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14. ABSTRACT

To support the constantly increasing performance and reliability expectations for tactical communications, wireless systems must cope with the formidable challenges that stem from wireless fading and multipath effects, interference, finite-precision signal processing, high signal dimension, and limited device size, to name a few. The goal of this proposal is to design low-cost wireless devices that can communicate effectively at high data rates. During the 9-month period of this grant, we have developed novel lattice-reduction aided detectors by further

15. SUBJECT TERMS

wireless communications, lattice reduction, detection, complexity, FPGA, fixed-point

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Xiaoli Ma
UU	UU	UU	UU		19b. TELEPHONE NUMBER 404-385-7456

Report Title

Realizing Lattice-Reduction-Based Detectors for High-Rate Wireless Communications

ABSTRACT

To support the constantly increasing performance and reliability expectations for tactical communications, wireless systems must cope with the formidable challenges that stem from wireless fading and multipath effects, interference, finite-precision signal processing, high signal dimension, and limited device size, to name a few. The goal of this proposal is to design low-cost wireless devices that can communicate effectively at high data rates. During the 9-month period of this grant, we have developed novel lattice-reduction aided detectors by further reducing the power consumption and improving the performance for high-dimensional and high-rate systems. Specifically, our innovative approaches include (i) investigating efficient hardware realization methodologies for performing soft-output LR with joint detecting and decoding, (ii) designing novel LR-aided equalizers which reduce the complexity for systems with large antenna arrays or high dimensional sizes (e.g, systems with long delays), and (iii) developing a hardware realization of LR algorithm with early terminating.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
2012/09/29 1	2	Qi Zhou, Xiaoli Ma. Element-Based Lattice Reduction Algorithms forLarge MIMO Detection, IEEE Journal Selected Areas in Communications, (01 2013): 0. doi:
2012/09/29 1	1	Xiaoli Ma, Brian Gestner, David V. Anderson. Incremental Lattice Reduction:Motivation, Theory, and Practical Implementation, IEEE TRANSACTIONS ON Wireless Communications, (01 2012): 188. doi:

TOTAL: 2

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
2012/09/29 1·	3	Qi Zhou, Xiaoli Ma. An Improved LR-aided K-Best Algorithm for MIMO Detection, IEEE Conference of Wireless Communications and Signal Processing. 2012/10/25 00:00:00, . : ,
2012/09/29 1·	4	Qi Zhou, Jie Pan, Xiaoli Ma, Stephen E. Ralph. Lattice-Reduction-Aided Wiener Filtering for Communications over ISI Channels, International Conference on Signal Processing. 2012/10/21 00:00:00, . : ,

TOTAL: **2**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
2012/09/29 1·	5	Qi Zhou, Xiaoli Ma. Improved Element-Based Lattice ReductionAlgorithms for Wireless Communications, IEEE TRANSACTIONS ON Wireless Communications (09 2012)

TOTAL: **1**

Number of Manuscripts:

Books

Received	Paper

TOTAL:

Patents Submitted

GTRC6193 - An Improved Lattice-Reduction-Aided K-Best Algorithm for Low Complexity and High Performance Communications

GTRC6192 - An Improved Complex Lattice-Reduction-Aided K-Best Algorithm for Low Complexity and High Performance Communications

GTRC - Element-based Lattice Reduction+ (ELR+) Algorithms for Wireless Communications

GTRC5504 - Incremental Lattice Reduction Systems And Methods

Patents Awarded

GTRC 5593 - Enhanced Lattice Reduction Systems And Methods

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Qi Zhou	0.30	
Qingsong Wen	0.60	
Minzhen Ren	0.20	
FTE Equivalent:	**1.10**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Xiaoli Ma	0.10	
David V. Anderson	0.10	
FTE Equivalent:	**0.20**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Minzhen Ren	
Total Number:	**1**

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Scientific progress and accomplishments

- 3 journal papers (2 published, 1 submitted), and 2 conference proceeding papers
- 1 M.S. degree will be awarded in summer 2013, 1 PhD student is still working on this topic
- 5 invention disclosures have been filed, two patents have been granted in US
- One start-up company, Ratrix Technologies is registered to help commercializing the proposed technologies
- One small grant from Georgia Research Alliance (GRA)
- Designed enhanced lattice reduction algorithms which optimize the asymptotic error performance of linear detectors [1,2].
- Developed an LR-aided K-best algorithm which outperforms the existing LR-aided schemes for both coded and uncoded systems and also K-best sphere decoding algorithms [3].
- Introduced an LR realization algorithm which distributes LR hardware complexity to different cycles and thus allow early termination [4].
- Applied LR to ISI channels (e.g., optical MIMO systems) and proposed LR aided Wiener filter [5].

