network analysis corporation

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FIFTH SEMIANNUAL TECHNICAL REPORT

August 1975

For the Project

LOCAL, REGIONAL AND LARGE SCALE INTEGRATED NETWORKS

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ARPA Order No. 2286

Contractor: Network Analysis Corporation

Contract No. DAHC15-73-C-0135

Effective Date: 13 October 1972

Expiration Date: 30 April 1976

Sponsored by

Advanced Research Projects Agency

Department of Defense

SUMMARY

Technical Problem

Network Analysis Corporation's contract with the Advanced Research Projects Agency has the following objectives: (1) to study the properties of packet-switched computer communication networks for local, regional and large scale data communications, (2) to develop performance measures and analyses for integrated command, control, and communication networks, (3) to determine the cost/throughput/reliability characteristics of large packet-switched networks for application to Defense Department computer communication requirements, and (4) to apply recent computer advances, such as interactive display devices and distributed computing to the analysis and design of large scale networks.

See #1473 (back - with a paper clip attached)

General Methodology

The approach to the solution of these problems had been the simultaneous:

- Study of fundamental network analysis and design issues.

- Development of efficient algorithms for large scale network analysis and design.

- Development of an interactive distributed display and computational system to deal with large scale problems.

- Application of the new analysis and design tools to study cost and performance tradeoffs for large systems including both terrestrial and satellite links.

Efforts have concentrated on the following areas:

- Packet Radio System Network Studies.

- Packet Radio System Network Algorithms and Controls.

- Local and Regional Data Network Performance and Cost Comparisons.

- Integrated Scale Packet-Switched Network Costs and Performance.

- Support Facility Development.

Technical Results

Major accomplishments achieved during the reporting period include:

- Alternative architectures for local, regional, and large scale integrated networks were defined. Models and measures for throughput, delay, and reliability for the network alternatives were developed. An array of individual network analysis and design programs, which previously operated in stand-alone modes, were integrated in order to perform a family of network architectural design studies.

- A major study of alternative Defense Communication design strategies for data networking was completed. The study encompassed optimization of 35 separate

DOD data communication systems, and integration of these systems using multiplexing, concentration, and packet switching. Overall network designs for AUTODIN II were developed. The use of a fully distributed ARPANET for handling unclassified DOD communications was investigated. Costs for providing high reliability to critical users and end-to-end and link by link encryption for designated secure users were calculated, as were hardware, access and backbone communication line costs for projected 1976 DOD traffic levels.

- A plan for evaluating the applicability of broadcast packet techniques on satellite channels for the Defense Communications System requirements was developed. This forms the basis for ARPA's Atlantic Satellite Tests scheduled to begin in fiscal year 1976 and for the evaluation of the use of packet satellite technology in an integrated command and control communications environment.

- The ARPANET design tools were made available to DCA personnel via the ARPANET. The tools are presently being transferred to DCA computers, and DCA/DCEC personnel are being trained in their use for their AUTODIN II studies.

- A design for testing the performance of the packet radio signaling scheme on an in-house laboratory packet cable system was completed.

- A joint experiment with Project MAC in distributed computing for solving network problems was completed. This experiment involved use of ARPANET, an IBM 360-91, two PDP-10's, and an interactive terminal and was aimed at facilitating the use of batch processing for large network problems while operating in a timesharing mode.

- The interactive Network Editor to serve as a general tool for establishing, editing, and displaying network data bases was completed.

- Packet transportation protocols, initialization procedures, network monitoring, control procedures, routing algorithms, and labeling algorithms were developed for the experimental Packet Radio System. Specifications for station programs and procedures for initialization, connectivity monitoring, and stability control were developed. Station-to-station packet radio unit communications procedures were devised. Definitions of packet types, packet headers, and formats were produced. Procedures for monitoring, control, and measurements were integrated. Enhancements of the simulation system for the packet radio network were incorporated and recent proposals for modification of the hierarchical routing algorithm for the experimental system were implemented within the simulation program and tested.

- The Packet Radio Simulation System was extended to handle multi-station systems. An efficient initialization procedure was developed, installed in the simulator, and the times required for total network initialization under various operating conditions were determined.

This report summarizes major accomplishments during the reporting period as well as tasks in process. The body of the report describes detailed results in the area of Packet Radio. Extensive descriptions of procedures for Packet Radio Network initialization, connectivity monitoring, and stability control are given. These issues are addressed at two levels: (1) procedures proposed for implementation in the Experimental Packet Radio Local Area Demonstration System, and (2) extensions and additions for application in second generation DOD systems.

Department of Defense Implications

The Department of Defense has vital need for highly reliable and economical communications. The results achieved over the reporting period establish that packet switching can be used for massive DOD data communications problems in a cost-effective manner. A major portion of the cost of implementing this technology will occur in providing local access to the networks. Hence, the development of local and regional communication techniques must be given high priority. The results on packet radio demonstrate that this technique can provide rapidly deployable, reliable, and efficient local access networks.

Implications for Further Research

Further research must continue to study the practical issues involved in the integration of DOD networks. Research must include investigation of tradeoffs between terminal and computer density, traffic variations, the effects of improved local access schemes, the use of domestic satellites in broadcast mode for backbone networks, and the effect of link and computer hardware variations in reliability on overall network performance. The potential of these networks to the DOD establishes a high priority for these studies.

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CHAPTER 1

SUMMARY OF ACCOMPLISHMENTS AND TASKS IN PROCESS

1.1 LOCAL, REGIONAL, AND LARGE SCALE PACKET DATA NETWORK PERFORMANCE AND COST COMPARISON

During previous contract years, a variety of tools were developed to allow economical cost/performance tradeoff studies within the local, regional, and large scale packet-switched network environment. The goals of the current year's study have been to evaluate an array of candidates for potential technologies for local, regional and large scale integrated data networks. The goals have been to determine the conditions under which one technology is preferable to another, and to develop a multi-dimensional picture of cost and performance tradeoffs for integrated networks including satellite, ground radio and terrestrial links.

At the initiation of the current contract year, few adequate methodologies were available to predict cost and performance for large networks. However, during the preceding contract year, laboratory hardware and software had reached the stage where a number of significant, never previously attempted investigation could be undertaken. These investigations required the integration of families of computer programs and techniques which previously operated only in stand-alone modes. In addition, methods of comparison for alternative systems had to be developed, and analysis and design models had to be extended in order to perform comparisons of various network alternatives.

Progress during the current contract year has been substantial. All of the previously projected tasks have either been completed or will be completed within this year. In addition, major inputs for the evaluation of DOD networking strategies have been provided, and the transfer of applicable network software to the Defense Communications Agency was initiated. Major accomplishments during the year are summarized as follows:

- Alternative architectures for local, regional and large scale integrated networks were defined. The architectures consist of multiple hierarchical levels, with packet switching and packet satellite technology used for backbone communications, multiplexing, concentration, and polling techniques used for local access. Alternatives for communications carrier selection, topological structure, and backbone switched implementations were derived.

- Models and measures for throughput, delay, and reliability for the network alternatives were developed. The performance models developed allow efficient designs of the global backbone network and for each of the individual local access networks. The techniques derived enable the verification for each subsystem that individual requirements are met at each step of the design process.

- The array of individual network analysis and design programs, which previously operated in a stand-alone mode, were integrated in order to perform the network studies. Major steps in the integration include:

  - Development of an efficient data base structure for the system parameters including host and terminal locations, traffic volumes and characteristics, and backbone switch candidate locations.

- Integration of local access and backbone network design modules to enable the automatic design of the overall network, given the requirements and the backbone node locations.

- Development of an interactive graphic capability for the purpose of displaying network topology and important graphical properties, and enabling manual intervention at any stage in the design process.

• Complete development of a graphical network editor system, including a network file management subsystem, macro input capabilities, a hierarchical tutoring system for novice users, and a non-graphical transportable subsystem which operates with any standard interactive terminal. The system has been used in project for ARPA, DCA, and the Army Material Command (AMC), and portions have been transferred to DCA and the AMC.

• The suitability of alternative network approaches for use in local and regional data distribution were evaluated for the AUTODIN II environment. Alternatives included were dedicated point-to-point lines, multiplexing, and concentration within the local access area. For 35 ADP systems, the following alternatives were addressed:

- Separate systems with hosts and terminals on dedicated lines.

- Separate systems with local line sharing, using concentrators, multiplexers and terminal control units.

- Separate systems with local and regional line sharing using the same array of devices.

- Limited system integration, through intersystem line sharing.

• User requirements including cost, reliability, survivability, security, traffic volume, and delay were explicitly addressed and the comparitive costs of these alternatives under the same set of performance requirements was derived.

• A design for testing the performance of the packet radio signalling scheme on an in-house laboratory packet cable system was completed.

• The ARPANET design tools were made available to DCA personnel via the ARPANET. The tools are presently being transferred to DCA computers, and DCA/DCEC personnel are being trained in their use for ongoing AUTODIN II work.

• An extensive and detailed study of alternative integrated network packet switching approaches for AUTODIN II was completed. The terminal and traffic requirements for 35 ADP systems containing 87 host computers, and 1,103 terminals generating 1.26 megabits/second traffic were examined. Designs for three basic network approaches were developed:

- A fully integrated network with packet switches located at 8 AUTODIN I store-and-forward switch sites.

- A fully integrated network in which switch locations are selected to minimize the overall communication line plus hardware costs without regard to specific security issues at each site.

- Two independent packet-switched networks, one handling only encrypted traffic generated by the 12 systems requiring encryption and the other handling all remaining traffic.

• For each of the above alternatives the cost impact of two different packet switch alternatives was assessed as were the costs of link and end-to-end encryption.

• A model for studying the impact of channel priorities on integrated packet network delay performance was developed. This model allows the evaluation of network delay for different classes of messages under given channel priority structures. The model is currently being applied to the AUTODIN II network example to evaluate the effect of priorities on average delay, throughput, and buffer utilization, and to establish criteria for the selection of efficient priority schemes.

• A program and procedure was developed (jointly with Project MAC) to facilitate the use of distributed computing on ARPANET for large network problems. The procedure was demonstrated via an IBM 360-91, two PDP-10's, and an interactive graphics terminal for a number of large scale network reliability problems. The new procedure provides much faster turnaround time for solving large network problems. It eliminates the need for a user to have explicit knowledge about the status and control language of the 360-91 and automatically handles all communications between the PDP-10 and the 91. If, for example, the 91 is down when the interactive work is being done on the PDP-10, the connections, file transmissions, and job submissions are made automatically when the 91 comes up, and the output is automatically returned to the PDP-10 when the 91 completes the computation. This allows a variety of parallel computations to be going on and increases the efficiency, effectiveness and power of the network design programs.

- A plan for evaluating the applicability of broadcast packet techniques on satellite channels to the Defense Communications System was developed. This plan will form the basis for the Atlantic Satellite tests scheduled to begin in FY-76 and for evaluation of the use of packet satellite technology in an integrated DOD command, control and communications network. The plan addresses the requirements, measures of performance, user profiles and traffic analysis, conduct of the experiment, and technical support activities. Additional efforts required for the satellite tests and associated technical support activities are also identified.

- The impact of satellite technology on large DOD data network integration is currently being studied. A variety of ground station options, including domestic satellite carrier sites, medium and large private satellite station installations, and roof top antennas are being considered. For each alternative cost, bandwidth, and reliability characteristics are being assessed. Alternatives under study include:

  - Integration of terrestrial and satellite links at the backbone level.

  - Backbone network implementations exclusively using satellite links.

  - Satellite access modes (ALOHA, Reservation, etc.).

  - Strategies for the selection of ground station number and location.

  The explicit cost and performance profile using satellite technology will be evaluated for the AUTODIN II example.

1.2 GROUND PACKET RADIO TECHNOLOGY

Network Analysis Corporation (NAC) has been actively involved in the Ground Packet Radio Technology Project since its inception. NAC's contributions have been in the areas of packet radio system architecture, the study of channel configurations, the study of tradeoffs of various hardware design proposals, the development of routing algorithms for reliable and efficient packet transportation, the proposition of communication protocols which take advantage of the properties of broadcast networks, and the development of tools for quantifying network performance.

NAC's efforts during the current contract year have been directed towards the following goals:

1. To determine the effect of various hardware and software design decisions on network performance, to determine a performance profile for the packet radio system, and to calculate effective network operating parameters.

2. To develop, validate, and specify, in detail, network algorithms and protocols for the efficient and reliable operation of the experimental packet radio system.

3. To develop necessary support facilities to carry out various system studies and algorithm development. This includes the development and continued enhancement of a dynamic system simulator which accurately models the essential aspects of system performance including message flow, device logic, and algorithms.

The remainder of this section details specific accomplishments during the current contract period. Goals, needs, and proposed tasks for further activity in the Ground Packet Radio area are discussed in subsequent sections of this chapter.

During the contract year, substantive progress was made towards the project goals. Accomplishments include:

- Defined a complete set of protocols, procedures and algorithms, for implementation in the packet radio experimental system. These included:

  - A virtual link communication protocol between a terminal and a station: This is an intra packet radio, end-to-end protocol with the capability of supporting various degrees of terminal sophistication.

  - Packet transportation protocols: These include a hop-by-hop echo acknowledgment protocol, a search protocol used by the alternate routing algorithm and by terminals for connecting to the packet radio network, channel access protocols, and a single hop packet transmission protocol.

  - Network initialization procedures: This set of procedures is used after network deployment to transform a set of repeaters and stations into a connected initialized network capable of efficient packet transportation. The functions performed by the procedures include: mapping of functional location of devices, mapping the local connectivity of devices, and a procedure for sending initialization information to repeaters.

- Network monitoring and control procedures: These include a procedure for monitoring the operational status of repeaters and terminals in the network, a procedure for monitoring network connectivity and determining when routing information assigned to repeaters should be modified, and a procedure for observing traffic flow and determining when control information should be dispatched.

- Routing algorithms: These include a routing algorithm which does not require a priori information, (for use during network initialization to speed up the initialization process), and a reliable and efficient routing algorithm for packet transportation in an initialized network.

- Labeling algorithms: Two algorithms were proposed: one which determines the set of repeater labels to satisfy predefined requirements for the entire network, and an algorithm which determines labels for a specified subset of repeaters to minimize changes of labels of repeaters not in this subset. The latter is applied during network operation when changes in network topology occur, and is required to minimize the communication time for updating routing information and to prevent the disruption of communications in the part of the network not needing changes.

- Specification of station programs and procedures for initialization, connectivity monitoring and stability control. This task included:

  - Development of data structures and fundamental updating algorithms: The data structures maintain the connectivity of a repeater, its operational state, the set of operational parameters, and the various states related to initialization and performance. The fundamental algorithms presented are those which are most suitable for those operations most frequently performed in maintaining the data structure.

  - Specifications of the functional interface of the station algorithms with the communication protocols at the station.

  - Station programs for initialization and labeling: These include a program which processes the "repeater-on" packet, a program for constructing a "label" packet to a repeater, a program for processing the end-to-end acknowledgment to a label packet, and a program for scanning the active repeaters and determining re-initialization needs.

- Station programs for monitoring device status and network connectivity: These include programs for maintaining status of terminals, the station front-end packet radio unit, and the repeater. The programs erase "old" information related to network connectivity and repeater initialization status, and reconstruct same from "new" information. The programs maintain the status of the data structure related to the reinitialization needs.

- Stability control programs: This task involved the initial proposition of a set of programs to process incoming packets to observe the traffic level and traffic sources in the network, and to determine the operational parameters which must be changed to prevent network overload and traffic instability. Most of the functions which relate observations to controls will be manually operated in the experimental system until further experience is gathered.

• Station-to-packet radio unit communication procedure. The packet radio unit can be a repeater, a terminal front-end, or a station front-end. The task included:

- Basic station-to-packet radio unit protocol, characterized by one outstanding packet between a packet radio unit and a station, and an optional end-to-end acknowledgment from the packet radio unit to the station this protocol assumes that the connections between the communicating devices are always open. It is an asymmetric protocol in which the station originates almost all communications, and the protocol at the packet radio unit is very simple and confined to responding to the station.

- Extended station-to-packet radio unit protocol, characterized by adding to the packet radio unit the functions of end-to-end retransmissions and acknowledgment. The extended protocol in a terminal front-end can serve simple terminals as an intra packet radio end-to-end protocol.

- Functional interfaces of the protocol with the processes it serves and with the lower level communication protocols it uses.

• Definition of packet types for the experimental system. The types defined constitute the minimum set required to perform the communication and control functions; these include: information, end-to-end acknowledgment, repeater-on packet (for control) pick-up packet (for measurements), and load/dump packet (for control, debug and measurements).

- Definition of a packet header format including an ordered list of fields corresponding to various level communication protocols.

- Integration of monitoring control and measurement procedures: This task integrated the procedures and the functions of the processes at the packet radio unit and at the station. The interfaces of the various programs were outlined and the measurement task was incorporated as one of the functions within the package of control programs. Emphasis was placed on the various levels of stability control functions recommended for implementation.

- Routing Algorithm for packet switching broadcast radio networks: For this task, the properties of packet transportation in broadcast radio networks were identified and compared with those of point-to-point networks. Three routing algorithms which take advantage of the properties of broadcast networks were perfected. These are:

  - A broadcast routing algorithm which provides high reliability at the expense of high overhead. Its advantage is that communication nodes need not have any information about network topology.

- A reliable and efficient routing algorithm for broadcast radio networks under the control of stations. The algorithm performs point-to-point packet transportation in the broadcast network.

- A reliable and efficient directed broadcast routing algorithm. The algorithm is suitable for distributed networks, but is not strictly a point-to-point algorithm. It is not suitable for highly mobile network nodes.

• Connectivity monitoring, initialization, and stability control in second generation packet radio networks. The algorithms and procedures for the functions identified for the experimental system, were based upon a pragmatic tradeoff between capabilities of the original packet radio units, ease of implementation and simplicity. Increase in efficiency can be obtained by improved routing labels, reduction of time delay for initialization and for updating the routing information. The areas addressed by this task provided preliminary description of an enhanced family of initialization and control procedures including:

- Network initialization: A faster initialization procedure for mapping global topology and local connectivity was proposed. This was obtained by introducing traffic by the station to stimulate repeater activities. A criterion for optimum labels was proposed, as was an algorithm for optimum relabeling.

- Additional procedures for monitoring status of network devices and connectivity in multi-station networks were devised. In this case, the station was assigned the capability of initiating a procedure to verify changes in connectivity rather than acting as a passive information sink.

- Stability control procedures and initial considerations of load balancing.

• A new reliability procedure, which provides exact solutions for relatively small packet radio networks in much shorter computation time than previous methods was developed. This procedure can be used in an interactive design mode to optimize the number and location of repeaters to meet specified reliability criteria.

Enchancements and extensions of the basic simulation program developed for the Packet Radio Project include:

• Enhancements of code efficiency and reliability. Improvements include addition of self documentation, reduction of running time, addition of new performance measures, and extension of output capabilities.

- A variety of recent proposals for modification in the hierarchical routing algorithms were implemented and tested.

- Zero capture and perfect capture capabilities of receivers were implemented.

- A set of preliminary initialization algorithms and protocols were implemented. Initial time estimates for mapping network connectivity and for sending labels to repeaters, in a single station network, were obtained. The results obtained were instrumental in devising a new family of procedures for implementation in the experimental system.

Tasks currently in progress which will be completed during the present contract year include:

- Communication protocols: This is a systematic derivation of protocols in data communication networks and a detailed outline of the set which constitutes the packet radio protocols. The protocols are being classified into hierarchical levels, with a correspondence between protocol levels, sections of the packet header and programs which process these. The packet radio protocols include:

  - Inter packet radio unit protocols, consisting of the radio communication protocol and the channel access protocol.

- End-to-end protocols between devices in the packet radio network, consisting of the hop transport protocol, the station-packet radio unit protocol, initialization procedures, and network control procedures.

• Preliminary analysis of stability control in the packet radio network. Simple analysis tools are being developed for modeling various levels of stability control. These include:

  - Single hop control parameters.

  - End-to-end protocol evaluation.

  - Evaluation of input rate control.

  - Evaluation of centralized (global) control algorithms.

• Efficient computational techniques for reliability analysis of broadcast radio networks have been developed. Reliability is computed as a function of node (repeater and station) failures. Reliability measures include: Probability that all up repeaters can communicate with the station, the expected fraction of repeater pairs which can communicate through the station, the expected fraction of repeaters which can communicate, probability that each repeater can communicate with the station, and probability that a specified pair of repeaters can communicate. The reliability procedures developed will be used during the remainder of the contract period to derive basic relationships between packet radio connectivity and reliability.

- Comparison of network performance for zero capture and perfect capture receivers. The objective of this study is to determine whether improved capture results in significant improvement in network performance, thus, justifying the development of repeaters with improved reception capabilities.

- Evaluation of network performance as a function of the maximum number of transmissions per hop used by devices. This study is being performed for a single station and moderate connectivity, thus, resulting in a large number of hops. The objective is to determine the maximum number of transmissions, possibly as a function of the number of hops from the station, for practical systems.

- Evaluation of network performance as a function of terminal-to-repeater and repeater-to-repeater data rates. The objective is to quantify the improvement in network performance as a result of an increase in the repeater-to-repeater data rate. This will enable one to determine the proper ratio of data rates, for potential DOD system applications.

- Initial study of network performance as a function of the number of stations. The study is preliminary because station-to-station protocols have not yet been defined. The objective of the study is to determine the increase in network capacity and/or the reduction in delay that results from additi of a station. This should lead to some initial guidelines for determining the required number of stations in a packet radio network design.

- Incorporation of current initialization procedures and algorithms, to be used in the experimental system, into the simulation program.

- Estimation of time delay for network initialization and determination of the values of parameters used for initialization. The traffic rate during initialization will depend on the number and location of repeaters and stations, the connectivity, etc. These factors are currently unknown under general network deployment. The objective of this task is to estimate the interval between the emission of repeater-on packets and the time out for sending labels to repeaters, so as to minimize the network initialization time. The results will be quantified as a function of the number of hops of repeaters from the station.

CHAPTER 2

PACKET RADIO NETWORK: STATION ALGORITHMS FOR INITIALIZATION, CONNECTIVITY MONITORING AND STABILITY CONTROL

2.1 INTRODUCTION

The packet radio system is a broadcast data network aimed at providing local collection and distribution of data over large geographical areas. The system is designed to be economical, reliable, secure, and conservative of spectrum.

The Packet Radio Network (PRNET) includes three logical devices: Packet Radio Terminals (PRT's), Packet Radio Stations (PRS's), and Packet Radio Repeaters (PRR's) (see Figure 2.1).

The Packet Radio Terminal consists of:

1. A device which sends or receives digital data, together with

2. An interface to the rest of the Packet Radio Network.

The basic function of the Packet Radio Repeater is to provide a network for connection of terminals to one or more stations, thereby increasing the size of the area that can be served by a station and providing paths to alternate stations to insure reliable communications.

The Packet Radio Station performs accounting, buffering, directory, traffic stability control and routing functions for the overall system. Furthermore, in the more general case, the PRNET may interface with other higher level networks in which case the station performs the functions related to "gateway control."

The physical implementation of these logical devices is based on the Packet Radio unit (PR) which is an RF transceiver together with a microprocessor, operating system, and appropriate interfacing electronics. In their simplest manifestations, a Packet Radio Terminal is realized as a digital data I/O Device linked to

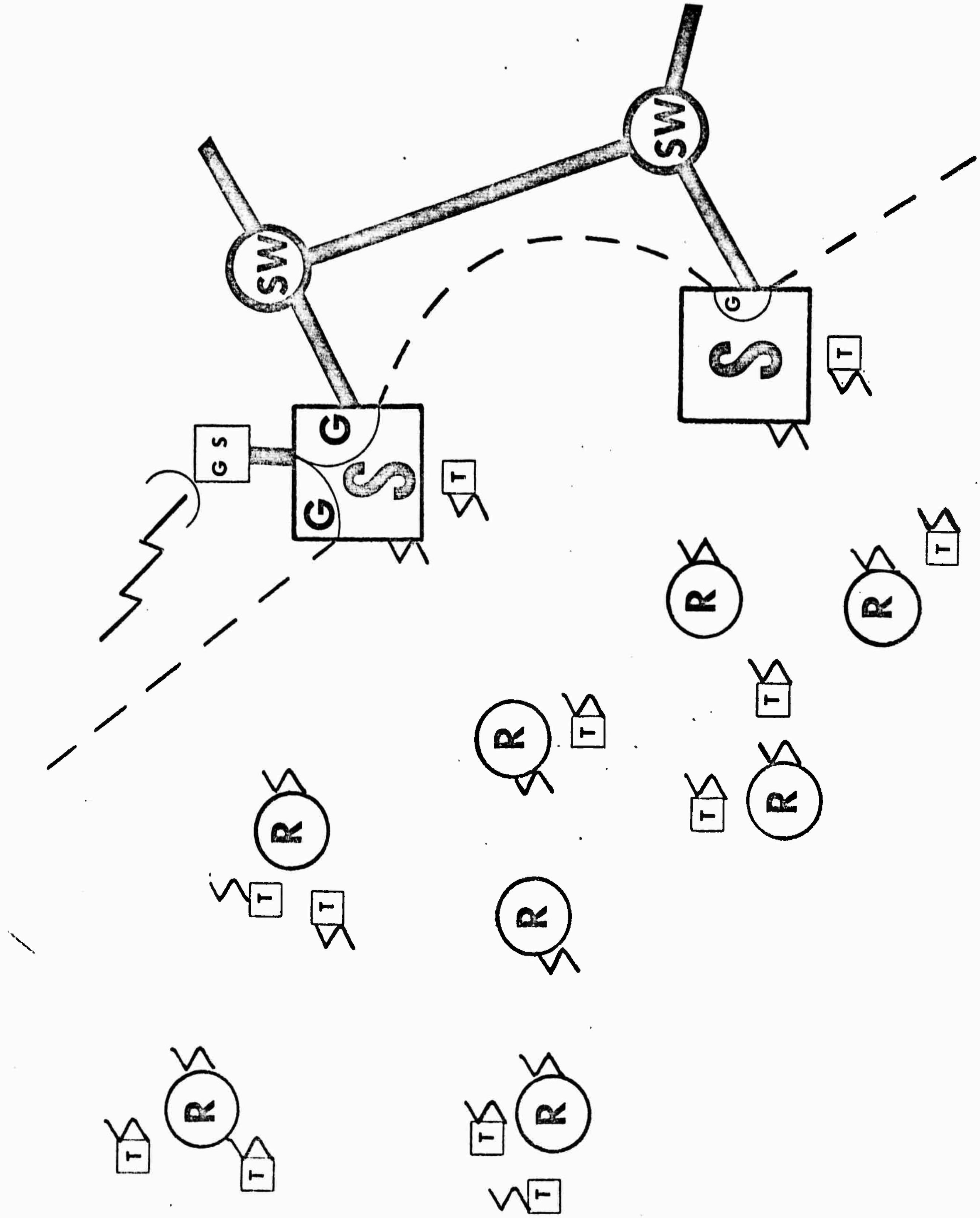

FIGURE 2.1: PACKET RADIO NETWORK

a PR which acts as the interface to the PRNET; The Packet Radio Repeater as a stand-alone PR, and the Packet Radio Station as a minicomputer and a PR acting as the interface to the PRNET. The PR is a versatile and general radio data communication device in that its logical function can be easily changed by reprogramming the microprocessor.

