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COVERED (From - To)
Sep 1, 96 - Aug 31, 01

1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE Final Report		3. PERIOD COVERED (From - To) Sep 1, 96 - Aug 31, 01	
4. TITLE AND SUBTITLE Telecommunication Networks for Mobile & Distributed Communications/ Computing				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER F49620-96-1-0472	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Dr. Sumit Roy				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Division Of Computer Science University of Texas at San Antonio 6900 North Loop 1604 West San Antonio, TX 78249				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Department of the Air Force Air Force Office of Scientific Research 4015 Wilson Blvd. Arlington, VA 22203-1954				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES DODAAD CODE: 7M065 AFOSR Program Manager: Dr. Jon Sjogren					
14. ABSTRACT Summary: The department of Computer Science was positively impacted by this funding, as it helped to insure research opportunities for both students and faculty at both the Master's and Ph.D. degree program levels. The Computer Science Ph.D. program was initiated in October 1995 so that this grant provided substantial opportunities in attracting quality students into the new program. Over this same period, the Electrical Engineering department was similarly influenced by the funding through its program offered a Master's Degree as its only graduate level program. However, the support that the grant did provide its faculty, can be credited in part for the approval and implementation of their Ph.D. program in October 2002. The list of publications, listed below, attests to the measurable efforts in training and supervision of both Master's and Ph.D. students in state-of-the-art research areas.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:		17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT			c. THIS PAGE	Dr. Sumit Roy
				19b. TELEPHONE NUMBER (include area code)	

20040105 046

**Telecommunication Networks for Mobile & Distributed
Communications/Computing**

AFOSR Grant F49620-96-1-0472 (URISP)

Final Report

Sep. 1, 96- Aug.31, 2001

No Cost Extension: Sep. 1 - Dec. 31, 2001

P. I.: Robert Hiromoto

**Co-Investigators: R. Boppana, S. Das, Gyungho Lee, W.-M. Lin,
Kleanthis Psarris, G. V. S. Raju, and Jon Weissman
and former Co-Investigators S. Roy, Christian Schlegel and Isaac Wong**

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Final Report:

This is the final report for the grant F49620-96-1-0472 which ended on Dec. 31, 2000. During the period from September 1996 through December 2000, the main objectives were to:

1. Build a research infrastructure (equipment, faculty, students)
2. Develop faculty research opportunities
3. Develop a graduate student research program within the Computer Science and Electrical Engineering Departments

Summary:

The department of Computer Science was positively impacted by this funding, as it helped to insure research opportunities for both students and faculty at both the Master's and Ph.D. degree program levels. The Computer Science Ph.D. program was initiated in October 1995 so that this grant provided substantial opportunities in attracting quality students into the new program. Over this same period, the Electrical Engineering department was similarly influenced by the funding though its program offered a Master's degree as its only graduate level program. However, the support that the grant did provide its faculty, can be credited in part for the approval and implementation of their Ph.D. program in October 2002. The list of publications, listed below, attests to the measurable efforts in training and supervision of both Master's and Ph.D. students in state-of-the-art research areas.

The UTSA faculty supported under this grant also benefitted in several ways; such as, funding support for graduate students to work on specific areas of faculty research, opportunities to

organize interacting research teams, initiating new research areas, preparation time for other funding opportunities, demanding higher research standards among students in EE and CS, establishing a university approved research center as a focal point for the faculty's research, and supporting equipment purchases for two laboratories that were extensively used in this grant.

Approach

1. Developed a focused research program in telecommunications, networks, and network based computing
2. Establish a computational research facility
3. Seek local industry support for research
4. Increase recruitment of Ph.D. and MS students

Developing research focus areas to complement and enhance faculty research interests. Recruit graduate students to train in designated research areas. Course lectures and independent studies. Establish computational facilities to support research efforts. Collaborative research projects.

Results

1. Two National Science Foundation Career Awards
2. Growing network research reputation in wireless & mobile network protocols.
3. The Center for Advanced Computing and Network Research.
4. Expansion of faculty and student research interests and capabilities
5. New labs in wireless & mobile communications, and parallel & distributed systems

Strong group research effort in wireless and mobile network protocols. Research spanning the breadth of network communications and network based computing. University approval (based on AFOSR funding) for The Center for Advanced Computing & Network Research (July 1999). Established a Wireless & Mobile Communications Laboratory, a Parallel & Distributed Systems Laboratory networked with an ATM switch and a 10- and 100-bit ethernet interconnections and the High-speed Gigabit Communications Laboratory.

Deliverables

1. Performance based simulators: networks; memory hierarchy; routing; switches.
2. Analytical and experimental results.

3. Public release of routing protocols for wireless & mobile networks.
4. Advance research capabilities for future projects with AFOSR.
5. Research trained student graduates.
6. Growing network research reputation in wireless & mobile network protocols.
7. New labs in wireless & mobile communications, parallel & distributed systems

An enumeration of the research efforts collectively funded the above URISP award is provided below. The research areas are classified under two technical clusters: (i) Communications & Networks, and (ii) Parallel & Distributed Computing. Key aspects reported on include: (1) Wireless networks; (2) Transmission rate controller in ATM Networks; (3) Fast parallel and distributed algorithms; (4) Memory Access Mechanism; (5) Metacomputing; (6) Optimal resource distribution in multiprocessor networks; (7) Compilation Techniques for Parallel and Distributed Systems.

The AFOSR (URISP) Grant F49620-96-1-0472 was a major reason for the establishment of the Center for Advanced Computing and Network Research. The Center's activities encompasses research, the support for graduate and undergraduate student research, community out reach programs and alliances with local information technology companies. The Director of the Center was Prof. Robert Hiromoto who is the PI for this grant, and is now the Chair of the Department of Computer Science at the University of Idaho.

Cluster I: COMMUNICATIONS & NETWORKS

1 Mobile and Wireless Communications

1.1 Objectives

During the period of this grant, we established several unified areas of research. These areas are categorized as 1) Protocols for Mobile, Wireless Networks, 2) Routing Techniques for Wireless Ad-Hoc Communication Networks and 3) Formal Analytical Models for Mobile and Wireless Networks.

Digital Wireless Networks

Objective

The design and analysis of low complexity multi-user (MU) detectors for future wireless systems employing code-division multiple access (CDMA). Desirable transceivers must meet a complexity-performance trade-off in the presence of impairments such as unknown, time-varying (fading)

channels and user motion. Hence, DSP-implementable receiver structures for joint equalization/diversity and channel estimation are investigated with a focus on performance evaluation in the presence of realistic worst case channel (large delay and Doppler spreads) and MAI conditions (signal to interference ratios of -10 dB).

