REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-00-

0664

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. ...
	1 Nov 00	Final Tech Report 1 Apr 96 to 31 May 99

4. TITLE AND SUBTITLE
Multicasting, Multiplexing, and Resource Allocation for Real-Time Communication in High-Speed Networks

5. FUNDING NUMBERS
F49620-96-1-0061

6. AUTHOR(S)
Douglas S. Reeves

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Computer Science
N.C. State University
Box 8206
Raleigh, NC 27695-8206

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
AFOSR/NM
801 N. Randolph Street, Rm 732
Arlington, VA 22203-1977

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-96-1-0061

11. SUPPLEMENTARY NOTES

20001211 059

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

... DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This grant was awarded under the AASERT program (Augmentati... Awards for Science and Engineering Research Training). The funding supported students conducting research in dynamic control of quality of service, and multicast routing for delay-constrained applications.

In general, our investigation is on how to provide Quality of Service in the Internet, using either ATM or IP techology. Quality of service means low packet delays, low delay jitter, and low packet losses. Examples of applications which require QoS include voice and video transmission, real-time data acquisition, distributed control, distributed interactive simulation, and others. We believe our ideas offers significant advantages in ease of use, and efficiency. The issues of efficiency and flexibility are especially important for wireless networks, where bandwidth is in limited supply, and the network conditions change frequently and rapidly.

We have worked on a number of protocol issues: multicasting, unicast routing, admission control, packet multiplexing, and resource allocation. The specific goals of the research supported by this grant included:

14. SUBJECT TERMS	15. NUMBER OF PAGES
	8
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Multicasting, Multiplexing, and Resource Allocation for Real-Time Communication in High-Speed Networks

AFOSR Grant F49620-96-1-0061

Final Report

1 Sept 1997 - 30 Aug 2000

PRINCIPAL INVESTIGATOR

==========

Douglas S. Reeves
Department of Computer Science
N. C. State University
Box 8206
Raleigh, NC 27695-8206
Telephone: (919) 515-2044
Fax: (919) 515-7896
Email: reeves@eos.ncsu.edu

OBJECTIVES

==========

This grant was awarded under the AASERT program (Augmentation Awards for Science and Engineering Research Training). The funding supported students conducting research in dynamic control of quality of service, and multicast routing for delay-constrained applications.

In general, our investigation is on how to provide Quality of Service in the Internet, using either ATM or IP techology. Quality of service means low packet delays, low delay jitter, and low packet

losses. Examples of applications which require QoS include voice and video transmission, real-time data acquisition, distributed control, distributed interactive simulation, and others. We believe our ideas offers significant advantages in ease of use, and efficiency. The issues of efficiency and flexibility are especially important for wireless networks, where bandwidth is in limited supply, and the network conditions change frequently and rapidly.

We have worked on a number of protocol issues: multicasting, unicast routing, admission control, packet multiplexing, and resource allocation. The specific goals of the research supported by this grant included:

- Demonstrate that dynamic resource allocation results in excellent quality of service (QoS) and dramatically higher bandwidth utilization for real-time traffic. Solve the practical implementation issues, and provide a firmer theoretical basis for its usage. Issues to be addressed include the feedback-delay problem that all dynamic control systems must overcome, system stability, and QoS apportionment to individual hops in a path (e.g., how to divide an end-to-end delay bound into smaller per-hop delay bounds).

- Develop improved methods for routing of real-time data. This includes unicast, multicast, and broadcast routing algorithms that incorporate delay bounds. Investigate the potential for hierarchical multicast routing, and dynamic tree construction.

An additional major new direction of our research has been pricing of network resources for ensuring fair, low-overhead allocation of quality of service to different users. This method is now also being applied to prevention of denial of service attacks.

STATUS OF EFFORT

==========

For real-time resource allocation, we have demonstrated how our method improves on other dynamic approaches. This work is 100% completed.

For delay-constrained routing (multicast, unicast, and broadcast), we have developed the best heuristics known (for unicast and broadcast), and substantially improved the state of understanding of multicast routing algorithms. This work is 100% completed.

