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R.P. Lippmann

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Routing in Circuit and Packet Switched Networks: An Annotated Bibliography

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Raymond L. Loiselle

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

ROUTING IN CIRCUIT AND PACKET SWITCHED NETWORKS: AN ANNOTATED BIBLIOGRAPHY

R.P. LIPPMANN

Group 24

TECHNICAL REPORT 585

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ABSTRACT

This report contains an annotated bibliography of papers which describe routing and design procedures used in circuit and packet switched networks and a topical index to these papers. Papers were selected either because they were judged to provide insight into routing algorithms potentially applicable to the future Defense Switched Network or because they provide background information on routing and network design. These papers contain studies of routing, congestion control, and network design performed using analytic models and event-by-event simulations. They also contain reviews of military networks, and descriptions of routing and design procedures for the current military telephone network (AUTOVON), the Bell System long distance DDD telephone network, and various packet switched networks including ARPANET and TYMNET.

CONTENTS

1. INTRODUCTION

The Defense Communications Agency (DCA) is currently developing a plan for a Defense Switched Network* (DSN) to provide survivable and endurable telecommunications for military users. The DSN must meet the dual requirements of survivability during stress conditions and economy in peacetime. It will utilize a mix of terrestrial and satellite media, and flexible digital control of switching and routing. New adaptive routing procedures are expected to be needed in the DSN in order to achieve the requirements of survivability and economy. Lincoln Laboratory, under DCA sponsorship, has been carrying out system studies aimed at the development and analysis of routing procedures with potential applicability to the DSN.

This report is the result of a literature search performed as part of this work. The initial purpose of this search was to bring together and review past network design and routing procedures used in circuit-switched networks which might be applicable to the DSN. Two circuit-switched networks, AUTOVON (The Automatic Voice Network) and the Bell System Long Distance Direct Dial (DDD) Network, were of particular interest. In the course of this literature search, it became evident that many of the routing and design procedures proposed and used in packet-switched networks (particularly ARPANET), either could also be used in circuit-switched networks or provided insight into circuit-switched network problems. A number of papers describing routing and

*G. J. Coviello and R. H. Levine, "Considerations for a Defense Switched Network," in Proc. 1980 Natl. Tele. Comm. Conf. (NTC '80), November 30-December 4, 1980.

design procedures for packet-switched networks were thus included in this report. These papers were included because of their applicability to circuit-switched network problems and they thus may not provide a comprehensive review of packet-switched network research. The selected topical indexes are also not comprehensive. They reflect the primary interest in circuit-switched networks and in topics related to the Defense Switched Network.

References to literature included in this report were obtained from (1) a computer search using INSPEC (1969 to present), DTIC (1940's to present), and NTIS (1964 to present) data bases; (2) review of the past five to ten years of IEEE Transactions on Communications, Bell System Technical Journal, Conference Record of the International Conference on Communications (ICC), and Conference Record of the National Telecommunications Conference (NTC); (3) cross-references; (4) friendly people at Lincoln Laboratory, the Defense Communication Engineering Center, and Bolt Beranek and Newman, Inc.; (5) browsing through interesting areas of the Lincoln Laboratory library.

This report contains two main sections--an index to papers on selected topics and an annotated bibliography. The topical index includes short, one-line descriptions of papers included under each topic. The bibliography includes more detailed reviews of all papers. These reviews focus on parts of the papers relevant to the DSN.

2. INDEX TO SELECTED TOPICS

2.1 Circuit-Switched Networks

2.1.1 Routing

Bernas and Grieco (1978)	POLYGRID vs. adaptive vs. flood search routing - AUTOVON simulation.
DCA (1980)	General description of AUTOVON.
Fitzpatrick and Horn (1980)	Flexible Routing - Canadian Bell System.
Gafni and Bertsekas (1981)	Distributed routing for packet radio network.
Gorgas (1968b)	General description of POLYGRID routing.
Grandjean (1967)	Overview of routing, single vs. alternate path routing - small network simulation.
Greene and Brown (1969)	Route Control Digit - AUTOVON.
Heggestad (1980)	Sequential Routing - with crankback.
Haenschke, Kettler, and Oberer (1981)	Hierarchical routing - Bell System.
Katz (1972)	Routing table generation - AUTOVON.
Lin, Leon and Stewart (1975)	Routing table updating - European AUTOVON.
Ludwig and Roy (1977)	Saturation routing limits.
Marx (1979)	AUTOVON and AUTOVON II simulation.
Merlin and Segall (1979)	Failsafe routing protocol.
Segal (1979a,b; 1981)	Failsafe routing protocol.
Shearer (1975)	Modified Forward Routing for AUTOVON.

Weber (1962)	Hierarchical and symmetric routing - small networks.
Weber (1964)	Hierarchical and symmetric routing, crankback, and trunk reservation - large west coast network simulation.
Wilkinson (1956)	Hierarchical routing for direct distance dialing - Bell System.

2.1.2 Analytic Models

Calabrese, Fischer, Hoiem, Kaiser (1980, 1979)	Complete AUTOVON model with preemption.
Chan (1980)	Node to node GOS from blocking probabilities.
Fischer and Knepley (1973)	Improved implementation of Katz (1967).
Fischer (1976)	Link model - both satellite and land lines available.
Fischer, Garbin, Harris, Knepley (1978)	AUTOVON model and minimum cost design program.
Fischer (1979)	Link model - preemption, different holding times.
Franks and Rishel (1973a)	Optimum network call - carrying capacity in the Bell System.
Franks and Rishel (1973b)	Overload model of Bell System.
Garbin (1978)	AUTOVON network dynamics.
Gaudreau (1980)	Node to node GOS from blocking probabilities - Bell System.
Grandjean (1967)	Single moment analysis for small networks.
Katz (1967)	First large-scale network analysis program - dual moment.

Katz (1972)	Routing table generation for AUTOVON.
Knepley (1973)	Minimum cost design for AUTOVON.
Lin and Leon (1974)	Preemption probability in small networks.
Lin, Leon, Stewart (1975)	Routing table updating - European AUTOVON.
Lin, Leon, Stewart (1978)	Single moment analysis - European AUTOVON.
Schneider and Minoli (1980)	Single moment analysis - GOS upper bound.
Wilkinson (1956)	Equivalent Random Method and other theories for toll traffic engineering - Bell System.

2.1.3 Event-by-Event Simulations

Bernas and Grieco (1978)	POLYGRID vs. adaptive vs. flood search routing - AUTOVON simulation. (Booz, Allen and Hamilton.)
DCA (1973)	AUTOVON simulation programs. (Computer Science Corporation.)
Grandjean (1967)	Single vs. alternate path routing - small networks.
Klukis, Bishop, Sauer, Wilder (1975)	European AUTOVON - survivability with adaptive routing (Martin-Marietta Corporation).
Marx (1979)	AUTOVON simulation (Harry Diamond Labs).
Ricci (1974)	Survivability - routing table updates.
Sauer, Bishop, Klukis (1978)	See Klukis <u>et al.</u>, (1975).
Weber (1962)	Hierarchical and symmetric routing - small networks.

