MEMORANDUM
RM-3767-PR
AUGUST 1964

ON DISTRIBUTED COMMUNICATIONS:

XI. SUMMARY OVERVIEW

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PREPARED FOR:
UNITED STATES AIR FORCE PROJECT RAND

The RAND Corporation
SANTA MONICA • CALIFORNIA

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PREFACE

This Memorandum is one in a series of eleven RAND Memoranda detailing the Distributed Adaptive Message Block Network, a proposed digital data communications system based on a distributed network concept, as presented in Vol. I in the series.* Various other items in the series deal with specific features of the concept, results of experimental modelings, engineering design considerations, and background and future implications.

The series, entitled _On Distributed Communications_, is a part of The RAND Corporation's continuing program of research under U.S. Air Force Project RAND, and is related to research in the field of command and control and in governmental and military planning and policy making.

The present Memorandum, the eleventh and final volume in the series, summarizes the development of the system proposal. The more salient features of the system, presented in much greater detail in the other Memoranda in the series, are gisted, allowing the casual reader to obtain a general overview of the network. A reading of the introductory Memorandum in the series and the present Memorandum should suffice for a general understanding of the proposed Distributed Adaptive Message Block Network.

Additionally, the advantages and disadvantages of the system are given, which will greatly facilitate critical evaluation of the system's feasibility.

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*A list of all items in the series is found on p. 21.

SUMMARY

Progress in synthesizing the Distributed Adaptive Message Block Network is reviewed in this Memorandum, and conclusions are drawn with respect to its anticipated characteristics. The advantages and disadvantages of the proposed system are listed in a comparison with traditional approaches to communication networks.

An outline of critical key tasks required for further development of these concepts is given.

Summarizing the last few years' work in this field:

1) It appears theoretically possible to build large networks able to withstand heavy damage whether caused by unreliability of components or by enemy attack.

2) Highly reliable and error-free digital communication systems using noisy links and unreliable components can be built without exceeding the present-day state-of-the-art of electronic components--provided we use digital modulation.

3) We are beginning to understand, or at least to appreciate, the cause of time delays and overloading phenomena in communication systems handling competing users with different levels of importance. There is a basis for hope that one day we may be able to automate highly sophisticated priority systems. Such systems may even be so effective as to provide the operational equivalent of exercised judgment.

4) It appears that a proper direction in which to move in attacking the secrecy problem in large military and commercial communication systems, is to design the

cryptographic provisions as an integral part of the digital switching system.

5) Digital communication systems able to serve highly automated sources can be more readily designed from the viewpoint of bit-transportation systems rather than the conventional approach of a tandem connection of real-time links.

6) One day in the future (and we are not foolhardy enough to predict an exact date), for economic reasons alone in the military environment it may be <u>necessary</u> to break away from existing analog signal communication network concepts in favor of all-digital networks.

7) It is appropriate to redesign user input-output instruments, such as telephones and teletypewriters, for the described system in order to gain the full benefit that accrues to an all-digital communications network.

CONTENTS

I. INTRODUCTION

The introductory Memorandum in the series On Distributed Communications described a set of basic concepts, the details of which have been greatly expanded in the intervening Memoranda in the series. The series as a whole is an examination of the feasibility of any digital communications system utilizing "hot-potato routing" and automatic error detection. While preparing the draft of this concluding number, it became evident that a distinct and specific system was being described, which we have now chosen to call the "Distributed Adaptive Message Block Network," in order to distinguish it from the growing set of other distributed networks and systems, as described in ODC-V.*

THE GOAL

An ideal electrical communications system can be defined as one that permits any person or machine to reliably and instantaneously communicate with any combination of other people or machines, anywhere, anytime, and at zero cost.

It should effectively allow the illusion that those in communication with one another are all within the same soundproofed room--and that the door is locked.

