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Kishor S. Trivedi

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Major Accomplishments Under AFOSR84-0132

Kishor S. Trivedi, P.I.
Department of Computer Science
Duke University

Under the auspicies of this grant, we have developed a hierarchical , combinatorial-Markov approach for solving large reliability/ availability/ performance models of systems. The approach allows the modeler to combine good aspects of both combinatorial models and Markov models to obtain a cost-effective solution to large models. The approach has been used in two Ph.D. dissertations (LTCL Jim Blake, who studied the performability of multprocessor interconnection networks and Malathi Veeraraghavan, who modeled many fault-tolerant systems, including Boeing's IAPSA, Draper Laboratories' AIPS). Jim Blake has joined the Army AIRMICS Laboratory and Malathi has joined AT&T Bell Laboratories in Columbus.

Other methods of dealing with complex system models that we have explored include automated methods of Markov model generation using Stochastic Petri nets. Efficient methods of solving stochastic Petri net models are being investigated by Gianfranco Ciardo in his dissertation. His work also involves applying SPN techniques for the performance analysis of concurrent programs.

Much of our research deals with the transient solution of large and stiff Markov and Markov reward models. We have developed a decomposition technique for the transient analysis of stiff Markov chains jointly with Dr. A. Bobbio of Institute Ferraris, Torino, Italy. A description of the technique was published in the IEEE Transactions on Computers (September 1986) and is receiving wide attention. We have carried out a thorough comparision of the transient analysis methods of Markov models within the scope of the Ph.D. thesis by Andrew Reibman. This work has received attention in Applied Probability and Operations Research community. Andrew has accepted a position at AT&T Bell Laboratories in order to further utilize this research in solving reliability models of communication systems.

Our work on Markov reward models is important not only because we have developed an efficient algorithm for numerical solution but also because of a large variety of applications we are exploring. The research on Markov reward models consists of interdisciplinary (with Dr. Kulkarni of Operational Research Curriculum at the University of North Carolina) and International (Dr. Francois Baccelli of INRIA, France and Dr. Raymond Marie of IRISA, Rennes, France) collaborations. The applications have addressed the effectiveness evaluation of 16×16 multiprocessor systems with various interconnection schemes, response-time distribution in an M/M/1 queue with processor sharing discipline, distribution of time-averages in queueing systems, and response time distributions of tasks in a system subject to failure and repair. Three Ph.D. dissertations have been completed in this area. One by Victor Nicola, who has joined IBM Yorktown Research Center, second by Roger Smith, who has joined Yale University and the third by Phil Chimento, who will remain at IBM Research Traingle Park.

Another important area of research is in the analysis of the coverage of a fault tolerant system, that is, the probablity that the system can recover from a fault. We have studied a variety of models, from simple phase-type models to very complex stochastic Petri net models, and have investigated solution techniques for each model type. Our methodology allows consideration of external events that can interfere with recovery, such as a hard limit on recovery time, or the occurrence of a second near-coincident fault. We discovered that a policy of attempting

transient recovery upon detection of an error (as opposed to automatically reconfiguring the affected component out of the system) may actually *increase* the unreliability of the system. This result holds if the error detectability is not nearly perfect, so that the risk of producing an undetectable error (if the transient error is present) is greater than the benefit gained by not discarding the component.

A list of all papers and thesis supported in part of by this grant is attached alongwith.

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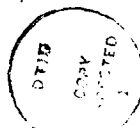
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Principal Investigator: Kishor S. Trivedi
Duke University
Durham, NC 27706
Phone: (919)684-3048. Electronic mail address: kst@duke.cs.edu

[1] F. Baccelli and K. S. Trivedi. A single server queue in a hard-real-time environment. *Operations Research Letters*, December 1985.

[2] J. Blake and K. S. Trivedi. Reliability analysis of interconnection networks using hierarchical composition. *IEEE Transactions on Reliability*, 1988. To appear.

[3] J. T. Blake, A. L. Reibman, and K. S. Trivedi. Sensitivity analysis of reliability and performance measures for multiprocessor systems. In *Proceedings of the 1988 ACM SIGMETRICS Conference on Measurement and Modeling of Computer Systems*, Santa Fe, New Mexico, May, 1988.

[4] J. T. Blake and K. S. Trivedi. Reliability of the shuffle-exchange network and its variants. In *21st Annual Hawaii International Conference on System Sciences*, January 1988.

[5] James T. Blake. *Comparative Analysis of Multistage Interconnection Networks*. PhD thesis, Department of Computer Science, Duke University, December 1987.

[6] James T. Blake and K. S. Trivedi. Comparing three interconnection networks embedded in a multiprocessor system, 1987.

[7] James T. Blake and K. S. Trivedi. Multistage interconnection network reliability. *IEEE Transactions on Computers*, 1987. accepted subject to revision.

