max-min precoding method.

2 OVERVIEW OF FIRST AND SECOND YEAR EFFORTS

In downlink wireless communication systems with multiple transmit antennas, it is often desirable to impose some fairness constraints when performing user selection at the base station. It turns out in this case, one needs to maximize the weighted sum rate. To this end, we have developed two lower bounds for the weighted sum rate under the context that the zero-forcing beamforming (ZF-BF) is used as the transmission scheme. A novel greedy user selection approach based on maximizing these lower bounds and ZF-BF has also been developed. Compared to existing user selection approaches, this new approach achieves a better tradeoff between the performance and its complexity.

The objectives included the development of a new user selection method for MIMO broadcast channel based on the sequential water-filling (SWF) algorithm. The algorithm was designed to maximize the sum rate of the zero-forcing beamforming (ZF-BF) strategy. A primary goal was to reduce complexity through a number of ways. First, an iterative procedure to calculate the Penrose-Moore inverse of the channel matrix, based on LQ decomposition, was used. This procedure converts the matrix inversion operation to one matrix-vector multiplication. In addition, the sequential nature of the user selection problem avoids the try-and-test phase for the water-filling approach. The program objectives also required that the search space of this algorithm be further pruned. Simulations were conducted that demonstrating that the proposed algorithm achieves a sum rate that is close to the maximal sum rate achievable by ZF-BF, with a complexity that is comparable to the best algorithms to date.

Results obtained during the phase of the research effort have been presented at and published in the proceedings of a number of high-profile conferences on communications and signal processing sponsored by the Institute of Electrical and Electronics Engineering (IEEE) and SPIE. A list of the papers either already presented and published, or accepted for presentation and publication in 2006, is provided in Section 13.

3 ACCOMPLISHMENTS/NEW FINDINGS

For multiple input multiple output (MIMO) broadcast channels, where independent data streams are to be transmitted to multiple users simultaneously, it has been shown that dirty paper coding (DPC) achieves the sum capacity. It has been shown that the DPC actually achieves the capacity region of MIMO broadcast channels. An iterative water-filling approach has been developed to compute the DPC sum capacity of the MIMO broadcast channel based on the duality between the uplink multiple access channel (MAC) and downlink broadcast channel.

However, the DPC scheme is well-known for its excessive computation load. For the case where each user has only one antenna, a suboptimal scheme, termed as zero-forcing beamforming (ZFBF), can be employed to reduce the computational complexity. The basic idea of ZFBF is that each user is assigned with one column vector of the pseudo-inverse of the downlink channel matrix (*beamforming vector*). Then the transmitted signal intended for each user is multiplied by its corresponding beamforming vector. By doing this, the inter-user interference can be completely removed, which eases the implementation as well as performance analysis. However, when the number of the user is equal to the number of transmit antennas, the downlink channel matrix can sometimes be near-singular, which makes it difficult to calculate the inverse matrix. To mitigate this problem, both a matrix perturbation method and Tomlinson-Harashima precoding are employed to achieve near-capacity performance.

When K , the number of users, is larger than M , the number of transmit antennas, it is generally difficult if not impossible to send data streams to all K users simultaneously without inter-user interference. One way to bypass this problem is to select a subset of M users so that applying ZFBF on this subset of users will result in maximum sum rate. One benefit of this scheme is that the subset of users that maximize the sum rate are usually near-orthogonal to each other, thereby avoiding the near-singularity problem. However, in general, the search space of finding the optimal subset of M users is of size $\sum_{i=1}^M \binom{K}{i}$, which becomes prohibitively large when the number of users K becomes large. To reduce the complexity, several suboptimal schemes have been proposed. In previous work, a semi-orthogonal user selection (SUS) algorithm is considered. It is also proved that as the number of users K goes to infinity, this algorithm achieves a sum-rate that is very close to that of DPC. Prior work also produced two strategies based on clique search, which have comparable performance as SUS algorithm, are provided. Other prior work considers the user selection problem with block diagonalization for systems with multiple antennas equipped at both sides. This scheme can be seen as an extension of ZFBF to systems with multiple receive antennas. For this model, two algorithms, one based on maximizing the sum rate and the other based on maximizing the Frobenius norm of the channel matrix, are proposed and their complexities are discussed.

