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Abstract

The growing importance of real-time computing in numerous applications poses problems for network architectures. This research proposes a model for evaluating safety-critical real-time Wide Area Networks (WANs), using assessment and performance requirements for highly reliably and dependable real-time networks, incorporating both human and technical performance criteria.

Keywords: WAN, performance evaluation, real-time networks, safety-critical systems, reliability

Research Objectives and Questions

Wide Area Networks (WANs) are important components in safety-critical environments where reliable data acquisition and distribution are essential. In such systems, network equipment and functions must be closely monitored and controlled to ensure safe operation and prevent costly consequences. As networks become more complex, the probability of system failure increases, particularly for real-time WANs, which contain hundreds of nodes.

Most large-scale networks such as WANs depend on hardware, software, human operators and other network elements to function correctly. Failure of any of the network elements can bring the entire network down and the consequence can be disastrous. As Demester et al. (1999) suggest, networks never reach 100 percent reliability, even though some precautions are taken to avoid network failures. A well-known example of a network failure is the 1990 nationwide AT&T network failure (Kuhn 1997). According to the FCC report, network failures in the United States with impacts on more than 30,000 customers happen with a frequency on the order of one every two days and the mean time to repair them is on the order of five to 10 hours (Demester, et al. 1999). Furthermore, the human, environmental, and economic consequences of network failures in safety-critical environments can be staggering.

The growing importance of real time computing in numerous applications poses problems for network architectures. First of all, time is a precious resource to manage. Secondly, reliability is crucial in safety-critical applications, since failure of a real-time system could cause an economic disaster or the loss of human lives (Shin, 1993).

Since survivability and reliability are crucial in safety-critical systems, careful evaluation of WANs in such systems is important because of the extremely low failure rate required of these networks. However, even though many studies have been done on different network architectures, few have focused on the evaluation of real-time, safety-critical networks. Thus, this research focuses on evaluation of real-time, safety-critical WANs, incorporating human and technical performance criteria.

Theoretical Foundations

Networks have been evaluated by different disciplines from different perspectives. Engineers often evaluate networks based on mathematical models such as queuing theory, Markov analysis and well-defined metrics such as throughput, response time, and utilization (Haverkort 1998; Bolch, et al. 1998; Lehoczky 1996; Higginbottom 1998). Other metrics utilized include network traffic performance (Adie, et al. 1998; Banerjee, et al. 1997), circuit overhead of switches (Niehaus et al. 1997; Da Silva et al. 1997), and equipment used and network conditions (Da Silva et al. 1997).

Statisticians frequently use statistical distributions to evaluate communication networks as distributions allow prediction of system performance measures to a reasonable degree of accuracy (Akar et al. 1998). For instance, the Weibull distribution is often used in reliability studies of equipment.

Technical communication models deal with networks in terms of interconnected networks using switches, routers, bridges, and repeaters. Since these interconnection devices affect traffic over the network, communication models consider behavior of traffic over these devices (Hemrick 1992; Gibson 1992; Gurneri and Lanting 1994; Khalil et al. 1995). Social and organizational communication models consider networks of organizations, their patterns of behavior and communication strategies, and organizational structures (Monge et al. 1998; Orlikowski et al. 1995).

Large-scale system models evaluate networks in terms of two important concepts, reliability and survivability. Most large, distributed real-time networks depend on hardware, software and human operators to function correctly. Failure of any of these elements can bring down an entire network. Hence, one of the most important issues in designing and implementing a real-time network is the survivability of a network**.** Survivability is defined as the percentage of total traffic surviving some network failure in the worst case (Myung et al. 1999). Reliability is a measure of the system's ability to provide deterministic and accurate delivery of information (McCabe 1998). In other words, reliability is the likelihood that a system will remain operational (potentially despite failures) for the duration of a mission (Somani and Nittin 1997).

