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6. AUTHOR(S)
Warren Stutzman and Rick Habayeb

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Virginia Polytechnic Institute & State University
Electrical and Computer Engineering Dept., Attn: W.L. Stutzman
340 Whittemore Hall (0111), Blacksburg, VA 24061

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Navy Collaborative Integrated Information Technology Initiative (NAVCIITI)

ONR Grant N00014-00-1-0549

Report No. 30

Final Report

Submitted to:	***Mr. Gary Toth*** ***ONR 311*** ***Office of Naval Research*** ***Ballston Centre Tower One*** ***800 North Quincy Street*** ***Arlington, VA 22217-5660***
Submitted by:	***Virginia Tech*** ***Blacksburg, VA 24061***

01 Apr. 2000 – Sept. 30, 2004

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Overview

Virginia Tech established the Navy Collaborative Integrated Information Technology Initiative (NAVCIITI) by responding to the Navy requirements outlined in the ONR BAA 00-007. The NAVCIITI program thrust areas were: wireless secure communications; wideband, multifunction and smart antennas; visualization tools; human computer interface and collaboration technologies; usability engineering; computer networking and interoperability; virtual platforms; real-time resource allocation and management; and virtual scenarios of network centric operations. In addition, the program evolved over its approximately five-year existence to a focus on providing a comprehensive road map for integrating and demonstrating information technologies, such as the Wireless Integrated NAVCIITI Network (WINN). In its latter stages it included positioning for the future AWINN (Advanced Wireless Navy Network) program. The initiative is bringing new and unique capabilities to support the Navy vision for knowledge superiority and situational awareness and has laid a strong foundation of science and technology to support the following areas:

1. The creation of an infrastructure of networking capabilities to achieve the Navy goal of Network Centric Warfare (called ForceNet), including high payoff technologies such as secure wireless communications, wideband multifunction antennas, digital ship, and generic environment modeling for physics-based simulation, computer networking, knowledge management, and distributed real-time systems. Elements of success in support of this objective include the following:
    - A space-time advanced software radio architecture that can collect and process narrow band multiple-input multiple-output (MIMO) measurements in non-line-of-sight (NLOS) environments.
    - Development of multifunction wideband antennas that can support shipboard functions such as communications over several radio bands, targeting and imaging radar, and electronic warfare.
    - Development of prototypes of secure configurable software radios for both secure and non-secure data environments.
    - Development of the Device Independent Virtual Environment Recconfigurable Scaleable Extensible (DIVERSE) tool that enables the visualization in a common tactical environment by integrating virtual devices including the CAVE, Immersive Work Bench, Immersive Desk, desktop workstation simulator, head-tracking devices, and hand-held devices.
    - Developed IP-based architectures, algorithms, and protocols for routing, policy-based quality of service (QoS), key management, and network management in wireless ad hoc networks and methods to evaluate ad hoc routing, key management, and bandwidth allocation protocols.
2. The creation of a virtual testbed called Digital Ships for the integration of new technologies. Developed the Digital Ships Laboratory to implement various operational models, e.g., the Command and Decision (C&D) of a ship weapon system, a ship air defense model, UML modeling of the next generation C&C ship the JCC(X), and cluster driven visualization. These facilities can be used to evaluate situation awareness in its various forms (SIAP, SISP, and SIGP).
3. The integration of several NAVCIITI technologies using the WINN platform, Digital Ships, the Virginia Tech CAVE, and the Command &Control visualization API DIVERSE.

Publications Summary

Reports

Technical reports submitted to the Navy: 30

Papers

Papers published in refereed journals: 80
Conference presentations: 120
Books and book chapters: 40

Patents

Patents granted and pending: 18

Support of Graduate Students

The program has supported 20 Ph.D. students and 75 masters students.

Contributions to the Navy Mission

- The wireless secure communication research at Virginia Tech is contributing to the Joint Tactical Radio Systems (JTRS), a major DOD program, through UWB communications, smart antennas, wideband multifunction antennas, and special material to make antennas stealthy.
- The simulation, visualization, and collaboration project at Virginia Tech has developed 3D visualization tools for submarines using our CAVE for NUWC Rhode Island. We developed unique synchronous and asynchronous (CORK and BRIDGE) collaboration tools.
- We developed a virtual reality API called DIVERSE and OpenGL DIVERSE. Also, we developed multi- modal interaction usability techniques.
- The computer networking and interoperability project is providing valuable inputs into the development of secure and robust ad hoc communications networks and mobile ad hoc networks (MANET) and has developed algorithms for policy-based QoS, routing, distributed key management, and network management by delegation.
- The real-time resource management project has developed several middleware software algorithms to improve resource allocation, scheduling, and multi-level security. We have successfully integrated policy-based QoS and real-time middleware.
- The digital ships and knowledge space project has created a digital environment to integrate and evaluate command and control technologies, developed a ship air defense model and supported PMS 377 to develop a UML model of the Command & Control architecture. We supported the Common Command and Decision (CC&D) of the Aegis weapon system. We are developing the Generic Environment Model of Digital Platforms (GEMDP) to support the simulation of Network Centric Operations and integrate the NAVCIITI technologies. Also, we are developing computer cluster visualization tools that put Virginia Tech at the cutting edge of this technology.

Related Navy Activity

The NAVCIITI team prepared a white paper in response to ONR Broad Agency Announcement BAA 03-003, "Technology for Knowledge Superiority and Assurance Future Naval Capability (KSA FNC) Block 2".

INTRODUCTION

The Virginia Polytechnic Institute and State University (Virginia Tech) was issued Grant N00014-99-1-0158 on November 1998 with a period of performance through September 30, 2000. The scope of the program was developed as a result of discussions and briefings with a group of Navy leaders. The program focused on identifying and investigating high-payoff experimental technologies that support JV2010 and the Navy's network centric vision called ForceNet and technologies that can be transitioned to Navy fleet customers. In the year 2000, through a competitive process, Virginia Tech was awarded contract N00014-00-1-0549 under ONR BAA 00-007. The thrust of the contract focused on communication and information technologies such as wireless secure communications; visualization; human computer interface and collaboration; computer networking; and real-time interoperability. The objective of the initiative was to improve the Navy's capability to support distributed computing, information visualization and collaboration among Joint and coalition forces.

This final report, which covers the entire grant time period 1999-2004, is organized into separate sections for the specific tasks, as indicated in the Table of Contents. The sections contain a review of task activities, facilities developed for the task, accomplishments, importance of the task, and a productivity summary. The technical details presented in previous reports and publications are referenced under the task discussions.

PROJECT 1

Task 1.1 Secure Communications - Peter Athanas and Mark Jones

1.1.1 Review of Task Activities

As security countermeasures continue to improve, it is becoming increasingly more difficult to protect both data and the intellectual property contained in computational hardware from reverse engineering. Reverse engineering of secure information systems is particularly troublesome, as the security of the information itself is compromised. Indeed, an integral part of information protection is the security of the system through which it passes. This section summarizes the research work performed by the Configurable Computing Group at Virginia Polytechnic Institute in the period spanning May 2000 to September 2004 of the NAVCIITI project. The work focuses on improved connectivity of mobile platforms.

The secure configurable platform provides a method for user specific integration of secure and insecure data environments as illustrated in Figure 1.1-1. When an authenticated user is not present, the platform enhances its own security by physically removing all functionality of the authenticated system. Users of the platform are provided access only after both token-based and biometric verification procedures have been satisfied. Once these criteria have been satisfied, the platform reconfigures itself to contain the hardware necessary to perform a user-specific function. For the purposes of demonstration, this function is the transfer of data between a secure data access point (wireless) and an insecure data access point (wired internal network). Within the secure platform, measures are taken to assure that no clear information is exposed that might allow for the internal user-specific function to be duplicated or reverse engineered.

Detailed documentation is found in the papers published under this task (listed in Section 1.1.5) and past Secure Communications quarterly and annual reports.

1.1.2 Facilities Developed for Task

Specialized resources were required to fulfill the objectives of this project. Over the course of this task, the Virginia Tech Configurable Computing Laboratory has strengthened its abilities to perform research in the areas of security, hardware encryption, software radios, and configurable computing. Some of the facility improvements made possible by this project are:

1. A testbed for secure communications research, featuring a selection of DINI DN3000K10 rapid prototyping platforms.
2. Custom printed circuit boards used to personalize the off-the-shelf rapid prototyping platforms for our specific research objectives. This is possible through the laboratory T-Tech printed circuit board design station.
3. Highly parameterized radio I/F cards enabling our research in software radios.
4. The computing infrastructure for designing and compiling large FPGA designs.

1.1.3 Accomplishments

With a clear vision of the final secure configurable platform, progress was made on several fronts. Improvements that will allow the platform to communicate at Ethernet-like data rates were pursued and steps were taken to provide off-platform configuration support for the system.

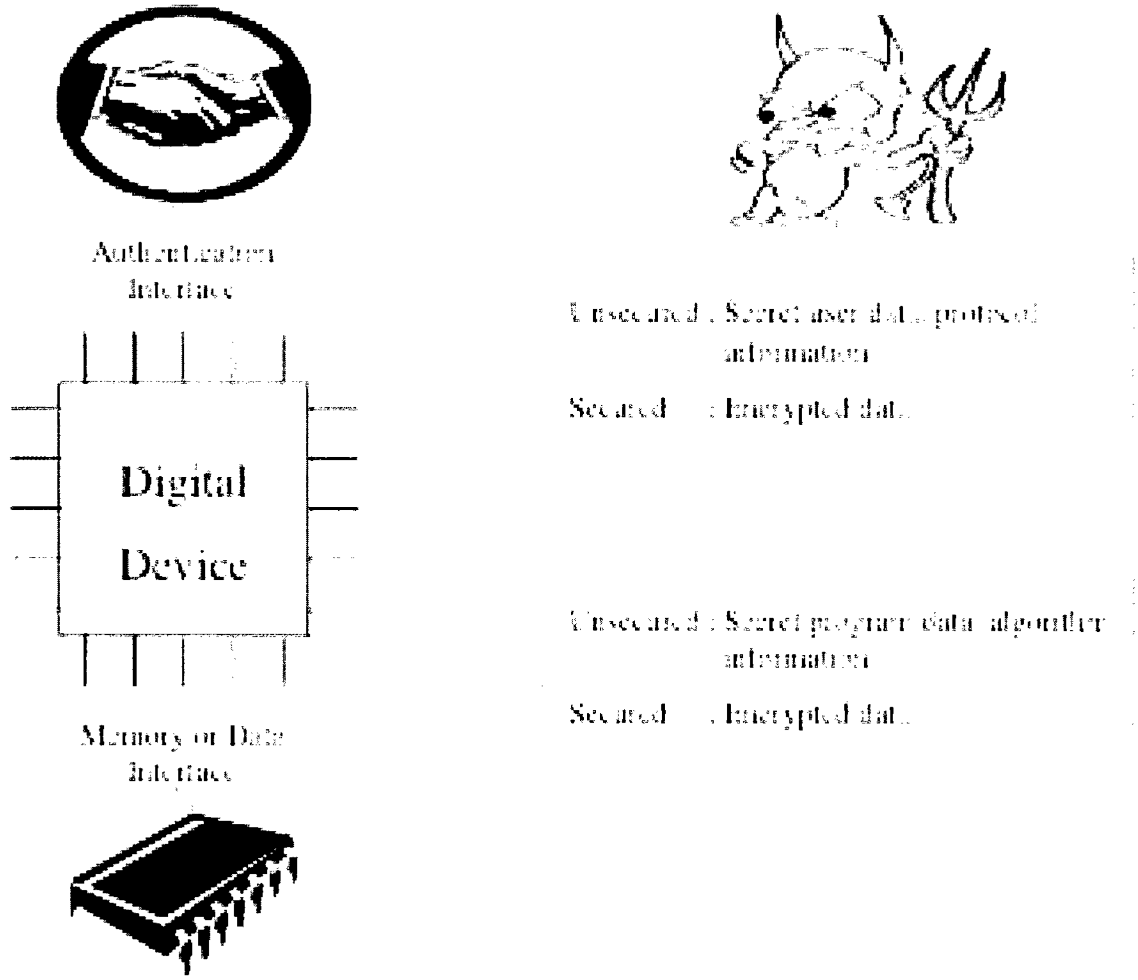

Figure 1.1-1 Illustration of privileged functions within a secure communications platform created in hardware with off-chip secure data transfers.

Both the token and wired network interfaces are undergoing facelifts that will eliminate slow, bulky, and power-consuming intermediate devices. A direct connection to the token is being developed, and a new network interface device was located to provide higher data throughput. The small package and readily available network features of the new (inexpensive) network connection will allow the platform to communicate without the need for additional expense and effort required to purchase or develop network IP for FPGA embedding.

Advancements in the wireless interface also provide the promise of higher system data rates. Initial communication between the selected wireless transceivers was established and development has begun on a high-speed data communications protocol.

The vision of a future system saw significant advancement as a framework for partial self-reconfiguration was developed and tested in a Xilinx Virtex-II FPGA. This development effort forges the way for an entire system contained within a single configurable logic device. The resulting platform was to be integrated with the efforts of other groups within the Virginia Tech NAVCIITI effort and provided to Task 1.4 (Secure Networking) as a network component.

Custom hardware was fabricated to allow for the removal of complex external systems (the TINI and Rabbit modules) for controlling user configuration and wired network traffic. This new interface provides a much more streamlined system contained to be contained more fully within the reconfigurable elements of the system. A PCI backplane was also constructed to support the system outside of a host computer. On the way to achieving these goals, the authorization token interface was to be moved to the new daughtercard and controlled by an FPGA while data rates for wireless communication were to be improved and tests of bi-directional communication performed.

Individually developed authentication, configuration, and network interfaces were integrated into a whole while communication between a stand-alone configurable platform and the selected radio interface was established. In addition, the user configuration needed to process radio traffic has been developed in VHDL and successfully simulated prior to system embedding.

1.1.4 Importance of the Task

Data security is becoming ever more important in embedded and portable electronic devices. The sophistication of the analysis techniques used by attackers is amazingly advanced. Digital devices' external interfaces to memory and communications interfaces to other digital devices are vulnerable to malicious probing and examination. A hostile observer might be able to glean important details of a device's design from such an interface analysis. Defensive measures for protecting a device must therefore be even more sophisticated and robust.

There is currently a strong trend towards embedding Internet capabilities into electronics and everyday appliances. Most network controllers used in small appliances or for specialized purposes are built using micro controllers. However, there are many applications where a hardware-oriented approach using Application Specific Integrated Circuits (ASICs) or Field Programmable Gate Arrays (FPGAs) is more suitable. One of the features of FPGAs that cannot be integrated into ASICs is runtime reconfiguration in which, certain portions of the chip are reconfigured at runtime while the other parts continue to operate normally. This feature is required for network controllers with multiple data transfer channels that need to preserve the state of the static channels while reconfiguration is taking place. It is also required for controllers with space constraints in terms of FPGA resources or time constraints in terms of reconfiguration times. We explored the impact of partial reconfiguration on the performance of a network controller. An FPGA-based network controller that supports partial reconfiguration has been designed and constructed. Partial bitstreams that can configure certain channels of the network controller without affecting the functioning of others were created. Experiments were performed that quantify the manner in which the performance of the controller can be changed by loading these partial bitstreams onto the FPGA.

1.1.5 Productivity Summary

This section summarizes the academic and scholarly accomplishments under the secure communications task.

1.1.5.1 Journal Publications

1. Peter Athanas, Jeffrey H. Reed, and William H. Tranter, "A Prototype Software Radio Based on Configurable Computing," *Advancing Microelectronics*, 1998 Special Wireless Issue, vol. 5, no. 3, pp. 33-38 (invited paper).
2. Srikathyayani Srikanteswara, J.H. Reed, P. Athanas and R. Boyle, "A Soft Radio Architecture for Reconfigurable Platforms," *IEEE Communications Magazine*, Vol. 38, No. 2, pp. 140-147, February 2000.

3. Kiran Puttegowda, David I. Lehn, Jae H. Park, P. Athanas and Mark Jones, "Context Switching in a Run-Time Reconfigurable System," in the *Journal of Supercomputing*, Kluwer Academic Press, June 2003.
4. S. Srikanteswara, R. Chembil Palat, J. H. Reed, P. Athanas, "Overview of Configurable Computing Machines for Radio Handsets," *IEEE Communications Magazine*, August, 2003.

1.1.5.2 Conference Publications

1. Paul Master and Peter Athanas, "Reconfigurable Computing Offers Options for 3G", *Wireless Systems Design*, vol. 4, no. 1 pp 20—27, January 1999.
2. Srikathyayani Srikanteswara, Michael Hosemann, Jeffrey Reed, Peter Athanas, "Design and Implementation of a Completely Reconfigurable Soft Radio," *IEEE Radio and Wireless Conference*, RAWCON2000, vol. 6, pp. 7 - 11, Denver, September 2000.
3. Srikathyayani Srikanteswara, Jeffrey Reed, Peter Athanas, "Implementation of a Reconfigurable Soft Radio Using the Layered Radio Architecture", in the IEEE *Asilomar Conference on Signals, Systems, and Computers*, pp. 360-364, Pacific Grove, CA, October 2000.
4. David Lehn, Rhett Hudson, Peter Athanas, "A Framework for Architecture-Independent Run-Time Reconfigurable Applications," in *Proceedings of SPIE: Reconfigurable Technology: FPGAs for Computing and Applications II*, vol. 4212, pp. 162 – 173, November 2000.
5. J. Ballagh, Scott McMillan, Peter Athanas, "Defining a Run-Time Reconfigurable FPGA I/O Interfacing Methodology," at the *International Computing Conference: Engineering Reconfigurable Systems and Algorithms*, pp. 107-110, Las Vegas, NV, June 2001.
6. S. Srikanteswara, J. Neel, J. Reed, and P. Athanas, "Designing soft radios for high data rate systems and integrated global services," in *the Thirty-Fifth Asilomar Conference on Signals, Systems and Computers*, vol. 1, pp. 51 –55, October, 2001.
7. Srikathyayani Srikanteswara, James Neel, Jeffrey H. Reed and Peter Athanas, "Soft radio implementations for 3G and future high data rate systems", in *GLOBECOM 2001 - IEEE Global Telecommunications Conference*, no. 1, pp. 3370-3374, November 2001.
8. David Lehn, Kiran Puttegowda, Jae H. Park, Peter Athanas, and Mark Jones, "Evaluation of Rapid Context Switching on a CSRC Device," at the *International Computing Conference: Engineering Reconfigurable Systems and Algorithms*, pp. 209-216, Las Vegas, NV, June 2002.
9. James Neel, Srikathyayani Srikanteswara, Jeffrey H. Reed, and Peter M. Athanas, "A Comparative Study of the Suitability of a Custom Computing Machines and a VLIWDSP for Use in the Handheld Domain," at the IEEE Workshop on Signal Processing Systems (SIPS'04), October 13-15, 2004, Austin, Texas.
10. R. Fong and P. Athanas, "A Versatile Framework for FPGA Field Updates: An Application of Partial Self-Reconfiguation," at the 14th IEEE International Workshop on Rapid System Prototyping, San Diego, CA, June 2003.
11. Scott Harper and Peter Athanas, "A Security Policy for Hardware Encryption," at the 37th Hawaii International Conference on Computing Systems, Waikoloa, HI, January, 2004.

1.1.5.3 Patents, Software, Etc.

1. S. Harper, A. Abraham, P. Athanas, *Securing Programmable Logic Configuration Streams via Biometric Data*, disclosed to VTIP, currently under review. This property was developed as a result of an ONR sponsored project.
2. R.Fong, P. Athanas, *Commucations portals within FPGA fabric*, disclosed to VTIP, currently under review. This property was developed as a result of an ONR sponsored project.

3. J. Graf, P. Athanas, A Key Management Architecture for Securing Off-Chip Data Transfers on an FPGA, disclosed to VTIP, currently under review. This property was developed as a result of an ONR sponsored project.

1.1.5.4 Student Advising

Ph.D. Students Completed

1. Scott Harper, "A Secure Network Processor" May 2002.

M.S. Students Completed

1. Santiago Leon, "A Self-Reconfiguring Platform For Embedded Systems" July 2001.
2. Jonathan Scalera, "Image Chipping with a Common Architecture for Microsensors (CauS)" July 2001.
3. Kiran Puttegowa "Context Switching Strategies in a Run-Time Reconfigurable System" April 2002.
4. David Lehn, "Framework for a Context-Switching Run-Time Reconfigurable System" May 2002.
5. Arya Abraham, "It is I: An Authentication System for a Reconfigurable Radio" July 2002.
6. Jonathan Graf, "A Key Management Architecture for Securing Off-Chip Data Transfers on an FPGA" May 2004.
7. Ryan Fong, "Improving Field-Programmable Gata Array Scaling Through Wire Emulation" September 2004.
8. Aditya Cherbal, "Design and Implementation of an FPGA-based Partially Reconfigurable Network Controller" July 2004.
9. Christian Schnieder, "Authentication in a reconfigurable secure radio system on an FPGA, Mitarbeiter- und Diplomandenseminar Sommersemester" University of Darmstat / co-advisor (German exchange student).
10. Rüdiger Jordan, "Radio management using an embedded RISC processor" Diplomarbeit of Darmstadt University, University of Darmstat / co-advisor (German exchange student).

Students Supported

1. Santiago Leon, 2001
2. Jonathan Scalera, 2001
3. Kiran Puttegowa, 2001-2002
4. David Lehn, 2001-2002
5. Arya Abraham, 2000-2002
6. Scott Harper, 2000-2002
7. Jonathan Graf, 2003-2004
8. Ryan Fong, 2001-2002
9. Aditya Cherbal, 2002-2004
10. Christian Schnieder (Univ. of Darmstadt), 2000
11. Rüdiger Jordan (Univ. of Darmstadt), 2001
12. Deepak Agarwal (MSEE expected in 5/05)
13. Nikhil Bhatia (MSEE expected in 12/04)
14. Jason Zimmerman (MSEE expected in 5/05)

1.1.5.5 Faculty Supported

1. Peter Athanas
2. Mark Jones

1.1.5.6 Other Personnel Supported

Post-Doc

1. Jae Park (half-time, 2001-2002)

Visiting Scholar

1. Thomas Mitchell (visiting scholar from NSA – unfunded)

<u>Task 1.2</u> MIMO Software Radio - Jeffrey H. Reed, Brian D. Woerner and William H. Tranter

1.2.1 Review of Task Activities

The objective of Task 1.2 is to demonstrate the feasibility of smart antennas to improve wireless links in the inter-ship and ship-to-shore communications environment. Smart antennas have been shown to provide substantial gain and interference rejection capability over a single-antenna system. Specifically, the objective of the project includes:

1. Software radio approach for radio design
2. Smart antenna techniques for performance enhancement
3. Design of a testbed and algorithms for Space-Time (ST) processing
4. Developing smart antenna API for SCA 2.2 (Software Communications Architecture version 2.2) implementation for software defined radio (SDR) applications.

This task has been performed in several stages during the performance time frame of 1999-2004. The overall goal of this work is to develop smart antenna techniques that: (1) reduce power consumption (i.e., increase talk time), (2) reduce the probability of intercept and exploitation of a communications link, and (3) improve link reliability and range by reducing jamming and multipath distortion. This work will lead to new approaches to designing wireless systems that take advantage of spatial diversity at *both* the transmitter and receiver.

Our research program for Year One culminated in a measurement campaign that illustrated the astonishing gains achieved by employing smart antennas at the handset. The results show that two spatially separated antenna elements, separated by as little as one-fifth a wavelength, provide 3 to 10 dB of diversity gain (exceeded 99% of the time) in line-of-sight environments and 5 to 11 dB of diversity gain in non-line-of-sight environments. This implies that handheld smart antennas can reduce the fade margin or transmitter power by an amount equal to the diversity gain. Our results also show that polarization diversity and pattern diversity provide comparable diversity gains in non-line-of-sight paths. Furthermore, very small separations (e.g., around a fifth of a wavelength) are sufficient to provide large diversity gains. Based on the experience gathered in Year 1, Year 2 identified and focused on these key research components: wideband vector channel measurements, transmit diversity techniques, space-time (ST) processing and channel simulation with hidden markov modeling (HMM). This year saw the completion of a 4-channel wideband vector channel measurement and its use is outdoor channel measurements and the building of the VT-STAR (Virginia Tech Space-Time Adaptive Receiver), the first MIMO prototype testbed in this program. In Year 3, VT-STAR was completed and several indoor measurements were performed and data analyzed, several transmit diversity and ST algorithms were developed and analyzed, a number of HMM approaches were studied and tested, and new 3D propagation models were developed. Years 4 and 5 saw the development of the 2nd MIMO prototype known as START (ST Advanced Radio Testbed) based on the SDR-3000, a software radio testbed, which was chosen as the testbed for smart antenna demonstrations in the NAVCIITI program. Additionally, the use of smart antenna in a network of nodes (user terminals) and further development in the ST processing were also achieved during these years. One key research thrust that was initiated during the latter part of the program was to develop smart antenna API for SDR applications on platforms that use SCA (Software Communications Architecture) as the core framework. The importance of this task for Navy goes without saying since all the future tactical radios will follow JTRS (Joint Tactical Radio System) standard that has adopted SCA as the architecture for all the devices.

1.2.2 Facilities Developed for the Task

Task 1.2 during its tenure generated a number of key facilities that include state of the art DSP based hardware testbeds, software defined radio (SDR) based measurement and demonstration platforms, key transmit diversity and ST processing algorithms, the use of measured data in modeling and the performance improvement from using smart antenna in a wireless network scenario. The developed facilities are discussed in the following subsections.

1. Wideband vector channel measurement system (VIPER): This system provides a wideband 4-channel measurement system capable of providing 100 MHz bandwidth per channel. This is a very versatile measurement system that is based on SDR principles offering flexibility of choosing measurement parameters and smart antenna algorithms for processing the measured data. This system is discussed in details in [1-2].
2. VT-STAR testbed: This is a 2X2 narrowband MIMO system developed in the MPRG Lab that provides both measurement and demonstration capabilities. It is also based on SDR concept and employs ST block coding (STBC) to implement MIMO processing. This system is detailed in [2-3].
3. START: This system is based on SDR-3000, a software radio prototype from Spectrum Signal Processing. This has the capability of supporting MIMO processing. A detailed discussion of it can be found in [4].
4. Transmit diversity (TD) testbed: This system was built on two Rockwell Collins radios and the VIPER system. The radios were programmed to work as time and phase synchronized transmitter that used feedback from the VIPER receiver to demonstrated a closed-loop transmit diversity system in indoor channels [5].
5. HMM software: Software codes were developed to implement several HMM algorithms that could work on either simulated or measured channel data [2].
6. Transmit diversity and ST algorithms: Numerous algorithms were developed and studied for transmit diversity and ST applications [2, 6].
7. Smart antenna in wireless networks: Algorithms and techniques to support smart antenna operation in wireless networks based on IEEE standard were developed and studied [4, 7].
8. SCA enhancements in terms of developing open source code to implement systems on testbed and work towards defining a smart antenna API.

1.2.3 Accomplishments

Accomplishments have been achieved in a variety of research components within the broader scope of the smart antenna research using the NAVCIITI created facilities discussed in Section 1.2.2. A brief description of them is presented in the following subsections.

1.2.3.1 Wideband channel sounder and measurements

A wideband 4-channel vector channel measurement system, known as the VIPER system was developed to perform measurements to characterize propagation channels and enable study of smart antenna algorithms. Three distinct outdoor measurements along with numerous indoor measurements were performed with the VIPER. These include: rooftop (receiver) to a vehicle in motion (transmitter), urban-like low-mobility channels and air-to-ground measurements (transmitter on a small plane and the receiver on ground). A 3D channel model was developed and tested with the air-to-ground measurements. [2],[4].