Technology Transfer

Project Final Report

Title: Realizing Lattice-Reduction-Based Detectors for High-Rate Wireless Communications
Grant Number: W911-NF-11-1-0542
Time Period covered by this report: 10/01/11-06/30/12
PI: Xiaoli Ma, School of ECE, Georgia Institute of Technology
Co-PI: David V. Anderson, School of ECE, Georgia Institute of Technology

1. Research Objectives

Through this grant, we seek to enhance our designs by further reducing the power consumption and improving the performance for high-dimensional and high-rate systems. Specifically, our innovative approaches in this proposal include

a) *investigating efficient hardware realization methodologies for performing soft-output lattice reduction (LR) with joint detecting and decoding,*
b) *designing novel LR-aided equalizers which reduce the complexity for systems with large antenna arrays or high dimensional sizes (e.g, systems with long delays), and*
c) *developing a new hardware realization structure for LR algorithms with early terminating and further reducing the hardware complexity.*

The combination of the proposed theory, software, and hardware contributions will naturally address the cost, reliability, latency, throughput, and power requirements of current and future wireless tactical communication systems. This interdisciplinary research advances both theoretical communication analysis and hardware realization technologies. The goals of this proposal are not only publications, but also a real demo on "LR-aided receiver on the chip" by combining theory, software, and hardware. The new scientific knowledge gained through this research will provide much better technology for communication through wireless channels.

2. Approaches and Scientific Achievements

♦ *Element-based lattice-reduction (ELR) aided detectors for large MIMO systems*

Large multi-input multi-output (MIMO) systems with tens or hundreds of antennas have shown great potential for next generation of wireless communications to support high spectral efficiencies. However, due to the non-deterministic polynomial hard nature of MIMO detection, large MIMO systems impose stringent requirements on the design of reliable and computationally efficient detectors. Recently, lattice reduction (LR) techniques have been applied to improve the performance of low-complexity detectors for MIMO systems without increasing the complexity dramatically. Most existing LR algorithms are designed to improve the orthogonality of channel matrices, which is not directly related to the error performance. We propose element-based lattice reduction (ELR) algorithms that reduce the diagonal elements of the noise covariance matrix of linear detectors and thus enhance the asymptotic performance of linear detectors. The general goal is formulated as solving a "shortest longest vector reduction" or a stronger version, "shortest longest basis reduction," both of which require high complexity to find the optimal solution. Our proposed ELR algorithms find sub-optimal solutions to the reductions with low complexity and high performance. The fundamental properties of the ELR algorithms are investigated. Simulations show that the proposed ELR-aided detectors yield better error performance than the existing low-complexity detectors for large

MIMO systems while maintaining lower complexity. Furthermore, a generalized column operation can be adopted to further improve the performance of ELR. This is called ELR+ algorithm [1,2].

- *An improved LR-aided K-best algorithm*

  LR technique has caught great attention for multi-input multi-output (MIMO) receiver because of its low complexity and high performance. However, when the number of antennas is large, LR-aided linear detectors and successive interference cancellation (SIC) detectors still exhibit considerable performance gap to the optimal maximum likelihood detector (MLD). To enhance the performance of the LR-aided detectors, the LR-aided K-best algorithm was developed at the cost of the extra complexity on the order O(Nt^2K + NtK^2), where Nt is the number of transmit antennas and K is the number of candidates. In this project, we develop an LR-aided K-best algorithm with lower complexity by exploiting a priority queue. With the aid of the priority queue, our analysis shows that the complexity of the LR-aided K-best algorithm can be further reduced to O(Nt^2K + NtKlog2(K)). The low complexity of the proposed LR-aided K-best algorithm allows us to perform the algorithm for large MIMO systems (e.g., 50x50 MIMO systems) with large candidate sizes. Simulations show that as the number of antennas increases, the error performance approaches that of AWGN channel [3].