Almost by definition, all electrical communications systems will fall short of meeting these goals, the

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*ODC is an abbreviation of the series title, On Distributed Communications; the number following refers to the particular volume within the series. A list of all items in the series is found on p. 21.

shortcomings we are content to live with being determined on the basis of intended application and price. Present-day networks are designed to do one particular set of tasks well. In the future, we shall make even greater demands upon our networks and shall consider new ways of building communications networks taking advantage of the newly emerging computer-based technology.

SYNTHESIS

Let us consider one way we might go about building a new system to meet the requirements of the future. We shall attempt to start from scratch and ignore the traditional approach of existing communications systems. We shall first focus upon those requirements--particularly military--not being fully satisfied by today's systems.

For example, in their outstanding study of Army communications, Bloom, Mayfield, and Williams, of the Franklin Institute,[*] conducted a survey among Army Officers on shortcomings of present-day Army communications. Their findings are shown in Fig. 1.

We have used the Bloom, Mayfield, and Williams data as a check list against which the distributed network has been evaluated. The separate mechanisms included within the distributed system to match these "problems" are presented in Table I.

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[*] Bloom, Joel N., Clifton E. Mayfield, and Richard M. Williams, People, Organizations, and Communications, Final Report, F-A2312. Prepared for Army Communications Systems Division by the Franklin Institute Laboratories for Research and Development, Philadelphia, January 1962.

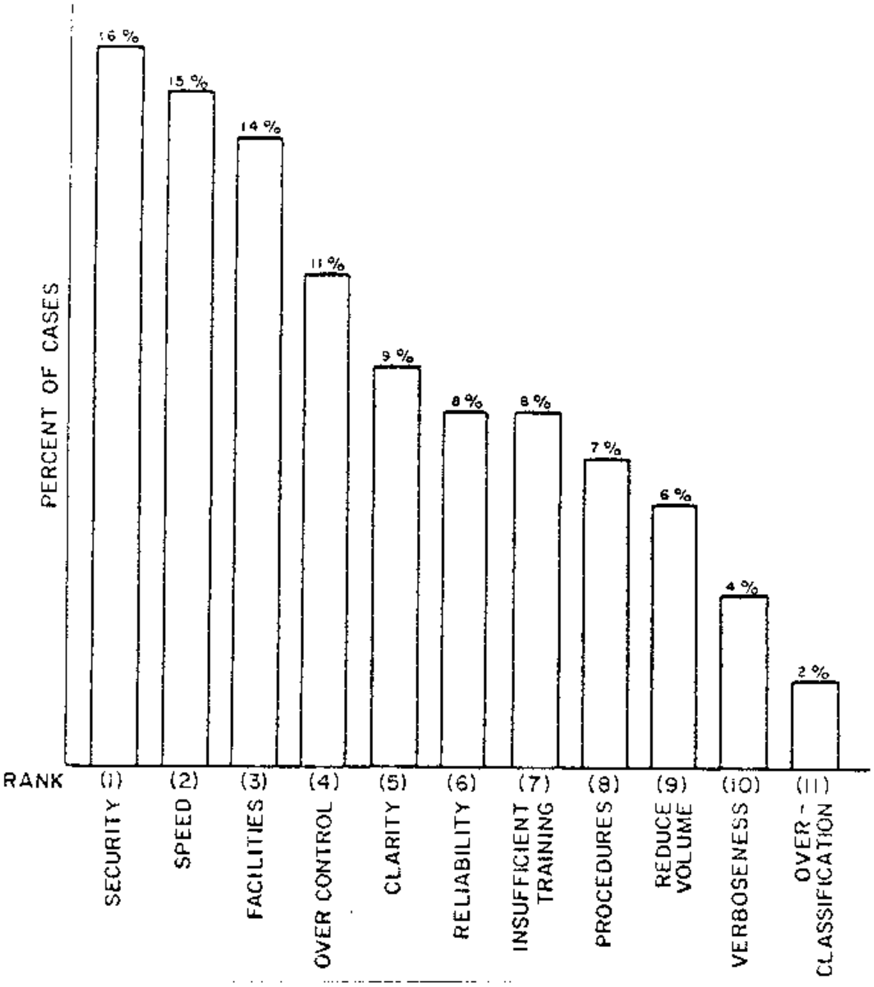

Fig. 1--Principal Problems in Army Communications*

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*From: Bloom, et al., ibid, p. 30.