As part of this research effort, we developed a sequential water-filling (SWF) algorithm for user selection. This algorithm is based on the sequential nature of user selection problem: when adding one user at a time, a one-step water-filling is sufficient – there is no need to go back and forth to find the users that ought to be allocated with nonzero power, as classical water-filling strategies usually do. In addition, the complexity of this algorithm is further reduced by an iterative procedure to calculate the Penrose-Moore inverse of a channel matrix based on LQ decomposition. The advantage

of this algorithm is that it results in a subset of users that achieves higher sum rate, with substantially reduced complexity.

3.1 Problems solved and their importance.

Under the category of waveform diversity for communications, one area we are working on is user selection for a MIMO broadcast channel where independent data streams are transmitted to multiple users simultaneously. The importance of this problem to the military is well known. In particular, we have been told the importance of this problem by Spectral Systems Inc (SSI) in Dayton, Ohio. SSI is a defense contractor that primarily works on research contracts with the Air Force. They are located very close to Wright Patterson AFB.

The basic scientific research issues involved here center on the capacity of so-called Dirty Paper Coding (DPC) schemes. For example, one basic result is that DPC actually achieves the capacity region of MIMO broadcast channels.

The technological challenges center on the fact that the DPC scheme has a heavy computational load and can be sensitive to channel matrix rank. For the case where each user has only one antenna, a suboptimal scheme, termed as zero-forcing beamforming (ZFBF), can be employed to reduce the computational complexity. The basic idea of ZFBF is that each user is assigned one column vector of the pseudo-inverse of the downlink channel matrix as a beamforming vector. Ideally, the inter-user interference is completely removed, thereby simplifying the associated implementation. Again, technological issues arise when the number of users is equal to the number of transmit antennas, for which the downlink channel matrix can sometimes be near-singular, making it difficult to calculate the inverse matrix. One method investigated for mitigating this problem is to use a matrix perturbation method in conjunction with Tomlinson-Harashima precoding to achieve near-capacity performance.

3.2 Progress relative to prior work in related areas.

It has been shown that dirty paper coding (DPC) can achieve the capacity region of MIMO broadcast channels. Jindal et al have developed an iterative water-filling approach to compute the DPC sum capacity of the MIMO broadcast channel based on the duality between the uplink multiple access channel (MAC) and downlink broadcast channel.

When the number of users, K , is larger than the number of transmit antennas, M , it is generally not possible to send data streams to all K users simultaneously without inter-user interference. Hochwald et al bypassed this problem by selecting a subset of the M users, so that applying ZFBF on this subset of users would result in the maximum sum rate. One benefit of this scheme is that the subset of users that maximize the sum rate are usually near-orthogonal to each other. This avoids the near-singularity issue mentioned previously.

However, in general, the search space of finding the optimal subset of M users is prohibitively large when the number of users K becomes large. To reduce the complexity, several suboptimal schemes have been proposed. In Andrea Goldsmith and her students have done a lot of work on this area. One of their schemes centers on a semi-orthogonal user selection (SUS) algorithm. They proved that as the number of users K goes to infinity, this algorithm achieves a sum-rate that is very close to that of DPC. Andrea Goldsmith and her students have developed two strategies based on a clique search, which has comparable performance to the SUS algorithm. Robert Heath and his students have addressed the user selection problem employing block diagonalization for systems with multiple antennas equipped at both ends. This scheme can be seen as an extension of ZFBF to systems with multiple receive antennas. For this model, two algorithms, one based on maximizing the sum rate and the other based on maximizing the Frobenius norm of the channel matrix, have been developed and

analyzed.

3.3 Achievements.

Our work centers on developing a sequential water-filling (SWF) algorithm for user selection. The algorithm is based on the sequential nature of user selection problem: when adding one user at a time, a one-step water-filling is sufficient – there is no need to go back and forth to find the users that ought to be allocated with nonzero power, as in classical water-filling strategies. In addition, the complexity of this algorithm is further reduced by an iterative procedure to calculate the Penrose-Moore inverse of a channel matrix based on LQ decomposition. The advantage of this algorithm, compared to prior work, is that it results in a subset of users that achieves a higher sum rate with significantly reduced complexity.

4 PERSONNEL SUPPORTED

Faculty:	Michael D. Zoltowski (PI)
Graduate Research Assistant:	Jianqi Wang

5 PUBLICATIONS

5.1 Journal Papers Published

In progress: several manuscripts under preparation for submission to the *IEEE Transactions on Signal Processing* and the *IEEE Transactions on Communications*.