From a business models perspective, the improvement of a network efficiency will usually be the main object of evaluation studies (Ferrari, et al., 1983) because the cost of a poorly implemented network can far outweigh any direct expenses of an organization. On the other hand, the benefits of a well-designed effective network can be worth many times the original investment (Axelrod 1982). Clearly, the real purpose of evaluation studies is the improvement of the cost-performance ratio, rather than mere performance improvement. Thus, economical aspects are always important (Ferrari et al. 1983).

From an organizational point of view, however, managers see networks as an investment. They are usually interested in knowing cost savings, reliability, accuracy, flexibility, timeliness of data, decision support applications, isolation, integration, user involvement, security, and back-up requirements (Axelrod 1982). As Peter Drucker (1997) suggests, "if you cannot measure it, you cannot manage it". Jurison (1996) argues that success measures of interest to managers are those that can be measured and expressed quantitatively, especially in monetary terms, because such measures can be used for justifying information technology investment and are universally accepted.

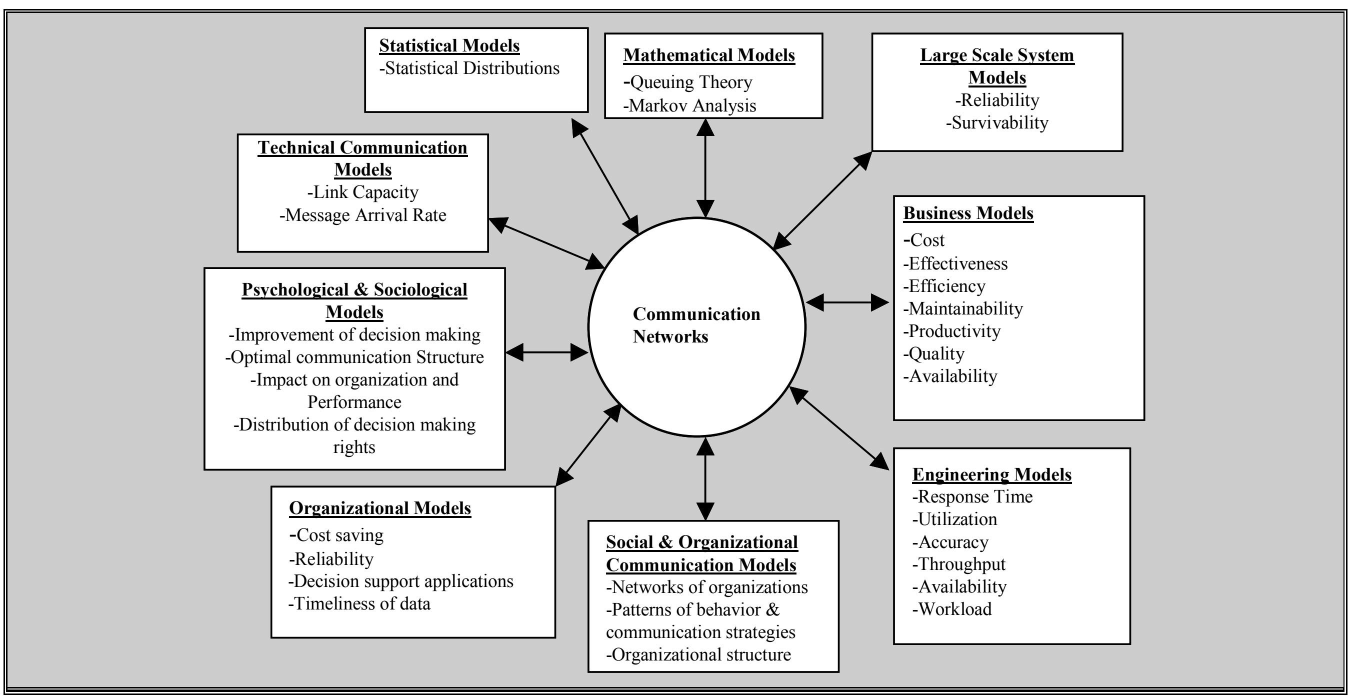

Figure 1. Network Evaluation Models and Metrics

Psychological and sociological models of network performance assess optimal communication structures, improvement of decision making, the impact of communication networks on organization and performance, and distribution of decision making rights over the network (Jehiel 1999; Mackenzie 2000).