Table I

THE DISTRIBUTED SYSTEM'S HANDLING OF PRINCIPAL MILITARY COMMUNICATIONS PROBLEMS

	Problem*	Number of Cases, %*	Possible Solutions Included in Distributed Network
1	Security	16	Built-in cryptographic protection services as an integral part of the system. All traffic is treated on a cryptographically secure base.
2	Speed	15	Design for a maximum of two seconds initial connection time. Permit quasi-real-time operation--even for store-and-forward traffic.
3	Facilities	14	Design for "area availability." Many tie-in points; many stations.
4	Over Control (Administrative Censorship)	11	User-to-user rather than emphasis on center-to-center operation.
5	Clarity	9	Error-free end-to-end "quasi-circuits." (Clarity may not be a technical problem.)
6	Reliability	8	Spatially organized parallel redundancy to buy high reliability using lesser-reliability subsystems.
7	Insufficient Training	8	Capability for unmanned operation; automatic fault location.
8	Procedures	7	Reduced cost of long-haul communications bandwidth. Allows cryptographic conference calls.
9	Reduce Volume	6	Automatic priority control, responsive to changing loads and demands.
10	Verboseness	4	Fast feedback to user to establish context. (Verboseness may not be a technical problem.)
11	Over-classification	2	Allow wider access to user-to-user cryptographic "circuits." All network traffic is treated as if it were highly classified.

*From Bloom, Mayfield, and Williams, *ibid*.

This list wasn't available at the time the system synthesis was initiated, and we chose a somewhat different, but similar, set of criteria. (Survivability was placed at the top of our list.)

The aim was towards an "ideal" electrical communication system. But a real-life system is a collection of compromises, and this system is no exception. The author believes, though, that it represents an acceptable price to have to pay for a national communications system able to meet the extreme demands of survivability in the face of a determined enemy. Some of the system's disadvantages and advantages are summarized in the next sections, together with references to the volumes in the series in which the particular topic is detailed.

II. DISADVANTAGES OF THE DISTRIBUTED ADAPTIVE MESSAGE BLOCK NETWORK

1. The system concept is difficult to explain and to comprehend. (ODC-I, -III, -VII, -VIII)

2. There is an almost fixed 0.5-sec time delay in voice transmission. (ODC-III, -VIII)

3. A small distributed network is a meaningless entity--only large networks are capable of emulating the system's desired properties. (ODC-I, -II)

4. No one has ever built or even fully designed all the hardware components required. (ODC-VII, -VIII)

5. It is an expensive system to simulate. (ODC-II, -III, -VIII)

6. The concept is especially sensitive to poor system design. A brute-force, massive-organization approach can easily end up with an expensive, fractional-GNP-priced kluge. (ODC-VII, -VIII, -X)

7. An understanding of digital computer design is mandatory to adequately evaluate feasibility. (ODC-VII, -VIII)

8. The cryptographic features have not yet been reviewed by those well-versed in the secrecy business and responsible for determining the acceptability of the proposed generalized secrecy arrangements. The analyses made on secrecy have been limited to information found in the open literature (plus a little common sense). (ODC-IX)

9. Analog-to-digital conversion is required. (While such transformation is apparently necessary in conventional cryptography, its present cost is high.)

10. The distributed system, at this time, is designed primarily for communications among large key military installations wherein it is possible to maintain secure areas for cryptographic material adjacent to the Multiplexing Stations. A later logical step in the development of the overall approach is to extend cryptographic protection to remote telephones, a facility not included in the present design. (Some preliminary work has been started on this problem.)

11. Another possible difficulty is that our present voice telephone plant usually provides excellent service for peacetime civilian communications, and the need for special communications capabilities for the military has not always been widely appreciated. Many tend to evaluate potential performance under combat conditions from the standards of their own civilian voice telephone experience. This is not the best measure for realistically determining the suitability of a military communications system.