- *Fixed-point realization of LR-aided detectors with soft-output decoders*

  To enhance the information rate, error-control codes (ECC), e.g., Turbo codes and low-density parity check (LDPC) codes, are incorporated in practical systems. A global optimal decoder is infeasible because the long length of the ECC can lead to excessively high complexity. Therefore, the challenge when incorporating these codes is to achieve reliable operation while exhibiting low complexity at the receiver. In the previous years, we have introduced three novel LR-aided soft-output detectors with low-complexity algorithms to generate candidates and to approach optimal performance. These three detectors are compared with the existing soft-decision methods in both performance and complexity. We demonstrate that with the same number of candidates, our algorithms achieve better performance compared to the alternatives. In this current project, we have focused on realization. The whole receiver fixed point implementation has been performed and the 2x2 LR-aided K-best algorithm [3] has been implemented on FPGA.

- *Incremental lattice reduction: LR with early termination*

  Current applications of LR-aided detectors involve executing a LR algorithm to completion and then utilizing this result in the sub- sequent symbol detection. In this project, however, we examine the possibility of partially executing the lattice reduction algorithm. We first demonstrate using a hypothetical LR-aided detector that early termination of LR algorithms is possible in the context of MIMO detection. Encouraged by these results, we develop and introduce incremental LR, which utilizes a practical early termination condition. We then apply this idea to develop a joint symbol detection and LR algorithm that is based on the LLL algorithm and successive interference cancellation. An evaluation using a spatial correlation channel model demonstrates that the proposed algorithm effectively distributes the lattice reduction processing over the length of each received packet. This behavior naturally enables the relaxation of throughput and latency requirements of lattice reduction algorithm hardware realizations [4].

- *LR-aided Wiener filtering for communications over ISI channels*

  Wiener filter is widely used to equalize the signals over inter-symbol interference (ISI) channels because of its low complexity and optimality in terms of mean square error (MSE). However, Wiener filter is generally not optimal in terms of symbol detection error and thus can exhibit considerable error performance degradation in ISI channels. In this project, we propose LR-aided Wiener filter that aims at minimizing the MSE for the symbols in lattice-reduced domain. Simulations show that the LR-aided Wiener filter exhibits significant error performance improvement over the Wiener filter, especially for higher-order modulations.

3. Significance and Relevance to the Army

The new vision of the Army calls for objective force that is responsive, is rapidly deployable, encompasses the full mission spectrum, is highly lethal, and is survivable. For future army wireless communications and networks, it is critical to develop signal processing methods that support high spectral efficiency, high transmission rate, low decoding delay, and high mobility. These methods are essential for war-fighters on-the-move, secure anti-jam links, and reduction of the probability of interception and detection. Our designs provide great potential along these lines. The proposed research will benefit the development of future tactical battlefield communication networks. Through technological innovations, we will enhance the robustness and improve the capacity of tactical communications. The combination of the proposed theory, software, and hardware contributions will naturally address the cost, reliability, latency, throughput, and power requirements of current and future wireless tactical communication systems. This interdisciplinary research will advance both theoretical communication analysis and hardware realization technologies. The goals of this proposal are not only publications, but also a real demo on ``LR-aided receiver on the chip'' by combining theory, software, and hardware. The new scientific knowledge gained through this research will provide much better technology for communication through wireless channels.

4. Accomplishments

- 3 journal papers (2 published, 1 submitted), and 2 conference proceeding papers
- 1 M.S. degree will be awarded in summer 2013, 1 PhD student is still working on this topic
- 5 invention disclosures have been filed, two patents have been granted in US
- One start-up company, Ratrix Technologies is registered to help commercializing the proposed technologies
- One small grant from Georgia Research Alliance (GRA)
- Designed enhanced lattice reduction algorithms which optimize the asymptotic error performance of linear detectors [1,2].

- Developed an LR-aided K-best algorithm which outperforms the existing LR-aided schemes for both coded and uncoded systems and also K-best sphere decoding algorithms [3].
- Introduced an LR realization algorithm which distributes LR hardware complexity to different cycles and thus allow early termination [4].
- Applied LR to ISI channels (e.g., optical MIMO systems) and proposed LR aided Wiener filter [5].

