Evaluating IEEE 802.16 Broadband Wireless as a Communications Infrastructure for Public Safety Activities

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Abstract

Public safety wireless networks traditionally have been agency-owned land mobile radio (LMR) networks. However advances in technology are giving agencies new and more powerful options. Future 3G/3G+/4G public networks will be able to provide broadband access sufficient to support voice, video and data to desired coverage levels throughout a state. However, excessive reliance on these systems is unwise. Because their complex infrastructure relies extensively on both the electric power and wired telephone grids, they are highly vulnerable to man-made and natural disasters. In emergency situations, voice and data services provided by public network providers are likely to be overloaded or damaged and therefore unusable.

In contrast, broadband wireless access systems such as 802.16 (also known as WiMAX) can provide a low-cost, wireless metropolitan area network (MAN) infrastructure with capabilities that equal or surpass those of 3G/3G+/4G public wireless networks. WiMAX networks can be deployed for temporary or permanent use and can be much more easily isolated from large-scale failures in the electric power or telephone grids. In the proposed research, in partnership with local public safety agencies, we investigate the use of WiMAX in public safety operations.

Our research has two primary thrusts. The first is to deploy fixed-base and portable WiMAX testbeds in which 802.16 equipment will be deployed and tested. We will investigate the coverage capabilities of such networks and, working with Clemson University's police and fire departments and with the local municipal police department, we will provide a proof-of-concept demonstrating how 802.16 can be utilized by public safety organizations.

The second thrust of our research is to continue our performance modeling and analysis of the 802.16 MAC protocol. This component of the research leverages an 802.16 network-compatible simulation tool that we have developed by running a set of experiments that would be difficult to do in the testbed. For example, we will investigate how well WiMAX scales to support many VoIP and video flows or how configuration parameters can be used to tune performance under heavy loads.

One product of the proposed project is an operational 802.16 network that can be used for test and evaluation purposes by state or national agencies. A second deliverable will be a publicly available document that describes 'best practices' surrounding the use of WiMAX. The guide will include feedback from the local public safety organizations that have evaluated the network.

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1. Introduction

Public safety agencies are now augmenting their 900 MHz two-way voice radio networks with packet radio networks for obtaining data in the field. Several states have built dedicated wireless wide area networks to provide data and voice service that can be shared by all public service organizations in the state. For example, the South Carolina Department of Public Safety in conjunction with the Division of the South Carolina CIO operates the Palmetto 800 radio and mobile data system [PALM06]. Based on Motorola's dataTAC wireless data technology [dataTAC] and radioIP's Mobile TCP/IP Gateway products [RADIOIP], the Palmetto 800 provides voice and data connectivity over most of the state. Data rates up to 19 Kbps provide real-time access to data from the field. However, in interviews with Clemson University police and fire department officials and with the City of Clemson police department officials, some significant limitations of the system have been identified: connectivity with the network is spotty[1]; the mobile data terminals are expensive ($3000- $5000 each); and the low data rates are restrictive. In spite of these issues, the system has proven remarkably effective at allowing multiple organizations to interoperate during critical public safety operations.

Other public safety radio systems that are in use are based upon public cell phone and paging services. These systems provide paging, short messaging, personal communications (PCS), and cellular digital packet data (CDPD)[IMHA03]. The public switched wireless network technology is advancing rapidly. Future 3G/3G+/4G public networks will be able to provide broadband access sufficient to support voice, video and data to desired coverage levels throughout a state.

[1] The Palmetto 800 system coverage does not extend through all areas of the Upstate region of South Carolina which explains why coverage is 'spotty'.

Nevertheless, excessive reliance on these systems is clearly unwise. Because their complex infrastructure relies extensively on both the electric power and wired telephone grids, they are highly vulnerable to man-made and natural disasters. In emergency situations, voice and data services provided by public network providers are likely to be overloaded or damaged and therefore unusable[2].

An alternative set of technologies, including 802.11 mesh networks, 802.16 broadband wireless access (WiMAX) and future 802.20 mobile broadband wireless access, can provide a low-cost, wireless metropolitan area network (MAN) infrastructure with connectivity through the Internet to the Public Switched Telephone Network (PSTN). Such a network can today provide capabilities that equal or surpass those of 3G/3G+/4G public wireless networks, can be deployed for temporary or permanent use, and can be much more easily isolated from large scale failures in the electric power or telephone grids.

Throughout this proposal, we refer to these networks as broadband wireless access (BWA) networks. BWA networks therefore play a complementary role to public switched wireless networks. A city might decide to operate a BWA network to support its local public safety needs. A public safety organization might have mobile BWA equipment that can be instantly deployed to disaster locations. Emergency situations are likely to involve multiple public service agencies. A BWA infrastructure based on industry standards will enhance interoperability.

[2] Overload can happen in non-emergency situations. For example, the Clemson University Fire Department is not able to reliably use cell phones during Clemson football games.

In the proposed research our focus will be on evaluating a BWA infrastructure that is based upon 802.16 WiMAX technology. 802.20 is several years from standardization, and early commercial products do not yet exist. While 802.11 mesh networks are available, they are more complex and more difficult to deploy in emergency situations and consequently less versatile than 802.16.

We propose to deploy fixed-base and portable 802.16 testbeds using WiMAX equipment that is selected in conjunction local public safety agencies. We focus on equipment and scenarios that support stationary or nomadic users[3]. Working with Clemson University's police and fire departments, and with the local municipal police department, we will provide a proof-of-concept demonstrating that 802.16 can be effectively utilized by public safety organizations.

The second major thrust of the research will extend a network simulation tool that we have developed for wired cable networks to support 802.16 networks. This simulation will be validated by ensuring that equivalent experiments run on the testbed and on the simulator produce equivalent results. The simulator will then be able to provide provisioning and performance guidance for workloads that are too large to duplicate on the testbed.

[3] We limit our study to equipment that supports the 802.16-2004 standard. These systems support mobile users within the coverage area of one base station. The WiMAX forum is in the process of finalizing the follow-on standard 802.16e which supports unrestricted mobility.

2. Background

Broadband wireless access systems

During the 1990's, both industry and academia developed solutions for wireless in the local loop (WLL). These efforts produced two fixed broadband wireless access protocols designed primarily to provide Internet access: local multipoint distribution service (LMDS) and multichannel multipoint distribution (MMDS). These protocols served as the foundations for the current non-line-of-site WiMAX standard. Two new broadband wireless access technologies have emerged recently, 802.11 mesh and 802.20. We summarize these systems and then describe WiMAX in detail.

802.11 mesh: Ad hoc wireless networks utilize multi-hop relaying and are capable of operating without the support of any fixed infrastructure. Most 802.11 networks operate in 'infrastructure mode' where a central node, the access point or AP, controls communication between stations sharing the wireless channel with each other and with wired networks. 802.11 also supports an ad hoc mode where nodes communicate directly with each other or forward messages through other nodes that are directly accessible. A mesh network is a type of ad hoc network. An 802.11 mesh network provides an alternate communication infrastructure for mobile or fixed nodes. One popular use of mesh networks is residential Internet access. 802.11 nodes located on houses collectively form a broadband wireless access network. At least one of the client nodes must be mutlihomed and provide connectivity to a wired network with connectivity to the Internet.

802.20: 802.20 is a new IEEE standards effort that is developing standards for mobile broadband wireless access. It is similar in function to 802.16e although technically different. It is designed to handle stations moving at higher speeds than 802.16e (155 mph versus 75 mph). The more significant difference is that 802.20 is likely to be used in large public wide area wireless networks while 802.16 is intended for broadband access.

WiMAX: WiMAX, defined by the IEEE 802.16 standard, is an emerging broadband Internet access wireless technology [802.16A, EMSW02]. 802.16 emerged from a market requirement to provide fixed-point, broadband line-of-sight (LoS) wireless connectivity in remote areas. However, it was not until the emergence of 802.16a, adding non-line-of-sight (nLoS) capabilities, that the technology became a serious competitor to DSL and cable [802.16B]. The current 802.16 standard, known as 802.16-2004, offers data rates up to 70 Mbps over a range of 20 miles and operates in the 2-11 GHz and 10-66 GHz ranges [802.16A]. In difficult terrains the data rate will drop to 30 Mbps, and the range can drop to 1-2 miles. Although 802.16-2004 is considered *fixed* broadband wireless access, it does allow nomadic movement within the area covered by a base station.

A follow-on version, known as 802.16e, will support unrestricted mobility where an endstation can seamlessly move between areas covered by different base stations. 802.16e is considered an enhancement to 802.16-2004. Vendors are building products so that a deployed 802.16-2004 network can be upgraded to 802.16e in the field with a software update. The proposed research focuses on 802.16-2004[4].

[4] We intend to propose a follow-on project that will be to examine 802.16e and 802.16 mesh mode for public safety applications.

802.16-2004 supports two modes: the point-to-multipoint (PMP) mode and the mesh mode. In mesh mode, there are two further operating modes: centralized or distributed scheduling. With centralized scheduling, certain stations are elected as leaders and perform bandwidth allocations for all stations in the local cluster. With distributed scheduling, stations compete with each other for channel access. Our interest is in the more popular PMP mode where nodes are organized into a cell-like structure with base stations (BS) serving hundreds of subscriber stations (SS). Frequency division multiplexing (FDM) can be used so that the upstream channel uses a different frequency than the downstream channel. Time division multiplexing (TDM) can be used so that the upstream and downstream transmissions share the same channel. Multiple SSs must contend for access to the upstream channel, and the channel allocation procedure is quite complex.