Approach

Extract signature information from CDMA modulation for user demodulation/decoding. Analyze multi-packet reception capabilities for all-digital wireless transceivers based on minimum mean-squared error principle. Determine performance in terms of multi-path channel spread, near-far ratio for multi-access interference and detector observation window

To counteract typical fading wireless channels and multiple access interference (MAI) dominated scenarios, the transceiver architecture must not only be efficient, but necessarily adaptive. Broadly speaking, a space-time receiver architecture is required that exploits in the most effective manner all available degrees of freedom (both temporal and spatial). Accordingly, an all-digital receiver is desired that performs the major sub-tasks (diversity combining, equalization, timing and carrier recovery) jointly in a data-adaptive manner to achieve signal separation/multi-user interference cancellation.

Specifically, linear adaptive detectors were studied that exploit the underlying signal subspace structure resulting from CDMA modulation appear attractive in counteracting typical fading wireless channels and multiple access interference (MAI) dominated scenarios. The benefits of a blind adaptive detector that assumes no information regarding the interfering user parameters (timing, code) and which operates only in the signal space (i.e., the space occupied by all active users) are highlighted for the AWGN-only channel with all synchronous users. The detector obtains an estimate of the signal subspace via a one-shot eigen-decomposition of the received data. However, the presence of either (interfering) user asynchronism or multipath leads to significant performance degradations to the above approach. Further, the detector is known to be sensitive to imperfections in timing/carrier recovery for the desired user. To render subspace detectors useful for fading multipath channels (as opposed to AWGN) and robust to model imperfections such as timing/carrier offset, joint signal subspace tracking and adaptive interference cancellation/timing and carrier estimation is necessary - a comparative performance analysis of some candidate approaches were performed. Continuing analytical and simulation experiments are required to quantify performance in terms of multipath channel spread in time and Doppler, near-far ratio for the MAI and detector observation window prior to a recommendation for DSP-transceiver architecture.

Results

Simulated slow/moderate fading channels performs better than other candidates; fast fading channels need further improvement. Slotted Aloha with MMSE detector is nearly optimal. Heavy

load response needs further improvement.

Deliverables

A DSP-implementable digit wireless transceiver architecture for fading channels; Design of a packet CDMA protocol exploiting link-level advances (multi-user detection).

Protocols for Mobile, Wireless Networks

The goal of the "Protocols for Mobile, Wireless Networks" project is to study protocols for mobile, ad-hoc networks. Dynamic routing being the key research challenge in ad-hoc networks, we emphasize on routing protocols. However, our goal also includes study of medium-access control or MAC protocols for ad-hoc networks. The traditional layered structure of network protocols is considered less desirable for wireless networks because of the highly unreliable and time-varying characteristics of radio channels. Achieving acceptable performance in wireless networks requires addressing of technical issues simultaneously at different layers. Thus, one major research emphasis was the unique characteristics of the radio link layer that affects the performance of higher networking layers and, secondly, how key link layer specific information can be exploited by the higher layers for better performance. As a part of this project we are also investigating fast simulation methodologies for efficient performance evaluation of wireless network protocols.

Routing Techniques for Wireless Ad-Hoc Communication Networks

This project developed routing algorithms and analyzes switch designs to provide fast and efficient communication in wireless, mobile and ad-hoc networks. Wireless networks consisting of only low-powered, mobile communicators pose special challenges in routing packets between non-adjacent nodes. The goal is to design routing methods that sustain performance under overloading conditions and have low overhead and energy consumption characteristics. The application of directional antennas were also studied with efficient protocols proposed.

Formal Analytical Models for Mobile and Wireless Networks

The goal of this project is to develop formal analytical models to predict the performance of mobile and wireless communication networks from both a theoretical and practical aspect. The performance of a particular mobile and wireless protocol based on empirical studies through the use of simulations alone is an imprecise and potentially inaccurate approach. Without a sound theoretical frame work, validations between the simulated protocol and the extension to actual practice is tenuous at best.

1.2 Status of Effort

Simulation model building: We have developed simulators for routing and MAC protocols for ad-hoc networks. These include the following:

(i) Augmenting MaRS (Maryland Routing Simulator) for simulating ad-hoc routing protocols; (ii) Developing some key routing protocols in MaRS; (iii) Using popular network simulator NS2 to develop a detailed simulation model of a routing protocol, called AODV; (iv) Developing several CSMA-based MAC protocol models in a home-grown event-driven simulator.

Performance evaluation of routing protocols: We have completed a thorough performance evaluation of several routing protocols for ad-hoc networks. They include current-generation on-demand protocols, as well as, more traditional, pro-active protocols.

Development of Internet standards: We participated actively in developing the Internet draft for the AODV protocol.

Optimization of routing protocols:

(i) Query localization: we developed a mechanism to localize the extent of broadcast floods in on-demand routing protocols. (ii) Multipath techniques: we developed a multipath technique to utilize redundant routes in on-demand protocols. This reduces the frequency of flooding. (iii) Several other optimizations to reduce the impact of flooding in under study.

MAC protocols: We developed a multichannel CSMA-based MAC protocol for wireless, multi-hop networks. It uses a form of "soft" channel reservation to reduce packet collisions.

Ad-Hoc testbed development: A testbed involving several Linux laptops and Lucent Wavelan wireless interface is under development. The testbed will implement the AODV protocol as an extension of the ARP. The testbed will be used for experimental performance evaluation of the AODV protocol with realistic networking applications.

Parallel simulation: We are developing parallel simulation technology to support fast simulation of large-scale wireless networks. Certain performance optimization techniques for a rollback-based parallel simulation mechanism, called Time Warp, have been developed. Currently, parallelization of a public domain network simulator (NS2) on workstation clusters is underway.

We have investigated network layer routing algorithms for wireless, mobile and ad-hoc networks (MANETs). We have conducted extensive performance analyses of various existing algorithms and designed variations of these for better performance. We have also looked at multicast communication on MANETs. Currently, we are designing newer algorithms that facilitate quality of services (QoS) support and implementation of differentiated services framework.

1.3 Status of Accomplishments

Our simulations of newly proposed wireless routing protocols, showed significant performance benefits in comparison with traditional techniques.

We have conducted extensive analysis of routing techniques for MANETs and exposed several weaknesses in two routing techniques called AODV and DSR. We designed a new routing technique that provides good performance under a variety of traffic loads and sustains its performance when the network is overloaded. We have shown that this algorithm has low overhead which might make them suitable for implementation in low-powered communication devices. Some of the results will be presented in an upcoming conference.

We have analyzed multicast group communication in MANETs. We have shown that in crowded MANETs, where each node has several neighbors sharing a common radio channel, tree based multicasts perform better than mesh based multicasts. Recently we improved on a mesh-based multicast technique to provide 100% improvement in throughput in dense MANETs.

Several analytical model has been designed for analyzing the performance of the Query Localization (QL) techniques proposed by Castaneda and Das. The model also points out the importance of boundary effects on the performance of the QL technique.

