REPORT DOCUMENTATION PAGE

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1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
17-03-2023	Final Report	15-Jul-2017 - 14-Jul-2018

4. TITLE AND SUBTITLE

Final Report: Computational Instrumentation for Research in Mobile Wireless Communication Networks

5a. CONTRACT NUMBER
W911NF-17-1-0244

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611103

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

Clemson University
300 Brackett Hall
Box 345702
Clemson, SC 29634 -5702

8. PERFORMING ORGANIZATION REPORT NUMBER

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

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

10. SPONSOR/MONITOR'S ACRONYM(S)
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11. SPONSOR/MONITOR'S REPORT NUMBER(S)
70086-NC-RIP.11

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

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

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Daniel Noneaker
UU	UU	UU	UU		19b. TELEPHONE NUMBER 864-656-0100

RPPR Final Report
as of 20-Mar-2023

Agency Code: 21XD

Proposal Number: 70086NCRIP **Agreement Number: W911NF-17-1-0244**
INVESTIGATOR(S):

Name: Daniel Noneaker
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DUNS Number: 042629816 EIN: 576000254
Report Date: 14-Oct-2018 Date Received: 17-Mar-2023
Final Report for Period Beginning 15-Jul-2017 and Ending 14-Jul-2018
Title: Computational Instrumentation for Research in Mobile Wireless Communication Networks
Begin Performance Period: 15-Jul-2017 **End Performance Period:** 14-Jul-2018
Report Term: 0-Other

Submitted By: Daniel Noneaker Email: dnoneak@clemson.edu
Phone: (864) 656-0100

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: **STEM Participants:** 9

Major Goals: Goal 1. Acquisition of high-performance, high-throughput computing server

The initial goal of this project is the acquisition and use of a high-performance, high-throughput hybrid CPU/GPU HP computing server consisting of 20 nodes, each consisting of two Intel E4-2680v4 CPU cards and two NVIDIA P100 GPU cards with accompanying high-speed interconnection, memory, mass storage, and communications subsystems.

Goal 2. Use of the computing server in support of individual DOD-funded and DOD-relevant research projects.

Projects and research topic include the following.

a. Army Research Office Grant Number W911NF-15-1-0545: Efficient Delivery of Information in Tactical Packet Radio Networks

b. Office of Naval Research Grant Number N00014-17-1-2418: New Techniques for Network-Coded Multicast Distribution in Wireless Communications Networks

c. Efficient transmission scheduling in ad hoc networks

d. Exploiting point-to-point MIMO in ad hoc networks with transmission scheduling

e. Spectrum sharing for distributed ad hoc networks

f. An investigation of the effect of fading on transmission scheduling protocols

g. Preliminary investigation of copperative distributed MIMO for ad hoc networks

Accomplishments: The accomplishments are detailed in the uploaded PDF document

Training Opportunities:
The research in which the instrumentation was utilized in the reporting period included participation by several undergraduate students, graduate students, and post-doctoral researchers. For each of these individuals, the research contributed to the development of their subject-matter expertise, their capabilities as an independent researcher, their modeling and simulation skills, and their technical writing abilities.

The following individuals benefitted from this training.

Undergraduate Students: Matthew D. Dierksheide, Patrick J. Dynes, Benjamin Hardaway

MS Students: William Johnson, Yifan Kang, Taylor Maier

Ph.D. Students: Vikas Bollapragada, Siddhartha S. Borkotoky, Madhabi Manandhar

Postdoctoral Research Fellows: Siddhartha S. Borkotoky, Madhabi Manandhar

Results Dissemination: The results of the research supported by the instrumentation in this period have been disseminated to the research and professional community in wireless communications through the publication of journal articles and conference papers (and through correspoing conference presentations). The journal articiles and conference papers are detailed in the Products section and in the uploaded PDF file.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Daniel Lee Noneaker
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co-Investigator
Participant: Michael Bader Pursley
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co-Investigator
Participant: Harlan Blaine Russell
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