The WiMAX channel allocation procedure, or medium access control (MAC) protocol, was derived from the MAC layer that is used in transmitting data over hybrid fiber coaxial (HFC) (cable TV) networks. It is known as the Data-Over-Cable Service Interface Specification (DOCSIS) [CableA]. We focus on the DOCSIS MAC layer as defined in [CableB] for cable networks and in [802.16A] for WiMAX networks. The channel allocation model is point-to-multipoint time division multiplexing in the downstream direction and time division multiplexing with a *request/grant* mechanism in the upstream direction. In contrast to ALOHA, which became synonymous with pure contention-based shared medium access [ABRA70], DOCSIS represents a centralized approach for managing bandwidth over shared medium networks.

The upstream channel is subdivided into transmission slots referred to as mini-slots. The capacity in bytes of a mini-slot on a given DOCSIS network is fixed and is in the range of 8 to 16 octets. Permission to transmit data in a block of one or more mini-slots must be granted to a SS by the BS. The BS grants mini-slot ownership by periodically transmitting a frame called the MAP on the downstream channel. In addition to ownership grants, the MAP also typically identifies some mini-slots as contention slots in which SSs may bid for quantities of future mini-slots.

To minimize collisions in the contention slots, a non-greedy backoff procedure is employed. Each SS is required to randomly select the contention slot in which it transmits a bid for mini-slots. When collisions do occur in contention slots, all parties that collide are required to employ an exponential backoff, doubling the size of the window of slots in which randomly placed. Two additional facilities reduce contention. When a SS has a backlog of upstream traffic it may piggyback a request for additional mini-slots using a request field in the current frame header. The concatenation facility allows multiple (typically small) IP packets to be transmitted as a single logical upstream MAC layer protocol data unit.

In previous work we developed analytic and simulation models of DOCSIS. Our results raises several issues. First, the many operating parameters of DOCSIS make it very challenging to identify settings that are optimal with respect to the characteristics of a particular workload. Second, DOCSIS has scalability, fairness, and denial-of-service (DoS) issues. In this project, we propose to explore the degree that these problems affect the suitability of 802.16 networks for

use in a public safety setting and to develop methods and tools that can help a public safety organization quickly deploy, configure, and manage WiMAX networks.

There are minor differences between wired and wireless DOCSIS. Unlike cable networks, an 802.16 network can either use the same channel for both upstream and downstream operation, or it can use separate channels. As with cable networks, 802.16 supports a centralized architecture, referred to as point-to-multipoint mode or PMP. In the proposed research, we assume the use of PMP mode and that the upstream and downstream channels are assigned to different frequencies.

In previous work we have conducted in-depth studies of the DOCSIS channel allocation model [CableC] and have constructed analytic and simulation models of its performance. These studies [MART04] have shown that it is quite challenging to identify settings of the many operational parameters of the protocol that will produce optimal performance with respect to a specific mix of voice, video, and data traffic. Second, DOCSIS has scalability, fairness, and denial-of-service (DoS) issues [MARTA05,MARTB05]. Building upon this work, we are adapting our simulation model to support 802.16. There have been very few 802.16 studies, and those that exist have focused primarily on the physical layer [GOSH05,RAMA04].

For the past several years vendors have sold ‘pre-WiMAX’ equipment. Current deployments include point-to-multipoint broadband Internet access by either a wireless ISP (known as a WISP) or by a city or organization. Validated WiMAX equipment is just becoming available. We expect there will be numerous products to choose from when we are ready to begin the proposed project.

Initial 802.16d-2004 products are likely to support channels in the 2.5-2.6 GHz range or in the unlicensed 3.5 GHz range. The use of unlicensed spectrum in the ISM band for public safety telecommunications is problematic because this spectrum can be very cluttered with WiFi activity. The 4.9 GHz licensed band was created in 2004 in response to the growing need for broadband wireless connectivity for public safety agencies. With this newly available spectrum, a broadband communication infrastructure can be deployed rapidly and deliver the bandwidth to carry data, voice and video traffic. When vendors have equipment that support 4.9 GHz, this will solve the interference and security issues associated with unlicensed frequencies. Depending on availability, we will use spectrum either in the 3.5 GHz or 5 GHz bands[5].

[5] We do not anticipate 4.9 GHz equipment becoming available in the timeframe of this project.

3. Research Goals and Objectives

The fundamental research question

The fundamental research question that we propose to address is whether the WiMAX technology is appropriate for both fixed-base and portable (i.e., small, rapidly deployed) broadband networks that carry voice, video, and data in support of public safety activities. The former could correspond to a scenario where a city provides an 802.16 infrastructure for its public service needs. The latter could correspond to multiple public safety agencies responding to a hazardous material situation.

We intend to answer that question via the deployment and assessment of both fixed-base and portable WiMAX testbeds. A critical component of this assessment will be feedback from the local public safety agencies who have expressed interest in evaluating a variety of applications on the WiMAX testbeds.

Research objectives

Specific research objectives will be addressed during the study include the following:

- Using a combination of analytic, simulation, and live measurement techniques, we will explore the performance of 802.16 networks in deployments designed to be representative of disaster recovery, crime scene investigation, or other public safety applications that require a mix of video, voice and data traffic.
- 802.16 is an emerging, complicated technology. Selecting optimal system parameters is difficult. Until reasonable rules-of-thumb are developed, initial deployments are likely to be

designed, provisioned, and configured using 'trial-and-error' methods. This represents a problem in public service scenarios where 802.16 networks must be constructed quickly to support operations where lives might be at risk. Therefore we will develop methods, benchmarks and tools that will help an organization quickly deploy, validate, and manage small 802.16 networks that are appropriate for public safety situations.

- The coverage of an 802.16 is likely to be very dependent upon both the location of the base station and the nature of the coverage area. For example, an antenna placed on a tall building will provide much better coverage than a mobile antenna on the top of a van. Similarly flat, open terrain will enlarge coverage while hilly, deeply forested, or urban terrain will diminish it. We will develop a set of guidelines for expected coverage area based upon BS antenna location and the nature of the surrounding terrain.
- Near the fringe of the coverage area, degraded performance is to be expected before the onset of total loss of service. We will characterize the relative size of the fringe areas and the nature of the partial failure modes observed therein.
- Although, for a variety of reasons, IP multicasting has not been notably successful in the global Internet, it can be a very powerful tool in a small network for conserving bandwidth and enabling conferencing. Examples might include distributing real-time video from a crime or disaster scene simultaneously to the offices of multiple responders or facilitating conference calls between responders at the site and at remote locations. Thus, we will develop applications that will enable public safety offices to assess the utility of such capabilities.
- Interoperation with the existing telephone system is an important objective. The current release maintainer of the *Asterisk* open source PBX system is a Clemson student with whom the

PIs have worked[6]. We will use an *Asterisk* gateway to assess the ability of 802.16d endsystems to interoperate with the public switched telephone network (PSTN).

[6] Available at http://www.asterisk.org

4. Research design and methods

We have identified four tasks that collectively achieve the research objectives. Refer to Appendix 4 for the project timeline.

Task 1: The first task is to design, deploy and verify the correct operation of the testbeds. We anticipate a significant number of 802.16 products to become available over the next 6 months. Therefore, we will make the final equipment selection after the project begins. To provide a price point, we have identified the Motorola Canopy 5.2 GHz system[7]. Although current Canopy equipment is considered 'pre-802.16-2004', Motorola has stated that fully compliant 802.16-2004 products will be available in early 2006 and that 'pre-802.16e' support will be available by the end of 2006[8]. A package that provides all necessary equipment for a 5.2 GHz system based on current products is available through distributors for $22,000[9]. This kit includes six base stations (six are necessary to provide 360-degree coverage because of the use of directional antennas), mounting hardware, power supplies, and 25 subscriber stations.

A seventh base station will be purchased for use in the portable testbed. During the product evaluation phase of the study we will identify appropriate directional and/or omni-directional

[7] A second vendor is Navini networks [http://www.navini.com/index.htm]. They have products that use unlicensed bands and also licensed 2.3 GHz band which is owned by BellSouth. We have talked to Bellsouth about this project and they have said it might be possible for us to use this band for the duration of the project.

[8] This is based on a printed interview with a Motorola executive. Available online at http://www.wimax.com/commentary/spotlight/spotlight8-15-2005

[9] Prices were obtained at http://shop.wirelessguys.com/s.nl/sc.2/category.471/.f

antennas capable of being mounted on a portable mast that can be transported in a small truck or van, raised by one or two persons and provide up to 40 feet of elevation for the antenna[10].

The terrain impact studies will be augmented by GIS and GPS tools. These tools will enable us to display signal strength and sustainable bit rates on terrain profile maps as a function of antenna characteristics, mobile base station power, and distance from the base station. We will use this data to develop rules of thumb whereby GIS data and GPS equipment can be used in the field to make site placement decisions for both mobile base stations and end user systems that will ensure successful communication without trial and error.

The testbeds will be initially disconnected from the main campus network, but Internet connectivity can be easily added to the fixed-base network via the base station(s) or through a wireless gateway. When the equipment is deployed, we will operate the testbed ourselves. Deliverables of this task will include a document describing coverage achieved, fringe area effects, terrain effects in the mobile testbed and a set of software tools that we develop to validate and characterize the operation of the network.

Task 2: When the testbed has been verified to be operating correctly, we will work with local public safety organizations to select and deploy applications that they would like to use on a trial basis. We will provide laptops with a PCMCIA 802.16-2004 adapter for use in response units. The Clemson fire department has identified several possible applications ranging from hazardous

[10] An example is the MobileMast system available at www.antennamast.com.

material first response software to in-car video systems to surveillance systems[11]. Each of these applications has a networking component that can make use of the WiMAX testbed. To facilitate a thorough performance evaluation, we plan to develop multimedia test applications (video and telephony) and evaluate the network capabilities in several realistic (although emulated) scenarios.