5.2 Conference Papers Published

1. Jianqi Wang; Peilv Ding; Zoltowski, M.D.; Love, D.J.; “Space-time coding and beamforming with partial channel state information,” *Global Telecommunications Conference, 2005. GLOBECOM '05. IEEE* Volume 5, Dec. 2005 Page(s):5 pp.
2. Jianqi Wang; Love, D.J.; Zoltowski, M.D.; “Improved Space-Time Coding for Multiple Antenna Multicasting,” *IEE 2006 International Conference on Waveform Diversity and Design*. Hawaii, 23-26 January 2006.
3. Jianqi Wang; Love, D.J.; Zoltowski, M.D.; “User Selection for MIMO Broadcast Channels with Sequential Water Filling,” *Proc. of 44-th Annual Allerton Conference on Communications, Systems, and Computing*, Monticello, IL, Sept.27-29 2006.

6 INTERACTIONS/TRANSITIONS:

6.1 A. Participation/presentations at meetings, conferences, seminars, etc

- see conference papers listed above
- **Chairman: Sensor Array and Multichannel Technical Committee of IEEE Signal Processing Society.** <http://www.engr.uconn.edu/willett/barney.html#SECTION1> Elected for two year term, 1 January 2005 - 31 December 2006. TC Chairs automatically become a member of the *Technical Directions Committee* of the IEEE SPS.
- **Technical Program Co-Chairman for SAM 2006: IEEE 2006 Sensor Array and Multichannel Workshop.** SAM-2006, 12-14 July 2006 in Waltham, MA; conference website: www.sam2006.org

- Served on the **Advisory Council for the Department of Electical and Computer Engineering at Drexel University.**

6.2 C. Transitions

Dr. Bruce Suter and CITE at Rome Labs continue to assess the performance of our MIMO based schemes with partial CSI.

7 NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

None.

8 HONORS/AWARDS

1. **Distinguished Engineering Alumnus, Department of Electical & Computer Engineering, Drexel University.** Ceremony held 30 June 2006.
2. **Technical Program Co-Chairman for SAM 2006: IEEE 2006 Sensor Array and Multichannel Workshop.** 12-14 July 2006, Waltham, MA; www.sam2006.org
3. **Vice-President for Awards and Membership, IEEE Signal Processing Society.** Elected for three year term, 1 Jan. 2008 - 31 Dec. 2010.

9 SUMMARY OF THIRD YEAR EFFORT

Achievements include the development of a hybrid automatic repeat request (ARQ) scheme for wireless multicast, i.e., common information broadcast, with incremental redundancy channel coding and packet retransmission. The underlying idea of this scheme is to reliably deliver the same copy of information to different users with mild delay. In addition, the design of the feedback channel for this scheme is to be simplified as expending no effort to combat the cross user interference. Three specific schemes were investigated: generalized slotted ALOHA (GSA), the repetition time diversity (RTD), and the general incremental redundancy (INR). A specific key result is as follows: let K be the number of users. When the rate per packet is finite, the average delay scales as $\Theta(\log K)$ for all three schemes where only a finite number of previously received packets are used for decoding. As a consequence, the average throughput scales as $\Theta(K/\log K)$. In addition, when we increase the rate per packet linearly with K , we obtain a linear scaling for both the throughput and the delay with respect to K . Since every user can achieve no more than the ergodic capacity, we actually achieve the optimal scaling law in this case.

10 OVERVIEW OF THIRD YEAR EFFORT

The military has a strong need to send the same information to a group of users. Mobile video is regarded as a 'must have' multimedia service in future mobile networks. In addition, there are also other commercial applications including group-oriented mobile commerce, distance education, and intelligent transportation systems relying on common information transmission. Multicast is an appropriate approach for these applications. By its nature, the wireless channel is a multicast channel in the sense that the electromagnetic wave is direction-less and all receivers within certain distance from the transmitter can receive the signal sent from the transmitter almost simultaneously. In contrast to unicast, where the transmitter sends the information to each user separately, multicast consumes less network resources and causes less delay by reducing these needs.

Results obtained during the phase of the research effort have been presented at and published in the proceedings of a number of high-profile conferences on communications and signal processing sponsored by the Institute of Electrical and Electronics Engineering (IEEE) and SPIE. A list of the papers either already presented and published, or accepted for presentation and publication in 2008, is provided in Section 13.