The PRNET is characterized by a Centralized Network Architecture, in which repeaters are provided with the minimum functional capabilities (mainly for relaying packets); whereas the station is given all the extra capabilities needed for reliable communication. In particular, it is assumed that:

1. A repeater does not have any information related to the existance or addresses of other repeaters or stations to which it can transmit packets.

2. Repeaters do not have the capability of updating their operating parameters (e.g. the number of times a packet is transmitted before it is discarded).

3. The station learns the network connectivity and assigns and updates (via control packets) the above parameters.

The algorithms of the station for performing the task in Item 3 are presented in this chapter. Other aspects of PRNET operation, not directly related to these algorithms, such as routing algorithms, communication of regular information packets, acknowledgment schemes, etc., are not discussed in this chapter. These are presumed known, and can be found in [NAC, 1974].

For the purpose of the discussion in this chapter we may consider the software of a packet radio device as being composed of two parts: communication protocols, and destination programs (or processes) of the device. Furthermore, we may assume that the communication protocols are the software means for communication between programs which reside in different communication devices. The emphasis of this chapter is on the outline of the station destination programs needed for the control of proper operation of repeaters and the interface of these programs with the communication protocols at the station.

More specifically, we present the station algorithms and programs for network initialization, monitoring status of devices and network connectivity, and stability control procedures. We also outline a possible way for interfacing these programs with the communication protocols at the station as well as propose a data structure for storing active repeater files in the station. We sometimes refer to this package of programs as Station Algorithms for Monitoring and Stability Control, or SAMSC programs.

We present the algorithm or procedure, definition of the control parameters used by the algorithm and a general flow diagram of the program to implement the algorithm.

The programs are outlined for a single station packet radio network, although not many changes in the programs outlined are anticipated for a multistation network.

Three identifiers are used throughout this chapter in referring to a repeater. A hardwired repeater identification, ID, a hierarchical label for routing purposes, LL, and an Index number, i. The operations performed by the algorithms described use the Index identifier. The other two identifiers are used more in the context of communication protocols, i.e., for finding the Index identifier when a packet is received and for constructing a packet to be sent to a repeater.

The following packet types are communicated between station and repeater programs for the functions defined:

LDP - Load Packet: A load packet addressed to a repeater or a set of repeaters causes code from the text of the packet to be read into the repeaters memory into the specified locations. This packet can be used for changing programs as well as serve control and management functions; such as:

1. On/Off Packet addressed to a repeater causes it to no longer transmit; it still receives, so it can be turned on. Turning it on reverses the process.

2. Choke On/Off Packet, addressed to a repeater causes it to no longer respond to terminal search packets. A choke off causes the repeater to resume responding to terminal search packets.

3. Parameter Packet. A parameter packet addressed to a repeater causes the repeater parameters (maximum handover number, time out values, and maximum number of retransmissions) to be reset according to values placed in the packet.

DMP - Dump Packet: A dump packet causes portions of an addressed repeater memory to be copied into the text of a packet and sent to the originator. The information dumped can be statistics, data or code.

LLP - Label Packet: A label packet is addressed to a specific repeater and assigns to the repeater information for routing purposes.

ROP - Repeater On Packet: Packet is used by a repeater to inform the station that it is "on" and operating. The packet will be used by stations to update, in repeater files, the time that the repeater last communicated.

2.2 DATA STRUCTURES AND FUNDAMENTAL ALGORITHMS

2.2.1 Introduction

Elements of data structure for maintaining network connectivity and status of active repeaters are proposed in this section. We also compare two alternative methods for storing the connectivity information in terms of storage requirements and fundamental operations needed for updating and using the information. The comparison suggests that a Bit Matrix representation of the connectivity information is proper.

An Index obtained from a hardwired ID and/or a Hierarchical Label via the application of a Hash function will be associated with every active repeater. All the information associated with the repeater will be maintained in an array associated with above index, as shown in Figure 2.2.

The sections of the array include the following information:

CONNECTIVITY: Repeaters to which connected.

OPERATION PARAMETERS: Values of parameters used by repeater in communication protocols some of which can be modified by the station. (E.g., maximum number of transmissions, power level indicator.)

LABEL AND ID: Hierarchical Label and related information (e.g., labeled successors), and the hardwired ID.

CONTROL PARAMETERS: Parameters which represent the state of the repeater as seen by the station and used to control the repeater.

The section PR Memory Locations indicates the locations in the PR memory where the various parameters below are stored. This is used for constructing load and dump packets.

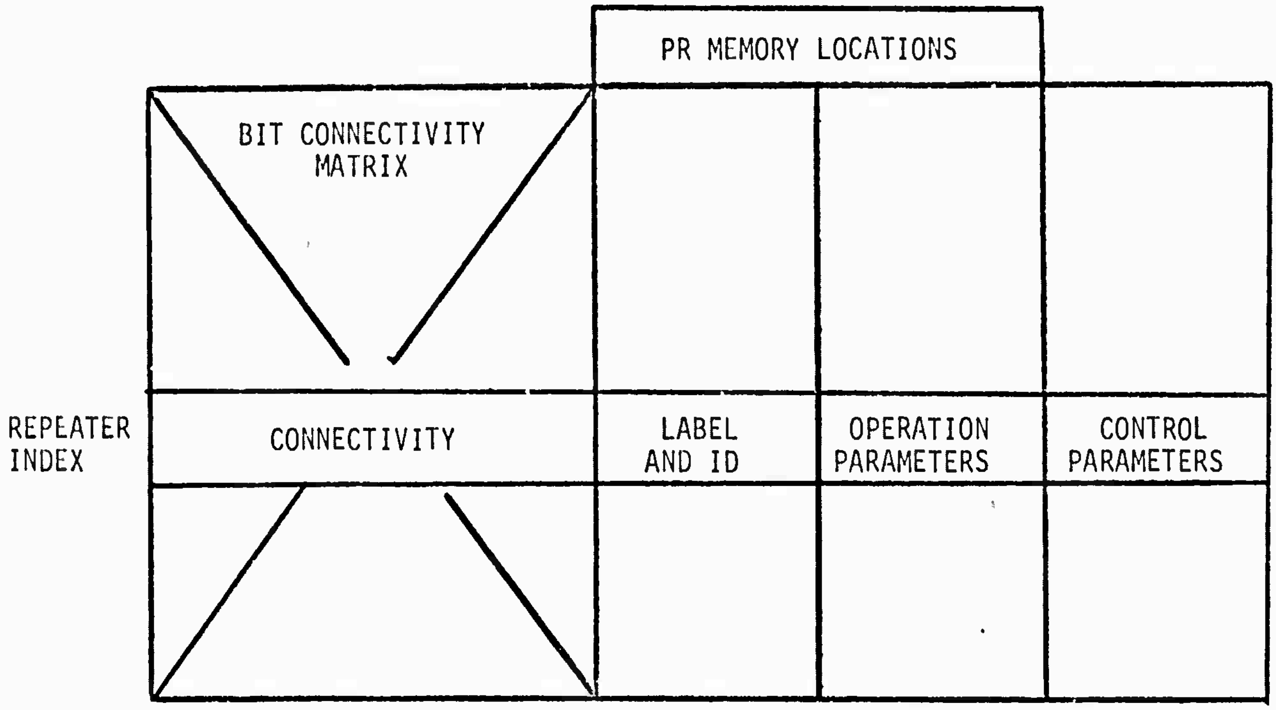

FIGURE 2.2: REPEATER DATA STRUCTURE

2.2.2 Repeater and Station Identifiers

Associated with each repeater are up to three identifiers. The first is the repeater's (hardwired) number which is presumably fixed at manufacture or at least not resetable by the PR system in its normal mode. The second is the (routing) label which identifies the repeater while simultaneously specifying routes for the hierarchial routing algorithm. This label is volatile; it may be changed frequently in response to hardware failure and repair, motion of the repeaters, and variations in broadcast conditions. In various states of initialization and reconfiguration, a repeater may even temporarily be without a routing label. The third identifier is the (internal) index of the repeater which is used in the station to point data associated with the repeater. This also may change from time to time.

The first data structures and algorithms arise from the necessity to rapidly translate from one ID to another. Labels are associated with hardwired numbers by the labeling procedure described in detail in Section 2.4. Labels and hardwired numbers of repeaters should be associated with internal entries of the repeaters by means of hash coding for simplicity and speed. Since repeaters will be arriving and leaving the system rather rapidly and labels changed even more frequently, the hashing scheme should be of the type which easily supports the deletion of elements as well as additions and searches. The type which resolves collisions by simple "chaining" is probably most appropriate [Knuth, 1973]. Thus, if we are dealing with NR repeaters, the hashing provides a rapid means of associating a unique index in the range 0, ..., NR with each number (label) which points to the data associated with the repeater in the station memory. We assume the station PR will always be assigned index = 0.

For the Area Test and for the foreseeable future, there will be few repeaters and the inelegant expediency of doing away with the hashing and using a simple linear search is also possible. However, since hashing will probably be necessary for other purposes, it is probably worth the slight extra work.

2.2.3 Connectivity

In order to perform initialization, labeling, and network monitoring functions, it is necessary to know which repeaters are in "line-of-sight" of each other. Conceptually, if we have repeaters, we can think of a connectivity matrix where the element (i,j) is 1 if the repeater with index i can "hear" the repeater with index j (we will assume for convenience that the matrix is symmetric; that is, if i can hear j, then j can hear i). If, for example, we have 64 repeaters this implies a matrix with 4096 entries. There are two possible data structures to implement this which come to mind:

A. Adjacency List Representation in which associated with each repeater is a list of repeaters it can hear.

B. Bit Matrix Representation in which $\lceil NR/NB \rceil$ words are used (where NB is the number of bits in a word) as a bit string. For each repeater, i, the jth bit, or bit $k = \lfloor j/NB \rfloor * NB$ of word $\lceil j/NB \rceil$ is set to 1 if and only if repeater i can hear repeater j. Where $\lceil x \rceil$ and $\lfloor x \rfloor$ are the least integer greater than x and the greatest integer smaller than x. Thus, for example, if NR = 64, and NB = 16, then if repeater i can hear repeater 24, bit 8 of the second word would be set to 1.

The basic operations to be performed on the connectivity information are:

1. Adding a connection.

2. Deleting a connection.

3. Finding repeaters adjacent to a given repeater.

4. Finding if a connection exists.

5. Deleting all connections involving a given repeater.

We compare the complexity of using the two possible data structures in both storage and execution time for the 5 basic operations.

The following are the relevant parameters including nominal values in parentheses:

NB(16) - Number of bits per word.

MR(64) - Maximum number of repeaters plus station.

ML(256) - Maximum number of links, that is, the maximum number of repeater pairs which are in "line-of-sight" of each other.

A. Storage Requirements

1. Adjacency List Representation

Assuming that pointers to the next repeater adjacent to a given repeater are kept in separate words from the pointer to the data for the repeater we need a maximum of MR + 4 * ML (1088) words.

2. Bit Matrix Representation

For each repeater $\lceil MR/NB \rceil$ (4) words are required, or MR*$\lceil MR/MB \rceil$ (256) words in all.

B. Adding a Connection Repeater i to Repeater j

1. Adjacency List Representation

The computations required are:

a. Find out if connection already exists.

b. Get two elements from free storage (4 words) to add to the lists.

c. Attach repeater i to the list associated with repeater j and attach repeater j to the list of i (remember that we are assuming symmetric connections).

2. Bit Matrix Representation

We assume throughout for the bit matrix representation that there are available NB words U(0),..., U(NB-1) such that U(k) has all its bits 0 except for bit k which is 1. The steps to add a connection are:

a. Find k and ℓ such that
$j = k * NB + \ell$ with $0 \leq \ell < NB$

b. Logically OR the (k+1) st word associated with repeater i with U (ℓ). This sets the bit corresponding to repeater j.

c. Repeat Steps a and b interchanging i and j.

NOTE: We do not have to test to see if the connection is already represented as we had to in Step a for the Adjacency List Representation. However, it may be that one wants to know if the connection is "new" or not for monitoring purposes.

C. Deleting a Connection Between Repeater i and Repeater j

1. Adjacency List Representation

a. Search for repeater j in list associated with repeater i.

b. Delete j and close in list.

1. Add emptied element to free storage.

2. Link element preceding j to element following.

c. Repeat Steps a and b interchanging i and j.

2. Bit Matrix Representation

a. Same as Step a for adding connection.

b. Logically AND the (k+1) st word associated with repeater i to the complement of $U(\ell)$. This resets the bit corresponding to repeater j.

c. Repeat Steps a and b interchanging i and j.

D. Finding Repeaters Adjacent to Repeater i

1. Adjacency List Representation

Run through the list associated with repeater i.

2. Bit Matrix Representation

Do MR logical AND's using the U(k), K = 0, 1, ..., NB - 1 plus a test for nonzero; or alternatively shift MR times and test for overflow. If (2 * ML/MR)/NB is small; that is, most of the bit matrix words are zero, considerable savings can be obtained by testing words (or bytes) for zero before doing the AND's and nonzero tests for the word.

E. Test to See if Repeater i is Adjacent to Repeater j

1. Adjacency List Representation

Search through list of repeaters adjacent to repeater i looking for j.

2. Bit Matrix Representation

a. Determine k and ℓ by
$j = k * NB + \ell$ with $0 \leq \ell < NB$

b. Logically AND U(ℓ) with the (k+1) st word associated with repeater j.

c. Test for 0.

F. Deleting All Links Incident to Repeater i

1. Adjacency List Representation

a. Go through list associated with repeater i.

b. For each j in list delete j, then

c. Go to list for j; search out i and delete.

NOTE: The search in Step c can be eliminated at the cost of extra storage by keeping pointers to the reverse links.

2. Bit Matrix Representation

a. Zero out words associated with repeater i.

b. Determine k and ℓ by $i = k * NB + \ell$ with $0 \leq \ell < NB$.

c. Zero out bit ℓ of the (k+1) st word for each repeater by taking logical AND of the complement of $U(\ell)$ and the (k+1) st word associated with each repeater.

G. Conclusions

Most of the operations are fast and equally so for each of the two data structures. The Adjacency List Representation is much more convenient when trying to find repeaters adjacent to a given repeater, on the other hand, it is easier in the Bit Matrix form to delete all links incident to a repeater. The Bit Matrix Representation takes less storage in the range of interest.

The two most frequently used functions will be adding a connection and deleting all connections to a given repeater (see Sections 2.4 and 2.5). Thus, it seems the Bit Matrix Representation is preferable.

H. Example

Consider an example where MR = 6, NR = 5, and NB = 2. That is, there can be at most 6 repeaters; there are currently 5, and our computer word consists of two bits. The network with its 3 ID's for each repeater and connections indicated is in Figure 2.3.

In Figure 2.4 is shown a possible hashing from the hardwire ID's to the internal indices and for the labels into the internal indices. Many possible hashing functions can be used. The ones chosen, for example, resulted in only one "collision." Namely, hardwire numbers 1002 and 2101 hash into the same number so there is a list associated with hash number 1.

Figure 2.5 shows a bit matrix map for the topology shown in Figure 2.3 assuming a word size of two bits.

Let us now illustrate the operation of adding a connection. Suppose a ROP is received which indicates repeater with hardwire number 1004 can be heard by the repeater with label (1,3,0). h(1004) = 3 which indicates the internal index is 3. h'((1,3,0)) = 3 which indicates the repeater with label (1,3,0) has internal index 1.

Thus, we want to set the bit corresponding to repeater 3 for repeater 1 and set the bit corresponding to repeater 1 for repeater 3.

$$3 = 1 * 2 + 1$$

which implies we take the second word (10) corresponding to repeater 1 and logically OR it with U(1) = (0,1) to obtain (1,1). Similarly, for repeater 3,1 = 0 * 2 + 1 so we OR U(1) with the first word associated with repeater 3 to obtain (1,1). The Resulting Bit Matrix Map is shown in Figure 2.6.

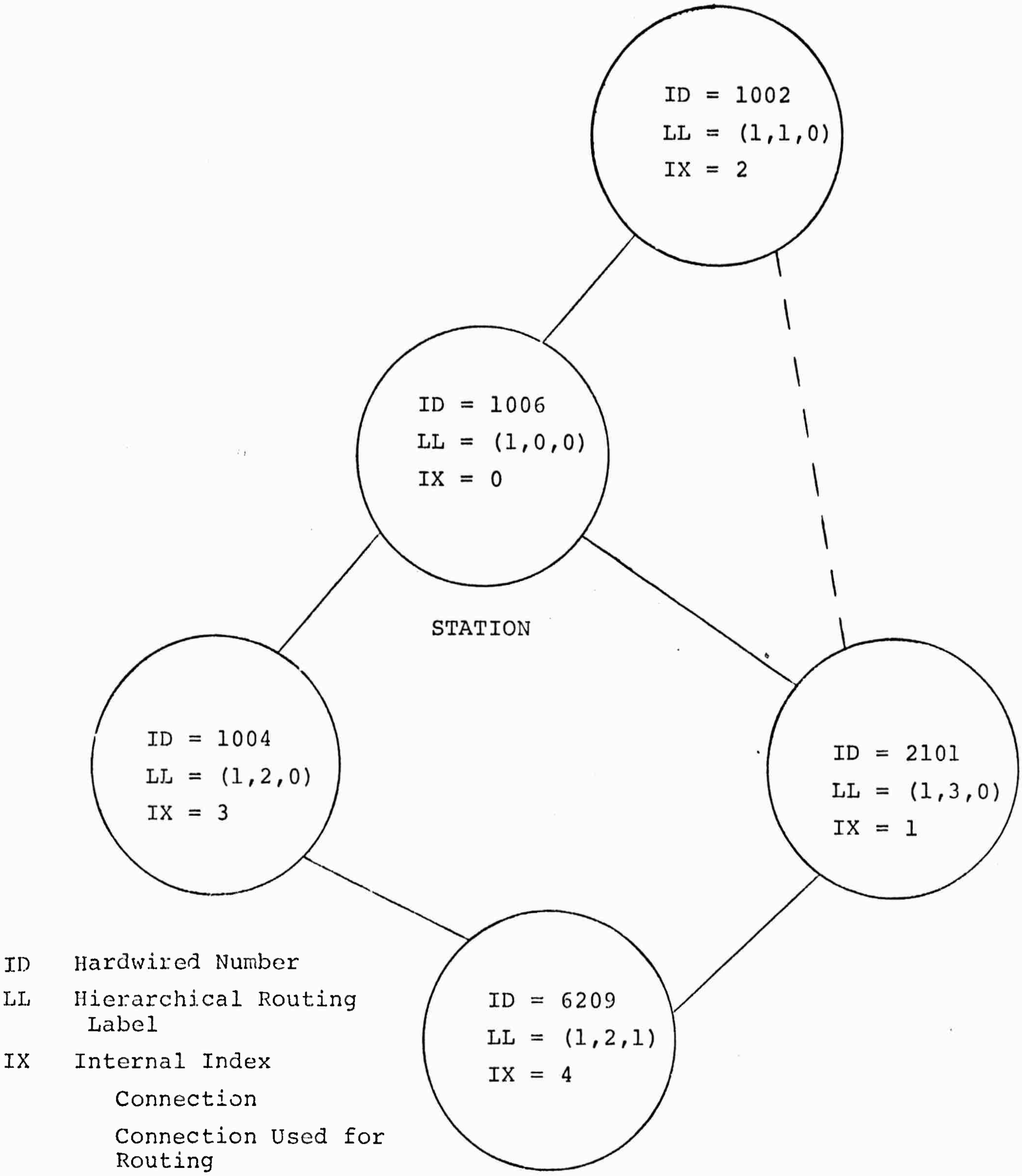

FIGURE 2.3: UPDATE OF ACTIVE REPEATER FILE - AN EXAMPLE

$h\ (ID) \rightarrow hash\ \# \rightarrow IX$

$h\ (ID) = ID \bmod 7$

Hash #	(Hardwire number, internal index)
0	(6209,4)
1	(1002,2), (2101,1)
2	
3	(1004,3)
4	
5	(1006,0)
6	

(a) HASH TABLE FOR HARDWIRE NUMBERS

Hash #	(Label, index)
0	
1	((1,2,0),3)
2	((1,2,1),4)
3	((1,3,0),1)
4	((1,0,0),0)
5	
6	((1,1,0),2)

$$h'(LL) = h'\ (\ell_1,\ell_2,\ell_3) = (\ell_1 * 256 + \ell_2 * 16 + \ell_3) \bmod 7$$

(b) HASH TABLE FOR LABELS

FIGURE 2.4: HASH TABLES

IX \ WORD	1		2		3	
0	0	1	1	1	0	0
1	1	0	1	0	1	0
2	1	1	0	0	0	0
3	1	0	0	0	1	0
4	0	1	0	1	0	0

FIGURE 2.5: BIT MATRIX MAP

IX \ WORD	1		2		3	
0	0	1	1	1	0	0
1	1	0	1	1	1	0
2	1	1	0	0	0	0
3	1	1	0	0	1	0
4	0	1	0	1	0	0

FIGURE 2.6: MAP AFTER LINK ADDED

2.3 INTERFACE OF ALGORITHMS WITH COMMUNICATION PROTOCOLS

The functional interfaces needed between SAMSC programs (or processes) and the communication protocols at the station are discussed. Assuming that a basic Station-PR protocol is characterized by one outstanding packet from a station to a PR and an ete ack from the PR in the form of a "reversed header." The only packet which originates from a PR to a station is the ROP. The presentation assumes a simple form of implementing these interfaces.

Packets which are originated by SAMSC programs or destined for them use the highest level communication protocol available in the station. The interface between the communication protocols and SAMSC programs is shown schematically in Figure 2.7.

When confined to a single station network, a packet which arrives at the station can be either from a PR or from a terminal. If the packet is from a PR, the packet dispatcher at the station will forward the packet to the SAMSC programs in the form of the command RX T(L_R) which indicates that a packet for these programs has been received and is stored in buffer L_R.