Task 3: In addition to the live network analysis, we will also conduct a simulation analysis of 802.16. We propose to leverage and extend our prior work involving an 802.16 simulation model. We will thoroughly validate the simulation model by comparing simulation results with equivalent tests conducted in the testbed. When complete, we can explore 802.16 in environments that are not possible with the testbed. In particular, we plan to investigate scenarios that involve hundreds of VoIP sessions. Results from this task will provide insight as to optimal 802.16 configuration settings for certain types of workloads and also provisioning guidance.

Task 4: The final task will be to effectively disseminate the results and knowledge obtained from the project. We have two methods. First, we will develop a 'guidebook' that will provide a set of 'best practices' designed to educate public safety personnel on the designing, deploying and managing 802.16 networks. This guidebook will be 'published' on our public web site along with the software programs that we develop in Task 1. Second, we will present our project at an appropriate public safety technology conference.

[11] First response software is from Adashi [http://www.adashi.org/brochure_fr.pdf]. In-car video products is from RoadRunner [http://www.apollovideotechnology.com/law_enforcement.htm]. Surveillance systems is from SearchCam [http://www.searchsystems.com/hazmat_Specs.html].

5. Review of relevant literature

Wireless technology is considered crucial for the public safety sector. The NIJ has published information to provide guidance to organizations on wireless technology [IMHA03]. The proposed project is unique as 802.16 is an emerging technology and there are no published measurement studies of deployed systems. There are several academic studies that are relevant. Preliminary simulation studies have focused on the physical layer [GOSH05,RAMA04]. Further studies have looked at routing issues in 802.16 mesh networks [CMZW05,WGIH05]. However these studies do not provide specific performance data points that we can use to validate our results.

6. Implications for policy and practice

While it is too early to know how successful 802.16 will be in competing against cable and DSL providers for Internet access customers, the technology holds considerable promise for providing a unified communications infrastructure for public service and public safety organizations. This infrastructure can, in theory, deliver voice, video, and data in both point-to-point or multicast modes using secure, high-speed, digital channels, free of interoperability issues and at a lesser cost than today's systems [12]. As the WiMAX protocols become available in silicon, and as mobility issues are resolved, laptops[13] and cell phones will be able to participate in WiMAX networks making the technology even more compelling for public service activities. For disaster

[12] The government already uses broadband wireless, typically based on proprietary products such those produced by Alvarion (http://www.alvarion-usa.com/RunTime/Products_2010.asp?tNodeParam=26). Our study focuses on the 802.16 standards-based products and in particular on their ability to meet the needs of public safety activities.
[13] Intel plans on including 802.16e chips in notebook computers by 2007.

recovery, we envision portable equipment in which a deployment could be effected by trucks carrying WiMAX base stations and equipped with a boom capable of lifting the antenna to the required height. Even in urban areas where the presence of large buildings may create multi-path effects and attenuate microwave signals, these systems can connect many endsystems located indoors or outdoors within a range of several miles.

Our project couples open research questions with an evaluation of communications systems that are likely to be deployed by government agencies. The results of the proposed project will help government officials make better-informed technology decisions. To facilitate this outreach in South Carolina, we will leverage our relationship the South Carolina Research Authority who operate the National Law Enforcement and Corrections Technology Center Southeast (NLECTC-SE)[14].

7. Management plan and organization

The project will be managed by PI Martin. CoPIs Weigle and Westall will assist in all phases of the project. We anticipate having one graduate research assistant and one undergraduate assistant student throughout the one-year project. We propose a start date of 1 October 2006 with an end date of 30 September 2007. Appendix 4 identifies the duration of work items associated with each of the four tasks.

[14] We have contacted John Bradham of the South Carolina Research Authority who indicated that they are interested in this project and are willing to help.

8. Dissemination strategy

We plan on disseminating our work in both academic and industry oriented conferences. Academic conferences that are appropriate for this work include IEEE Broadnets and Globecom[15]. In the past we have presented our DOCSIS performance research to the cable industry's premier trade show, the National Show[16]. In the same spirit, we will volunteer for speaking engagements at 802.16 industry forums such as at conferences sponsored by the WiMAX forum. To reach government technologists, we will present our work at appropriate government technology related conferences[17]. All software and planning and management tools that we developed will be made available via a project web site that we will maintain.

[15]The IEEE Broadnets conference web site is at http://www.broadnets.org/2006/ and the Globecom web site is at http://www.ieee-globecom.org/2006/

[16] J. Martin, "DOCSIS Performance Issues", National Cable and Telecommunications Association, The National Show, April 2005

[17] There are various government technology conferences to target as identified: http://www.govtech.net/events/

Appendix 1 References

[802.16A] IEEE 802.16-2004, IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems, 7/2004.

[802.16B] IEEE 802.16a-2003, IEEE Standard for Local and Metropolitan Area Networks Part 16a: Air Interface for Fixed Broadband Wireless Access Systems, Amendment 2: MAC Modifications and Additional PHY layer Specifications for 2-11Ghz, April 2003.

[ABRA70] N. Abramson, "The Aloha System – Another Alternative for Computer Communications", Proceedings of the Fall Joint Computer Conference, Jan 1970.

[CableA] Cable Television Labs Inc., CableLabs, Docsis specifications, http://www.cablemodem.com /specifications/specifications11.html

[CableB] Cable Television Labs Inc. , CableLabs, "Data-Over Cable Service Interface Specifications- Radio Frequency Interface Specification", SP-RFIv2.0, available at http://www.cablemodem.com/specifications/-specifications20.html.

[CableC] Cable Television Labs Inc. , CableLabs, "Baseline Privacy Plus Interface Specification", April, 2004.

[CMZW05] M. Cao, W. Ma, Q. Zhang, X. Wang, W. Zhu, "Modeling and Performance Analysis of the Distributed Scheduler in IEEE 802.16 Mesh Mode", MobiHoc 2005, 2005.

[DataTEC] Motorola's private DATATAC. http://www.motorola.com

[EMSW02] C. Eklund, R. Marks, K. Stanwood, S. Wang, "IEEE Standard 802.16: A Technical Overview of the WirelessMAN Air Interface for Broadband Wireless Access", IEEE Communications Magazine, June 2002.

[GOSH05] A. Ghosh, D. Wolter, J. Andrews, R. Chen, "Broadband Wireless Access with WiMax/802.16: Current Performance Benchmarks and Future Potential", IEEE Communications Magazine, Feb 2005, pp. 129-136.

[IMHA03] K. Imel, J. Hart, "Understanding Wireless Communications in Public Safety", National Law Enforcement and Corrections Technology Center, Second edition, Jan 2003. Available at http://www.nlectc.org/pdffiles/wireless2003.pdf

[MART04] J.Martin, "The Interaction Between the DOCISS 1.1/2.0 MAC Protocol and TCP Application Performance", Proceedings of the International Working Conference on Performance Modeling and Evaluation of Heterogeneous Networks, (Ikley, UK, July, 2004), pp. P57/1-10.

[MARTA05] J. Martin, “The Impact of the DOCSIS 1.1/2.0 MAC Protocol on TCP”, Proceedings of the IEEE Consumer Communications and Networking Conference, (Las Vegas, NV, Jan 2005).

[MARTB05] J. Martin, “Validating an ‘ns’ Simulation Model of the DOCSIS Protocol”, Under review. http://www.cs.clemson.edu/~jmarty/docsis-model.pdf

[PALM06] The 800 MHz Palmetto radio and mobile data system. http://www.cio.sc.gov /cioContent.asp?pageID=756&menuID=411

[RADIOIP] Radio IP Software Inc., http://www.radio-ip.com
http://www.radio-ip.com/about-radio-ip.php

[RAMA04] S. Ramachandran, C. Bostian, S. Midkiff, “Performance Evaluation of IEEE 802.16 for Broadband Wireless Access”, Opnetwork Conference, 2002.

[WIMAX] The WiMAX forum, http://www.wimaxforum.org/home

[WGIH05] H. Wei, S. Granguly, R. Izmailov, Z. Haas, “Interference-aware IEEE 802.16 WiMAX Mesh Networks”, IEEE Vehicular Technology Conference, May 2005.