11 ACCOMPLISHMENTS/NEW FINDINGS

The problem of wireless multicast has been studied intensively in the medium access control (MAC) layer. In previous work, a generalized threshold based multicast has been developed. It was proved that this scheme is throughput optimal subject to stability. This scheme is also used in related work where transport layer erasure coding is employed to enhance the multicast reliability. Thanks to the spatial degrees of freedom added by multiple-input multiple-output (MIMO) systems, wireless multicast is also a subject of physical layer designs. Studies have been conducted of the capacities of several MIMO multicast schemes, with performance dictated by the user with the worse channel condition.

Prior work includes a precoding method to maximize the capacity of the user with the worse channel condition. Max-min beamforming schemes have been investigated, in which the beamforming vector is determined to maximize the minimum user's signal-to-noise power ratio (SNR). Most of these physical layer approaches for MIMO wireless multicast assumes full channel state information (CSI) for every user at the base station. Typically, for frequency division duplex (FDD) systems, the CSI

can be obtained through user feedback. For time division duplex (TDD) systems, it can be obtained by direct estimation. However, when the number of users is large, the overhead associated with both of the two cases would be prohibitive. Moreover, these methods using max-min optimization do not perform well for large number of users. In fact, the capacities of these schemes converge to zero as the number of users increases to infinity.

For applications with a large number of users, it is more realistic to assume that the base station does not have the CSI. In this case, we assume that the whole network is a homogenous network where every downlink channel has the same statistics. The optimal scheme for this system is to transmit at a rate as close to the ergodic capacity as possible. However, this requires using codes that span a large number of fading state. As a consequence, the incurred delay is infinite for all users, which is not suitable for delay sensitive applications. The hybrid-ARQ approach studied previously provides an effective way to combine channel coding with ARQ. By encoding the information bits into a sequence of packets with incremental redundancy and only sending the redundant packets upon request from the receiver, this scheme provides a better solution to achieve large data rates with very small error probabilities for a *short time*. The generalization of the incremental redundancy (INR) hybrid-ARQ provides an excellent info-theoretic view of this scheme and facilitates its performance analysis. Other researchers studied the wireless multicast system using INR, where only a fixed fraction of users are allowed to endure packet loss. Their results shed some insights on the scalability of the throughput as a function of this fraction. In prior work, the incremental redundancy scheme is applied to multimedia broadcast and multicast services (MBMS) for GSM/EDGE Radio Access Network (GERAN). Their research shed some insight on the system throughput and packet loss rate. It has been proved that if the pre-determined rate is constant and if all the received packets are involved in decoding, the throughput of the systems scales as $K \log \log K / \log K$, with K being the number of users.

During this past year's effort, we adapted a hybrid-ARQ scheme for wireless multicast. We have demonstrated that our wireless multicast scheme using hybrid-ARQ has the two advantages. First, it provides a good throughput-delay tradeoff which is essential for delay-sensitive applications. Secondly, although this scheme also requires a feed-back channel for the users to send back retransmission requests to the base station, the overhead is dramatically reduced as all users can share the same feedback channel and the detection of the retransmission request at the base station is greatly simplified.

Our past year contributions include:

1. We proposed a wireless multicast protocol termed as with memory m and packet protocol based on incremental. This protocol is designed to reliably deliver the information to all the users.
2. For systems using repetition coding at the base station and only the current packet for decoding at the user side, we obtain a closed form solution to the average delay and the average throughput.
3. For systems using repetition coding or incremental redundancy coding, we obtain the scaling law of the delay and throughput when only a fixed number of previously received packets are exploited in decoding. For both of the coding schemes, the delay scales as $\Theta(\log K)$ and the throughput scales as $\Theta(K / \log K)$, where $f(K) = \Theta(g(K))$ if there exist two constants c_1 and c_2 such that $c_1 g(K) < f(K) < c_2 g(K)$ for $K > K_0$ for some K_0 .
4. For systems using incremental redundancy coding, we establish that by increasing the pre-determined rate linearly with K , we can obtain a throughput and a delay that both scale linearly with K .

We have developed several hybrid ARQ schemes for wireless multicast with incremental redundancy channel coding the packet retransmission. Three specific schemes, GSA, RTD and INR, have been

investigated. The GSA scheme employs a simple packet retransmission and the decoding is on the recent packet the user receives. The RTD scheme uses maximum ratio combining to combine a number of previously received packets prior to decoding. The general INR scheme concatenates the previously received packets into a long code prior to decoding. We showed that, with these schemes, we can reliably deliver the information to the receiver with relatively mild delay. Specifically, when the rate per packet is finite, the delay scales as $\Theta(\log K)$ for all these three schemes. As a consequence, the throughput scales as $\Theta(K/\log K)$. In addition, when we increase the rate per packet linear with K , we obtain the linear scaling of both the throughput and the delay with respect to K . Since every user can achieve no more than the ergodic capacity, we actually achieve the optimal scaling law at this case.