Network evaluations often consider the network's technical performance. However, in safety-critical settings, both human and technical dimensions must be considered in evaluating performance. This research recognizes the need to consider both dimensions in network evaluation, and proposes an approach incorporating technical approaches (mathematical, statistical, large-scale system, engineering and technical communication models) as well as human-oriented approaches (business, organizational, psychological and sociological models) (Figure 1).

Theoretical Model

Real-time networks interact with humans, the environment, and other technologies, and interactions between these different elements may contribute to network failures. Hence, in addition to traditional technical performance considerations, our proposed model of WAN evaluation deems human factor and environmental considerations crucial in evaluation studies. This is because human error and acts of nature are among the major sources of failures in networks (Kuhn 1997).

Technical variables, such as network reliability, accuracy, response time and utilization, certainly impact network performance, as do system and environmental variables such as hardware failures, software failures and acts of nature, interactions between the network and its working environment, and users' performance with the network. In turn, network performance influences human performance with the network, as well as the performance of the system that the network serves. Individual and group variables such as user knowledge and skills, vigilance and workload, also influence human performance with the network. Figure 2 illustrates this theoretical model.

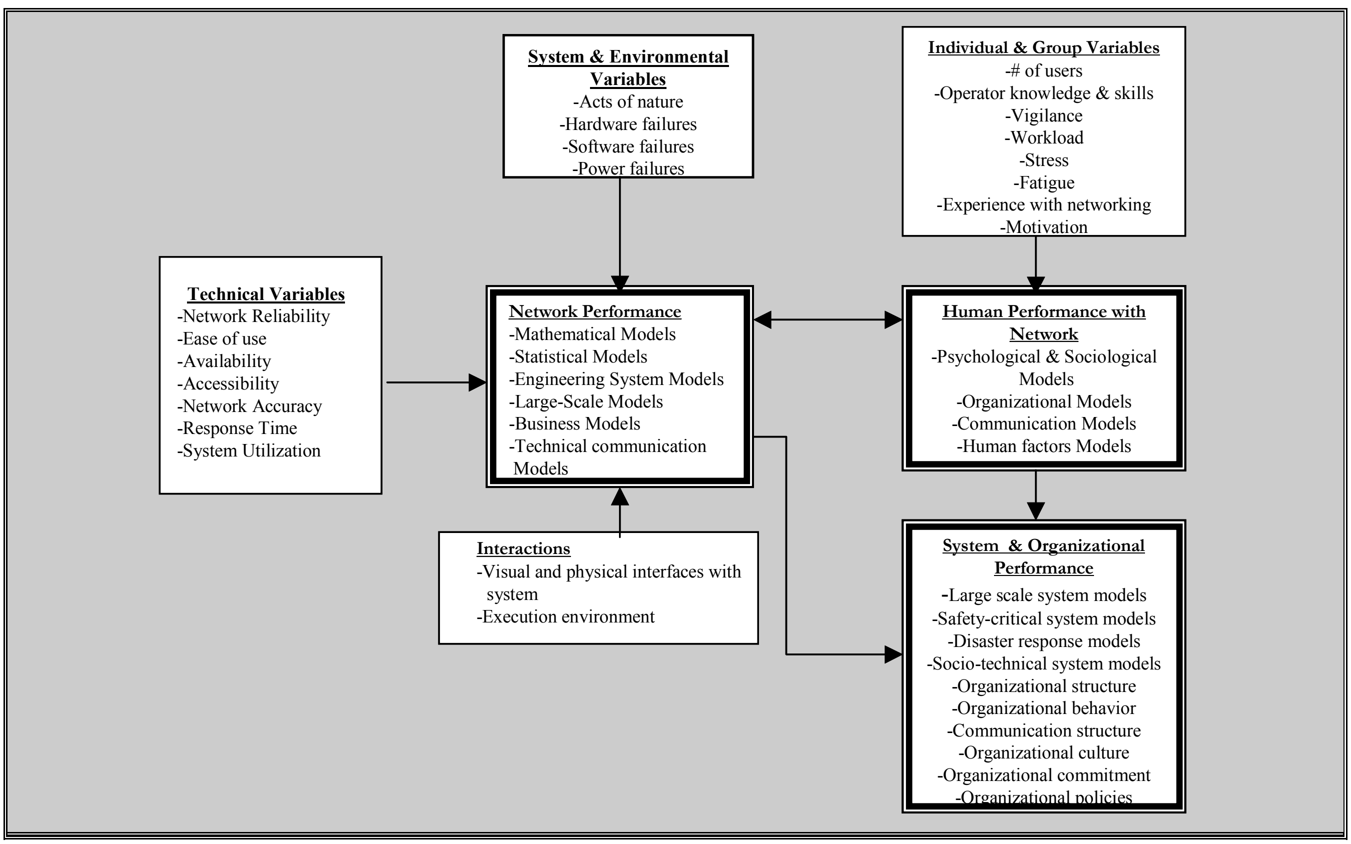

Figure 2. Proposed Model

Research Methodology

Subjects

There are two sets of subjects for this research: an operational wide area network (WAN) for the network performance evaluation, and the operators who utilize the network for the human performance evaluation.

The real-time WAN is known as the Continuous Operational Real-Time Monitoring System (CORMS), which was designed and built by the U.S. National Oceanic and Atmospheric Administration (NOAA). CORMS was implemented in April 1998 and takes input from two NOAA systems, the Physical Oceanographic Real Time System (PORTS) and the National Water Level Observation Network (NWLON). PORTS collects data from San Francisco, New York, Tampa Bay, Houston/Galveston, Chesapeake Bay, Narragansett