Appendix 2 List of key personnel

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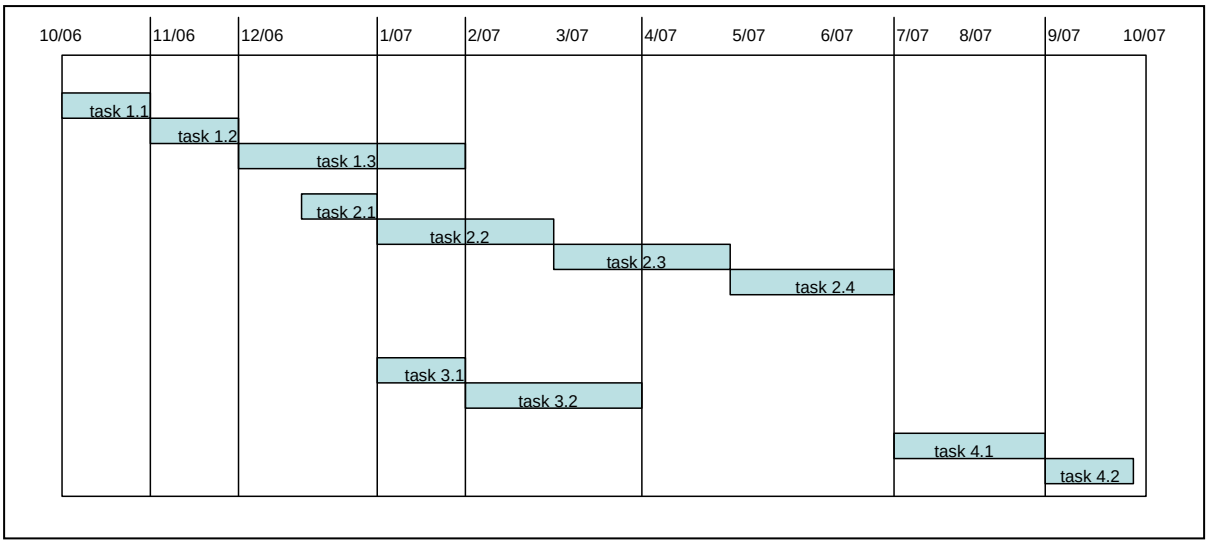
Appendix 3 Letters of cooperation/support

Appendix 4 Project milestones and timeline



Task 1 - Testbed

1.1 select equipment
1.2 design network
1.3 deploy and test network

Task 2 – WiMAX analysis

2.1 select applications for trial use by Clemson fire and police
2.2 develop tools for test: a program that pushes GIS maps to response units, a program that transmits live video from response units to control center, VoIP test using open source code
2.3 test scenario 1: fixed-base deployment
2.4 test scenario 2: portable deployment

Task 3 – 'ns' simulation model

3.1 validate model
3.2 scalability test

Task 4 - Dissemination

4.1 – develop a 'best practices' guide
4.2 - present to an appropriate public safety technology conference

Appendix 5 Resumes of key personnel

RESUME - Jim Martin

PERSONAL DATA

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EDUCATION

Ph.D., North Carolina State University, 1999, Electrical Engineering (dissertation topic: end-to-end congestion avoidance for TCP)
M.S., Arizona State University, 1989, Computer Science
B.S., University of Illinois (Champaign/Urbana), 1983, Electrical Engineering

PROFESSIONAL EXPERIENCE

Clemson University, 2002-, Assistant Professor of Computer Science
Gartner Group, 2000 to 2002, telecommunications consultant for GartnerConsulting. Engagements included the development of performance management tools, network analysis studies, development of technical white papers.
IBM Corporation, 1991 to 2000, R&D staff engineer. Contributions included the performance analysis of networking protocols and the design/development of network security systems.
Filenet Corporation, 1989 to 1991, Unix kernel/application developer.
Motorola Government Electronics Division, 1983 to 1989, design engineer. Developed hardware and software for military communications systems.

CONSULTING EXPERIENCE

CableLabs, 2005, cable network traffic modeling and protocol evaluation.

MEMBERSHIPS

Member Association for Computing Machinery, ACM, 1989.
Member IEEE and IEEE Communications Society, 1989.

PUBLICATIONS

Refereed Journal Publications:

J. Martin, A. Nilsson, I. Rhee, "Delay-based Congestion Avoidance for TCP", *IEEE/ACM Transactions on Networking*, 11(3), 356-369 (2003).

Conference Proceedings (Reviewed):

A. Swaminathan, J. Martin, "Fairness Issues in Hybrid 802.11b/e Networks", *to appear in Proceedings of the IEEE Consumer Communications and Networking Conference*, (Las Vegas, NV, Jan 2006).

R. Geist, J. Martin, J. Westall, V. Yalla, "Performance Tuning of Gigabit Network Interfaces", *to appear in the proceedings of Computer Measurement Group 2005 Conference,* (Orlando, Florida, Dec 2005).

N. Shah, D. Kouvatsos, J. Martin, S. Moser, "A Tutorial on DOCSIS: Protocol and Performance Models", *Proceedings of the International Working Conference on Performance Modeling and Evaluation of Heterogeneous Networks*, (Ikley, UK, July, 2005).

J. Martin, M. Westall, V. Rajasekaran, "Virtual Machine Effects on Network Traffic Dynamics", *Proceedings of the IEEE International Performance, Computing, and Communications Conference*, (Phoenix, AZ, April 2005), pp. 233-238.

S. Howard, J. Martin, "DOCSIS Performance Evaluation: Piggybacking versus Concatenation", *Proceedings of the ACM Southeast Conference,* (Kennesaw State, GA, March, 2005).

J. Martin, "The Impact of the DOCSIS 1.1/2.0 MAC Protocol on *TCP"*, *Proceedings of the IEEE Consumer Communications and Networking Conference*, (Las Vegas, NV, Jan 2005).

J. Martin, M. Westall, V. Rajasekaran, "On the Impact of Virtual Machine Overhead on TCP Performance", *Proceedings of the IASTED International Conference on Communication and Computer Networks*, (Boston, MA, Nov, 2004), pp. 287-292.

J. Martin, H. Karlapudi, "Web Application Performance Prediction", *Proceedings of the IASTED International Conference on Communication and Computer Networks*, (Boston, MA, Nov, 2004), pp. 281-286.

R. Geist, J. Martin, J. Westall, "Small Aggregations of ON/OFF Traffic Sources", *Proceedings of the IASTED International Conference on Communication and Computer Networks*, (Boston, MA, Nov, 2004), pp 312-318.

S. Biyani, J. Martin, "A Comparison of TCP-Friendly Congestion Control Protocols", *Proceedings of the International Conference on Computers Communications and Networks 2004*, (Chicago, IL, October 2004).

J. Martin, "The Interaction Between the DOCISS 1.1/2.0 MAC Protocol and TCP Application Performance", *Proceedings of the International Working Conference on Performance Modeling and Evaluation of Heterogeneous Networks*, (Ikley, UK, July, 2004), pp. P57/1-10.

J. Martin, "Managing Best Effort IP Networks over Heterogeneous WANs", *Proceedings of the International Working Conference on Performance Modeling and Evaluation of Heterogeneous Networks*, (Ikley, UK, July, 2004), pp WP7/1-6.

J. Martin, N. Shrivastav, "Modeling the DOCSIS 1.1/2.0 MAC Protocol", *Proceedings of the 2003 International Conference on Computer Communications and Networks*, (Dallas TX, October 2003), pp. 205-210.

J. Martin, A. Nilsson, "On Service Level Agreements for IP Networks", in *Proceedings of INFOCOM*, (New York, New York, July 2002), pp. 855-863.

J. Martin, A. Nilsson, I. Rhee, "The Incremental Deployability of RTT-based Congestion Avoidance for High Speed TCP Internet Connections", in *Proc. of ACM SIGMETRICS 2000, International Conference on Measurement and Modeling of Computer Systems* (ACM SIGMETRICS), (Santa Clara, CA, 2000), pp. 134-144.
J. Martin, A. Nilsson, "On Congestion Avoidance for TCP/IP Networks", *Proceedings of the 15th IFIP World Computer Congress*, (Budapest, 1998).
J. Martin, A. Nilsson, "Congestion Control in HPR", in *Proceedings of IEEE GLOBECOM*, (Phoenix, AZ, 1997).

Technical Reports:

J. Martin, A. Nilsson, "A Comparison of RTP and TCP/Reno Transport Protocols", IBM TR 29.2337, December 1997.
J. Martin, A. Nilsson, "The Evolution of Congestion Control in TCP/IP networks", IBM TR 29.2277, June 1997.
J. Martin, "Optimal MultiLink Transmission Group Scheduling Algorithms, IBM TR 29.1967, August 1997.

PRESENTATIONS

"DOCSIS Performance Issues", National Cable and Telecommunication Association's National Show, San Francisco, CA, April 2005.

PATENTS

An Optimal Multilink Scheduling Algorithm, United States, patent number 6178448, granted 1/23/01.
Adapting Receiver Thresholds to Improve Rate-Based Flow Control, United States, patent number 6657954, granted 12/2/03.

SPONSORED RESEARCH

Pending Funding:

"Managing Bandwidth in DOCSIS-based Broadband Access Networks", National Science Foundation, Principal Investigator, $491,790, July 2005.

Current Funding:

"Developing Application Level Prediction Services in a WebSphere and Globus Grid Environments", IBM University Partnership Proposal, Principal Investigator, $30,000, (Aug 2005-).

Informal equipment gift (cable networking gear), Cisco Systems, $20,000, (Jan 2005-).

GRADUATE STUDENT ADVISING

Masters Graduates

Tanuja Ingale (MSCS), "Denial of Service Vulnerabilities in 802.11 LANs", (August 2005).
Prabu Surendra (MSCS), "Modeling Packet Loss over the Internet", (August 2005).
Jeff Vales (MSCS), "Mapping Quantifying User Level to Network Measurables", (May 2005).
Kalyan Chintalapati (MSCS), "A Tool for Rapid Model Parameterization and its Applications", (December 2004).
Surekha Biyani (MSCS), "Comparison of TCP-Friendly Congestion Control Protocols", (August, 2004).
Himadeepa Karlapudi (MSCS), "Web Application Performance Prediction", (August 2004).
Mayukh Mukherjee (MSCS), "The Development of a New TCP-Friendly Transport Protocol for Streaming", (August 2004).
Manigandan Natarajan (MSCS), "Assessing Streaming Application Performance over the TFRC Transport Protocol" (August 2004).
Vinod Rajasekaran (MSCS), "Impact of Virtual Machine Overhead on TCP Performance", (August 2004).
Shobhana Kirtane (MSCS), "Predicting the Performance of the gridFTP Application over Wide Area Grid Environments", (May 2004).