12 PERSONNEL SUPPORTED

Faculty:	Michael D. Zoltowski (PI)
Graduate Research Assistant:	Jianqi Wang

13 PUBLICATIONS

13.1 Book Chapter Published

1. J. Wang, D. J. Love, and M. D. Zoltowski, "Improved Space-Time Coding for Multiple Antenna Multicasting", Chapter B-IV-4, **Principles of Waveform Diversity and Design**, Edited by M. Wicks *et al*, Scitech Publishing, Raleigh, NC, 2009.

13.2 Journal Papers Published

1. J. Wang, D. J. Love, and M. D. Zoltowski, "User Selection with Zero-Forcing Beamforming Achieves the Asymptotically Optimal Sum Rate", IEEE Trans. on Signal processing, Vol. 56, Issue 8, pp. 3713-3726, Aug. 2008.
2. J. Wang, D. J. Love, and M. D. Zoltowski, "A result on order statistics", Purdue Technique report, <http://docs.lib.purdue.edu/ecetr/347>
3. P. Ding, D. J. Love, J. Wang and M. D. Zoltowski, "Low-Complexity Adaptive Design for Full-Diversity Full-Rate Space-Time Codes", IEEE Trans. On Signal Processing, Vol. 54, No. 8, pp. 3180-3189, Aug. 2006.
4. J. Wang, D. J. Love and M. D. Zoltowski, "The fundamental trade-offs between throughput and delay for wireless multicast systems with Hybrid-ARQ", submitted to IEEE Trans. on Information Theory.
5. J. Wang, D. J. Love, and M. D. Zoltowski, "MIMO multicast with quality of service requirement", in preparation.
6. J. Wang, D. J. Love, and M. D. Zoltowski, "User selection for the MIMO broadcast channel with proportional fairness constraints", accepted to IEEE Trans. On Signal Processing.

13.3 Conference Papers

1. J. Wang, D. J. Love and M. D. Zoltowski, "The trade-offs between throughput and delay for wireless multicast systems with hybrid ARQ", submitted to Asilomar conference, 2008 for student paper contest.

2. J. Wang, D. J. Love and M. D. Zoltowski, "MIMO multicast with minimum quality of service requirement", submitted to Allerton conference, 2008.
3. J. Wang, D. J. Love and M. D. Zoltowski, "Minimizing the Number of Dropped Users in MIMO Multicasting Channels", Military communication conference, 2007.
4. J. Wang, D. J. Love and M. D. Zoltowski, "User Selection for the MIMO Broadcast Channel with A Fairness Constraint", IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2007.
5. J. Wang, D. J. Love, and M. D. Zoltowski, "User Selection for MIMO Broadcast Channel with Sequential Water-Filling", 46th Allerton Conference on Communication, Control, and Computing, 2006. Allerton Park, IL.
6. J. Wang, D. J. Love, and M. D. Zoltowski, "Improved Space-Time Coding for Multiple Antenna Multicasting", Int. Waveform Diversity and Design Conference, Lihue, Hawaii, Jan. 2006.

14 INTERACTIONS/TRANSITIONS:

14.1 A. Participation/presentations at meetings, conferences, seminars, etc

- see conference papers listed in Section 5.2.
- **Vice-President for Awards & Membership, IEEE Signal Processing Society**, carries three concurrent positions: **Awards Board (Chair)**, **Executive Committee**, **Board of Governors**. TERM: 1 January 2008 - 31 December 2010.
- Served on the **Advisory Council for the Department of Electical and Computer Engineering at Drexel University**.

14.2 C. Transitions

Dr. Bruce Suter and CITE at Rome Labs continue to assess the performance of our MIMO based schemes with partial CSI. We are also working on transitions of this work with Lee Patton at AFRL in Dayton, Ohio.

15 NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

None.

16 HONORS/AWARDS

1. **Thomas J. and Wendy Engibous Endowed Chaired Professor of Electical & Computer Engineering, Purdue University**. Ceremony with the Board of Trustees of Purdue University held 26 September 2008.