1.2.3.2 VT-STAR and measurements

A 2X2 narrowband MIMO system, known as the VT-STAR testbed, was built on SDR principles and state-of-the-art DSP platform to demonstrate MIMO techniques and perform channel measurements in indoor propagation environments. The system provides real-time demonstration of the improvement from MIMO system over a conventional single antenna system and was demonstrated in the Virginia Tech Wireless Symposium in 2002. Indoor channel measurements were performed and analyzed. [2],[6].

1.2.3.3 TD testbed and real-time demonstration

A two-element TD system was developed to demonstrate in real-time the benefits of the system over a single antenna system. An FPGA based transmitter was designed that used two Rockwell Collins radios as the two transmit chains. One channel of the VIPER was used as the receiver. Phase scanning was used as the transmit diversity algorithm. The system was demonstrated in Virginia Tech Wireless Symposium in 2000. [5].

1.2.3.4 START and demonstration

SDR-3000 system, an SDR testbed from Spectrum Signal Processing, was chosen as the START testbed to support MIMO system development for high data-rate systems. The physical layer functionalities of several industry standards for WLAN systems, namely IEEE802.11b and IEEE802.11a, were implemented on the testbed. The baseband system was demonstrated to Gary Toth during his visit in 2002. The system is nearing its completion towards a smart antenna based modem that uses 802.11a physical layer and provides real-time operation in a practical indoor channel. [4],[6-7]

1.2.3.5 ST algorithms development

In the algorithm development efforts for ST processing, numerous algorithms were developed and analyzed for two distinct categories: Transmit Diversity and MIMO systems. For the TD category, algorithms for both flat fading and frequency selective channels were developed for handheld-like devices and analyzed in simulation. These algorithms were also tested for their implementation in the next-generation wideband cellular communication system (3G system). In the ST category, both ST block codes (STBC) and trellis codes (STTC) were studied. Different performance trade-offs along with system level issues were discussed. [2],[4],[6].

1.2.3.6 HMM algorithms

The performance of discrete channel models for W-CDMA channels has been analyzed. Reliable models were obtained that could replace the waveform level channel model satisfactorily. Waveform level channel usually contains distortion, fading, interferences and multipaths, and, simulation of these channels usually takes prohibitive amount of computational memory and simulation runtime. We tested four models that can replace the waveform level channel models with discrete channel models using hidden Markov models. Results were shown for W-CDMA channels using all these four algorithms. We compared the bit error probability and error-free interval distributions of these models with the original sequences and the results we found were quite promising [2],[6].

1.2.3.7 Smart antenna applications in wireless networks

The feasibility of using smart antenna algorithms in WLAN systems for range extension and interference mitigation was studied. This took into consideration the actual PHY/MAC layer description of the existing IEEE802.11 standards. The use of MIMO techniques provided significant range extension/throughput improvement. Additionally, effective interference mitigation was achieved with smart antenna techniques for multiple nodes/networks [4],[7].

1.2.3.8 Smart antenna API development

Through NAVCITTI support and a grant from Mercury Computer Corp., MPRG is working with the SDR Forum and the Object Management Group (OMG) on refining the current SCA standard which will eventually become the fundamental architecture for the JTRS radio system. Our first effort addressed the Antenna API already present in the previous SCA's Communication Equipment Package. Currently, we are developing a Smart Antenna API to be incorporated to the standard as well. We are looking at developing Smart Antenna API that can be as generic as possible to incorporate all of the available algorithms while staying at a high level of abstraction to avoid confining the evolution of communication standards and system hardware. [7].

1.2.4 Importance of the Task

The overall goal of this work is to develop smart antenna techniques that (1) reduce power consumption (i.e., increase talk time), (2) reduce the probability of intercept and exploitation of a communications link, and (3) improve link reliability and range by reducing jamming and multipath distortion. This work will lead to new approaches to designing wireless systems that take advantage of spatial diversity at both the transmitter and receiver. The VIPER testbed developed during the NAVCIITI program has been playing an important educational role, enabling students to develop and complete class projects on this testbed. The NAVCIITI project has been one of the major factors in the culmination of two courses at the Virginia Tech: DSP Implementation of Communication Systems and Software Radios: A Modern Approach to Radio Engineering. The work on SCA is also very pertinent to the Navy needs. The Software Communications Architecture (SCA) is an open architecture framework that outlines how elements of hardware and software are to operate in harmony within the JTRS. The goal of this specification is to ensure the portability and configurability of the software and hardware and to ensure interoperability of products developed using the SCA. Developing a smart antenna API and building algorithms on this platform will significantly reduce product development cycle and will ensure that the devices and the systems are interoperable across the diverse branches of the military communications systems.

Virginia Tech had a collaborative Navy/DARPA program in the area of smart antennas and software radios for sometime over the duration of the NAVCIITI program. The Navy point of contact was SPAWAR in Charleston, South Carolina. During that period, we visited this group to bring them up to date on the technology and to discuss future cooperative efforts. Virginia Tech has had a record of leveraging Navy support to attract commercial contributions to the technology. Corporate sponsors attracted by our ongoing smart antenna activity under NAVCIITI and Navy/DARPA efforts include HRL, Raytheon, ITT, LGIC, Metawave, and Texas Instruments. Contracts from these corporations total about $1.9 M. Thus, Navy funding functions as seed money for research attracting additional investment in the technology. Further, the software radio work sponsored under the NAVCIITI and Navy/DARPA efforts has created another set of potential commercial spin-off projects. Virginia Tech is negotiating with one company to commercialize the software radio intellectual property.

References:

1. William G. Newhall, "Radio Channel Measurements and Modeling for Smart Antenna Array Systems Using a Software Radio Receiver" April 2003.
2. Year 2 NAVCIITI Quarterly Reports.

3. R. Gozali, R. Mostafa, M. Robert, R. C. Pallat, W. G. Newhall, B D. Woerner and J. H. Reed, "Design Process of the VT-STAR MIMO Testbed," MPRG TR-01-12, Technical Report, MPRG Lab, August 2001.
4. Year 4 NAVCIITI Quarterly Reports.
5. R. Mostafa, K. Dietze, R. C. Pallat, W. L. Stutzman, and J. H. Reed, "Demonstration of Real-time Wideband Transmit Diversity at the handset in an Indoor Wireless Channel," VTC Fall 2001, pp. 2072-2076.
6. Year 3 NAVCIITI Quarterly Reports.
7. Year 5 NAVCIITI Quarterly Reports.

1.2.5 Productivity Summary

1.2.5.1 Journal and Magazine Publications

1. Raqibul Mostafa, A. Annamalai, and Jeffrey H. Reed, "Performance Evaluation of Cellular Mobile Radio Systems with Adaptive Interference Nulling of Dominant Interferers," *IEEE Transactions on Communications*, vol. 52, No. 2, pp. 326-335, February 2004.
2. Raqibul Mostafa, Uwe Ringel, Ashok A. Tikku, and Jeffrey H. Reed, "Practical Issues for Transmit Diversity Techniques at Small Wireless Terminals in a Flat Fading Channel" in the review process in *IEEE Transactions on Vehicular Technology.*
3. Raqibul Mostafa, Max Robert, and Jeffrey H. Reed, "Performance Evaluation and Integration of a Reduced Complexity MIMO Technique for IEEE 802.11b," submitted to *IEEE Transactions on Wireless Communications.*
4. Raqibul Mostafa, Fakhrul Alam, and Kyung Kyoon Bae, "3G- Around the world and back again," cover story in *RF Design*, pp. 52-66, February 2002.
5. R. Gozali, R.M. Buehrer, and B. D. Woerner, "The Impact of Multiuser Diversity on Space-Time Block Coding," *IEEE Communications Letters,* vol. 7, no. 5, pp. 1-3, May 2003.
6. R. Gozali, R. Mostafa, M. Robert, R. C. Pallat, W. G. Newhall, B D. Woerner and J. H. Reed, "Design Process of the VT-STAR MIMO Testbed," MPRG TR-01-12, Technical Report, MPRG Lab, August 2001.
7. R. Ziemer, W. H. Tranter, T. S. Rappaport, R. M. Buehrer, "Mobile Radio Communications," in *Encyclopedia of Telecommunications*, Wiley 2002.
8. T. S. Rappaport, A. Annamalai, R. M. Buehrer, W.H. Tranter, "Wireless Communications: Past Events and a Future Perspective," *IEEE Communications Magazine*, 50th Anniversary Issue, pp. 148-161, May 2002.

1.2.5.2 Conference Presentations

1. R. Gozali, R.M. Buehrer and B.D. Woerner, "On the performance of scheduling over space-time architectures," IEEE Vehicular Technology Conference - VTC Fall '02, Vancouver, Canada, 2002.
2. R. Gozali, R. Mostafa, R.C. Palat, S. Marikar, P.M. Robert, W.G. Newhall, C. Beaudette, S.A. Tsiakkouris, B.D. Woerner and J.H. Reed, "Virginia Tech Space-Time Advanced Radio (VT-STAR)," RAWCON 2001, pp. 227-231.
3. R. Gozali, R. Mostafa, R. C. Palat, P.M. Robert, W.G. Newhall, B.D. Woerner and J.H. Reed, "MIMO Channel Capacity Measurements Using the VT-STAR Architecture", IEEE Vehicular Technology Conference VTC' Fall '02, Vancouver, Canada, pp. 884-888.
4. R. Gozali, R.M. Buehrer and B.D. Woerner, "The impact of multiuser diversity on space-time block coding," IEEE Vehicular Technology Conference - VTC Fall '02, Vancouver, Canada.

5. R. Gozali and B. D. Woerner, "The Impact of Channel Estimation Errors on Space-Time Trellis Codes Paired with Iterative Equalization/Decoding", IEEE VTC Proceedings, Spring 2002, Birmingham Alabama.
6. R. Gozali and B. D. Woerner, "On the Robustness of Space-Time Block Codes to Spatial Correlation", IEEE VTC Proceedings, Spring 2002, Birmingham Alabama.
7. R. Gozali and B. D. Woerner "Performance Analysis of Space-Time Trellis Codes in Correlated Rayleigh Fading Channels", 3G Wireless '02, San Francisco, CA.
8. R. Gozali and B. D. Woerner, "Theoretic Bounds of Orthogonal Design Transmit Diversity," *IEEE International Symposium on Information Theory – ISIT 2002,* Lusanne, Switzerland, p. 304, June 30-July 5, 2002.
9. R. Gozali, S. Bayram, J. A. Tsai, B. D. Woerner, and J. H. Reed, "Interpolation Based Data-Aided Timing Recovery for Multi-User CDMA Receivers," *Wireless 2001,* Calgary, Alberta, Canada, pp. 544-548, July 9-11, 2001.
10. R. Gozali and B. D. Woerner, "Upper Bounds on the Bit-Error Probability of Space-Time Trellis Codes Using Generating Function Techniques," *VTC Spring 2001,* Rhodes, Greece, pp. 1318-1323, May 6-9, 2001.
11. Ran Gozali and Brian Woerner, "Applying the Calderbank-Mazo Algorithm to Space-Time Trellis Coding," *IEEE SoutheastCon 2000,* Nashville, Tennessee, pp. 309-314, April 7-9, 2000.
12. R. Mostafa, K. Dietze, R. C. Pallat, W. L. Stutzman, and J. H. Reed, "Demonstration of Real-time Wideband Transmit Diversity at the handset in an Indoor Wireless Channel," VTC Fall 2001, pp. 2072-2076.
13. R. Mostafa, A. Hannan, J. H. Reed, "Narrowband Transmit Diversity Measurements at the Handset for an Indoor Environment," 3rd International Conference on Information, Communications, and Signal Processing, Singapore, October 2001.
14. Raqibul Mostafa, Kai Dietze, Richard B. Ertel, Carl Dietrich, Jeffrey H. Reed, and Warren L. Stutzman, "Wideband Characterization of Wireless Channels for Smart Antenna Applications," RAWCON 2003, pp. 103-106.
15. Raqibul Mostafa, Max Robert, and Jeffrey H. Reed, "Reduced Complexity MIMO Processing for WLAN (IEEE 802.11b) Applications," RAWCON 2003, pp. 171-174.
16. W. G. Newhall, R. Mostafa, K. Dietze, J. H. Reed and W. L. Stutzman, "Measurement of Multipath Signal Component Amplitude Correlation Coefficients Versus Propagation Delay," 2002 IEEE Radio and Wireless Conference (RAWCON2002), 133-136.
17. W. G. Newhall, R. Mostafa, C. Dietrich, C. R. anderson, K. Dietze, G. Joshi and J. H. Reed, " Wideband Air-to-Ground Radio Channel Measurements Using an Antenna Array at 2 GHz for Low-Altitude Operations", published in MILCOM 2003.
18. William G. Newhall, Jeffrey H. Reed, "A Geometric Air-to-Ground Radio Channel Model" MILCOM 2002.
19. William G. Newhall, Jeffrey H. Reed, "A Geometrically based Radio Channel Model for Air-to-Ground Communications," presented to Virginia Space Grant Consortium, March, 2002.
20. M. Robert and Jeffrey H. Reed, "Software Design Issues in Networks with Software-Defined-Radio Nodes" presented at the WETICE 2001, pp. 55-59.
21. W. L. Stutzman, J. H. Reed, C. B. Dietrich, B. Kim and D. Sweeney, "Recent Results from Smart Antenna Experiments—Base Stations and Handsets," RAWCON 2000, Denver, CO, pp. 139-142, September 2000.
22. S. Al-Ghadhban and B. D. Woerner, "Iterative Joint Interference Nulling/Cancellation Decoding Algorithms for Multi-Group Space Time Trellis Coded Systems," *IEEE Wireless Communications and Networking Conference (WCNC)*, Atlanta, March 2004.

23. M. Mohammad, S. Al-Ghadhban, B. Woerner, and W. Tranter, "Comparing Decoding Algorithms for Multi-Layered Space-Time Block Codes," *IEEE SoutheastCon 2004*, Greensboro, NC, March 26-28, 2004.
24. S. Srikanteswara, J. A. Neel, J. H. Reed and S. Sayed, "Resource Allocation in Software Radios using CCM based on the SCA,", SDR Forum Workshop, CA, Nov 2002.
25. S. Srikanteswara, J. H. Reed and P. M. Athanas, "Implementation of a Reconfigurable Soft Radio using the Layered Radio Architecture," IEEE 34th Asilomar Conference on Signals, Systems and Computers, Monterey, CA, pp. 360-364, October 29 -November 1, 2000.

1.2.5.3 Books and Book Chapters

1. J.H. Reed, "Software Radio A Modern Approach to Radio Engineering," Prentice Hall, 2002.
2. J. H. Reed, working on *DSP Implementations Lab Book*, for the DSP Implementation Course at Virginia Tech.
3. *Wireless Personal Communications: Channel Modeling and Systems Engineering*, edited by William H. Tranter, Brian D. Woerner, Theodore S. Rappaport, and Jeffrey H. Reed, Kluwer Academic Publisher, 1999. ISBN 0-7923-7705-2.
4. *Wireless Personal Communications: Emerging Technologies for Enhanced Communications*, edited by William H. Tranter, Theodore S. Rappaport, Brian D. Woerner, and Jeffrey H. Reed, Kluwer Academic Publishers, 1999. ISBN 0-7923-8359-1.
5. Tranter, W. H., Shanmugan, K. S., Rappaport, T. S., and Kosbar, K. L., *Principles of Communication Systems with Wireless Applications*, Upper Saddle River, NJ: Prentice Hall, 2003.
6. R. E. Ziemer, W. H. Tranter, D. R. Fannin, *Principles of Communication: Systems, Modulation and Noise,* Fifth Edition, Prentice Hall, 2002.

1.2.5.4 Patents, Software, etc.

1. VIPER software: C++ based data acquisition and receiver operation software for 4-element antenna array system.
2. OSSIE (Open Source SCA Implementation::Embedded) program.

1.2.5.5 Professional Activities

1. J. H. Reed, "Key Challenges in the design of a software radio," presented at the IDGA workshop on Software Radio, Alexandria VA, February, 2004.
2. J. H. Reed, "Software Radio: The Key for Enabling 4G Wireless Networks," International Forum on 4G Mobile Communications, Centre for Telecommunications Research, King's College London, London, UK, May 27-28, 2003.
3. J. H. Reed chaired a session titled "Mobile Computing and Software Defined Radios," International Conference on Engineering of Reconfigurable Systems and Algorithms, Las Vegas, June, 2003.
4. J. H. Reed, Keynote speaker at the Marine Corps SIGINT Stakeholders conference at the Naval Postgraduate School, Monterey, CA, August 2003.
5. J. H. Reed, S. Srikanteswara, J. A. Neel, "Design Choices for Software Radios," presented at the SDR Forum Workshop, CA, November, 2002.
6. J. H. Reed is serving as a co-technical chair for SDR Forum.
7. J. H. Reed attended as an invited speaker to discuss results of our research to FutureWei and Texas Instruments at Dallas.

8. B. D. Woerner, "Space-time Processing for Organic Wireless Networks," presented at University of Texas, Austin, TX, December 20, 2002.
9. B. D. Woerner, "Space-time Processing for Organic Wireless Networks," presented at West Virginia University, Morgantown, WV, November 11, 2002.
10. B. D. Woerner, Panel Moderator, FCC Workshop on Interference Protection, Washington, D.C., August 2, 2002.
11. B. D. Woerner, Panelist, "Future of Wireless Communications," Panel Session at Midwest Symposium on Circuits and Systems, July 2002.
12. Robert Boyle, Ran Gozali, Raqibul Mostafa and Fakhrul Alam, "A tutorial on Space-time processing for 3G systems" The Wireless Symposium at Virginia Tech, June 2001.
13. VT-STAR was demonstrated during the Wireless Symposium at Virginia Tech in June 2001.
14. B. D. Woerner presented a briefing on ST coding and MIMO channels to ITT, Fort Wayne, Indiana, April 1st, 2002.
15. B. D. Woerner "Software Radios," presented at Monterrey Technical University, Monterrey, Mexico, February 4, 2000.
16. B. D. Woerner, "Software Radio Technology," short course presented to Honeywell, Inc., Minneapolis, Minnesota, May 1999.
17. B. D. Woerner, "The Theory and Practice of Error Correction Coding," short course presented to Lucent Technologies, New Jersey, April 1999.
18. B. D. Woerner, "Siting of Antennas for Wireless Communication Systems, Brian D. Woerner, presented to Salem, Virginia Town Meeting, April 21, 1999.
19. B. D. Woerner, "Multiuser Detection for Peer-to-Peer Packet Radio Environments," Brian D. Woerner, presented to ONR Principle Investigator's Meeting, San Diego, CA, January 6, 1999.
20. B. D. Woerner, "Performance of Turbo Codes in Fading Channels," Brian D. Woerner, presented to NRL Joint Workshop on Turbo Codes and Iterative Decoding, Washington, D.C., December 3, 1998.
21. William H. Tranter, Vice President – Technical Activities, IEEE Communications Society, 2002 – Present.
22. William H. Tranter, Senior Editor, *IEEE Journal on Selected Areas in Communications*, 2002 – Present.
23. William H. Tranter, Director of Education – IEEE Communications Society, 2004-2005.
24. William H. Tranter, Member, Steering Committee for the *IEEE Transactions on Wireless Communications*, 2004-2005.

1.2.5.6 Honors and Recognitions

1. J. H. Reed received the College of Engineering Award for Excellence in Research, April 2001.
2. J. H. Reed, nominated to the Technology Advisory Board for TechContinuum, a Wireless Internet Incubator.
3. J. H. Reed, promoted to Full Professor, 2001.
4. B. D. Woerner, Dean's list for outstanding student teaching evaluations (top 25%): 1998- 2003.
5. B. D. Woerner, Dean's 1999 Award for Teaching Excellence: Recipient of one of three awards (out of approximately 280 faculty), for excellence in teaching innovation.
6. B. D. Woerner, 2004 College Certificate of Teaching Excellence: Recipient of one of four awards (out of approximately 280 faculty), for excellence in classroom teaching.
7. William H. Tranter, IEEE Third Millennium Medal – 2000.

8. William H. Tranter, Dean's Award for Excellence in Service, Virginia Tech – 2000.
9. William H. Tranter, IEEE Communications Society Publications Exemplary Service Award – 2001.
10. William H. Tranter, Elected Vice President – Technical Activities, IEEE Communications Society – 2002.

1.2.5.7 Student Advising (students supported, completed, and in progress)

Ph.D. Students Completed

1. Raqibul Mostafa, "Feasibility of Smart Antennas for Small Wireless Terminals" April 2003 (Advisor: Jeffrey H. Reed).
2. Ran Gozali, "Space-Time Codes for High Data Rate Wireless Communications" April 2002 (Advisor: Brian D. Woerner).
3. William G. Newhall, "Radio Channel Measurements and Modeling for Smart Antenna Array Systems Using a Software Radio Receiver" April 2003 (Advisor: Jeffrey H. Reed).
4. Song Hun Kim, "Distributed Reconfigurable Simulation for Communication Systems," Ph.D., 2002 (Advisor: William H. Tranter).

M.S. Students Completed

1. Ihsan Akbar, "Markov Modeling of Third Generation Wireless Channels", May 2003 (Advisor: William H. Tranter).
2. Anil Hebbar, "TBD", August 2004 (tentative).
3. Ramesh C. Palat, "VT-STAR design and implementation of a test bed for differential space-time block coding and MIMO channel measurements," October 2002 (Advisor: Jeffrey H. Reed).

Students Supported

1. A. Hannan
2. R. Chembil Palat
3. R. Gozali
4. R. Mostafa
5. S. Kim
6. G. Joshi
7. I. Akbar
8. H. Kim
9. A. Hebbar
10. M. Mohammad
11. Carlos Aguayo
12. John Mandeville
13. Rashimi Kumar

1.2.5.8 Faculty Supported

A. Darwish, Visiting Faculty, 1998

S. Srikanteswara, Research Faculty, 2002-2003

R. Mostafa, Research Faculty, 2003-2004

Task 1.3 Advanced Antennas - William Davis and Warren Stutzman

1.3.1 Review of Task Activities

1.3.1.1 Objective

The multifunctional antenna task investigates technologies that support the Navy's future needs in multifunctional communication systems. The emphasis is on antennas that have wide bandwidth, are low profile, and support smart functions. In addition, concepts for advanced array analysis have also been addressed, primarily as part of the smart functions. This task has extended during the full period of the contract, 1999-2004

1.3.1.2 Specific Tasks

The following summarizes the work performed for the specific antenna tasks, including wideband elements, extended bandwidth elements, and adaptive elements.

Sub-Task 1.3.1.2.1 Construction of Test Facility

NAVCIITI and University funding were used to created a unique and major antenna testing facility at Virginia Tech. An indoor anechoic chamber (30 x 11 x 11 feet) contains a combination near-field/far-field measurement system complete with all hardware and software.

The spherical near field scanner and network analyzer equipment are used for a variety of measurements, including measurements on the antennas to be discussed in the following tasks. Major effort in this task has been to verify the performance of the near-field range using known antennas as well as standard gain horns.

Sub-Task 1.3.1.2.2 Wideband Element Antenna Design

A new class of wideband antennas was invented in VTAG (Virginia Tech Antenna Group) just prior to the NAVCIITI program. The foursquare and fourpoint antennas are low profile, dual-polarized antennas capable of over 2:1 bandwidth. With small cross sections, they are ideal wide scan angle phased arrays.

We found by numerical simulation and measurement that adding a tuning plate on the bottom of the Foursquare and Fourpoint antennas increases the antenna bandwidth, extending the operating band at high frequencies. Several models were investigated to evaluate the tuning plate effect on the Foursquare and the Fourpoint antennas. The calculated results demonstrate that the tuning plate enhances the antenna performance significantly without increasing the antenna size.

Several new antenna structures have been presented, based on the premise of the Foursquare antenna element of the previous years. Substantial progress was made in the analysis by the use of a FDTD code for electromagnetic antenna analysis. The principle for the development of the new antenna structures might be thought of as morphing, where the original structure is altered or adapted to meet physical or electrical constraints including array periodicity needs. The periodicity takes on the form of fractal like antennas. The advantages of these concepts are the ability to adapt antennas to new environmental applications. The consideration of the new elements, and the completion of the parametric studies of the elements developed in previous years were the focus to provide new alternatives to the Navy.

Other new antennas were developed that offer bandwidths up to 10:1 in relative frequency. The initial design was mounted over a ground plane and was a planar structure that simulated an imaged, two-way

Vivaldi antenna near the feed point with a loading that simulates a monopole at the lower frequencies. The resultant impedance performance was found to be extremely good, covering 10:1 bandwidth. The radiation patterns were also found to be reasonable, though there was variation about the antenna structure due to the planar nature of the antenna.

Fourpoint Antenna

We investigated the tuning plate effect on the Fourpoint antenna with a test model, which was designed for operation between 5.5-13 GHz. The Fourpoint antenna geometry was enhanced with a star-shaped tuning plate in the feed region. Impedance demonstrated that the tuning plate tunes the resistive and reactive component dramatically at the mid and high end of the operating band.

Foursquare Antenna

Since the tuning plate performed so well with the Fourpoint antenna, we examined its use with the Foursquare antenna. The Foursquare antenna with a circular tuning plate was simulated. In order to demonstrate the effect of the tuning plate, we also simulated the Foursquare antenna without a tuning plate and the same outer dimensions. The Foursquare antenna performance is found to be enhanced by employing a tuning plate as found with the Fourpoint antenna. The circular tuning plate in the Foursquare antenna increased the bandwidth of the Foursquare antenna from 35 % to 60 % for $VSWR \leq 2$.

PICA Antenna

Many CPW planar wideband dipole antennas were investigated for compact antennas suitable for embedding in portable devices in a variety of military and commercial applications. Of particular interest is Ultra Wideband (UWB) Communications. The antennas were measured in the Virginia Tech Antenna Group (VTAG) laboratories in both the time and frequency domains. A typical wideband performance is demonstrated by the transient response shown in Fig. 1.3-1. The return loss, patterns, and gains of the antennas were measurement in the constructed test facility for a variety of developed antennas. The antennas were also simulated using a variety of software available in our facilities and complimented by some software developed for specific antenna analysis, specifically the FDTD code developed for analysis of the Four-Square element. The pulse width of the PICA antenna response shown is about 1 nano-second, which is the typically required pulse duration for UWB applications.

Radiation patterns were computed using the commercial FDTD code Fidelity by Zeland Co and presented in the quarterly reports. The patterns are omni-directional and are similar to those of a thin-wire, half-wavelength dipole antenna at all frequencies.

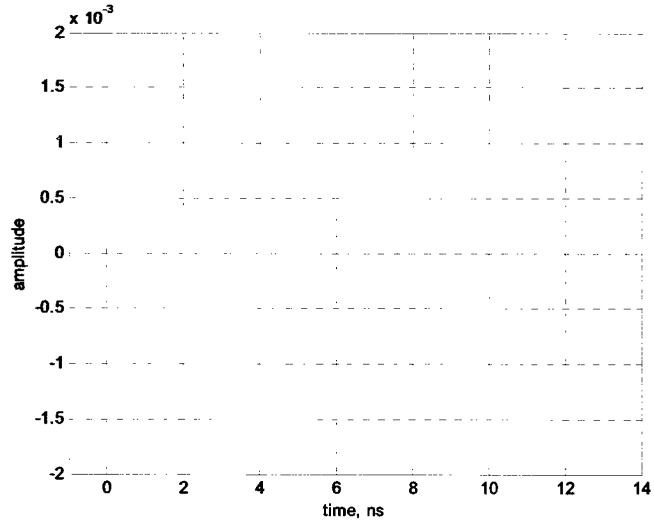

Figure 1.3-1 Measured impulse response of the CPW PICA antenna.