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as of 20-Mar-2023

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE/ACM Transactions on Networking
Publication Identifier Type: DOI Publication Identifier: 10.1109/TNET.2018.2882303
Volume: 27 Issue: 1 First Page #: 29
Date Submitted: 3/17/23 12:00AM Date Published: 2/1/19 5:00AM
Publication Location:
Article Title: Fountain-Coded Broadcast Distribution in Multiple-Hop Packet Radio Networks
Authors: Siddhartha S. Borkotoky, Michael B. Pursley
Keywords: Fountain coding, packet radio networks, wireless ad hoc networks
Abstract: We devise and evaluate five methods for fountain- coded broadcast distribution of a file from a source to multiple destinations in an ad hoc wireless network that consists of half-duplex packet radios. The methods differ in their use of intermediate nodes, their use of forwarding, and their reliance on a network spanning tree. All five methods employ contin- ued fountain coding to prevent nodes from receiving duplicate fountain-coded packets. We derive an analytical approximation for the throughput of fountain-coded broadcast file distribution in a four-node network with time-varying radio links modeled by independent two-state Markov chains, and we show that our approach to fountain-coded file distribution gives throughput that is very close to the approximation. We employ simulations to examine larger networks in which each radio link has correlated Rayleigh fading and the radios use adaptive modulation and channel coding.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE Transactions on Cognitive Communications and Networking
Publication Identifier Type: DOI Publication Identifier: 10.1109/TCCN.2018.2890620
Volume: 5 Issue: 1 First Page #: 73
Date Submitted: 3/17/23 12:00AM Date Published: 3/1/19 5:00AM
Publication Location:
Article Title: Analytical Methods for Performance Evaluations of Adaptive Modulation and Coding in Cognitive Radio Systems That Employ Distance Statistics
Authors: Siddhartha S. Borkotoky, Sneha Latha Kottapalli, Michael B. Pursley
Keywords: Cognitive radio ad hoc networks, packet radio, adaptive modulation and coding, fading, interference
Abstract: Abstract—Distance statistics have been employed in previous investigations of packet transmission and reception in cognitive radio systems. Such statistics are a good source of control infor- mation for packet-to-packet adaptation of modulation and coding to mitigate the effects of time-varying fading or interference. Previous research on distance statistics has relied on simulation for protocol design and performance evaluation. We devise new analytical methods for use in the design and evaluation of pro- tocols for adaptive modulation and coding that obtain control information from a distance statistic. The primary advantage of our approach is the avoidance of simulations of the time- varying channel, generation of the adaptive control information, and adaptation process.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE Communications Letters
Publication Identifier Type: DOI Publication Identifier: 10.1109/LCOMM.2019.2943174
Volume: 23 Issue: 12 First Page #: 2412
Date Submitted: 3/17/23 12:00AM Date Published: 12/1/19 5:00AM
Publication Location:
Article Title: Adaptive Transmission for Network-Coded All-to-All Broadcast in Multi-Hop Ad Hoc Wireless Networks
Authors: Siddhartha S. Borkotoky, Michael B. Pursley
Keywords: Packet radio, adaptive modulation, adaptive coding, networks
Abstract: We describe and evaluate a new suite of protocols for the delivery of information from each node to every other node in a multi-hop ad hoc wireless network. The protocol suite is integrated with random linear network coding to mitigate the effects of packet losses due to noise and time-varying fading on the radio links. The suite includes a practical three-mode protocol for packet-by-packet selection of the channel code and modulation based on control information from statistics derived by the nodes themselves. Our performance metric is energy efficiency, and our emphasis is on robust performance in practical networks for which optimization is not feasible.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Wireless Communications and Mobile Computing
Publication Identifier Type: DOI Publication Identifier: 10.1155/2018/2484897
Volume: 2018 Issue: First Page #: 1
Date Submitted: 3/17/23 12:00AM Date Published: 12/1/18 5:00AM
Publication Location: London, UK
Article Title: RMTS: A Novel Approach to Transmission Scheduling in Ad Hoc Networks by Salvaging Unused Slot Transmission Assignments
Authors: Vikas Bollapragada Subrahmanya, Harlan B. Russell
Keywords: wireless networks, mobile ad hoc networks, channel-access protocols, transmission scheduling
Abstract: In mobile ad hoc networks (MANETs) there is no centralized supervision over the network operations. In such networks, it is imperative to have protocols that are implemented locally in a distributed manner. To achieve high network performance utilizing only the wireless channels a distributed transmission-scheduling medium-access control (MAC) protocol is desirable. This type of protocol can guarantee a certain level of quality of service (QOS) and works well in congested networks. However, the transmission schedules are often decided in advance and if a node does not have a packet to transmit in its assigned slot then the slot is unused. We propose a protocol called recovering minislots transmission scheduling (RMTS) that salvages these unused transmission slots that would have otherwise been wasted. We show that the proposed protocol produces significant improvements in network performance over traditional transmission-scheduling approaches.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 IEEE Military Communications Conference (MILCOM)
Date Received: 17-Mar-2023 Conference Date: 23-Oct-2017 Date Published:
Conference Location: Baltimore, MD
Paper Title: A comparison of three adaptive transmission protocols for fountain-coded multicast
Authors: Siddhartha Borkotoky, Patrick Dynes, Michael Pursly
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 20-Mar-2023