Weber (1964)	Hierarchical and symmetric routing, crankback, and trunk reservation - large west coast network.

2.1.4 Congestion Control

Burke (1968)	Automatic controls - Bell System.
Franks and Rishel (1973b)	Overload model of Bell System.
Grandjean (1967)	Alternate routing degrades GOS at high traffic levels.
Greene, Haenschke, Hornbach, Johnson (1977)	Congestion control in No. 4 ESS.
Haenschke, Kettler, Oberer (1981)	Automatic controls - Bell System.
Lemieux (1979, 1981)	Theory and application - Canadian Bell System.
Lewis and Schwenzfeger (1966)	General description of automatic controls - Bell System.
Weber (1964)	Restricting alternate routing improves GOS - west coast network simulations.

2.1.5 Overviews of Military Networks

Blackman (1979)	AN/TCC-39 and AN/TTC-42 digital switches.
Coviello and Lyons (1980)	Integrating circuit and packet switched networks.
Coviello and Levine (1980)	Considerations for Defense Switched Network.
DCA (1980)	General description of AUTOVON.
Deardorff et al., (1978)	Comprehensive review of strategies for updating AUTOVON.

Gorgas (1968a,b)	General description of AUTOVON.
Ridd (1978)	Reviews need for common channel signaling and status monitoring in AUTOVON.
Rosner (1978)	Reviews need for status monitoring and control in AUTOVON.
Shimabukuro (1980)	Summarizes Deardorff et al., (1978) and describes the Defense Switched Network concept.

2.1.6 Routing Procedures Which Enhance Survivability

Bernas and Grieco (1978)	POLYGRID, adaptive and flood search routing.
Gafni and Bertsekas (1981)	Distributed routing for packet radio network.
Gorgas (1968b)	General description of POLYGRID routing.
Heggestad (1980)	Sequential routing - with crankback.
Katz (1972)	Routing table generation - AUTOVON.
Ludwig and Roy (1977)	Saturation Routing Limits.
Merlin and Segall (1979)	Failsafe routing protocol.
Ricci (1974)	Updating AUTOVON routing tables.
Segall (1979a,b; 1981)	Failsafe routing protocol.
Shearer (1975)	Modified Forward Routing for AUTOVON.
Tajibnapis (1977)	Protocol to exchange routing information when topology changes.

2.1.7 Network Design

Fischer, Garbin, Harris, Knepley (1978)	Minimum cost design program for AUTOVON.

Gorgas (1968a,b)	General overview of AUTOVON design.
Katz (1972)	Considerations in AUTOVON design including routing table generation.
Knepley (1973)	Minimum cost design program for AUTOVON.
Shearer (1975)	Modified forward routing algorithm - fast enough to use in AUTOVON design program.
Wilkinson (1956)	Design of Bell System direct distance dialing network.

2.2. Packet-Switched Networks

2.2.1 Reviews and Books

Boorstyn and Frank (1979)	Reviews network design - problems and algorithms.
Frank and Frisch (1972)	Communication, Transmission and Transportation Networks.
Fultz and Kleinrock (1971)	Review of routing research prior to 1971.
Gerla and Kleinrock (1977)	Reviews ARPANET design - problems and algorithms.
Gerla (1981)	Review of routing research prior to 1980.
Kleinrock (1964)	Communication Nets: Stochastic Message Flow and Delay.
Kleinrock (1975)	Queueing Systems Vol. I: Theory
Kleinrock (1976)	Queueing Systems Vol. II: Computer Applications.
McQuillan (1974)	Review of routing research prior to 1974.

McQuillan (1977)	Review of routing research from 1974 to 1977.
Puzman and Porizek (1980)	Communication Control in Computer Networks.
Rudin (1976)	Review of routing research prior to 1976.
Schwartz (1977)	Computer-Communication Network Design and Analysis.
Schwartz and Stern (1980)	Review of routing in TYMNET, ARPANET and TRANSPAC.
Soi and Aggarwal (1981)	Review of terminology and classification schemes for computer networks.

2.2.2 Routing

Boorstyn and Frank (1977)	Reviews network design - problems and algorithms.
Boorstyn and Livne (1981)	Two stage adaptive routing.
Cantor and Gerla (1974)	Extremal flow routing algorithm.
Chou and Frank (1972)	Cut-saturation routing algorithm.
Chou, Powell, Bragg (1979)	Comparison of deterministic and adaptive routing.
Chou, Bragg, Nilsson (1981)	Need for adaptive routing when traffic is chaotic and unbalanced.
Frank and Chou (1972)	Reviews network design - problems and algorithms.
Fratta, Gerla, Kleinrock (1973)	Flow deviation routing algorithm.
Fultz and Kleinrock (1971)	Reviews routing research prior to 1971 and describes distributed adaptive routing algorithms.
Gafni and Bertsekas (1981)	Distributed routing for packet radio network.

Gallager (1977)	Loop-free minimum delay routing using distributed computation.
Gerla and Kleinrock (1977)	Reviews ARPANET design - problems and algorithms.
Huynh, Kobayashi, Kuo (1977)	Routing when satellite and land links are available.
Lemieux (1979, 1981)	Congestion and flow control.
McQuillan (1974)	Review of ARPANET routing and of prior routing research.
McQuillan (1977)	Review of ARPANET routing and of routing research from 1974 to 1977.
McQuillan, Richer, Rosen (1978)	New SPF routing for ARPANET (first BBN report).
McQuillan, Richer, Rosen, Bertsekas (1978)	New SPF routing for ARPANET (second BBN report).
McQuillan, Falk, Richer (1978)	ARPANET routing problems.
McQuillan, Richer, Rosen (1980)	Review of new SPF ARPANET routing.
Merlin and Segall (1979)	Failsafe routing protocol.
Natarajan, Tang, and Maruyama (1979)	Path selection criteria.
Neblock and Pooch (1978)	Traveling header or trace prevents loops.
Rosen, Herman, Richer, McQuillan (1979)	New SPF routing for ARPANET (third BBN report).
Rosen, Mayersohn, Sevcik, Williams, Attar (1980)	Proposed ARPANET improvements and proposed routing for AUTODIN II.
Rudin (1976)	Delta routing (both centralized and local control).
Rudin (1979)	Routing and flow control interactions.

Schwartz and Stern (1980)	Shortest path algorithms, routing in TYMNET, ARPANET and TRANSPAC.
Segall (1979a,b, 1981)	Failsafe routing protocol.
Tajibnapis (1977)	Protocol to exchange routing information when topology changes.
Thymes (1981)	TYMNET.
Yum (1979, 1981)	Semidynamic deterministic routing (maximum bifurcation).
Yum and Schwartz (1981)	Join Biased Queue - like Delta Routing.

2.2.3 Network Design

Boorstyn and Frank (1977)	Review of design problems and algorithms.
Cantor and Gerla (1974)	Extremal flow routing algorithm.
Chou and Frank (1972)	Cut-saturation routing algorithm.
Frank and Chou (1972)	Review of design problems and algorithms.
Gerla and Kleinrock (1977)	Review of ARPANET design problems and algorithms.
Huynh, Kobayashi, Kuo (1977)	Design of networks with satellite and land links.