UWB Concepts

Recently, much interest for Ultra wideband (UWB) technology has arisen. As well as high data rates, UWB technology has two key advantages over the conventional narrow band communication technologies: lower cost architecture and no need for an intermediate frequency stage. Low cost CMOS technologies may be applied to future UWB receivers. Thus, UWB systems can have a nearly all-digital structure. There is also a projected immunity to multipath and interference. Because mulipath pulses appear with time delays, they can be gated out. UWB technology has a very wide spectrum with low energy density, making it difficult to intercept and exhibiting excellent immunity to interference from other wireless communication system.

Antennas in the frequency domain are typically characterized by radiation pattern, directivity, efficiency, gain, and bandwidth with clear standard definitions related to antenna performance. However, time-domain antenna characterization is a different story. The critical performance factors are phase dispersion, peak pulse amplitude (efficiency), pulse width (data rate), and omni-directional impulse response. We investigated UWB antennas with those critical performance factors in mind.

Starting with the spheroid antenna, we created disc and half disk antennas with consideration of voltage standing wave ratio (VSWR), phase linearity between two identical antennas, and the impulse response versus azimuth and elevation. In addition, we also examined the pulse duration, the omni-directional radiation characteristic in the time domain, and the potential occurrence of a chirp or ringing response. Our goal was to obtain practical UWB antennas with a very small size, a planar structure, and a low fabrication cost with simplicity for mass production. As such, we consider antennas mounted in the same plane as the finite ground plane.

Sub-Task 1.3.1.2.3 New Approaches to Wideband Arrays

The antennas of the previous tasks are to be considered in an innovative approach to develop a multi-band phased arrays in a single planar aperture. We investigated a new type of antenna array consisting of sub-elements that are excited together to form the primary element. All of the sub-elements of the array are excited for the highest operating band. Only the primary elements are excited for the low frequency band. This fractal geometry has the potential for wideband operation. The advantage of this array is that the effective element spacing changes with the frequency band to maintain the required small electrical spacing over the operating band. Initial simulations of this dual-band Foursquare have shown that it performs well and that the subdividing of each square does not degrade the low frequency behavior. The Foursquare is ideal for the fractal geometry since it consists of expanding squares in concept, forming a photonic-style surface. The basic bandwidth properties were considered in the previous tasks.

The performance of large array antenna systems is typically considered to be limited by the effect of mutual coupling between the elements that vary with frequency and scan direction. The coupling effects are often stronger for wideband array antennas. The performance characteristics of a large array are usually predicted using a combination of infinite array antenna analysis techniques such as waveguide simulation and Floquet series boundary cell analysis, along with active element pattern analysis and network analysis. A waveguide simulator can be implemented with either experimental or numerical simulations. However, waveguide simulator techniques are applicable only for certain geometries, frequencies and scan angles. A Floquet series analysis is more general than waveguide simulator technique. It can be applied to an infinite linear or an infinite planar array of any uniform geometry. Unfortunately, the Floquet expansion method can only be implemented as a numerical simulation. There is no equivalent experimental method to verify the numerical analysis.

Sometimes, an antenna element in an array environment is evaluated using the active-element input impedance. The active-element input impedance of an element is determined by terminating all but the single fed element with a reference impedance. The reference impedance generally should be the equivalent source impedance for the array. Typically, 50 ohms is used for the reference impedance. The active input impedance is not a good indicator of the antenna element performance in the fully active array since the induced currents from neighboring elements modify the input impedance in a fully active array.

The fully active input impedance is the input impedance of an element in an array when all elements are excited. It is a function of array geometry and array excitation. In the case of an infinite array, all elements are excited uniformly in amplitude with a phase progression among the elements to produce the desired beam scanning. It has been shown that approximately a 9x9 or larger array fully active input impedances behave similar to a corresponding infinite array [4]. Unfortunately, it is difficult to numerically simulate or experimentally evaluate 9x9 arrays.

We have developed a novel technique to estimate fully active input impedance of infinite array antennas. The technique is based on an eigenvalue analysis of the coupling matrix. In this technique, the antenna characteristics of infinite array are predicted from the coupling matrix of a small subsection of the infinite array using eigenvalue analysis techniques. The eigenvalue analysis can be applied to both simulated data and measured data.

Sub-Task 1.3.1.2.4 Reconfigurable Elements/Multi-use Apertures

Reconfigurable array geometries can be used for the construction of multiuse antenna apertures. A fixed antenna aperture area may be used for multiple tasks via reconfigurable aperture elements. Array morphing may be accomplished via element reconfiguration. Individual elements can be reconfigured to optimize performance at the current frequency of interest. These elements can be reconfigured in-situ and in real time based on the frequency of operation while the array pattern can be reconfigured according to the needs of the coverage area. The focus for the multiuse aperture reconfiguration task is the element and array morphing techniques. Several techniques have been investigated as possible element morphing solutions and ultimately multiuse aperture implementations.

Active Bandwidth Control

The concept of *active bandwidth control* has been introduced to address the requirement of using a single aperture to service multiple signals of interest and in multiple signal environments. A linear array of sub-elements connected together via switches has been used to demonstrate bandwidth control. Active bandwidth control utilizes reconfigurable antenna elements to selectively change the desired frequency of operation and the level of antenna bandwidth. The active bandwidth control concept addresses one of the fundamental problems of typical reconfigurable antenna designs. The frequency selective and adaptive behavior of conventional reconfigurable antenna designs often comes with the cost of losing control over the other key electrical characteristics of the antenna. Adequate control over pattern, gain and polarization performance is often sacrificed in order to achieve frequency agility. The active antenna bandwidth control presented here aims to maintain consistent electrical behavior over the other major antenna performance characteristics. Intelligently selecting the reconfigurable basis element and employing an understanding of the structure's radiating properties accomplish the bandwidth control and predictable electrical behavior. Several reconfigurable antennas were considered, including a variable bandwidth dipole, tuned patch, and adjustable PIFA antennas. These designs were developed to demonstrate the concept of active bandwidth control.

Reconfigurable Geometries

From a systems standpoint, antennas have historically been viewed as static devices with time-constant characteristics. Once an antenna design is finalized, its operational characteristics remain unchanged during system use. However, the recent advent of micro-electromechanical system (MEMS) components into microwave and millimeter wave applications has opened new and novel avenues of antenna technology development. High quality, miniature RF switches provide the antenna designer with a new tool for creating dynamic radiating structures that can be reconfigured during operation. MEMS switches are of particular interest because they offer broadband operation, low insertion loss and high contrast between active states. In the near future, the antenna will evolve as a component that will offer intelligence that alters itself in-situ to meet operational goals. This development is similar to the introduction of viable field programmable gate arrays for integrated circuit logic in the late 1980s.

While the method of antenna operation is evolving, its role in communication systems still remains the same. The task that an antenna must perform is fundamentally that of a radiator and thus the metrics by which antennas operate and are measured are still intact. Gain, bandwidth, polarization, antenna feature size, etc. are still the realizable quantities of interest. Only now the introduction of dynamic radiating structures has given the antenna designer an additional degree of freedom to meet these design goals.

Reconfigurable Antenna Methodologies

Classical non-reconfigurable design methods have dominated antenna engineering for the majority of antenna design history. To make the transformation from fixed element operation to reconfigurable antenna design requires a suitable conversion in design methodology. The short existence of reconfigurable has produced two primary design methods: total geometry morphing and matching network morphing. A third method is also identified and expanded -- smart geometry reconfiguration. Thus, three broad methodologies have been identified for achieving reconfigurable antenna designs and operation.

Total geometry morphing represents the most structurally complicated of the methods. It is implemented though a large array of switchable sub-elements which are combined to form the desired radiating structure. Matching network morphing is the simplest of the methods and modifies only the feed structure or impedance matching network of the antenna while the radiating structure remains constant. The smart geometry reconfiguration method lies between the other two in its structural implementation complexity.

It modifies only critical parameters of the antenna radiating structure to achieve the desired range of reconfigurable control.

The focus for the multiuse aperture reconfiguration task is the element and array morphing techniques. Several techniques have been investigated as possible element morphing solutions and ultimately multiuse aperture implementations. The concept of *active bandwidth control* was been introduced to address the requirement of using a single aperture to service multiple signals of interest and in multiple signal environments. Active bandwidth control utilizes reconfigurable antenna elements to selectively change the desired frequency of operation and the level of antenna bandwidth. The active bandwidth control concept addresses one of the fundamental problems of typical reconfigurable antenna designs. The frequency selective and adaptive behavior of conventional reconfigurable antenna designs often comes with the cost of losing control over the other key electrical characteristics of the antenna. Adequate control over pattern, gain and polarization performance is often sacrificed in order to achieve frequency agility. The active antenna bandwidth control presented here aims to maintain consistent electrical behavior over the other major antenna performance characteristics. Intelligently selecting the reconfigurable basis element and employing an understanding of the structure's radiating properties accomplish the bandwidth control and predictable electrical behavior.

Sub-Task 1.3.1.3 Implementation of the Wireless Network - WINN

Single Fourpoint antennas were constructed and used in the WINN demonstrations. The experimental aspects of a related project will be used to provide some of the fundamental offshoots to implement a planar adaptive array for the WINN project. The adaptive nature will be incorporated to provide beam forming from a planar aperture using the array concepts above as well as provide the possibility of a multi-use aperture. The latter would conceivably include ESM, ECM, radar, and communications applications. The initial development will be in support of a adaptive single-use array to create a demonstration test-bed for the WINN network in cooperation with the other communication-link tasks.

We currently have developed adaptive array techniques that use DSP technology to beam-form on selected sites. We will be changing these concepts to work in the harsher military environment in conjunction with the array design processes of Task 1.3.1.2.3.

1.3.2 Facilities Developed for Task

The spherical near field scanner and network analyzer equipment was installed and has been used for a variety of measurements, including measurements on the antennas to be discussed in the following tasks. Major efforts in this task have been to verify the performance of the near-field range using known antennas as well as standard gain horns. The range provides unique capabilities with the inclusion of both far-field and near-field measurement capabilities. The far-field capabilities were obtained by the construction of the tapered chamber, with a far-field source mounted in the throat of the chamber. The near-field capabilities are enabled with a near-field scanning system with planar, cylindrical, and spherical modes of operation. For most applications, the spherical near-field mode has found the most use.

The system also provides the capability of doing both impedance measurements and equivalent transient measurements. The transient based data is critical for the development of ultra-wideband antennas and prediction of the performance enhancements that may be obtained by various geometrical design features. The system has also been used to do preliminary studies of the scattering performance of objects in an indoor channel environment. The ability to predict the performance of specific objects and shapes is expected to lead to improved propagation channel design for indoor environments. Such studies only scratch the surface of the needs of shipboard communications.

A finite-difference-time-domain (FDTD) code was developed for the analysis of the four-square antenna. This code was used to assist in the explanation of the performance and operational understanding of the specific antenna. Since the development of this code, commercial codes have been released that provide similar or improved capabilities and verify the results obtained.

1.3.3 Accomplishments

1.3.3.1 Accomplishments

The efforts focused on the creation of an anechoic chamber measurement system to support antenna measurements for the task, development of enhanced bandwidth and ultra-wideband (UWB) antenna elements, creation of analysis and design techniques for large array systems (allowing improved performance prediction, design, and adaptation), and work on adaptive elements. The adjustable bandwidth of adaptive elements is useful in minimizing potential interference with pre-filtering at the antenna. Measurement processes for multipath prediction and diversity has also been a major consideration in the work of the group. The new antenna designs find direct application to future Navy needs for broadband applications. Future work is planned in the areas of arrays and UWB antennas.

1.3.3.2 NAVCIITI Contribution

In the area of advanced antennas, contributions include results in each of the following areas:

- New antenna array analysis and design techniques
- New wideband and UWB antenna designs to support future military communications
- Development of adaptive elements for bandwidth and frequency control
- Support of the wireless network demonstration with wideband antennas and support of receiver/transmitter design
- Support of the Digital Ship task for physically based models

Note: This task is closely coordinated with the smart antenna task and WINN. The tasks continue the progress toward the Navy's future needs in multifunctional communication antenna systems. The emphasis is on antennas that have wide bandwidth, are low profile, and support smart functions.

1.3.3.3 The Wireless Integrated Navy Network – WINN

The NAVCIITI program in the wireless communications area focused on the ingredients for building and implementing a wireless network that will meet the Navy's future needs. They consist of the following components:

- Secure Reconfigurable Communications Hardware
- Network Protocol Interoperability
- Secure and Efficient Adaptive Real-time Resource Management
- Wideband Antennas
- Smart Antennas

The network and security issues are addressed as well as the radio frequency (RF) challenges. These permit a mobile, secure, wideband wireless network. Year 4 lead to a coordinated demonstration of these technologies in the realization of WINN that will serve as a demonstration facility to investigate technologies developed in NAVCIITI, of which the Multifunctional Antennas tasking plays a major role. We will continue to support the WINN effort as needs arise from the team members. Additional support within the NAVCIITI team has been to provide assistance in developing physically based models for the communications scenarios used in the digital ship project.

1.3.4 Importance of the Task

1.3.4.1 The NACIITI Connection

This task provides adaptive and broadband antenna designs for future use in advanced Navy applications. In addition, antenna hardware and radio engineering support for the Wireless Integrated NAVCIITI Network (WINN) test bed is provided. The test bed is a focus of the efforts for all of the current 1.x tasks. Lastly, physical modeling support for antennas and radar systems is provided to the Digital Ship task.

1.3.4.2 Value to the Navy

New antenna element designs and array antenna concepts for wideband applications will permit integration of several shipboard functions, including: communications over several radio bands, radar and imaging, electronic warfare. The design of adaptive antenna elements providing bandwidth and frequency adjustment offer an ability to tune an antenna to a specific need within a range of applications. The current effort is centered on adaptive elements.

1.3.4.3 Teaming arrangements

VTAG has worked with DARPA in the area of wideband antenna designs for government applications. This direct interaction with DARPA has focused on Ultra-WideBand (UWB) antennas. VTAG has also been affiliated in designs for jammer mitigation of GPS receiver systems through diversity approaches based on the Foursquare antenna effort. Considerable leveraging of effort has resulted from both the previous commercial teaming and the efforts with DARPA. VTAG also teamed with MPRG on the design of adaptive beamforming antennas for the Raytheon ACN and FCS programs.

1.3.4.4 New Techniques

Measurement capability to support rest, new antenna designs for broadband performance and ultra-wideband applications, concepts of large array design and implementation, element morphing and prediction capabilities provide important design strategies in the development and deployment of new antenna and array systems in the Navy.

1.3.5 Productivity Summary

1.3.5.1 Journal and Magazine Publications

1. W.L. Stutzman and C. Buxton, "Radiating Elements for Wideband Phased Array," *Microwave Journal*, vol. 43 pp. 130-141 Feb. 2000.
2. Carl B. Dietrich, Jr., Warren L. Stutzman, Byung-Ki Kim, and Kai Dietze, "Smart Antennas in Wireless Communications: Base-Station Diversity and Handset Beamforming," *Antennas and Propagation Magazine*, vol. 42, No. 5, pp. 142-151, October 2000.
3. Carey G. Buxton, Warren L. Stutzman, Randall R. Nealy and Aaron M. Orndorff, "The Folded Dipole: A Self-Balancing Antenna," *Microwave and Optical Technology Letters*, vol. 29, No. 3, pp. 155-160, May 5, 2001.
4. C.B. Dietrich Jr., R.M. Barts, W.L. Stutzman and W.A. Davis, "Trends in Antennas for Wireless Communications", *Microwave Journal*, January 2003.
5. A. Petris, I. Zafar, and S. Licul, "Reviewing SDARS Antenna Requirements," *Microwave and RF*, Vol. 42, pp. 51-62, Sept. 2003.
6. Joseph A.N. Noronha, Timothy Bielawa, Christopher R. Anderson, Dennis G. Sweeney, Stanislav Licul, William A. Davis, "Designing Antenna for UWB Systems", *Microwaves and RF*, June 2003.

7. Taeyoung Yang, Seong-Youp Suh, Randall Nealy, William A. Davis, and Warren L. Stutzman, "Compact Antennas for UWB Applications", *Systems Magazine* (IEEE Aerospace and Electronic Systems Society), Vol. 19, No.5 pp. 16-20, May 2004.
8. Taeyoung Yang, Seong-Youp Suh, Randall Nealy, William A. Davis, and Warren L. Stutzman, "Compact Antennas for UWB Applications", *Proceedings of IEEE Conference in Ultra Wideband Systems and Technologies* (Reston, VA), November 2003.
9. Seong-Youp Suh, Warren L. Stutzman, William A. Davis, " A New Ultrawideband Printed Monopole Antenna: The Planar Inverted Cone Antenna (PICA)," *IEEE Transactions on Antennas and Propagation*, May 2004.
10. Taeyoung Yang, Seong-Youp Suh, Randall Nealy, Warren L. Stutzman, William A. Davis, "Compact Antennas for UWB Applications", *IEEE A & E Systems Magazine*, May 2004.
11. Minh-Chau Huynh, Warren Stutzman, "A Review of Radiation Effects on Human Operators of Hand-held radio", *Microwave Journal*, Vol. 47, pp. 22-42, June 2004.

1.3.5.2 Conference Presentations (Navciiti and related)

1. C. Buxton, W. Stutzman, and J. Nealy, "Implementation of the Foursquare antenna in broadband arrays," *URSI National Radio Science meeting* (Orlando, FL), July 1999.
2. E.D. Caswell and Dr. W. A. Davis, "Remote Measurement of Antenna Input Impedance", *URSI National Radio Science Meeting* (Orlando, FL), July 1999.
3. S.Y. Suh, W.L. Stutzman, and W. A. Davis, "A Reduced Biohazard Antenna for Handheld Radios," *URSI National Radio Science Meeting* (Boulder, CO), Jan. 2000.
4. M.T. Huynh and W.L. Stutzman, "Ground Pane Effects in PIFA Antennas," *URSI Radio Science Meeting* (Salt Lake City, UT), July 2000.
5. W.L. Stutzman and N.P. Cummings, "Integrated Low Profile GPS and Cellular Antenna," *URSI Radio Science Meeting* (Salt Lake City, UT), July 2000.
6. W.A. Davis, W.L. Stutzman, and E.D. Caswell, "Fundamental Limits on Small Antennas," *URSI Radio Science Meeting* (Salt Lake City, UT), July 2000.
7. K. Takamizawa, N. P. Cummings, W. L. Stutzman, and W.A. Davis, "Comparative Study of Analysis Techniques and Measurement Methods of Canonical Microstrip Antenna," *URSI Radio Science Meeting* (Salt Lake City, UT), July 2000.
8. C. Buxton and W.L. Stutzman, "The Folded Dipole, a Self-Balancing Antenna," *URSI National Radio Science Meeting*, (Salt Lake City, UT), July 2000.
9. W.L. Stutzman, J.H. Reed, C.B. Dietrich, B-K Kim, and D.G. Sweeney, "Recent Results from Smart Antenna Experiments – Base Station and Handheld Terminals," *Proceedings of IEEE Radio and Wireless Conference* (Denver, CO), pp. 139-142, Sept. 10-13, 2000.
10. Tom Biedka, Robert J. Boyle, Carl Dietrich, Kai Dietze, Richard B. Ertel, Byung-ki Kim, Raqibul Mostafa, William Newhall, Uwe Ringel, Jeffrey H. Reed, Dennis Sweeney, Warren L. Stutzman, and Ashok Tikku, "Smart Antenna for Handsets," *TI DSPFest*, Houston, August 2000.
11. B-K Kim, W.L. Stutzman, and D.G. Sweeney, "Indoor and Outdoor Measurements of Space, Polarization, and Angle Diversity for Cellular Base Stations in Urban Environments," *Proceedings of IEEE Vehicular Technology Conference (Boston)*, pp. 22-29, Sept. 2000.
12. William A. Davis and Carl Dietrich, "The Virginia Tech Antenna Group – Ongoing Research," *Wireless Personal Communications Symposium*, (Virginia Tech, Blacksburg, VA), poster paper, June 6-8, 2001.

13. Derek Wells, William A. Davis, Jeffrey H. Reed, and Warren L. Stutzman, "Preliminary Results of a Base Station Antenna Array Configuration Simulation Study," *Wireless Personal Communications Symposium*, (Virginia Tech, Blacksburg, VA), poster paper, June 6-8, 2001.
14. Raqibul Mostafa, Kai Dietze, Ramesh C. Pallat, Warren L. Stutzman, and Jeffrey H. Reed, "Demonstration of Real-Time Wideband Transmit Diversity at the handset in an Indoor Wireless Channel," *Proceedings of the IEEE Vehicular Technology Conference*, (Atlantic City, NJ), pp. 2072-2076, July 2001.
15. Carl Dietrich, Randall Nealy, Saul Sila, and Heinrich Foltz, "Bandwidth Enhancement Techniques for Printed Cloverleaf Antennas," *URSI Digest*, p.74, National Radio Science Meeting, (Boston) July 2001.
16. K. Takamizawa, W. A. Davis, W. L. Stutzman, "Novel Techniques for Analysis of Array Antennas," *URSI Digest*, p.174, National Radio Science Meeting, (Boston) July 2001.
17. Gaurav Joshi, C. B. Dietrich, and W. L. Stutzman, "Diversity Combining and Interference Rejection Performance Comparison Between Linear and Square Arrays: Measurements and Simulation," *Wireless Personal Communications Symposium*, (Blacksburg, VA), poster paper, June 2002.
18. C.G. Buxton and W.L. Stutzman, "FDTD Model of the Foursquare Antenna in a 3x3 and Infinite Array", *URSI National Radio Science Meeting* (San Antonio, TX), June 2002.
19. G. Joshi, D. Wells, C. Dietrich, W. Stutzman, W. Davis, and H. Foltz, "Diversity Combining and Interference Rejection Performance Comparison between Linear and Square Arrays of Low-Profile Monopole Elements with Omni Directional and Sector Patterns: Measurements and Simulation", *URSI National Radio Science Meeting* (San Antonio, TX), June 2002.
20. G. Joshi, C. Dietrich, W. Stutzman, W. Davis, D. Schaffner, H.P. Hsu, and D. Sievenpiper, "Adaptive Beamforming and Diversity Combining Measurements at 2.05 GHz Using Arrays of Four Low-Profile Wire Elements Backed with an Electromagnetic Band Gap Structure", *URSI National Radio Science Meeting* (San Antonio, TX), June 2002.
21. C. B. Dietrich, K. Dietze, and W.L. Stutzman, "An Expression for Optimum Beamformer SINR in Multipath channels and Comparison to Adaptive Array Measurements", *IEEE Antennas and Propagation Society International Symposium Digest* (San Antonio, TX), vol. 2, pp. 640-643, June 2002.
22. W.L. Stutzman, N.P. Cummings, and W.A. Davis, "Active Antenna Bandwidth Control Using Reconfigurable Antenna Elements", *URSI National Radio Science Meeting* (San Antonio, TX), June 2002.
23. K. Takamizawa, W.A. Davis, and W.L. Stutzman, "Comparison of Array Design Methods for Strongly-coupled Large Arrays Using a Network Description of Array Antennas", *URSI National Radio Science Meeting* (San Antonio, TX), June 2002.
24. M-C Huynh, W.L. Stutzman, W.A. Davis, and K. Takimizawa, "Comparison of Wheeler Cap Efficiency Measurement Methods using Various types of Enclosing Structures", *URSI National Radio Science Meeting* (San Antonio, TX), June 2002.
25. S. Licul and W.A. Davis, "Near-Field Measurements of a 'Folded' Quadrifilar Antenna for Automotive Applications," *URSI National Radio Science Meeting* (San Antonio, TX), June 2002.
26. Stanislav Licul and W.A. Davis, "Ultra-Wideband Antenna Characterization and Measurements," *Proceedings of Virginia Tech MPRG Symposium on Wireless Personal Communications,* (Blacksburg, VA), June 2003.
27. Seong-Youp Suh, W.A. Davis and Warren Stutzman, "New Planar Wideband Antennas, WLAN, UWB, and Base-station application", *Proceeding of Virginia Tech MPRG Symposium on Wireless Personal Communications*, (Blacksburg, VA), June 2003.

28. C.B. Dietrich, Jr., K. Dietze, W.L. Stutzman, "Comparison of Array Configurations of Optimum Beamforming in Terms of Signal Spatial Signature Angle Difference, Angle of Arrival Difference, and Polarization Angle Difference", *URSI North American Radio Science Meeting*, (Columbus, OH), June 2003.
29. S.Y. Youp, W.L. Stutzman, W.A. Davis, "Low-profile, Dual-Polarized Broadband Antennas", *IEEE International Antennas and Propagation Symposium*, (Columbus, OH), June 2003.
30. Stani Licul, Argy Petros, W.A. Davis, W.L. Stutzman, "Drooping Quadrifilar Antenna for Land-Mobile Satellite Communications", *IEEE International Antennas and Propagation Symposium*, (Columbus, OH), June 2003.
31. A.I. Zaghlouol, O. Kilic, "Antenna System Solution for Uninterrupted Satellite-on-th-Move (SOTM) Communications", *IEEE International Antennas and Propagation Symposium*, (Columbus, OH), June 2003.
32. Eric C. Kohls, Amir I. Zaghloul, "A Heuristic Method for the Design of Flat Antennas", IEEE *International Antennas and Propagation Symposium*, (Columbus, OH), June 2003.
33. S.Y. Suh, W.L. Stutzman, W.A. Davis, "Multi-Broadband Monopole Disc Antennas", IEEE *International Antennas and Propagation Symposium*, (Columbus, OH), June 2003.
34. Laure Mousselon. R. Michael Barts, Stani Licul, Gaurav Joshi, "Radio Wave Propagation Measurements for Land-Mobile Satellite Systems at 2.33 GHz", *IEEE International Antennas and Propagation Symposium*, (Columbus, OH), June 2003.
35. Stani Licul, W.A. Davis, "A Comparison between a Cavity Backed Spiral and a Resonat Monopole – An Ultra-Wideband Consideration", *IEEE International Antennas and Propagation Symposium*, (Columbus, OH), June 2003.
36. R. Michael Beuhrer, William A. Davis, Ahmad Safaai-Jazi, and Dennis Sweeney, "Characterization of the Ultra-wideband Channel", *Proceedings of IEEE Conference in Ultra Wideband Systems and Technologies* (Reston, VA), November 2003.
37. Stanislav Licul, William A. Davis, and Warren L. Stutzman, "Ultra-Wideband (UWB) Communication Link Modeling and Characterizations", *Proceedings of IEEE Conference in Ultra Wideband Systems and Technologies* (Reston, VA), November 2003.
38. M.-C. Huynh, W. Stutzman, "Ground Plane Effects on Planar inverted-F Antenna (PIFA) Performance", *IEEE Proceedings Microwaves Antennas Propagation*, August 2003.
39. S. Licul, J. N. A. Noronha, C. R. Anderson, T. M. Bielawa, W. A. Davis, D. G. Sweeney, "A Parametric Study of Time-Domain Characteristics of Possible UWB Architectures", *Vehicular Technology Conference*, (Orlando, FL), Fall 2003.
40. Koichiro Takamizawa, William A. Davis, "A Two-Part Measurement Technique of Balanced Antenna Radiation Patterns", *UNSC/URSI National Radio Science Meeting*, (Monterey, CA), June 2004.
41. C. B. Dietrich Jr., K. Takamizawa, W.A. Davis, D. Colatosti, "Beamforming with a Dual-Polarized Array for Reception of Satellite Signals", *UNSC/URSI National Radio Science Meeting*, (Monterey, CA), June 2004.
42. Koichiro Takamzawa, William A. Davis, Warren L. Stutzman, "Impedance Bandwidth Characterization of Highly Coupled Antenna Arrays Using Scattered Parameter Network Models", *UNSC/URSI National Radio Science Meeting* (Monterey, CA), June 2004.
43. Seong-Youp Suh, Warren Stutzman, William Davis, Alan Waltho, Jeffrey Schiffert, "A Novel Broadband Antenna, the Low-Profile Dipole Planar Inverted Cone Antenna (LPdiPICA)", *IEEE Antennas and Propagation Society International Symposium Digest* (Monterey, CA, June 2004.