III. SOME POSITIVE ATTRIBUTES OF THE DISTRIBUTED ADAPTIVE MESSAGE BLOCK NETWORK

1. The system uses automatic learning to obtain "perfect switching"* in its fully-distributed network configuration. Thus, it is less vulnerable to enemy attack than conventional networks. (ODC-I, -II, -III)

2. The system has been designed completely from scratch to meet future requirements of military security, physical survivability, digital data flexibility, and ease of adding new services. (ODC-I, -IV, -V, -VIII, -IX)

3. The system handles start-stop teletype, as well as standard "high-speed" binary-stream synchronous data rates of 600, 2400, 4800, 9600, and 19,800 bits/sec. It could easily be adapted to handle very-high-speed data, if required. (ODC-VIII)

4. Each of the up to 1024 Multiplexing Stations simultaneously handles some 128 cryptographically-secure telephone subscribers, together with 866 other simultaneous subscribers using other data input devices. (ODC-VIII, -IX)

5. Automatic user-to-user cryptography is integrated into the network switching apparatus to eliminate the need for slow, manual cryptographic synchronization. (ODC-VII, -VIII, -IX)

6. User-to-user information flows through the network only during <u>actual</u> transmission of information. For example, after a "pseudo-circuit" is established, blank spots lasting longer than 1/20 sec in speech modes are

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*See ODC-IV, p. 12.

not transmitted. Thus, high-quality speech need only load the transmission plant to an average equivalent data rate of about 5000 bits/sec. (ODC-VIII)

7. The system is readily amenable to the use of satellites as links. (ODC-VII)

8. The system is able to withstand heavy network damage without interruption of on-going, end-to-end traffic. (ODC-I, -II, -III, -IX)

9. From the user's viewpoint, the system appears to be virtually noise- and error-free when handling data. (ODC-VIII, -IX)

10. No cumulative distortion occurs on voice circuits (whether 1 mi or 10,000 mi long) other than a fixed initial quantization noise. (ODC-III, -VIII, -IX)

11. Undetected digital errors are expected to be extremely rare. (ODC-III, -VIII, -IX)

12. The network is designed to handle a broad mixture of input/output devices. (ODC-III, -VIII, -IX)

13. Automatic error detection and repeat transmission is built into the system on a link-by-link basis, simplifying the design of highly automated, low-cost digital input devices. (ODC-I, -VII)

14. Multi-level cryptography and automatic error-tracking procedures make the system far more immune to sophisticated sabotage than any other known communications system. (ODC-VII, -VIII, -IX)

15. Instantaneous, multi-station, cryptographically-secure conference calls can be set up even after the conversation is underway. (ODC-VIII)

16. The potentially high degree of security protection provided permits a mixing of classified and unclassified traffic, both military and civilian, over the same facilities. (ODC-VII, -VIII, -IX)

17. As Message Blocks usually travel by different routes, it appears impossible for an eavesdropper to decrypt traffic unless all preceding Message Blocks are received. (ODC-II, -III, -VIII, -IX)

18. The system appears to be highly resistant to overload--even when subjected to heavy damage. (ODC-V)

19. The overall system reliability offers hopes of being far better than today's systems; and, it can be built of elements of lower-reliability than presently used. (ODC-I, -III, -VII, -X)

20. The system uses regenerative (saturated) amplification to circumvent the effects of cumulative distortion, thereby permitting the use of inexpensive, high-data-rate links. (ODC-VIII, -X)

21. The system uses the "mini-cost" microwave to build new high-data-rate links at very low cost; 4.5-megabit/sec rates appear feasible at a link cost a decimal order of magnitude lower than in conventional systems. (ODC-VI)

22. Cost, even on a per-subscriber basis, appears roughly comparable to that of present-day conventional networks. (ODC-VIII, -X)

23. Signaling symbols are transmitted as repetitive binary patterns at the same bit rate as the data information, permitting additional signaling, if desired, while the receiver is "off-hook." This feature can be used to

simplify future automatic computer-to-computer conversation. (ODC-VIII)

24. Automatic error detection and analysis is easily implemented by virtue of the all-digital nature of the equipment, facilitating the locating of possible sources of trouble. (ODC-VII, -IX)

25. This system has the security, speed, and low-error characteristics to make it useful as a signaling network to set circuit switches for possible extremely-high-data-rate circuit-switched systems in the far future.