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 IEEE Military Communications Conference (MILCOM)
Date Received: 17-Mar-2023 Conference Date: 23-Oct-2017 Date Published:
Conference Location: Baltimore, MD
Paper Title: RMTS-a: A scheduling based MAC protocol with frame aggregation for multi-rate radios in an Ad Hoc network
Authors: Vikas Bollapragada, Harlan Russell
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: Clemson University
Date Received: 17-Mar-2023 Completion Date: 3/18/17 4:33AM
Title: Acceleration of High-Fidelity Wireless Network Simulations
Authors: Madhabi, Manandhar
Acknowledged Federal Support: **N**

Publication Type: Thesis or Dissertation
Institution: Clemson University
Date Received: 17-Mar-2023 Completion Date: 12/8/88 8:43PM
Title: A multiple-frequency transmission scheduling scheme for mesh net- works that employ spectrum sharing
Authors: Taylor, Maier
Acknowledged Federal Support: **N**

Publication Type: Thesis or Dissertation
Institution: Clemson University
Date Received: 17-Mar-2023 Completion Date: 5/15/20 8:09PM
Title: A Transmission Scheduling Protocol Using Radios With Multiple Antennas For Ad Hoc Networks
Authors: John, Hardaway
Acknowledged Federal Support: **N**

Partners

,

I certify that the information in the report is complete and accurate:
Signature: Daniel L. Noneaker
Signature Date: 3/17/23 4:53PM

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1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
28-09-2018	Final Technical Report	15 July 2017 — 14 July 2018

4. TITLE AND SUBTITLE

Computational Instrumentation for Research in Mobile Wireless Communications Networks

5a. CONTRACT NUMBER

W911NF-17-1-0244

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Noneaker, Daniel L.
Pursley, Michael B.
Russell, Harlan B.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

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US Army ACC-APG-RTP W911NF
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12. DISTRIBUTION / AVAILABILITY STATEMENT

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report summarizes the instrumentation purchases and resulting research activities that have benefited from the ARL/ARO equipment Grant W911NF-17-1-0244. The instrumentation forms a high-performance computing system that permits simulation of communication links and distributed radio networks to aid in research on advanced coding and modulation schemes, high-fidelity channel models, novel receiver structures, adaptive transmission protocols, adaptive MAC protocols, and adaptive routing protocols for use in ad hoc packet radio networks. The progress of research in these areas depends to a significant extent on the ability to utilize novel, high-fidelity systems models which of necessity require substantial computational power to implement. The new instrumentation has greatly enhanced the ability of our research group to obtain results for computationally demanding problems in a timely manner, thus leading to a great improvement in the efficiency with which research in these topics is conducted.

15. SUBJECT TERMS

Wireless Networks, Communication Systems, Computational Methods, High-Performance Computing, Adaptive Protocols, Rateless Coding

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FINAL REPORT FOR US ARMY GRANT W911NF-17-1-0244: Computational Instrumentation for Research in Mobile Wireless Communications Networks

Final Report

to the Army Research Laboratory/Army Research Office

by

Daniel L. Noneaker, Principal Investigator,
Clemson University

Dept. of Electrical and Computer Engineering
102 Riggs Hall
Clemson University
Clemson, SC 29634-0915

September 28, 2018

This report summarizes the instrumentation purchases and resulting research activities that have benefited from the ARL/ARO equipment Grant W911NF-17-1-0244. The research equipment purchased under this instrumentation grant is described under the heading **Instrumentation purchased under the grant**. The research instrumentation has made possible new research capabilities and enhanced the quality of previously existing research facilities in wireless communications that are part of the Wireless Communications Program (WCP) at Clemson University. The research instrumentation is greatly enhancing research that is being conducted through DOD-funded research grants and other research of related to DOD interests. The research grants are listed later in the report under the heading **DOD grants and contracts benefiting from instrumentation**. Other research on topics of interest to the DOD are described under the heading **Other DOD-related research benefiting from instrumentation**. Students and post-docs whose research experience has benefitted from utilizing the instruction are identified under the heading **Professional development of personnel through research utilizing grant equipment**. Research utilizing the instrumentation has contributed to several publications thus far, which are listed under the heading **Publications thus far from research utilizing grant equipment**.