When SAMSC programs need to send a packet to a PR, SAMSC programs request a sending buffer Ls, construct the packet in Ls, and send the command Send P(Ls). The communication protocols append to the packet a sequence number, and handle the packet in the same manner as one destined for a terminal. Specifically, the station protocol is responsible for the end-to-end retransmission, whereas the Hop Transport Protocol at the station PR is responsible for the single hop retransmission (same as any other repeater). Let MNTE and MNTH be the maximum number of end-to-end (ete) and single hop transmissions, respectively. The station protocol will forward a packet to its PR and time out for awaiting an end-to-end ack; if one is not received within the time out period, the same packet is forwarded again to the station PR, up to MNTE times. If an ete ack from a PR is not received after forwarding the packet MNTE times, the communication protocols send the command NAK P(Ls)

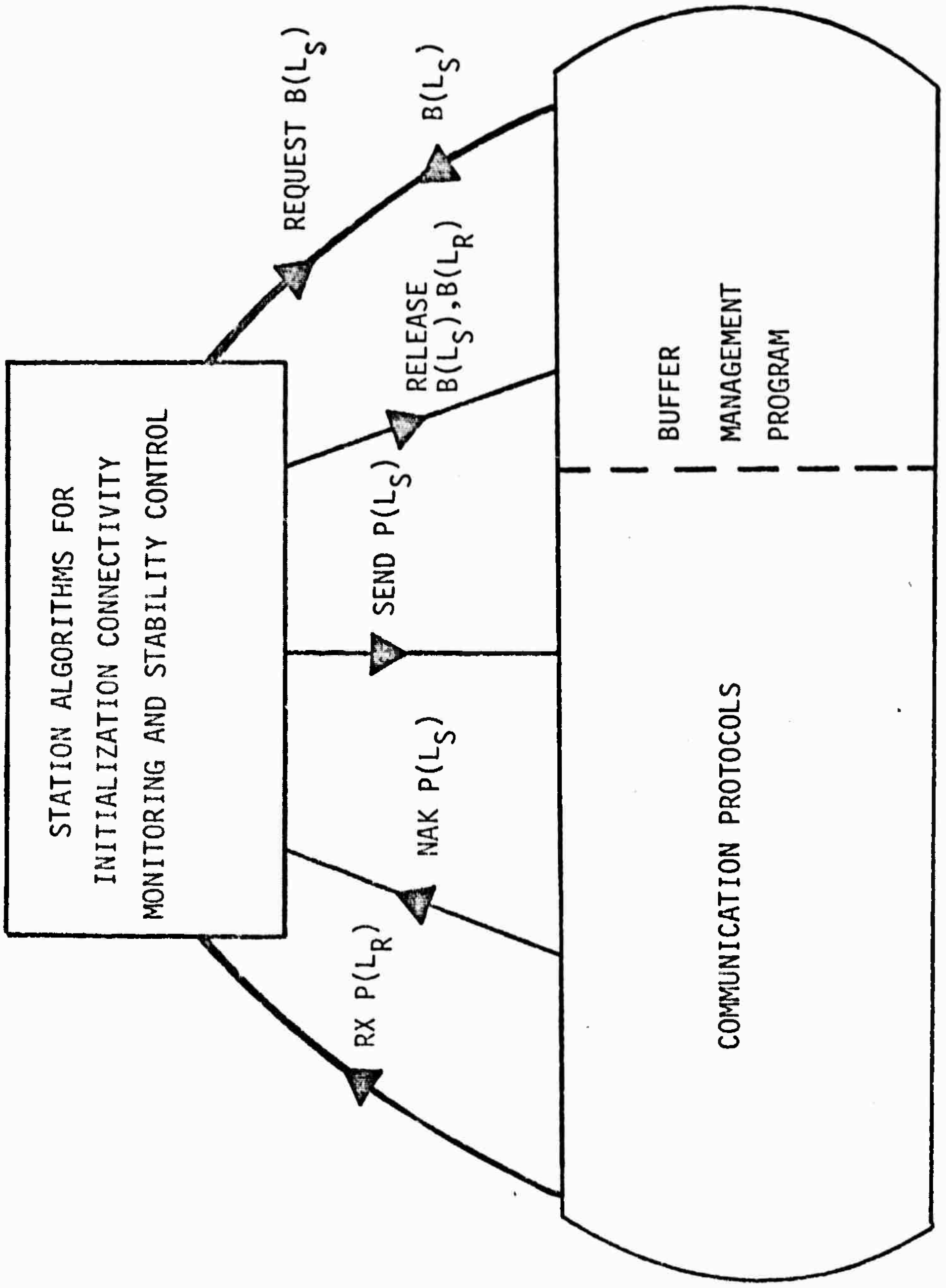

FIGURE 2.7: INTERFACE OF PROCESSES WITH COMMUNICATION PROTOCOLS

to the SAMSC programs. Note that the station PR need not send a NAK to the station when it discards a packet since a copy of the packet is stored in the station. Thus, the station PR operates the same way as a repeater which repeats a packet over a single hop. That is, the station PR will transmit the packet at most MNTH times and if a hop Echo ack is not heard, the packet is transmitted to ALL, after which it is discarded.

The SAMSC programs outlined in this document also perform the functions of end-to-end Station-PR protocol. The reason being that packets sent by SAMSC programs to a PR are sometimes needed for processing after the ete ack from the PR is received. For example, SAMSC programs maintain the operating parameters currently used by each PR. When the SAMSC programs schedule a Load Packet for changing some parameters in a PR, the parameter changes are not recorded in the PR file until the reception of the ete ack from the PR, at which time the parameter changes are taken from the stations copy of the packet before its buffer, Ls, is released.

The fact that the SAMSC programs perform the Station-PR ete protocol is completely transparent to the communication protocols and consistent with their standard operation. This is because a PR does not construct an ETE packet code; instead, the PR changes the direction bit of the packet received and then sends its Header. Thus, when this header packet arrives at the communication protocols at the station, it appears as a packet sent from a PR to the SAMSC programs, and is consequently forwarded to these programs.

The SAMSC programs are activated by the RX $P(L_R)$ and NAK P(Ls) commands from the communication protocols, by events scheduled by the SAMSC programs or as a result of traffic flow observations. The latter two are outlined in the section on Stability Control Algorithms. When interrupted from the communication protocols, the entry is to a packet dispatcher at the SAMSC programs, which pass the control to one of the SAMSC programs. This is shown schematically in Figures 2.8 and 2.9.

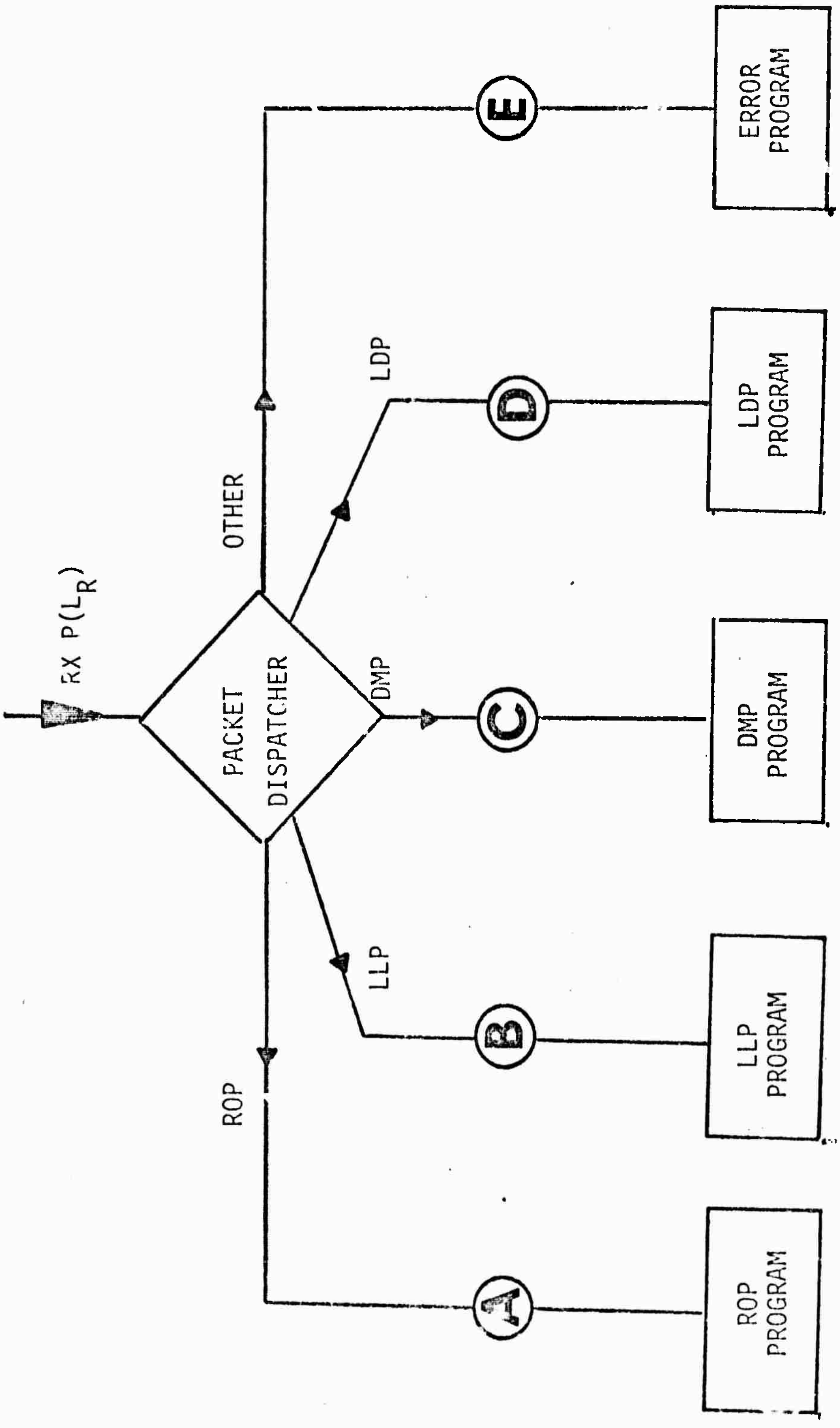

FIGURE 2.8: DISPATCHER FOR RECEIVED PACKET

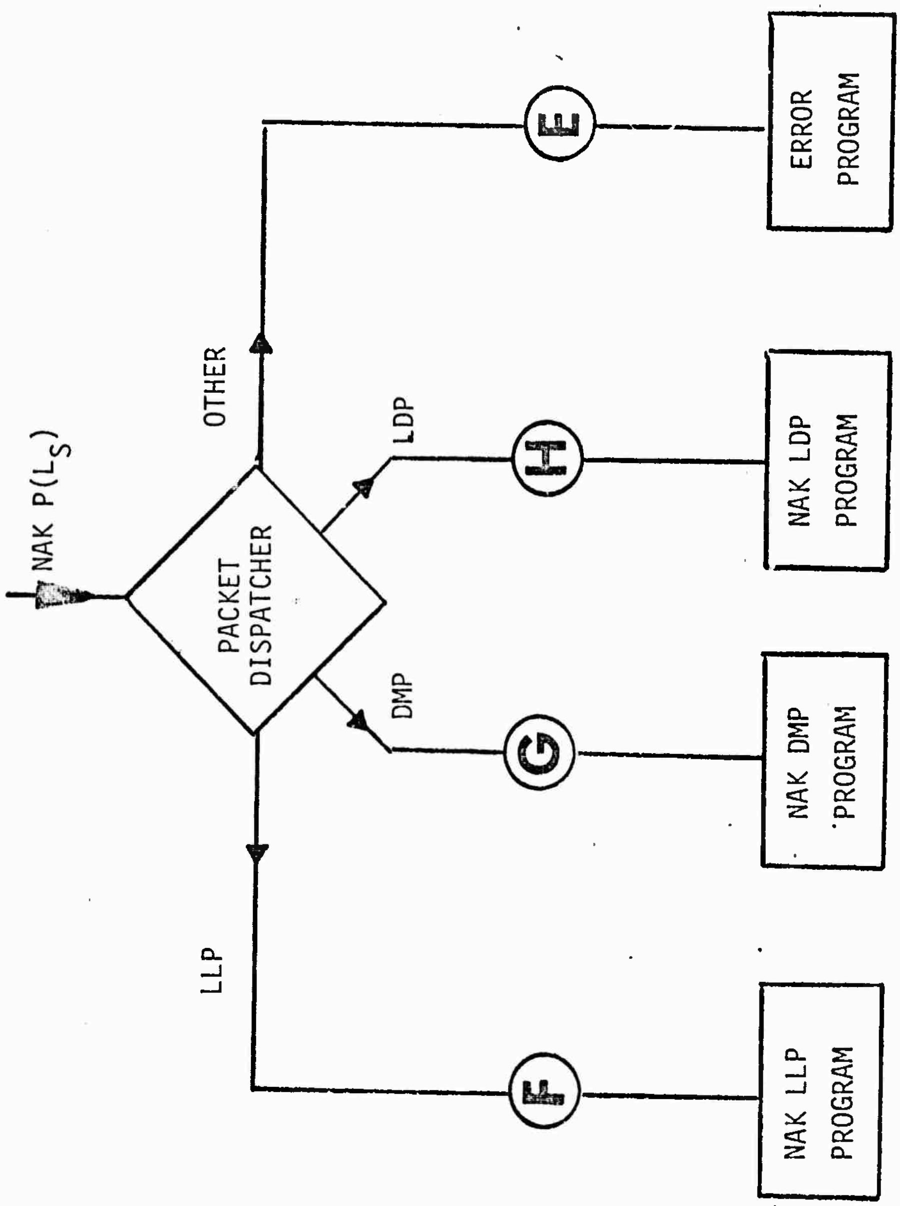

FIGURE 2.9: DISPATCHER FOR UNDELIVERED PACKET

The Error Programs are not considered in this chapter. The other programs of Figures 2.8 and 2.9 as well as algorithms associated with these are presented in the next two sections.

A single control parameter is used by SAMSC programs to maintain the Station-PR Protocol. The parameter is:

PL - Outstanding Packet Indicator (one for each repeater)

$$PL = \begin{cases} 0 - \text{No Outstanding Packet} \\ Ls - \text{The Location of the Sending buffer where the outstanding packet is stored.} \end{cases}$$

As can be seen in Figure 2.7, the SAMSC programs do not have or manage buffers for sending packets. Although there may be buffers reserved for sending control packets, it is assumed that these will be managed by a buffer management program, not part of the SAMSC programs. When SAMSC programs need to send a packet, the procedure shown in Figure 2.10 can be used.

2.4 INITIALIZATION AND LABELING ALGORITHMS

2.4.1 Introduction

Initialization involves the detection of repeaters, the determination of hierarchical labels for repeaters and the verification of links on paths associated with labels. The philosophical approach adopted for the experimental system is the integration of the procedures for labeling and connectivity monitoring. That is, rather than detecting all repeaters and all the links in the network before initializing repeaters and/or attempting to globally optimize the labels by reinitializing all repeaters periodically, the algorithms attempt to label repeaters as soon as identified.

The following packet types are used for initialization and labeling:

ROP - Repeater on Packet
LLP - Label Packet

ROP is originated by a repeater every TROP seconds, independent of its state of initialization. ROP is utilized by station algorithms to detect new repeaters and identify communication links which connect these to known repeaters. It is also used as a reassurance that a repeater is still "on" even when known and initialized, as well as for maintaining an updated connectivity matrix by removing "old" links and reestablishing new links from more recent ROP's.

LLP initializes the repeater for efficient packet transportation. It is originated by station programs and destined to a particular repeater. LLP contains the hierarchical label and possibly other parameters to be used by the Hop Transport Protocol and Station-PR Protocol.

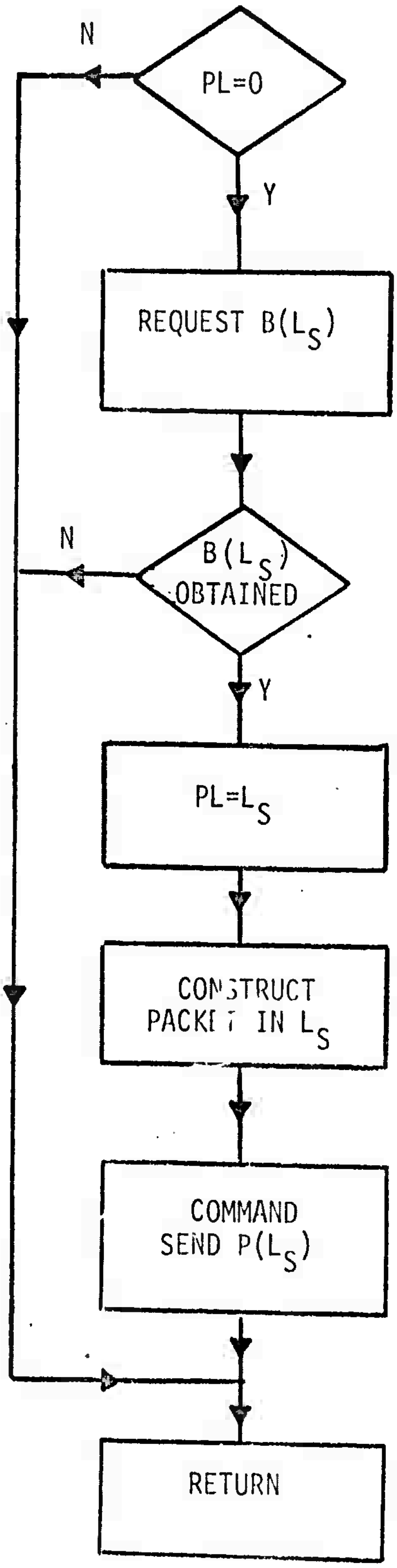

FIGURE 2.10: PACKET SENDING PROCEDURE

The operation of a noninitialized repeater is limited to accepting a LLP and emitting ROP's. It does not engage in relaying packets or in responding to terminal packets.

The Hierarchical Routing Algorithm (HRA) recommended for implementation in the experimental system does not utilize a search procedure when encountering blocking on the primary path. Thus, for simplicity and uniformity of operation of an initialized and noninitialized repeater in emitting ROP's, it is recommended that a repeater not use a search procedure before transmitting the ROP. Instead, an initialized repeater which receives a ROP will append to it its hierarchical label and forward it using HRA. Some or all of the duplicate ROP's which are created due to the nondirectionality of transmission over the first hop may be eliminated along the path since all duplicates have the same Unique Packet Indentifier (UPI). (This procedure has an advantage in multi-station networks in that a ROP emitted from repeaters equally distant from more than one station will traverse to several stations).

2.4.2 Parameters and Notation

The parameters and notation of variables used in this section are outlined below. Parameters with indices in brackets are needed for each device. Parameters without an index are either used for all devices or used for notation only.

U - Set of active repeaters registered in the station.

B - Number of bits per subfield in the hierarchical label.

H - Number of subfields in the hierarchical label.

R(i) - A Repeater whose Index (see Data Structures) is i.

$$C = \begin{cases} (c(i,j)) & = \text{Pairwise connectivity matrix between repeaters.} \\ c(i,j) & = 1 \text{ if } R(j) \text{ can directly receive from } R(i) \text{ and } 0 \text{ otherwise.} \end{cases}$$

HL(i) - Hierarchy level.

NL(i) - Number of successors.

LL(i) - Hierarchical Label.

LL(i,j) - Value of subfield j in the Label.

SUCC(i) - The values of subfield HL(i) + 1 of successors of R(i).

SINIT(i) - State of Initialization

$$SINIT = \begin{cases} S_0 & \text{- Non-initialized} \\ S_1 & \text{- In Initialization Process} \\ S_2 & \text{- Initialized} \end{cases}$$

PL(i) - Outstanding Packet Indicator

$$PL = \begin{cases} 0 & \text{- No Outstanding Packet} \\ L_S & \text{- Address of sending buffer where Outstanding Packet is stored} \end{cases}$$

LBFSH(i) - Indicates whether the label needs to be refreshed (i.e., old label resent for path verification).

$$LBFSH = \begin{cases} 1 \text{ when needs to be refreshed, and} \\ 0 \text{ otherwise.} \end{cases}$$

$SEQ(L_S)$, $SEQ(L_R)$ - The sequence number of the packet sent or received.

2.4.3 Station Initialization

The tasks that the station performs to activate an initialization and labeling process are very simple. The station is essentially passive and does not stimulate repeaters to emit ROP's.

The procedure carried out by the station to activate the initialization involves:

1. Erase Files of Active Repeaters, and

2. Send an LLP to the station's own PR (or PR's).

This procedure is carried out when a station is newly introduced or when it "comes up cold." The procedures for connectivity monitoring and labeling outlined in this document are sufficiently dynamic in that "old" links and labels are refreshed. Nevertheless, one may introduce a protocol which will periodically activate the reinitialization of the whole network either as a function of time or as a result of network performance.

2.4.4 Network Initialization

Network initialization programs include the labeling algorithm and the programs for ROP, LLP, and NAK LLP. The flow diagrams for the last three programs and their interaction with other programs are given in Figures 2.11, 2.12, and 2.13.

The flow diagrams are self explanatory. However, it is noted that in the NAK LLP program, if a new label can be obtained, it is constructed in the sending buffer in which the unsuccessful packet was stored. Thus, the program need not release the buffer since otherwise another sending buffer needs to be requested from the Buffer Management Program.

2.4.5 On Program Implementation

Some of the processing, in particular, the part related to the Station-PR protocol for the various packet types, will be the same. Consequently, rather than having separate programs at the exit of the packet dispatcher shown in Figures 2.8 and 2.9, one can integrate Programs A through D and F through H. Figure 2.14 shows one way for integrating the programs activated by the RX $P(L_R)$ command.

2.4.6 The Labeling Algorithm and Program

The station algorithm for determining hierarchical labels to be implemented in the experimental system is presented. Given a set of repeaters and the pairwise connectivity matrix, the algorithm does not determine a set of labels, one for each repeater, which optimizes some global criterion. Instead, it is assumed that the network is partially initialized and it is necessary to determine a hierarchical label for a single repeater. The algorithm determines a feasible label with the minimum number of hops for the given repeater. If a feasible label does not exist, the return is negative. The algorithm can be classified as a local optimum algorithm, for a given state of initialization.

The algorithm for finding a label for a single repeater R(p) proceeds as follows:

1. Construct the set S:

   $S = \{R(i) \text{ in } U | c\ (p,i) = 1\}$

2. If S is empty go to Step 10.

3. Construct the set $S_L \subset S$:

   $S_L = \{R(i) \text{ in } S | SINIT(i) = S_2\}$

4. If S_L is empty go to Step 10.

5. Construct $S_F \subset S_L$:

   $S_F = \{R(i) \text{ in } S_L | NL(i) < 2**B-1\}$

6. If S_F is empty go to Step 10.

7. Find R(m) in S_F such that:

   $$HL(m) = \min_{R(i) \text{ in } S_F} HL(i)$$

8. Construct LL(p):

   Let K be an integer, o < K < 2**B-1, which is not used by any of the successors of R(m) in subfield HL(m) + 1. Then

   $LL(p,i) = LL(m,i)$, for $1 \le i \le HL(m)$

   $LL(p,i) = K$, for $i = HL(m) + 1$

   $LL(p,i) = 0$, for $HL(m) + 1 < i \le H$

   $HL(p) = HL(m) + 1$

9. End.

10. No Feasible Label.

11. End.

There is one possible simplification of the algorithm which will determine "a feasible label" rather than "a feasible label with the minimum number of hops." The simplification will eliminate Step 7.

The labeling program is shown in Figure 2.15. As shown in the program, there is no need to construct the various sets formally defined in Steps 1, 3, and 5 of the algorithm. The parameter ITEM in the program is a temporary Index which records on index of the home repeater. If ITEM = 0 when returning to the calling program, it indicates that no label was obtained.

2.4.7 The Relabel Program

Some of the active repeaters in the station files may be unlabeled (non-initialized), or have wrong labels. One of the reasons for having a non-initialized repeater is due to the unavailability of a sending buffer when the SAMSC programs attempted to send a label to the repeater. Labels may be wrong or unreliable when changes in network topology occur. When changes in network topology are identified by the connectivity monitoring procedures, the repeaters whose labels become incorrect are classified as non-initialized. Furthermore, periodically, some labels are resent to repeaters in order to verify the communication path defined by these.

The Relabel program presented in this section scans all the active repeaters; it resends old labels to repeaters whose labels need to be refreshed, and constructs and sends new labels to repeaters classified as non-labeled (SINIT = S_0). This program is called from the program which maintains the status of network devices and network connectivity, described in the next section. The relabel program is illustrated by Figure 2.16.