26. The system allows ready implementation of sophisticated automatic priority, precedence, and overload controls. (ODC-IV)

IV. SUGGESTED DEVELOPMENT

To this point we have spoken primarily of a system concept. In order to evolve a hardware system, more study and prototype development is indicated. Only after this series has been carefully scrutinized and only after we have ironed out possible flaws in the concept, should such further development be considered.

Such a development program might include the following items. These items are merely "guesstimates" based on the writer's judgment of what work must be done.

Study and Research Phase	Cost ($ in millions)
1. Investigate new problems that may be encountered in a bit-transportation communications system.	.25
2. Perform a traffic analysis for this future system and recommend a detailed system growth plan.	1.00
3. Study the precise degree of secrecy required in future systems.	.50
4. Amplify the detailed description of the mechanisms used for automating precedence.	.50
5. Simulate entire system operation in maximum depth with emphasis on reliability.	2.00
6. Investigate some of the better analog-to-digital modulation schemes, such as High Information Delta Modulation, applicable to this system.	.25
7. Perform cost-comparison studies	.50
Total	5.00

Design Phase	Cost ($ in millions)
1. Design a low-cost all-digital telephone with push-button signaling.	.20
2. Design the Switching Node in full detail.	1.50
3. Design the Multiplexing Station in full detail.	3.00
4. Design the "Mini-Cost" microwave in full detail.	.20
5. Design of low-cost high-data-rate plowed cable line in full detail.	.20
6. Design low-cost graphic and text input/output devices suitable for user-to-user service in this system.	1.50
Total	6.60

Hardware Test Phase	
1. Build and test mini-cost microwave.	.25
2. Build and test low-cost plowed cable line.	.20
3. Build and test critical assemblies proposed for the Switching Node.	.50
4. Build and test critical assemblies proposed for the Multiplexing Station.	.75
5. Build and test low-cost text handling devices.	2.00
6. Build and test teletype and voice High Information Delta Modulation data modems.	.40
Total	4.10

Development Phase	Cost ($ in millions)
1. Build and test three Switching Nodes.	2.00
2. Build and test three Multiplexing Stations.	4.00
Total	6.00

Final Test Phase	
1. Evaluate performance of test units before proceeding.	2.00
Total	2.00

The expenditure milestone points that can be earmarked for system evaluation would occur at about the $1.25-million level (during the Study and Research Phase), after the $5-million point (at the conclusion of the entire Study and Research Phase), at the $11.6-million level (at the end of the Design Phase), at the $15.7-million mark (at the end of the Test Phase), at the $21.7-million level (at the end of the Development Phase), and at the $23.7-million point (at the end of the Final Test Phase). Thus, there are many early opportunities to re-evaluate and redirect this program upon discovery of unforeseen difficulties or better alternative approaches.

V. NEXT-GENERATION RESEARCH

Even though the system has yet to be studied in actual implementation detail, it is felt appropriate to start thinking about further development of the system notion. Consideration today of a next-generation system will simplify orderly system evolution tomorrow.

New areas for research, for example, might include the investigation of the feasibility of using links in the 15- to 150-megabit/sec range. Or, we might study the possibility of forming links of low-cost infrared lasers.

Very-low-cost microwave is also a possible avenue to reduce the feeder network cost.