3. ANNOTATED BIBLIOGRAPHY

[1] G. W. Bernas and D. M. Grieco, "A Comparison of Routing Techniques for Tactical Circuit-Switching Networks," in Proc. 1978 Int. Conf. on Comm. (ICC '78), pp. 23.5.1-23.5.5, 1978.

Describes a study of routing schemes which could be used in AUTOVON. Compared deterministic (originating office control and spill forward), adaptive (backwards learning based on link count), flood search, and limited area flood search routing schemes using an event-by-event simulation of AUTOVON. This simulation included preemption and the ability to cause traffic overloads and to damage the network. Routing schemes were evaluated on the basis of GOS (by precedence level), incidence of preemption, signalling traffic requirements, call placement time, and cost. Network dynamics following damage were also studied. Although the flood search scheme provided best overall GOS and lowest incidence of preemption, it required more than an order of magnitude, more signalling bandwidth than the other schemes. The adaptive, shortest-path scheme was recommended for future use. It responded rapidly to network damage and performed nearly as well as the flood search scheme but required much less signalling bandwidth.

[2] J. Blackman, "Switched Communications for the Department of Defense," IEEE Trans. Comm. COM-27, 1131, 1979.

Describes the AN/TCC-39 and AN/TCC-42 digital circuit switches being built for the Department of Defense which can switch from 30 to 600 lines and can be used in AUTOVON.

[3] R. Boorstyn and H. Frank, "Large-Scale Network Topological Optimization," IEEE Trans. Comm., COM-25, pp. 29-47, January 1977.

Reviews problems found in designing a large network consisting of a backbone network with a distributed traffic pattern and local access networks with centralized traffic patterns. Presents algorithms which can be used to solve many design problems.

[4] R. B. Boorstyn and A. Livne, "A Technique for Adaptive Routing in Networks," IEEE Trans. Comm., COM-29, pp. 474-480, April 1981.

Describes a two-level adaptive routing scheme for packet-switched networks. In the first quasi-static level, a network control center determines which links coming from each node are allowable parts of "good" paths to each destination node. In the second dynamic level, the node determines which of the allowable links to route each packet on using various rules which have as inputs the lengths of all output queues. Simulations of small networks indicate that this routing scheme produces average delays which are less than those produced when only shortest paths are used. Also see Yum and Schwartz (1981).

[5] P. J. Burke, "Automatic Overload Controls in a Circuit-Switched Communications Network," in Proc. Natl. Electronics Conf., pp. 667-672, December 1968.

Reviews congestion problems and congestion controls used in the Bell System. Includes simulations which demonstrate effectiveness of congestion controls.

[6] D. Calabrese, M. Fischer, B. Hoiem, and E. Kaiser, "An Algorithm for Predicting the Performance of a Voice Network with Preemption," Defense Communications Engineering Center Technical Note No. 6-79, January 1979.

See Calabrese _et al._, 1980.

[7] D. G. Calabrese, M. J. Fischer, B. E. Hoiem and E. P. Kaiser, "Modelling a Voice Network with Preemption," IEEE Trans. Comm., _COM-28_, pp. 22-27, January 1980.

Describes an analytic computer model of AUTOVON which can be used to compute GOS of calls with two priority levels when either ruthless or friendly preemption is used. (Preemption allows a low priority call to be disconnected when links are necessary for a high priority call.) This model expands the capability of the model described in Fischer _et al._, 1978. Results agree closely with those obtained using a network simulator and CPU time needed is measured in minutes instead of the hours required with a simulator.

[8] D. G. Cantor and M. Gerla, "Optimal Routing in a Packet-Switched Computer Network," IEEE Trans. Computers, _C-23_, pp. 1062-1069, October 1974.

Describes the Extremal Flows algorithm for computing routing in a packet-switched network. This algorithm uses a steepest descent type iteration and converges faster than the flow deviation method described in Fratta _et al._, 1973.

[9] W. S. Chan, "Recursive Algorithms for Computing End-to-End Blocking in a Network with Arbitrary Routing Plan," IEEE Trans. Comm., _COM-28_, pp. 153-164, February 1980.

Allows end-to-end blocking probability (GOS) of each node pair to be calculated in a circuit-switched network when the arbitrary alternate routing plan and link blocking probabilities are known. Assumes link blocking probabilities are independent. When arbitrary routing (e.g., originating office control as in the European AUTOVON) is used, route sequences (all possible paths between nodes) must be generated by hand and are used in a recursive algorithm to compute end-to-end blocking probabilities. This algorithm thus simplifies procedures to compute end-to-end blocking probabilities for the European AUTOVON which were described in Lin, Leon, and Stewart (1978). When hierarchical spill-forward routing is used (as in North American Bell System networks), route sequences are generated automatically using procedures first described by Gaudreau (1980) and end-to-end blocking probabilities are calculated recursively as above.

[10] W. Chou and H. Frank, "Routing Strategies for Computer Network Design," in Proc. Symp. on Comm. Networks and Teletraffic, Brooklyn, New York, pp. 301-309, April 1972.

Formulates routing as a multicommodity flow problem and presents the cut-saturation technique which yields near optimal routing. This technique requires little computer time and thus can be used as part of iterative network design programs.

[11] W. Chou, J. D. Powell, and A. W. Bragg, "Comparative Evaluation of Deterministic and Adaptive Routing," in Flow Control in Computer Networks, edited by J. L. Grange and M. Gien, (IFIP North-Holland Publishing Company, New York, 1979).

Data obtained using a simulation model of the ARPANET suggests that deterministic routing should be used unless there is unpredictable surge traffic or the traffic requirements are unknown and the network cannot be reconfigured to match the traffic.

[12] W. Chou, A. W. Bragg, and A. O. Nilssor, "The Need for Adaptive Routing in the Chaotic and Unbalanced Traffic Environment," IEEE Trans. Comm., COM-27, pp. 481-490, April 1981.

Simulations of a ten node network were performed in which traffic patterns were varied and either ARPANET-like routing schemes were used or routing was static and deterministic. A well-chosen deterministic routing strategy was found to be better for a balanced, stable traffic flow. Both deterministic and adaptive procedures were appropriate for balanced traffic with surges and a well-chosen adaptive routing strategy was better for unbalanced or chaotic traffic. A new routing strategy that is static when traffic is balanced and becomes dynamic otherwise is described. Also see Chou, Powell, and Bragg (1979).

[13] G. J. Coviello and R. E. Lyons, "Conceptual Approaches to Switching in Future Military Networks," IEEE Trans. Comm., COM-28, pp. 1491-1498, August 1980.

Reviews differences between circuit-switched and packet-switched networks. Describes integrated or mixed networks which can perform both types of switching and which may be desirable in the future.

[14] G. J. Coviello and R. H. Levine, "Considerations for a Defense-Switched Network," in Proc. IEEE 1980 Natl. Tele. Comm. Conf. (NTC '80), November 30-December 4, 1980.

Discussion of some of the issues involved in development of the Defense-Switched Network concept and presentation of a proposed structure for this network.