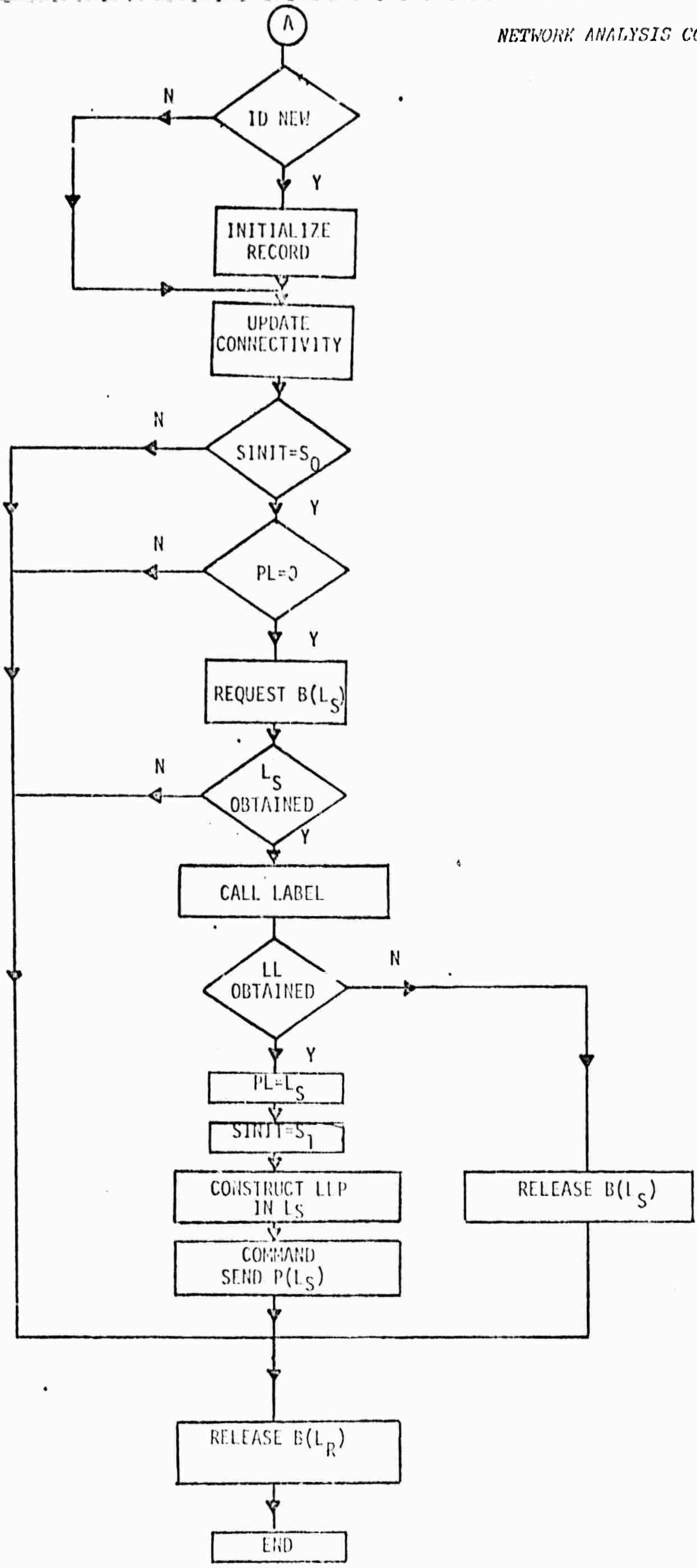

FIGURE 2.11: ROP PROGRAM

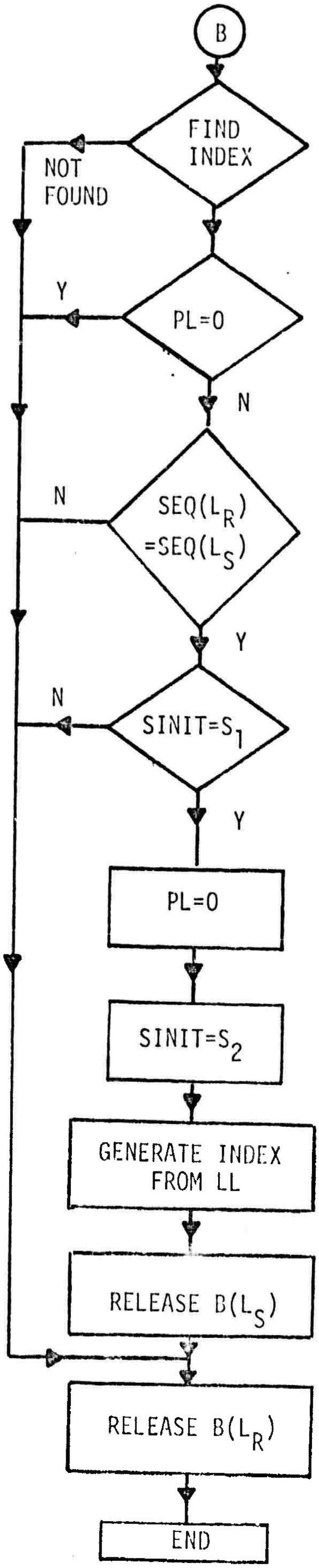

FIGURE 2.12: LLP PROGRAM

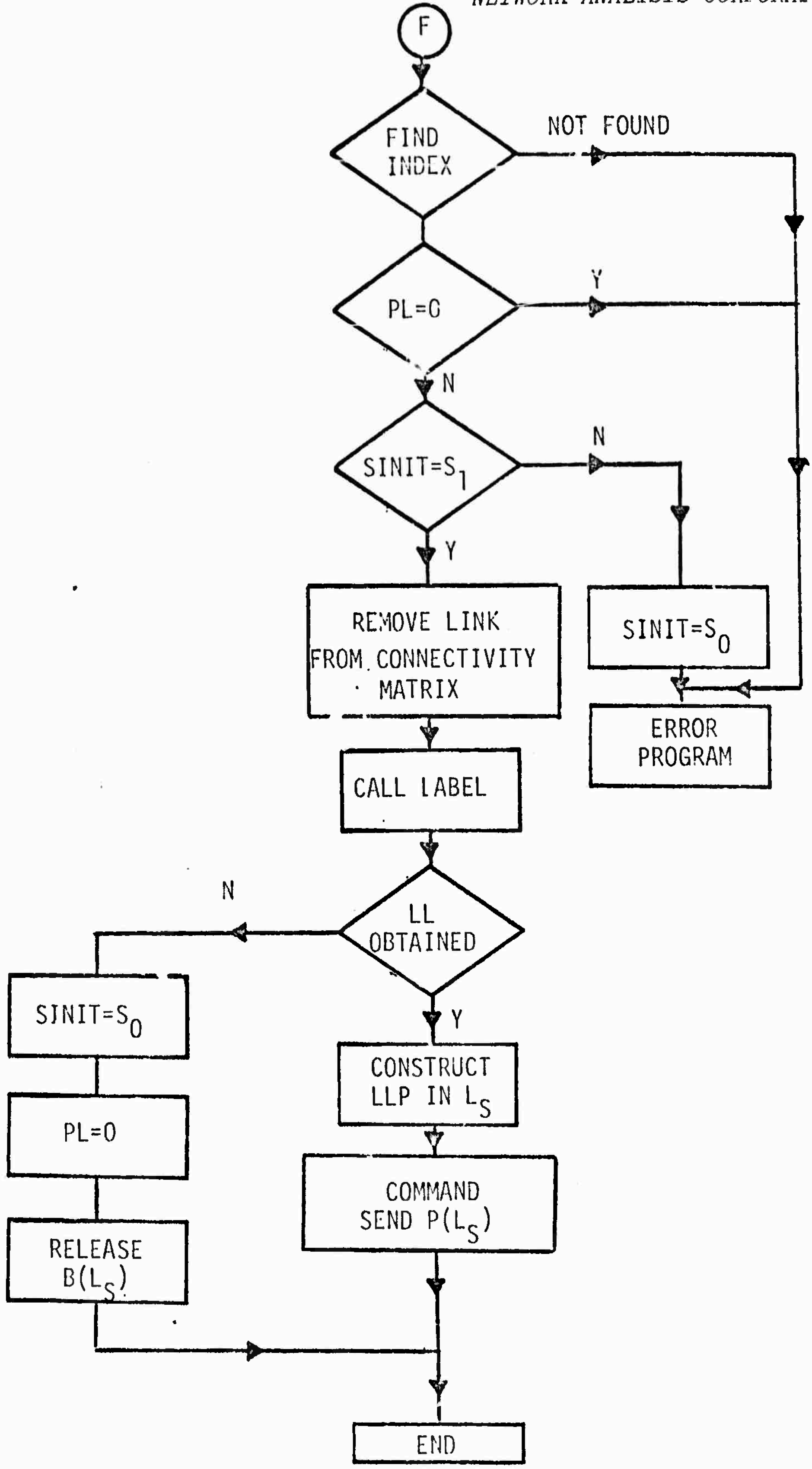

FIGURE 2.13: NAK LLP PROGRAM

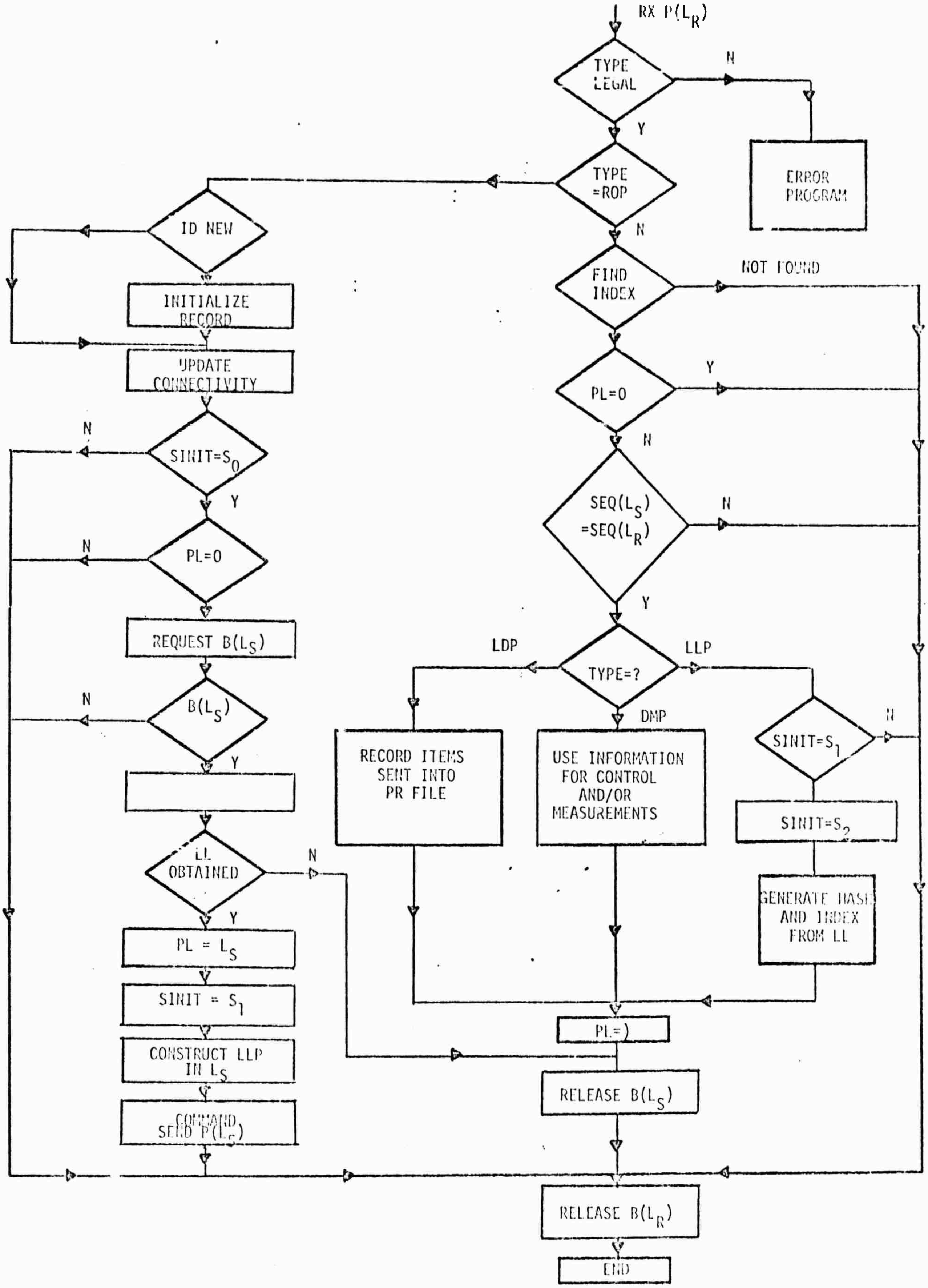

FIGURE 2.14: AN EXAMPLE OF PROGRAM INTEGRATION

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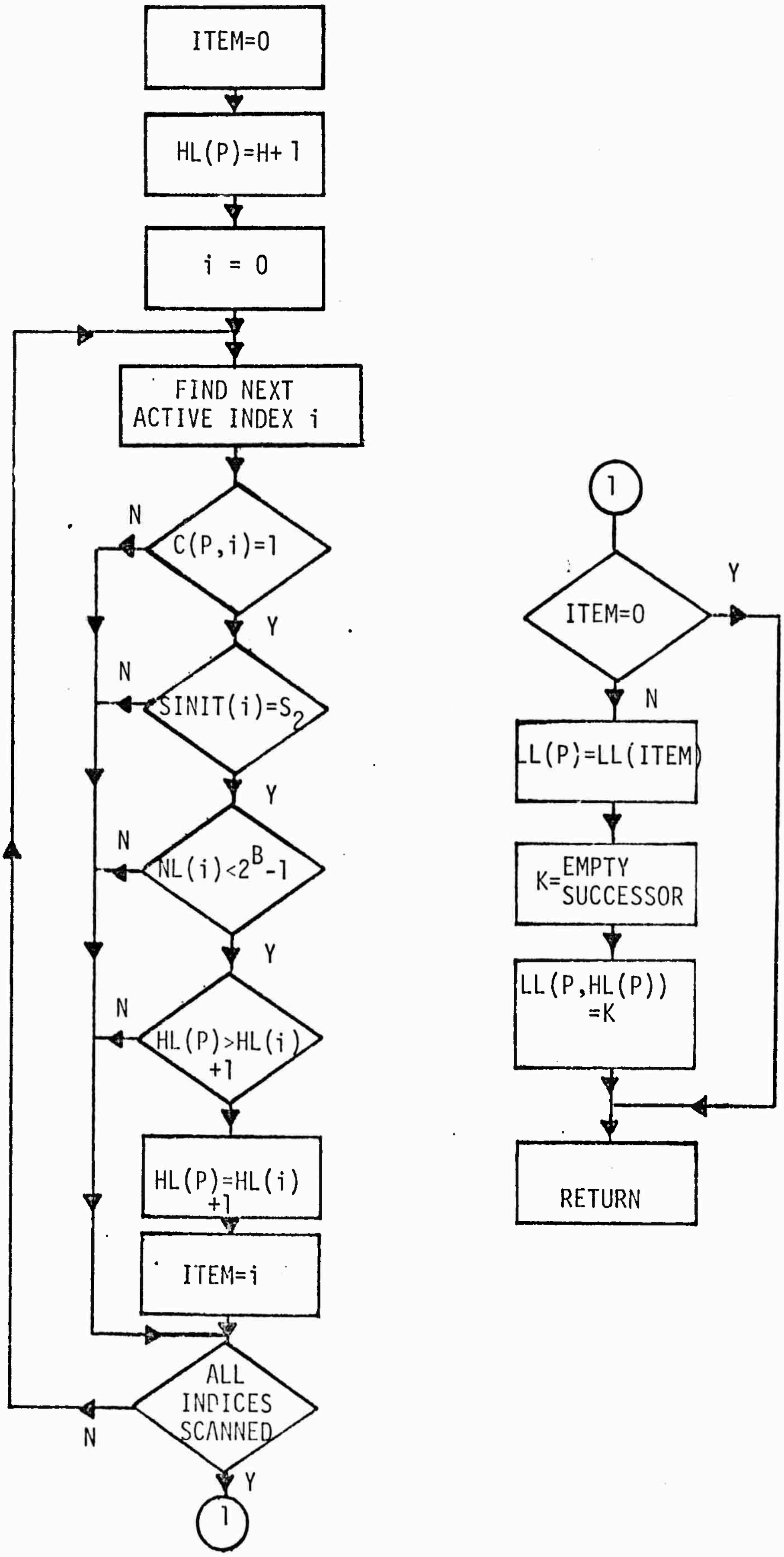

FIGURE 2.15: LABEL PROGRAM

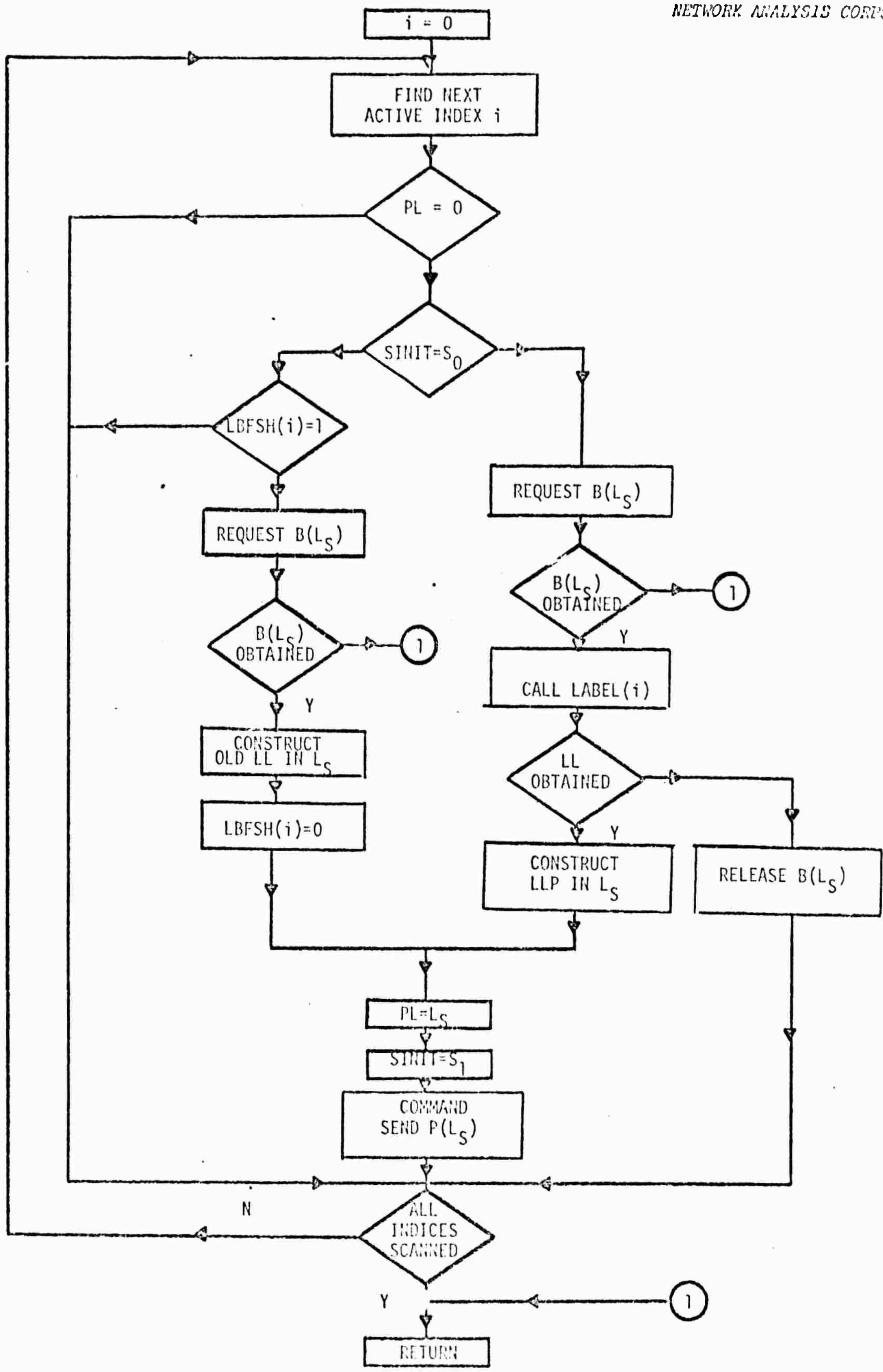

FIGURE 2.16: RELABEL PROGRAM

2.5 MONITORING NETWORK STATUS AND CONNECTIVITY

2.5.1 Introduction

The objective of the status monitoring procedures is to maintain repeater and terminal directories in the station, and to update the parameters associated with active repeaters and terminals.

The objectives of connectivity monitoring procedures are the following:

1. Detect changes in network connectivity resulting from power reduction, relocation of mobile repeaters, or presence of an obstacle on the RF path,

2. Update the connectivity matrix to reflect such changes, and

3. Update parameters used by the relabeling routine for repeater relabeling.

There are three basic ways of monitoring the PRNET:

1. Inspection of ROP's periodically emitted by repeaters,

2. Monitoring regular network traffic, and

3. Interrogation of the device by station via a DUMP packet.

The monitoring procedures proposed here are based on a combination of the above approaches.

2.5.2 Parameters

The following parameters are used by the station monitoring procedures:

A. Repeater Parameters

TRLH(i):	Time Repeater Last Heard. The time when the most recent ROP from repeater i was received.
TFRESH(i):	Time when the row in the connectivity matrix corresponding to repeater i was last refreshed.
SINIT(i):	Status of initialization of repeater i. SINIT(i) = S_0: repeater not labeled. SINIT(i) = S_1: repeater labeling in progress. SINIT(i) = S_2: repeater labeled (see Section 4).
DPFLG(i):	Departure Flag. It indicates departures from primary route of packets originating (or transiting) at repeater i, and directed to station. DPFLG(i) = 1 if one or more departures were detected at node i during the last observation interval. Otherwise, DPFLG(i) = 0.
NPR:	Number of active repeaters.
TFR:	Time interval after which network connections and repeater labels are refreshed.

TROP: Time interval between successive ROP generations.

TROPxK: If LBFSH(i) = 1, the label of repeater i must be refreshed (i.e., verified by delivering to repeater i a LLP with present label). If LBFSH(i) = 0, the label of repeater i need not be refreshed.

B. Terminal Parameters

TTLH(i): Time Terminal Last Heard. The time when the most recent packet from terminal i was received.

HOME(i): Label of the most recent homing repeater for terminal i.

TTER: Timeout after which a terminal is interrogated to determine status.

NTER: Number of active terminals.

2.5.3 Repeater Status Monitoring Procedure

1. The station reads originator ID from ROP and updates TRLH (Time Repeater Last Heard) for corresponding repeater. The station also updates TRLH for the repeater which relayed ROP.

2. The list of TRLH(i) for i = 1, ..., NPR is periodically checked for old time stamps. The program that checks the repeater list can be activated by a clock interrupt or by a ROP interrupt (e.g., ROP from station PR).

3. If TIME-TRLH(i) $\geq$ TROP×K (where K is an input specified parameter) a signal is sent to "repeater dead routine," which updates connectivity matrix and cleans up dead repeater records.

2.5.4 Monitoring Status of Terminals

1. For each data packet that arrives from the PRNET, the station reads the terminal ID (internal ID which is assigned by station to terminal PR's and is different from PR hardwired ID) and updates time stamp TTLH(ID) (Time Terminal Last Heard).

2. At the same time, the station writes the label of the homing repeater into HOME(ID). The HOME label is used to deliver packets from station to terminal.

3. Periodically, the station checks time stamps of terminals and interrogates terminals with TIME-TTLH(ID) > TTER. If no answer is received after several trials, the terminal is declared dead and is eliminated from the active terminal list.

2.5.5 Monitoring Status of Station PR

The station PR sends ROP packets only to the station, via hardwired interface. The monitoring procedure is based on the inspection of ROP's and is the same as for all the other repeaters.

2.5.6 Monitoring Network Connectivity

1. Upon reception of each ROP, a new entry to the connectivity matrix is made in correspondence to the directed link between the repeater that originated ROP and the repeater which relayed it.

2. The connectivity matrix, therefore, at any given time contains all the links detected since the matrix was last initialized. A periodic refresh is required, in order to eliminate links which are no more valid. Also, a periodic refresh of the labels is required. This will be done as follows. Let TFRESH(i) indicate the time when row i of the connectivity matrix (i.e., the links for repeater i) was last refreshed. If TIME-TFRESH(i) > TFR, set all entries in row i to zero; set TFRESH(i) = TIME and, if repeater i has no successors (i.e., it is a spur in the hierarchical label tree), set LBFSH(i) = 1. (Notice that in order to verify the validity of all network labels, we only need to check the labels of the "spur" repeaters.) The task of refreshing labels for repeaters with LBFSH bit = 1 is the responsibility of the RELABEL Routine (Figure 2.16), which is called at the end of the Repeater Monitoring Routine.

3. Whenever a repeater is declared dead, the parameter SINIT is set to S_0 for all the hierarchical descendants of the dead repeater.

4. Departure from primary route for packets transmitted to the station is a potential symptom of failure of some of the links along the path from repeater to

station (due to power reduction, obstacles, mobile repeater relocation, etc.). The station detects departure from a field in the packet header, and identifies the repeater at which the last departure occurred. This information is obtained from the hierarchical level, which is stamped next to the departure field, and from the label in the packet header. Whenever a departure from repeater i, say, is observed, the departure flag DPFLG(i) for repeater i is set to 1.

5. The repeater monitoring program periodically scans the repeater directory and checks DPFLG for each active repeater. If DPFLG(i) = 1, the connectivity matrix is inspected to verify whether the first hop on the hierarchical path from repeater to station correspnds to a valid link. If the link is no more valid, SINIT(i) is set to S_0.

2.5.7 The Repeater Monitoring Routine

The repeater monitoring routine periodically scans the repeater directory to perform the tasks described in the previous paragraphs (i.e., detect dead repeaters, identify potential bad labels, and refresh connectivity matrix and labels). A flow chart of the routine is shown in Figure 2.17.