The instrumentation forms a high-performance computing system that permits simulation of communication links and distributed radio networks to aid in research on advanced coding and modulation schemes, high-fidelity channel models, novel receiver structures, adaptive transmission protocols, adaptive MAC protocols, and adaptive routing protocols for use in ad hoc packet radio networks. The progress of research in these areas depends to a significant extent on the ability to utilize novel, high-fidelity systems models which of necessity require substantial computational power to implement. The new instrumentation has greatly enhanced the ability of our research group to obtain results for computationally demanding problems in a timely manner, thus leading to a great improvement in the efficiency with which research in these topics is conducted.

Instrumentation purchased under the grant

The instrumentation purchased under this grant is a high-performance, high-throughput hybrid CPU/GPU HP computing server consisting of 20 nodes, each consisting of two Intel E4-2680v4 CPU cards and two NVIDIA P100 GPU cards with accompanying high-speed interconnection, memory, mass storage, and communications subsystems. The instrumentation purchased from the grant funds has been complemented by a purchase by Clemson University of 12 additional nodes using university internal funds. The cluster will provide our research group with an increase in aggregate computing capability of approximately eight fold, depending on the ability of the application to exploit the resources of the GPUs.

The server equipment is mounted in standard racks with supporting power uninterruptible power supplies and a high-speed interconnect switch - all supplied by Clemson University. It is housed in Clemson's Information Technology Center, which provides the necessary power and cooling for high-performance computing. The hardware; its operating system, support software, and security software; and the installed application software ware administered by the high-performance computing staff of Clemson's Computing and Information Technology organization. Faculty and students conducting DOD-funded research access the system remotely via the on-campus network or a VPN.

Depending on the application, the proposed equipment will provide nearly an order of magnitude increase in computing power over our current equipment. The increase in computational capability is the key to our ability to obtain timely link and network simulation results in the future as our research encompasses problems entailing every greater modeling complexity. The use of GPUs in the equipment will also allow us to develop the GPU-programming expertise necessary to exploit future developments in GPU architectures for our simulations.

INSTRUMENTATION PURCHASE

Item	Qty	Equipment	Cost
1	20	2 x Intel E4-2680v4 CPUs	
2	20	128 GB RAM	
3	20	2 x Nvidia P100 GPUs	
4	20	Mellanox ConnectX-3 dual port FDR IB card	
5	20	Intel X710 dual port 10GB Ethernet card	
6	20	2 x 1TB 7.2k rpm hard drives	
		Subtotal	$250,895.00
		Tax	0.00
		Shipping	0.00
		TOTAL	$250,895.00

DOD grants and contracts benefitting from instrumentation

The following two current DOD grantshave benefitted from the instrumentation between the time of its installation in October 2017 and the writing of this report in September 2018. It is anticipated that many future grants in mobile wireless communication networks will also benefit from the instrumentation over its lifetime. The second-listed grant builds in part on research completed in the first-listed grant.

Army Research Office Grant Number W911NF-15-1-0545: Efficient Delivery of Information in Tactical Packet Radio Networks

Office of Naval Research Grant Number N00014-17-1-2418: New Techniques for Network-Coded Multicast Distribution in Wireless Communications Networks

We have developed and evaluated methods and protocols for network-coded broadcast distribution of packets and files in tactical multi-hop ad hoc wireless networks that consist of half-duplex packet radios. Two forms of network coding have been employed, fountain coding and random linear network coding. In our broadcast distribution schemes, we increase the throughput and reduce the delay by exploiting overhearing, which is defined as follows: If a radio sends a packet to another radio on a channel and a third radio that is tuned to the channel receives it, then the third radio is said to overhear the packet. In frequency-division multiple access, each frequency band represents a channel. In spread-spectrum multiple access, each spreading sequence or each frequency-hopping pattern represents a channel. The radio links employ adaptive modulation and channel coding that is integrated with the network coding system. Our protocols for adaptive modulation and channel coding derive their control information from low-complexity receiver statistics that are obtained as the radios demodulate and decode incoming packets. We developed analytical methods that we employ for performance evaluations of small networks. The analytical results are extended to larger and more complex networks by simulations that include realistic models for time-varying fading on the radio links.