44. Stanislav Licul, William A. Daivs, "Ultra-Wideband (UWB) Antenna Measurements using Vector Network Analyzer", *IEEE Antennas and Propagation Society International Symposium Digest* (Monterey, CA), June 2004.
45. Stanislav Licul, William A. Davis, "Pole/Residue Modeling of UWB Antenna Systems" *IEEE Antennas and Propagation Society International Symposium Digest* (Monterey, CA), June 2004.
46. Minh-Chau Huynh, Warren L. Stutzman, "A Low-Profile Compact Multi-Resonant Antenna for Wideband and Multi-Band Personal Wireless Applications", *IEEE Antennas and Propagation Society International Symposium Digest* (Monterey, CA), June 2004.
47. Taeyoung Yang, William A. Davis, "Planar Half-Disk Antenna Structures for Ultra-Wideband Communications, *IEEE Antennas and Propagation Society International Symposium Digest* (Monterey, CA), June 2004.
48. Stanislav Licul, William A. Davis, "Frequency-Domain pattern Extraction from Pole/Residue Model of UWB Antenna System", *IEEE Antennas and Propagation Society International Symposium Digest* (Monterey, CA), June 2004.
49. Seong-Youp Suh, Warren Stutzman, William Davis, Alan Waltho, Jeffrey Schiffert, "A Generalized Crossed Dipole Antenna, the Fourtear Antenna", *IEEE Antennas and Propagation Society International Symposium Digest* (Monterey, CA), June 2004.
50. Seong-Youp Suh, Warren Stutzman, William Davis, Alan Waltho, Jeffrey Schiffert, "A Novel CPW-fed Disc Antenna, *IEEE Antennas and Propagation Society International Symposium Digest* (Monterey, CA), June 2004.

1.3.5.3 Books and Book Chapters

1. Warren L. Stutzman and William A. Davis, contribution to *Wiley Encyclopedia of Electrical and Electronics Engineering*, Vol. 1, "Antenna Theory", pp. 595-609, 1999.
2. Warren L. Stutzman and William A. Davis, contribution to *Wiley RF Encyclopedia*, Vol. 1, "Antenna Theory", 2004.
3. William A. Davis, Chapter in *Ultra Wideband Communications Systems*, "Antennas, to be published.

1.3.5.4 Patents, Software, and Etc.

1. J.R. Nealy, Foursquare Antenna Radiating Element, U.S. Patent No. 5,926,137, July 20, 1999. VTIP 96.056. http://www.vtip.org.
2. R. Michael Barts and W.L. Stutzman, "Stub loaded helix antenna". U.S Patent No. 5,986,621, November 16, 1999. VTIP 96.059. http://www.vtip.org (not supported by NAVCIITI).
3. Randall Nealy, J. Matthew Monkevich, Warren Stutzman, and William Davis, "Improvements to the Foursquare Radiating Element-Trimmed Foursquare." U.S. Patent No. 6,057,802, May 2, 2000. VTIP 98.001. http://www.vtip.org.
4. J. Rawnick, W.L. Stutzman, J.R. Nealy, "Wideband Phased Array Antenna Employing Trimmed Four-Square Element Subarrays and Power Divider Feed laminate Structure", U.S. Patent No. 6,300,906, October 7, 2001.
5. Minh-Chau Huynh and W.L. Stutzman, "A Wideband Compact PIFA Antenna", VTIP Disclosure No. 00.017, U.S. Patent No. 6,795,028 B2, Sept. 21, 2004. Allowed. Molex has a non-exclusive license.

__Pending__

1. S-Y Suh and W.L. Stutzman, "The Fourpoint Antenna," VTIP Discplosure No. 00.141. Patent Application Filed.
2. S-Y Suh and W.L. Stutzman, "A Planar Inverted Cone Antenna," VTIP Disclosure No. 00.130. Might reapply.

1.3.5.6 Student Advising (students supported, completed and in progress)

__Ph.D. Students__

1. Takamizawa, Ko, "Analysis of Highly Coupled Wideband Arrays Using Scattering Parameter Network Models", January 2004.
2. Cummings, Nathan, "Active Antenna Bandwidth Control Using Reconfigurable Antenna Elements" PhD Thesis, December 2003.
3. Suh, Seong-Youp, "A Comprehensive Investigation of New Planar Wideband Antennas", Ph.D. Dissertation, Report No. 02-05, July 2002.
4. Kim, Byung-Ki, "Smart Base Station Antenna Performance for Several Scenarios – an Experimental and Modeling Investigation" Ph.D. Dissertation, Report No. 02-1, May 2002
5. Huynh, Minh-Chau, to be completed December 2004.
6. Buxton, Carey G., "Design of a Broadband Array Using the Foursquare Radiating Element", PhD Dissertation, Virginia Tech Antenna Group, June 2001.

__M.S. Students__

1. Gaurav Joshi, "Four Branch Diversity Combining And Adaptive Beamforming Measurements using Mobile Arrays at 2.05 GHz", July 2002.
2. Minh-Chau T. Huynh, "A Numerical and Experimental Investigation of Planar Inverted-F Antennas for Wireless Communication Applications", October 2000.

__Students Supported__

1. Kevin Mescher 2000 – 2001
2. Josh Arritt 2001 – 2002
3. Nathan Cummings 2003
4. Seong-Youp Suh 2000 – 2003
5. Minh-Chau Huynh 2002 – 2003
6. Gaurav Joshi 2003
7. Ko Takamizawa 2000 – 2002
8. Byung-Ki Kim 2001

1.3.5.8. Faculty Supported

1. William A. Davis 2001
2. Warren L. Stutzman

1.3.5.9 Other Personnel Supported

__Post-Doc__

1. Seong-Youp Suh, 2002 - 2003

Engineer

1. Randall Nealy, 2000 – 2004

1.3.6 Major Equipment Purchase/Construction

1. Anechoic Test Chamber (estimated value $450K)

<u>Task 1.4</u> Network Protocol and Interoperability – Scott Midkiff

This report summarizes the objectives and accomplishments for Task 1.4, Network Protocol and Interoperability, of the NAVCIITI program at Virginia Tech. This task builds on Task 3.1, Network Protocol Interoperability, from Years 2-4 of NAVCIITI. (Note that Task 3.1 was not funded during Year 1 of NAVCIITI.) Faculty investigators are Scott Midkiff (Electrical and Computer Engineering), Luiz DaSilva (ECE), Nat Davis (ECE), Jahng Park (ECE), and Clark Gaylord (Communications Network Services). Graduate research assistants supported during all or part of the NAVCIITI program are Palaniappan Annamalai (M.S.), Vijayanand Ballapuram (M.S.), Mike Christman (M.S.), George Hadjichristophi (M.S. and Ph.D.), Henry Hia (M.S.) Tao Lin (Ph.D.), Kaustubh Phanse (Ph.D.), Agnes Tan (M.S.), and John Wells (M.S.). Links to theses, dissertations, technical reports, presentations, and additional information are at http://www.irean.vt.edu/navciiti/.

1.4.1 Review of Task Activities

Task 1.4 addressed network protocol and interoperability issues within the Wireless Integrated NAVCIITI Network (WINN). There were two key objectives for Task 1.4.

1. Provide an interoperable Internet Protocol (IP) network infrastructure to extend the WINN to Virginia Tech's Alexandria Research Institute (ARI) over the production IP network. The node at the ARI will provide visibility into the WINN using (i) remote compressed video and audio for "live" observation of equipment and demonstrations, and (ii) network management tools to monitor and characterize the performance of the network. The research objective of the node at the ARI is to further investigate and demonstrate distributed management and virtual private network security features as part of the WINN.
2. Integrated commercial-off-the-shelf (COTS) IEEE 802.11b or 802.11a wireless local area networking (WLAN) equipment into the WINN in both Blacksburg and at the ARI. The research objective of this integration is to continue to investigate and demonstrate mobile routing, quality of service (QoS), and other capabilities in the WINN.

This task built on Task 3.1, Network Protocol Interoperability, from Years 2-4 of NAVCIITI. (Note that Task 3.1 was not funded during Year 1 of NAVCIITI.) In that task, we investigated functional and performance issues, developed deployment scenarios, and demonstrated enabling Internet Protocol-based technologies for network interoperability in a wireless and mobile environment. The objective of Task 3.1 was to provide the Navy with guidance in the selection, configuration, and operation of new and emerging standards-based Internet protocols. This work was particularly relevant to solutions for wireless and mobile network infrastructure problems, such as those present in the Navy's Virtual Operations Network (VON), the Information Distribution (ID) component of the Future Navy Capability (FNC), and other environments characterized by mobile networks and wireless connectivity. Task 3.1 had four core thrust areas: (i) wireless networks and mobility; (ii) policy-based quality of service; (iii) network security in wireless and mobile environments; and (iv) and network management in heterogeneous networks.

1.4.2 Facilities Developed for the Task

We have built a distributed test bed for Task 1.4 consisting of two deployments, one in Blacksburg and the other at Virginia Tech's Alexandria Research Institute (ARI). The test bed was used for experiments to test the architectures, protocols, and applications developed for the task. During Year 5, the test bed at both locations went through a major upgrade to increase its capabilities. Table 1.4-1 shows the equipment list of the current test bed.

Table 1.4-1. Blacksburg and ARI Test Bed Equipment

Blacksburg	Alexandria Research Institute (ARI)
13 Gateways (10 desktop PCs, 3 notebook PCs)	7 Gateways (5 desktop PCs, 2 notebook PCs)
8 Subnet Hosts (6 desktop PCs, 2 notebook PCs)	5 Subnet Hosts (3 desktop PCs, 2 notebook PCs)
5 Subnet Mobile Hosts (5 Pocket PCs, 2 Tablet PCs)	5 Subnet Mobile Hosts (3 Pocket PCs, 2 Tablet PCs)
1 Server PC	1 Server PC
1 Dynamic Switch	1 Dynamic Switch
2 Cisco Routers	2 Cisco Routers
2 Cisco Layer-3 Switches	1 Cisco Layer-3 Switches
2 Cisco Layer-2 Switches	1 Cisco Layer-2 Switches

One of the key elements of the test bed is the Dynamic Switch. It is a mobility emulator to facilitate controlled experiments with changing topologies using a wireline network (specifically, Ethernet). The emulator is, essentially, a switch implemented through a modification to the Linux kernel. Incoming link layer frames are forwarded to neighbors according to a specification of the topology as a function of time. The topology can be generated manually, using a stand-alone mobility simulator that we implemented in Java, or by using data from other sources, such as traces. This system enables experimental research in mobile routing and other areas. In addition to the emulated mobile ad hoc networks (MANETs) created by the Dynamic Switch and wired desktop personal computers (PCs), we also have notebook computers using actual wireless network interface cards (IEEE 802.11b) incorporated in the test bed at both locations. Figure 1.4-1 shows one particular topology of the test bed in Blacksburg.

To extend the WINN capability to the ARI, we created a secure tunnel to link the two locations over a production IP network. This link connects the two parts of the distributed test bed, thus allowing investigation and demonstration of distributed management and virtual private network security features. With the link, video conferencing sessions for "live" observation of equipment and demonstrations and use of network management tools to monitor and characterize the performance of the network are possible. We have chosen the Data Link Switching (DLSw) protocol and Cisco routers to create the link. DLSw allows transporting of LAN traffic over an IP network. It was chosen because of its easy implementation and because it has lower overhead compared to other similar transport protocols, requiring minimal unnecessary traffic forwarding. To secure the link, we have incorporated the Message Digest-5 (MD5) algorithm for authentication of the communication channel and use a restricted access list to allow only authorized clients to communicate over the link. This secure link allows two physically separate MANETs to behave as one MANET, where all machines in both locations use the same subnet address space.

1.4.3 Accomplishments

Task 1.4 can be divided into four main subtasks: (i) policy-based network management in an ad hoc environment, (ii) network security in a wireless environment, (iii) routing for mobile networks, and (iv) network management. Accomplishments in each subtask are presented below. Figure 1.4-2 summarizes the core technology areas of Task 1.4, their integration within the scope of Task 1.4, and their integration

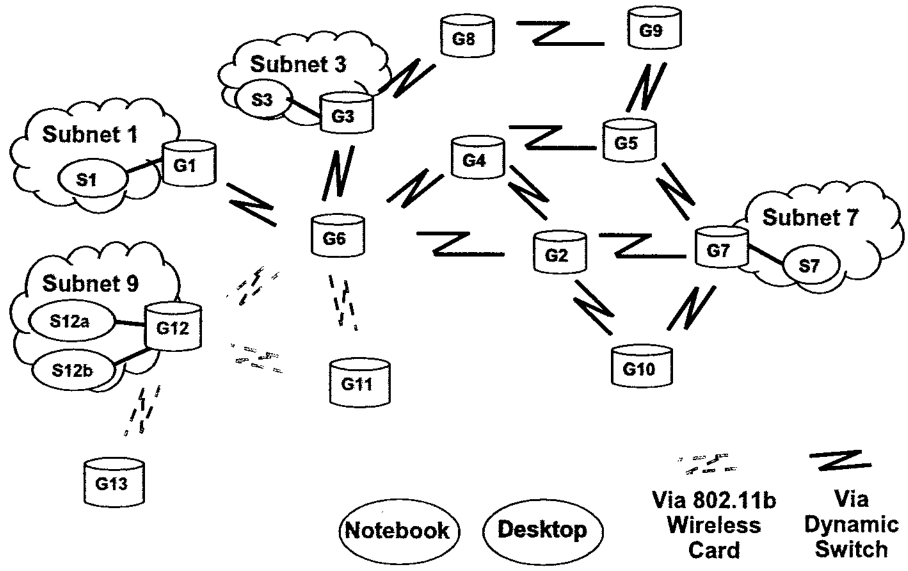

Figure 1.4-1. An example topology of the test bed in Blacksburg.

within the context of the WINN. Our quarterly and annual reports provide more detailed descriptions of our accomplishments. Accomplishments in the four core areas – policy-based network management, wireless security, mobile routing, and network management – are summarized below.

1.4.3.1 Policy-Based Network Management in an Ad Hoc Environment

We investigated mechanisms to provide policy-based bandwidth allocation based on applications, hosts, and users. We explicitly considered environments where hosts and/or networks are mobile. We have utilized the Common Open Policy Services (COPS) standard and have developed a novel suite of solutions to deploy an intelligent, adaptive, and robust policy-based network management system for mobile ad hoc networks. The key components of the system are: (i) extensions to the Common Open Policy Service (COPS) protocol to enable policy negotiation in a multi-domain network environment, such as the U.S. Navy's VON; (ii) a *k*-hop clustering algorithm to limit the number of wireless hops between a policy server and client and to efficiently manage the network; (iii) a service discovery mechanism to allow policy clients to automatically discover policy servers in the network; and (iv) the Dynamic Service Redundancy (DynaSeR) technique, which consists of redirection and delegation mechanisms to improve management system service coverage. As part of the WINN, we integrated the PBNM-based QoS system (and security and ad hoc routing) with the Choir real-time middleware system (of NAVCIITI Task 1.5) to support "soft" real-time applications in an ad hoc network environment.

The PBNM solution suite was implemented on the NAVCIITI test bed and its capabilities were demonstrated. It was also implemented using the QualNet network simulator. This model allowed us to study a range of research questions related to the PBNM system, including questions related to scalability. After completion of simulation experiments, we developed an analytical model using stochastic Petri nets to do cross-validation between simulation and analytical results. To do so, we developed an analytical model, using Stochastic Petri Nets (SPNs), for a PBNM system for MANETs. The model, built from a policy client's perspective, assumes non-Markovian state transitions, parameterized from simulations. We solved the analytical model using the new version of the WebSPN tool (WebSPN 3.2) and validated the results obtained against simulation results based on the QualNet models.

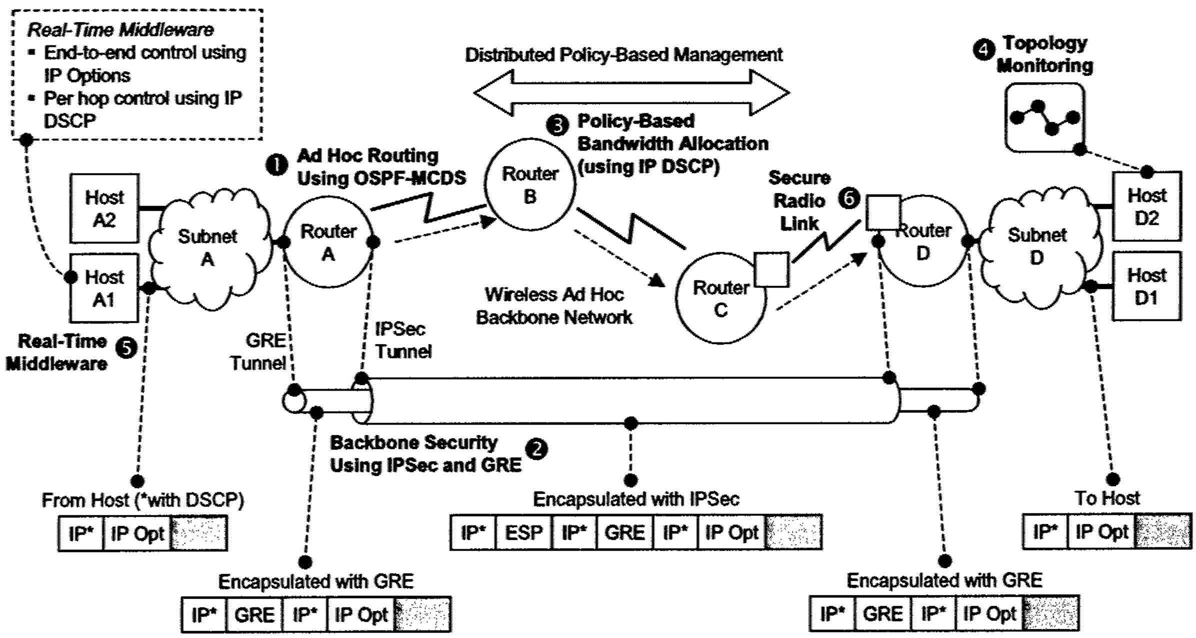

Figure 1.4-2. This figure illustrates the technical concepts investigated in Task 1.4 and their integration with each other and with results from other NAVCIITI tasks. Key components include: (1) ad hoc routing between mobile networks, where a mobile network consist of one or more hosts connected through a gateway router that supports OSPF-MCDS; (2) secure tunnels using IPSec and GRE that provide authentication and privacy for traffic flows between mobile networks; (3) PBNM-based resource allocation to ensure that bandwidth in the backbone network is allocated according to organizational policies; (4) a tool to monitor the ad hoc topology of the backbone network; (5) real-time middleware, provided by NAVCIITI Task 1.5, that can utilize routing, QoS, and security in the backbone network; and (6) incorporation of a link using a secure radio provided by NAVCIITI Task area 1.1.

1.4.3.2 Network Security in a Wireless Environment

We investigated and demonstrated the use of IP Security (IPSec) to provide authentication and security in mobile networks using ad hoc routing. The basic approach is illustrated in Figure 1.4-1. We demonstrated methods to establish IPSec tunnels by using public and private keys instead of shared keys. Shared keys do not scale as well as public keys and are better suited for ad hoc networks. Rivest, Shamir, and Adleman (RSA) public keys were obtained either by storing them on each gateway or by having gateway routers acquire the public keys via a Domain Name Service (DNS) server.

We also investigated and demonstrated the interoperability of IPSec with ad hoc routing, policy-based QoS architectures, network monitoring, real-time middleware (NAVCIITI Task 1.5), and the secure radio (NAVCIITI Task area 1.1). We identified a number of problems with current approaches and systems and found specific solutions to enable IPSec interoperability with policy-based QoS, real-time systems, and network management functions based on the Simple Network Management Protocol (SNMP). We identified several issues and limitations of current IPSec-based security methods with respect to scalability. Configuring IPSec, establishing security associations, and bringing up multiple IPSec tunnels is difficult in a large network, especially an ad hoc network.

To overcome these limitations, we developed a new distributed Key Management System (KMS) for a mobile ad hoc environment. The new KMS is better suited for highly mobile and partitioned networks than traditional KMS schemes. The new scheme also uses node behavior grading to record the trustworthiness of nodes as positive and negative reputations. The new KMS is different from the existing implementation of using IPSec with a Domain Name Service (DNS) server for key distribution in a number of ways (see Figure 1.4-3), as listed below.

1. The use DNS is replaced by Delegated Certificate Authorities (DCAs). The IPsec implementation no longer communicates with DNS for key management.
2. IPsec communicates with the KMS application running on each gateway. The application determines the method used to retrieve the certificates.
3. The DCAs store certificates instead of only public keys, removing the notion of dual authentication per host and allowing multiple hosts (or users) to be authenticated.
4. The certificates used comply with the X.509 version 3 format (as being adopted by the Internet Engineering Task Force's Public-Key Infrastructure working group) and includes some extensions to allow for behavior grading of the nodes in a MANET.

We implemented and integrated the modified KMS and deployed it in the NAVCIITI test bed.

1.4.3.3 Routing for Mobile Networks

We investigated routing in backbone networks that connect mobile platforms, such as ships. Results are also applicable to more general routing for mobile hosts. We addressed both unicast and multicast routing. We considered three basic approaches: (i) traditional routing protocols, specifically the widely used Open Shortest Path First (OSPF) protocol, that are "tuned" for improved performance in Navy use scenarios; (ii) mobile ad hoc network (MANET) routing protocols; and (iii) Internet Protocol (IP) mobile routing to allow low-capability platforms to connect to any of a set of high-capability platforms that form a network "cloud" via satellite or other connections. Key accomplishments within this subtask are summarized below.

We implemented a test bed and have conducted preliminary studies of IP mobile routing techniques. The test bed consists of standard Cisco routers, Linux routers, Linux hosts, and Microsoft Windows hosts. We considered two approaches: (i) mobile routing, where a mobile router on a mobile platform obtains a group of addresses from a permanently connected platform; and (ii) Mobile IP coupled with Network Address Translation (NAT) where the "mobile router" is actually only a mobile node and supports a network behind it by using NAT. We have measured the performance of bulk data transfer using TCP in a dynamic network topology.

We developed a novel framework to provide a theory and method for comparing and evaluating different MANET routing protocols. The framework is based on the fact that all routing protocols must create a set of nodes to use as a path from source to destination. We refer to the set of intermediate nodes as the relay node set (RNS). The frame work considers the behavior and complexity of four tasks: creating the RNS, maintaining the RNS, propagating routing control messages, and ensuring reliable delivery of control messages. We used the framework to gain insight into potential improvements in routing protocols and into the applicability of different routing protocols for potential Navy use. We then developed a mobility emulator to facilitate controlled experiments with changing topologies for the investigation of ad hoc routing protocols. The emulator, called the Dynamic Switch, was discussed in Section 1.4.2.

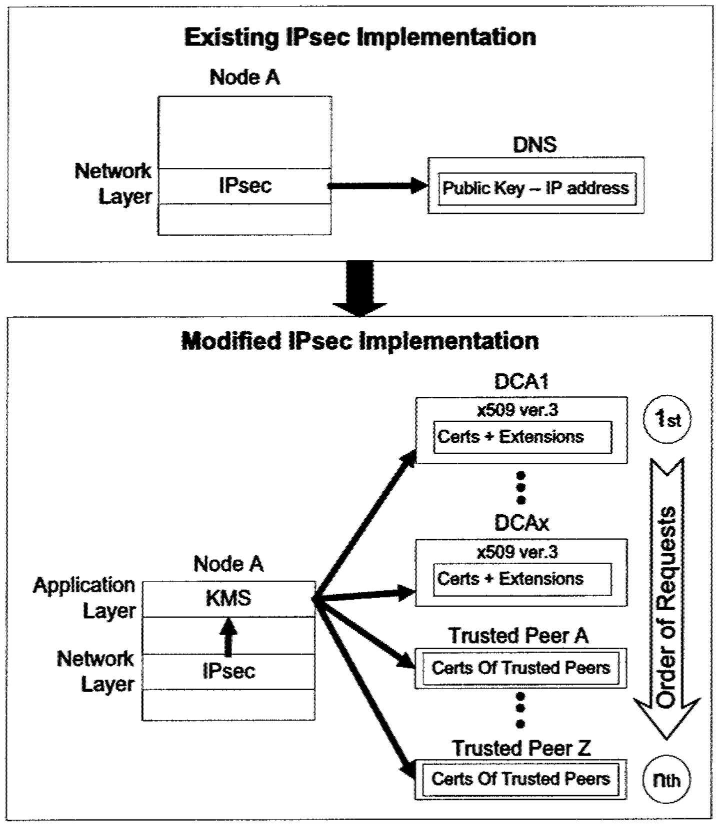

Figure 1.4-3 The new modified KMS implementation versus the existing implementation of IPSec using DNS.

Based on insight gained from the framework, we further modified OSPF to make it suitable for MANETs. This modified version is based on forming a minimal connected dominating set (MCDS) that is, effectively, a dynamically selected backbone network. We call the protocol OSPF-MCDS. We created and evaluated four approximation algorithms to create the MCDS. OSPF-MCDS is well suited for mobile networks and emphasizes low control overhead for routing. Figure 1.4-4 illustrates the operation of OSPF-MCDS. The working version of OSPF-MCDS has been implemented and demonstrated on the NAVCIITI test bed.

We also examined simulation methods for ad hoc networks with a goal to improve the methods used to evaluate such systems. We have used the RNS framework and simulation techniques to study control overhead in the Ad hoc On-demand Distance Vector (AODV) and Optimized Link State Routing (OLSR) protocols based on an analytical model drawn from our RNS framework.

We extended OLSR to support multicast (OLSR+Multicast) in a Linux implementation. This extension and evaluation allowed us to better characterize overhead and other performance issues related to multicast in wireless ad hoc networks of interest to the Navy.