We have devised a new method of network bandwidth allocation based on pricing. Our method is distributed, has low overhead, is provably fair, and is more general (providing more forms of fair allocation) than any other method known. We have also shown how this approach can accomodate two kinds of users: those requiring the minimum price, and those requiring the maximum guarantees. This research direction was unanticipated at the time of the proposal.

ACCOMPLISHMENTS / NEW FINDINGS

==========

Delay-Constrained Unicast Routing
We studied the NP-hard delay-constrained least-cost routing problem. We proposed a simple, distributed heuristic solution, called DCUR. It requires limited network state information at each node. We proved DCUR's correctness and analyzed its worst-case complexity. We demonstrated that it is low overhead, and that in general its solutions are within 10% of an optimal-quality solution.

Evaluation of Multicast Routing Algorithms for Real-Time Communication
Multicast (MC) routing algorithms capable of satisfying the quality of service (QoS) requirements of real-time applications are essential for future high-speed networks. We compared the performance of all of the important MC routing algorithms when applied to networks with asymmetric link loads. We showed that unconstrained algorithms are not capable of fulfilling the QoS requirements of real-time applications in wide-area networks, and that one of the unconstrained algorithms currently used in the Internet (reverse path multicasting), is quite inefficient when applied to asymmetric networks. We identified the strongest delay-constrained methods, the advantages of each, and determined that existing heuristics are satisfactorily close to optimal to preclude the need for further research on this topic. Our work was the first detailed, quantitative evaluation of all of these algorithms under realistic high-speed networking environments.

The Delay-Constrained Minimum Spanning Tree Problem
Many distributed real-time applications require broadcasting information to all participants. This information must be received by within some delay bound, and at the lowest possible cost. We proved that this problem is NP-complete, and we proposed the first efficient heuristic to solve this problem. Simulation results under realistic networking conditions show that our heuristic's performance is close to optimal when the link loads are symmetric as well as when asymmetric link loads are used.

Statistical Models of Variable Bit-Rate Video
The transport of compressed video will be an important application of computer networks. Variable bit-rate (VBR) video is expected to major part of this traffic. Suitable statistical source models are required to analyze network performance metrics such as packet loss, delay, and jitter. We investigated VBR source models for videos containing moderate to significant scene changes and moderate to full motion. A description of each model was given, along with corresponding advantages and shortcomings.

Online dynamic bandwidth allocation
Network multimedia applications require performance guarantees that can be provided through proper resource allocation. We developed an online allocation method called the Dynamic Search Algorithm that dynamically adjusts the resource allocation based upon the measured quality of service. We demonstrated that it can dynamically allocate bandwidth to achieve a given loss rate for actual variable bit-rate MPEG-compressed videos. We investigated how to minimize both the

bandwidth allocated and the number of renegotiations. As compared to an off-line peak-rate allocation, DSA+ saved 13--58% in bandwidth. Methods previously proposed either over-allocated bandwidth or renegotiated up to 50 times more frequently. Multiple-hop bandwidth allocation was also addressed. Two implementations were investigated (allocation at the first node only, or at each node). Both methods were able to provide the end-to-end QoS.

Network Resource Pricing

Networks use flow control to manage network resources fairly and efficiently. We developed a distributed microeconomic flow control technique that models the network as competitive markets with three entities; users, Network Brokers (NB) and switches. Switches own the resources sought by users, and price their resources based on local supply and demand. A user requires these resources to maximize their individual QoS. Representing the user in the economy, the NB makes the resource purchasing decisions based on current needs of the user and prices. Users and switches act independently, which yields a decentralized flow control method. This competitive market structure encourages high utilization and Pareto optimal resource distribution.

We showed how this economy properly handles network dynamics, such as users entering/exiting, and VBR sources. Simulation results demonstrate the ability of the economy to successfully price link bandwidth of a network with a large number of users, each transmitting an actual MPEG-compressed video. Utilization for this network was over 90% and the distribution of link bandwidth was considered optimal over 92% of the time. The price method has also been shown to perform better than standard flow control schemes such as max-min or demand-based weighted max-min. We showed how the method can be incorporated into the existing ATM ABR service class very directly for explicit rate control, with minimal overhead.