Current Graduate Advising

John Parramore (MSCS), "Adaptive MAC Parameters in DOCSIS Networks", (May 2006).
Zhixin Li (MSCS), "Adaptive MAC Parameters in 802.11b/e Networks", (May 2006).
Shobhana Kirtane (PHDCS), "Predicting Application Performance in a WebServices Environment", (December 2006).
Scott Moser (PHDCS), "Denial of Service Vulnerabilities in DOCSIS networks", (December 2008).

TEACHING EXPERIENCE

Courses Taught at Clemson:

CPSC 360, Distributed and Network Programming, Fall 2004, Spring 2004
CPSC 826, Internet Protocols, Spring 2004, Spring 2003, Fall 2002
CPSC 881, Internet Performance Analysis, Fall 2005, Fall 2004, Fall 2003

New Course Development at Clemson:

CPSC 881, Internet Performance Analysis, Fall 2005, Fall 2004, Fall 2003

Courses Taught at North Carolina State University:

CSC/ECE 573, Internet Protocols, Spring 2001

UNIVERSITY AND PUBLIC SERVICE

Committees:

Department Research Committee, 2003-2004
Department Computing Facilities Committee, 2004-2006

Other service:

Clemson's Emerging Scholars, taught rural SC high school students Internet skills, June 2005.
Fostering undergraduate research: I have 2 extremely talented undergraduate students working on research related projects.
NSF proposal review panel member, Spring 2005.
Member program committee, International Conference on Computer Communications and Networks, October 2005, 2004, and 2003.
Advisory Board, International Conference on Performance Modeling and Evaluation of Heterogeneous Networks, Ikley, UK, July 2005.
Reviewer for FBI's white paper, "FBI 2005 Computer Crime Survey", FBI Agent Bruce Verduyn, October 2005.

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PERSONAL DATA

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EDUCATION

M.S., UNC Chapel Hill, 1978, Computer Science
Ph.D., UNC Chapel Hill, 1973, Mathematics
B.S., Davidson College, 1968, Mathematics & Physics

PROFESSIONAL EXPERIENCE

Clemson University

2004 -	Professor of Computer Science
1994 - 2004	Professor of Computer Science and Director of Graduate Affairs
1980 - 1994	Associate Professor of Computer Science
1978 - 1980	Assistant Professor of Computer Science
1974 - 1978	Assistant Professor of Mathematical Sciences

University of North Carolina at Chapel Hill

1973 - 1974	Instructor (Evening College)

United States Army

1968 – 1978	US Army Reserve, Signal Corps (2LT, 1LT, CPT)
1973	Signal Officer's Basic Course, Ft. Gordon, GA

HONORS AND AWARDS

Sigma Pi Sigma Physics Honor Society

Distinguished Graduate, US Army Signal School, Signal Officer's Basic Course

Sigma Xi Scientific Research Society

Guenther Enderle Award for Best Paper 26th Annual Eurographics Conference

CONSULTING

Series One Inc., Greenville SC (1977 - 1978), Design and implementation of the I/O and file management components of a multitasking operating system for the Series/1 minicomputer.

QS Inc., Greenville SC (1979 - 1980), Design and implementation of an online vital records system for the state government of Wisconsin.

Broadway & Seymour, Inc., Charlotte NC (1984), Design of an IBM SNA LU type 7 emulation mode for the IBM 470x family of banking terminals.

IBM Corporation, Charlotte, NC (1986 - 1997), Development of systems used in the segmentation and recognition of unconstrained handwritten characters on financial documents.

General Electric Corporation, Greenville, SC (1990, 1997), Design and implementation of systems for evaluating the alignment and balance of multi-rotor gas turbines.

Neural Technologies Inc., Pendleton SC (1996, 1997), Techniques for identifying and preventing intrusion in computer networks.

PROFESSIONAL AFFILIATIONS

Association for Computing Machinery, ACM, SIGOPS, SIGARCH, SIGMETRICS , SIGCOMM

Affiliate, IEEE Computer Society

Sigma Xi

PUBLICATIONS

Journal Publications

Westall, J. M., ``Banach Spaces of L_p Valued Holomorphic Mappings", *Duke Math Journal*, **40**(4), 755-763 (1973).

Geist, R. M., Reynolds, R. R., and Westall J. M., ``Selection of a Checkpoint Interval in a Critical Task Environment", *IEEE Transactions on Reliability*, **37**(4), 395-400 (1988).

Westall, J. M. and Narasimha, M. S., ``Vertex Directed Segmentation of Handwritten Numerals," *Pattern Recognition*, **26**(10), 1473-1486 (1993).

Westall, J. M. and Narasimha M. S., ``An Evolutionary Approach to the Use of Neural Networks in the Segmentation of Handwritten Numerals" , *The International Journal of Pattern Recognition and Artificial Intelligence*: Special issue on bank check processing, **5**(May 1997), 717-734.

Geist, R. M. and Westall J. M., ``Correlational and Distributional Effects in Network Traffic Models: Extended Version", *Performance Evaluation*, **44**(1), 121-138 (2001).

Rache, K., Geist, R. M., and Westall, J. M., ``Detail Preserving Reproduction of Color Images for Monochromats and Dichromats," *IEEE Computer Graphics and Applications*, **25**(3), 22-30, (May/June 2005).

Rasche, K., Geist, R., and Westall, J., "Re-Coloring Images for Gamuts of Lower Dimension", *Computer Graphics Forum*, **24**:3 (2005), pp. 423 - 432.

Peer Reviewed Papers in Conference Proceedings

Westall, J. M., Norton, H. T., and Narasimha, M. S. ``Segmentation of Handwritten Numeric Characters", in *Proc. of the IBM Internal Technical Liaison Conference on Image Processing* (San Jose Ca.., Aug. 1988).

Stevenson, D.E., Toppur, R., and Westall, J. M., ``Performance of Mutual Exclusion Algorithms on Hypercubes", in *Proc. of the 1989 Hypercube Conference* (Charleston S. C., Feb. 1989).

Westall, J. M., ``Cache and Block Size Considerations in Personal Computer Disk Caches", in *Proc. of the 29th Annual ACM Southeast Conf.* (Auburn Al., Apr. 1990).

Westall, J. M. and Narasimha, M. S., ``Neural Network Extensions to Vertex Directed Segmentation", in *Proc. of the IBM Internal Technical Liaison Conference on Neural Networks* (East Fishkill N. Y., May 1992).

Madison, A. W., Malloy, B. A., Peck, J.C. and Westall, J. M., ``A Cost Effective CIM System for Apparel Manufacture", in *Proc. of the 4th Academic Apparel Research Conf.* (Raleigh N.C., Feb. 1993).

Westall, J. M. and Narasimha, M. S., ``Performance Analysis of Vertex Directed Segmentation", In *Proc. of the IBM Internal Technical Liaison Conference on Image Processing* (Charlotte N.C., Oct. 1993).

Geist, R. M. and Westall, J. M., ``Disk Scheduling in Linux", in *Proc. 20th Int'l CMG Conference* (Orlando Fl., Dec. 1994), pp. 739-746.

Madison, A. W., Murray, T. J., and Westall, J. M., ``Lookahead Page Placement", in *Proc. of the 33rd Annual ACM Southeast Conf.* (Clemson S.C., Apr. 1994), pp. 146-155.

Fennell, R. E., Westall, J. M., and Wypasek, C. J., ``Identifying Periods of Availability in Elements of a Distributed System", in *Proc. of the Seventh IASTED & ISSM Conf. on Parallel and Distributed Computing* (Washington D.C., Oct. 1995).

Fennell, R. E., Kiessler, P., Westall, J. M., and Wypasek, C. J., ``Markov Renewal Models for Traffic Exhibiting Self-Similar Behavior", in *Proc. of the IEEE Southeastcon* (Tampa Fl., Apr. 1996).

Madison, A. W., Murray, T. J., and Westall, J. M., ``Colored Page Stealing", in *Proc. of the 34th Annual ACM Southeast Conf.* (Tuskegee Al., Apr. 1996), pp. 28 - 34.

Geist, R. M., Smotherman, M. K., and Westall, J. M., ``Performance Evaluation of NUMA Architectures", in *Proc. of the 34th Annual ACM Southeast Conf.* (Tuskegee Al., Apr. 1996), pp. 78 - 85.

Geist, R. M. and Westall, J. M., ``Performance and Availability Evaluation of NUMA Architectures", in *Proc. of the IEEE Int. Computer Performance and Dependability Symp. (IPDS '96),* (Urbana Ill., Sept. 1996), pp. 271 - 280.

Geist, R. M. and Westall, J. M., ``A Hybrid Tool for the Performance Evaluation of NUMA Architectures", in *Proc. of the 1997 Winter Simulation Conf.* (Atlanta Ga., Dec. 1997), pp. 1029-1036.

Geist R., and Westall, J., ``Bringing the High End to the Low End: High Performance Device Drivers for the Linux PC", in *Proc. of the 36th Annual ACM Southeast Conf.* (Marietta, Ga., Apr 1998), pp. 251-260.

Bahadur, S., Kalyanakrishnan, V., and Westall, J. M., ``An Empirical Study of the Effects of Careful Page Placement in Linux", in *Proc. of the 36th Annual ACM Southeast Conf.* (Marietta, Ga., Apr 1998), pp. 241-250.

Flower, A., Geist, R. M., and Westall, J.M., ``ATM Device Driver Development in Linux", in *Proc. of the 4th Annual Linux Expo* (Durham, NC, May 1998).

Geist R., Treglia D., and Westall, J.M., ``Real-time 3-D Graphics for the Linux PC", in *Proc. of the 24th International CMG Conference,* (Anaheim, CA, Dec 1998).