The technology upon which the system is based is developing at an explosive rate. For instance, our design examination of the Switching Node (ODC-VII) indicated a physical size of about 72 cu ft, using late-1962 digital computer technology. Autonetics Division of North American Aviation, Inc., however, has announced a new microminiaturized computer (see Table II) in late stages of development. This unit appears to have a computing capacity almost as great as that we have proposed in 72 cu ft, but in a package of about 0.3 cu ft--and, at a comparable cost.

The implication of what the changing computer technology offers the communications designer has not always been fully appreciated in the past. Therefore, we should strive to become better prepared to take advantage of this developing technology by continuing the research

Table II

COMPARISON OF THE MONICA-C COMPUTER
WITH THAT PROPOSED FOR THE SWITCHING NODES

	Monica-C[a]	Proposed Switching Node
Words, core storage	8192	4000
Word length, bits	30	32
Memory cycle (μsec): Main memory Scratch pad (256 words)	 6 1	 1 -
Clock rate (mc)	1.0	1.5
MTBF[b] (hr)	19,500	720
Size (cu ft)	0.3	72
Power (kw)	0.19	5
Temperature (°C)	65	40
Cost (in production quantities)	<$100,000 (?)	~$100,000 to $150,000

[a] North American Aviation, Inc., Autonetics Division.
[b] Mean-Time Between Failures.

effort, even while building the hardware.

In retrospect, the designs described in ODC-VII and -VIII are now somewhat out of date, in light of the microminiature developments of the past year.

VI. CONCLUSIONS

A new system has been described offering much promise in solving many military communications problems. It is, however, a difficult system to understand and further research is necessary in order to achieve sufficient confidence in the notion to permit investment of large sums for its construction. Some paths leading to further examinations of these concepts have been described. The amount of work and its nature is such that it is beyond the scope of work appropriate to RAND.

Thus, the majority of the future work will have to come from other organizations and agencies. Now the hard work must begin.

POSTSCRIPT--A POSSIBLE PITFALL

There is the human tendency for those who would suggest new systems to overstate the value of their projects and to understate the problems.

The writer believes that he has called attention to the individual technical problems as they have arisen within each of the Memoranda describing the system. However, there are still a few problems that are not so specifically elucidated.

These are not technical problems in the usual sense, but will probably be the key problems which will set the upper bound upon the speed of development of the proposed system. They include: the limited diffusion of technical competence in the computer/communications art; a very human fear of "complicated" systems; the right of free access between existing communications networks; etc.

We would like to discuss briefly one of these key problems. In this series we have proposed a radically different communications system--one that started with a difficult military goal and has been shown to require complex equipment to satisfy a large set of military "needs."

We have discussed a new large communication system, one markedly different from the present in both concept and in equipment, and one which will mean a merging of two different technologies: computers and communications. People with competence in both these fields are not numerous. Our concern is whether we will have enough well-trained people capable of understanding both the communications ~~and digital computer techniques to make~~

this venture a success. Here may lie the real question of feasibility. Our present-day components are fully adequate. The difficult problems lie in hooking them together.

This is not to say that there will be a dearth of organizations happy to bid on providing such a system on a cost-plus-fixed-fee basis. There may even be some foolhardy enough to have a go at a fixed cost (banking on the returns from the inevitable engineering changes to bail them out). The skills that we need are exactly those which are most heavily advertised in the help-wanted pages of our newspapers and magazines. Thus, where we can go and what we can do may be substantially limited by the breadth and extent of our computer technology manpower base.

Historically, we upgrade the level of responsibility of each of the engineers on a "Big-L" military electronics project--or fracture the project into enough small pieces, in hopes that sheer numbers of warm bodies alone will make up for an acknowledged lack of technical foundations.

But, in the development of a system of this type, numbers alone will not substitute for competence.

ON DISTRIBUTED COMMUNICATIONS:

List of Publications in the Series

I. Introduction to Distributed Communications Networks, Paul Baran, RM-3420-PR.

Introduces the system concept and outlines the requirements for and design considerations of the distributed digital data communications network. Considers especially the use of redundancy as a means of withstanding heavy enemy attacks. A general understanding of the proposal may be obtained by reading this volume and Vol. XI.