[15] R. F. Deardorff, W. P. Dotson, T. C. Harris, W. G. Hartung, J. E. Knepley, N. A. Sica, T. M. Shimabukuro, E. M. Stubsten, G. W. Swinsky, and W. F. Vogelzang, "Design Concepts for the Next Generation CONUS AUTOVON," Defense Communications Engineering Center Technical Report No. 18-78, December 1978.

Reviews current status of AUTOVON and provides a comprehensive review of strategies for upgrading AUTOVON. Also see Shimabukuro (1980).

[16] Defense Communications Agency Circular, "Global Automatic Voice Network (AUTOVON)," 310-V55-6, 1980.

Describes in general terms how AUTOVON works and is managed.

[17] Defense Communications Agency Technical Note, "Descriptions of the Simulation Models of the Defense Communications System Performance Simulator," 6-73, 1973.

Describes in a general manner models developed for the Defense Communications Agency by the Computer Science Corporation. These include event-by-event simulations of CONUS AUTOVON, European AUTOVON, and AUTODIN and an analytic model of AUTODIN.

[18] M. J. Fischer and J. E. Knepley, "Circuit-Switched Network Performance Algorithm (MOD-1)," Defense Communications Agency Technical Note 1-73, January 1973.

Describes the implementation of an improved version of the analytic method of Katz (1967) which allows spill-forward routing and is used to determine the performance of AUTOVON. The method employs iterative procedures to estimate node-to-node, trunk group, and network GOS. It assumes that traffic can be adequately described by its mean and variance. The GOS measures predicted by this method are very close to those obtained using event-by-event simulations of small networks.

[19] M. Fischer, "Mixed Media: Optimizing Link Performance for a Circuit-Switched System," Defense Communications Engineering Center Technical Note 15-76, August 1976.

Describes the analysis of a system consisting of two nodes connected by two transmission facilities (e.g., satellite and submarine cable) with differing costs. Analysis includes two classes of traffic with different arrival rates and similar holding time distributions. Different access rules which allow either one or both classes of traffic onto each link type were examined.

[20] M. J. Fischer, D. A. Garbin, T. C. Harris, and J. E. Knepley, "Large Scale Communication Networks - Design and Analysis," Omega. 6, pp. 331-340, April 1978.

Describes how analytic computer models of AUTOVON which allow spill-forward routing are used by the Defense Communications Agency for network design and analysis. The major circuit-switched performance model is derived from that presented in Katz (1967). The models have been used to reconfigure AUTOVON and save three million dollars per year. GOS results agree very well with event-by-event simulation results for both single and dual moment models. Also see Knepley (1973).

[21] M. J. Fischer, "Priority Loss Systems - Unequal Holding Times," Defense Communications Engineering Center Technical Note 1-79, February 1979.

Presents performance model of a link in a circuit-switched system with high and low priority traffic and preemption. The model allows probabilities of blocking and preemption to be computed when holding times of high and low priority calls are not equal.

[22] G. J. Fitzpatrick and R. W. Horn, "Evaluating Flexible Routing for an Intertoll Telephone Network," in Proc. 1976 Intl. Conf. on Comm. (ICC '80), pp. 27.6.1-27.6.7, 1980.

Flexible routing (changing routing tables every hour) can save roughly eight percent in trunking costs when compared to hierarchical routing as presently used in the Canadian Bell System.

[23] H. Frank and W. Chou, "Topological Optimization of Computer Networks," Proc. of the IEEE, 60, pp. 583-594, November 1972.

Reviews algorithms which have been used for the design of distributed computer communication networks such as the ARPANET. Describes the cut-saturation procedure to optimize routing and gives sample results obtained with this method.

[24] H. Frank and I. T. Frisch, Communication, Transmission and Transportation Networks, (Addison Wesley, Reading, Massachusetts, 1972).

Presents analysis techniques which can be used with many types of deterministic and probabilistic networks. Topics covered include maximum flow problems, minimum cost problems, connectivity and vulnerability, and time delay.

[25] R. L. Franks and R. W. Rishel, "Optimum Network Call-Carrying Capacity," BSTJ, 52, pp. 1195-1214, July 1973a.

Describes an analytic model which can be used to determine the maximum number of calls which a Bell System Network can carry under overload. The model includes switching machine and trunk congestion. Results suggest that current network management congestion controls allow carried traffic to come very close to the upper bound determined by this model

[26] R. L. Franks and R. W. Rishel, "Overload Model of Telephone Network Operation," BSTJ, 52, 1589-1615, September 1973b.

Presents an analytic single moment model of a Bell System network under overload conditions. The model includes both switching machine and trunk models and some network management controls.

[27] L. Fratta, M. Gerla, and L. Kleinrock, "The Flow Deviation Method: An Approach to Store-and-Forward Communication Network Design," Networks, 3, pp. 97-133, February 1973.

Describes an iterative algorithm, the Flow Deviation Method, which can be used to determine optimal routing in packet-switched networks. This algorithm has been used in ARPANET design and analysis programs (see Gerla and Kleinrock, 1977). It has also been called the "best stochastic" routing rule because traffic is bifurcated stochastically at each mode using fixed probability assignments which minimize the overall average delay.

[28] G. Fultz and L. Kleinrock, "Adaptive Routing Techniques for Store-and-Forward-Computer-Communication Networks," in Proc. 1976 Intl. Conf. on Comm. (ICC '71), pp. 39.1-39.8, 1971.

Classifies various routing schemes and reviews research prior to 1971. Also describes performance of distributed adaptive routing algorithms such as the algorithm which was first used on the ARPANET.

[29] E. M. Gafni and D. P. Bertsekas, "Distributed Algorithm for Generating Loop-Free Routes in Networks with Frequently Changing Topology," IEEE Trans. Comm., COM-29, pp. 11-18, January 1981.

Describes an algorithm which could be used in a mobile packet radio network to maintain communication between nodes of the network and a central station in the presence of frequent topological changes. Flooding techniques are not used and both the frequency of activation and communication overhead required to establish routes is less than in Segall's algorithm. Shortest paths are not guaranteed, but freedom from loops is.

[30] R. G. Gallager, "A Minimum Delay Routing Algorithm Using Distributed Computation," IEEE Trans. Comm., COM-25, pp. 73-83, January 1977.

Describes an adaptive distributed routing algorithm which provides loop-free paths and minimizes overall delay in a packet-switched network when traffic input is stationary. Requires each node to estimate the derivative of the delay on all attached links.

[31] D. A. Garbin, "Analytic Modeling of Dynamic Network Behavior," in Proc. 1978 Intl. Conf. on Comm. (ICC '78), pp. 23.3.1-23.3.4, June 1978.

Modification of circuit-switched network model described in Fischer _et al._, (1978) which allows network dynamics to be determined when links or nodes are destroyed or traffic changes.

[32] M. D. Gaudreau, "Recursive Formulas for the Calculation of Point-to-Point Congestion," IEEE Trans. Comm., COM-28, pp. 313-316, March 1980.

Describes procedures which can be used to calculate node-to-node blocking probabilities in a circuit-switched network when the blocking probability of each link is known and the hierarchical spill-forward routing plan used in the North American telephone network is followed. See Chan (1980) for extensions of this work and a better description of these procedures.