5. List of Publications (Oct. 2011- June 2012)

[1] Q. Zhou and X. Ma, "Element-Based Lattice Reduction Algorithms for Large MIMO Detection," *IEEE Journal of Selected Areas in Communications* (special issue on large MIMO), accepted Sept. 2012.

[2] Q. Zhou and X. Ma, "Improved Element-Based Lattice Reduction Algorithms for Wireless Communications," *IEEE Trans. On Wireless Communications*, Submitted Sept. 2012.

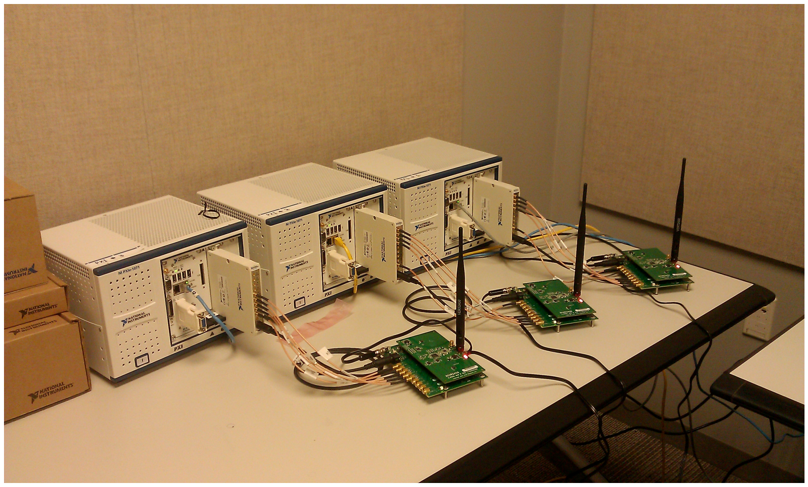
[3] Q. Zhou and X. Ma, "An Improved LR-aided K-Best Algorithm for MIMO Detection," *Proc. of International Conf. on Wireless Communications and Signal Processing*, Huangshan, China, Oct. 2012.

[4] B. Gestner, X. Ma, and D. V. Anderson, "Incremental Lattice Reduction: Motivation, Theory, and Practical Implementation," *IEEE Trans. on Wireless Communications*, Vol. 11, No. 1, Jan. 2012.

[5] Q. Zhou, J. Pan, X. Ma, and S. E. Ralph, "Lattice-Reduction-Aided Wiener Filtering for Communications over ISI Channels," *Proc. of International Conf. on Signal Processing*, Beijing, China, Oct. 2012.

6. Technology transfer

- One start-up company has been registered in 2011. Currently, the company has two part-time engineers (Dr. Sungeun Lee, Jeol Jackson), three consultants (Dr. Xiaoli Ma, Dr. David Anderson, Dr. Brian Gestner), and one marketing person (Drayt Avera).
- National Instruments has shown great interest to collaborate on the project. They have donated the hardware (PXI boxes) to build 2x2 MIMO.



7. Conclusions

During the project period, the PI, Co-PI, and three graduate research assistants have conducted extensive research guided by the proposal that we submitted. The proposed objectives have been fully achieved, 3 journal papers, 2 conference proceeding papers, and 1 technical report have been published/submitted, one MS degree will be awarded (the MS student is finishing this fall). In addition, during this period, new ideas and approaches along this topic have emerged to better finish up the rest of the project period and develop continued proposal for possible future funding.

8. Current and near future plans

- *FPGA implementation of CLLL-aided K-best Algorithm for 8x8 256-QAM MIMO systems*

Currently, we already have the CLLL algorithm realized on FPGA and the LR-aided K-best detector proposed in [3] have also been realized on FPGA for 2x2 MIMO systems. Now we are extensively working on the 8x8 MIMO systems. Our target deadline is at the end of 2012.

- *2x2 live demo based NI PXI*

In the past year, we have spent a lot of efforts in developing a live-demo based on NI PXI chasses. In Aug. 2012, we have successfully delivered a point-to-point live-demo at NI Week (an annual event by NI) using NI PXI chasses. We build the reference base line model (from symbol transmission to synchronization and until BER calculation). Now NI has adopted our codes as the reference base line model for other PXI users. Now we are working on MIMO systems.