Our simulations of newly proposed wireless routing protocols, showed significant performance benefits in comparison with traditional techniques.

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1.4 Personnel Supported

Rajendra V Boppana - Faculty investigator

Samir Das - Faculty investigator

Robert Hiromoto - Faculty investigator

Asis Nasipuri - Postdoc fellow

Saman Desilva - Network engineer and PhD student

Robert Castaneda - PhD student

Suvro Ghosh - MS student

Ramakanth Gunuganti - PhD student

Kevin Jones - PhD student
Satyadeva P Konduru - PhD student
Mahesh Marina - PhD student
Sumit Roy - Subcontractor (University of Washington)
Veronica Schiaffini - MS student (graduated)
Shanmuka Voona - PhD student
Jiangtao Yan - MS student (graduated)
Shengchun Ye - MS student
Jun Zhuang - MS student (graduated)

Note that some of the above personnel were only partially supported by the project funds.

1.5 Technical Publications

Journals -

Published or accepted for publication in refereed journals or conference proceedings:

1. Supavadee Aramvith, Chia-Wen Lin, Sumit Roy, and Ming-Ting Sun, "Wireless video transport using conditional retransmission and low-delay interleaving," submitted to *IEEE Trans. Circuits and Systems for Video Technology*, Special Issue on Wireless Video (submitted, Apr. 2001).
2. R. V. Boppana and S. Chalasani, "Fault-Tolerant Communication with Partitioned Dimension-Order Routers," to appear in *IEEE Transactions on Parallel and Distributed Systems*, Special Issue on Fault-Tolerant Routing.

Conference Proceedings/Presentations

1. Supavadee Aramvith, Chia-Wen Lin, Sumit Roy, and Ming-Ting Sun, "Wireless video transport using conditional retransmission and low-delay interleaving," *Proc. IEEE Int. Symp. on Circuits and System*, V-101 104, Jun. 2001, Sydney, Australia.
2. H. Yan and S. Roy, "A FREQUENCY DOMAIN METHOD FOR CHANNEL ESTIMATION IN MULTIRATE COMMUNICATION SYSTEMS," *IEEE International Conference on Acoustics, Speech, and Signal Processing* Salt Lake City, Utah, May 7-11, 2001, vol. 4, pp. 2057-2060.
3. H. Yan and S. Roy, "FIR CHANNEL IDENTIFICATION IN MULTIRATE COMMUNICATION SYSTEMS WITH A SUBSPACE METHOD," *IEEE International Conference on Acoustics, Speech, and Signal Processing* Salt Lake City, Utah, May 2001.

4. K. Jones and S. R. Das, Time-Parallel Algorithms for Simulation of Multiple Access Protocols, in Proceedings of the 9th. International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS 2001), Cincinnati, Ohio, August 2001.
5. N. Jain, S. R. Das and A. Nasipuri, "A Multichannel MAC Protocol with Receiver-Based Channel Selection for Multihop Wireless Networks," Proceedings of the 9th Int. Conf. on Computer Communications and Networks (IC3N), Phoenix, Oct 2001.
6. S. R. Das, C. E. Perkins, E. M. Royer and M. K. Marina, "Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks," IEEE Personal Communications Magazine, special issue on Mobile Ad Hoc Networks, Vol. 8, No. 1, Feb 2001, pages 16-29.
7. A. Nasipuri, R. Castaneda and S. R. Das, "Performance of Multipath Routing for On-Demand Protocols in Ad Hoc Networks," ACM/Kluwer Mobile Networks and Applications (MONET) Journal, Vol. 6, No. 4, 2001, pages 339-349.
8. M. K. Marina and S. R. Das, "Performance of Route Caching Strategies in Dynamic Source Routing," Proceedings of the 2nd Wireless Networking and Mobile Computing (WNMC), Phoenix, April 2001. In conjunction with the Int'l Conference on Distributed Computing Systems (ICDCS) 2001.
9. M. K. Marina and S. R. Das, On-demand Multipath Distance Vector Routing for Ad Hoc Networks, in Proceedings of the International Conference for Network Protocols (ICNP) , Riverside, Nov. 2001.
10. S.R. Voona, R. Gunuganti, and R.V. Boppana, "On the Performance of Tree and Mesh Based Multicast Routing in Mobile and Ad-Hoc Networks," Submitted to IEEE Infocom, April 2000.
11. A. Abouzeid, S. Roy and M. Azizoglu, "Stochastic modeling of TCP over lossy links," in Proc. INFOCOM'2000, 2000, pp. 1724-1733.
12. S. R. Das, R. Castaneda and J. Yan, "Simulation Based Performance Evaluation of Mobile, Ad Hoc Network Routing Protocols," ACM/Baltzer Mobile Networks and Applications (MONET) Journal, July 2000, pages 179-189.
13. A. Nasipuri and S. R. Das, "Multichannel CSMA with Signal Power-Based Channel Selection for Multihop Wireless Networks," Proceedings of the IEEE Vehicular Technology Conference (VTC), Boston, Sept 2000.
14. S. Desilva and S.R. Das, "Experimental Evaluation of a Wireless Ad Hoc Network," Proceedings of the 9th Int. Conf. on Computer Communications and Networks (IC3N), Las Vegas, October 2000.

15. R.V. Boppana and M.K. Marina, "An Adaptive Routing Algorithm for Mobile and Ad-Hoc Networks," Submitted to IEEE Infocom, April 2000.
16. S.R. Das, C. E. Perkins and E. M. Royer, "Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks," Proceedings of INFOCOM 2000 Conference, Tel-Aviv, Israel, March 2000.
17. R.V. Boppana and C.S. Raghavendra, "Designing Efficient Benes and Banyan Based Input-Buffered ATM Switches," International Conference on Communications (ICC), June 1999.
18. R. V. Boppana, M. K. Marina, S. P. Konduru, "An Analysis of Routing Techniques for Mobile and Ad-Hoc Networks," International Conference on High Performance Computing, December 1999.
19. S. R. Das, R. Castaneda and J. Yan, "Simulation Based Performance Evaluation of Mobile, Ad-Hoc Network Routing Protocols," accepted for publication in ACM/Baltzer Wireless Network Journal, 1999.
20. A. Nasipuri and S. R. Das, "On-demand Multipath Routing for Mobile Ad-Hoc Networks," to appear in the Proceedings of the 8th. IEEE International Conference on Computer Communications and Networks (IC3N), Boston, Oct. 1999.
21. A. Nasipuri, J. Zhuang and S. R. Das, "A Multichannel CSMA MAC Protocol for Multihop Wireless Networks," to appear in the Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), New Orleans, September, 1999.
22. R. Castaneda and S. R. Das, "Query Localization Techniques for On-Demand Routing Protocols for Mobile Ad-Hoc Networks," Proceedings of the Fifth ACM International Conference on Mobile Computing and Networking (MOBICOM), Seattle, August, 1999.
23. K. Jones and S. R. Das, "Combining Optimism Limiting Schemes in Time Warp Based Parallel Simulations," Proceedings of the 1998 Winter Simulation Conference, Washington, DC, Dec. 1998, pages 499-505.
24. S. Desilva and S. R. Das, "Experimental Evaluation of Channel State Dependent Scheduling in an In-building Wireless LAN," Proceedings of the 7th. IEEE International Conference on Computer Communications and Networks (IC3N), Lafayette, LA, Oct 1998, pages 414-421.
25. S. R. Das, R. Castaneda, J. Yan and R. Sengupta, "Comparative Performance Evaluation of Routing Protocols for Mobile, Ad-Hoc Networks," Proceedings of the 7th. IEEE International Conference on Computer Communications and Networks (IC3N), Lafayette, LA, Oct 1998, Lafayette, LA, pages 153-161.
26. R. Castaneda, S. R. Das and M. Marina, "Query Localization Techniques for On-Demand Routing Protocols for Mobile Ad-Hoc Networks, submitted to ACM/Baltzer Wireless Networks (WINET) Journal (invited as an expanded version of the MOBICOM'99 paper).