Geist R., Treglia D., and Westall, J.M., ``Real-time 3-D Graphics in Linux ", in *Proc. of the 5th Annual Linux Expo,* (Raleigh, NC, May 1999), pp. 9-17.

Geist, R., Spicer, K., and Westall, J., ``Simulation Modeling of Self-similarity in Network Traffic Models", in *Proc. of the 25th International CMG Conference*, (Reno, NV, Dec 1999), pp. 803-811.

Geist, R. and Westall J., ``Correlational and Distributional Effects in Network Traffic Models", in *Proc. of the IEEE Intl. Computer Performance and Dependability Symp. (IPDS 00),* (Chicago Ill., Mar. 2000), pp. 113-122.

Geist, R. and Westall, J., Practical Aspects of Simulating Systems Having Arrival Processes with Long-range Dependence, in Proc. of the 2000 Winter Simulation Conf. (Orlando, Fl., Dec 2000), pp. 666-674.

Geist, R., Paramisivam, K., and Westall, J., ``Enhanced Scheduling Performance on Linux Disk Mirrors", in *Proc. of the 26th International CMG Conference,* (Orlando, FL,

Dec 2000), pp. 515-522.

Westall, J., ``A Simple, Configurable, and Adaptive Firewall, for Linux", in *Proc. of the 39th Annual ACM Southeast Conference*, (Athens, Ga., Mar. 2001), pp. 162-168.

Geist, R., Sekhar, V., and Westall, J., ``Graphics Benchmarking," In *Proc. of the 27th Annual International CMG Conference, (CMG 2001),* (Anaheim, CA, Dec 2001), pp 151-160.

Geist, R., and Westall, J., ``Fast and Accurate Synthesis of Correlated Processes by Pre-compensated Transfer of Correlation," in *Proc. of Communication Networks and Distributed Systems Modeling and Simulation (CNDS 02),* (San Antonio, TX, Jan 2002), pp. 11-17.

Geist, R., Rache, K., and Westall, J., ``An HSV Representation of non-Newtonian Lattice-Boltzmann Flows", in Proc. of the SPIE - Data Analysis and Visualization 2002, (San Jose, CA, Jan 2002), pp 246-258.

Geist, R., Rasche, K., and Westall, J., ``Out of Order Rendering on Visualization Clusters," in *Proc. of the IASTED Intl. Conf. on MODELLING and SIMULATION*, (Palm Springs, Ca., Feb. 2003), pp. 461-467.

Geist, R., Wells, P., and Westall, J., ``The Effect of Leaky Bucket Filters and TCP Congestion Feedback on Network Traffic Arrival Processes," in *Proc. of the 41st Annual ACM Southeast Conference*, (Savannah, Ga., Mar. 2003, pp. 286-291.

Geist, R., Rasche, K., Srivatsavai, R., and Westall, J., ``A Distributed Rendering System for Scientific Visualization," in *Proc. of the 41st Annual ACM Southeast Conference*, (Savannah, Ga., Mar. 2003, pp. 359-364.

Davis, T., Geist, R., Matzko, S., Westall, J., ``Texni: A First Step", in Proc. of the 35th SIGCSE Technical Symposium on Computer Science Education, (Norfolk, VA, Mar. 2004), pp. 125-129,

Davis, T., Geist, R., Wang, S., Westall, J. and Kundert-Gibbs, J., ``Digital Production Arts: Coming Soon to a College Near You!", in *Proc. of the 42nd Annual ACM Southeast Conf.*, (Huntsville, AL, Apr. 2004), pp. 416 - 421.

Geist, R., Rasche, K., Westall, J., and Schalkoff, R., ``Lattice-Boltzmann Lighting," *Rendering Techniques 2004 (Proc. Eurographics Symposium on Rendering),* Norrköing, Sweden, June, 2004, pp. 355 - 362, 423.

Davis, T., Geist, R., Matzko, S., and Westall, J., ``Course Development in Texni," *Proc. of the 2004 Eurographics Education Program*, Grenoble, France, August, 2004, pp. 23 - 27.

Geist, R. Martin, J., and Westall, J., ``Small Aggregations of ON/OFF Traffic Sources", *Proceedings of the IASTED International Conference on Communication and Computer Networks*, (Boston, MA, Nov, 2004), pp 312-318.

Martin, J., Westall, M., Rajasekaran, V., ``On the Impact of Virtual Machine Overhead on TCP Performance," *Proceedings of the IASTED International Conference on Communication and Computer Networks*, (Boston, MA, Nov, 2004), pp. 287-292.

Martin, J., Westall, J., and V. Rajasekaran, "Virtual Machine Effects on Network Traffic Dynamics", *Proceedings of the IEEE International Performance, Computing, and Communications Conference*, (Phoenix, AZ, April 2005), pp. 233-238.

Geist, R., Hicks, J., Smotherman, M., and Westall, J., ``Parallel Simulation of Petri Nets on Desktop PC Hardware," *Proc. of the 2005 Winter Simulation Conf. (WSC 2005)*, (Orlando, Florida, December, 2005), pp. 374-383.

Geist, R., Steele, J., and Westall, J., ``Enhancing Webserver Performance Through the Use of a Drop-in, Statically Optimal, Disk Scheduler," *Proc. of the 31st Annual Int. Conf. of the Computer Measurement Group (CMG 2005)*, (Orlando, Florida, December, 2005, v.2), pp. 697-706.

Geist, R., Martin, J., Westall, J., and Yalla, V., ``Performance Tuning of Gigabit Network Interfaces," *Proc. of the 31st Annual Int. Conf. of the Computer Measurement Group (CMG 2005)*, (Orlando, Florida, December, 2005, v.2), pp. 687-696.

Other Peer Reviewed Publications

Westall, J. M., ``Analysis and Splitting of Potentially Connected Numeric Handprint Characters", *IBM Technical Disclosure Bulletin*, **33**(6a), Nov. 1990, pp. 236-241.

Narasimha, M. S., Westall, J. M., and Will, T. A., ``Grayscale Assist in Machine Recognition of Courtesy Amounts", *IBM Technical Disclosure Bulletin*, **34**(5), Oct. 1991, pp. 374-377.

Westall, J. M., Norton, H. T., and Narasimha, M. S., ``A Graphical Interface for Image Attribute Specification, *IBM Technical Disclosure Bulletin*, **35**(11), Nov. 1992, pp. 374-375.

Westall, J. M., Partitioned Class Recognition by Computational Neural Network, *IBM Technical Disclosure Bulletin*, **37**(11), Nov. 1994, pp. 7-10.

Westall, J. M., Mai, D. D., and Narasimha, M. S., ``Edge and Vertex Directed Identification and Removal of Fraction Lines" (with M.S. Narasimha and D. Mai), *IBM Technical Disclosure Bulletin*, **38**(8), Aug. 1995, pp. 517-520.

Westall, J. M. and Narasimha, M. S., ``A Binary Tree Structure for Managing Alternate Segmentation Paths in the Optical Character Recognition of Courtesy Amount Fields", *IBM Technical Disclosure Bulletin*, **38**(12), Dec. 1995, pp. 215-218.

Invited Papers

Westall, J. M., ``A CIM Architecture for Apparel Manufacturing", *Bobbin*, *32*(6), Feb. 1991, pp. 14-18.

Westall, J. M., ``Accelerated 3D Graphics in an Xfree86 Environment", in *Proc. 38th Annual ACM Southeast Conf. (Clemson, SC, Apr. 7-8), 2000.*

Other Publications

Smotherman, M. K. and Westall, J. M., ``Dynamic Control of Job Arrival Distributions", in *Proc. 24th Annual ACM Southeast Conf.* (Tampa Fl., Apr. 13-15), 1985.

Madison, A. W. and Westall, J. M., ``Advanced Memory Management Architectures and Virtual Machine Monitors", in *Proc. 24th Annual ACM Southeast Conf.* (Birmingham Al., Apr. 1986).

Hollis, W. M. and Westall, J. M. ``C Language Portability Considerations" in *Proc. 24th Annual ACM Southeast Conf.* (Birmingham Al., Apr. 1986).

Technical Reports

Westall, J. M., ``The Clemson Editor User's Guide", Clemson University Computer Center (1976).

Westall, J. M., ``The *X* Command Procedure Processor User's Guide", Clemson University Computer Center (1977).

Warner, D. D., Westall, J. M., Jervis, J., and McKeever, K., ``Using the Tactical Air Land Combat (TALC) Simulation Model", Dept. of Mathematical Sciences Technical Report, Clemson University (1985).

Westall, J. M. and Narasimha, M. S., ``Efficient Generation of Interpel Distance Tables and Their Use in Segmentation of Handwritten Numerals", IBM Internal Invention Disclosure (Jan. 1988).

Westall, J. M. and Narasimha, M. S., ``Tree Structured Management of Alternative Paths in Segmentation of Handwritten Numeric Data", IBM Internal Invention Disclosure (June 1988).

Westall, J. M., ``Disk Cache Performance Effects in Personal Computer Systems", A technical report prepared for the NCR Corporation (Aug. 1988).

Westall, J. M., ``Using the CDT Distributed Debugging System", A technical report prepared for the IBM Corporation (July 1989).

Westall, J. M., ``Reduction of Invalidate Traffic in Non-snooping Caches by Use of an Invalidated Address Stack", A technical report prepared for the NCR Corporation (Aug. 1989).

Westall, J. M., ``The Performance Effects of Alternative Combining Store Designs in Write Update and Write Through Cache Memories", A technical report prepared for the NCR Corporation (Oct. 1989).