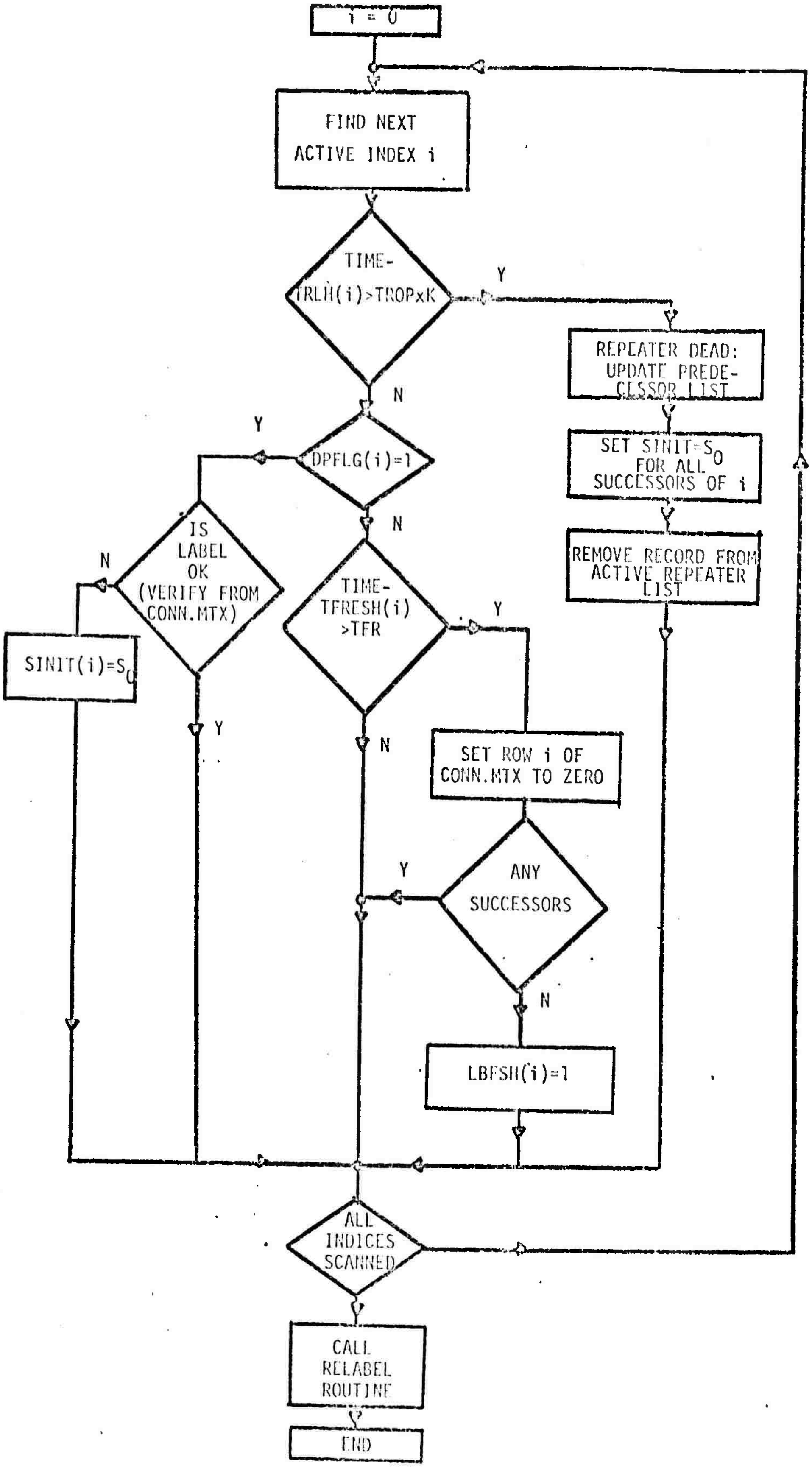

FIGURE 2.17: REPEATER MONITORING ROUTINE

2.6 STABILITY CONTROL PROCEDURE

2.6.1 Introduction

The function of the Stability Control Procedure is to prevent the PRNET from becoming congested due to excessive traffic input from PR terminals or HL net (Higher Level Network) gateways. Stability and congestion protection is obtained by the regulation of input rates and the appropriate allocation (and possibly reservation) of buffer resources in the station.

The design of a stability control procedure for PRNET attempts to optimize the tradeoff between congestion protection and network performance. The following performance criteria have been considered:

- Response time for interactive users.
- High bandwidth for bulk data transfers.
- Graceful degradation with traffic load increase.
- Fairness with respect to all network users.

The stability control procedure proposed here is the combination of the following controls:

- Station buffer control and management.
- Distributed control of repeater input traffic rates.
- Centralized control of network parameters.

No assumption is made here concerning the end-to-end protocols between terminal and station and of their impact on network stability. It must be pointed out, however, that the presence of a terminal-station protocol will introduce one more control capability on input traffic, in addition to the control capabilities mentioned in this section (which are independent of end-to-end protocols).

End-to-end protocols will in general improve stability, performance and station buffer utilization. Consequently, some of the control schemes proposed in this section may need revision, when PRNET end-to-end protocols are finalized.

Gateway control is examined here under the assumption that the station is the gateway to only one Higher Level net. In general, however, the PRNET may interface with more than on HL net; for example, it may interface with both a terrestrial point-to-point packet network such as ARPANET and a packet satellite broadcast network. When the PRNET station acts as the gateway to more than one network, some of the gateway control procedures proposed here (e.g., buffer management scheme) need to be revised and generalized.

2.6.2 Parameters

The Stability Control Procedure consists of the observation of network variables related to traffic load and stability, and of the control of network parameters on the basis of such observation.

The station monitors the following variables:

RFRPR: Rate of packets received at the station from the PRNET.

RTOPR: Rate of packets delivered into PRNET from the station.

RDEP: Rate of departures from primary path.

DPFLG(i): Path departure activity for repeater i (see Section 2.5.2).

TTRF(i): Traffic indicator for terminal i. TTRF(i) = 1 indicates that one or more packets were received from terminal i during the interval TSCAN. TTRF(i) = 0 indicates that no packet was received since the last scanning time.

NRP: Total number of active repeaters.

NTERM: Total number of active terminals in the PRNET.

NTERP(i): Number of active terminals homed onto repeater i.

Size of station output queues.

Total number of station free buffers.

The Stability Control Procedure controls the following parameters:

1. Station Parameters

   a. Minimum and maximum buffer allocation in the station to each output queue (station-HLNET and Station-PRNET queues).

   b. Maximum number of active terminals allowed in PRNET.

2. PR Parameters

a. Interval between subsequent hop retransmissions.

b. Maximum number of retransmissions.

c. MHN: Maximum handover number.

d. RF power (for connectivity control).

e. ON/OFF Low Data Rate: Turn ON or OFF the 100 Kb/s data rate in a repeater, to enable/disable terminal access.

f. CHOKE ON/OFF: Disable/enable the response to terminal initiation packets. If CHOKE is turned OFF, old terminals can still home onto this repeater, but new terminals cannot access it.

g. INALL(i): Initial packet allocation for repeater i. More precisely, the number of packets that repeater i can accept from terminals (on the 100 Kb/s channel) and forward to the station, in each time interval TALL, in absence of "allocate" commands from the station.

h. REALL: Packet allocation granted by the station to a repeater with an "allocate" command. The allocation is temporary; it is valid from the time the repeater receives the allocate command to the time of the next TALL interrupt in the repeater. The interrupt restores the initial allocation INALL(i).

2.6.3 Station Buffer Management

In the station, we can identify two output queues: (1) the queue of packets (or messages) directed to the HLNET switch (e.g., IMP), and (2) the queue of packets directed to the PRNET. The latter queue includes: packets originating from HL network, packets originating from PRNET and switched back to PRNET, and station-repeater control packets (e.g., label and allocate packets).

A specified minimum number of buffers is permanently reserved for each queue. Furthermore, the buffers reserved in the queue to PRNET are apportioned between HLNET packet, PRNET switched packet, and station control packet applications.

Buffers are also reserved for inputs from HLNET and PRNET. However, input buffer requirements are much less critical than output requirements, under the reasonable assumption that the system is network bandwidth limited, rather than station CPU limited.

The remaining station buffers are in a common buffer pool and can be shared among all queues. However, maximum buffer allocations are specified so that each queue cannot use more than its maximum allowance.

Priorities may be implemented within each queue. In the output queue to PRNET, for example, station control packets will have higher priority than regular packets.

Packets arriving from PRNET which find no available buffers in the output queue to their destination (either HLNET or PRNET) are discarded. Packets from HLNET (or from a station process) which are directed to PRNET are not accepted unless buffers in the PRNET output queue are available.

The block diagram for the schematic buffer organization is shown in Figure 2.18.

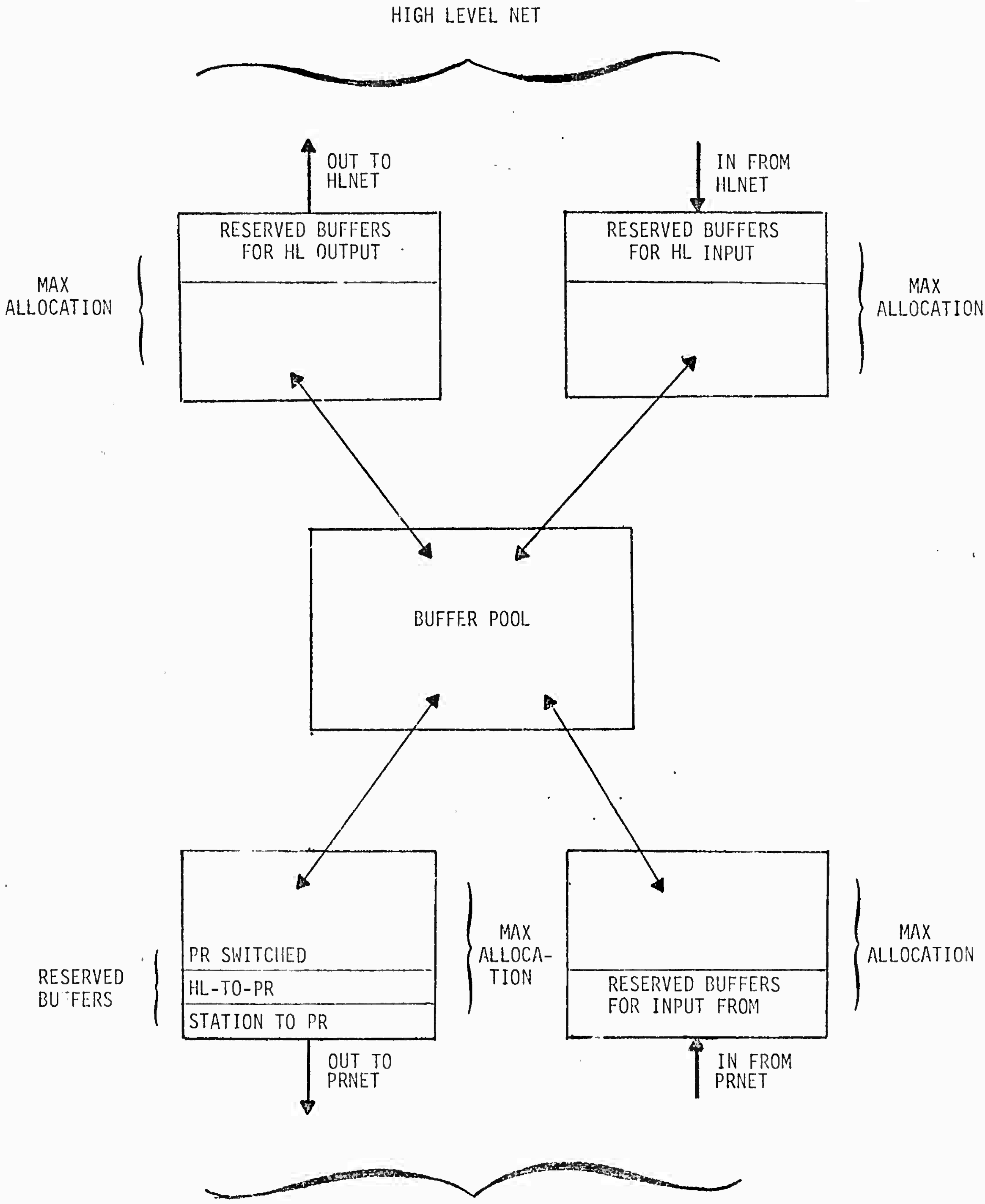

FIGURE 2.18: STATION BUFFER ORGANIZATION

2.6.4 Distributed Repeater Input Rate Control

Under the distributed control procedure proposed here, repeater i accepts only up to INALL(i) packets from terminals (to be forwarded to the station) in each time interval TALL. The implementation can be as follows. Each TALL seconds, a clock interrupt in the repeater restores the packet count PCOUNT to INALL(i). For each packet received from terminals and passed to the Channel Access Protocol for delivery to the station, PCOUNT is decreased by 1. If PCOUNT = 0, all packets from terminals are discarded (both regular and search packets).

The station can modify the value of PCOUNT with an "allocate" packet, which is a LOAD packet that loads the value REALL in the location PCOUNT.

Allocate packets are sent from station to repeaters on the basis of the activity of the associated terminals. The allocate mechanism in the station can be implemented as follows. Upon receiving a packet from terminal j, say, the station updates the time stamp TTLH(j) and enters the label of the homing repeater in HOME(j), as discussed in Section 2.5. In addition, the station sets the activity flag TTRF(j) = 1. Every TSCAN seconds an Allocate Routine in the station is activated, which scans the terminal directory and whenever it finds TTRF(j) = 1, it sends an allocate packet to repeater HOME(j) and resets TTRF(j) = 0. The block diagram of the Allocate Routine is shown in Figure 2.19.

The distributed repeater rate control described above has the effect of providing high bandwidth to terminals engaged in file transfers when the network is lightly loaded; this is obtained by quickly returning packet allocation to the associated repeaters.

At the same time the control prevents congestion when the network becomes heavily loaded, since only a few allocates can be successfully delivered to repeaters due to network traffic interference and, on the other hand, INALL(i) rates alone cannot cause congestion.

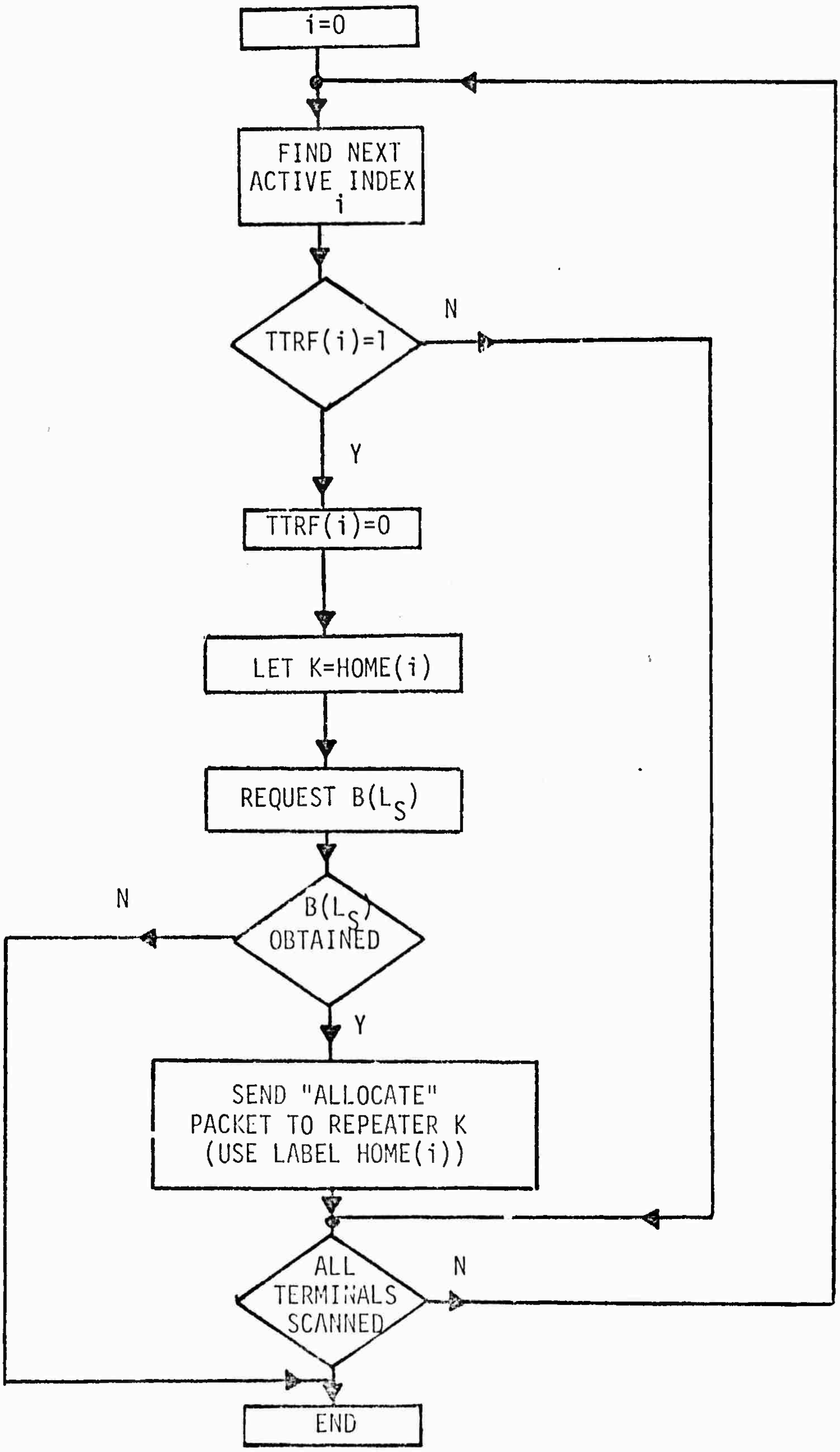

FIGURE 2.19: ALLOCATE ROUTINE

The distributed repeater input rate control procedure requires some overhead in the repeater, to keep the packet count and schedule the TALL interrupt. This overhead can be somewhat reduced by setting TALL = TROP (where TROP is the interval between ROP transmissions) and using the ROP interrupt to reset the packet count.

2.6.5 Centralized Control of Network Parameters

Later versions of the PRNET implementation will include a centralized stability algorithm residing in the station. The inputs to the algorithm are the observation variables; the outputs are the values of the stability control parameters.

At the present stage, however, there is no sufficient understanding of the interaction between observation, control, and performance parameters to enable the development of a global stability control algorithm. Therefore, the preliminary PRNET implementation will have no provision for such a global algorithm.

The specifications for the station control algorithm will be in part the result of analytical studies and simulation experiments. But analysis and simulation results need to be further verified and complemented with measurements on the experimental network before proceeding to the design of an effective and reliable centralized control.

In the preliminary PRNET version, therefore, the station will monitor the variables introduced in Section 2.6.2, and will be equipped with the protocols necessary for the implementation of the controls (typically, generation of LOAD packets for parameter setting). The loop between observation variables and control commands will be closed by the human to enable the testing of a large gamut of control strategies.

Network parameters will be initialized to values which provide acceptable performance and stability for a very wide range of traffic conditions. Better performance is obtained by dynamically adjusting parameters to traffic and network conditions. This adaptivity will be made available in a systematic way through the centralized station algorithm, to be implemented in later PRNET versions.

The monitoring of the variables discussed in Section 2.2 does not seem to represent a critical software implementation problem in terms of creation of excessive overhead for the station. Procedure for monitoring some of the repeater parameters were described in Section 2.5. Traffic input rates are obtained with counts over an appropriate time interval. The number of active terminals NTERP(i) homed onto repeater i is obtained by periodically scanning the terminal directory.

CHAPTER 3

CONNECTIVITY MONITORING, LABELING, AND STABILITY CONTROL IN SECOND GENERATION PACKET RADIO NETWORKS

3.1 INTRODUCTION

It may seem ironic to speak about the second generation packet radio network, when the first generation is still in its infancy. We justify the notion "second generation" in the following manner: the algorithms and procedures proposed for implementation in the first experimental system ("first generation") is the minimum set needed for testing the feasibility of the packet radio technology. The main criterion for developing the first generation functions was simplicity, rather than efficiency.

In this chapter, we discuss additional algorithms and procedures which, together with the initial set of Chapter 2, enables more efficient performance of the functions of network initialization, connectivity monitoring, and stability control. Furthermore, unlike the presentation of Chapter 2 which is addressed to a single station packet radio network, we discuss the procedures in a multi-station network context.

As far as the repeater is concerned, the additional capabilities include the Broadcast Routing Algorithm (see Chapter 4) and the modification of its protocols to enable the processing of another packet type, the Path Packet. At the station, it is necessary to add a procedure for issuing path packets, an algorithm for determining an "optimum" set of labels, an algorithm for comparing the optimum set of labels with an existing set of labels to determine whether relabeling is needed, procedures for a faster detection of changes in network topology, and procedures for the control of the traffic level in the PRNET and at the gateway with other networks.

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3.2 NETWORK INITIALIZATION

3.2.1 Introduction

It is apparent [Kahn, 1975, Frank, 1975, NAC, 1974] that:

1. Repeaters and stations cannot be provided, in the manufacturing plant, with the capability of efficient routing of packets.

2. When repeaters and stations are allocated to form a PRNET, they may not be physically accessible to enable the testing of reliable communication links and for manual initialization to obtain efficient routing.

3. If devices are physically accessible, there may be a time constraint for obtaining an operational PRNET which will make manual initialization unacceptable. Consequently, the approach adopted is to initialize the PRNET via the air by utilizing a set of basic capabilities provided to the repeater and station in the manufacturing plant. The efficiency of initialization procedures and algorithms is particularly significant due to the anticipated changes in topology because of battery drainage and/or possibly mobile network devices.

Network initialization functions include the following procedures and algorithms:

1. Procedures for mapping of network topology.

2. Algorithms for using the network topology information to determine network structure (in the form of Labels) to be assigned to repeaters.

3. Procedures for dispatching network structure information to repeaters.

The procedures described enable the initialization of PRNET with the following assumptions:

1. Repeaters and stations have fixed, hardwired ID numbers.

2. Repeaters and stations have a basic set of capabilities which include the Broadcast Routing Algorithm (BRA) of Chapter 4 and the programs for the procedures described in this section and in Chapter 2. All these capabilities are independent of the network structure.

3. Repeaters and stations do not have any information related to the existence, location, identification numbers, or the state of initialization of any other repeaters and stations in the area.

3.2.2 Mapping of Network Topology

Two independent processes contribute to the mapping of network topology:

Process A: Repeaters are trying to register their hardwired ID at stations by using the ROP procedure.

Process B: Each station, independent of other stations, is attempting to discover the existence of other stations and repeaters in its area, and to identify the communication links between these devices.

3.2.2.1 The ROP Procedure

The procedure involves the transmission of a Repeater On Packet (ROP) by each repeater every TROP seconds. The ROP serves two purposes:

1. It enables a newly introduced repeater or a repeater which has been temporarily disabled and "comes up cold" to register at stations in its area, independent of simulation from stations, and

2. It provides reassurance to stations that an already registered and initialized repeater is "on" and operating.

The ROP can also be used to detect whether a repeater is mobile (relative to its neighbors) by observing the link of the repeater to one of its neighbors, which is recorded in the ROP. If there is an indication of a change in location (relative to neighbors), it may activate a procedure by which a station can obtain all the current neighbors of a repeater, and compare these with its old neighbors (see Section 3.3).

The following remarks briefly summarize the ROP procedure:

1. Every repeater transmits a ROP every TROP seconds, independent of whether it is initialized.

2. A station PR (a repeater which is connected to a station via a hardwired interface) also sends a ROP every TROP seconds, however, it forwards the ROP into the station via the hardwired interface, rather than broadcasting the ROP.

3. A repeater which is not initialized by any station does not accept ROP's for relaying. An initialized repeater which receives a ROP without a label (the ROP is always emitted without a label) accepts it and forwards it as described in Item 5.

4. A station which receives a ROP processes it using the ROP program outlined in Chapter 2.

5. Routing of a ROP: We assume that a ROP needs to be delivered to several stations in the area and outline four ways of doing it:

   a. Transmit ROP using the Broadcast Routing Algorithm (BRA). The ROP will usually arrive at all stations within a "distance" specified by the Maximum Handover Number (MHN) of the originating ROP.

   b. Transmit ROP using the Hierarchical Routing Algorithm (HRA) of Chapter 4 to the primary (nearest) station, and have the latter forward the ROP to other appropriate stations in the area, via point-to-point channels between stations or via the PRNET using HRA.

   c. Modify repeater operation so that when an initialized repeater receives a ROP (without a label), it generates several ROP's, one for each station that labeled it, and transmits each ROP using HRA.

d. Modify repeater operation so that when receiving a ROP (without a label), it sends the ROP to one of the stations that labeled it using HRA. The repeater either alternates the labels (i.e., the stations) or chooses one at random.

3.2.2.2 Mapping of Global Network Topology

The objective is to discover ID's of repeaters and obtain a connectivity matrix C = C(i,j) between repeaters.

As assumed in the previous section, a station need not know about the existence of other stations to perform the topological mapping. Every station performs the procedure independently. Furthermore, there is no need for station-to-station communication to exchange connectivity information or decide upon the labels.

A single packet type, the Path Packet (PAP), is used for the global mapping. The procedure involves issuing PAP's in which the paths that the packets traverse are written in, in the form of an ordered sequence of repeater hardwired ID's, and the recording of these paths by the stations.

When a PAP is issued by a station, it contains two Maximum Handover Numbers (MHN's), MHN1, and MHN2. The PAP first traverses "away" from the issuing station until MHN1 reaches zero. All repeaters and station PR's at which the packet arrives with a handover number equal to zero and a direction bit-oriented from station, reverse the direction bit of the packet, sets MHN2 to be the active handover number, and forward the packet.

As indicated in Chapter 4, there is no directionality in routing packets when using BRA. However, the need to reverse the direction bit is related to the performance of BRA, and in particular, the control parameter FORGET used in it. FORGET is the time after which a device forgets that it repeated a packet and will accept the same unique packet for repetition. Assume for the moment that a repeater or station has unlimited storage for Unique Packet Identifiers (UPI's). Then, in order to prevent looping and cycling of packets, one assigns a large numerical value to FORGET. Thus, if FORGET is large, there is a low probability that the station which issued a PAP will receive PAP's back with paths recorded in them. The reversing of the direction bit makes the PAP look like a new packet since the bit is part of the UPI.

The global mapping is a generalized approach of that in which the station records all repeaters one hop away from it, then all repeaters two hops away from it, etc. The latter is a special case when MHN1 = MHN2 and when the station uses first MHN1 - MHN2 = 0, then MHN1 - MHN2 = 1, etc. For example, if a station begins with MHN1 = MHN2 = 1, then all the links of repeaters which are one hop away from the station as well as their ID's can be discovered. Thus, in general, it seems more efficient to originate PAP's from further away, since the repeaters on the paths to stations will be identified as a by-product. The generality of the global approach is particularly useful for multi-station PRNET's.