1.6 Transitions/Interactions

Software in public domain: We are releasing a simulation model of the AODV protocol as a part of the public domain network simulator NS2. NS2 being a widely used simulator for internetworking protocols, our work will get very good visibility.

Industry interactions: The development and evaluation of the AODV protocol is carried out in cooperation with the Sun Microsystems Labs, Palo Alto, and Nokia Research Center, Mountain View. A faculty investigator, Samir Das, spent the Spring'99 semester in Sun Microsystems as a part of this effort. This effort resulted in the submittal of a Internet Draft of the specification of the AODV protocol.

Multicast algorithms implemented in the widely used NS-2 network simulator are being distributed to researchers for their use and comments. We are currently interacting with researchers at UCLA (S.J. Lee), USC/ISI (K. Obraczik), and Sun Microsystems (C. Perkins).

1.7 Patent Disclosures - None.

1.8 Honors/Awards

Samir Das:

- NSF Faculty Early CAREER Award, 1998-2003, Parallel Discrete Event Simulation: Protocols, Tools and Applications.
- NSF Networking Research Award, 1999-2003, Collaborative Proposal: Protocols for Mobile Ad Hoc Networking (with Co-PI Asis Nasipuri, in collaboration with Nitin Vaidya).

2 Transmission Rate Controller for Congestion Control in ATM Networks

2.1 Objectives

This research concerned itself with the performance improvements of a traffic controller that simultaneously manages congestion control and connection admission control for asynchronous transfer mode (ATM) network. Asynchronous transfer mode (ATM) is a key technology for integrating multimedia services in high speed networks. ATM network supporting multimedia services have to be capable of handling bursty traffic and satisfying various quality of service (QOS) and bandwidth requirements and also to achieve high system utilization. The ATM forum

has specified several service categories in relation to traffic management in an ATM network. These service categories are divided into constant bit-rate (CBR), variable bit-rate (VBR), available bit-rate (ABR) and unspecified bit-rate (UBR). For the purposes of this study, the traffic (service) is categorized into two types: real-time (type 1) and non-real time (type 2). Video and voice services are examples of type 1 traffic and data services are examples of type 2 traffic. Because of the unpredictable statistical fluctuations in the traffic flows of multimedia services, network congestion may still occur even though an appropriate connection admission control scheme is provided. In order to prevent the quality of service (QoS) from severely degrading during short-term congestion, an appropriate congestion control must be provided.

In this study we have developed two control techniques for congestion control in ATM networks for ABR traffic.

The fuzzy approach exhibits a soft behavior with an ability to adapt itself to dynamic, imprecise, and bursty environments of an ATM network which requires a sophisticated real-time traffic controller that manages connection admission control and congestion control, to guarantee the QoS for existing calls and to achieve high system utilization. All congestion control and connection admission control schemes that utilize either buffer thresholds or capacity estimation have limitations due to incomplete statistics of input traffic. Fuzzy logic systems have been developed to overcome some of these limitations.

In this study, we added a transmission rate manager for type 2 traffic of the Fuzzy Traffic Controller, and improved congestion controller design to achieve superior system utilization and to obtain low cell loss ratio. The congestion controller is improved through the modification of its rule structure. The output of the congestion controller is used to design a transmission rate manager to adjust the transmission rate of data sources of type 2 traffic to obtain high system utilization while lowering cell loss ratio.

2.2 Status of Effort

The input traffic coming from customers is categorized into two types: real-time (type 1) and non-real time (type 2). The network system supports two separate finite buffers with size K_1 for type 1 traffic and size K_2 for type 2 traffic. When the buffer is full, incoming cells are blocked and lost. The system reserves a portion of its capacity for type 1 traffic and the remaining portion to type 2 traffic. When there is unused type 1 or type 2 capacity, it is used for other type.

The performance measures estimator measures the queue length q , queue length change rate Dq and cell loss probability (ratio) pl for type 1 and type 2 traffic, and feeds these measures to fuzzy congestion controller. The fuzzy congestion controller generates a control action y according to a set of input linguistic variables of q , Dq and pl and a set of built in fuzzy control rules. A negative value of y denotes that the system has a certain degree of congestion, a new call has little chance

of being accepted. A positive value of y indicates that the system is free of congestion to a certain degree, new calls have a good chance of entering the network, and existing calls' rates can be adjusted to achieve higher system utilization. This report presents an improved congestion controller and a transmission rate manager for type 2 traffic to achieve overall higher system utilization. The fuzzy admission controller is same as in previous report. A call accept/reject control action Z is determined by the linguistic variables pl , y , and available capacity Ca of the network for both type 1 and type 2. The fuzzy traffic controller simultaneously handles congestion control and call admission control.

Fuzzy Congestion Controller

The queue length q , queue length change rate Dq , and cell loss ratio pl are used as input linguistic variables. The congestion control action y is used as output linguistic variable.

We defined the term sets for queue length, rate of change of queue length and cell loss ratio. The membership functions for the above term sets are developed. The rule structure for the congestion controller is obtained by utilizing the knowledge available in the literature and by extensive simulation. The max-min inference method for the inference engine and Tsakamoto's defuzzification method for the defuzzifier are applied to obtain a crisp value y_0 of the control action y . Based on the crisp value y_0 , the transmission rate manager, described in the next section, sends a transmission rate control command to adjust the incoming type2 traffic to achieve high system utilization while improving QOS provisioning through reduction of cell loss ratio.