We also investigated a distributed multi-market approach to network resource allocation. In this approach link bandwidth is bought and sold in two types of markets: the reservation market and the spot market. Reserved bandwidth has the advantage of ownership over a period of time, providing the user with some predictability of their expected QoS. In contrast, spot bandwidth has the advantage of immediate availability without the reservation overhead. Therefore, the multi-market approach integrates the benefits of the spot market and the reservation market in one allocation technique.

We are now investigating the use of this technique to prevent or reduce denial of service (DoS) attacks in the Internet. DoS attacks are a significant threat to the reliability and availability of new quality-of-service mechanisms such as the ones we have proposed. Our method of pricing resources promises to provide protection in a framework that is highly flexible and easy to understand. The method also has potential for application in critical-need environments where priorities for resource allocation must be considered, such as military command and control.

PERSONNEL SUPPORTED

==========

- Faculty -- Douglas S. Reeves (Associate Professor, N.C. State University)
- Post-Docs -- Errin Fulp (August 1999-July 2000)

- PhD Student: Errin Fulp (graduated August 1999)
- Graduate Students (all Ph.D.) -- Mike Izquierdo (partly supported by this grant, graduated November 1998)

PUBLICATIONS

==========

(This list only includes publications supported by this grant.)

ACCEPTED

Journals—

- D. Reeves and H. Salama, "A Distributed Algorithm for Delay-Constrained Unicast Routing", IEEE/ACM Transactions on Networking, Vol. 8, No. 2, April 2000, pp. 239-250.
- M. Izquierdo and D. Reeves, "Statistical Source Models for Variable Bit-Rate Compressed Video", ACM/Springer-Verlag Multimedia Systems Journal, Vol. 7, No. 3, May 1999, pp. 199-213.
- H. Salama, D. Reeves, and Y. Viniotis, "Evaluation of Multicast Routing Algorithms for Real-Time Communication on High-Speed Networks", IEEE Journal on Selected Areas in Communication, Vol. 15, No. 3, April 1997, pp. 332--345.

Conferences--

- H. Wang, K. Shin, H. Xin, and D. Reeves, "A Simple Refinement of Slow-start of TCP Congestion Control", Intl. Symp. on Computing and Communications (ISCC 2000), July 2000, Antibes, France.
- E. Fulp and D. Reeves, "QoS Rewards and Risks: A Multi-Market Approach to Resource Allocation", Networking 2000, Paris, France, May 2000.
- E. Fulp and D. Reeves, "ABR Rate Control for Multimedia Traffic Using Microeconomics", 2nd International Conf. on ATM (ATM '99), Colmar France.
- E. Fulp and D. Reeves, "Online Dynamic Bandwidth Allocation", International Conference on Network Protocols, Atlanta Georgia, October 1998.
- E. Fulp, M. Ott, D. Reininger, and D. Reeves, "Paying for QoS: An Optimal Distributed Algorithm for Bandwidth Pricing", 6th International Workshop on Quality of Service, May 1998.
- H. Salama, D. Reeves, and Y. Viniotis, "The Delay-Constrained Minimum Spanning Tree Problem", IEEE Symposium on Computers and Communications (ISCC '97), 1997.
- H. Salama, D. Reeves, and Y. Viniotis, "A Distributed Algorithm for Delay-Constrained Unicast Routing", IEEE Infocom '97, April 1997.

SUBMITTED, IN REVIEW

Journals—

- E. Fulp and D. Reeves, "The Fairness and Utility of Pricing Network Resources Using Competitive Markets", submitted to Computer Networks Journal, April 2000.

INTERACTIONS / TRANSITIONS

==========

PARTICIPATION / PRESENTATIONS AT MEETINGS, CONFERENCES, SEMINARS, ETC.