[33] M. Gerla and L. Kleinrock, "On the Topological Design of Distributed Computer Networks," IEEE Trans. Comm., COM-25, pp. 48-60, January 1977.

Reviews algorithms which have been used for the design of the ARPANET and of other computer communication networks. Algorithms are presented which (1) assign link capacities which minimize cost, (2) determine routing which minimizes delay, (3) determine routing and link capacities which minimize cost and (4) determine number and location of links, and link capacities which minimize cost. Algorithms used for routing optimization are reviewed. Two of these algorithms, the minimum link algorithm and the flow deviation algorithm, are described in detail.

[34] M. Gerla, "Routing and Flow Control," in _Protocols and Techniques for Data Communication Networks_, edited by Franklin F. Kuo, (Prentice Hall, New Jersey, 1981).

Provides an overview of static and adaptive routing procedures which have been used in packet-switching networks. Describes both centralized (Fratta, 1973) and distributed (Gallager, 1977) routing algorithms in detail. Shorter reviews of other routing algorithms such as delta routing (Rudin, 1976) are also provided.

[35] J. W. Gorgas, "AUTOVON: Switching Network for Global Defense," Bell Lab. Rec., 46, pp. 106-111, April 1968a.

General overview of AUTOVON, its five level precedence scheme and features including off-hook service, conferencing, and special grade connections.

[36] J. W. Gorgas, "The Polygrid Network for AUTOVON," Bell Lab. Rec., 46, pp. 223-227, July 1978b.

General description of polygrid routing used in AUTOVON.

[37] C. H. Grandjean, "Call Routing Strategies in Telecommunication Networks," Electrical Communication, 42, pp. 380-391, March 1967.

Presents comprehensive review of routing strategies which have been used in circuit-switched networks. Demonstrates using simulations and analytic models of simple networks that the network GOS obtained with alternate routing can be worse than that obtained with single-path routing when the offered traffic is high. Presents single moment iterative analysis which can be used to determine node-to-node GOS in simple networks given routing, topology, and offered traffic.

[38] T. V. Greene and L. C. Brown, "Route Control in AUTOVON Electronic Switching Centers," IEEE Trans. Comm., COM-17, pp. 442-446, April 1969.

Reviews routing in AUTOVON and describes how the route control digit (RCD) was added to avoid loops, shuttling and excessively long routes.

[39] T. V. Greene, D. G. Haenschke, B. H. Hornbach, and C. E. Johnson, "No. 4 ESS: Network Management and Traffic Administration," BSTJ, 56, pp. 1169-1202, July 1977.

Describes real-time control and surveillance provided in the No. 4 ESS. Also reviews automatic congestion controls. These include Hard-to-Reach (HTR) code analysis which labels an area hard-to-reach when probability of blocking is high, Selective Dynamic Overload Control which blocks HTR area calls and calls which use alternate routing when traffic load increases, and Automatic Out-of-Chain routing which routes calls on routes outside the normal hierarchical routing structure when spare capacity is available (for example, when busy hour occurs nonsimultaneously in two adjacent time zones).

[40] D. G. Haenschke, D. A. Kettler, and E. Oberer, "Network Management and Congestion in the United States Telecommunications Network," IEEE Trans. Comm., COM-27, pp. 376-385, April 1981.

Tutorial paper on network management and congestion controls in the Bell System. Provides both an historical review and a description of current practices. Describes hierarchical routing, common channel signalling, network overload characteristics, and automatic and manual congestion controls. Simulation results demonstrating the effectiveness of automatic controls including selective dynamic overload control and selective trunk reservation are presented. Manual controls including "call gapping" which were used to handle the New York City 13th Street building fire and the "ask President Carter" call-ins are described. Also see Greene et al., (1977) and Franks and Rishel (1973).

[41] H. M. Heggestad, "A Flexible Routing Algorithm for the Future Defense Switched Network," in Proc. IEEE 1980 Natl. Telecomm. Conf. (NTC '80), pp. 74.3.1-74.3.5, 1980.

Describes "sequential routing algorithm" which allows crankback when trying to complete a call and explicitly provides for routing table changes when link outages occur. Analytically compares sequential routing to spill-forward routing in an idealized network when the grade of service on each link is given.

[42] D. H. Huynh, H. Kobayashi, and F. F. Kuo, "Optimal Design of Mixed-Media Packet-Switching Networks: Routing and Capacity Assignment," IEEE Trans. Comm., COM-25, pp. 158-168, January 1977.

Analysis of packet-switched network which includes low-cost, high-bandwidth satellite links with large delay and high-cost limited bandwidth ground links. The satellite is used either as a slotted ALOHA channel or as a MASTER channel wherein packets are retransmitted via ground links whenever a collision occurs on the satellite link.

[43] S. Katz, "Statistical Performance Analysis of a Switched Communication Network," in Proc. 5th Intl. Teletraffic Cong., New York, June 1967.

Describes a two moment computer algorithm which can be used to determine the steady-state performance of a large circuit-switched network such as AUTOVON. Various performance measures including node-to-node GOS are determined given the network topology, link sizes, alternate routing plan, and offered traffic. This algorithm runs much faster than event-by-event simulations and performance measures obtained with this algorithm are very close to those obtained using simulations. Also describes the "carried equivalent" method for computing the mean and variance of traffic overflowing a link with "smooth" offered traffic (variance less than mean).

[44] S. S. Katz, "Alternate Routing for Nonhierarchical Communication Networks," in Proc. IEEE 1972 Natl. Telecomm. Conf. (NTC '72), pp. 9A.1-9A.8, December 1972.

Describes route selection in AUTOVON and how the Bell System determines routing tables for AUTOVON. Procedures tend to both minimize cost and enhance survivability.

[45] L. Kleinrock, Communication Nets: Stochastic Message Flow and Delay, (McGraw-Hill Book Company, New York, 1964), reprinted 1974.

Analytic and simulation models of store and forward networks.

[46] L. Kleinrock, Queueing Systems, Volume I: Theory, (John Wiley and Sons, New York, 1975).

Analytic treatment of queueing theory with emphasis on results with practical implications.

[47] L. Kleinrock, Queueing Systems, Volume II: Computer Applications, (John Wiley and Sons, New York, 1976).

Describes how computer communication networks can be analyzed using queueing theory. Includes discussion of satellite and ground radio packet-switching networks and a detailed discussion of the ARPANET.

[48] J. K. Klukis, J. K. Bishop, G. J. Sauer, and B. L. Wilder, "Hybrid Computer Simulation Study of Adaptive Routing Techniques for Switching Networks to Enhance Survivability for Optimum System Performance," Martin-Marietta Corp., AD-AOR 494 Final Report, June 1975.