Transmission Rate Manager

A negative value of y_0 indicates the system has a certain degree of congestion. A positive value of y_0 indicates that the system is free of congestion to a certain degree. A transmission rate manager is designed using y_0 as input to adjust the transmission rates of sources. Thus, the network available bandwidth is maximally utilized while maintaining the quality of service.

Simulation Results

The buffer sizes for type 1 and type 2 traffic are assumed as 100 cells each. Simulation results showed that with the new rule structure for congestion controller alone, the cell loss probability is reduced from $2.9e-3$ to $1.96e-3$, a 32.4 % reduction. The total system utilization has increased slightly (5%). With the addition of the proposed transmission rate manager for type 2 traffic, the total system utilization has increased from 69 % to 98.5% The maximum cell loss probability has decreased from $2.9e-3$ to $1.85e-5$.

2.3 Status of Accomplishments

We have developed a Pole-Placement and an Optimal Control methodologies for the design of an ABR congestion controller for ATM networks using closed loop rate based flow control. In particular, these methods show how to design an explicit rate controller. Simulation studies have been made for the optimal control method using MATLAB to show transient and steady state performance. For appropriate values of K, simulations have shown good transient and steady state behavior.

In addition we studied methods for the improvement of performance of a fuzzy traffic controller that simultaneously manages congestion control and call admission control for asynchronous transfer mode (ATM) networks . We introduced a new rule set for the congestion control part of fuzzy traffic controller. In addition, we added a transmission rate manager to adjust the source transmission rate of data traffic. The transmission rate manager reduces source rate when there is certain degree of congestion and increases source rate when the system is free of congestion to a certain degree. As a result of these improvements, the total system utilization has improved from 69% to 98.5% and QOS improved by the reduction of the cell loss probability from $2.9e-3$ to $1.85e-5$.

2.4 Personnel Supported

G.V.S.Raju - Faculty investigator
G.Hernandez - Graduate student
Zhaohua Qiu - Graduate student
Xin Wang - Graduate student
S.Ye - Graduate student
Q.R.Zou - Graduate student

2.5 Technical Publications

1. G.V.S.Raju,Z.Qiu and X.Wang, "Transmission Rate Manager for Traffic Control in ATM Networks," submitted for publication.

Conferences -

1. G.V.S. Raju, Z.Qou,and X.Wang Transmission Rate Manager for Fuzzy Logic Control of ATM networks," 2000 IEEE International Conference on Systems, Man, and Cybernetics, Nashville, TN, October, 2000.

2. G.V.S.Raju, G.Hernandez and Q.R.Zou, "Quality of Service in Ad Hoc Networks," IEEE WCNC 2000, Chicago, September 2000.
3. G.V.S.Raju, "Techniques for Traffic Control in ATM networks," IEEE International Conference on Systems, Man, and Cybernetics, San Diego, CA, October,1998.

2.6 Interactions - See conferences above.

2.7 Transitions - None.

2.8 Patent Disclosures - None.

2.9 Honors/Awards

G.V.S. Raju:

- IEEE 3rd Millennium Medal

Cluster II: PARALLEL & DISTRIBUTED COMPUTING

3 Fast Parallel and Distributed Algorithms

3.1 Objectives

During the report period, our efforts were to continue our development of fast parallel and distributed algorithms for the coordination of parallel tasks on a distributed system. Computer resource issues such as memory demands, parallel task scheduling and network communications protocol dominated our interests. Using an in house clusters of distributed multiprocessors, "fast-ethernet and high-speed switching networks (such as ATM and Myrinet), proved an affordable high-performance computational platform to test and evaluate different implementation strategies.

Three basic levels of parallel algorithm designs are analyzed. Verification of both the theoretical computational and communication complexities are two standard approaches. For a cluster of distributed multiprocessor, the complexity of network communications is complicated by the integration across different platform interfaces. The third level complexity arises from the particular choice of network hierarchy employed and the particular overhead costs that arises from its use.

An example that illustrate this case is the partitioning of a graph into P segmented portions. If the graph is fully connected the number of connections grow quadratically in the number of

portions P . This assumes that each portion is allowed to communicate with all other portions; thus, the quadratic growth. This implementation is clearly neither scalable in the hardware scaling nor in the communications demand. A technique to reduce this interconnection complexity can be introduced that reduces the complexity to P (linear) but at the cost of incurring additional memory demands. This approach, though memory intensive, is a candidate for scalable implementational consideration.

3.2 Status of Accomplishments

1. SYNET is a large-scale synaptic network simulator that has been developed to simulate the dynamic electro-ionic behavior of the neuronal network of the brain. The simulation uses the Hodgkin-Huxley equations that models the coupling of electrical stimulations of the neuron with the ionic currents that are connected through corresponding axons. Aside from the consideration of implementing numerical techniques to decrease the simulation time, the simulation is represented as a dynamic graph problem with N nodes (neuronal cells) and fully connected amongst all $(N-1)$ remaining nodes. Although the graph node connections (arcs) are known statically, the use of these connections are dynamically resolved based on the solutions of the system of ODEs that model the firing or non-firing of a neuronal cell. The graph nature of this problem suggests a naive algorithm implementation that for P distributed processors would result in a complexity that would grow quadratically in P . At this point we have debugged and verified the correctness of a linear complexity scheme that uses a Master/Slave parallel structure where one (or a subset of) processor(s) is used to receive tokens from all nodes that indicates the activated connections and their destination processors. Finally, in this way, each processor receives a single buffer with firing information for all cells handled by that particular processor. Although the Master/Slave paradigm address the problem to some degree, the scalability of the resulting implementation is limited by the memory available to the Master processor. In this regard we have designed a multi-stage, circular shift memory configuration that can be implemented on clusters of distributed workstations. We are now in the process of analyzing its memory complexity and testing an actual implementation.
2. A comparison of message passing protocols on different communications architectures was completed. The performance of TCP/IP and reliable UDP has been studied on both a 10 Megabit ethernet as well as the Fore-ATM switch. The preliminary findings indicate that TCP/IP exhibits better performance on both the ethernet and the ATM over UDP; however, this is only the case for statically assigned TCP/IP connections. For randomly dynamic connection reliable UDP is still better. These results have been incorporated in to several distributed simulations that are reported here.

Finally, the cost of synchronizing processes on an ATM switch is being designed and measured. This examination is done from two vantage points. The first takes a set of single processor machines and connects them through an ATM switch. The second takes a set

of small multiprocessor machines and examines the effect of using their internal bus for interprocessor communication and the ATM switch for inter-node communication.

3. The parallel spin-glass simulated annealing algorithm that has been implemented on clusters of SPARC-20s and Ultra-2 workstations has given rise to further studies of a modified cooling scheme central to the simulated annealing technique. The proposed cooling scheme is a "split phase" technique where rapidly converging methods are replaced by less rapidly converging methods at the tail end of the cooling process. This procedure increases the probability of jumping out of a local minimum and increases the sample space. This result emerged from the different parallel mapping constructs considered for the implementation of the spin-glass simulation.