Adaptive modulation can improve the performance and reliability of orthogonal frequency division multiplexing (OFDM) systems that must communicate over dynamic fading channels. For this to occur, appropriate modulation formats must be selected to match the sub-channel conditions from packet to packet. We have developed a method for adapting the modulation formats without relying on traditional channel measurements to assess sub-channel quality. Performance evaluations for our protocol have been obtain from simulations, and we have compared the throughput of our protocol with that obtained by hypothetical ideal protocols that are given perfect channel state information.

Other DOD-related research benefitting from instrumentation

The following current additional DOD-related research has benefitted from the instrumentation between the time of its installation in November 2013 and the writing of this report in May 2014. It is anticipated that most or all of these topics will be incorporated into DOD-funded research at some time during the lifetime of the instrumentation.

Accelerated high-fidelity simulations of mobile ad hoc packet radio networks

Monte Carlo simulations serve as a vital tool in characterizing the performance of mobile packet radio networks using newly developed protocols and architectures. The complexity of modeling networks of even moderate scale results in a severe tradeoff between the fidelity of the simulation model and the computation time of the simulations, however. We are currently examining methods to improve the fideltiy/computation-time tradeoffs in wireless network simulations by taking a two-prongs approach: improved analytical approximations to probably of success in a link transmission under given conditions, and acceleration of bit-by-bit simulation of the behavior of the link. We have begun to investigate the use of the GPUs in the new equipment as a means to accelerate bit-by-bit simulations in a manner that can be exploited effectively in network-scale simulations. The GPUs are also being used for rapid simulation of wireless link performance for use in characterization of the accuracy of the analytical approximation techniques.

Channel-access and network protocols for ad hoc networks of frequency-agile software-defined radios

Project 1: Efficient transmission scheduling in ad hoc networks

The applications for mobile ad hoc networks (MANETs) have increased rapidly and today MANETs are capable of providing a variety of services. One of the major contributing factors is the availability of radios that are able to adapt to the channel conditions and can transmit at multiple data rates. A common approach for channel access is to employ a CSMA/CA based mechanism. However, these protocols tend to under perform at heavy loads or due to exposed or hidden nodes. One solution to this problem is to use a scheduling based MAC protocol. While transmission scheduling avoids collisions, these approaches often suffer from inefficient utilization of the channel. In most of these protocols, the transmission schedules are decided in advance and if a node does not have a packet to transmit in its assigned slot then the slot is wasted. In this project, we are investigating multiple extensions to scheduling based MAC protocols that can recover the unused slots. In [VBS18], we design and investigate a protocol called recovering mini-slots transmission scheduling (RMTS) that salvages unused transmission slots that would have otherwise been unutilized. The RMTS protocol allows a node to utilize a transmission opportunity that is assigned to another node if the slot is not used, but only if the substitute transmission creates similar multiple-access interference. We show that our protocol produces a large improvement in network

performance over traditional scheduling approaches. We extend the RMTS approach in [VBS17] to support an adaptive transmission protocol that provides considerable increases in the degrees of freedom in recovering transmission opportunities in ad hoc networks. The new protocol exploits the multirate transmission capability of the radios to increase the utilization of transmission assignments.

Project 2: Exploiting point-to-point MIMO in ad hoc networks with transmission scheduling

It is critical to exploit high quality links in mobile ad hoc networks by adapting the coding and modulation parameters to achieve high data rates. However, a significant challenge is to account for the multiple-access interference environment and only adapt the transmission parameters when the channel quality can support the higher rate transmissions. In our previous work, we have consider only changes to the data rate that are possible by modifying the coding and modulation parameters. However, when a pair of transmit and receive nodes can support multiple transmit and receive antennas, then point-to-point MIMO provides another mechanism to increase the effective data rate on the link. We show that when considering the multiple-access interference environment created by a distributed transmission scheduling algorithm, exploiting MIMO capability over simpler adaptive transmission approaches provides only modest improvements in network performance under a simple channel model that does not consider inter-symbol interference for the adaptive transmission protocol. In [YK18], we show that if both MIMO and adaptive transmission are jointly exploited then improved network performance can be achieved compared to utilizing either approach by itself. However, a significant challenge is integrating the improved link performance into the network protocols so that the links that can provide high data rates are included in forwarding packets. Another significant challenge is to ensure that a transmitter has sufficient packets to fully utilize the high data rate links.