Westall, J. M., ``Cache Memory Effects of Task Migration in Multiprocessor Systems", A technical report prepared for the NCR Corporation (Jan. 1990).

Westall, J. M., ``The Effects of Cache Write Miss Policy (Allocate or Not) on Bus Loading", A technical report prepared for the NCR Corporation (Oct. 1990).

Westall, J. M., ``An Evaluation of the Effectiveness of Single and Multi-line Instruction Prefetch Buffers in Both Single and Multilevel Cache Memory Systems", A technical report prepared for the NCR Corporation (Jan 1991).

Westall, J. M., ``A Procedure for Evaluating Alignment and Balance in Multi-rotor Turbine Stacks", A technical report prepared for the General Electric Corporation (March 1991).

Westall, J. M., ``A Performance Comparison of a 4 Way Set Associative Cache with Sectored Writebacks to a Non-sectored 2 Way Set Associative Cache", A technical report prepared for the NCR corporation (June 1992).

Madison, A. W., Westall, J. M., Buddhavaparu B., and Moolky, S., ``The MicroCIM Architecture Manual", A technical report prepared for the Defense Logistics Agency (Aug. 1992).

Madison, A. W., Westall, J. M., Buddhavaparu B., and Moolky, S., ``The MicroCIM Operator's Manual", A technical report prepared for the Defense Logistics Agency (Aug. 1992).

Madison, A. W., Westall, J. M., Buddhavaparu B., and Moolky, S., ``The MicroCIM Programmer's Manual", A technical report prepared for the Defense Logistics Agency (Aug. 1992).

Westall, J. M., ``An Analysis of the Use of Long Lines and Sectored Staging in Large Secondary Caches", A technical support prepared for the NCR corporation (Aug. 1992).

Baker, J. N. and Westall, J. M., ``An Analysis of the Effects of Page Placement in Systems with Large Real Indexed Direct Mapped Caches", A technical report prepared for the NCR Corporation (Nov. 1992).

Westall, J. M., ``Principles of Working Set Based Workload Characterization and Cache

Miss Ratio Prediction in First and Second Level Caches", A technical report prepared for the NCR Corporation (Jan. 1993).

Moolky, S. and Westall, J. M., ``Working Set Based Workload Characterization and Cache Miss Rate Prediction", A technical report prepared for the NCR Corporation (Aug. 1993).

Other Conference Presentations

Westall, J. M., ``An Introduction to the Clemson Editor and Source Management System", SHARE 53 (New York N.Y., Aug. 1979).

Westall, J. M., ``TSO Performance Effects of the Use of the Clemson Editor System", Southern Computer Measurement Group (Charlotte N. C., Oct. 1979).

Westall, J. M., ``Applications of Operational Analysis of Closed Queuing Networks", Southern Computer Measurement Group (Charlotte N. C., Oct. 1980).

Westall, J. M., ``Performance Management of a Large TSO Subsystem", CMG National Conference (Boston Ma., Dec. 1980).

Westall, J. M., ``An Analysis of Selected DASD Performance Models", Southern Computer Measurement Group (Atlanta Ga., Apr. 1982).

Madison, A. W., and Westall, J. M., ``A Computer Operating System for Distributed Control of Manufacturing", Academic Apparel Research Conference (Clemson S.C., Feb. 1991).

Fennell, R. E., Westall, J. M. and Wypasek, C. J., ``Distribution of Load in Large Networks of Workstations", CCCS Annual Conference (Clemson S. C. , Sept. 1992).

Fennell, R. E., Westall, J. M. and Wypasek, C. J, ``Identifying Sources of Available Capacity in Workstation Networks", CCCS Annual Conference (Clemson S. C. , Nov. 1993).

Fennell, R. E., Westall, J. M. and Wypasek, C. J, ``Stochastic Point Process Models for Workstation Utilization", 14th Annual Southeast-Atlantic Regional Conf. on Differential Equations (Knoxville Tenn., Oct. 1994).

Fennell, R. E., Westall, J. M. and Wypasek, C. J., ``Filtering of a Semi-martingale Base upon Non-orthogonal Point Process Observations", 19th Annual Meeting of the SIAM Southeastern Atlantic Section (Charleston S.C., March 1995).

SPONSORED RESEARCH

Warner, D. D. and Westall, J. M., ``Communications, command, and control: Studies in communications methodology". Funded by DOD Test and Evaluation through the C3

Countermeasures Joint Test Force at Kirtland AFB, Albuquerque N. M. from June 1983 through November 1985 at $660,000.

Madison, A. W. and Westall, J. M., ``Virtual Machine Monitors for Advanced Microprocessor Based Systems". Funded by the NCR Corp. from July 1986 through December 1986 at $40,000.

Westall, J. M., ``Performance Effects of Disk Caching in Microprocessor Based Systems". Funded by the NCR Corp. from July 1987 though October 1987 at $27,000.

Madison, A. W., Peck, J. C., and Westall, J. M., ``An Operating System for Distributed Control of Manufacturing". Funded by DOD through the Defense Logistics Agency from October 1989 through February 1990 at $148,000

Madison, A. W., Peck, J. C., and Westall, J. M., ``Extensions to the Operating System for Distributed Control of Manufacturing". Funded by DOD through the Defense Logistics Agency from June 1990 through September 1991 at $52, 560.

Madison, A. W. and Westall, J. M. ``Performance Measurement of the MicroCIM Operating System". Funded by DOD through the Defense Logistics Agency from September 1991 through September 1992 at $10,839.

Madison, A. W., Pargas, R. P., and Westall, J. M., ``Investigations of Multiprocessor Design Issues". Funded by the NCR Corp. from December 1988 through May 1990 at $158,000.

Westall, J. M., ``Analysis and Evaluation of Multiprocessor Design Alternatives". Funded by the NCR Corp. from Sept. 1990 through Sept. 1991 at $49,194.

Westall, J. M., ``Analysis of Memory Referencing Behavior Models and Cache Memory Performance". Funded by NCR Corp. from Nov. 1991 through Feb. 1993 at 49,343.

Westall, J. M., ``Analysis of Frame Buffer Referencing and Video Subsystem Performance". Funded by the NCR Corp. from May 1993 through Jan 1994 at $52,000.

Geist, R. M. and Westall, J. M., ``A Linux Workstation for High Performance Graphics". Funded by NASA from January 1997 through February 2000 at $148,056.

Geist, R. M. and Westall, J. M., ``ATM Network Support for the Linux Operating System". Funded by the IBM Corp. from January 1997 through December 1998 at $58,000.

Geist, R. M. and Westall, J.M., IBM SUR Equipment Grant, Dec 1997, $350,000.

Geist, R. M. and Westall, J.M., IBM ATM Switch Grant, July 1998, $20,000.

Druffel, L., Geist, R. M., Westall, J.M., et al. ``SCINET- An Internet II Connection Proposal for the State of South Carolina", January 1998, Funded by the National Science Foundation from Sept 1998 through Sept 2000 at $350,000.

Geist, R. M., Westall, J.M., et. al. ``An Upgrade to Clemson's Graphics-Supercomputer" Internal research proposal to CU Provost, Funded by the CU Foundation at $115,000.

Geist, R.M, Davis, T. A. Oagle, A., and Westall, J.M., ``Real-Time Visualization of Polymer Flows", Funded by NASA through the SC Space Grant Consortium from Jan 2000 through Dec 2000 at $25,000.

Geist, R. M., and Westall, J.M., ``Graphics Benchmarking for Linux Systems", Funded by the Dell Computer Corporation from Oct 2000 through Oct 2001 at $48,875.

Geist, R. M., and Westall, J. M., ``ITR/SI: Design and Implementation of a Graphics Supercomputer from Commodity Components", Funded by the National Science Foundation from August 2001 through July 2004 at $267,010

Geist, R.M., and Westall, J.M. , ``Validated Modeling of Network Component Performance: A Collaborative Research Effort Involving the Center for Advanced Computing and Communication (CACC) and Clemson University. Funded by the National Science Foundation from Oct 2001 through Sep 2002 at $50,000

Wang, S., Geist, R. M., Westall, J.M. et al., Investigation of Space-Time Photography, a CHE SCRIG Infrastructure project , Funded by the Clemson University Research Office in Oct 2001 at $47,000.

Leudeman, J.K., Westall, J.M., et al., Clemson University GK-12 Project Sponsored by NSF (National Science Foundation) from Apr 2001 through March 2002 at $421,461.

Davis, T. A., Geist, R. M., Westall, J. M. et. al., TEXNH: A New Approach to the B.A. Degree in Computer Science, Sponsored by the NSF (CISE/EIA) July, 2003 - July, 2006 at $330,000.

Westall, J. M. (Associate Investigator), Center for Advanced Engineering Fibers and Films, NSF (ERC), $16,571,478, Summer 2002-2003.

Geist, R., Westall, J. et al., IBM Parallel Processing Laboratory, IBM, xSeries Blade Center (equipment, U.S. list $125,000) June, 2004.

Geist, R. M and Westall J. M., Performance Evaluation of Large Disk Array Systems, Network Appliance Corp., $24,000 (graduate student fellowship), January, 2005 - May, 2005.

Geist, R. M and Westall J. M., Motion Capture in Clinical Science, Mindfield, LLC, Charleston County, U.S. Dept. of Education, $146,688, October, 2004 - September, 2005.