3.3 Personnel Supported

Robert E. Hiromoto - Faculty investigator
Lichun Zhao - Research Assistant
Siva Pochiraju - Research Assistant

3.4 Technical Publications

Journals -

1. Robert E. Hiromoto and Joanne Simmons, "A Split-Phase Simulated Annealing Algorithm," to be submitted to the journal of Computational Physics.
2. Georgios Kousi and Robert E. Hiromoto "Psi-net: a large-scale parallel synaptic network simulator," to appear in Parallel Computing.
3. Robert E. Hiromoto, Lichun Zhao, "Verifying the 40 Hz neuronal synchronization frequency using Psi-net," submitted to the Journal of Computational Neuroscience.

Conferences -

1. Robert E. Hiromoto, "Strictness Analysis for Parallelism," Third Scottish Functional Programming Workshop, Stirling, Scotland, 22-24 Aug. 2001.
2. A. Nasipuri, J. Mandava, H. Rao, and R.E. Hiromoto, "On-Demand Routing Using Directional Antennas in Mobile Ad Hoc Networks," Proceedings: 9th International Conference on Computer Communications and Networks, Las Vegas, Nevada, Oct. 16-18, 2000, pp. 535-541.

3. A. Nasipuri, S. Ye, J. You, and R.E. Hiromoto, "A MAC Protocol for Mobil Ad Hoc Networks Using Directional Antennas, IEEE Wireless Communications and Networking Conference 2000, Chicago, IL. Sept. 23-28.
4. R.E. Hiromoto, "Notes on Optimizing Parallel Strategies in GpH," Second Scottish Functional Programming Workshop, St. Andrews, Scotland, 26-28 July 2000.

3.5 Interactions

Hiromoto - Invited presentations:

1. "A Simulated Annealing Split-Phase Cooling Scheme for Memory Recall," Advanced Research Workshop on "High Performance Computing: Technology and Applications, Cetraro, Italy, June 12-15, 2000.
2. "An Information-Based Complexity Metric for the Degree of Algorithmic Parallelism," Heriot-Watt University, Edinburgh, Scotland, July 15, 1999.
3. "A Design for a Large Scale Synaptic Network Simulator," Advanced Research Workshop on "High Performance Computing: Technology and Applications, Cetraro, Italy, June 22-24, 1998.
4. "A Parallel Elliptic PDE Solver Using a Hybrid Monte Carlo Boundary Propagation Method," Tuskegee University, Tuskegee, Alabama, Jan. 22, 1998.
5. "Information-Based Complexity and Parallelism," Stirling University, Stirling, Scotland, Sept. 19, 1997.

3.6 Transitions - None.

3.7 Patent Disclosures - None.

3.8 Society Service/Distinction

Hiromoto:

1. Program Co-Chair (Advanced Computing): Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, Foros, Crimea Ukraine, 1-5 July 2001.
2. Steering Committee Member: ParCo2001, Naples, Italy, 4-7 Sept. 2001.
3. Director: Center of Advanced Computing and Network Research, July 1999 - Dec. 2001.

4. Selected for inclusion in the 5th edition of Marquis Who's Who in the Science and Engineering.
5. Research Advisory Committee for the Army High Performance Computing Research Center (AHPARC), November 2000.
6. Program Committee: International Conference on Supercomputing, Santa Fe, New Mexico, May 8-11, 2000.
7. Steering Committee Member: ParCo99, Delph, Netherlands, August 1999.
8. Program Committee Member: Discrete Mathematics and Theoretical Computer Science Conference, Auckland, New Zealand, January, 1999.
9. Program Committee: IPPS99 Workshop on High Performance Data Mining, San Juan, Puerto Rico, April 6, 1999.
10. Invited Public Presentation: President Clinton's Commission on Critical Infrastructure Protection, May 13, 1997, Houston, Texas.
11. Regional Editor for the journal Parallel Computing.

3.9 Honors/Awards

Robert Hiromoto:

1. NSF, "Research Experience for Minority Students in High-Performance Computing and Communication," \$1.5 million, Sept. 2001 - August 2006, PI.
2. NSF, "Computational and visualization methods for large-scale biophysical neural networks," \$100,000, Jan. 1997 - Dec. 1999, PI.

4 Designing Versatile High-Speed LANs

4.1 Objectives

This research investigates new routing and switch design techniques to provide predictable, high bandwidth for variety of applications such as video streaming services and large-scale scientific computing using computer clusters. The current high-speed local and wide area networks (LANs and WANs) offer impressive data rates and increasingly use the Internet Protocol (IP). Because IP provides packet routing with no quality of service (QoS) guarantees, such networks though relatively inexpensive to deploy, do not meet latency constraints for applications high volume of

communication. Examples of such applications include large-scale scientific computing and video streaming services. The goal is to design new LANs that interconnect 100s of PCs or workstations to provide dependable performance for a variety of data communication needs even under high loads.

4.2 Status of Accomplishments

Path-Based Multicasting in Multicomputer Networks. We have developed a path-based multicast (one-to-many communication) method and evaluated its performance with many other such techniques proposed in the literature. We have shown that this technique performs well by using fewer resources and reducing congestion in the network. This work has been published in *IEEE Transactions on Parallel and Distributed Systems*.

Low-cost Adaptive Switches. We have developed adaptive message routing methods that work using small 3X3 crossbars as building blocks. In particular, we have shown that using such building blocks, adaptive routing switches can be designed for networks with mesh topology. This result is different from those known in literature, which assume the use of large crossbars for adaptive routing. This work has been published in *IEEE High Performance Computing (HiPC)* conference.

4.3 Personnel Supported

Rajendra V. Boppana - participating investigator
Kui Cai - Research Assistant

5 Memory Access Mechanism

5.1 Objectives

This research tackles the issue of providing high local memory utilization at low cost. We study the issue in the context of Distributed Shared Memory (DSM) multiprocessors and of high-performance out-of-order superscalar microprocessors.

5.2 Status of Accomplishments

Directory-based cache coherence schemes are commonly used in large-scale distributed shared-memory multiprocessors. However, the directory schemes proposed so far have two major drawbacks when compared to shared-bus based 'snooping' schemes. One drawback is its excessive cost for maintaining a directory, in terms of storage requirement and access time. The other drawback is its difficulty of obtaining system-wide information on the status of all memory blocks matching to a given address. We propose a new address mapping to remedy the two drawbacks by changing our viewpoint on memory address from 'memory-centric' to 'cache-centric'. The proposed address mapping guarantees minimum storage space for the directory and provides the system-wide status information on all memory blocks as easy as in shared-bus snooping scheme. Based on the new directory scheme we proposed, we devised a non-blocking coherency protocol, which reduces potentially long directory processing time due to conflicts at the directory.