II. Digital Simulation of Hot-Potato Routing in a Broadband Distributed Communications Network, Sharla P. Boehm and Paul Baran, RM-3103-PR.

Describes a computer simulation of the message routing scheme proposed. The basic routing doctrine permitted a network to suffer a large number of breaks, then reconstitute itself by rapidly relearning to make best use of the surviving links.

III. Determination of Path-Lengths in a Distributed Network, J. W. Smith, RM-3578-PR.

Continues model simulation reported in Vol. II. The program was rewritten in a more powerful computer language allowing examination of larger networks. Modification of the routing doctrine by intermittently reducing the input data rate of local traffic reduced to a low level the number of message blocks taking excessively long paths. The level was so low that a deterministic equation was required in lieu of Monte Carlo to examine the now rare event of a long message block path. The results of both the simulation and the equation agreed in the area of overlapping validity.

IV. Priority, Precedence, and Overload, Paul Baran, RM-3638-PR.

The creation of dynamic or flexible priority and precedence structures within a communication system handling a mixture of traffic with different data rate, urgency, and importance levels is discussed. The goal chosen is optimum utilization of the communications resource within a seriously degraded and overloaded network.

V. History, Alternative Approaches, and Comparisons, Paul Baran, RM-3097-PR.

A background paper acknowledging the efforts of people in many fields working toward the development of large communications systems where system reliability and survivability are mandatory. A consideration of terminology is designed to acquaint the reader with the diverse, sometimes conflicting, definitions used. The evolution of the distributed network is traced, and a number of earlier hardware proposals are outlined.

VI. Mini-Cost Microwave, Paul Baran, RM-3762-PR.

The technical feasibility of constructing an extremely low-cost, all-digital, X- or K_u-band microwave relay system, operating at a multi-megabit per second data rate, is examined. The use of newly developed varactor multipliers permits the design of a miniature, all-solid-state microwave repeater powered by a thermoelectric converter burning L-P fuel.

VII. Tentative Engineering Specifications and Preliminary Design for a High-Data-Rate Distributed Network Switching Node, Paul Baran, RM-3763-PR.

High-speed, or "hot-potato," store-and-forward message block relaying forms the heart of the proposed information transmission system. The Switching Nodes are the units in which the complex processing takes place. The node is described in sufficient engineering detail to estimate the components required. Timing calculations, together with a projected implementation scheme, provide a strong foundation for the belief that the construction and use of the node is practical.

VIII. The Multiplexing Station, Paul Baran, RM-3764-PR.

A description of the Multiplexing Stations which connect subscribers to the Switching Nodes. The presentation is in engineering detail, demonstrating how the network will simultaneously process traffic from up to 1024 separate users sending a mixture of start-stop teletypewriter, digital voice, and other synchronous signals at various rates.

IX. Security, Secrecy, and Tamper-Free Considerations, Paul Baran, RM-3765-PR.

Considers the security aspects of a system of the type proposed, in which secrecy is of paramount importance. Describes the safeguards to be built into the network, and evaluates the premise that the existence of "spies" within the supposedly secure system must be anticipated. Security provisions are based on the belief that protection is best obtained by raising the "price" of espied information to a level which becomes excessive. The treatment of the subject is itself unclassified.

X. Cost Estimate, Paul Baran, RM-3766-PR.

A detailed cost estimate for the entire proposed system, based on an arbitrary network configuration of 400 Switching Nodes, servicing 100,000 simultaneous users via 200 Multiplexing Stations. Assuming a usable life of ten years, all costs, including operating costs, are estimated at about $60,000,000 per year.

XI. Summary Overview, Paul Baran, RM-3767-PR.

Summarizes the system proposal, highlighting the more important features. Considers the particular advantages of the distributed network, and comments on disadvantages. An outline is given of the manner in which future research aimed at an actual implementation of the network might be conducted. Together with the introductory volume, it provides a general description of the entire system concept.

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