TEACHING

Graduate Course Development

CPSC 825 - Software Systems for Data Communication (1985)

CPSC 826 - Internetworking (1998)

CPSC 853 - Implementation of TCP/IP Protocols (2005)

Graduate Students (Chair of Advisory Committee)

C. Zeringue, T. Ledford, R. Moss, M. Yang, D. Sikkema, M. Shuler, B. Starcher, S. Able, W. Hollis, J. Chern, J. Maybry, S. Palkar, L. Williams, B. Buddhavaparau, N. Deep, A. Sinha, S. Shrivastava, J. Baker, S. Moolky, T. Tatum, S. Bahadur, V. Ranjan, C. Freise, S. Hingorini, R. Bahukudumbi, N. Aerrabatu, H. Gilkey, M. Page, V. Kalyanakrishnan, A. Flower, S. Bhikshesvaran, S. Viswanathan, K. Spicer, I. Ahmed, V. Sharma, C. Bhasin, V. Mamidi, V. Manan, H. Gangani, V. Mamtan, M. Gokhale, A. Desai, H. Narendra, S. Pathak, V. Nagapraveen, P. Wells, R. Ramenini, N. Paul, T. Landry, E. Gosnell, A. Godavarthy, A. Patil, A. Tripathy, S. Drachova, A. Hussein, K. Padwal, A. Shah, G. Sreenivasan, K. Sadaram, R. Srivatsavai, V. Yalla, R Bhat.

RESUME – Michele Clark Weigle

PERSONAL DATA

Assistant Professor
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EDUCATION

Ph.D., University of North Carolina at Chapel Hill, 2003, Computer Science

M.S., University of North Carolina at Chapel Hill, 1998, Computer Science

B.S., Northeast Louisiana University, 1996, Computer Science

PROFESSIONAL EXPERIENCE

Clemson University, 2004- , Assistant Professor of Computer Science

University of North Carolina at Chapel Hill, 2003-2004, Visiting Assistant Professor of Computer Science

MEMBERSHIPS

Member, Association of Computing Machinery, ACM (1998-)

Member, ACM Special Interest Group in Communications, SIGCOMM (2000-)

PROFESSIONAL ACTIVITIES

International Conference on Distributed Computing Systems, Reviewer (2006).

IEEE INFOCOM, Reviewer, (2004, 2005).

ACM Symposium on Applied Computing Special Track on Computer Networks, Reviewer, (2004).

Thomson Course Technology, Book Reviewer, (2004).

International Conference on Distributed Computing and Sensor Systems (DCOSS), Reviewer, (2005).

PUBLICATIONS

Refereed Journal Publications

Weigle, M.C., Jeffay, K., and Smith, F. D., "Quantifying the Effects of Recent Protocol Improvements to TCP: Impact on Web Performance," *Computer Communications, to appear*, (2006).

Weigle, M.C., Jeffay, K., and Smith, F. D., "Delay-Based Early Congestion Detection and Adaptation in TCP: Impact on web performance," *Computer Communications*, **28/8**, 837-850 (2005).

Conference Proceedings (Reviewed)

Weigle, M.C., Sharma, P., and Freeman, J., "Performance of Competing High-Speed TCP Flows," *Proceedings of IFIP Networking*, (May 2006), to appear.

Cao, J., Cleveland, W.S., Gao, Y., Jeffay, K., Smith, F.D., and Weigle , M.C., "Stochastic Models for Generating Synthetic HTTP Source Traffic," *Proceedings of IEEE INFOCOM*, Hong Kong (March 2004).

Weigle, M.C., Jeffay, K., and Smith, F.D., "Quantifying the Effects of Recent Protocol Improvements to Standards-Track TCP," *Proceedings of the 11th IEEE/ACM International Symposium on Modeling, Analysis and Simulation of Computer Telecommunication Systems* (MASCOTS), Orlando, FL (October 2003).

Hudson, T., Weigle, M.C., Jeffay, K., and Taylor II, R.M., "Experiments in Best-Effort Multimedia Networking for a Distributed Virtual Environment," *Proceedings of Multimedia Computing and Networking, SPIE Proceedings Series*, Volume 4312, San Jose, CA (January 2001).

Clark, M. and Jeffay, K., "Application-Level Measurements of Performance on the *vBNS*," *Proceedings of the IEEE International Conference on Multimedia Computing and Systems*, Florence, Italy (June 1999).

Nee, P., Jeffay, K., Clark, M., and Danneels, G., "A Two-Dimensional Audio Scaling Enhancement to an Internet Videoconferencing System," *Proceedings of the Intl. Workshop on Audio-Visual Services over Packet Networks*, Aberdeen, Scotland, UK (September 1997).

Other Scholarly Publications

Weigle, M.C., "Investigating the Use of Synchronized Clocks in TCP Congestion Control," Ph.D. Dissertation, Technical Report TR03-038, Department of Computer Science, University of North Carolina at Chapel Hill (August 2003).

PRESENTATIONS

Weigle, M.C., “Issues in Network Protocol Evaluation”, Networking and Telecommunications Seminar, College of Computing, Georgia Tech, Atlanta, GA (February 20, 2006).

“Issues in Network Protocol Evaluation”, Systems Seminar, Department of Computer Science, University of North Carolina at Chapel Hill, Chapel Hill, NC (February 10, 2006).

Weigle, M.C., “Evaluation of High-Speed TCP Proposals,” *Research Seminar*, Department of Computer Science, University of North Carolina at Charlotte, Charlotte, NC (October 28, 2005).

Weigle, M.C., “Transport Protocols in Wireless Sensor Networks,” *Virginia Tech-Clemson Workshop on Networking Research*, Virginia Tech University, Blacksburg, VA (April 2, 2005).

Weigle, M.C., “Delay-Based Congestion Detection and Adaptation for TCP,” *Department Colloquium*, Department of Computer Science, University of Georgia, Athens, GA (October 1, 2004).

Weigle, M.C., “Investigating the Use of Synchronized Clocks in TCP Congestion Control,” *Research, Careers, and Computer Science: A Maryland Symposium*, Department of Computer Science, University of Maryland, College Park, MD (November 16-17, 2001).

Weigle, M.C., “Sync-TCP: Using GPS Synchronized Clocks for Early Congestion Detection in TCP,” *Poster Session, ACM SIGCOMM 2000*, Stockholm, Sweden (August 31, 2000).

Clark, M., “Using Synchronized Clocks in TCP Congestion Control,” Sprint Advanced Technology Labs, Burlingame, CA (September 15, 1999).

HONORS AND AWARDS

Phi Kappa Phi (1995).

Upsilon Pi Epsilon (1995).

National Science Foundation Graduate Research Fellowship (1996-1999).

SPONSORED RESEARCH

“Exploring the Use of Mobile Ad-Hoc Networks for Inter-Vehicular Communication,” Clemson University Research Grant Committee, Principal Investigator, $2,979, (November 2005 – November 2006).

GRADUATE STUDENT ADVISING

Current Graduate Advising

Adurthi, Prashanth (MS), "Simulation of tmix Traffic Generation in ns-2," (May 2006).

Sharma, Pankaj (MS), "An Investigation of the Performance of Large High-Speed TCP Flows," (August 2006).

TEACHING

Courses Taught (Beginning Fall 2004)

CPSC 826/852, Internetworking, F04, F05.

CPSC 360, Distributed and Network Programming, S06, S05, F05.

Last updated March 5, 2

Appendix 6 Letters of Support/Collaboration

CLEMSON
UNIVERSITY
POLICE DEPARTMENT

March 9, 2006

National Institute of Justice
810 Seventh St., NW
Washington, DC 20531

To Whom it May Concern:

This letter is to indicate the support of the Clemson University Police Department to the Clemson University proposal for funding entitled "Evaluating IEEE 802.16 Broadband Wireless as a Communications Infrastructure for Public Safety Activities." The Clemson University Police Department is excited about the assistance this infrastructure could provide our department in our various public safety functions.

The Clemson University Police Department would plan to attend all demonstrations offered by the Department of Computer Science so that we may understand the full operability of this equipment. Furthermore, we would dedicate police officers and other staff members to test this equipment in the field and provide feedback as to its effectiveness.

The Clemson University Police Department is in full support of this project, and it is committed to assisting in the proper testing of this equipment.

Sincerely,

Michael K. Reidenbach
Office of Training and Accreditation

Clemson University Police Department * Centennial Blvd * Clemson S.C. 29634
864-656-2222 Office ~ 864-656-0714 Fax

CLEMSON
UNIVERSITY

Memorandum

To: National Institute of Justice

From: William E. Daniel, Fire Chief
Clemson University Fire & EMS

Reference: Letter of Support for the Clemson University proposal
"Evaluating IEEE 802.16 Broadband Wireless as a Communications Infrastructure for Public Safety Activities".

Date: March 8, 2006

Cc. Jim Martin, Assistant Professor
Clemson University Department of Computer Science
Mary Poore, AVP for Municipal Services
Clemson University Division of Student Affairs

The Clemson University Department of Computer Science has approached our department for assistance and is proposing to build an 802.16 network on campus. There are many applications for cost effective and secure voice, data, and real time video transmission that would benefit our agency during incident response, pre-incident planning, and large venue coverage such as Clemson Football game day when our population swells from 25,000 to 125,000 in addition to day to day duties.

Clemson University Fire & EMS as the primary fire and emergency response agency for the University and the City of Clemson are greatly interested in the project and plan on actively participating by attending demos, supplying access for field testing, and evaluating of the network during routine and emergency responses within our area of responsibility. Our command staff will be able to commit time for experimenting with the network and provide feedback to the research group.

If you are in need of more information I can be reach by email at dw@clemson.edu or phone 864-656-2242.

FIRE/EMERGENCY MEDICAL SERVICES • EMERGENCY PREPAREDNESS
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