1.4.3.4 Network Management

We have characterized two alternative approaches for securing network management traffic across a backbone: (1) using SNMPv3, a secure version of the Simple Network Management Protocol (SNMP),

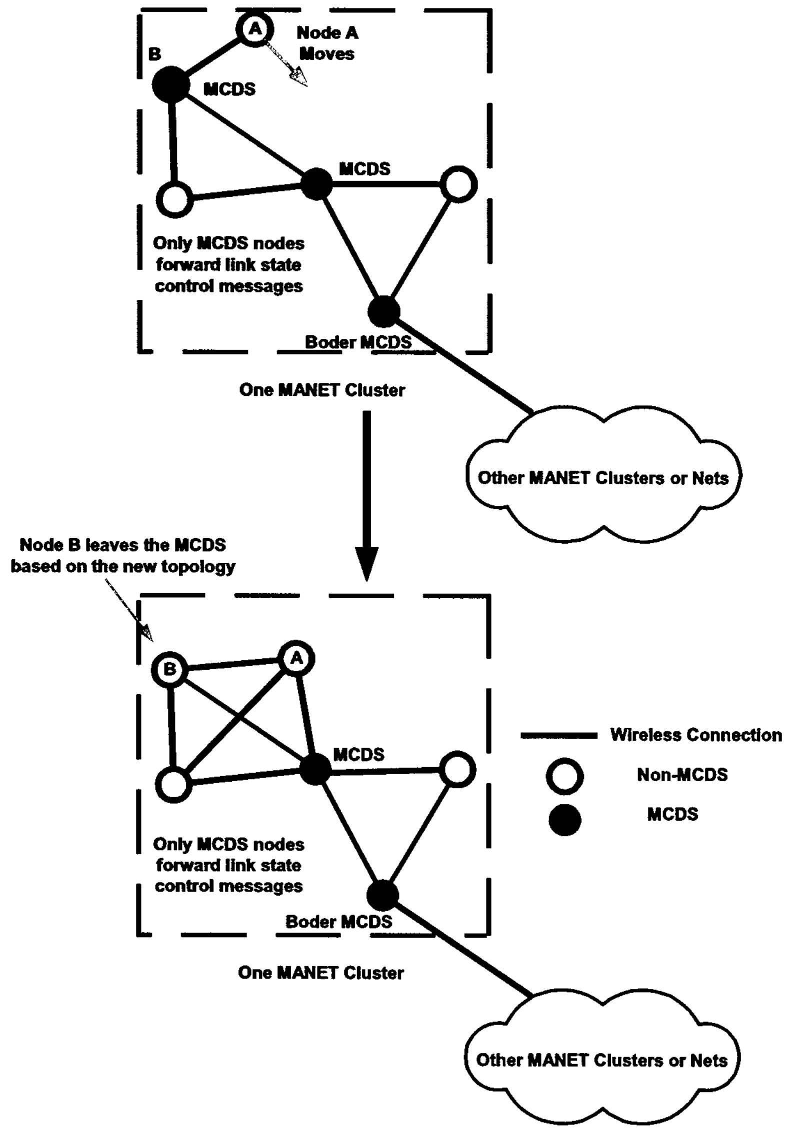

Figure 1.4-4 This figure illustrates the concepts of clusters and MCDS nodes in the OSPF-MCDS ad hoc routing protocol. As Node A moves (from the position in the top topology to its position in the bottom topology), the network topology changes and the MCDS nodes are updated. The affects of such changes are usually limited to a single cluster, which improves scalability.

and (2) using non-secure SNMPv1 or SNMPv2 with IPSecurity (IPSec) to provide security. Experiments show that the SNMPv3 scheme consumes as much as 24 percent more network capacity than SNMPv2c-over-IPSec when utilizing both authentication and privacy services. We then examined a distributed management technique to enable bandwidth-efficient network management in rapidly assembled networks that consist of geographically distributed LANs interconnected by a separately controlled backbone network.

We also developed SNMP agents that reside on each gateway router and can report connectivity and an SNMP-based management system that queries gateway routers for neighbors and displays a graphic representation of the ad hoc network topology in real-time. This system was integrated with the OSPF-MCDS ad hoc routing protocol (and should work with other routing protocols in Linux) and the IPSec-based security mechanisms. The system has been implemented and demonstrated on the NAVCIITI test bed.

1.4.4 Relevance of the Task

Our task relates to network infrastructure problems encountered in a variety of potential situations. These include data communications between U.S. Navy vessels and those of other countries, e.g., in a coalition humanitarian mission, using COTS hardware and communications in a network-centric environment in rapidly formed battle groups, including communications at sea, to the air, and to and within the littoral. Such networks rely on a backbone network built from relatively low data rate wireless links with a dynamic, ad hoc topology. Our investigation of routing protocols, quality of service, network management, and security in this environment can lead to improved solutions to critical problems. The extension of our system to the ARI facilitates larger scale testing and provides a test bed to further investigate security and management. Our work is unique in that it looks at these multiple issues in an integrated manner. In addition, our work is unique in that it is integrated, through the WINN, with work on secure radio platforms and real-time systems. This work should provide long-term value to the Navy and near-term value to the Navy's VON and related programs.

As added value, we bring relevant current and recent research experience in wireless local area networks, wireless ad hoc networks (with recent research funded by DARPA and Microsoft), rapidly deployable broadband wireless networks (with a current program funded by the National Science Foundation's Digital Government program), on-ship network modeling (via a past project for CVN-76 funded through Newport News Shipbuilding), and network management and characterization (previously funded by IBM). We are and will be utilizing additional equipment in related concurrent programs, including support from a National Science Foundation "Integrative Graduate Education and Research Training" (IGERT) grant.

1.4.5 Productivity Summary

1.4.5.1 Journal Publications

1. L. A. DaSilva and K. Phanse, "Prioritizing Access to Scarce Resources: Network Survivability through Policy-supported Quality of Service," *International Journal on Critical Infrastructures*, vol. 1, no.1, 2004, pp. 20-37.
2. K. Phanse and L. DaSilva, "Addressing the Requirements of QoS Management in Wireless Ad Hoc Networks," *International Journal of Computer Communications*, vol. 26, no. 12, pp. 1263-1273, July 2003.
3. K. Phanse, L. A. DaSilva, and S. F. Midkiff, "Design and Demonstration of Policy-based Management in a Multi-hop Ad Hoc Network Testbed," *Ad Hoc Networks Journal*, to appear.

1.4.5.2 Conference Publications

1. G. C. Hadjichristofi, N. J. Davis, and S. F. Midkiff, "IPSec Overhead in Wireline and Wireless Networks for Web and Email Applications," *Proc. IEEE International Performance, Computing, and Communications Conf.*, Phoenix, AZ, April 9-11, 2003, pp. 543-547.
2. H. E. Hia and S. F. Midkiff, "Securing SNMP Across Backbone Networks," *Proc. IEEE Conf. on Communications and Computer Networks*, Scottsdale, AZ, Oct. 15-17, 2001, pp. 190-196.
3. S. F. Midkiff, "Simulation and Emulation of Mobile Ad Hoc Networks: Fidelity and Complexity," *Proc. Communication Networks and Distributed Systems Modeling and Simulation Conf.*, San Antonio, TX, Jan. 27-31, 2002, pp. 109-114.

4. T. Lin and S. F. Midkiff, "Mobility versus Link Stability in the Simulation of Mobile Ad Hoc Networks" (invited paper), *Proc. Communication Networks and Distributed Systems Modeling and Simulation Conf.*, Orlando, FL, Jan. 19-23, 2003, pp. 3-8.
5. T. Lin, S. F. Midkiff, and J. S. Park, "A Dynamic Topology Switch for the Emulation of Wireless Mobile Ad Hoc Networks," *Proc. 27th Annual IEEE Conf. on Local Computer Networks (Workshop on Wireless Local Networks)*, Tampa, FL, Nov. 6, 2002, pp. 791-798.
6. T. Lin, S. F. Midkiff, and J. S. Park, "A Framework for Wireless Ad Hoc Routing Protocols," *Proc. IEEE Wireless Communications and Networking Conf.*, vol. 2, New Orleans, LA, March 16-20, 2003, pp. 1162-1167.
7. T. Lin, S. F. Midkiff, and J. S. Park, "Minimal Connected Dominating Set Algorithms and Application for a MANET Routing Protocol," *Proc. IEEE International Performance, Computing, and Communications Conf.*, Phoenix, AZ, April 9-11, pp. 543-547.
8. T. Lin, S. F. Midkiff, J. S. Park, and Y. Lin, "Quantitative Study of Connectivity Changes in Mobile Ad-Hoc Network Simulation," Proceedings of Communications Networks and Distributed Systems (CNDS) Conference, San Diego, CA, Jan. 19-22, 2004, 6 pages on CD-ROM.
9. K. Phanse and L. A. DaSilva, "Protocol Support for Policy-Based Management of Mobile Ad Hoc Networks," *Proc. IEEE/IFIP Network Operations and Management Symp.*, April 19-23, 2004, Seoul, Korea.

1.4.5.3 Patents, Software, etc.

1. Tao Lin, "Linux Dynamic Switch," distributed at http://sourceforge.net/projects/dynamic-switch/.

1.4.5.4 Honors and Recognitions

1. Luiz DaSilva was promoted to the rank of Associate Professor and granted tenure, effective 8/15/04.

1.4.5.5 Student Advising

M.S. Students Completed

1. M. Christman, "A New Network Mobility Architecture with a Mobile IP Multiple Address Extension," M.S. Thesis, Virginia Polytechnic Institute and State University, August 2002.
2. G. Hadjichristofi, "IPSec Overhead in Wireline and Wireless Networks for Web and Email Applications," M.S. Thesis, Virginia Polytechnic Institute and State University, November 2001.
3. H. E. Hia, "Secure SNMP-Based Network Management in Low Bandwidth Networks," M.S. Thesis, Virginia Polytechnic Institute and State University, April 2001.
4. J. D. Wells, "A Network Mobility Survey and Comparison with a Mobile IP Multiple Home Address Extension," M.S. Thesis, Virginia Polytechnic Institute and State University, July 2003.

Ph.D. Students Completed

1. Tao Lin, "Mobile Ad-hoc Network Routing Protocols: Methodologies and Applications" Ph.D. Dissertation, Virginia Polytechnic Institute and State University, March 2004.
2. Kaustubh Phanse, "Policy-Based Quality of Service Management in Wireless Ad Hoc Networks" Ph.D. Dissertation, Virginia Polytechnic Institute and State University, August 2003.

Students Supported

1. Michael Christman, 2000-2002

2. George Hadjichristofi, 2000-2004
3. Henry. Hia, 2000
4. Tao Lin, 2000-2004
5. Kaustubh Phanse, 2000-2003
6. John Wells, 2001-2002

1.4.5.8 Faculty Supported

1. Luiz A. DaSilva, Assistant Professor, 2000-2004
2. Nathaniel J. Davis, Professor, 2000-2004
3. Scott F. Midkiff, Professor, 2000-2004
4. Jahng S. Park, Research Assistant Professor, 2001-2004

1.4.5.9 Other Personnel Supported

Post-Doc

1. Kaustubh Phanse, 2003

Task 1.5 Real-Time Middleware – Binoy Ravindran

1.5.1 Review of Task Activities

The Task 1.5 Real-Time Middleware was conducted during the period of April 1, 2000 through June 4, 2004. The main objective of the task was to develop algorithms, protocols, and system software (including middleware) for time-critical resource management in dynamic, asynchronous, real-time distributed systems such as Navy's network-centric warfare systems. Asynchronous real-time distributed systems are fundamentally distinguished by significant *non-determinisms* that are inherent in their operating environments, causing great run-time uncertainties in application and system behavior. Typically, execution and communication latencies in such systems do not have known upper bounds and event and failure occurrences are non-deterministically distributed. For example, many DoD surface combatant systems (e.g., Navy's Aegis, Air Force's AWACS) include radar-based tracking subsystems that associate sensor reports to airborne object tracks. When a significantly large number of sensor reports arrives, it exceeds the system processing capacity, causing overloads, resulting in important tracks to go undetected.

The non-determinism that is inherent in dynamic, asynchronous, real-time distributed systems violates the foundations of classical real-time computing theory. This theory achieves predictability determinism by deterministically postulating bounds and distributions on application properties such as execution and communication latencies, and event and failure occurrences.

Toward the objective of developing algorithms, protocols, and system software for time-critical resource management in dynamic, asynchronous, real-time distributed systems, the project goals included:

1. Developing adaptive real-time resource management algorithms
2. Developing real-time networking algorithms and protocols
3. Developing real-time scheduling algorithms
4. Developing real-time middleware that contains implementations of the real-time resource management, networking, and scheduling algorithms

1.5.1.1 Past Work on Dynamic, Asynchronous, Real-Time Distributed Systems

The timeliness requirements of real-time systems can be easily specified and reasoned through the concept of "time/utility functions" (or TUFs) devised by E. Douglas Jensen. A TUF specifies the utility to the system for completing an application activity as an application- or situation-specific function of activity completion time. Figure 1.5-1 shows example TUFs. The "step" TUF shown in Figure 1.5-1(a) implies that a constant utility is obtained for completing the activity anytime before a "critical time" (denoted here as t_c), and zero utility for completing the activity after t_c.

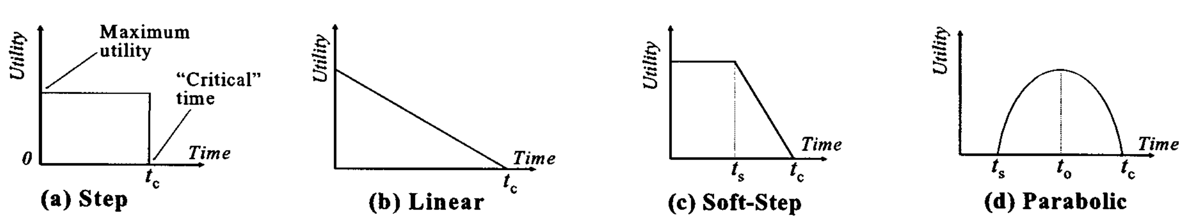

Figure 1.5-1 Example timeliness requirements specified using Jensen's Time/Utility Functions

Most real-time systems have a multiplicity of activities. Further, many require a distribution, for scalability and dependability. Thus, to design a real-time system having multiple activities where each activity is subject to an individual time constraint, a timeliness optimality criterion must be defined and algorithms that satisfy the criterion must be designed. Furthermore, the resulting timeliness behavior must be *predicted;* i.e., satisfaction of the timeliness optimality criterion must be known in advance to some degree.

Classical real-time systems research focuses on: (1) *step TUFs* for expressing activity timing constraints; (2) the timeliness optimality criterion that *all activities must complete before their* t_c; and (3) *determinism* for timeliness predictability; i.e., the fact that all activities will complete before their t_c is known with absolute certainty. These three aspects form the foundation of "hard" real-time computing theory. The theory achieves predictability determinism by deterministically postulating bounds/distributions on application properties such as execution/communication latencies, and event/failure occurrences.

As mentioned previously, asynchronous real-time distributed systems are subject to significant run-time uncertainties and thus, they violate the hard real-time theory's premises. Hence, adaptivity and flexibility are important design goals for such systems. For example, a desirable behavior for radar-based tracking subsystems is to process all tracks when resources are sufficient, and "drop" less important tracks before dropping more important tracks when resources are insufficient and thereby gracefully degrade performance during overloads. Timeliness optimality criteria that facilitate such adaptation can be specified using TUF predicates such as *maximizing summed utility* and *percentage of activities completing before their* t_c. Such adaptation is inconsistent with the hard timeliness optimality criterion.

Our past work performed as part of DARPA's Quorum program developed a mathematical formalism for specifying asynchronous real-time distributed systems [wr+98]. This work focused on step TUFs and the optimality criterion of maximizing percentage of activities completing before their t_c. Further, the work developed resource allocation algorithms that use the formal system description for reasoning about system behavior at run-time, detecting situations of high likelihood for timing failures, and dynamically reallocating application resources for improving timeliness [rws01]. Furthermore, the algorithms were implemented to construct a real-time middleware called *DeSiDeRaTa* [ws+98]. *DeSiDeRaTa* was evaluated using prototype, futuristic, US Navy combat applications including *DynBench* that approximated next generation Navy surface combatants [sw+00]. The middleware was later transitioned to Navy test-beds including HiPer-D and SC-21 for large-scale experimental studies [ww+99, wr+99].

1.5.1.2 Summary of Task 1.5 Work Performed on Dynamic, Asynchronous, Real-Time Distributed Systems

The work in [wr+98] only scratched the surface of the problem of understanding how asynchronous real-time distributed systems can be built. An immediate problem of interest was to develop a paradigm for constructing such systems that facilitate their cost-effective evolution, besides satisfying their timing constraints. Many asynchronous real-time distributed systems such as command and control (C2) systems have large development costs and have long life cycles, during which they undergo significant changes to their requirements and technology bases. Thus, they require a cost-effective way to evolve and meet new requirements and exploit new technology bases.

We addressed this problem by developing a systems engineering (SE) framework, where system details such as architecture and timing requirements are decoupled from platform-specifics through a formal systems description language [rav02]. The language abstractions then drive resource allocation.

The efforts in [wr+98, rav02] focused on "reactive" resource allocation i.e., allocation of resources *when* there is high likelihood for timing failures. While resources can be reactively allocated for activities that execute in a repetitive manner, they are impractical for event-triggered activities as their inter-arrival times are highly unpredictable. To solve this problem, we developed a family of *proactive* resource allocation algorithms that optimize timeliness objectives *before* event arrival, using application-defined, situation-specific workload scenarios. In [heg01] and [hr02, rh01], we presented resource allocation algorithms called RBA, RBA*, and OBA that consider step TUFs and maximize summed utility.

The RBA, RBA*, and OBA algorithms were later extended in many fundamental directions including:

1. Dependability, by tolerating processor failures [rlh03]
2. Comparable performance with lower computational costs [lr04]
3. Decentralization, for tolerating processor and network failures, and scalability [hr02-a]
4. Optimization of non-step, but non-increasing TUFs (e.g., Figures 1.5-1(b, c)) [lr03-choir]
5. Enhanced timeliness utility by network-level resource allocation in
   5.1. Single-hop networks [wang02, wr02, wr04]
   5.2. Multi-hop networks i.e., those with multiple switches and routers [chan03, crj04]

We implemented the resulting algorithms and constructed a real-time middleware called *Choir* [lrwk03, lr03-choir]. *Choir* is *DeSiDeRaTa*'s next generation form that supports non-increasing TUFs, an optimality criterion of maximizing summed utility, and decentralized resource allocation (none of which is supported in *DeSiDeRaTa*). *Choir*, however, is restricted to activities with no resource constraints and non-increasing TUFs. Resource constraints are common in most real-time systems; they define when and how non-CPU resources can be used by activities and must be respected by scheduling algorithms. Thus, in [li-prop04] and [lrwj04], we developed the GUS scheduling algorithm that considers activities subject to resource constraints and almost arbitrarily-shaped TUFs, including increasing TUFs (e.g., Figure 1.5-1(d)), and schedules them to maximize summed utility. This scheduling problem was *open* until GUS was developed.

As the efforts leading to GUS were progressing, Object Management Group published the Real-Time CORBA 1.2 (RTC1.2) standard in 2001. RTC1.2 addressed many of the issues involved in developing asynchronous real-time distributed systems such as adaptive timeliness optimality criteria that are central to Task 1.5 research (e.g., maximizing summed utility is RTC1.2's core aspect).

Thus, to leverage our research results toward an industry-standard platform, we constructed the next generation of *Choir*, called *Tempus* [lrcj04, lrcj04-tc]. *Tempus* is currently partially compliant with RTC1.2, allows activities that are subject to resource constraints and arbitrarily-shaped TUF time constraints, and schedules them to maximize summed utility. Furthermore, *Tempus* uses real-time operating systems (RTOS) that are compliant with IEEE's POSIX standard as its underlying RTOS base, through the concept of "meta-scheduling." Meta-scheduling is an application-level, TUF scheduling framework for POSIX RTOS, which do not support TUF scheduling. The application-level architecture eliminates the need for modifying RTOS for TUF scheduling, facilitating middleware portability and usage of commercial off-the-shelf (COTS) RTOS [lrwk03, lrsf04].

Several new TUF scheduling algorithms that build upon GUS have also been developed. These algorithms significantly expand the activity and system model considered by GUS in many different dimensions, and thus expand the scope and applicability of TUFs. The algorithms include the Combined Utility Accrual algorithm (or CUA) [wrj04], Resource-Constrained Utility Accrual algorithm (or RUA) [wrjb04], Stochastic Utility Accrual Scheduling (or S-UA) [lrj04], Energy-Efficient Utility Accrual Algorithm (or EUA) [wrj04-codes], Resource-constrained Energy-Efficient Utility Accrual Algorithm (or ReUA) [wrjl04], and Memory-Aware Utility Accrual Scheduling Algorithm (or MSA) [frj04].

The CUA algorithm extends the TUF model with the notion of joint utility, where activities accrue utility depending upon the completion time of *other* activities. RUA allows arbitrary TUF shapes, resource dependencies, and multi-unit resource request models (GUS only allows a single-unit request model). RUA achieves the timeliness optimality of classical real-time algorithms during under-loads.

While RUA provides assurances on timeliness behavior similar to that of hard real-time scheduling algorithms, it is restricted to deterministic activity models, where activity worst-case execution times are known with absolute certainty. This restriction is overcome in algorithms including S-UA, EUA, and ReUA. These algorithms allow stochastic activity models, where activity execution times and inter-arrival times are stochastically described. While S-UA allows non-increasing, unimodal TUFs and resource dependencies, EUA is restricted to step TUFs and no resource dependencies. However, EUA considers system-level *energy* consumption – an important concern in emerging battery-powered, embedded real-time systems. ReUA advances EUA's model by allowing non-increasing, uninmodal TUFs and resource dependencies.

S-UA, EUA, and ReUA provide statistical guarantees on timeliness behavior including probabilistically-satisfied lower bounds on utility accrued by each activity, besides maximizing the sum of the activities' attained utilities. Being concerned with energy, EUA and ReUA also minimize system-level energy consumption.

The MSA algorithm considers another important resource of real-time systems: memory. While memory is statically allocated in traditional systems, MSA allows memory to be dynamically allocated, thereby permitting greater flexibility, and maximizes activities' attained utilities. MSA also allows unimodal TUFs and resource dependencies, and provides the same timeliness optimality as that of RUA during under-loads.

1.5.2 Facilities Developed for Task

The facilities developed for the task include the following:

1. The *Tempus* real-time middleware software system [lrcj04, lrcj04-tc]
2. The *Choir* real-time middleware software system [lrwk03, lr03-choir]
3. The TUF *meta-scheduler* software system [lrwk03, lrsf04]
4. TUF-driven *packet scheduling* software [wang02, wr02, wr04]
5. TUF-driven *network routing* software [chan03, crj04]

1.5.3 Accomplishments

The major accomplishments of the Task 1.5 research include development of TUF real-time algorithms, protocols, and software systems for time-critical resource management in dynamic, asynchronous, real-time distributed systems. The results produced have significantly expanded the scope of TUF real-time research and are summarized in Figure 1.5-2.

Figure 1.5-2 shows the scope of TUF research using a 2-dimensional matrix. Each matrix row represents an application/system model attribute such as: no resource dependency, resource dependency, power, and memory. Each matrix column represents a class of TUF shape such as step: non-increasing (i.e., those functions for which utility never increases as time advances), unimodal (i.e., those functions which have a single optimal completion time interval), and arbitrary-shaped. Further, each matrix element (denoted by a row and column position) is partitioned into deterministic and stochastic task models. Algorithms developed in past research and those developed as part of Task 1.5 research are now shown in the appropriate matrix elements, illustrating the scope of Task 1.5 research.

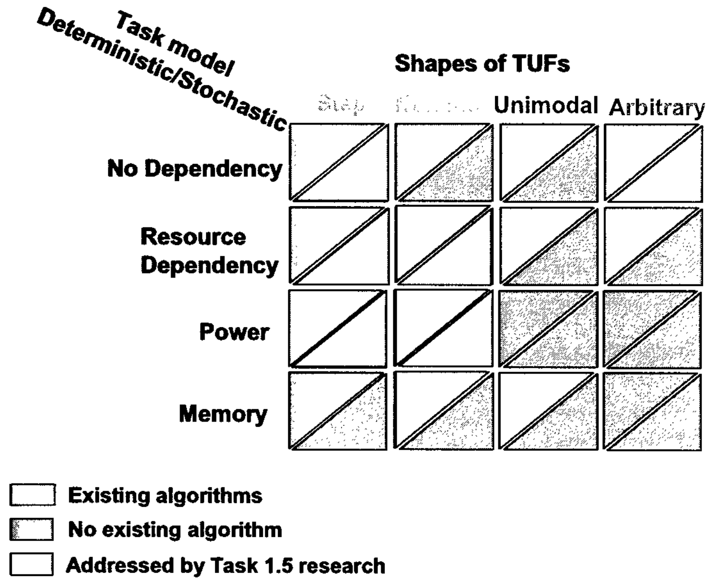

Figure 1.5-2 Scope of TUF research results produced by Task 1.5 research

Another major accomplishment of the research is the transfer of technology to US government agencies and industry. The GUS, *Tempus*, and meta-scheduling efforts have generated significant interest by government agencies — NASA and Air Force — for technology transfer. NASA's Jet Propulsion Laboratory (JPL) has decided to employ GUS and its successor algorithms in their Mission Data System, to be first deployed on the Mars Science Laboratory to be launched in 2009. Toward this, we filed two IP disclosures to facilitate government use license and are closely working with The MITRE Corporation for technology transition. Furthermore, the next generation of GUS that is being developed in [wu-prop04] is selected for transitioning into Air Force's E-10A/Multi-Platform Radar Technology Insertion Program (MP-RTIP). Collaborative efforts with MITRE are in progress for this technology transition. Both these technology transition efforts are currently ongoing.

We summarize the accomplishments as follows:

1. Development of a family of TUF real-time algorithms and protocols including:
   1.1. TUF adaptive real-time resource management algorithms
   1.2. TUF real-time networking algorithms and protocols including packet scheduling algorithms and routing protocols
   1.3. TUF real-time scheduling algorithms including process/thread scheduling algorithms
2. Development of TUF real-time software systems that contain implementation of the real-time algorithms and protocols. The software systems include:
   2.1. TUF real-time middleware software systems including *Tempus* and *Choir*
   2.2. TUF real-time scheduling software system including *meta-scheduler*
   2.3. TUF real-time networking software systems including packet scheduling software and routing software
3. Technology transfer to US government agencies including NASA and Air Force and industry (including The MITRE Corporation.

1.5.4 Importance of the Task

The TUF real-time technology developed in Task 1.5 is directly relevant to Navy's network-centric warfare concept and many Navy surface combatant systems, including DD(x). The past research on dynamic, asynchronous real-time distributed systems (summarized in Section 1.5.1.1) was directly motivated by Navy combat systems including Aegis. Results from that research including middleware software was transitioned to Navy test-beds including HiPer-D and SC-21. That research laid the foundation for Task 1.5 research.

The core results produced by Task 1.5 research – COTS-based *Tempus* real-time middleware that directly supports the distributable threads abstraction, TUF real-time scheduling and networking for end-to-end, time-critical, mission-oriented resource management – are directly applicable to the class of real-time problems exemplified by systems such as Aegis, HiPer-D, SC-21, and DD(x). In fact, the fundamental aspects of this class of real-time problems include:

1. Need for transparent programming and scheduling abstractions for end-to-end timeliness
2. Systems that are subject to significant run-time uncertainties that are often manifested in execution and communication times, and event and failure occurrences that are non-deterministically distributed
3. Systems that are subject to transient and permanent overloads
4. Need for time-critical and mission-oriented resource management (i.e., timely management of resources in the best interest of the current application mission)
5. Need for industry/commercial standards- and COTS-based solutions for portability, robustness, and maintainability

All these aspects are addressed by Task 1.5 research. In particular, the distributable threads abstraction of *Tempus* middleware provides a transparent programming and scheduling abstraction for specifying and enforcing end-to-end timeliness. Further, the class of TUF real-time scheduling and networking algorithms and protocols (that are part of *Tempus*) precisely targets application activities, whose execution/communication latencies and event/failure occurrences are non-deterministically distributed and are subject to overloads. TUF algorithms and protocols provide time-critical and mission-oriented resource management by system-wide scheduling to maximize system-wide, accrued application utility, where utility represents application timeliness and importance. Furthermore, the meta-scheduling scheduling framework of *Tempus* uses POSIX APIs for TUF scheduling and resource management. Thus, *Tempus* facilitates usage of COTS POSIX operating systems as its underlying OS base.

Thus, Task 1.5 technology is directly relevant to many Navy combat systems.