[8] James T. Blake and K. S. Trivedi. Reliabilities of two fault-tolerant interconnection networks. In *Proceedings of the Eighteenth International Symposium on Fault-Tolerant Computing*, Tokyo, Japan, 1988.

[9] Andrea Bobbio and K. S. Trivedi. An aggregation technique for the transient analysis of stiff Markov chains. *IEEE Transactions on Computers*, C-35(9):803–814, September 1986.

[10] M. A. Boyd, M. Veeraraghavan, Joanne Bechta Dugan, and K. S. Trivedi. An approach to solving large reliability models. In *AIAA/IEEE Digital Avionics Systems Conference, San Jose, CA*, October 1988.

[11] P. F. Chimento and K. S. Trivedi. The performance of block structured programs on processores subject to failure and repair. In E. Gelenbe, editor, *High Performance Computer Systems*, pages 269–280. North-Holland, 1988.

[12] G. Ciardo, R. Marie, B. Sericola, and K. S. Trivedi. Performability analysis using semi-Markov reward processes. *IEEE Transactions on Computers*, 1988. To appear.

[13] Gianfranco Ciardo. Toward a definition of modeling power for stochastic Petri net models. In *Proceedings of the International Workshop on Petri Nets and Performance Models*, Madison, Wisconsin, August 1987.

[14] Joanne Bechta Dugan. Fault trees and imperfect coverage. *IEEE Transactions on Reliability*, 1987. Accepted, subject to revision.

[15] Joanne Bechta Dugan, Andrea Bobbio, Gianfranco Ciardo, and K. S. Trivedi. The design of a unified package for the solution of stochastic Petri net models. In *Proceedings of the International Workshop on Timed Petri Nets*, Torino Italy, July 1985.

[16] Joanne Bechta Dugan and Gianfranco Ciardo. Stochastic Petri net analysis of a replicated file system. In *Proceedings of the International Workshop on Petri Nets and Performance Models*, Madison, Wisconsin, August 1987.

[17] Joanne Bechta Dugan and Gianfranco Ciardo. Stochastic Petri net analysis of a replicated file system. *IEEE Transactions on Software Engineering*, To appear 1988.

[18] Joanne Bechta Dugan and K. S. Trivedi. Coverage modeling for dependability analysis of fault-tolerant systems. *IEEE Transactions on Computers*, 1989. To appear.

[19] Joanne Bechta Dugan, K. S. Trivedi, Robert M. Geist, and Victor F. Nicola. Extended stochastic Petri nets: Applications and analysis. In E. Gelenbe, editor, *Performance '84*, pages 507–519, Amsterdam, 1984. Elsevier Science Publishers B. V. (North-Holland).

[20] M. C. Hsueh, R. K. Iyer, and K. S. Trivedi. A measurement-based dependability model for a multiprocessor system. In P. J. Courtois G. Iazeolla and O. J. Boxima, editors, *Proceedings of the 2nd International Workshop on Applied Mathematics and Performance/Reliability Models of Computer/Communication Systems*, pages 337–352, Rome, Italy, May 1987.

[21] V. G. Kulkarni, V. F. Nicola, R. M. Smith, and K. S. Trivedi. Numerical evaluation of performability and job completion time in repairable fault-tolerant systems. In *Proceedings of the Sixteenth International Symposium on Fault-Tolerant Computing*, pages 252–257, July 1986.

[22] V. G. Kulkarni, V. F. Nicola, and K. S. Trivedi. On modeling the performance and reliability of multi-mode computer systems. *The Journal of Systems and Software*, 6(1 & 2):175–183, May 1986.

[23] V. G. Kulkarni, V. F. Nicola, and K. S. Trivedi. The completion time of a job on multi-mode systems. *Advances in Applied Probability*, 19(4):932–954, December 1987.

[24] Vidyadahr G. Kulkarni, Victor F. Nicola, K. S. Trivedi, and Roger M. Smith. A unified model for the analysis of job completion time and performability measures in fault-tolerant systems. Technical report, Duke University Computer Science Department, Durham, NC, 1985.

[25] R. A. Marie, A. L. Reibman, and K. S. Trivedi. Transient solution of acyclic Markov chains. *Performance Evaluation*, 7(3):175–194, 1987.

[26] J. McGough, A. L. Reibman, and K. S. Trivedi. Markov reliability models for digital flight control systems. *AIAA Journal of Guidance, Control and Dynamics*, 1988.

[27] John McGough, Mark Smotherman, and K. S. Trivedi. The conservativeness of reliability estimates based on instantaneous coverage. *IEEE Transactions on Computers*, C-34(7):602–609, July 1985.

[28] M. Mulazzani and K. S. Trivedi. Dependability prediction: Comparison of tools and techniques. In *IFAC Proceedings of the SAFECOMP 1986*, Sarlat, France, October 1986.