- D. Reeves, DARPA ITO Information Assurance Conference, Honolulu, Hawaii, July 2000.
- D. Reeves, DARPA ITO Tolerant Networks Program Meeting, Rome, NY, October 1999.
- D. Reeves, AFOSR Contractors Meeting, Los Angeles, CA, March 2000.
- D. Reeves, AFOSR Contractors Meeting, Colorado Springs, CO, February 1999.
- D. Reeves, AFOSR Contractors Meeting, Rome NY, October 1997.
- H. Wang, Intl. Symposium on Computing and Communications (ISCC 2000), July 2000, "A Simple Refinement of Slow-Start for TCP Congestion Control"
- D. Reeves, Networking 2000, May 2000: "QoS Rewards and Risks: A Multi-Market Approach to Resource Allocation"
- D. Reeves, Workshop on Pricing in Networks, September 1999: "Goals and Assumptions for Pricing in Networks"
- E. Fulp, 2nd International Conference on ATM (ATM '99), July 1999: "ABR Rate Control for Multimedia Traffic Using Microeconomics"
- E. Fulp, International Conf. on Network Protocols (ICNP '98), October 1998: "Online Dynamic Bandwidth Allocation".
- E. Fulp, 6th International Workshop on Quality of Service, May 1998: "Paying for QoS: An Optimal Distributed Algorithm for Bandwidth Pricing"
- Hussein Salama, IEEE Symposium on Computers and Communications, July 1997: "The Delay-Constrained Minimum Spanning Tree Problem"

CONSULTATIVE AND ADVISORY FUNCTIONS TO OTHER LABS AND AGENCIES

During this period I reviewed proposals for AFOSR, the Army Research Office, and the National Science Foundation. I also reviewed papers for approximately 10 journals and 5 conferences, and I have been a member of 3 conference program committees, including Infocom (one of the top two international networking conferences).

STUDENTS GRADUATED

- Mahesh Shankar, M.S. in Computer Engineering. Thesis title: "An Architecture for Provisioning Services in H.323 Voice-over-IP Networks", expected December 2000. Currently employed at Vovida, Inc. (recently acquired by Cisco) developing Voice-over-IP products.
- Xiaobing Zhang, M.S. in Computer Science. Thesis title: "TCP Dropping Attacks and Intrusion Detection", May 2000. Currently employed at Ericsson developing DiffServ protocols for IP networks.
- Errin W. Fulp, Ph.D. in Computer Engineering. Thesis title: "Resource Allocation and Pricing for QoS Management in Computer Networks", August 1999. Currently employed at Wake Forest University as an Assistant Professor of Computer Science.
- Mike R. Izquierdo, Ph.D. in Computer Engineering, "Modeling, Transmission, and Multiplexing of MPEG VBR Sources Over Packet-Switched Networks", November 1998. Currently employed at Osprey Technologies developing videoconferencing products.
- Haining Wang, M.S. in Computer Science. Thesis title: "Refining TCP Congestion Control Schemes at End Hosts and Routers", August 1998. Currently pursuing a Ph.D. at the University of Michigan.
- I am currently advising 4 Ph.D. students and 3 M.S. students.

TRANSITIONS

- Errin Fulp spent the summer of 1997 as a member of the technical staff at NEC Research (Princeton, NJ).
- Douglas Reeves spent 4 months in Spring 2000 working at Nortel Networks (Research Triangle Park, NC) as a consultant on Voice-over-IP products.
- Our web sites (http://www.csc.ncsu.edu/faculty/rtcomm and http://www4.ncsu.edu/eos/users/r/reeves/rtcomm/ARQOS/main.htm) include publications and software available publicly. One piece of software, the MCRSIM multicast routing simulator, has been copied and used by researchers from at least 20 sites around the world. Other software includes a dynamic resource allocation simulator, and a resource pricing tool and simulator.

NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

==========

Douglas Reeves submitted a patent application with Nortel Networks in October 2000. The title of the submission is "A Method for Authorizing Allocation of Resources for Voice Services in IP-Based Networks".

Errin Fulp submitted a patent application with NEC in Fall 1998 for "A Distributed Method of Pricing Network Resources".

HONORS / AWARDS

==========

In this reporting period I have continued to be on the Editorial Board for IEEE Concurrency, and have been a member of four conference program committees.

NEC awarded a grant of $12,000 to support our research in 1998.