We hope to build upon the ongoing technology demonstrations and transitions to NASA and Air Force (through The MITRE Corporation) for technology transitions to the Navy. Interactions with NSWCDD's Dr. Michael Chang have been ongoing since the start of the project for technology demonstrations and transitions. We are planning to do a technology demonstration of *Tempus* to Dr. Chang (or others at NSWCDD) in the near-term.

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1.5.5 Productivity Summary

1.5.5.1 Journal Publications

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2. H. Wu, B. Ravindran, E. D. Jensen, "On the Joint Utility Accrual Model," *IEEE Workshop on Parallel and Distributed Real-Time Systems*, April 2004.
3. S. Feizabadi, W. Beebee, Jr., B. Ravindran, P. Li, and M. Rinard, "Utility Accrual Scheduling With Real-Time Java," *Proceedings of The First Workshop on Java Technologies for Real-Time and Embedded Systems*, Catania, Sicily, Italy, November 2003, 10 pages.

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1. E. Douglas Jensen and B. Ravindran, *IEEE Transactions on Computers*, Special Issue on "Asynchronous Real-Time Distributed Systems," 2002, Bibliography of editorial: E. D. Jensen and B. Ravindran, "Guest Editor's Introduction to Special Section on Asynchronous Real-Time Distributed Systems," *IEEE Transactions on Computers*, Volume 51, Number 8, pages 881-882, August 2002.

1.5.5.6 Software

1. *Meta-Scheduler* scheduling framework. Meta-scheduler is a portable, application-level scheduling framework that allows time/utility function scheduling on IEEE POSIX-compliant real-time operating systems (RTOSes), without modifying the RTOSes. Meta-Scheduler is currently being transitioned to NASA Jet Propulsion Laboratory, E-10A/Multi-Platform Radar Technology Insertion Program (MP-RTIP) of the US Air Force, and The MITRE Corporation.
2. *Generic Benefit Scheduling (GBS)* real-time scheduling algorithm (it is later renamed as GUS). GUS is the first real-time scheduling algorithm to solve the problem of optimizing almost arbitrarily-shaped, Jensen's time/utility function timing constraints and resource constraints. GUS is currently being transitioned to NASA Jet Propulsion Laboratory, E-10A/Multi-Platform Radar Technology Insertion Program (MP-RTIP) of the US Air Force, and The MITRE Corporation. GUS is to be deployed in NASA's Mission Data System (MDS), which is a next-generation architecture that runs on the Mars Science Lab Rover robot. MDS is to be first deployed on the Mars Science Laboratory (to be launched in October 2009).
3. *Tempus* real-time middleware. *Tempus* facilitates specification and optimization of end-to-end timing requirements that are expressed using almost arbitrarily-shaped Jensen's time/utility functions. *Tempus* contains the GUS scheduling algorithm, is the next generation of the *Choir* real-time middleware, and is partially-compliant with OMG's Real-Time CORBA 1.2 (Dynamic Scheduling) standard. *Tempus* is currently being transitioned to E-10A/Multi-Platform Radar Technology Insertion Program (MP-RTIP) of the US Air Force and The MITRE Corporation.
4. *Choir* real-time middleware. *Choir* facilitates specification and optimization of timing constraints specified using step-shaped Jensen's time/utility functions. *Choir* is the next generation of the *DeSiDeRaTa* real-time middleware and is one of the first examples of decentralized, adaptive, TUF real-time resource management technology.

1.5.5.7 Intellectual Property Disclosures

1. *Meta-Scheduler* scheduling framework. VTIP Intellectual Property Disclosure No. 03-

128 (disclosure filed October 2003). VTIP URL: http://www.vtip.org/licensing/disclosures/03-128.htm.

2. ***GBS* real-time scheduling algorithm. VTIP Intellectual Property Disclosure No. 03-095 (disclosure filed July 2003). VTIP URL:** http://www.vtip.org/licensing/disclosures/03-095.htm.

(Both disclosures filed (i) toward patent and (ii) to allow government use license for facilitating technology transfer to NASA Jet Propulsion Laboratory, E-10A/Multi-Platform Radar Technology Insertion Program (MP-RTIP) of the US Air Force, and The MITRE Corporation.).

1.5.5.8 Awards and Recognitions

1. B. Ravindran, IEEE Senior Membership, Awarded November 2003
2. P. Li, Graduate Student Support Grant sponsored by DARPA to attend the *2003 IEEE Real-Time and Embedded Technology and Applications Symposium.*
3. B. Ravindran, *Invitation talk*: "The *Choir* Real-Time Middleware," *IFIP Working Group 10.4 (Dependable Computing and Fault-Tolerance) Workshop on Middleware for Adaptivity and Dependability*, 43rd IFIP Working Group Meeting, Santa Maria, Sal Island, Cape Verde, January 4-7 2003 (invitation received, but could not give the talk due to restrictions on international travel).
4. B. Ravindran, *Invited Talk*, "Distributed, Asynchronous Real-Time Systems: Language, Middleware Support, and Application," *ARTES (Swedish National Strategic Initiative in Real-Time Systems funded by the Swedish Foundation for Strategic Research) Summer School Tutorial*, Linkoping, Sweden, August 27, 1999 (invited talk funded by ARTES).
5. B. Ravindran, *Invited Talk*, "Engineering Distributed, Asynchronous Real-Time Systems: Language, Middleware Support, and Application," INRIA Rocquencourt, Le Chesnay Cedex, France, June 14, 1999 (invited talk funded by INRIA).
6. B. Ravindran, *Invited Talk*, "Adaptive Resource Management in Asynchronous Real-Time Distributed Systems," Department of Computer Science, National University of Singapore, May 14, 2001 (invited talk funded by the National University of Singapore).

1.5.5.8 Student Advising (students supported, completed, and in progress)

PhD Students (Dissertation Advisees)

1. Hyeonjoong Cho, PhD 2006 (expected), PhD Dissertation (in Computer Engineering): "Utility Accrual Real-Time Publish Subscribe: Protocols and Middleware".
2. Haisang Wu, PhD 2005 (expected), PhD Dissertation (in Computer Engineering): "Utility Accrual Scheduling Under Completion Time, Execution Time, Resource, Precedence, and Energy Constraints," Passed PhD Preliminary Examination, May 3, 2004.
3. Shahrooz Feizabadi, 2005 (expected), PhD Dissertation (in Computer Science): "Automatic Timeliness-Utility Accrual Memory Management," Passed PhD Preliminary Examination, May 3, 2004.
4. Peng Li, PhD 2004 (expected), PhD Dissertation (in Computer Engineering): "Utility Accrual Scheduling of Resource-Constrained Real-Time Activities," Passed PhD

Preliminary Examination on August 1, 2003; Final defense is anticipated to be held in July 2004.

MS Students (MS Thesis Advisees)

1. Umut Balli, MS 2005, Master's Thesis, "A Time/Utility Function Design and Assurance Analysis Toolkit".
2. Karthik Channakeshava, MS 2003, Master's Thesis: "Utility Accrual Real-Time Channel Establishment in Multi-hop Networks," Thesis Advisor, Defended August 29, 2003.
3. Jinggang Wang, MS 2002, Master's Thesis: "Soft Real-Time Switched Ethernet: Best-Effort Packet Scheduling Algorithm, Implementation, and Feasibility Analysis," Thesis Advisor, Defended September 24, 2002.
4. Tamir Hegazy, MS 2001, Master's Thesis: "Using Application Benefit for Proactive Resource Allocation in Asynchronous Real-Time Distributed Systems," Thesis Advisor, Defended September 20, 2001.
5. Ravi Devarasetty, MS 2001, Master's Thesis: "Heuristic Algorithms for Adaptive Resource Management of Periodic Tasks in Soft Real-Time Distributed Systems," Thesis Advisor, Defended February 6, 2001.

MS Non-Thesis Advisees

1. Muhammad Albandagji, MS 2003, Project: "A Graphical User Interface for Shipboard Air Defense System," GRA Co-advisee, Co-advisor with Professor Ali H. Nayfeh, Department of Engineering Science and Mechanics, Virginia Tech, Presented April 17, 2003.
2. Lakshmi Ramaswamy, MS 2003, Project: "A Best-Effort Communication Protocol for Real-Time Broadcast Networks," GRA Advisee, Fall 2001 and Spring 2002 (work resulted in a conference publication).
3. Baoping Zhang, MS 2001, Independent Study in Real-Time Systems, Project: "Adaptive Communication in Asynchronous Real-Time Distributed Systems," GRA Advisee, Summer 2000 and Fall 2000 (work resulted in one conference publication and one journal publication).

BS Students

1. Brian Hartsock, Independent Study (undergraduate research), "Implementation of a Meta-Scheduler in the VxWorks Real-Time Operating System," University Honors program, Spring 2003.
2. Glenn Konowicz, Independent Study (undergraduate research), "Implementation of Soft Real-Time Best-Effort Scheduling Algorithms in Real-Time Linux," University Honors program, Spring 2003.
3. Glenn Konowicz, Independent Study (undergraduate research), "Design and Implementation of an Integrated Development and Monitoring Environment (IDME) for the *Choir* Real-Time Middleware," University Honors program, Fall 2002.

<u>Task 1.6</u> Mechanically Flexible Multifunctional Display Materials and Devices - Liangmin Zhang, Fajian Zhang and Richard O. Claus

1.6.1 Background

The original objective of this task was to investigate methods for the formation of multifunctional display materials and devices for use in the presentation of data for Digital Ship visualization applications. Near the beginning of the program, and with input from the program manager, we shifted the focus of this task toward the implementation of flexible materials for control of electromagnetic properties. This topic is important to onboard conformal and multi-band antenna systems, as well as wideband electromagnetic signature control of Navy and other DoD system platform assets.

Since the re-focus of program, we have: fabricated a wide range of prototype flexible conducting materials, measured their broadband electrical and electromagnetic properties, visited DoD and industrial locations to discuss applications, and presented results to both ONR and other Navy personnel.

1.6.2 Facilities Developed for Task

Our planned effort was to implement and evaluate the properties of electrically conducting mechanically flexible materials. This expanded on prior work in this area within our group, and on intellectual property licensed from the university to NanoSonic, a small company located near Virginia Tech in Blacksburg. NanoSonic has graciously provided us with materials for evaluation that have properties exceeding those that we have been able to fabricate on campus.

We have built various facilities to support the objectives of task 1.6. We developed and demonstrated the capability to control and evaluate the permeability, permittivity and conductivity of multifunction materials. We built a facility to evaluate the properties of self-assembled broadband electrically conducting and wavelength-controlled transparent thin film materials with Navy and prime contractor staff. The electromagnetic material control is required for a number of topside Navy ships applications including both antenna systems and signature control for stealth application. Details about these facilities and capabilities are given in our quarterly reports no.17 through 29.

1.6.3 Accomplishments

The electrically conducting flexible material called Metal Rubber™ was investigated in this task. Metal Rubber is a substance that conducts electricity like metal, but also stretches like rubber up to 250% of its original length. Research effort was devoted to this material because of its potential for huge impact on Naval applications. Some possible application areas are: electrostatic materials, conducting adhesives, electromagnetic shielding, printed circuit boards, flex circuits, flexible electronics, artificial nerves, antistatic clothing, as electrodes on high strain sensors and actuators, and in aircraft structures. With proper manufacturing techniques, the materials will be inexpensive to fabricate and is non-toxic.

The materials are specifically not "conducting polymers" that have been researched and developed for many years. They are instead "self-assembled" nanocomposites that contain mechanically flexible polymers and electrically-conducting metal nanoclusters. As in most composites, control over the percentages of both constituents can be used to obtain different properties.

Self-assembly refers to the material synthesis methods whereby large number of molecules form together to create useful components without substantial directed interaction from external sources or operators. Often it relies on the electronic charge properties of cationic and anionic molecules that may be alternately deposited on substrates to form multilayered media. Virginia Tech and NanoSonic have used this electostatic self-assembly (ESA) method to combine noble metal, metal oxide and metal alloy nanoclusters, cage-structured molecules such as nanotubes and buckeyballs, polymers and biomolecules, to obtain thin films with a wide range of constitutive properties. Of some interest has been the degree of control obtained over permittivity, permeability, electrical and thermal conductivities, and mechanical modulus and fatigue behavior. Unfortunately, individual molecular layers are one-molecule thick (i.e. on the order of nanometers), so ESA is practically limited to the formation of ultrathin films on the order of 100 nm in thickness (a thousandth in thickness of a human hair), that can require several-day fabrication times.

However, recently a modified approach was developed that allows a significant speed increase in the self-assembly process, yielding materials at a rate on the order of millimeters of thickness per hour of synthesis time. This improvement is significant to both potential commercial scale-up, and to the production of nanomaterials that are of practical use in the macroworld.

If a chemical release layer is applied to the surface of the substrate prior to the self-assembly of these thicker materials, they may be formed and then chemically released from the substrate. What results is free-standing, mechanically robust, multi-millimeter thick films with properties determined by the constituent molecules and the order of the multilayer deposition. Metal Rubber is made this way. It combines low modulus (less than 10 MPa) with high electrical conductivity (on the order of 10^5 to 10^6 $W^{-1}m^{-1}$).

1.6.4 Importance of the Task

The objective of this task is to reduce the radar cross section (RCS) of antennas by using special material to control the electromagnetic properties of the antennas. Antennas are basic components of communications and radar systems. From countermeasures point of view antennas provide the gates to increase the vulnerability of electronics hardware. Reducing the RCS of antennas will reduce the susceptibility for detection and the vulnerability to jamming these systems.

We are discussing with Lockheed Martin, Northrop Grumman and others how the technology developed on this part of the NAVCIITI program can be transitioned to shipboard, aircraft, spacecraft and other DoD systems use. Virginia Tech has already licensed related technology to NanoSonic.

1.6.5 Productivity Summary

1.6.5.1 Journal Publications and Book Chapters

1. Y-X Wang, R. Claus, W. Spillman, and J. Robertson, "Effects of the Chemical Structure and the Surface Properties of Polymeric Biomaterials on their Biocompatibility", *J. of Biomedical Materials*, July 2004.
2. R. Claus and L. Supriya, "Self-Assembly Materials and Devices", book chapter, John Wiley, *Nanotechnology*, edited by M. Schultz, June 2004.
3. L. Zhang, Y-X Wang, F. Zhang, and R.O. Claus, "Second-Harmonic Generation and Determination of Second Order Nonlinear Optical Coefficients in electrostatic Self-Assembly Thin Films", submitted to *Journal of Applied Physics*, January 2003.
4. I. Matias, I.Del Villar, F. Arregui and R. Claus, "Analysis of One-Dimensional Photonic Bandgap Structures and Defects towards Development of an Optical Refractometer", submitted to *Optic Letters*.

5. L. Supriya and R. Claus, "Patterned Self-Assembly Materials and Electrodes", submitted to *Smart Materials and Structures Journal*, April 2003.

1.6.5.2 Conference Publications

1. "Self-Assembly Electronic and Photonic Materials and Devices". AMAPS Conference (sponsored by AFRL, Fayetteville, AK), June 24-26, 2003.
2. J. Lalli, B. Lepene, J. Huie, J. Mecham and R. Claus, "Self-Assembled Free-Standing Materials and Devices", ICEES (Corfu, Greece), July 24-29, 2003, invited paper.
3. J. Lalli, B. Lepene, J. Huie, J. Mecham and R. Claus, "Extending Nanoscale Self-Assembly to Macroscopic Structural Materials", International Conference on Structural Health Monitoring (Palo Alto, CA), September 15-17, 2003.
4. "Self-Assembled Nanostructured Materials for Defense Applications", Invited Seminar, Naval Postgraduate School, (Monterey, CA), January 2004.
5. J. Lalli, A. Hill and R. Claus, "Self-Assembled Nanostructured Conducting Elastomeric Electrodes", *SPIE Smart Materials and Structures Conference* (San Diego, CA), March 2004.
6. J. Lalli, A. Hill, R. Goff and R. Claus, "Self-Assembled Nanostructured Sensors", *SPIE Smart Materials and Structures Conference* (San Diego, CA), March 2004.
7. R. Claus, B. Davis, F. Arregui and I. Matias, "Self-Assembled Optical Fiber Chemical Sensors", European Workshop on Optical Finer Sensors (Santander), June 2004.
8. R. Claus, J. Mecham, L. Duncan, J. Lalli, M. de Vries and B. Davis, "Technology Transfer for Optical and Optical Finer Science", Invited Paper and Session, European Workshop on Fiber Sensors (Santander), June 2004.
9. J. Lalli, A. Hill, and Richard O. Claus, "Metal Rubber ™", *ICCEES 04 Conference* (Maderia, PT), July 2004.
10. R. Claus, "Elastomeric Conductive Membranes as Two-Dimensional Shape and Deformation Sensors", IEEE Sensors Conference (Vienna), November 2004.
11. R. Claus, "Nanostructural Self-Assembled Strain Sensor", IEEE Sensors Conference (Vienna), November 2004.

1.6.5.3 Short Courses Presented

1. "Smart Materials and Structures", Virginia Tech CEC, May 14, 2003. Richard Claus was one of the short course instructors.
2. Part of Smart Materials and Structures Short Course, with Professors D. Inman and R. Batra, Blacksburg, VA, May 17-19, 2004.

1.6.5.4 Awards and Honors

1. Ph.D. Student Lakshmi Supriya was awarded a graduate internship at GE Corporate R&D for her work on self-assembled materials and devices.
2. M.S. student Eric Herz was awarded a Fulbright Scholarship to work in Germany on the synthesis of materials used to self-assemble nanostructured materials.

1.6.5.5 Navy Related Contacts

1. Richard Claus visited Pax River on May 8, 2003, in part to discuss this program.
2. Richard Claus visited EAFB and Lockheed Martin Palmdale on May 19, 2003, to discuss this program.
3. Richard Claus visited Lockheed Martin (Palo Alto) on May 20, 2003, to discuss this program.

4. Richard Claus visited DARPA on July 9, 2003, in part to discuss this program.
5. Richard Claus visited KAFB on July 21, 2003, in part to discuss this program.
6. Richard Claus visited Hughes Research Lab, May 10, 2004.
7. Richard Claus visited Northrop Grumman (El Segundo), May 11, 2004.
8. Richard Claus visited NASA Dryden Space Flight Center, May 12, 2004.
9. Lockheed Martin (Palo Alto) visited Richard Claus at Virginia Tech, May 18, 2004.
10. Richard Claus visited Lockheed Martin (Bethesda), June 3, 2004.
11. Richard Claus visited Boeing (Huntington Beach), September 14, 2004
12. Richard Claus visited Lockheed Martin (Palmdale), September 14, 2004.
13. Richard Claus has arranged to meet with members of the staff of Senator Warner and Congressman Rick Boucher (9^{th} district, Virginia) to discuss the results of this part of the NAVY program.

1.6.5.6 News Coverage

1. *Economist* magazine in June 2004.
2. *Chemical and Engineering News*, August 2004.
3. *Gizmado* website, September 2004.
4. *Popular Science*, August 2004.
5. ScienCentral website, September 2004.
6. ABC News, September 2004.

Note that a Google search on "Metal Rubber" gives about 19,000 website hits. Also, note that NanoSonic has entered into an Alliance Agreement related to this work. A Google search on "NanoSonic Lockheed Martin" yields about 150 sites.

Note also that we have given interviews for the PBS show "The History Channel," specifically the "Tactical to Practical" show, and to the publication "Esquire," for its science column.

PROJECT 2

Tasks 2.1 and 2.2 Command and Control Visualization – Ronald Kriz, Lance Arsenault, and John Kelso

2.1.1 Review of Task Activities

The NAVCIITI Project Task 2.1 experienced several modifications as our Navy Point of Contact (POC) collaborations and resources evolved and as we learned how to implement and use state-of-the-art Virtual Environment (VE) hardware and software tools to build usable command and control interfaces for naval undersea warfare applications. VE hardware and software is "cutting edge" technology and is constantly evolving. This evolution was also indicative of an active participation between the Virtual Realty Laboratory at the Naval Research Laboratory (NRL-POC: Dr. Larry Rosenblum), the Naval Undersea Warfare Center (NUWC-POC: Mr. Kenneth Lima and Mr. Richard Shell), and the Virginia Tech University Visualization and Animation Group (UVAG-Co-PIs: Dr. Ronald Kriz, Dr. Lance Arsenault, and Mr. John Kelso). This evolution is also reflected in Statements of Work (SOWs) and quarterly reports, which have been posted on the *NAVCIITI Task 2.1 Command and Control Web pages*: http://www.sv.vt.edu/future/cave/resprj/navciiti/nuwc_task2-1/task2-1.html.

A noteworthy accomplishment for Task 2.1 was the development of a new VE Application Programming Interface (API) called DIVERSE (Device Independent Virtual Environment: Scalable, Reconfigurable, and Extensible), http://diverse.sourceforge.net, that created a new architecture for working with Input/Ouput (I/O) devices and Dynamic Shared Objects (DSOs) that facilitated moving executable objects into and out of a simulation based design during execution within a VE. Because this, API is device independent and scales so that applications run the same in a CAVE, Immersive Work Bench, Head Mounted Display, or a VE desktop simulator. The new I/O and DSO VE architecture also facilitated the development of networked collaborative VE design environments. This new VE-API not only benefited Task 2.1 but other NAVCIITI Tasks that used the motion based platform as an I/O device, which was constructed in the floor of the CAVE at Virginia Tech. This benefit to the Navy continues as the DIVERSE API is now supported as an open-source ("free" – GPL/LGPL license) format on the Sourceforge Web site and maintained by a newly formed company, Opentech Inc., http://www.opentechinc.com, located at the Corporate Research Center at Virginia Tech. The future benefit to the Navy has already been realized where Opentech Inc. has been active in setting up and supporting other Navy projects using DIVERSE as the primary VE software API. At Virginia Tech, the UVAG is now supported under the Institute for Critical Technologies in the Applied Sciences (ICTAS), a university initiative that will facilitate future VE research of interest to the Navy.

Tasks were organized and reorganized over the last five years into the following four chronological segments:

BAA 98-014: First year

1. Design requirements established for developing command and control VE hardware and software design environment.

BAA-0007: Years 2-5

1. Years 2-3: Collaboration with NRL, NUWC, and UVAG-VT organized as the NUWC: CONRAY-SubVE, and NRL: DRAGON-IVRS projects.
2. Years 3-4: Task 2.1 subdivided into two subtasks:
   a. Task 2.1a, NUWC-TALOSS OpenGL project in DIVERSE called DGL.
   b. Task 2.1b, Development of DGL in support of TALOSS.
3. Final year five: Task 2.1 recombined into one task, developing DGL and TALOSS.

Statements of Work (SOWs) and quarterly reports of accomplishments can be accessed from the NAVCIITI Task 2.1 web site: http://www.sv.vt.edu/future/cave/resprj/navciiti/nuwc_task2-1/task2-1.html. The task chronology listed above is indicative of how the collaboration between the Virtual Reality Laboratory at the Naval Research Lab (NRL), the Naval Undersea Warfare Center (NUWC) at Newport Rhode Island, and the Virginia Tech University Visualization and Animation Group (UVAG) evolved into a working relationship over the last five years.

2.1.1.1 Task summary for years one and two

Our task objective was to provide a distributed collaborative network of graphical and device independent tools in a shared virtual environment, which can be used by Command and Control (C&C) personnel to gain a strategic advantage. In *year one* we focused on cognitive processes that could be used in tactical decision making processes and the creation of shared collaborative virtual environments such as the CAVE Collaborative Console (CCC). In *year two* we focused on the mission critical C&C interpretation of acoustic undersea data from towed arrays for the Naval Undersea Warfare Center (NUWC) using the CONRAY simulation models. These simulation models can be extended to "real-time" data acquisition systems such as ICE. Under the direction of personnel from NUWC and the Naval Research Laboratory (NRL) we identified a working prototype, "MIX", which we have successfully incorporated into our Device Independent Virtual Environment Reconfigurable-Scalable-Extensible (DIVERSE) tool that works in stereo in the (C)AVE Automated Virtual Environment (CAVE), Immersive Work Bench (IWB), Immersive Desk (I-Desk), desktop workstation simulator, and Head Mounted Display (HMD) systems at the Virginia Tech UVAG, see Figures 2.1-1, 2.1-2, and 2.1-3.

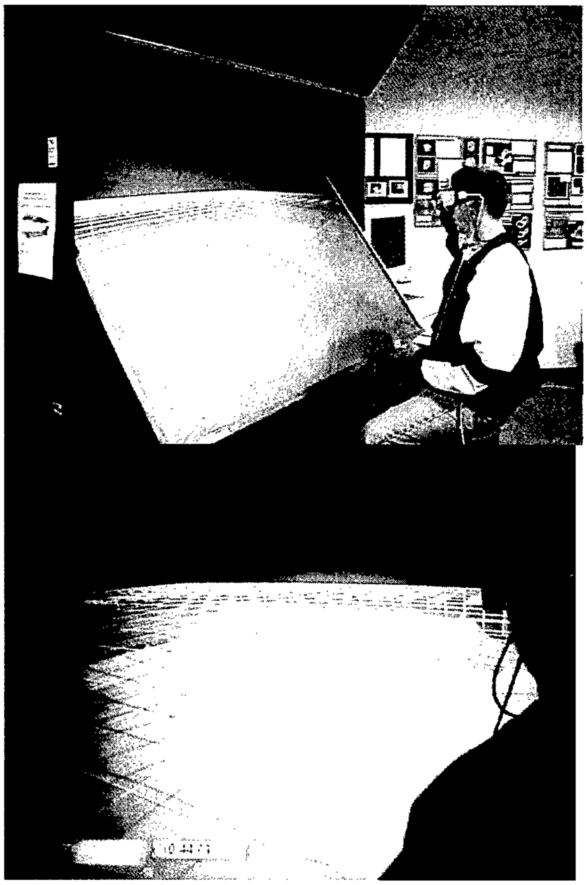


Figure 2.1-1 Performer-based TALOSS on the UVAG I-Desk at Virginia Tech

2.1.1.2 Task summary for years three, four, and five

In the *third year* this research became part of the NUWC-TALOSS (Three-dimensional Advanced Localization-Observation Submarine System) project. The third year also required the sub-division of Task 2.1 into two tasks. Task 2.1a continued the development of TALOSS based on the new OpenGL version of DIVERSE called DGL and Task 2.1b focused on development of DGL used by Task 2.1a.

In *year three* Task 2.1b was directed by a new NAVCIITI Co-PI, Dr. Lance Arsenault, who was the author of the DTK portion of the DIVERSE API that "glued" various Input/Output (I/O) devices into a network shared memory architecture which was used for simulation based design in support of Task 2.1a and other simulation based design NAVCIITI projects such as the Virtual Craneship project. When Dr. Arsenault left Virginia Tech, Mr. John Kelso became the Co-PI the fall 2003, and when Mr. Kelso left Virginia Tech in the June 2003, Dr. Kriz became Co-PI of both tasks, who recombined both tasks back into one Task 2.1 (year five).

Figure 2.1-2 Performer-based TALOSS in the UVAG CAVE at Virginia Tech

2.1.1.3 Task summary for Year Four

A Micorsoft Windows version of DTK was created where DTK and DPF were released as separate DIVERSE 2.3.x modules. The summer of 2004 was the last year and was a critical year for Task 2.1b. In the absence of Dr. Arsenault and Mr. Kelso, who were the original DIVERSE API authors, Dr. Kriz hired Mr. Andrew Ray, Mr. Patrick Shinpaugh, and Mr. Daniel Larimer who successfully created a beta release of DGL that is now accessible for the DIVERSE Sourceforge Web site: http://diverse.sourceforge.net. DGL was successfully used to create TALOSS-DGL by Mr. Rich Shell at NUWC and Mr. Fernando das Neves, the NAVCIITI GRA at UVAG; see Figure 2.1-4. Although DGL was successfully used to create TALOSS-DGL, DLG at best was a beta version with minimal documentation. The lastest working copy of TALOSS-DGL can be accessed from the NAVCIITI Task 2.1 Web site. Mr. Andrew Ray became the new NAVCIITI GRA replaced Mr. das Neves, who continued to work with Mr. Patrick Shinpaugh from the summer 2004..