Bay, and Soo Locks. NWLON, which collects water-level data, is comprised of 189 water level gauges located around the coastal United States, including Alaska, Hawaii, and U.S. territories in the Pacific, and Great Lakes. The objective of CORMS is to provide a 24 hour/day monitoring and quality control capability to ensure the availability and accuracy of tide and water current observations that are used for navigation and safety of life and property decisions.

Currently, the network is monitored in 24 hour/7 day mode by 7 watchstanding operators who monitor CORMS and determine what actions are necessary if the accuracy of any of the measured parameters is deemed to be questionable (NOAA 1999).

Method

Hypotheses, variables, operationalizations and measurements for evaluating the safety-critical real-time WAN were developed. Network performance will be evaluated by utilizing well-defined and well-known network performance metrics such as reliability, availability, and response time. The appropriate statistical tests and mathematical analysis will be run on collected data, and the results of the mathematical analyses and statistical tests will be used to evaluate hypotheses.

Metrics associated with operator performance such as vigilance, workload, satisfaction, and operator error rate will be evaluated by utilizing survey techniques, real-time observations, interviews and questionnaires. Results of both analyses-network and human performance-will be analyzed.

Sample Result: Tampa PORTS

In this section, we present results from a performance evaluation of Tampa PORTS. The main issue that we concentrate on in the first phase of this multiphase research is to determine reliability metrics. Here, the main emphasis is placed on three primary reliability metrics: Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), and Availability.

Tampa PORTS network performance was evaluated using 10 months' worth of data collected between December 1999 and September 2000, inclusive. In 10 months, the average time that Tampa PORTS network performed its functions between failures (i.e., its MTBF) was 4279.24 minutes, which is 71.32 hours or 2.97 days. The maximum and minimum time spans between two consecutive network failures were 21240 (14.75 days) and 24 minutes respectively. Total network repair time in 10 months was 1488 minutes, which is 24.8 hours, and number of outages was 101 times, and the average time to correct a failure (i.e., its MTTR) was 14.73 minutes.