Describes event-by-event simulator for the European AUTOVON developed at the Martin-Marietta Corporation. This simulator included originating office control routing, single-path routing and two restricted types of "adaptive routing" which selected paths based on the percent utilization of links and number of links in a route. The adaptive routing procedures could use only a restricted set of paths consisting of those which could be generated using originating office control and a fixed routing table. The simulation also included preemption and the ability to overload links and destroy links or nodes. All routing procedures except single-path routing led to roughly equivalent GOS results. Various ways to improve the network GOS after damage including cancelling calls to destroyed nodes, adding new links and supplemental routing which added new paths to those considered for routing were examined. Supplemental routing (which is equivalent to using a routing algorithm with a greater degree of freedom) significantly improved the GOS, as did the other measures.

[49] J. E. Knepley, "Minimum Cost Design for Circuit-Switched Networks," Defense Communications Agency Technical Note 36-73, July 1973.

Describes an algorithm which has been used extensively by the DCA to design circuit-switched networks. Using the traffic requirements, cost data, desired node-to-node and overall GOS and node locations, this algorithm designs a minimum cost network and determines the trunk group sizes, routing tables, overall and node-to-node GOS, and cost of the network. It can be used for nonhierarchical networks such as AUTOVON and includes a performance evaluation model similar to that described in Katz (1967).

[50] C. Lemieux, "Flow Control in Switched Telephone Networks: Theory and Experience. Extension of Theory to Packet-Switched Networks," in Flow Control in Computer Networks, edited by J. L. Grange and M. Gien, (IFIP North-Holland Publishing Company, 1979).

Overview of congestion and flow control problems in circuit-switched networks. Compares circuit to packet-switched networks and suggests that dynamic routing should not be used in packet-switched networks.

[51] C. Lemieux, "Theory of Flow Control in Shared Networks and Its Application in the Canadian Telephone Network," IEEE Trans. Comm., COM-27, pp. 399-413, April 1981.

This paper is an expanded version of Lemieux (1979). It contains a qualitative theory of congestion control in circuit-switched and packet-switched networks. This theory indicates that alternate routing and preconnection holding times should be limited at high offered traffic levels. Congestion controls used in the Canadian Bell System are also described. These controls are very similar to those used in the U.S. Bell System which are summarized in Haenschke et al., (1981).

[52] E. E. Lewis and E. E. Schwenzfeger, "Automatically Controlling Heavy Telephone Traffic," Bell Lab. Rec., 44, pp. 135-138, April 1966.

Describes automatic congestion control available in the Bell System networks in 1966.

[53] P. M. Lin and B. J. Leon, Call Preemptions in a 2-Level Circuit-Switched Communication Network, in Proc. IEEE 1974 Natl. Telecomm. Conf. (NTC '74), pp. 683-687, December 1974.

Presents method of determining the probability that a high priority call will not preempt a low priority call in AUTOVON. The method involves a new form of terminal-pair reliability analysis and requires an analytic model which provides estimates of overall node-to-node GOS such as that described in Fischer and Knepley (1973).

[54] P. M. Lin, B. J. Leon, and C. R. Stewart, "System Control for Circuit-Switched Communications," in Proc. IEEE 7th Annual Southeastern Symposium on System Theory, pp. 256-260, 1975.

Describes a single moment method which uses path loss sequences to determine node-to-node GOS given the offered traffic, routing plan, and network topology. This method is a simpler and presumably less accurate version of the procedure described in Katz (1967). Also describes a procedure which uses this method as part of an iterative algorithm which modifies routing tables such that the maximum node-to-node GOS is below a specified level (e.g., five percent). This algorithm involves adding extra routing choices from the most overloaded node on the path between nodes with the worst GOS. The procedure is illustrated by application to European AUTOVON.

[55] P. M. Lin, B. J. Leon, and C. R. Stewart, "Analysis of Circuit-Switched Networks Employing Originating - Office Control with Spill-Forward," IEEE Trans. Comm., COM-26, pp. 754-765, June 1978.

Describes an analytic procedure which can be used to determine the node-to-node grade of service when originating office control routing

(which is employed in the European AUTOVON) is used. The procedure involves determining all path-loss sequences (all possible blocked and completed call paths) for each node pair by hand and using a single moment iterative procedure to determine link blocking probabilities. The node-to-node GOS is then determined from the link blocking probabilities and the path-loss sequences.

[56] G. Ludwig and R. Roy, "Saturation Routing Network Limits," Proc. of the IEEE, 65, pp. 1053-1062, September 1977.

Reviews flooding routing schemes for circuit-switched networks and calculates traffic limits assuming various common channel signalling bit rates and a PDP-11/34 switch processor. Describes regional flood search schemes and a network with satellite links between regions.

[57] E. Marx, "Event-by-Event Models of Communication Networks," Proc. IEEE Computer Networking Symposium, Gaithersburg, Maryland, pp. 21-25, December 1979.

Describes event-by-event simulation programs written in GPSS V at Harry Diamond Laboratories which simulate AUTOVON and AUTODIN II networks. The AUTOVON simulation demonstrated that under certain load conditions, ten percent more calls could reach destination if a more flexible routing strategy than is currently used in AUTOVON were implemented.

[58] J. M. McQuillan, "Adaptive Routing Algorithms for Distributed Networks," BBN Report No. 2831, and Ph.D. thesis, Harvard University, May 1974.

Comprehensive review of routing research prior to 1974 and discussion of ARPANET routing.

[59] J. M. McQuillan, "Routing Algorithms for Computer Networks: A Survey," in Proc. IEEE 1977 Natl. Telecomm. Conf. (NTC '77), pp. 28.1.1-28.1.1, December 1977.

Comprehensive overview of routing research from 1974 to 1977, discussion of problem areas, and review of ARPANET routing.

[60] J. M. McQuillan, I. Richer, and E. C. Rosen, "ARPANET Routing Algorithm Improvements - First Semiannual Technical Report," BBN Report No. 3803, April 1978.

Describes new ARPANET routing algorithm. Includes: review of problems with old routing algorithm, review of line up/down protocol, review of delay measurement problems, and a comprehensive discussion of the Shortest Path First (SPF) algorithm.

[61] J. M. McQuillan, J. Richer, E. C. Rosen, and D. P. Bertsekas, "ARPANET Routing Algorithm Improvements - Second Semiannual Technical Report," BBN Report No. 3940, October 1978.

Describes new ARPANET routing algorithm. Includes discussion of line up/down protocol, methods to measure and report delay, dynamic behavior of SPF algorithm, multiple homing, group addressing, and congestion control.

[62] J. M. McQuillan, G. Falk, and I. Richer, "A Review of the Development and Performance of the ARPANET Routing Algorithm," IEEE Trans. Comm., COM-26, pp. 1802-1810, December 1978.

Describes problems with the dynamic routing scheme used in the ARPANET prior to 1979.

[63] J. McQuillan, I. Richer, and E. C. Rosen, "The New Routing Algorithm for the ARPANET," IEEE Trans. Comm., COM-28, pp. 711-719, May 1980.

Describes problems with old ARPANET routing algorithm and a new algorithm which has been used since May 1979. In the new algorithm each node maintains a data base describing the complete network topology and the delays on all links. This data is used to calculate minimum delay paths to every other node (using a Shortest Path First algorithm) and generate new routing tables whenever the data base changes significantly. Line and CPU overhead are less than two percent with this new algorithm. Also see McQuillan et al., (April 1978, October 1978) and Rosen et al., (April 1979).