2.1.1.4 DIVERSE Adaptable Display System (DADS) - year five.

In year five, Mr. Andrew Ray and Mr. Patrick Shinpaugh created a new OpenGL based VE computing system to control the CAVE at Virginia Tech and similar VE systems for the Navy. The development of the OpenGL DIVERSE Adaptable Display Sytem (DADS) was completed and documented on the Sourceforge Web site. A more complete set of DADS documentation is also available from the NAVCIITI Task 2.1 Web site.

The DADS system used PNY Technologies FX3000 quad-buffered/genlock NVIDIA cards, which was acknowledge on PNY's case study Web site, http://www.pny.com/pressroom/caseStudies/vc.asp, as an affordable alternative to expensive legacy VE computing systems or large expensive Linux cluster systems. Future OpenGL based VE applications are supported on the new DADS systems by the use of the DIVERSE interface to SGI-Performer for OpenGL (DPFGL). The new DPFGL interface is fully documented and can be downloaded from the DIVERSE Sourceforge Web site. This was demonstrated by successfully running OpenGL Visualization ToolKit (VTK) applications on a DADS system controlling the Virginia Tech CAVE projection system.

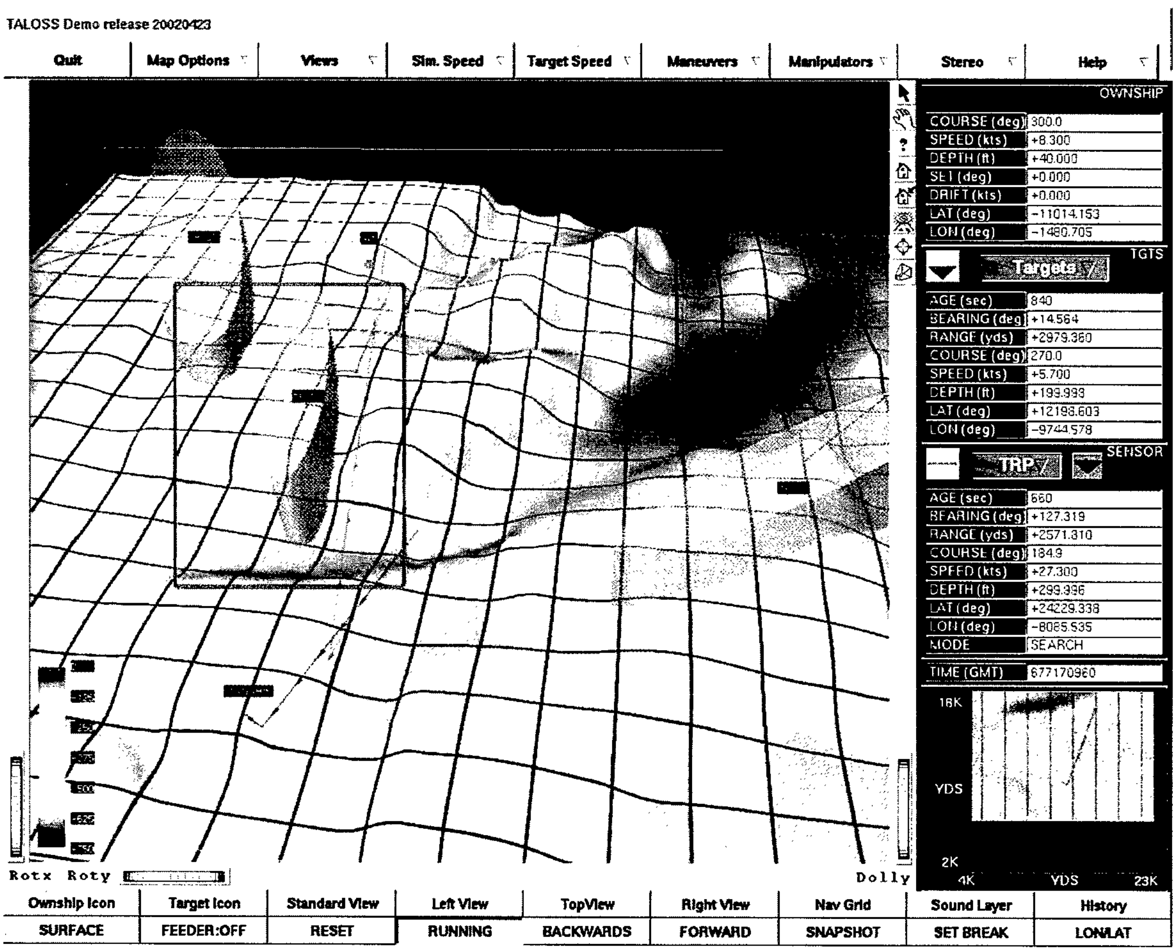


Figure 2.1-3 Inventor-based TALOSS on a Linux desktop computer.

2.1.1.5 TALOSS Project Description

A significant issue in today's Navy is the effectiveness with which naval combat systems can be operationally integrated to yield maximal battlespace awareness for the commanders and crews of all vessels involved. A critical requirement is a common operational/tactical picture. Information superiority can be achieved through a better awareness and understanding of the battlespace. Creating a detailed cognitive picture of the undersea battlespace is vital for the success of the undersea warfare mission. The challenge in achieving "speed of command" is in developing an awareness and understanding of the entire battlespace.

Traditionally and currently, decision makers develop a "mental model" of the battlespace by assimilating data from multiple two-dimensional (2D) displays and paper plots. In situations requiring immediate action, the mental processing required to extend 2D representations to a third dimension uses valuable time and energy. A significant issue in this concept pertains to the effectiveness with which naval combat systems can be operationally integrated to yield maximal battlespace awareness for the commanders and crews of all vessels involved.

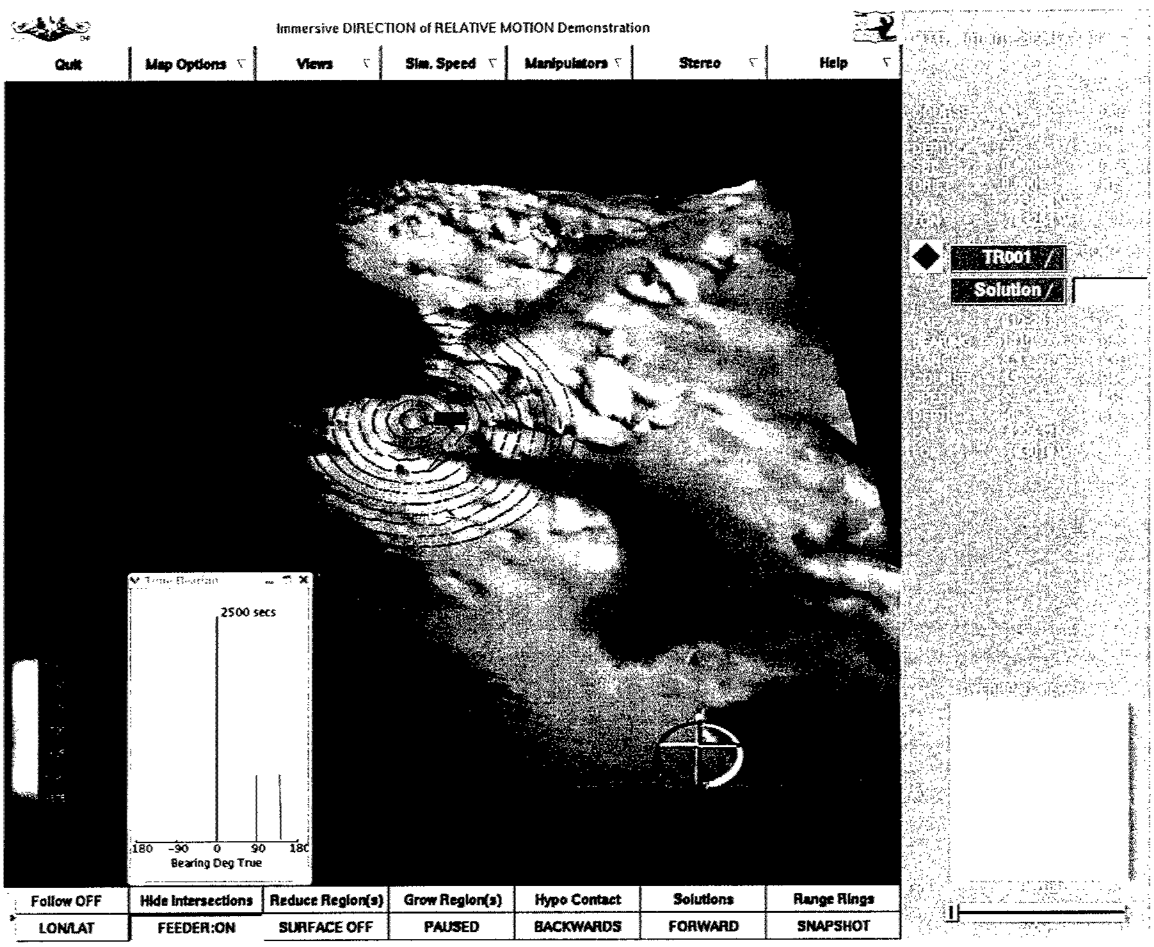


Figure 2.1-4 DGL based TALOSS on Linux desktop computer.

Advances in three dimensional (3D) presentation tools coupled with the continuing increases in computer power make the use of 3D visualization techniques to alleviate the mental information processing issues achievable. Computers today possess a greater capacity to support the modeling and processing of the types of complex information that the undersea environment requires. The combination of 3D visualization software and current/future computational resources provides the opportunity to generate detailed acoustic and environmental models and enables the depiction of the undersea domain in a manner that is more natural and robust than ever before. High-speed computers make it possible to include discrete simulation models of tactical systems as well as physically realistic simulation models of other mission critical C&C activities such as underwater acoustic phenomena related to undersea warfare.

In fleet systems today, Target Motion Analysis (TMA) operators view only a depth slice of the ideal conical angle. Target localization is manually (operator) intensive. Probabilistic estimators are not generally invoked, as the scenarios do not often lend themselves to an observable solution. The operator spends valuable time trying to determine the best solution.

TALOSS is a joint project coordinated by NUWC with NRL and Virginia Tech's UVAG group and funded by ONR NAVCIITI Task2.1a. It addresses the problem of visualizing the 3D nature of measurements received from a submarine towed line array and comprises three main areas of research in the context of a submarine Anti-Submarine Warfare (ASW) mission. The first area of research pertains to the design and development of algorithms that model the undersea environment and ship kinematics. The second area of research focuses on the identification, implementation, and validation of data representation techniques. The last area of research focuses on the development of principles for guiding 3D development for undersea information and on the 'value added' in the use of 3D techniques.

The TALOSS Project has two branches: The first branch involves trying to improve the current system used in the submarines, by designing a 3D visualization interface that can be effectively used with a monitor screen, with the input devices normally found on a submarine (keyboard and trackball). The second branch tries to find which tactical scenarios are best described in a 3D display, like CAVE or I-Desk, cut due to space limitations are not feasible for use on board submarines.

The success of the TALOSS project from NUWC's viewpoint motivated NUWC to submit this project for consideration as a Future Naval Capabilities (FNC) project, but due to budget cuts the Office of Naval Research (ONR) did not fund TALOSS as an FNC project. Recently SGI has ported Performer to run on both Microsoft Windows and Linux. SGI is now considering porting Performer to Mac OS-X Panther. If SGI successfully ports Performer to Windows and Mac OS-X, the NUWC can port the existing Performer based and OpenGL based TALOSS code in the future when funding becomes available. As a future benefit to the Navy, Performer, Inventor, and OpenGL based TALOSS code have been archived and made accessible from the NAVCIITI Task 2.1 Web site. This same Web site with archived code downloads has been archived on Compact Disks (CD) and will be distributed to NUWC and others interested upon request. DIVERSE and all derivative software and applications are licensed "open-source" (GPL/LGPL)

2.1.2 Facilities Developed for Task 2.1

2.1.2.1 The existing NSF CAVE Virtual Environment (VE) system was moved and upgraded

Existing CAVE and I-Desk VE systems were used extensively for the NAVCIITI project. The existing CAVE VE system was funded at $890,000 by the NSF Academic Research Infrastructure (ARI) program, Dr. Ronald Kriz PI, with $650,000 in cost sharing matching funds from Virginia Tech, that were exclusively used to purchase the equipment to build the CAVE VE system at the Virginia Tech Corporate Research Corporation (off-campus) while the Advanced Communication and Information Technology Center (ACITIC) was under construction on campus. The NSF-ARI proposal outlined how Virginia Tech in partnership with the NSF National Center for Supercomputing Applications (NCSA) would support and include the CAVE as part of the ACTIC building, now called Torgersen Hall, which would be supported as a multidisciplinary resource on campus. Five colleges contributed over $300,000 in cost sharing funds with 30 proposal CoPIs from four colleges. Prior to any of the ONR grants, Dr. Kriz worked with the university architects, as director of the University Visualization and Animation Group (UVAG) to create a unique space in the ACITC building that would realize future uses of the CAVE VE system, e.g. an open pit in the floor of the CAVE was designed to include a glass floor with a projection system below the CAVE floor and extra ceiling height was constructed above the

CAVE with a ceiling projection system as well. Hence, the ACITC building was designed to provide a working space for a six-sided fully enclosed CAVE VE projection system.

Since there was no returned overhead associated with the NSF-ARI grant, Virginia Tech sought new proposals that would provide funds to move and upgrade the existing NSF CAVE VE system. Three ONR grants provided the necessary funds: MURI, DURIP, and NAVCIITI. The ONR MURI/DURIP Virtual Craneship grants, Professor Ali Nayfeh, PI, provided funds that were used to move and upgrade the CAVE into the ACTIC building (Torgersen Hall) by constructing a six-degree (6-DOF) of freedom motion platform in the floor of the CAVE. There were insufficient funds to build a six-sided CAVE with a ceiling and glass floor projection system -- only a motion platform was created in the floor of the existing NSF CAVE VE system. With *First year* NAVCIITI funds, Professor Ali Nayfeh, NAVCIITI Co-PI, were used to upgrade the NSF CAVE tracking system with an Intersense IS-900 and a SGI-Cirrus video capability with audio serial option for controlling the various I/O devices related to the motion platform in the floor of the CAVE. After *year one* NAVCIITI funds, Dr. Ronald Kriz, NAVCIITI Co-PI, were used to provide maintenance on the existing upgraded NSF CAVE VE system. The overlap between NSF and ONR CAVE related grants was coordinated by Dr. Ronald Kriz, Director of the University Visualization and Animation Group of the ACITC, who supervised the construction of the motion platform in the floor of the CAVE in the ACITC building on campus. Dr. Lance Arsenault, who was working for Caterpillar Inc. at NCSA's CAVE, was hired by Professor Nayfeh to build motion platform hardware system for the ONR MURI/DURIP Virtual Craneship project, similar to those built for Caterpillar at NCSA's CAVE. The reader is referred to Professor Nayfeh's NAVCIITI report for accomplishments and costs associated with the Virtual Craneship project. Two documents associated with the construction of the motion platform in the CAVE floor can be accessed at the NAVCIITI Task 2.1 Web site: 1) Chronology of CAVE Floor Construction in ACITC (Torgersen Hall), and 2) Timeline on the CAVE Floor 6-DOF Motion Platform Construction. The construction of a motion platform in the floor of the CAVE at Virginia Tech represents a significant effort and unique resource for future Navy research projects that will be facilitated under the Virginia Tech ICTAS initiative as previously described.

2.1.2.2 DIVERSE VE API

Unique to the motion platform embedded in the CAVE VE system was an Application Programming Interface (API) called DIVERSE that would facilitate the development of VE applications in the CAVE. Unlike previous CAVE VE systems the UVAG CAVE VE system required coordination of a variety of I/O devices: 1) 6-DOF motion tracking system for both the CAVE user's head and hand, 2) 6-DOF motion platform embedded in the CAVE floor, and 3) future hand held I/O devices such as 6-DOF haptic force feed-back systems and pocket PCs anticipated as future command and control devices for Task 2.1. Dr. Arsenault conducted a survey of current VE software systems and concluded that there was no existing VE API that could handle the multiple I/O devices needed for the ONR Virtual Craneship project. With *second year* NAVCIITI Task 2.1 funds, Dr. Ronald Kriz, NAVCIITI Co-PI, the DIVERSE (Device Independent Virtual Environment: Reconfigurable, Scalable, and Extensible) API was created both for the Virtual Craneship and Task 2.1. Dr. Lance Arsenault developed the DIVERSE ToolKit (DTK), which was used to "glue" the various I/O devices used in the upgraded NSF CAVE VE system with the motion platform and Mr. John Kelso developed the DIVERSE interface to Performer (DPF) that was used to create three-dimensional (3D) scenegraphs, which were controlled by various DTK I/O devices. Together DPF and DTK were used for a variety of NSF and ONR VE projects. Several other companies, Lockheed Martin Astronautics, TASC's IT Division of Northrup Gruman, and the National Institute for Standards and Technology (NIST-Dept. of Commerce) were also interested in using DIVERSE DTK and

DPF and co-funded the development of DIVERSE VE API. Hence, the DIVERSE API was licensed under the GNU Public License (GPL) as a shared "open-source" resource for all participants. DIVERSE can be accessed at the Sourceforge Web site: http://diverse.sourceforge.net. DIVERSE related applications can be accessed at the NAVCIITI Task 2.1 Web site: http://www.sv.vt.edu/future/cave/resprj/navciiti/nuwc_task2-1/task2-1.html.

2.1.3 Accomplishments

2.1.3.1 Collaborative CAVE Console (CCC): based on the CAVE-library API

In the first year we developed a networked collaborative Virtual Environment (VE) application called the Collaborative CAVE Console (CCC), which was based on the University of Illinois VE API called the CAVE-Library and the Electronic Visualization Laboratory (EVL) networked VE application called LIMBO. The CCC VE application was working prototype that provided a basis for creating future networked tactical interfaces: http://www.sv.vt.edu/future/cave/software/ccc/

2.1.3.2 Atomview and CCC_atom

In the first year the CCC was combined with the existing Performer based application called Atomview to demonstrate how existing VE CAVE applications could be extended as a network collaborative application called CCC_atom: http://www.sv.vt.edu/future/cave/software/cccatom/.

2.1.3.3 CAVE motion platform construction

The construction of the motion platform was funded by ONR MURI/DURIP grant, Professor Ali Nayfeh PI, built by Dr. Lance Arsenault and coordinated by Dr. Ronald Kriz, as Director of the University Visualization and Animation Group (UVAG) and PI on the NSF ARI Grant. The motion platform was an addition to the existing NSF ARI CAVE grant. Accomplishments are summarized in two documents which can be accessed at the NAVCIITI Task 2.1 Web site: 1) Chronology of CAVE Floor Construction in ACITC (Torgersen Hall), and 2) Timeline on the CAVE Floor 6-DOF Motion Platform Construction.

2.1.3.4 The DIVERSE VE API supports both Performer-based and OpenGL-based versions

The DIVERSE VE API under went several revisions as reflected in the original Web site, http://www.diverse.vt.edu/old_index.html which was Performer-based, as well as the recent OpenGL-based Sourceforge Web site: http://diverse.sourceforge.net. Both are "open-source" web sites.

2.1.3.5 TALOSS

Several versions of TALOSS were created as the project with NRL and NUWC evolved. The current DGL version of TALOSS is documented and can be downloaded from the NAVCIITI Task 2.1 Web site: http://www.sv.vt.edu/future/cave/resprj/navciiti/nuwc_task2-1/task2-1.html.

2.1.3.6 DIVERSE Adaptable Display System (DADS) Linux VE computer system.

The Linux DADS system is a well documented DIVERSE application, that was designed to be adapted to future VE projection systems, e.g. tiled walls. Currently the DADS system at Virginia Tech is used to control the CAVE projection system. Performer-based DIVERSE applications will run on the Linux DADS system and are fully backward compatible with previous legacy

Performer-based code that ran on the SGI Irix computer. All the Performer programmer needs to do is load a new DADS DSO with legacy Performer code. Detailed information about the DADS computer system is available both on the DIVERSE Sourceforge and the NAVCIITI Task 2.1 Web sites. PNY Technologies recognized DADS on their case study Web site: http://www.pny.com/pressroom/caseStudies/vc.asp.

2.1.3.7 OpenGL DIVERSE interface to Performer (DPFGL)

A new OpenGL interface to Performer (DPFGL) was created that will allow OpenGL programmers to run their OpenGL legacy code on the new Performer-based DADS Linux computer system. This is as simple as change the GLUT interface to the DPFGL interface. This interface is relatively new, as is the DADS system. Preliminary results show that an experienced OpenGL programmer, who was using the Kitware Inc. Visualization ToolKit (VTK), experienced little difficulty running legacy OpenGL VTK code on the new Linux DADS VE CAVE system. DPFGL can be downloaded from the DIVERSE Sourceforge Web site.

2.1.3.8 DADS motion platform

This was largely motivated by the fact that the SGI Power Onyx CAVE computer system was eight years old and would most likely no longer be supported by SGI. Since the motion platform in the floor of the CAVE is currently controlled through an RS-422 port on the SGI CAVE computer, the DADS Linux system was upgraded with an RS-422 card and the old DTK 2.1 moog code was modified to run on DTK 2.3.2 on the DADS system. A DADS motion platform user's guide with simple examples will be posted on the NAVCIITI Task 2.1 web site which will provide continuity for future Navy projects that will inevitably have to use the motion platform on the new DADS Linux computer system when the Virginia Tech SGI CAVE computer system becomes obsolete.

2.1.4 Importance of the Task

The work performed for the NUWC-POC resulted in a proposed Future Navy Capability (FNC). As evidence, an unsolicited letter from NUWC is copied below in italics.

" The work performed at VT under the NAVCIITI project has had an invaluable impact on the Navy's initiatives to assess virtual reality technology within the context of warfighter needs. These needs include tactical, training, and planning operations. VT has developed a unique application tool called DIVERSE which provides a versatile backbone for combining a broad spectrum of applications and interface devices, and will soon be extended to an Open GL version, which will allow the software to run on a broad spectrum of machines from UNIX to SG to LINUX PCs. This will facilitate the Navy's ability to get VR programs and devices operational on shipboard and submarine systems quickly. A specific beneficiary of the work conducted under NAVCIITI funding is a program entitled "Visualization for Multiwarfare Planning and Execution" - an Office of Naval Research (ONR) funded effort led by the Naval Undersea Warfare Center and the Naval Research Laboratory. This project rated as ONR's best C4I project at their May 2001 review, specifically addresses the "value added" of 3D visualization and VR in the context of the submarine passive localization problem. In FY03 this program will evolve into a Future Naval Capabilities (FNC) effort aimed at developing a 3D VR-based sensor-to-shooter decision aid for submarines. Without the support of VT and specifically the NAVCIITI project, which laid the necessary groundwork and developed the necessary expertise at VT, this project would neither have evolved as quickly as it

has and would not have had the tool (DIVERSE) we are using to assess VR options or to integrate VR technology into the current UNIX-based Navy submarine combat system (Open GL DIVERSE). VT has done an excellent job under NAVCIITI support in furthering the state of the art in virtual reality, has developed an outstanding VR tool in DIVERSE and has developed outstanding scientists who have made significant contributions to Navy programs."

Kenneth Lima (Principal Investigator) and Richard Shell (Technical Lead Engineer) at the Naval Undersea Warfare Center, Newport, RI -"Visualization for Multiwarfare Planning and Execution".

2.1.5 Productivity Summary

2.1.5.1. Journal Publications

1. J.T. Kelso, S.G. Satterfield, L. E. Arsenault, P.M. Ketchan, R.D. Kriz, "DIVERSE: A Framework for Building Extensible and Reconfigurable Device-Independent Virtual Environments and Distributed Asynchronous Simulations", *Presence*, Vol. 12, pp. 19-36, 2003.
2. Churcher, N. , Irwin, W., and Kriz. R., "Visualising class cohesion with virtual worlds", Conferences in Research and Practice in Information Technology Series, Proceedings of the Australian symposium on Information visualization, Adelaide, Australia, Vol. 24, pp. 89–97, 2003.

2.1.5.2 Conference Presentations

1. J.T. Kelso, L.E. Arsenault, R.D. Kriz, R.D., and F. Das-Neves, "DIVERSE: a Software Toolkit to Integrate Distributed Simulations and Heterogeneous Virtual Environments", Joint Aerospace Weapon Systems: Support, Sensors, and Simulations Symposium Exhibition, San Diego, CA, July 22-27, 2001.
2. R.D. Kriz, F. Das-Neves, and J.T. Kelso, "Virtual and Collaborative Design Environments," ONR Undersea Weapon Simulation Based Design Workshop, College Park, MD, June 13-15, 2001.
3. A. Nayfeh, L. Arsenault, D. Mook, and R. Kriz, "Virtual Environment for Ships and Ship-Mounted Cranes," ONR Undersea Weapon Simulation Based Design Workshop, College Park, MD, June 13-15, 2001.
4. A. Nayfeh, L. Arsenault, D. Mook, and R. Kriz, "Virtual Environment for Ships and Ship-Mounted Cranes," Undersea Weapon Simulation Based Design Workshop, Newport, RI, June 7-9, 2000.

2.1.5.3 Patents, Software, Etc.

Software (all software licensed GPL/LGPL)

1. DIVERSE: http://diverse.sourceforge.net
2. Collaborative Toolkit for DIVERSE: http://www.sv.vt.edu/future/cave/software/D_collabtools/D_collabtools.html
3. X-Wand: http://www.sv.vt.edu/future/cave/software/D_XWand/D_XWand.html
4. D_Atomview: http://www.sv.vt.edu/future/cave/software/D_atomview/D_atomview.html

2.1.5.4 Honors and Recognitions

1. Keynote Speaker along with Dr. Lance Arsenault and Mr. John Kelso at the ONR Undersea Weapon Simulation Based Design Workshop, "Virtual and Collaborative Design Environments", College Park, MD, June 13-15, 2001.

2.1.5.5 Student Advising

M.S. Students Completed

1. Gregory Edwards, "Performance and Usability of Force Feedback and Auditory Substitutions in a Virtual Environment Manipulation Task", Chair Woodrow Barfield, ISE, November 2000.
2. Andrew Ray, "A Metrics Study in Virtual Reality", Co-chair: S. Henry, C.S. and R.D. Kriz, ESM, May 2004.

Students Supported

1. Greg Edwards, ISE, 1999-2000
2. Fernando das Neves, CS, 1999-2003
3. Andrew Ray, CS, 2003-2004

2.1.5.6 Faculty Supported

1. Lance Arsenault, Assistant Research Professor, CS, 1999-2001
2. John Kelso, Assistant Research Professor, CS, 1998-2003

2.1.5.7 Other Personnel Supported

Undergraduate Research Assistants

1. Andrew Ray, 2001-2003
2. Daniel Larimer, Summer 2004

Task 2.3 Usability Engineering - Debbie Hix & Joe Gabbard

2.3.1 Review of Task Activities

Year 1

We developed and refined an initial sequential usability engineering process, focusing on usability evaluation. In particular, our process moves from guidelines-based expert evaluation to user-based formative evaluations to comparative, summative evaluations in a cost-effective and efficient manner. We have used this process on several large Navy applications with great success. In fact, a publication on our work was awarded "Best Technical Paper" at the VR'99 conference, the premiere international conference in virtual environments. [Citation for this paper: Deborah Hix, Edward Swan, Joseph Gabbard, Mike McGee, Jim Durbin, and Tony King, "User-Centered Design and Evaluation of a Real-Time Battlefield Visualization Virtual Environment" *Proc. IEEE Virtual Reality '99* (Houston, TX), March 1999.]