[29] V. F. Nicola, V. G. Kulkarni, and K. S. Trivedi. Queueing analysis of fault-tolerant computer systems. *IEEE Transactions on Software Engineering*, SE-13(3):363–375, March 1987.

[30] A. Reibman, R. M. Smith, and K. S. Trivedi. Markov and markov reward models: A survey of numerical methods. *European Journal of Operations Research*, 1988. Accepted subject to revision.

[31] A. L. Reibman. *Transient Analysis of Large, Stiff Markov Models: Numerical and Approximate Solution Techniques*. PhD thesis, Department of Computer Science, Duke University, October 1987.

[32] A. L. Reibman and K. S. Trivedi. Numerical transient analysis of Markov models. *Computers and Operations Research*, 15(1):19–36, 1988.

[33] R. Sahner and K. S. Trivedi. Performance and reliability analysis using directed acyclic graphs. *IEEE Transactions on Software Engineering*, pages 1105–1114, October 1987.

[34] R. Sahner and K. S. Trivedi. Reliability modeling using SHARPE. *IEEE Transactions on Reliability*, R-36(2):186–193, June 1987.

[35] R. A. Sahner and K. S. Trivedi. A hierarchical, combinatorial-Markov method of solving complex reliability models. In *Proceedings of the Fall Joint Computer Conference*, pages 817–825, Dallas, TX, November 1986. ACM and Computer Society of the IEEE.

[36] Robin Sahner and K. S. Trivedi. SPADE: A tool for performance and reliability evaluation. *International Workshop On Techniques and Tools for Performance Analysis*, June 1985.

[37] Robin A. Sahner. *Hybrid Combinatorial-Markov Methods for Solving Large Performance and Reliability Models*. PhD thesis, Department of Computer Science, Duke University, 1985.

[38] R. M. Smith. *Markov Reward Models: Application Domains and Solution Methods*. PhD thesis, Department of Computer Science, Duke University, September 1987.

[39] R. M. Smith and K. S. Trivedi. Calculating the distribution of accumulated reward using partial differential equations. In preparation, 1987.

[40] R. M. Smith and K. S. Trivedi. A performability analysis of two multiprocessor systems. In *Proceedings of the Seventeenth International Symposium on Fault-Tolerant Computing*, pages 224–229, July 1987.

[41] Roger Smith, K. S. Trivedi, and A. V. Ramesh. Performability analysis: Measures, an algorithm, and a case study. *IEEE Transactions on Computers*, C-37(4):406–417, April 1988.

[42] H. Tardif, A. V. Ramesh, and K. S. Trivedi. Closed-form transient solution of cyclic Markov chains. In preparation.

[43] K. S. Trivedi. Modeling and analysis of fault-tolerant systems. In D. Potier, editor, *Modeling Techniques and Tools for Performance Analysis*. North-Holland, Amsterdam, 1985.

[44] K. S. Trivedi and Joanne Bechta Dugan. Computer-aided reliability analysis of fault-tolerant systems. *Sadhana*, 1987.

[45] K. S. Trivedi, Robert Geist, Joanne Bechta Dugan, and Mark Smotherman. Issues in reliability modeling of fault-tolerant systems. In *Proceedings of the 2nd GI/NTG/GMR Conference on Fault-Tolerant Computer Systems*, pages 228–239, Bonn, September 1984.

[46] K. S. Trivedi, Andrew Reibman, and Roger Smith. Transient analysis of markov and markov reward models. In P. J. Courtois G. Iazeolla and O. J. Boxma, editors, *Computer Performance and Reliability*, pages 535–545. Elsevier Science Publishers B. V. (North Holland), Amsterdam, 1988.

[47] K. S. Trivedi and P. S. Yu. Reliability and performance analysis of a ringnet. Technical Report RC-9792, IBM T. J. Watson Research Center, January 1983.

[48] M. Veeraraghavan and K. S. Trivedi. An improved algorithm for the symbolic reliability analysis of networks. *submitted to IEEE Transactions on Reliability*, 1988.

[49] Malathi Veeraraghavan. *Modeling and Evaluation of Fault-Tolerant Multiple Processor Systems*. PhD thesis, Department of Electrical Engineering, Duke University, August 1988.

[50] Malathi Veeraraghavan and Joanne Bechta Dugan. Modeling fault-tolerant computer, network and control systems. Technical Report TR CS-1988-20, Duke University Computer Science Department, Durham, NC 27706, July 1988.

[51] Malathi Veeraraghavan and K. S. Trivedi. Hierarchical modeling for reliability and performance measures. In B. W. Dickson S. K. Tewksbury and S. C. Schwartz, editors, *Concurrent Computations: Algorithms, Architecture and Technology*. Plenum Press, New York, 1987.

[52] Philip Yu, K. S. Trivedi, and W. E. Smith. Reliability and performance analysis of a ringnet. In *Proceedings of the IFIP International Symposium on Local Communication Systems: LAN & PBX*, pages 111–123, November 1986.