[64] P. M. Merlin and A. Segall, "A Failsafe Distributed Routing Protocol," IEEE Trans. Comm., COM-27, pp. 1280-1287, September 1979.

New improved algorithm also described in Segall (1979b) includes recovery from arbitrary topological changes in addition to the minimum delay, distributed computation and loop freedom characteristics of the original algorithm presented in Segall (1979a).

[65] K. S. Natarajan, D. T. Tang and K. Maruyama, "On the Selection of Communication Paths in Computer Networks," in Proc. IEEE Computer Networking Symposium, Gaithersburg, Maryland, pp. 65-71, December 1979.

Discusses problem of choosing paths in a store-and-forward computer network when criterion for evaluating a path is hop count, physical length, reliability, or capacity. Presents efficient algorithms to generate paths when hop count or distance determine performance. Heuristic solutions are also presented which can be used to generate paths when reliability and capacity determine performance.

[66] C. Neblock and V. W. Pooch, "Loop-Free Distributed Adaptive Routing," in Proc. 4th Intl. Conf. on Computer Comm., pp. 395-403, 1978.

Describes methods which can be used to avoid loops when ARPANET type adaptive routing is used. The most general method is for each packet to include a traveling header or trace which lists all visited nodes to prevent a node from being visited twice. A bit mapping variant (each node is allocated one bit in the trace) is described as is the problem of trapping.

[67] J. Puzman and R. Porizek, Communication Control in Computer Networks, (John Wiley and Sons, New York, 1980).

Reviews communication functions (synchronization, addressing, error control, routing, link capacity sharing) and communication protocols. Includes extensive bibliography.

[68] F. J. Ricci, "Routing Concepts for the Future DCS as Related to System Control and Survivability," in Proc. 1974 Intl. Conf. on Comm. (ICC '74), 20B.

Compares various adaptive routing strategies using an event-by-event AUTOVON simulation. Strategies were used to change routing tables after the network was damaged or traffic changed. Updating routing tables preserved, and in some cases, improved GOS.

[69] J. M. Ridd, "An Approach for Network Reconstitution for Command, Control, and Communications," in Proc. 1978 Intl. Conf. on Comm. (ICC '78), pp. 31.2.1-31.2.5, 1978.

Suggests AUTOVON should include monitoring of the status of subsystems and common channel signalling to enhance survivability.

[70] E. C. Rosen, J. Herman, I. Richer, and J. M. McQuillan, "ARPANET Routing Algorithm Improvements - Third Semiannual Technical Report," BBN Report No. 4088, April 1979.

Describes new ARPANET routing algorithm. Includes discussion of the SPF data base and tests of the new routing algorithm. Also see McQuillan et al., (April 1978, October 1978, 1980).

[71] E. C. Rosen, J. Mayersohn, P. J. Sevcik, G. J. Williams, and R. Attar, "ARPANET Routing Algorithm Improvements - Volume I," BBN Report No. 4475, August 1980.

Describes possible improvements to ARPANET routing including logical addressing and the use of multiple paths between nodes. Also describes an SPF routing algorithm and a congestion control scheme which could be used to AUTODIN II. In addition, a network simulator is described and statistical problems involved in simulation are discussed.

[72] R. D. Rosner, "Communications Systems Control for the Defense Communications System," in Proc. 1978 Intl. Conf. on Comm. (ICC '78), pp. 31.1.1-31.1.5, 1978.

Suggests improvements in AUTOVON status monitoring and control.

[73] H. Rudin, "On Routing and 'Delta Routing': A Taxonomy and Performance Comparison of Techniques for Packet-Switched Networks," IEEE Trans. Comm., COM-24, pp. 43-59, January 1976.

Classifies and reviews routing schemes. Also describes "delta routing" wherein routing control is shared between a centralized routing computer and local nodes. A parameter, delta, determines the degree of decentralization. When delta is near zero, only one routing choice specified by the centralized routing computer is allowed. As delta grows larger, routing tends to be based on shortest queues.

[74] H. Rudin and H. Muller, "More on Routing and Flow Control," in Proc. IEEE 1979 Natl. Telecomm. Conf. (NTC '79), pp. 34.5.1-34.5.9, 1979.

Results obtained using a simple analytic model and an event-by-event simulation suggests that dynamic routing should be suppressed at high traffic levels to prevent reduction in overall GOS caused by excessively long routing paths. Results also suggest that flow control and routing algorithms must be evaluated simultaneously because of strong interactions.

[75] G. J. Sauer, J. K. Bishop, M. K. Klukis, "Interactive Computer Simulation for Switched Network Studies," in Proc. 1978 Intl. Conf. on Comm. (ICC '78), pp. 23.4.1-23.4.5, 1978.

Describes event-by-event simulator of European AUTOVON developed at the Martin-Marietta Corporation. Also presents some plots of GOS versus time when network is overloaded or damaged. Also see Klukis *et al.*, (1975).

[76] K. S. Schneider and D. Minoli, "An Algorithm for Computing Average Loss Probability in a Circuit-Switched Communication Network," IEEE Trans. Comm., COM-28, pp. 27-33, January 1980.

Describes an algorithm which can be used to compute GOS in a circuit-switched network where spill-forward or originating office control routing is used. Simulations demonstrate that the algorithm provides an upper bound on the average GOS (sometimes a factor of two too high). The algorithms described in Fischer *et al.*, (1978) and Katz (1967) are much more accurate.

[77] M. J. Schwartz, *Computer-Communication Network Design and Analysis*, (Prentice-Hall, New Jersey, 1977).

Contains a discussion and overview of packet-switched computer networks. Includes description of existing networks and discussion of routing and flow control, capacity assignment and queueing theory.

[78] M. Schwartz and T. E. Stern, "Routing Techniques Used in Computer Communication Networks," IEEE Trans. Comm., COM-28, pp. 539-552, April 1980.

Overview of shortest path routing algorithms and of routing in TYMNET, ARPANET, and TRANSPAC.

[79] A. Segall, "Optimal Distributed Routing for Virtual Line-Switched Data Networks," IEEE Trans. Comm., COM-27, pp. 201-209, January 1979a.

Extends algorithm presented in Gallager (1977) to a virtual line-switched store-and-forward network. This new algorithm provides distributed, adaptive, minimum delay, loop-free routing.

[80] A. Segall, "Failsafe Distributed Algorithms for Routing in Communication Networks," in Flow Control in Computer Networks, edited by J. L. Grange and M. Gien, (IFIP, North-Holland Publishing Company, New York, 1979b).

New improved algorithm also described in Merlin and Segall (1979) includes recovery from arbitrary topological changes in addition to the minimum delay, distributed computation, and loop-freedom characteristics of the original algorithm presented in Segall (1979a).

[81] A. Segall, "Advances in Verifiable Failsafe Routing Procedures," IEEE Trans. Comm., COM-27, April 1981.

Describes a distributed procedure for establishing and maintaining loop-free routing tables when topology changes occur in a network. If topology changes stop and traffic flows are stationary, then minimum average delay routing is produced. This newest improved algorithm is simpler and requires less communication and storage than the algorithms presented in Segall (1979a, 1979b) and Merlin and Segall (1979).