On-chip Data cache memory for high-performance processors has grown tremendously in size and in complexity to a point that it consumes more transistors than processor core and that its access takes more than single processor cycles. However, faster processor cycle due to reduced feature size demands faster data access latency, and higher exploitation of ILP in wide-issue superscalar processors requires higher data bandwidth. On-chip data cache memory design becomes increasingly inefficient and adds to the hardware complexity significantly. We propose a way of splitting data cache memory to mitigate the problems. By splitting cache based on 'access region', i.e. an area in which data variable is allocated, the memory stream for data access can be partitioned into multiple independent streams early in the processor pipeline. By feeding each stream to a separate memory access queue and cache, we can provide the high bandwidth and fast latency requirement more efficiently with less hardware complexity.

5.3 Personnel Supported

Gyungho Lee - Faculty investigator

5.4 Technical Publications

Journals -

1. S. Cho, J. Kong, and G. Lee, "Coherence and Replacement Protocol of DICE - A Bus-Based COMA Multiprocessor," *Journal of Parallel and Distributed Computing*, Vol. 57, pp. 14-32, 1999.
2. J. Kong and Gyungho Lee, "Local Memory Binding in Distributed Shared Memory Multiprocessors", under review for the *IEEE Transactions on Parallel and Distributed Systems*

(currently being revised for second review).

3. J. Kong, P. Yew, and Gyungho Lee, "Minimizing directory size in large-scale distributed shared memory multiprocessors", submitted to the Journal of Parallel and Distributed Computing, May 1999.
4. J. Kong, P. Yew, and Gyungho Lee, "Non-blocking directory protocol for large-scale distributed shared memory multiprocessors," submitted to the IEEE TPDS, June 1999.

Conferences -

1. S. Cho, P. Yew, and Gyungho Lee, "Decoupling Local Variable Accesses in a Wide-Issue Superscalar Processor", Proc. of the 26th International Symposium on Computer Architecture, Atlanta, GA., May 1999.
2. S. Cho, P. Yew, and Gyungho Lee, "Access Region Locality for high bandwidth processor memory design", to be presented at the IEEE Micro-32, Haifa, Israel, Nov. 1999.

5.5 Interactions

5.6 Transitions - None.

5.7 Patent Disclosures - None

5.8 Society Service/Distinction

Gyungho Lee:

- Guest editorial introduction to the special issue on Interaction between Compilers and Computer Architecture, ACM SIGARCH Computer Architecture News, Vol. 27, No. 1, March 1999 (with P. Yew).

6 Metacomputing: Application Models, Scheduling Algorithms, and System

6.1 Objectives

The objective of this research project is to examine several important problems in the area of metacomputing: the seamless integration of geographically-dispersed computing resources connected by emerging high-speed wide-area networks. We are working in four key problem areas

within metacomputing: scheduling and resource management, wide-area I/O, fault tolerance, and applications.

6.2 Status of Accomplishments

In the area of wide-area I/O we have successfully applied SFO technology to a distributed gene sequence application running across the Internet and the vBNS, and performance was improved by 30%. We have also applied the concept to a mpeg player accessing Internet mpeg files, and playtime was improved by 20% and download wait was reduced by 50%.

In the area of scheduling and resource management we have had success in building two scheduling systems, Prophet and Gallop. Prophet is a scheduler for SPMD data parallel and task parallel pipeline applications in shared, heterogeneous, workstation networks. It has been successfully applied to numerous parallel scientific applications such as gene sequence comparison, electromagnetic scattering using finite elements, and image processing pipelines achieving good results (20% performance improvement). Gallop is a scheduler for SPMD applications in wide-area networks. It consults a set of network sites to determine where the application will be most efficiently executed. The sites use dynamically-constructed performance prediction models to estimate application performance using the available resources within the site. We have constructed an Internet-based Gallop testbed that has demonstrated the benefits of exploiting remote resources to achieve better performance even with current Internet technology (14% improvement over local execution).

6.3 Personnel Supported

Jon B. Weissman - Faculty investigator

6.4 Technical Publications

Journals -

1. Jon B. Weissman, Mike Gingras, and Mahesh Marina, "Optimizing Remote File Access for Parallel and Distributed Network Applications," *Journal of Parallel and Distributed Computing*, November 2001.
2. Jon B. Weissman, "Prophet: Automated Scheduling of SPMD Programs in Workstation Networks," *Concurrency: Practice and Experience*, Vol. 11, No. 6, May 1999.
3. Jon B. Weissman, "Gallop: The Benefits of Wide-Area Computing for Parallel Processing," *Journal of Parallel and Distributed Computing*, Vol. 54, No. 2, pp. 183-205, November

1998.

4. Jon B. Weissman and Xin Zhao, "Scheduling Parallel Applications in Distributed Networks," *Journal of Cluster Computing*, Vol. 1, No. 1, pp. 109-118, May 1998, invited paper.

Conferences -

1. Jon B. Weissman, "Fault Tolerant Wide-Area Parallel Computing," IEEE Workshop on Fault-Tolerant Parallel and Distributed Systems, International Parallel and Distributed Processing Symposium IPDPS, May 2000.
2. Jon B. Weissman, "Scheduling Multi-Component Applications in Heterogeneous Wide-area Networks," Heterogeneous Computing Workshop, International Parallel and Distributed Processing Symposium IPDPS, May 2000.
3. Jon B. Weissman, "Fault Tolerant Computing on the Grid: What are my options?," to appear in the Eighth IEEE International Symposium on High Performance Distributed Computing (HDPC), August 1999 (short paper).
4. Mike Gingras and Jon B. Weissman, "Smart Multimedia File Objects," to appear in IEEE Workshop on Internet Applications (WIA), July 1999.
5. Jon B. Weissman, "Smart File Objects: A Remote File Access Paradigm," Sixth ACM Workshop on I/O in Parallel and Distributed Systems (IOPADS), May 1999.
6. Jon B. Weissman, "Metascheduling: A Scheduling Model for Metacomputing Systems," Proceedings of the Seventh IEEE International Symposium on High Performance Distributed Computing, August 1998 (short paper).
7. Jon B. Weissman, "Gallop: The Benefits of Wide-Area Computing for Parallel Processing," *Journal of Parallel and Distributed Computing*, Vol. 2, No. 54, November 1998.

6.5 Interactions

6.6 Transitions - None.

6.7 Patent Disclosures - None.

6.8 Honors/Awards

J. Weissman:

- Texas Advanced Research Program, "Smart File Objects: An Application-directed File Access Paradigm," January 1998 - December 1999.
- NSF Faculty Early Career Development (CAREER) award, "Resource Management for Parallel and Distributed Systems," August 1996 - July 2000.