Each station must have an algorithm for processing a PAP. The algorithm examines the sequence of hardwired ID's in the PAP and adds to its active repeater files the newly discovered repeaters. The algorithm then updates the connectivity matrix by recording the links of the PAP. For example, if PAP contains the ordered sequence (R(i), R(j), R(k), ...), the algorithm sets c(i,j) = 1, c(j,k) = 1, etc.

Upon the reception of a PAP, the station PR handles it as any other repeater, and in addition, it transfers a copy of the PAP into the station. The processing of a PAP before its forwarding includes, among others, incrementing the count of the number of hardwired ID's in the packet and adding its hardwired ID in the proper location.

The routing indicator carried in the packet can be used to improve the efficiency of the global mapping. Specifically, the station may use HRA for a PAP until MHN1=0. When the direction bit in a PAP is reversed, the routing indicator is always set to BRA. This is particularly useful for monitoring network connectivity when a station wishes to map only a small section of the network.

Figure 3.1 shows an example of paths traversed by a PAP and some information content of the PAP on the various links. The PAP was issued by station 427 with MHN1=2 and MHN2=8. The direction bit of the PAP is reversed by repeater 96 which also sets MHN2 to be the active handover number. We note that station 427 identifies communication links in two directions between the repeaters in the PAP sequence. Station 307 will record the path information of the PAP received as well as add its ID and forward the PAP. Station 307 also identifies station 427 (we assume that the device type can be identified either from its hardwired ID or by an additional bit, associated with each hardwired ID in the sequence, which distinguishes between a station and a repeater) as well as a possible path to it.

3.2.2.3 Mapping of Local Links

The mapping of local links can be done efficiently while performing the global mapping. The procedure performed by a repeater is as follows: whenever a repeater receives (correctly) a PAP, it extracts the last hardwired ID of the ordered sequence in the packet and records it. That is, even when the repeater does not accept the packet for relaying (e.g. when same has been handled recently), the repeater nevertheless extracts the link information. This procedure may also be utilized in a network with mobile repeaters and stations, in which case the repeater may discard some (keeping only the latest information) or all the links after a time interval. Some properties of this procedure are discussed below.

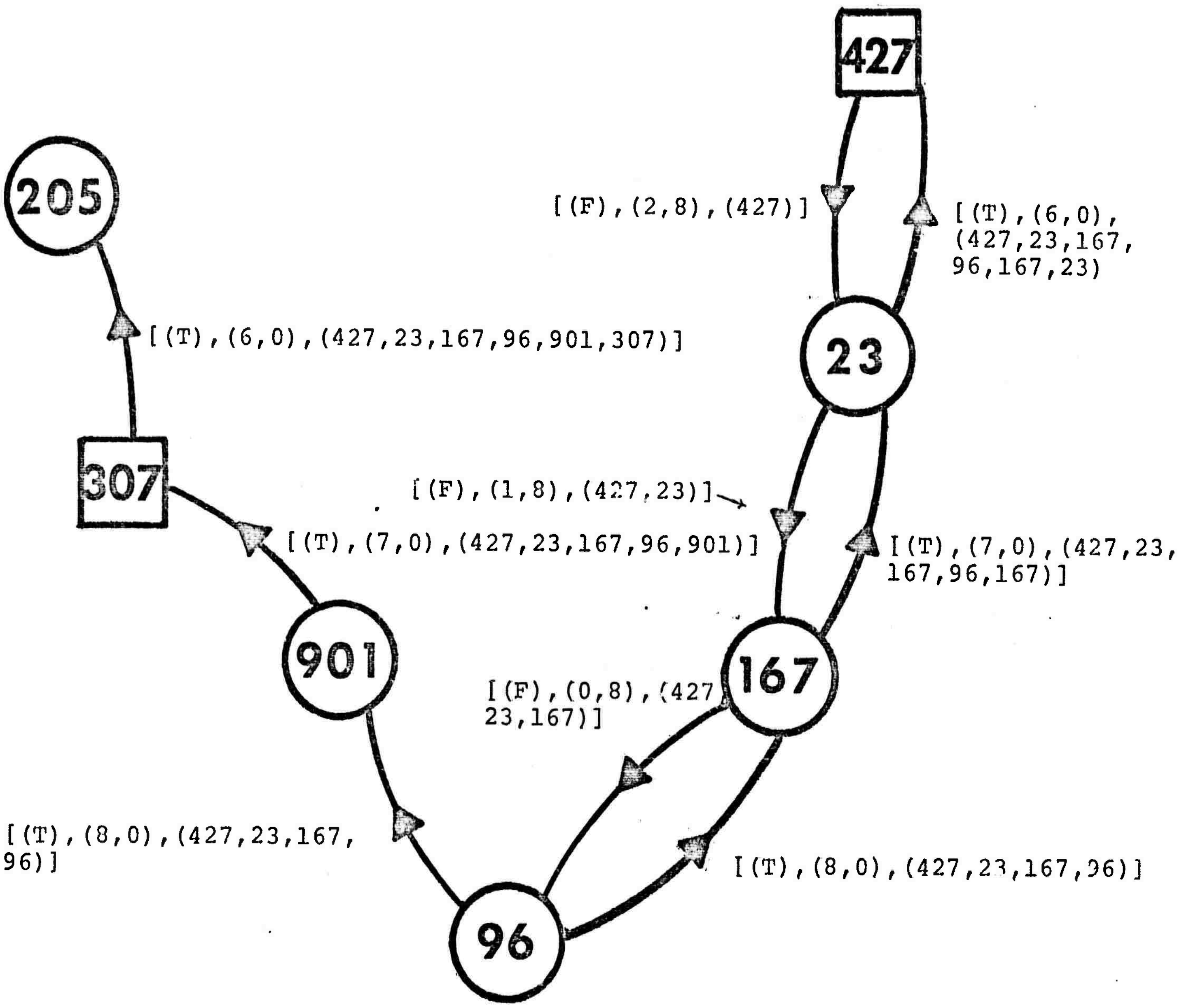


FIGURE 3.1: AN EXAMPLE OF PAP TRAVERSAL

[(DIRECTION BIT),(MHN1,MHN2),(SEQUENCE OF HARDWIRED IDs)]

○ - REPEATER, THE NUMBER IS THE HARDWIRED ID

□ - STATION, THE NUMBER IS THE HARDWIRED ID

The procedure seems very economical in terms of channel utilization because all the information generated during the global mapping is locally recorded in repeaters. That is, much of the connectivity information generated during the global mapping will otherwise not reach any station for the following reasons:

a. All the path packets which reach repeaters with a handover number equal to zero and a direction bit pointing toward a station are discarded.

b. Many path packets will not reach stations even when the handover number is large; if the network is traffic saturated, the packets are discarded after a maximum number of transmissions.

c. The procedure records more links than the total number recorded in path packets as shown in Figure 3.2.

Suppose that R1 has the path packet which has not yet been repeated by R2, R3, and R4. Further, suppose that R1 transmits the PAP and that it is correctly received by R2 and R3, which process the PAP and begins to transmit it. R4 can receive the PAP from either R2 or R3 but not from both (same UPI). If R4 receives the PAP from R3, then the links recorded in the PAP are R1 ro R3 and R3 to R4. All other links which are generated in the process of forwarding the packet are not recorded.

The procedure proposed reduces the time needed for mapping the network topology because the global mapping and the local mapping are done simultaneously.

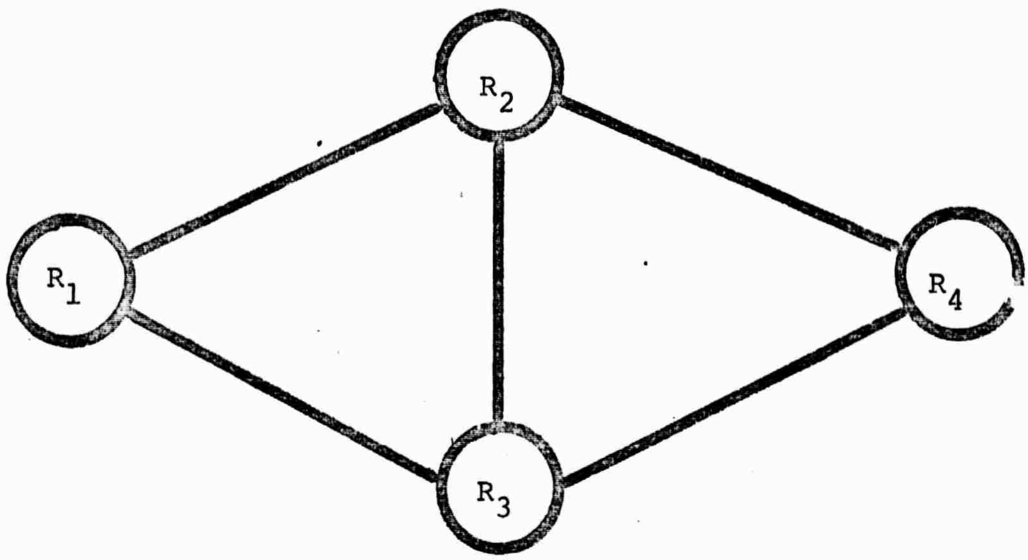


FIGURE 3.2: THE LINES SHOW EXISTING POINT-TO-POINT LINKS

3.2.3 Optimum Labeling of Repeaters

3.2.3.1 Non-Optimality of First Generation Labels

We demonstrate that the initialization and labeling algorithms which were proposed for implementation in the experimental system (Chapter 2) do not guarantee an optimality labeled network, and we propose an algorithm for optimizing the network structure.

Recall from Chapter 2 that the Label Algorithm was classified as "a local optimum algorithm for a given state of initialization." Specifically, the algorithm determines a hierarchical label for a single repeater at a time and finds "the minimum hop feasible label," given a state of network initialization. Furthermore, the station programs attempt to label a repeater as soon as one is identified, and there are no provisions for testing the optimality of the entire network and for relabeling labeled repeaters.

Figure 3.3 shows an example of a packet radio network which is not optimally labeled for hierarchical routing. The optimum structure (using the "minimum hop criterion") will consist of R3 connected for routing to R4 rather than to R2. Several practical cases which may result in a network labeled as in Figure 3.3 are given below (many other cases can be demonstrated):

Case 1: R4 is newly introduced into the network.

Case 2: The network was optimally labeled, R4 went temporarily down which results in relabeling R3 to R2. When R4 comes up again the network will remain non-optimally labeled.

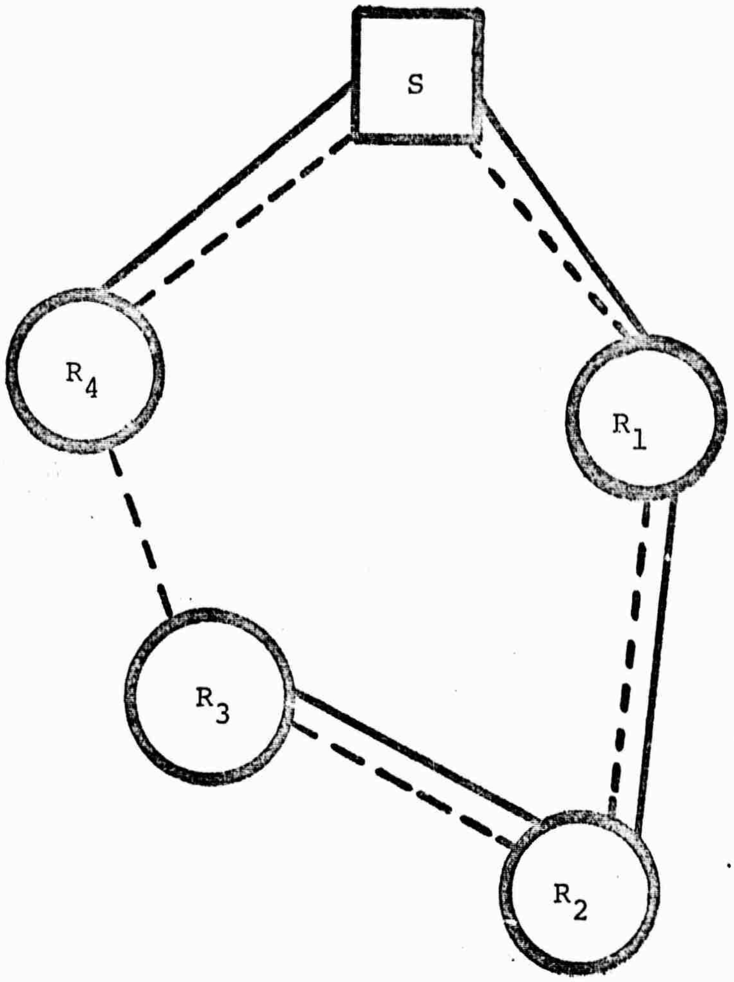


FIGURE 3.3: NON-OPTIMUM LABELS

- - - - EXISTING LINK

——— LINK ASSIGNED FOR HRA BY LABELS

Case 3: Assume that TROP is much greater than the average delay of packet transmission per hop and much greater than the processing at the station for determining a label. With the above assumption, the distribution time of ROP originations (by the set of repeaters) can be such that R4 (note there is no stimulation by the station) is discovered last by the station. This will result in the non-optimum structure shown in Figure 3.3.

3.2.3.2 A Criterion for Optimum Network Labels

The criterion and the algorithm of the next section are described for a single station case. This is because each station will use the algorithm independent of other stations; hence, each station attempts to optimize the paths towards it, or the set of labels assigned by it.

Notation:

R(i): A repeater whose index is i

HL(i): Hierarchy level

LL(i): Hierarchical label

SINIT(i): State of initialization of repeater as seen by the station;

$$\text{SINIT(i)} = \begin{cases} \text{S0: Non-initialized} \\ \text{S1: In initialization process} \\ \text{S2: Initialized} \end{cases}$$

SUCC(i): The values of subfield HL(i) + 1 of successors of R(i)

$$C = \begin{cases} (C(i,j)) = \text{Pairwise connectivity matrix between repeaters} \\ C(i,j) = 1 \text{ if } R(j) \text{ can directly receive from } R(i), \text{ and 0 otherwise.} \end{cases}$$

DEFINITION (Repeater Norm): The norm of repeater R(i) is defined as its number of hops from the station on the path corresponding to its label, we denote the norm by NO(i): NO(i) = HL(i) - 1.

If R(i) is not initialized or in the process of initialization, NO(i) = ∞. Also, the norm of the station PR is 0.

We note that the norm of a repeater, as well as other values associated with it, is seen by a particular station; thus, a repeater will generally have different norms at different stations.

A label of R(i), LL(i), is said to be feasible if for every R(k) along the path defined by LL(i), SUCC(k) $\leq$ (2**B) - 1. Let S be a set of connected repeaters (we always assume that the station-PR belongs to the set); that is, if R(i) is in S, there exists an R(j) in S, such that C(i,j) = 1. We associate with S a set of labels L(S), one for each repeater in the set. We say that L(S) is a feasible set of labels if: (a) NO(i) < ∞ for every R(i) in S, and (b) every LL(i) in L(S) is feasible. Note that a connected set of repeaters may not have a feasible set of labels; for example, if 2**B or more repeaters are connected to the station-PR and no repeater is connected to any other repeater in the set.

DEFINITION (Optimum Set of Labels): Let S be a set of connected repeaters, L(S) a feasible set of labels of repeaters in S, and F(S) the family of all feasible sets of labels. We say that L*(S) in F(S) is an optimum set of labels if:

$$D(L^*(S)) = \text{Min}\cdot D(L(S)), \text{ over all } L(S) \in F(S) \qquad (3.1)$$

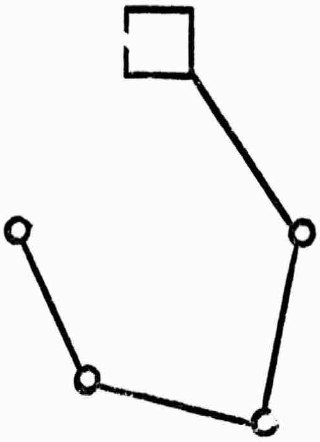
where:

$$D(L(S)) = \sum NO(i), \text{ over all } i \text{ such that } R(i) \in S \text{ and } LL(i) \in L(S) \qquad (3.2)$$

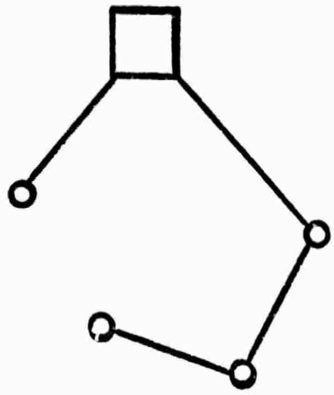
The summation in (3.2) is over labels which belong to the same feasible set L(S). The above definition considers a set of labels as optimum if the total number of hops from repeaters to the station PR is smallest.

EXAMPLE: Figure 3.4 shows the communication paths formed by the five sets of feasible labels which comprise the family F, for the network with the connectivity shown in Figure 3.3. The value of the measure D is shown for each set of labels, and the optimum set of labels for this network is the set which corresponds to the paths in (c).

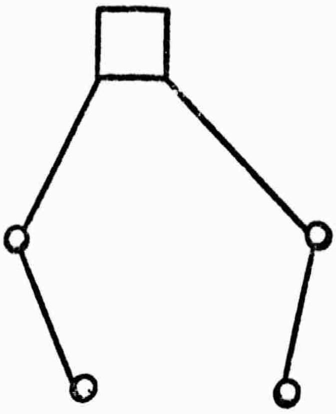
Note that the defin tion of the optimum set of labels implies that the optimum is not necessarily unique. Figure 3.5 shows a case in which R5 is the only unlabeled repeater. If R5 is labeled on R3



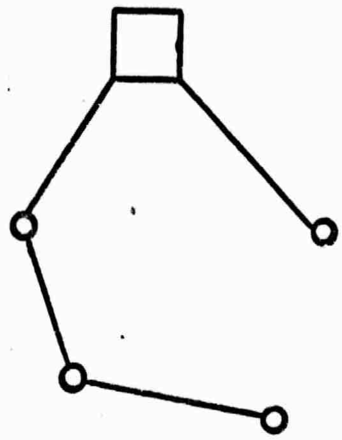
(a) D = 10



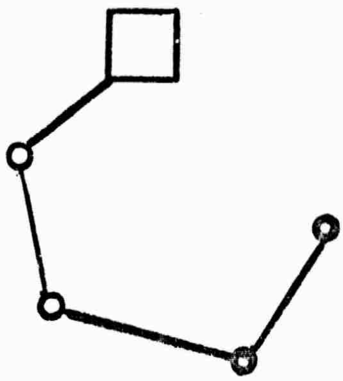
(b) D = 7



(c) D = 6



(d) D = 7



(e) D = 10

FIGURE 3.4: THE POSSIBLE SETS OF LABELS FOR THE NETWORK OF FIGURE 3.[illegible]

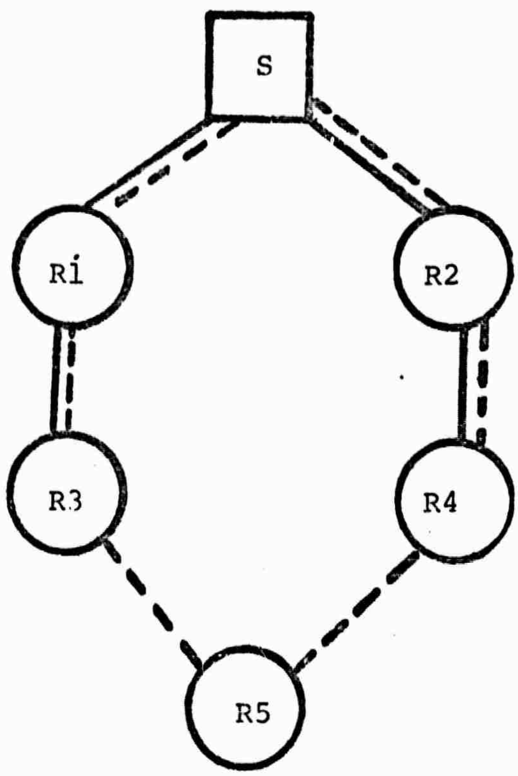


FIGURE 3.5: OPTIMUM LABEL NOT UNIQUE - AN EXAMPLE

- - - - - EXISTING LINK

———— LINK ASSIGNED BY LABEL

or on R4 we obtain two corresponding sets of feasible labels, each of which is optimum by the definition.

It is clear from the definitions that if there exists a connected set of repeaters and the number of connections of each repeater to other repeaters in the set is less than 2**B - 1, then every set of labels for the set of repeaters is feasible, one of which is the optimum.

3.2.3.4 A Station Algorithm for Optimum Relabeling

Recognizing that the set of labels assigned to repeaters may not be optimal (by the definition of the previous subsection), we propose an algorithm for periodically testing the optimality of the set of labels assigned to repeaters and deciding whether the network should be relabeled. To state the algorithm, one needs to specify the period at which the optimality will be tested and a measure of departure from the optimum set of labels which will be used to decide whether the network should be relabeled.

DEFINITION: Let Da and Db be the values of Equation (3.2) for sets of labels La(S) and Lb(S), respectively. The distance measure between the two sets of labels is defined by:

$$M = M(Da, Db) = |Da - Db|$$

where:

$|\ |$ denotes the absolute value.

We assume that the procedures outlined in Chapter 2 which attempt to label a repeater as soon as identified are used here as well. However, periodically an algorithm of the form stated below will be applied.

Algorithm:

Let $Se = \{R(i): SINIT(i) = S2\}$

0. Compute De:

$$De = \sum_{R(i)\ \varepsilon\ Se} NO(i) = \sum_{R(i)\ \varepsilon\ Se} (HL(i)-1)$$

1. Compute the Optimum Set of Labels Lo(S), where S is the set of active connected repeaters.

2. Compute:

$$Do = \sum_{R(i)\ \varepsilon\ Se} NOo(i) = \sum_{R(i)\ \varepsilon\ Se} (HLo(i)-1)$$

where NOo(i) and HLo(i) are the norm and hierarchy level of repeaters with labels of the set Lo(S).

3. If $M = |Do-De| \leq Mt$, go to (5);

4. Relabel the network;

5. End.

Remarks:

1. The test of optimality in Step 3 is the distance measured between the existing set of labels and the optimum set of labels for the set of initialized repeaters. This distance is compared with a threshold Mt to determine

whether relabeling should be done. The algorithm and/or the test can be generalized. For example, one may want to relabel repeaters only if they are K or less hops away from the station, using the argument that the bottleneck is near the station so that non-optimum labels which are many hops away from the station are not significant. The latter will involve a different selection of the set Se to be used in the algorithm. Another consideration for deciding whether to relabel may be the number of active terminals currently in the system, in which case, the threshold Mt may be a function of the number of active terminals.

2. The algorithm for finding the optimum set of labels is different from the Label Program of Chapter 2, in that one ignores the fact that the network is partially initialized and one finds the set of labels for the whole set of connected repeaters simultaneously. Such an algorithm has been developed, programmed, and tested at Network Analysis Corporation [NAC, 1973].

3. The interval at which the above algorithm is applied is a matter of subjective judgment, which depends upon several factors, e.g., the mobility of network devices (repeaters and stations). If we assume that network devices are stationary or moving slowly, we recommend the following procedure:

Let To = K x TROP, where K is a parameter valued from 10 to 20. When the station comes up, and after the discovery of each new repeater, an event is rescheduled for t = Current TIME + To, at which time the algorithm will be applied. Note that the algorithm will be applied only if no new repeater has been discovered for a period of To seconds. This procedure implies that under fairly general conditions, the consideration for relabeling the network takes place after all repeaters (which can be discovered) have been discovered by the station. Another consideration for determining the time at which the algorithm should be applied may be a function of departures of regular packets from primary paths, as observed at the station.

3.2.4 Discussion

We briefly state the improvements in efficiency and/or the additional capabilities provided by adding the set of functions of this section to the original set in Chapter 2.

1. More complete mapping of network topology by utilizing PAP's and the Local Mapping of Links procedure.

2. Item 1 and the algorithms for testing optimality and obtaining an optimum set of labels, will result in an optimally labeled network and consequently a higher maximum utilization of the channel capacity.

3. Faster network initialization and faster adaptation to changes in network topology due to the stimulation by the station in using PAP's.

4. The more complete topological mapping which can be obtained by the procedures of this section is particularly significant when one wishes to use a different routing algorithm, e.g. the Directed Broadcast Algorithm described in Chapter 4.

3.3 MONITORING STATUS OF NETWORK DEVICES AND CONNECTIVITY

3.3.1 General

Network topology and repeater status information (and station status information in multistation systems) is needed in order to establish and maintain feasible and efficient routes between repeaters and (active) stations. Terminal status and activity information is needed for the delivery of packets from station to terminal, and for stability control.

The objective of the status and connectivity monitoring activity is therefore to maintain, in the station, the updated information of active terminals and repeaters, and of network connections. In a multistation system, each station (and possibly each repeater) must also monitor the status of the other stations.

In this section we first describe monitoring procedures for the single station system, and discuss the capability of the system to detect and adjust to network changes such as failures and repeater relocation. We then extend such procedures and apply them to multistation operations.