Having calculated MTBF and MTTR, we now can calculate availability, which can be expressed as either

$$Availability = \frac{uptime}{uptime + downtime} \quad \text{or} \quad Availiabiltiy = \frac{MTBF}{MTBV + MTTR}.$$

As Hennessy (1999) suggests, availability represents the ability of the network to work almost continuously within assigned performance value. Availability is particularly a key metric for servers in safety critical applications. A value of 99.8% is typical. For Tampa PORTS,

$$Availability = \frac{4279.24}{4279.24 + 14.73} = 99.65\%$$

What we found here is around typical availability value.

As previously indicated (Demester et al. 1999), network failures in the United States happen with a frequency on the order of one every two days and the mean time to repair them is on the order of five to 10 hours. Our evaluation results show that MTBF of the Tampa PORTS network is 2.97 days, which is well above the network failure frequency and the MTBF rate reported by the FCC (2 days). We found that MTTR of this sample network is 14.73 minutes, which is significantly better compared with results reported by the FCC (5 to 10 hours)

Expected Contribution

This research involves multiple disciplines and considerations. Completion of this research will expand knowledge regarding safety-critical real-time WANs. Much effort has been expanded in academia and industry to provide real-time network services over different network architectures. However, without understanding clearly the performance issues of real-time networks, the future of safety-critical real-time networks may not be realized.

Completion of this research will shed light on evaluation issues for real-time WANs, at a theoretical and practical level. At the theoretical level, the metrics, criteria and evaluation methods that will be used will be valuable to academia. At the practical level, the proposed research will expand knowledge of the technical, management and organizational challenges of a real-time WAN.

The research will also advance the field of safety-critical real-time network architectures and their evaluations. Finally, this research will establish a foundation for evaluating safety-critical real-time WANs, using assessment and performance requirements for highly reliably and dependable real-time networks. The proposed evaluation model may be a useful tool for practitioners and academia for evaluating and analyzing large-scale networked systems. By combining traditional quantitative methods of network evaluation with qualitative human and organizational network evaluation models, contribution of our model is expected in the development of a comprehensive evaluation method for real-time safety-critical wide area networks.

Current Status and Conference Presentation

The literature review is concluded, and the proposed model, hypotheses, dependent variables, and their operationalizations to evaluate subjects have been defined. Currently, data collection and survey administration are in progress, as is analysis of the collected data. Results will be available for conference presentation.

References

Adie, R. G., Zukerman, I., and Neame, T. D. "Broadband Traffic Modeling: Simple Solutions to Hard Problems," *IEEE Communications Magazine* (36:8), August 1998, pp.88-95.

Akar, N., Oguz, N.C., and Sohraby, K."TELPAC: An Advanced Teletraffic Analysis Package," *IEEE Communications Magazine*, (36:8), August 1998, pp.84-87.

Axelrod, C. W. *Computer Productivity: A Planning Guide for Cost Effective Management*, John Wiley, New York, 1982

Banerjee, S., Tipper, D., and Weiss, B.H.M., and Kahlil, A. "Traffic Experiments on the vBNS Wide Area ATM Network," *IEEE Communications Magazine*, (35:8), August 1997, pp.126-133

Bolch, G., Greiner, S., de Meer, H., and Triverdi, K, S. *Queuing Networks and Markov Chains, Modeling and Performance Evaluation with Computer Science Application*, John Wiley &Sons, New York, 1998.

DaSilva, L. A., Evans, J.B., Niehaus, D., Frost, V. S., Jonkman, R., Beng O. L., Lazarou, G.Y. "ATM WAN Performance Tools, Experiments, and Results," *IEEE Communications Magazine*, (35:8), August 1997, pp.118-124.