[82] C. N. Shearer, "Modified Forward Routing for CONUS/CSN AUTOVON," Defense Communications Engineering Center Technical Report 26-75, September 1975.

Describes a shortest path algorithm which can create routing tables for switches in AUTOVON which use spill-forward routing. This algorithm is fast (CPU time less than 15 seconds for a 60 node network), leads to minimum cost routing, provides as many alternate routes as required, and allows specific switches to appear arbitrarily unattractive to tandem traffic. The monthly cost of networks which use tables generated by this algorithm is less than the cost of networks which use current POLYGRID routing and the survivability of networks with the new routing tables appears to be not much worse than that of existing networks. Suggests real-time routing table updating to maintain survivability in damaged networks.

[83] T. M. Shimabukuro, "The Next Generation CONUS AUTOVON," IEEE Trans. Comm., COM-28, pp. 1460-1466, September 1980.

Review of alternate methods of updating AUTOVON which use digital switching and small satellite earth terminals to evolve AUTOVON into the Defense Switched Network. Summary and extension of Deardorff et al., (1978).

[84] I. M. Soi and K. K. Aggarwal, "A Review of Computer-Communication Network Classification Schemes," IEEE Communications Magazine, pp. 24-32, March 1981.

Overview of terminology and classification schemes for computer networks.

[85] W. D. Tajibnapis, "A Correctness Proof of a Topology Information Maintenance Protocol for a Distributed Computer Network," Communications Assoc. Comput. Mach., 20, pp. 477-485, July 1977.

Describes a protocol which nodes in the MERIT computer network use to exchange information necessary to update routing tables when links or nodes fail or are added. This information allows each node to update distance tables (distance from a node to other nodes via each outgoing link) from which routing tables are formed.

[86] L. Thymes, "Routing and Flow Control in TYMNET," IEEE Trans. Comm., COM-29, pp. 392-398, April 1981.

Reviews the history of TYMNET and describes current TYMNET routing and congestion control procedures. The TYMNET network currently includes almost 1,000 nodes and also is attached to gateways to other networks. Virtual circuits are established by a central network supervisor whenever a new user logs on. The supervisor assigns a cost to each link which is based on link bandwidth, link load factor, satellite versus land-based lines, terminal type, and other factors. For example, for an interactive user, a 9600 bit/s low delay land link would be assigned a lower cost than a 56,000 bit/s high delay satellite link. The satellite would, however, have a lower cost if files were being passed between computers. A shortest path algorithm is used by the supervisor to route paths of virtual circuits. In the newer TYMNET II, network nodes have more intelligence, data traffic to and from the central supervisor is minimized, and simple but effective flow control procedures are used. The interested reader can find out what the phrase "note that a needle followed by some data followed by a nongobbling zapper is similar to a datagram" means. See also Schwartz (1977, Chapter 2) and Schwartz and Stern (1980).

[87] J. H. Weber, "Some Traffic Characteristics of Communications Networks with Automatic Alternate Routing," BSJT, 41, pp. 769-796, March 1962.

Describes event-by-event simulation studies of small networks with from three to six nodes. Hierarchical networks (as used in the Bell System) which included both high usage links and final links and also symmetrical networks (such as AUTOVON) with only high usage links were simulated. At low traffic densities, symmetrical routing was superior to hierarchical routing, while at higher traffic densities, the two types of routing were equivalent.

[88] J. H. Weber, "A Simulation Study of Routing and Control in Communications Networks," BSTJ, 43, pp. 2639-2676, November 1964.

Describes event-by-event simulation studies of a 34 node, west coast telephone network with relatively low connectivity. Various routing schemes were examined using this network including successive office control with and without crankback, hierarchical routing (as used in the Bell System), symmetrical routing (used, for example, in AUTOVON), and reservation of trunks for first-routed traffic only. Hierarchical routing and symmetrical routing led to similar network performance. Restriction of alternate routing improved the GOS at all load levels for symmetric networks. Crankback offered only a slight advantage at low traffic levels but was clearly disadvantageous for high traffic levels when used in symmetric networks. Trunk reservation for first-routed traffic improved the performance of almost all networks.

[89] R. I. Wilkinson, "Theories for Toll Traffic Engineering in the U.S.A.," BSTJ, 35, pp. 421-511, March 1956.

Detailed review of toll traffic engineering practice in the United States. Describes hierarchical alternate routing used to allow direct long distance dialing. Also describes the "equivalent random" method for computing the mean and variance of traffic overflowing a link with "rough" offered traffic (variance greater than mean).

[90] T. Yum, "A Semidynamic Deterministic Routing Rule in Computer Communication Networks," in Proc. IEEE 1979 Natl. Telecomm. Conf. (NTC '79), pp. 34.1.1-34.4.7, 1979.

Describes a routing scheme for packet-switched networks in which traffic is bifurcated or routed to different outgoing links using deterministic sequences. The elements of these sequences specify which outgoing links a packet should use. This scheme assumes that routing is determined by a network control center which tries to maximize bifurcation (make usage of outgoing links as equal as possible). It differs from the "best stochastic routing rule" (Fratta et al.) in that bifurcation is maximized and deterministic routing sequences instead of a random process are used to assign a given percentage of traffic to each link. An example of the application of this routing scheme to a small common channel interoffice signalling network is presented.

[91] T. P. Yum, "The Design and Analysis of a Semidynamic Deterministic Routing Rule," IEEE Trans. Comm., COM-27, pp. 498-504, April 1981.

Expansion of Yum (1979) which includes an analysis of semidynamic deterministic routing. This analysis demonstrates that the proposed routing scheme has the best delay performance among the fixed, deterministic schemes which have been proposed in the past.

[92] T. Yum and M. Schwartz, "The Join-Biased-Queue Rule and Its Application to Routing in Computer Communication Networks," IEEE Trans. Comm., COM-29, pp. 505-511, April 1981.

Describes a two-level routing procedure which is similar to delta routing (Rudin, 1976). In this new procedure the "best stochastic routing rule" (Fratta et al., 1973) is used globally to allocate traffic flows. This rule bifurcates traffic at each node using fixed probability assignments which minimize overall average delay in the network. An adaptive "join-biased-queue" rule is used locally to bifurcate traffic and achieve the traffic flows which the best stochastic rule requires. Analyses of small networks indicate that this new procedure produces average delays which are 10 to 27 percent less than those produced when only the best stochastic routing rule is used. Also see Boorstyn and Livne (1981).

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report contains an annotated bibliography of papers which describe routing and design procedures used in circuit and packet switched networks and a topical index to these papers. Papers were selected either because they were judged to provide insight into routing algorithms potentially applicable to the future Defense Switched Network or because they provide background information on routing and network design. These papers contain studies of routing, congestion control, and network design performed using analytic models and event-by-event simulations. They also contain reviews of military networks, and descriptions of routing and design procedures for the current military telephone network (AUTOVON), the Bell System long distance DDD telephone network, and various packet switched networks including ARPANET and TYMNET.

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