Year 2

We began integrating our efforts into other NAVCIITI areas. Specifically, an eye-tracking service was integrated into DIVERSE and an eye-tracker was integrated into the existing Dragon (software from NRL) application. By summer 2001, we had a "usability evaluator's workstation" prototype and several multi-modal interaction techniques prototypes. For more details, see NAVCIITI Report 10.

Year 3

During the course of NAVCIITI *year three*, we accomplished the following tasks in support of our overall NAVCIITI research tasks and goals. For more details, see NAVCIITI Report 19.

1. Hired and trained additional programmers.
2. Installed additional power and battery backup capabilities.
3. Designed and developed an electro-mechanical device used to sense and report the (dynamic) angle of our Immersive Workbench (IWB).
4. Upgraded and ported all previous software to Linux-based DIVERSE systems.

Year 4

Accomplishments for *year four* are summarized below. For more details, see NAVCIITI Report 25.

1. Integrated eye tracking calibration and real-time monitoring into the evaluator's workstation.
2. Developed software driver to support stereo graphics on the Linux platform. This enabled our evaluator's workstation to be presented in stereo on a portable laptop.
3. Further developed DIVERSE-based software tools to support multi-modal interaction on the immersive workbench.
4. Evaluated the use of the touch screen as a multimodal input device.
5. Further developed software tools to support multi-modal interaction.
6. Further developed software tools to support the usability engineering process.
7. Codified research plans to examine how the real-world background may effect AR visual user interface design.

8. Continued to leverage ongoing Navy usability engineering opportunities in order to identify needed modifications and effective extensions to the usability engineering process, especially for developing VE/AR systems.

Year 5:

Accomplishments for *year five* are summarized below.

1. Finalized and published results from our user-based evaluations to examine real-world backgrounds that may affect AR visual user interface design.
2. Planed second user-based study to examine effects of real-world backgrounds and lighting on AR visual user interface design.
3. Conducted user-based study to examine heads-up multi-modal interaction techniques for mobile AR and effects of "context switching" using those techniques.

2.3.2 Facilities Developed for Task

Our equipment and lab facilities were greatly expanded by our NAVCIITI work. Additions to our core usability engineering capabilities include:

1. An Immersive Workbench.
2. An eye tracking system.
3. A state-of-the-art motion tracking system for VR and AR work.
4. An augmented reality display (SONY Glasstron).
5. Numerous computers to support 3D development and experimentation.

These equipment purchases allowed us to set up Virginia Tech's first registered augmented reality testbed. This testbed is being leveraged in our other NAVY based work, including our support of the Battlefield Augmented Reality System (BARS). Contact: Larry Rosenblum: ONR/Naval Research Lab.

2.3.3 Accomplishments

1. May-July 2001– Planned Virginia Tech FDI program presentation on VEs including a session on some of our NAVCIITI work.
2. July 2001 – Hosted 3-day research working session with NRL's Dr. J. Edward Swan.
3. July 2001 – Finalized one-year contracts on two new Navy-based sponsored programs that will allow us to further leverage our NAVCIITI research efforts:
   - "Battlefield Information Display Technology", $40K, Concurrent Technologies and Office of Naval Research.
   - "Usability Engineering of Dominant Battlefield Command", $100K, Concurrent Technologies and Office of Naval Research.
4. August 2001 – Performed usability evaluation of Dominant Battlefield Command application, an IWB application with multi-modal input.
5. November, December 2001, January 2002 – Coordinated ongoing funded program efforts (reported in FY03 Q3 report) with NAVCIITI Task COTR Larry Rosenblum.
6. November 2001 – Gave invited presentation at Indian Head, Maryland, on usability engineering process.
7. December 2001 – Gave presentation to ONR project manager on BARS and related NAVCIITI work in Washington DC.
8. January 2002 – Discussed collaboration on VR eye tracking issues with NRL's BARS group.

9. February 2002 – Attended Operational Knowledge Management Consortium conference in Virginia Beach.
10. March 2002 – Attended IEEE VR2002 annual conference in Orlando.
11. April 2002 – Presented presentation on Usability Engineering to NAVSEA Dahlgren Division.
12. April 2002 – Hosted 4-day research working session with NRL's Dr. J. Edward Swan.
13. June 2002 – Presented Usability Engineering efforts to ONR Augmented Reality Review.
14. August 2002 – Participated in NAVCIITI Program Review, visited by Mr. Gary Toth.
15. November – December 2002 – Collaborated with a large government contractor to identify and prioritize critical research issues in a head-worn retinal writer display to be used in AR systems.
16. January 2003 -- Provided usability engineering input to Virginia Tech's response to ONR BAA# 03-003.
17. January 2003 -- Invited by large government contractor to provide usability engineering expertise to Army effort that incorporates 3D VR-like graphics and user interaction.
18. February 2003 – Participated in Augmented Reality review at the Naval Research Lab; presenting our recent usability engineering activities for the BARS program.
19. April 2003 – Invited by government contractor to potentially collaborate on usability engineering activities for the next-generation Navy Tomahawk missile UI development effort.
20. July 2003 – Participated in ONR review of NAVCIITI activities at Virginia Tech.
21. July 2003 – Participated in ONR review of NAVCIITI activities at Virginia Tech.
22. August 2003 – Co-hosted Jim Foley and Rob Jacob at Virginia Tech to discuss HCI at Virginia Tech. We also discussed our NAVCIITI work and other Navy-related activities.
23. September 2003 – Hosted Alan Thomas from NSWCD. Gave presentation on our NAVCIITI work as well as other Navy efforts. During the visit, we also co-ordinated his meeting with 6 other HCI researchers.
24. September – Attended semi-annual ONR, AR Review, in Orlando Florida; gave detailed presentation Presented our AR work, including AR study on text drawing techniques and comprehensive survey of AR literature on hardware design issues in AR.
25. October – Co-hosted Shuman Zhai from NSWCD. Gave presentation on our NAVCIITI work as well as other Navy efforts.
26. November 2003 – Participated in user training at SBCCOM, Aberdeen Proving Grounds, MD.
27. November 2003 – Invited presentation at NUWC, Newport, RI, entitled "Human-Computer Interaction (HCI) and Usability Engineering at Virginia Tech".
28. December 2003 – Hosted Dr. Edward J. Swan II from the Naval Research Lab for collaborative discussions on a number of user-based evaluations that we are jointly planning.
29. January 2004 – Hosted Upul Obeysekare and Tracy Brown from Concurrent Technologies to discuss and receive a monocular Microvision Nomad display. We also discussed our plans and efforts under the BIDT program, which is one of our Navy-based UE projects.
30. January 2004 – Several telecons with the Naval Research Lab to discuss ongoing user-based studies at both locations.
31. March 2004 – Conducted a full-day tutorial on conducting user-based studies in VR/AR at IEEE VR 2004, Chicago, IL. This tutorial was done in collaboration with Edward Swan of the NRL VR Lab.
32. May 2004 – Submitting a paper entitled:
33. Joseph L. Gabbard, J. Edward Swan II, Mark A. Livingston and Deborah Hix, "*Visually Active User Interfaces for AR*", currently submitted to ISMAR 2004.

34. May 2004 – Presented a panel discussion at the Undersea HSI Symposium - May 3-5, 2004. Newport, Rhode Island.

2.3.4 Importance of the Task

Our results produced usable NAVCIITI software components. Our results also included cost-effective methods for evaluating VE user interfaces for Naval applications. Further, this work continues our long-term (nearly 12 years) collaboration with the Naval Research Laboratory in Washington DC.

Our user-based AR studies have provided contributions to AR user interface design (and thus are applicable to Navy/Marine AR-based applications), by providing:

1. Empirical evidence regarding effectiveness of text drawing styles in conveying text-based information to mobile outdoor AR users.
2. Rankings of the components of text drawing styles by several different measures of effectiveness.
3. Guidelines to aid designers in choosing among various drawing styles and components of drawing styles produced by this study and those resulting from other studies.
4. A list of candidate parameters, metrics and values (ranges of values) that may support an active AR display system.

Our NAVCIITI research has also been used to assist our usability engineering support to the Battlefield Augmented Reality System (BARS). Contact: Larry Rosenblum: ONR/Naval Research Lab.

PROJECT 3

Tasks 3.1, 3.2, 3.3, and 3.4 Digital Ships and Knowledge Space - Rick Habayeb and Ali Nayfeh

3.1.1 Review of Task Activities

The objective of Project 3 is to create a digital ship environment to demonstrate the utility of the knowledge space in integrating information technologies, and to support the ship Command and Control functionality. This report covers the activities of all these tasks. During the first year, the effort started by defining the digital ship information system and determining the value and metrics of the command and control functionality. Three-tier architecture composed of client tier, middleware (enterprise logic) and applications tier, and database tier was selected for the implementation of the Digital Ships testbed. Subsequently, in years two and three our effort concentrated on creating and building the infrastructure of the digital ship testbed. The infrastructure was designed with sufficient capacity and flexibility to provide the visualization capability for integrating and evaluating the NAVCIITI technologies. Later on, the effort concentrated on mapping three important models into the Digital Ships Laboratory. The first model is an air defense model called Dynamic Bench (DYNBENCH). The second model is the Common Command Decision of the Aegis weapon system. In order to structure the CC&D, the Habayeb Sensor-to-Shooter loop was used to establish the architecture of the CCD. A masters thesis was written on the modeling of the sensor-to-shooter loop using the Unified Modeling Language (UML). The third model is the Capability Degradation model. The model was developed using prototype simulations and software using agent technology to model the shipboard systems during normal operations and threat condition. Our NAVCIITI quarterly Reports 16, 17, 18, 19, 20, and 21 of years two, three and four discuss these models in detail. During the year three, the ONR sponsor requested that we support PMS 377 the program management office of the next generation command and control ship JCC(X). We worked diligently with the program office and their contractor. Our task was to model the JCC(X) system using the UML. The JCC(X) Draft Architecture was used as the domain information source. Use cases, and logical views were derived and analyzed. The findings were documented and reported to the program office. More details on this effort are reported in Reports 18 and 19. Our JCC(X) modeling task has inspired us to develop the Generic Environment Modeling (GEM). The GEM is a component-based simulation and has a flexible framework through which the combat system and the C&C of the JCC(X) systems can be simulated. Our Reports 21, 22, 23, 24, and 25 provide more details on the GEM. Early on, the visualization effort of this task concentrated on integrating the Digital Ships Laboratory with the CAVE facility. Our CAVE facility is unique, because the base of it is a motion platform which can be used to simulate ship motion under various sea states. The embedded platform provides motion in six degrees of freedom. This capability can be used in physics-based simulation. While modern scientific simulation and modeling provide more realism and accuracy, however, increased complexity and computing requirements are serious side effects. Toward this end, this task created a simulation facility consisting of parallel computing and visualization platforms geared towards the real-time execution of such simulation. Currently, the facility consists of a mixed visualization and computing clusters, and a One-Wall CAVE as discussed in Reports 26, 27, and 28.

3.1.2 Facilities Developed for the Task

Several key facilities were developed including the Digital Ships Laboratory, the cluster computing and visualization facility, and the One-Wall CAVE laboratory. The developed facilities are discussed in the following.

1. DSL (Digital Ships laboratory): This is a three-tier architecture facility to represent the ship information system. This facility is discussed in detail in Reports 16, 17, 18, and 19.
2. Common Command and Decision (CC&D) Model of the Aegis Weapon System. This is a MATLAB and Simulink model of the CC&D to simulate the sensor multi-track issue.
3. Ship Air Defense Model using the DYNBENCH representation into a three-tier Architecture and operational scenarios generator called DS3 Distributed Sensor Simulation System.
4. UML representation of the JCC(X) command and Control, it is discussed in details in Reports 21, 22, and 23.
5. Generic Environment Modeling (GEM): The GEM facility is a component-based environment that will allow flexible and scalable simulation of operational scenarios.
6. Cluster Computing Laboratory: This facility will be used to perform physics-based simulation of ships under various sea states. Details about the computing cluster are given in Reports 22, 23, and 24.
7. Visualization Cluster laboratory: The visualization cluster will provide an order of magnitude in rendering capability at much lower cost than using conventional method.
8. One-Wall CAVE Facility: The One-Wall CAVE facility provides three-dimensional visualization using a two-projector and dark screen system. It is a half-way house to the more expensive CAVE.

3.1.3 Accomplishments

Accomplishments have been achieved in several research areas within the framework of the Digital Ships environment using the NAVCIITI-developed facilities discussed in Section 3.1.2. A brief description of them is presented in the following subsections.

3.1.3.1 Digital Ships Infrastructure

A three-tier architecture consisting of a client tier, ship information application tier, and a database tier. Three-tier architecture provides great deal of flexibility, scalability and performance in modeling the ship information system as discussed in Report 16.

3.1.3.2 Ship Air Defense Model

The ship air defense model called the Dynamic Bench uses simulated sensors and actuators, and employs real algorithms for filtering, evaluating, acting, and guidance. The model was restructured into three-tier architecture to make more flexible and scalable as discussed in Reports 17, 18, and 19.

3.1.3.3 Common Command and Decision (CC&D) of the Aegis Weapon System

The CCD model was developed as an ad hoc architecture that resulted in several shortcomings such as, lack of interoperability, excessive cycle time, and increased LCC. We applied the Habayeb sensor-to-shooter loop to analyze the CC&D model. We investigated two critical aspects of the CC&D model: reliability and synchronization further details are given in Reports 18, 19, and 20.

3.1.3.4 Ship Capability Degradation Model (SCDM)

The purpose of the SCDM is to monitor the health of the ship, identify anomalous conditions, report all monitored states, and make recommendations for remedial actions as needed. We used agent software to formulate and exercise the model. Reports 18, 19, and 20 provide further details on the SCDM.

3.1.3.5 JCC(X) UML-Based Modeling

The JCC(X) is the next generation command and Control ship. We used the JCC(X) Draft Architecture as the domain information source to create the UML representation of the JCC(X) functionalities. Use case view and logical (design) view of the JCC(X) are described in detail in Report 18. Further details on the JCC(X) modeling effort are provided in Reports 18, 19, 20, and 21.

3.1.3.6 Digital Ships Computing and Graphics Clusters

The goal of the project is to build an economical yet powerful testbed using off-the-shelf commodity hardware and open source software for use in prototyping cutting edge research in the fields of virtual and augmented reality systems. The facility consists of a mixed graphics and computing clusters with a collective processing power of over a billion IPS, memory capacity of 144 Gigabytes and storage capacity of over 2 Terabytes. Further details on the computing and graphics clusters are provided in Reports 23, 24, and 25.

3.1.3.7 Generic Environment Model (GEM)

A Command and Control platform has to perform many varieties of complex operations under variable environments. These complex operations demand the capability to perform a multiplicity of functions and tasks, e.g., communication, command decision, targeting, threat assessment, mission planning, battle management, and sensors netting. In order to support the multiplicity of missions, operations and scenarios, the simulation of the Command and Control platform must be flexible, scalable and adaptive to the changing environment. The need for extensibility in simulation leads us to creating the Generic Environment Model (GEM). The GEM is a component based environment, it has components that simulate hardware, software, and operators. These components are grouped into packages. The packages can represent the three Command and Control grids: sensor grid, information and knowledge grid and the shooter grid. Further details on the GEM are provided in Reports 19, 20, 21, and 22.

3.1.3.8 One-Wall CAVE

The One-Wall CAVE is a low-cost three-dimensional visualization environment using off-the-shelf hardware. It consists of a PC computer with dual video output (or two computers with single output), two projectors, two polarizing filters and matching viewing glasses. To achieve the stereo effect the computer generates two distinct images for the left and right eye. The two images are sent to the projectors, polarized by the lenses for a specific eye, projected onto a screen which preserves the left/right eye polarization, and filtered for each eye by matching-polarization glasses worn by the viewer. Further details on the One-Wall CAVE are provided in Report 27.

3.1.4 Importance of the Task

The overall objective of this task is to develop the modeling, simulation and visualization infrastructure of network centric environment, and the building blocks of the Navy ForceNet architecture. ForceNet is the NAVY vision for network centric warfare. Visualization environment such as the CAVE, One-Wall CAVE and tools such as, cluster rendering, Digital Ships, and Generic Environment Modeling are used to gain insight into the functionalities of Command and Control. The modeling and simulation environment of this task can be used to define the boundaries of the Command and Control functionalities and integrate technologies. Operational functionalities of Command and Control such as: situation awareness, mission planning, threat assessment, SRI (surveillance, reconnaissance and intelligence) and targeting are critical drivers of combat effectiveness. The modeling, simulation and visualization technologies supported by this task are very critical in creating realistic digital environment to evaluate the various Navy Command and Control technologies and scenarios. The task provides a very cost effective approach to conceptualize and design future Navy systems prior to sea trial and building them. Our investigation of the Common Command and Decision (CC&D) of the Aegis weapon system, the ship air defense model, and our UML application to the JCC(X) are examples of how this task can contribute to the Navy programs. The supporting technologies of this task will provide long term value in Sea Basing, Sea Shield and Sea Strike.

3.1.5 Productivity Summary

3.1.5.1 Journal Publications

1. S. K. Mazumder, A. H. Nayfeh, and D. Borojevic, ``A Theoretical and Experimental Investigation of the Fast- and Slow-Scale Instabilities of a DC-DC Converter," *IEEE Transactions on Power Electronics*, Vol. 16, No. 2, pp. 201-216, 2001.
2. M. F. Daqaq and A. H. Nayfeh, ``A Virtual Environment for Ship-Mounted Cranes," submitted for publication, *International Journal of Modeling and Simulation.*

3.1.5.2 Conference Publications

1. A. H. Nayfeh, ``Ship-Mounted Cranes," International Conference on Monitoring and Control of Marine and Harbour Structures, Genoa, Italy, June 1-4, 1999.
2. A. R. Habayeb, ``Image Guided Weapons," MSS (Military Sensors Symposia), Charleston, SC, November 1999.
3. A. Nayfeh, L. Arsenault, D. Mook, and R. Kriz, ``Virtual Environment for Ships and Ship-Mounted Cranes," Undersea Weapon Simulation Based Design Workshop, Newport, RI, June 7-9, 2000.
4. Z. Masoud and A. H. Nayfeh, ``Cargo Pendulation Reduction on Ship-Mounted Cranes," Invited Lecture - 3rd International Workshop on Structural Control, Paris, France, July 6-8, 2000.
5. A. Nayfeh, L. Arsenault, D. Mook, and R. Kriz, ``Virtual Environment for Ships and Ship-Mounted Cranes," ONR Undersea Weapon Simulation Based Design Workshop, College Park, MD, June 13-15, 2001.
6. A. R. Habayeb, ``Systems Engineering and Effectiveness Analysis," 5th Annual Systems Engineering Conference, National Defense Industrial Association, Tampa, FL, October 2002.

3.1.5.3 Honors and Recognitions

1. A. H. Nayfeh, College of Engineering Dean's Award for Excellence in Research, 1998.
2. A. H. Nayfeh, Honorary Doctorate, Technical University of Munich, Munich, Germany, 1999.
3. S. K. Mazumder, A. H. Nayfeh, and D. Borojevic, ``A Theoretical and Experimental Investigation of the Fast- and Slow-Scale Instabilities of a DC-DC Converter," IEEE

Transactions on Power Electronics, Vol. 16, No. 2, pp. 201-216, 2001. [Winner of the IEEE Power Electronics Society Transactions Prize Paper Award for 2001.]

4. A. H. Nayfeh, Honorary Doctorate, Politechnika Szczecinska, Poland, May 2004.

3.1.5.4 Student Advising

M.S. Students

1. M. Al-Aqrabawi, "Combat System Modeling: Modeling Large-Scale Software and Hardware Application Using UML", 2001.
2. M. Daqaq, '"Virtual Reality Simulation of Ships and Ship-Mounted Cranes", 2003.
3. K. Channakeshava, "Utility Accrual Real-Time Channel Establishment in Multi-Hop Networks", 2004.

Students Supported

1. M. Al-Agrabawi, 1999-2000
2. M. Al-Bandakji, 2001-2003
3. A. Anwar, 2002
4. X. Bao, 2002-2003
5. M. Campbell, 1999-2002
6. K. Channakeshava, 2002
7. Y. Chen, 2002-2003
8. M. Daqaq, 2002-2003
9. A. Desouky, 2002-2003
10. L. Hu, 2002
11. K. Lamba, 2000-2003
12. J. Mukherjee, 2001-2002
13. A. Paul, 2002
14. L. Ramaswamy, 1999-2002
15. E. Sarigul, 2002-2003
16. S. Singh, 2001
17. R. Surendranath, 2002

3.1.5.5 Faculty Supported

1. L. Arsenault, Assistant Research Professor, 1998-1999

3.1.5.6 Other Personnel Supported

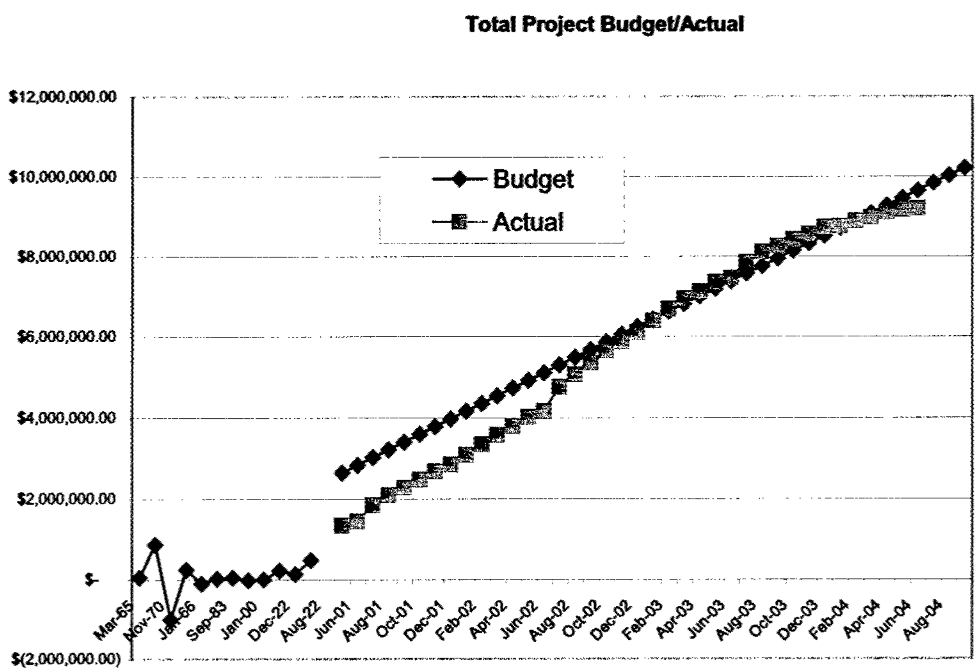
Post-Doc

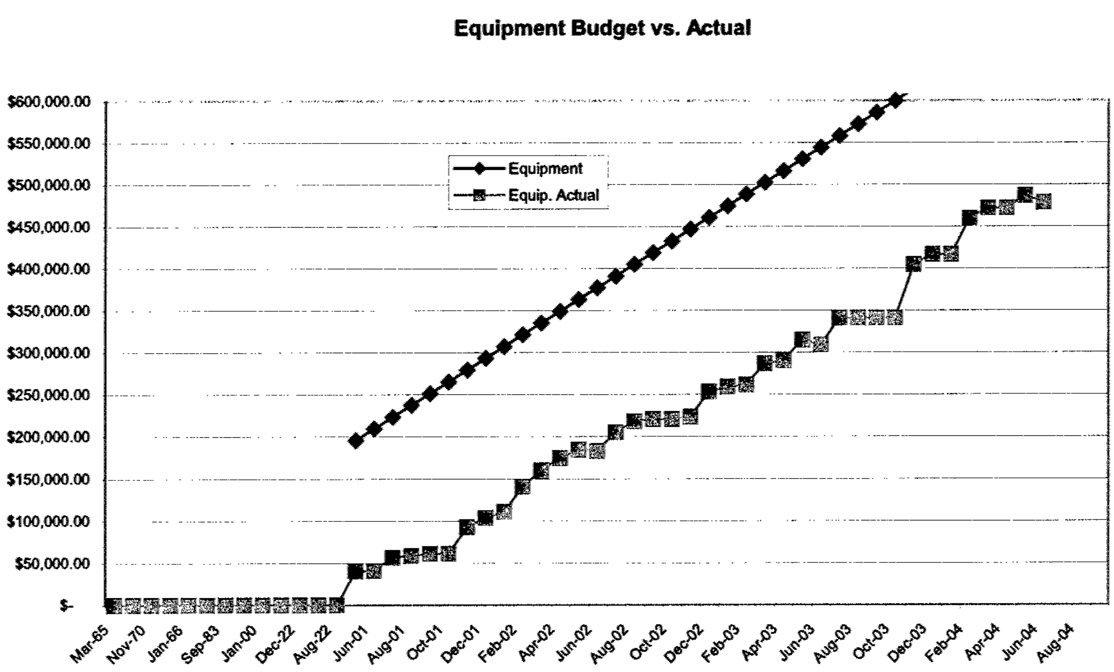
1. M. Arafeh, 2001-2003

Engineer

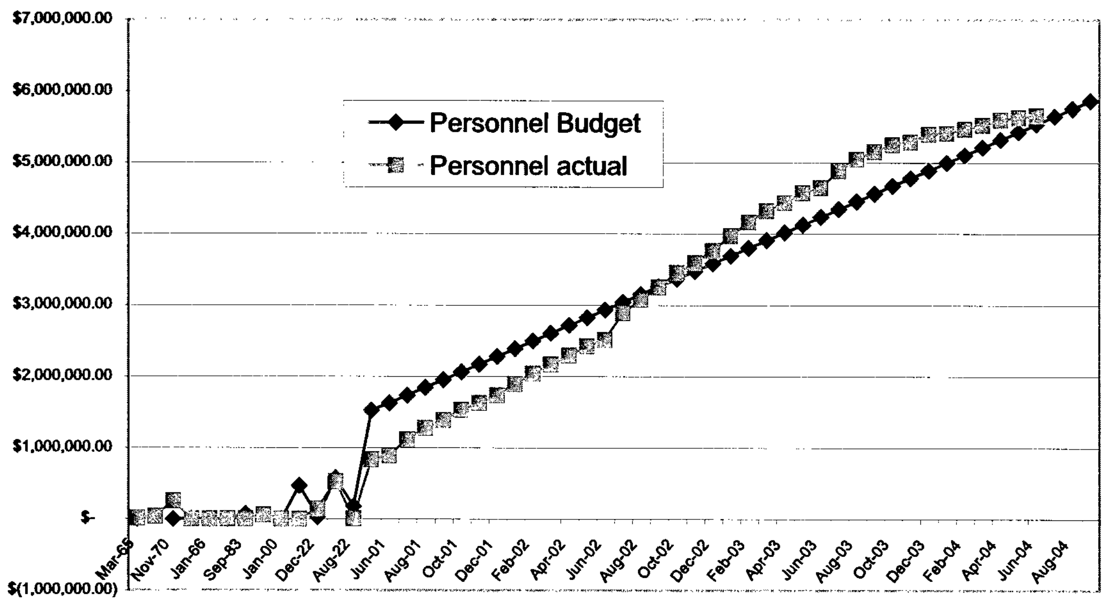
1. A. Desouky, April 2002-October 2003

FINANCIAL REPORT





Personnel Budget vs. Actual



Other Direct Costs vs. Budget