Demeester, P., Wu, T., and Yoshikai, N. "Survivable Communication Networks," *IEEE Communications Magazine*, (37:8), August 1999, pp.40-42.

Drucker, P. "Building The Measurement System For Information Systems and Technology*," Total Quality in Information Systems and Technology*, The St.Lucie Press, 1997.

Ferrari, D., Serazzi, G., and Zeigner, A. *Measurement and Tuning of the Computer Systems*, Prentice-Hall, Englewood Cliffs, NJ, 1983.

Gibson, T. "Packet-Switched WANs: More with Less," *IEEE Network*, (6:4), July 1992, pp.34-39.

Guarneri, R., and Lanting, C.J.M. "Frame Relaying as a Common Access to N-ISDN and B-ISDN Data Services," *IEEE Communications Magazine*, (32:6), June 1994, pp. 39-43.

Haverkort, B, R. *Performance of Communication Systems, A Model-Based Approach*, Wiley, Chichester, NY, 1998.
Hemrick, C. "Building Today's Global Computer Inter-networks," *IEEE Communication Magazine*, (30:10), October 1992, pp.44-49.
Hennessy, J. "The Future of Systems Research," *Computer*, (32:8), August 1999, pp.27-33.
Higginbottom, G.N. *Performance Evaluation of Communication Networks*, Artech House, Boston, 1998.
Khalil, K., Hand, J.C., Mariswamy, M., and Obaidat, M.S. "Methodologies for Characterizing Traffic in Wide Area Networks: Analysis and Benchmarking," *International Journal of Communication Systems*, (8:2), March-April 1995, pp. 117-127.
Jehiel, P. "Information Aggregation and Communication in Organizations," *Management Science*, (45:5), May 1999, pp. 659-669.
Jurison, J. "The Temporal Nature of IS Benefits: A Longitudinal Study," *Information & Management*, (30:2), May 1996, pp.75-79.
Kuhn, R. D. "Sources of Failure in the Public Switched Telephone Network," *Computer*, (30:8), August 1997, pp. 31-36.
Lehoczky, P.J. "Real-Time Queuing Theory," *Proceedings of the IEEE Real Time Systems Symposium,* December, 1996.
Mackenzie, K.D. "Processes and Their Frameworks," *Management Science*, (46:1), January 2000, pp. 110-125.
McCabe, J.D. *Practical Computer Network Analysis and Design*, Morgan Kaufmann Publishers, San Francisco, CA, 1998.
Monge, P. R., Fulk, J., Kalman, M. E., and Flanagin, A. J. "Production of Collective Action in Alliance-Based Interorganizational Communication and Information Systems." *Organization Science*, (9:3), May-June 1998, pp.411-433.
Myung, Y., Kim, H., and Tcha, D. "Design of Communication Networks with Survivability Constraints," *Management Science*, (45:2), February 1999, pp.238-252.
Niehaus, D., Battou, A., McFarland, A., Decina, B., Dardy, H., Sirkay, V., and Edwards, B. "Performance Benchmarking of Signaling in ATM Networks," *IEEE Communications Magazine*, (35:8), August 1997, pp. 134-142.
National Oceanographic and Atmospheric Administration (NOAA), Center for Operational Oceanic Products and Services (CO-OPS), Silver Spring, Maryland, 1999
Orlikowski, W. J., Yates, J., Okamura, K., and Fujimoto, M. "Shaping Electronic Communication: The Metastructuring of Technology in the Context of Use." *Organization Science* (6:4), July-August 1995, pp.423-444.
Shin, K.G. *HARTS: A Distributed Real-Time Architecture, Advances in Real Time Systems*, IEEE Press, 1993.
Somani, K. A., and Nitin, H. V. "Understanding Fault Tolerance and Reliability," *Computer*, (30:4), April 1997, pp.45-50.