Project 3: Spectrum sharing for distributed ad hoc networks

The reallocation of underutilized spectrum becomes increasingly important as available frequency bands continue to diminish. The Citizens Broadband Radio Service (CBRS) presents spectrum-sharing opportunities, but the interference protection it requires for legacy users can create network performance issues for newer users that look to share the spectrum. It is possible that not all nodes in a network can use a single frequency band. Ad hoc networks that support relay of packets between distributed nodes provides a mechanism to exploit disjointed spectrum opportunities. To overcome disjointed network connectivity, we introduce bridge nodes into the network - dedicated traffic-forwarding nodes that help ease the connectivity issues and bottlenecking caused by legacy node protection protocols. In this project, we design and investigate an augmented connected dominating set (ACDS) algorithm for selecting bridge nodes from a list of bridge node candidates within a network [TM18]. Simulation results show the effectiveness of this selection scheme in terms of end-to-end success rate, end-to-end throughput, and end-to-end delay in a variety of network

topology scenarios. We show the effectiveness of our algorithm by comparing it to simpler bridge node selection schemes.

Project 4: An investigation of the effects on fading on transmission scheduling protocols

We investigate methods for reducing packet loss in mobile ad hoc networks (MANETs) caused by the presence of fading. The modeled system employs an adaptive transmission protocol. This protocol works well when link performance is consistent and predictable, but system performance deteriorates when link quality begins to vary. A log-normal block fading model is implemented to test system performance with time-varying link performance. We propose two different methods for addressing the effects of fading. First, we propose the transmission success probability (TSP) link-rate control protocol, which uses link performance measures to modify the existing adaptive transmission protocol and reduce the number of packets lost due to fading. Second, we show that modifying the routing metric can improve system performance. We show that a cross-layer design for the TSP protocols and routing metrics that jointly considers both link and network performance results in better system performance compared to selecting each protocol separately.

Project 5: Preliminary investigation of cooperative distributed MIMO for ad hoc networks

Recent implementations have shown that in a fixed infrastructure network cooperative MIMO (CO-MIMO) can exploit multiple point-to-point links to achieve performance similar to a conventional MIMO link. In this undergraduate research project, we consider a simplified model of coordinated multipoint CO-MIMO for an ad hoc network. We investigate strategies to improve the performance of transmission schedules for mobile ad hoc networks by taking advantage of CO-MIMO techniques. Traditionally, transmission scheduling protocols have been designed to allow only a single node to transmit at a time within a local area. Point-to-point MIMO systems use multiple collocated antennas that transmit simultaneously for significant performance gains. Recent improvements allow for relaxing the restriction of collocated antennas and allow for distributed transmitter receiver pairs leading to coordinated multipoint MIMO. We show that Lyui?s scheduling protocol can be extended to support CO-MIMO, providing performance gains in end-to-end network performance [BH18].

Professional development of personnel through research utilizing grant equipment

The following development and training of researchers in wireless communication systems and networks has been enhanced through research conducting in part utilized the instrumentation from the grant, either (or both) during their time at Clemson or through subsequent collaboration to complete research conducted during their time at Clemson.

Undergraduate Students: Matthew D. Dierksheide, Patrick J. Dynes, Benjamin Hard-

away MS Students: William Johnson, Yifan Kang, Taylor Maier Ph.D. Students: Vikas Bollapragada, Siddhartha S. Borkotoky, Madhabi Manandhar Postdoctoral Research Fellows: Siddhartha S. Borkotoky, Madhabi Manandhar

Publications thus far from research utilizing grant equipment

The following publications have resulted thus far from research utilizing the instrumentation. It is anticipated that many future publications in mobile wireless communication networks will result from research utilizing the instrumentation over its lifetime.

[SDP17] S. S. Borkotoky, P. J. Dynes, and M. B. Pursley, "A comparison of three adaptive transmission protocols for fountain-coded multicast," Proceedings of the 2017 IEEE Military Communications Conference, pp. 500–505, October 2017.

[SP17] S. S. Borkotoky and M. B. Pursley, '"Fountain-Coded Broadcast Distribution in Multiple-Hop Packet Radio Networks," submitted for publication, being revised for resubmission.

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