3.3.2 Monitoring Status and Connectivity of Repeaters

3.3.2.1 Repeater Monitoring

For the efficient operation of the PRNET, the station must keep and periodically update the directory of active repeaters, and maintain fresh information of network topology. This is achieved, in part, via repeater status monitoring. In the sequal, two alternative procedures for repeater status monitoring are described and compared.

The simplest technique for repeater status monitoring consists of inspecting the ID's of all ROP's received at the station.

Recall that each repeater emits a ROP (Repeater On Packet) at regular intervals of TROP seconds. The ROP packet is forwarded to the station by the neighbor repeaters that hear it. Each ROP contains the hardwired ID of the originating repeater and the label (or ID) of the neighbor who forwarded it to the station.

Upon receiving a ROP, the station updates the repeater directory accordingly. More precisely, the station reads originator ID from ROP and updates the parameter TRLH (Time Repeater Last Heard) for the corresponding repeater. The repeater directory is periodically checked for old time stamps. Repeaters that have been silent for more than a specified time interval are declared dead, and are eliminated from the active repeater directory. A detailed discussion of the repeater monitoring routine is presented in Chapter 2.

As an alternative to the ROP inspection procedure, the station may monitor the status of repeaters by observing regular network traffic. A possible technique based on this approach is described in the sequal.

For each repeater in the active repeater directory, the station maintains and periodically updates two parameters:

a. The Activity (ACT) parameter, and

b. The Alternate Path (AP) parameter.

At the beginning of an observation interval, ACT and AP are set to zero. The following update procedure is then applied:

ACT(k) is set to 1 whenever the station receives a packet originating from repeater k (or from a terminal associated with repeater k) which followed the primary route (note: the station can detect a primary route departure from departure information in the packet header).

AP(k) is set to 1 if the packet originating from repeater k (or from an associated terminal) departed from the primary route. At the end of the observation period, the station scans the list of active repeaters for k = 1,...NN, where NN is the total number of active repeaters. If ACT(k) = 1, then ACT(m) is set to 1, for all m on the primary path from k to station. Next, ACT(k) is set to 1 for all k such that AP(k) = 1. At the end of this procedure, we classify repeaters under three categories:

1. ACT(k) = 1, AP(k) = 0: Such repeaters are alive and OK.

2. ACT(k) = 1, AP(k) = 1: Such repeaters are alive, but some difficulty was encountered along the path to station. The station might further investigate the path.

3. ACT(k) = 0, AP(k) = 0: Such repeaters did not handle traffic during the last observation interval.

The repeaters in Classes 1 and 2 are declared active. Repeaters in Class 3 require further interrogation from the station to determine whether they are active or dead.

Finally, the ACT and AP bits are reset to zero, and a new observation period is started. The update frequency is properly chosen so as to optimize the tradeoff between timely status information and update overhead.

The selection between the traffic observation approach and ROP approach should be based on the tradeoff between station overhead due to the observation of all regular traffic, and network channel overhead due to the periodic emission of ROP's. Indeed, the ROP implementation may be required for other reasons beside repeater status monitoring (for example, connectivity monitoring). In such cases, the traffic observation procedure may be efficiently combined with the ROP procedure to reduce ROP traffic overhead (for example, the frequency of ROP emission may be reduced when a repeater is traversed by regular network traffic).

3.3.2.2 Network Connectivity Monitoring

The station stores a connectivity data base (e.g., the connectivity matrix) containing the information of all active network links. Links are directed, and are identified by a source-sink pair. The connectivity data base is used to determine effective hierarchical routes in PRNET. The purpose of the connectivity monitoring activity is to maintain, in the station, an updated version of such data base.

In second generation PRNET's, the station can obtain and monitor network connectivity more promptly and accurately than in the experimental version, using new capabilities offered by BRA (Broadcast Routing) and PAP (Path Packet). In particular, the station may implement the following connectivity monitoring procedures:

1. Extraction of connectivity information from ROP packets, and

2. Delivery of a PAP (Path Packet) to the repeater under consideration, followed by a DUMP packet to collect local mapping information.

The first procedure is based on ROP's. The station, upon receiving a ROP, extracts the ID of the originating repeater and the label of the relaying repeater, and marks as active the link corresponding to such repeater pair in the connectivity matrix.

The second procedure employs the PAP described in Section 3.2. A PAP is issued from the station to the repeater whose connectivity is being monitored. Routing from station to repeater is hierarchical. Upon arrival at the repeater, the direction bit is reversed and broadcast routing is used, with MHN = 2. Typically, the PAP will not be able to return to the station (e.g., if the station is more than two hops away). However, the copies of PAP that, during broadcast routing, are reflected from the neighbor ID's (see Section 3.2). A DUMP packet is later issued by the station to the repeater to collect the neighbor ID list. From such a list, the links from repeater to neighbors are entered in the connectivity matrix.

The two above-mentioned procedures can be implemented and performed concurrently. The ROP procedure provides a continuous monitoring capability required to detect unexpected (or not easily predictable) connectivity changes deriving from situations such as repeater or link failure, repeater relocation, etc.

The Path Packet procedure, on the other hand, is used by the station when a more complete (or faster) mapping process is required such as: network initialization or periodical refreshing of connectivity matrix and labels.

Both ROP and PAP procedures enable the station to detect the links that are up. They do not notify the station when a link goes down. In order to maintain an updated version of the connectivity matrix, we need a procedure to eliminate links that are no more valid. A simple refresh procedure consists of periodically resetting to zero one row (or column) of the connectivity matrix, and issuing a PAP to the corresponding repeater to obtain a more recent local mapping. After an appropriate time interval (sufficiently long to allow regeneration of the connectivity matrix), the validity of the repeater label is also verified.

The monitoring procedures described here are adequate to protect a single station system against link and repeater failures, and enable it to adjust to installation of new repeaters (in an already initialized network) and to detect repeater relocation. The following sections discuss some examples of network recovery and adjustment to topological changes.

3.3.2.3 Mapping an Unlabeled Repeater in a Labeled Network

An unlabeled repeater can be found in a labeled network for one of the following reasons:

1. The repeater was not detected by the global procedure, or

2. The repeater was installed in an already initialized network.

The unlabeled repeater does not relay regular packets, but makes its presence known to the station via ROP's.

The station, upon receiving the first ROP and verifying that it contains a new ID, attempts to assign to the new repeater a label homed on the repeater that relayed the ROP. If such a label is not feasible, the station can wait for more ROP's to come from the new repeater, or can issue a PAP, in order to gain more information on local mapping. Eventually, the station will succeed in homing the new repeater onto one of the neighbors; in some rare event, this may require relabeling of some of the neighbors.

Some applications may require the installation of redundant repeaters, which are kept in the unlabeled status until they need to be made operational for area coverage. The station maintains and updates the connectivity of the unlabeled repeaters much in the same way as it does for labeled repeaters, using the ROP procedure.

3.3.2.4 Monitoring Link Failures

During the life of the PRNET, an existing RF link between two repeaters may fail (i.e., may become disrupted) because of any of the following reasons:

1. RF power reduction.

2. Obstacles on the RF path.

3. Mobile repeater relocation.

We may distinguish between links which are on hierarchical routing paths (i.e., links actively used for packet routing) and links which are not on a hierarchical routing path.

For the link failures not on the hierarchical path, we may rely on a relatively slow detection and monitoring procedure such as the periodic connectivity matrix refresh. For link failures on the path, we need a faster detection mechanism to enable the prompt correction of routing labels and establishment of a valid path.

If the link failure on the primary path is in the direction to the station, or if it is in both directions (which is the most frequent case), the station can promptly detect such failure from packet departures from the primary path.

Upon link failure, packet departures will occur. The station thus can identify the suspect repeater from the "departure field" in the header of the incoming packet and perform a connectivity and label refresh on it. A station algorithm for "departure" monitoring is described in Chapter 2.

In summary, the periodic refresh of connectivity and labels is sufficient to ensure connectivity and routing label consistency at steady state. However, the departure monitoring technique is a desirable complement to the refresh technique when link failures and connectivity changes occur at a faster rate than the refresh activity (e.g., mobile repeaters). In general, the implementation of the departure monitoring feature in the station may warrant the reduction of the refresh frequency, and thus reduce station and PRNET overhead.

3.3.2.5 Monitoring Mobile Repeaters

The relocation of a repeater may disrupt its original connections. In particular, it may disrupt the link on its primary path to the station. If the speed of the repeater is not too high (e.g., $\leq$ 100 miles per hour) the recovery techniques described in the preceding section enable continuous tracking of the repeater from the station. If the station knows (or learns) that a repeater is mobile, it can make traking more effective by reducing the TROP interval of such repeater and by refreshing its connectivity and label more frequently than for static repeaters. Furthermore, to avoid extensive relabeling after each relocation, the station will usually not label stationary repeaters to "home" on mobile repeaters.

3.3.2.6 Recovery From Station Failure

When the station comes up after failure, it may have lost the network connectivity information and the repeater and terminal active directories. In such case the network must be reinitialized. Network reinitialization differs from initialization of an unlabeled net in that repeaters are labeled and may carry regular (residual) traffic. It can be readily seen, however, that global and local mapping procedures based on ROP's and PAP's are independent of labeled or unlabeled status of repeaters and presence of regular traffic. Therefore, such procedures can be applied also for reinitialization.

3.3.3 Monitoring Terminal Status and Connectivity

The station keeps a directory of active terminals. For each active terminal the homing repeater (i.e. the repeater through which the terminal last communicated) is also registered.

Terminal activity information is needed in order to remove terminals that are no longer active, and thus free some slots for new terminals. Homing repeater information is needed in order to deliver packets from station to terminal. A simple procedure for terminal monitoring is described in the sequal.

For each packet that arrives from PRNET, the station reads the terminal ID (internal ID assigned by the station, at terminal log-in, different from the fixed handwired ID of the terminal PR), and updates time stamp and homing repeater label. Time stamps are periodically checked, and terminals that have been silent for a specified interval of time are interrogated by the station. If a terminal fails to answer after several interrogation trails, it is declared dead and eliminated from the active list.

An example of terminal monitoring implementation is described in Chapter 2.

A mobile terminal is continuously tracked by the station by virtue of the fact that its homing repeater is updated in the terminal directory after each packet received from the terminal. Clearly, the rate of regular data packets from the mobile terminal must be sufficiently high so as to maintain up-to-date homing repeater information in the station. If regular data packet rate is not sufficient, artificial "tracking" packets may be used. As an alternative, broadcast routing may be employed when terminal speed is very high and packet rate very low (sensors, alarms etc.).

3.3.4 Connectivity Monitoring in Multistation Nets

Multistation functions and requirements are not yet completely defined at this stage of PRNET development. Therefore, a thorough investigation of alternative connectivity monitoring procedures for the multistation environment is premature. Here, instead, we address the more limited issue of how to extend single station procedures to enable some basic multistation operations.

First, we recall that the fundamental motivations for installing more than one station in a PR system are:

1. Station redundancy (for reliability), and

2. Load balancing among stations.

Stations communicate with each other via PRNET and/or via a High Level (HL) packet network (point-to-point packet switched or packet satellite broadcast network). Terminals in the PRNET communicate with each other through a common intermediate PRNET station or through two different stations. In the latter case, interstation communication can be either via PRNET or via HLNET.

In order to satisfy the basic multistation requirements of reliability, load sharing capability and interstation communications via PRNET, each repeater stores several labels, in the limit one for each station (in practicality, three labels are deemed more than adequate for reliability and load sharing purposes). The labeling of a repeater by more than one station is described in Chapter 4.

Each station keeps a directory of all repeaters to which it has assigned labels. Repeater status monitoring is based on the ROP mechanism already discussed for the single station case.

As a difference from the single station procedure, the multistation ROP procedure requires that each neighbor, upon receiving a ROP from the originating repeater, relays the ROP to all the stations by which it has been labeled. This may be accomplished either by sending a different copy of ROP to each station, using HRA (Hierarchical Routing), or by issuing only one ROP via BRA (Broadcast Routing), with MHN set equal to the hop distance to the most distant (in hierarchical level sense) labeling station. The selection between multiple ROP copies via HRA or single ROP copy via BRA will depend upon traffic overhead considerations (see also Section 3.2).

Connectivity monitoring is performed in the same way as in the single station case, using ROP's and PAP's.

Load sharing among stations is based on the nearness criterion. The repeater which receives a packet from a terminal will always deliver such packet to its primary station (unless the terminal specifies a preferred station). Intermediate repeaters along the path relay packets as specified in the label.

For reliability of repeater to station communications, repeaters must be able to determine when the primary station is down, and thus switch to another station. The following alternative approaches can be proposed for station status monitoring:

1. Checking for old labels by the repeaters (distributed approach).

2. Interstation monitoring and station to repeater notification (centralized approach).

The first technique consists of timing out old labels in the repeaters. (This approach assumes that each label is periodically refreshed by the station.) When a label is too old, the repeater, suspecting a failure, resets the hop distance of the corresponding station to a very large number. As a consequence, the repeater may still relay transit traffic to the station, but will not accept packets from terminals requesting such station. With this procedure, all the incoming traffic will eventually be switched to the second nearest station.

The second technique assumes that each station monitors (by periodical interrogation, for example) the status of the stations that have labeled its PR. If Station A, say, does not hear from Station B for a specified time interval, it decides that Station B is down, or it has become disconnected from PRNET. It then sends to all repeaters in its directory (i.e., all the repeaters that carry the label of Station A) a label packet with the ID of B, and a fake label with very large hop distance. As a consequence, all the repeaters that were associated with B are forced to reselect a new primary station.

3.3.5 Conclusion

In second generation PRNET's we postulate the existence of more powerful repeaters than in the experimental PRNET. This additional hardware capability, together with the experience gained during the Local Area Demonstration will enable the development and implementation of efficient second generation monitoring procedures, as opposed to the simple and robust, but rather inefficient procedures applied in the first PRNET phase.

The introduction of the Path Packet (PAP) protocol will speed up the network initialization process and make network monitoring more complete and effective. Furthermore, the presence of Broadcast Routing (BRA) will facilitate communications with repeaters and terminals moving at high speed.

Second generation PRNET's will be equipped with multiple stations for redundancy and load sharing. Effective network monitoring in a multistation environment is a challenging problem. In this section we have discussed some multistation alternatives derived from the single station implementation. Further research is required in the following areas:

1. A clear definition of the objectives of multistation operations,

2. Identification of alternative multistation monitoring procedures, and

3. Evaluation of such alternatives (via analysis and simulation) following the criteria of effectiveness, overhead and simplicity of implementation.

3.4 STABILITY CONTROL PROCEDURE

3.4.1 General

The function of the Stability Control Procedures is to prevent the PRNET from becoming congested due to excessive input rates from PRNET terminals or HL (High Level) network gateways. The procedures regulate input rates and distribute load among gateways (in a multistation system) so as to maintain stable network operation and yet provide satisfactory throughput and response time performance.

The design criteria for stability control algorithms in PRNET are similar to those of other packet networks. In particular, in a lightly loaded network, such algorithms must have minimal impact on network performance, where performance is measured in terms of:

1. Response time for interactive users and real time applications.

2. Bandwidth for bulk data transfers.

When traffic load increases, the algorithms must guarantee the following characteristics:

1. Graceful performance degradation.

2. Fairness with respect to users in the same priority class.

Chapter 2 provides a description of "first generation" stability control procedures proposed for the experimental PRNET implementation. Such procedures were developed following the criteria of robustness and simplicity rather than efficiency.

The "second generation" stability control design will expand the first generation model to include the following issues:

1. Automated control of network parameters from station(s).

2. Load balance among stations.

3. Coordination of station controls in multi-station environment.

4. Control of end-to-end protocol parameters for stability.

Furthermore, second generation algorithms will be aimed at optimizing the trade-off between performance and stability.

At this stage, it is premature to propose final second generation algorithms. In fact, the operational environment and functions of multi-station PRNET have not been completely defined. Furthermore, we need to gain more insight into the stability characteristics of a single station PRNET via simulation and measurement experiments.

In this section, therefore, we limit ourselves to possible extensions of single station procedures and new trends to satisfy future requirements. The reader is referred to Chapter 2 for the station buffer management procedures, repeater, input rate control, and the network operating parameters.

3.4.2 Stability Control Functions

The stability control of PRNET results from the combination of various types and levels of control. The organization of these control functions in a (possibly hierarchical) structure, as it was done for other PRNET protocols, is not attempted here, since the interrelationship between different functions is not yet well defined.

A preliminary classification of stability control functions is the following:

1. Control (from station) of network parameters related to stability.

2. Repeater input rate control.

3. Station buffer management.

4. Control of Intranet (terminal to station) protocol parameters.

5. Multistation load balancing control.

A general (and somehow vague) characterization of the global stability control procedure is that of monitoring an appropriate set of network variables, and of implementing network traffic and resource allocation controls by means of the previously mentioned control functions.

In a single station system, most of the control decisions reside in the station. In a multi-station system, some of the control decisions may be distributed among all stations, while other decisions (e.g., station load balancing) may be centralized in one "master" station. Some simple control decisions may also be distributed among repeaters.

3.4.3 Monitoring Network Variables

The station monitors some or all of the following variables:

1. Packet input rates (from PRNET and HLNET, separately).

2. Packet output rates (to PRNET and HLNET, separately).

3. Rate of packet departures from primary path.

4. Terminal traffic activity.

5. Repeater traffic activity.

6. Number of active repeaters.

7. Number of active terminals.

8. Number of terminals homed onto a given repeater.

9. Size of queues in the station.

10. Number of station free buffers.

The values of the above variables are used as inputs to a global control strategy. Subsets of the above variables are used as inputs to the individual control functions.

3.4.4 Control of Intranet Protocol Parameters

Intranet transmission protocols provide reliabile terminal-to-station communications by means of end-to-end acknowledgment, duplicate packet detection, and possibly, buffer reservation at the station.

The presence of intranet protocols is clearly beneficial to network stability in that it provides an additional control on terminal input rates through the terminal-station acknowledgment mechanism. In particular, if the protocol implementation allows an adjustable window of outstanding, non-acknowledged packets on the link from terminal to station, the window size becomes a very effective stability control parameter.

If the network is lightly loaded, window size is allowed to be large to optimize bandwidth. If the network is heavily loaded, window size can be reduced to unity to limit terminal input rate. Similarly, window size can be reduced when station buffers are scarce, to limit buffer overflow probability, retransmissions, and therefore, network overhead.

Intranet protocols, beside having a substantial impact on PRNET stability, provide significant bandwidth improvements in internet (process-to-process) communications. The selection of a specific intranet protocol, therefore, is based not only on stability, but also on throughput performance considerations.

3.4.5 Multi-station Load Balancing

In a multi-station system, repeaters are assigned to stations according to min hop distance. If the traffic pattern is non-uniform, it may occur that the min hop assignment does not yield a balanced load distribution among stations. An uneven distribution of load may reduce network performance and lead to instability, and must be corrected by readjusting the assignment of repeaters and terminals to stations.

The issue of optimal load balancing in a multi-station environment can be properly discussed only after all other multi-station protocols (e.g., intranet and routing protocols) are defined. Some limited load balancing capability however is already available through previously introduced protocols, and is discussed here.

An overloaded station may reduce its load by disabling the response to new terminals in some of the repeaters within its region (i.e., repeaters for which the station is the "primary"). Such repeaters will then respond to new terminals with the secondary label, since response has been disabled for primary label. New terminal traffic is thus automatically switched to secondary stations.

Similarly, an overloaded station may reduce its load by modifying the hierarchical labels in some of the repeaters within its region (preferably the repeaters on the boundary). For example, the station may reset hop distance numbers to itself to artificial values much higher than the real values. This modification will force the repeaters to select a new primary station.

The above procedures are examples of the distributed load balancing approach, in which a station adjusts its load independently from the actions taken by the other station. The distributed approach may lead to inefficient load leveling and to oscillations. Therefore, the implementation of a centralized type of control may be considered to coordinate the load balancing operations and to ensure stable operating conditions.

3.4.6 Conclusion

In this section, we have identified the need for several stability control functions; namely, control of radio and retransmission parameters, input rate control, gateway buffer control, and multi-station coordination.

For the experimental PRNET, only a simple, dynamic control of repeater input rates has been proposed for implementation. The other controls will be executed manually from the station console, and sensitivity of network performance to parameter changes will be studied as part of the experiment.

In the second generation PRNET, the various control functions will be coordinated and, possibly, integrated in a unified control module. The goal of stability control design will be to achieve the best trade-off between performance and stability.

Second generation stability procedures will be the result of two parallel efforts: the experimental effort during the first PRNET phase, and the research effort based on analytical and simulation models. Important areas of future research are the following:

1. Network performance and stability characteristics at steady state as a function of traffic profile (traffic pattern, traffic volume, etc.), network parameters (topology, number of buffers, connectivity, etc.), and protocols (retransmission, transportation, end-to-end protocols).

2. Dynamic (transient) behavior of network performance following selective changes in network parameters and traffic input rates.

3. Identification of alternative stability control strategies for a single station system and their evaluation (via analysis and simulation) following the criteria of effectiveness, overhead, and simplicity of implementation.

4. Stability in a multi-station environment, development of a station load balancing algorithm, transfer of single station stability concepts and algorithms to the multi-station case.

CHAPTER 4

ROUTING IN PACKET SWITCHING BROADCAST RADIO NETWORKS

4.1 INTRODUCTION

Consider a set of resources (e.g., terminals, computers, human resources) that wish to communicate (i.e., exchange messages). We define the medium via which messages are transported as a communication network. In order to use the network, the resources need a proper interface or connection to the network. Similarly, networks which are not homogeneous (i.e., differ in hardware and/or in the set of rules used for message transportation) need interfaces or gateways if messages are to be transported between them. The notions of gateway, interface, and connection are synonymous as far as their functional need is concerned. We will use the notion interface mainly in the context of a "hardware connection," gateway in the context of a "software connection" between non-homogeneous networks, and connection in a general context of any type of association.

Network tasks related to packet transportation can be classified as follows:

1. Origination and destination functions.

2. Relay functions.

3. Management and control functions.

4. Gateway functions.

The gateway functions are needed only when one considers message transportation between non-homogeneous networks (i.e., when the origination and destination resources do not "reside" in the same network).

We consider store-and-forward packet switching networks in contrast to circuit switching and store-and-forward message switching networks [Miyahara, 1975]. Network elements are communication nodes and communication channels. The network is a packet switching broadcast network as distinguished from a point-to-point packet switching network, such as the ARPANET. Furthermore, it is a radio network as distinguished from a hardwired cable network. The distinguishing characteristics of the network we consider are:

1. A communication channel in a point-to-point packet switching network is associated with two nodes, say channel (i,j) between nodes i and j. Thus, when node i wishes to send a packet to node j, it transmits the packet on the channel (i,j) without the need to specifically address the packet (e.g., via an address field in the packet header) to node j. The notion of a communication channel in a broadcast radio network, on the other hand, cannot be associated with two nodes. A node in a radio network broadcasts the packet (we assume omnidirectional antennas) which may be received by a set of nodes (in fact, all nodes within an effective transmission range from the node that emitted the packet). If node i wishes to send a packet to node j (only), it needs to specify in the packer header: "this packet is addressed to node j, all other nodes should discard the packet". This also implies that when node j receives a packet with error, it does not know that the packet was addressed to it, and consequently cannot request a retransmission of that packet.

2. In a point-to-point network, channel (i, j) is dedicated to nodes i and j; thus, if node i has several packets to be sent to node j, it can queue the packets and use any queueing discipline to transmit them. On the other hand, in the broadcast radio network, we consider the channel shared by all network nodes. One cannot dedicate the channel to a pair of nodes; one can divide the time into non-overlapping intervals, assign to each node an interval for transmission and request each node to receive whenever it does not transmit. Numerous studies, e.g., [Abramson, 1970, 1973, Kleinrock, 1973, Kleinrock, 1975, Roberts, 1973, Gitman, 1975], have shown that this "fixed assignment" of the channel capacity is wasteful for many types of applications of radio networks. We shall, therefore, assume that nodes use a "random access transmission scheme" (see above references) which results in a dynamic sharing of the channel capacity without centralized control. The particular scheme used is of no significance to the issues addressed herein. The random transmission scheme, however, implies that, unlike in point-to-point networks, a radio node can simultaneously receive several packets (on the same channel), all of which may be received in error. This, in turn, implies that the probability of receiving a packet with error is much greater than on a point-to-point channel, and that this probability varies as a function of the traffic level in the network, the spatial distribution of the traffic sources, and the spatial distribution of nodes (assuming a fixed effective transmission range).

The characteristics discussed above, make packet radio networks particularly suitable for applications in which:

a. Resources (e.g., terminals, computers) are mobile, so that a broadcast mode is necessary.

b. Resources are located in remote or hostile locations where hardwire connections are uneconomical or not feasible.

c. The traffic characteristics of resources is of a bursty nature; that is, there is a high ratio of peak bandwidth to average bandwidth requirements.

Specific packet radio networks in the stage of design or in current use were discussed [NCC, 1975].

We say that a network is a "single hop" network if no relay functions are needed at its nodes. Most of the analyses of radio networks address single hop networks, (e.g., [Abramson, 1973, Kleinrock, 1973]), or intentionally avoid the issue of packet routing by proper assumptions [Gitman, 1975]. The issue of packet routing in radio networks was first addressed in [NAC, 1973, 1974, Frank, 1975, Kahn, 1975]. The analysis of multi-hop packet radio networks is extremely difficult and one has to resort to simulation [NAC, 1974], or analyze very simple models for studying some properties of such networks.