7 Optimal Resource Distribution in Multiprocessor Networks

7.1 Objectives

This project is focused in developing advanced resource distribution strategies for wormhole routed networks to enhance system performance in both packet transmission latency and sustained data traffic rate.

7.2 Status of Accomplishments

Our simulation results have shown the proposed techniques outperform traditional ones easily. Two papers on these results have been presented in PDPTA'98 and APADS'98. Several other related papers have also been published.

7.3 Personnel Supported

Wei-Ming Lin - Faculty investigator
Chunhui Zhao - MS graduate student
An-Yi Yang - MS graduate student
Qing Wan - MS graduate student

7.4 Technical Publications

Journals -

1. Wei-Ming Lin and Xiaomei Zhu, "Allocation Time-Based Processor Allocation Scheme for

2D Mesh Architecture," *Journal of Information Science and Engineering*, Vol. 16, No. 2, March 2000, pp.301-311, 2000.

2. Wei-Ming Lin and Wei Xie, "Load Skewing Task Assignment to Minimize Communication Conflicts on Network of Workstations," *Parallel Computing* 26 (2000), pp. 179-197.
3. Wei-Ming Lin and Qiuyan Gu, "Task Scheduling on Bus-based Networks of Workstations", to appear on *Parallel and Distributed Computing (PDCP) Journal*, Special Issue: Cluster Computing, Vol. 2, pp. 175-184, June 1999.
4. Wei-Ming Lin and Wei Xie "Minimizing Communication Conflicts with Load-Skewing Task Assignment Techniques on Networks of Workstations," to appear on *Informatica*, Vol. 23, No. 1, 1999.

Conferences -

1. Wei-Ming Lin and Chi-Mo Dai, "An Advanced Deadlock Recovery Scheme for Wormhole-Routed Networks," *IASTED International Conference on Parallel and Distributed Computing and Systems (PDCS 2000)*, Las Vegas, NV, Nov. 2000.
2. Wei-Ming Lin and Qing Wan, "Intelligent Job Scheduling for Mesh-Connected Multi-computers with Feedback Control," *IASTED International Conference on Parallel and Distributed Computing and Systems (PDCS 2000)*, Las Vegas, NV, Nov. 2000.
3. Wei-Ming Lin and Ding Wei, "Cost-Efficient Branch Prediction Hardwares", *13th International Conference on Computers and Their Applications (CATA'98)*, Honolulu, Hawaii, March 1998.
4. Wei-Ming Lin, Qiuyan Gu and Wei Xie, "DCP-NOW: A DCP-based Task Scheduling Technique for Networks of Workstations", *1998 International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA'98)*, Las Vegas, NV, July 1998,
5. Wei-Ming Lin and Chunhui Zhao, "Wormhole Routing with Priority-based Channel Allocation", *1998 International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA'98)*, Las Vegas, NV, July 1998,
6. Wei-Ming Lin and Chunhui Zhao, "Look-Ahead Traffic Distribution in Wormhole-Routed Networks", *Workshop on Advances in Parallel and Distributed Systems (APADS'98)*, West Lafayette, IN, Oct. 1998,
7. Xiaomei Zhu and Wei-Ming Lin, "Allocation Time-Based Processor Allocation Scheme for 2D Mesh Architecture", *International Conference on Parallel and Distributed Systems*, Taiwan, Dec. 1998,

7.5 Interactions - See conferences above.

7.6 Transitions - None.

7.7 Patent Disclosures - None.

7.8 Society Service/Distinction - None.

7.9 Honors/Awards

Wei-Ming Lin:

- Office of Naval Research (Augmentation Awards for Science and Engineering Research Training): Performance Analysis, Prediction and Enhancement for Generic Correlated Parallel Computations, PI, Sept. 1996 - August. 1999, \$58,650.
- Faculty Research Award -UTSA, 1999-2000.

8 Compilation Techniques for Parallel and Distributed Systems

8.1 Objectives

This research project studies program analysis techniques for compilation and execution on parallel and distributed systems. The development of fast restructuring compilers for the automatic parallelization of sequential programs requires efficient dependence analysis techniques to obtain exact dependence information and to rule out parallelism restricting false dependences. The objective of this project is the implementation and analysis of an efficient and exact dependence analyzer for parallelizing compilers.

8.2 Status of Accomplishments

The proposed dependence analysis techniques fall into two categories, either efficient and approximate or exact and exponential. In our analytical evaluation we proved the fundamental relationship between the major data dependence tests. We derived the conditions under which the polynomial tests produce exact answers. We also derived the conditions under which the exponential tests become efficient. In our empirical evaluation we compared the data dependence tests in terms of accuracy and efficiency. We run various experiments using benchmarks and scientific libraries. We concluded that most cases can be resolved with polynomial time techniques. In the extreme cases in which polynomial tests can not provide an exact answer an exponential

test can be invoked as a back up test. This approach significantly reduces the cost of performing exact dependence analysis in practice.

8.3 Personnel Supported

Kleanthis Psarris - Participating investigator
Konstantinos Kyriakopoulos - Ph.D. student
David Niedzielski - Ph.D. student

8.4 Technical Publications

Journals -

1. Ece Yaprak, Anthony Chronopoulos, Kleanthis Psarris and Yi Xiao, "Dynamic Buffer Allocation in an ATM Switch," *Computer Networks journal*, Vol. 31, No. 18, pages 1927-1933, August 1999.
2. Rajiv Gupta, Santosh Pande, Kleanthis Psarris and Vivek Sarkar, "Compilation Techniques for Parallel Systems," *Parallel Computing journal*, Vol. 25, No. 12, October 1999.

Conferences -

1. Konstantinos Kyriakopoulos and Kleanthis Psarris, "Data Dependence Analysis for Complex Loop Regions," *Proceedings of the 2001 International Conference on Parallel Processing*, IEEE Computer Society Press, pp. 195-204, Valencia, Spain, September 2001.
2. Kleanthis Psarris and Konstantinos Kyriakopoulos, "Measuring the Accuracy and Efficiency of the Data Dependence Tests," *Proceeding of the ISCA Fourteenth International Conference on Parallel and Distributed Computing Systems*, pp. 211-218, Dallas, Texas, August 2001.
3. David Niedzielski and Kleanthis Psarris, "An Analytical Comparison of the I-Test and Omega Test," *Proceedings of the Twelfth International Workshop on Languages and Compilers for Parallel Computing*, Lecture Notes in Computer Science, Springer-Verlag, San Diego, California, August 1999.
4. Kleanthis Psarris and Konstantinos Kyriakopoulos, "Data Dependence Testing in Practice," *Proceedings of the 1999 International Conference on Parallel Architectures and Compilation Techniques*, IEEE Computer Society Press, Newport Beach, California, October 1999.

8.5 Interactions - See conferences above.

8.6 Transitions - None.

8.7 Patent Disclosures - None.

8.8 Society Service/Distinction - None.