Without efficient routing and flow control in large scale radio networks:

1. A packet may endlessly circulate among nodes,

2. Many copies of a packet will be generated, and

3. If we assume that the destination nodes are on another network, then many copies of a packet, and/or

different packets of one message, will arrive at different gateway nodes and be introduced into other networks.

The above paragraphs demonstrate that a broadcast radio network easily be saturated and ceases to fulfill its function. It also implies that the routing and flow control strategies used for packet transportation are of utmost importance in the efficient network operation.

The network model we assume is characterized by a large number of nodes which use a random transmission scheme and share a single channel using omnidirectional antennas. Two types of nodes are assumed. A node with origination, destination, and relay functions, which we call a Repeater; and a node with additional capabilities such as gateway, global control, global initialization, accounting, and directory functions; we call the latter a Station. If one assumes a large geographical area which needs to be "covered" with a communication network for serving mobile terminals, one would recognize that not all nodes need to have all the functions (economy consideration). Repeaters which have limited capabilities are provided for area coverage. Stations are provided on the basis of network capacity requirements through the gateways, and for reliability purposes. Throughout the chapter we avoid discussing terminals, users, or any other resources that the network serves. These sources are not an integral part of the network by our definition and do not directly affect the problems discussed here. It is assumed that the rules of packet transportation in the network are transparent to terminals. Terminals will contain special communication protocols which will enable them to attach themself temporarily or permanently to a network node and be served by it [NAC, 1974].

The problems addressed are: flow control functions related to packet transportation, the rules for packet transportation (routing strategies), and the network architecture implied by the routing. The objectives of packet transportation are:

1. Reliability: Insuring that a packet launched into an arbitrary point in the network will reach its destination with high probability.

2. Efficiency: To be able to deliver a large number of messages with a relatively small time delay.

The above objectives are rather qualitative statements. The reason being that it is extremely difficult to evaluate by analysis the algorithms presented in the chapter. Our evaluation is in terms of general properties which can be deducted from the theoretical presentation of the algorithms. Furthermore, the probability that a packet will reach its destination ignores the task of end-to-end communication protocols which ideally will insure packet delivery via the mechanism of end-to-end retransmission. In general, given two routing algorithms A and B, we say that A is more efficient than B if it uses less network resources (channel and node capacities per packet) than B does. For simulation experiments see [Frank, 1975].

The packet radio routing algorithms have evolved over the last two years. Descriptions of proposed algorithms have appeared in previous NAC reports. This chapter provides an updated summary of current procedures for implementation in the experimental system and in a second generation system. Three algorithms are described: The Broadcast Routing Algorithm which satisfies objective (1) but fails to satisfy objective (2 ; n two algorithms which satisfy both objectives for different traffic patterns. The Broadcast Algorithm may be needed in an operational network as a backup algorithm and/or for initialization of nodes for using the efficient algorithm under general deployment assumptions, possibly with mobile network nodes.

4.2 BROADCAST ROUTING ALGORITHM

Given a packet and its destination, a routing algorithm determines the best node (in some sense, to which to send the packet While in point-to-point packet switching networks, every correctly receive packet is accepted for switching and the routing algorithm then det ines the outgoing line; in radio networks there is almost no decision to make in determining the next node, the decision made by the routing algorithm is whether to accept the packet for switching. This is a property of our radio network model, since many repeaters may correctly receive a packet and the main task becomes to eliminate the "bad" paths rather than to find a "good" one.

The broadcast routing algorithm is merely a flow control procedure which prevents looping and cycling of packets in the network. The following mechanisms are used:

1. A hop-by-hop acknowledgement to guarantee that the packet was accepted by the next repeater.

2. A (maximum) handover number (carried in the packet), which is decremented by a repeater which accepts the packet for switching, and guarantees that the packet will traverse no more than the maximum number of hops assigned.

3. A variable transmission power mechanism which enables to increase the power as a function of the number of transmissions without acknowledgement. The increase in power increases the number of potential receivers.

4. Parameters which control the random transmission scher (e.g., time interval for rescheduling unacknowledged packet, maximum number of transmissions per packet).

5. A time parameter, FORGET, which is the maximum interval of time during which a packet previously switched by a repeater will not be accepted for switching.

We purposely do not outline a strict routing algorithm. The reader may conceive of several algorithms which utilize Items 1 through 5 or a variation of these. Items 1 through 4 are controls which can be recommended for all routing algorithms in radio networks. These, however, do not prevent looping and cycling of packets. The particular mechanism which defines the broadcast routing algorithm is Item 5.

It is assumed that every packet has a unique identifier and that a repeater has storage for a certain number, say L, of unique identifiers. When a packet receives an acknowledgment or is discarded after exceeding the maximum number of transmissions per hop, its identifier and the time are recorded by the repeater. When a new packet is received, its identifier is compared with identifiers stored and with identifiers of packets waiting for transmission. If a match occurs and the elapsed time is less than FORGET, the packet is not accepted for switching. Thus, when the repeater has storage, it accepts a packet for switching if: (i) it did not switch the same packet for at least FORGET seconds, or (ii) it switched L other packets after the arriving packet.

4.2.1 Properties

1. The algorithm is non-directional. There is no addressing along the path, the destination node recognizes that the packet is for it by comparing the destination ID against its own ID.

2. If L and FORGET are large, the packet will not be switched by a node more than once.

3. The advantage of this algorithm is its simplicity and reliability repeaters need not know any information related to network connectivity or the location of the destination node. Furthermore, if the origination and destination nodes are connected, and the maximum hand-over number assigned to a packet is large compared to the shortest path to the destination, there is a high probability that the packet will reach its destination.

4. The algorithm is inefficient as far as network utilization or maximum throughput are concerned because, in general, a large number of duplicate packets will be generated. Moreover, when a packet originated at the radio network is destined for another network, it is probable that copies of the packet will be introduced into other networks by several gateway nodes (stations), unless communication between stations takes place to prevent it.

4.2.2 Discussion

Among the features which take advantage of the radio network and are not possible in point-to-point (PTP) networks are the transmission power control and a special form of hop-by-hop acknowledgment (HBH ack).

The transmission power control enables increase in network connectivity and bypass of failed nodes, thus, increasing network reliability. The HBH ack cannot be directional since the receiving node does not know the ID of the transmitting node. However, there is no need to transmit an acknowledgment packet at all, when the receiving node transmits the packet to the "next" node the packet can also be received by the node which sent the packet to it, the latter recognizes that it is an ack by comparing the identifier of the packet waiting for retransmission.* In fact, this is more efficient than a specific acknowledgment since a single packet transmission can acknowledge several nodes.

The broadcast routing algorithm has the feature of flooding the network (or a subset of it). This feature can be utilized for mapping the network connectivity by stations for the purpose of assigning routing information to repeaters, and thus obtain more efficient routing. It can also be used when a packet must visit every repeater; for example, when a station needs to change parameters in all repeaters. As for permanent use, it is applicable to networks whose nodes are mobile such that updating routing information based on connectivity becomes infeasible.

Finally we note that a flooding routing algorithm for PTP networks was suggested in [Boehm, 1966]. However, it is easy to verify that the broadcast routing for radio networks described here is much more economical, in terms of storage and processing at nodes, since it takes advantage of network properties. The performance comparison is further enhanced in favor of radio networks when one considers HBH acks.

*This form of HBH ack assumes that if node i can receive from node j, node j can also receive from node i. We assume that every node has at least one such link, otherwise it is considered not connected.

4.3 HIERARCHICAL ROUTING ALGORITHM

The main factor which contributes to the inefficiency of the Broadcast Routing Algorithm is its non-directionality property. We attempt to overcome this limitation in the algorithms of this and the next sections.

The assumption that guided the development of the hierarchical routing algorithm is that the radio network will be used for local collection and distribution of traffic. This implies that the traffic pattern in the network is from repeaters to stations (gateways) and from stations to repeaters. If there is a traffic requirement from a repeater to another repeater in the network, its routing towards the destination will be via a station. Among other virtues, this method has the advantage of centralized control.

The essence of the technique is to assign to repeaters routing information, during an initialization procedure, and utilizing this information for routing. We refer to the information assigned to a repeater by a station as "hierarchical label", or "label". The set of labels assigned to the repeater network by a single station forms a hierarchical structure of repeaters, or a tree structure rooted at the station. Labels assigned to repeaters may need to be changed during network operation when changes in network topology occur.

The routing strategy performs shortest path (minimum hop) routing from repeaters to stations and from stations to repeaters, and prevents, wherever possible, duplicate copies of a packet from being generated and/or circulated in the network. However, the routing procedure includes sufficient flexibility so that when the first choice shortest path cannot be used, the packet departs from this path and uses a shortest path from its new location.

4.3.1 The Hierarchical Label

We first discuss the case of a single station. The shortest path routing is obtained by labeling the repeaters to form, functionally, a hierarchical structure as shown in Figure 4.1. Each label includes the following information: (i) a specific address of the repeater for routing purposes, (ii) the minimum number of hops to the station, and (iii) the specific address of all repeaters on a shortest path to the station, and particularly, the address of the repeater to which a packet has to be transmitted when destined to the station.

A label is composed of H fields. A repeater, say R, at a distance of j-1 hops to the station, has a unique label in which the first j fields contain nonzero integers and the remaining H-j fields are zero; we say that R is at level j of the hierarchy. The repeater to which R addresses its packets when routing towards the station is called the "home" of R. The labels of a set of repeaters at level j, which have the same home repeater, differ only in the entry in field j. Thus, the label of the station has a nonzero entry in the first field and a zero in all other fields; the labels of repeaters at a distance of one hop to that station have the station's entry in the first field, nonzero unique entries in the second field, and zero in all other fields, etc. Figure 4.1 shows an example of a labeled set of repeaters which form a tree network for routing purposes.

4.3.2 The Routing Algorithm

Unlike point-to-point routing in which the packet carries the ID of the destination, in the hierarchical routing algorithm the packet carries the path, in the form of the repeater label.

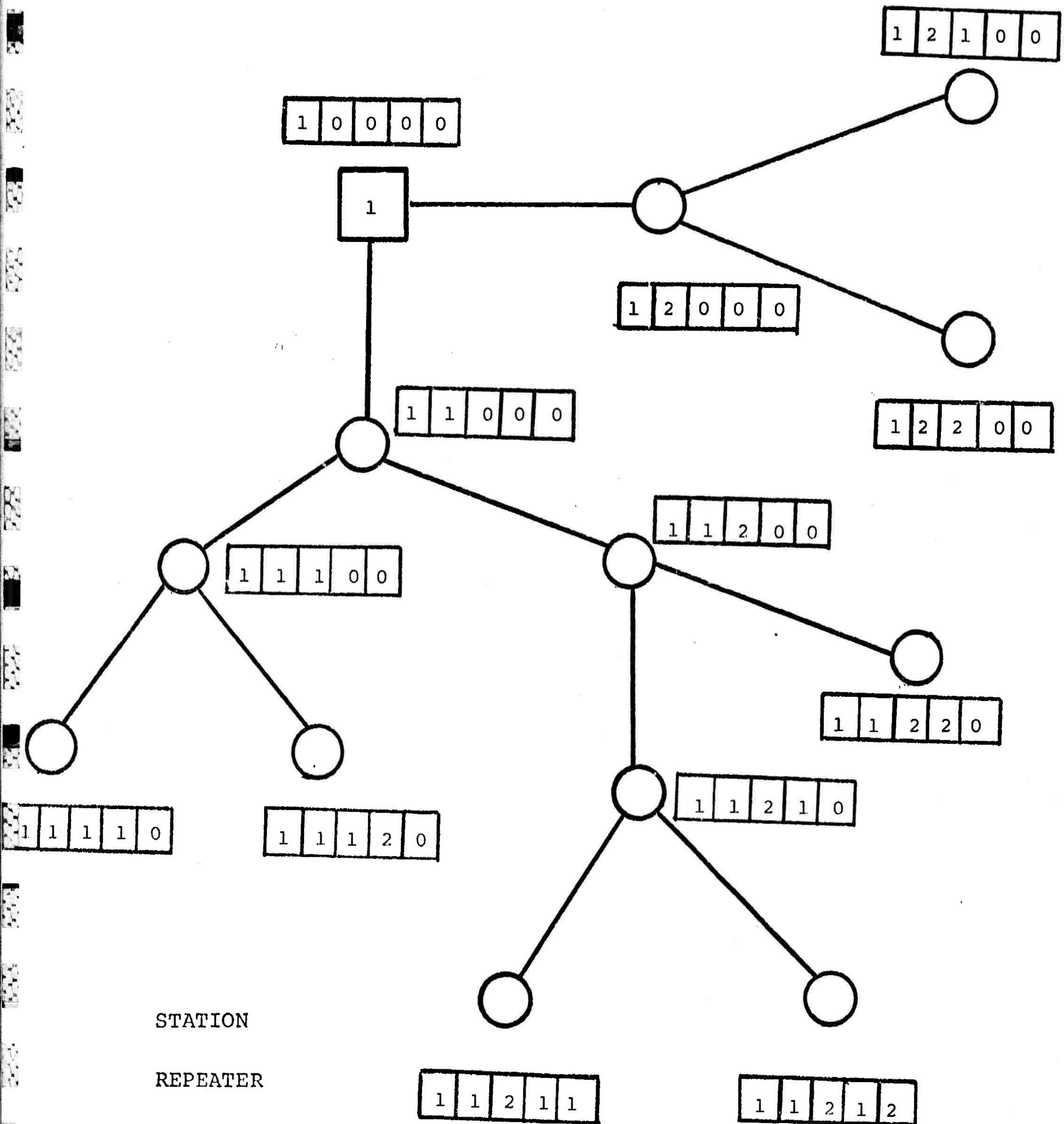


FIGURE 4.1: THE HIERARCHICAL LABELS OF REPEATERS AND STATION, AND THE TREE STRUCTURE FORMED

The complete path between the station and a repeater is defined by the label of the repeater. Figure 4.2 shows the information carried in the packet header, used for packet transportation.

The handover number is used for flow control and for the HBH ack test as in the Broadcast Routing Algorithm. The "ALL" indicator is used for alternate routing.

When the ALL indicator is non-active, the packet is addressed to a single, unique, repeater. The address of that repeater is defined by the hierarchy level indicator and by the label. The hierarchy level indicator is a pointer to the label and defines the number of nonzero fields of the repeater; if these nonzero fields of the repeater match those in the packet label, the packet is addressed to it.

When a repeater exhausts its allowed number of transmissions without receiving a HBH ack, it begins the alternate routing stage. Alternate routing is initiated by activating the ALL indicator in the packet*. This addresses the packet to all repeaters which match the Hierarchy Level Indicator. When a repeater is switching a packet received via alternate routing, it attempts to send the packet back onto the primary route. The objective of the alternate routing is to bypass a repeater which is down or temporarily busy. Figure 4.3 shows, schematically, the packet flow when using alternate routing. The example shows alternate paths available to repeater A for sending the packet to repeater C, when encountering blocking on the primary path. All the alternate paths are used simultaneously.

The processing performed by a repeater upon packet reception is as follows (the test for determining a HBH ack is not specified):

1. If packet is received in error, discard packet, go to (8);

*Other schemes for alternate routing are presented in Section 4.3.5.

HANDOVER NUMBER	TO/FROM STATION INDICATOR	"ALL" INDICATOR	HIERARCHY LEVEL INDICATOR	HIERARCHICAL LABEL	UNIQUE PACKET IDENTIFIER (UPI)

FIGURE 4.2: HEADER SECTION FOR PACKET TRANSPORTATION USING HIERARCHICAL ROUTING

2. If repeater's hierarchy level does not match that in the packet, discard packet, go to (8);

3. If the nonzero fields of repeater label match those in the packet, go to (5);

4. If ALL indicator is not active, discard packet, to to (8);

5. Deactivate ALL indicator;

6. (a) Decrement handover number,

   (b) If packet is TO station, decrement hierarchy level indicator,

   (c) If packet is FROM station, increment hierarchy level indicator;

7. Initialize packet for transmission;

8. End.

The only step required for addressing the next repeater on the assigned path is changing the hierarchy level indicator in (b) or (c) of Step 6.

4.3.3 Routing in Multi-Station Radio Networks

In a multi-station network, a repeater is assigned a hierarchical label by several stations during the initialization procedure. Upon receiving a new label, the repeater determines its Primary Label, Secondary Label, etc. according to its distance in number of hops to the corresponding stations. The above order may be changed as a result of changes in network topology. The primary label can be used for packets without a label (e.g., packets from terminals).

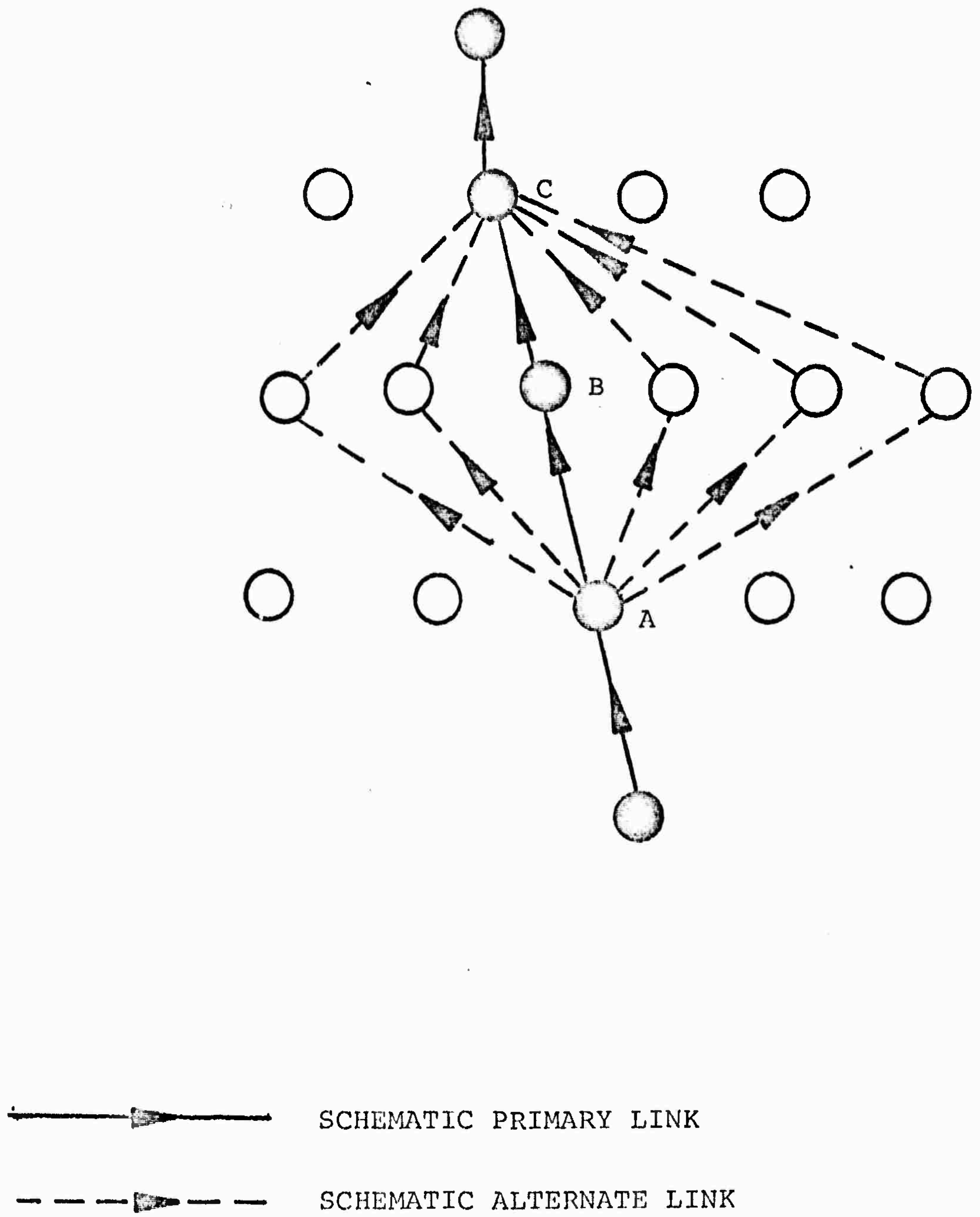


FIGURE 4.3: ALTERNATE ROUTING EXAMPLE

Every repeater can simultaneously route packets to any of the stations to which it is connected by using essentially the same algorithm outlined for a single station case. The station towards which a packet is routed is essentially transparent to the repeater. A repeater matches the packet label with one of its labels and then decrements or increments the hierarchy level indicator depending on whether the packet is directed TO or FROM a station. The structure, for routing purposes, formed by the assignment of labels by two stations is shown in the following set of figures. Figure 4.4 shows connectivity of a network of 48 repeaters and two stations. Figure 4.5 shows the tree structure generated by the hierarchical labels assigned by Station S-1, and Figure 4.6 the corresponding tree generated by the labels assigned by Station S-2. Figure 4.7 shows the two trees overlaid, and the partition of the set of repeaters between the two stations generated by the choice of the primary and secondary labels. All the repeaters above the separation line have a smaller number of hops to S-1 and thus selected the label assigned by S-1 as their primary label; whereas repeaters below the line have chosen S-2 as their primary station. R4, R11, and R18 have the same number of hops to the two stations and their choice is arbitrary.

Station-to-station communication via the radio network using the hierarchical routing algorithm is accomplished by the originating station when acting like a terminal.

4.3.4 Properties

1. The algorithm performs point-to-point (PTP) routing in the radio network. This enables shortest path routing between repeaters and stations when the labels are properly assigned. The PTP routing results in minimum utilization of processing capacity of nodes, and consequently minimum utilization of the channel capacity due to the small number

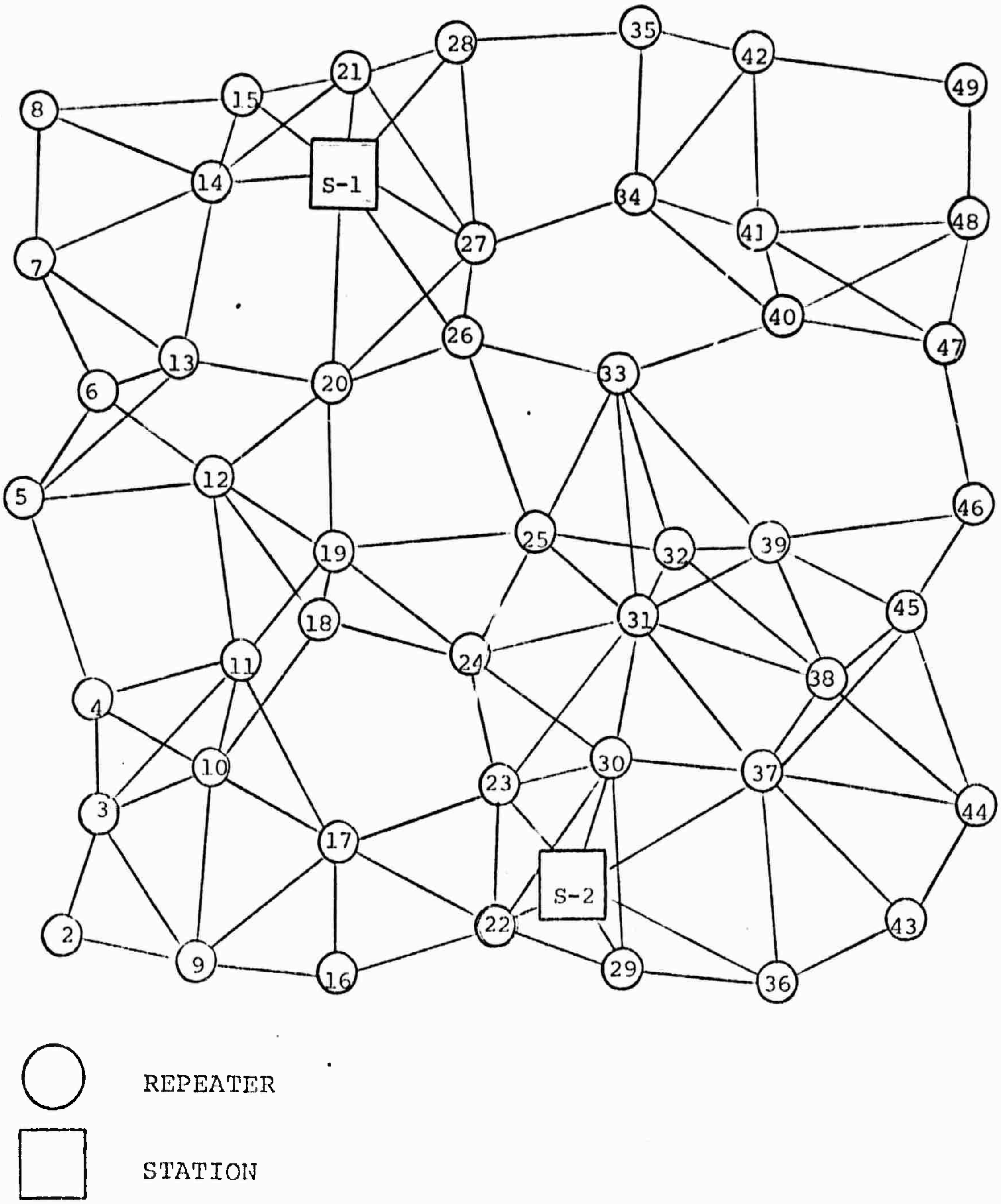


FIGURE 4.4: CONNECTIVITY OF A RADIO NETWORK WITH TWO STATIONS

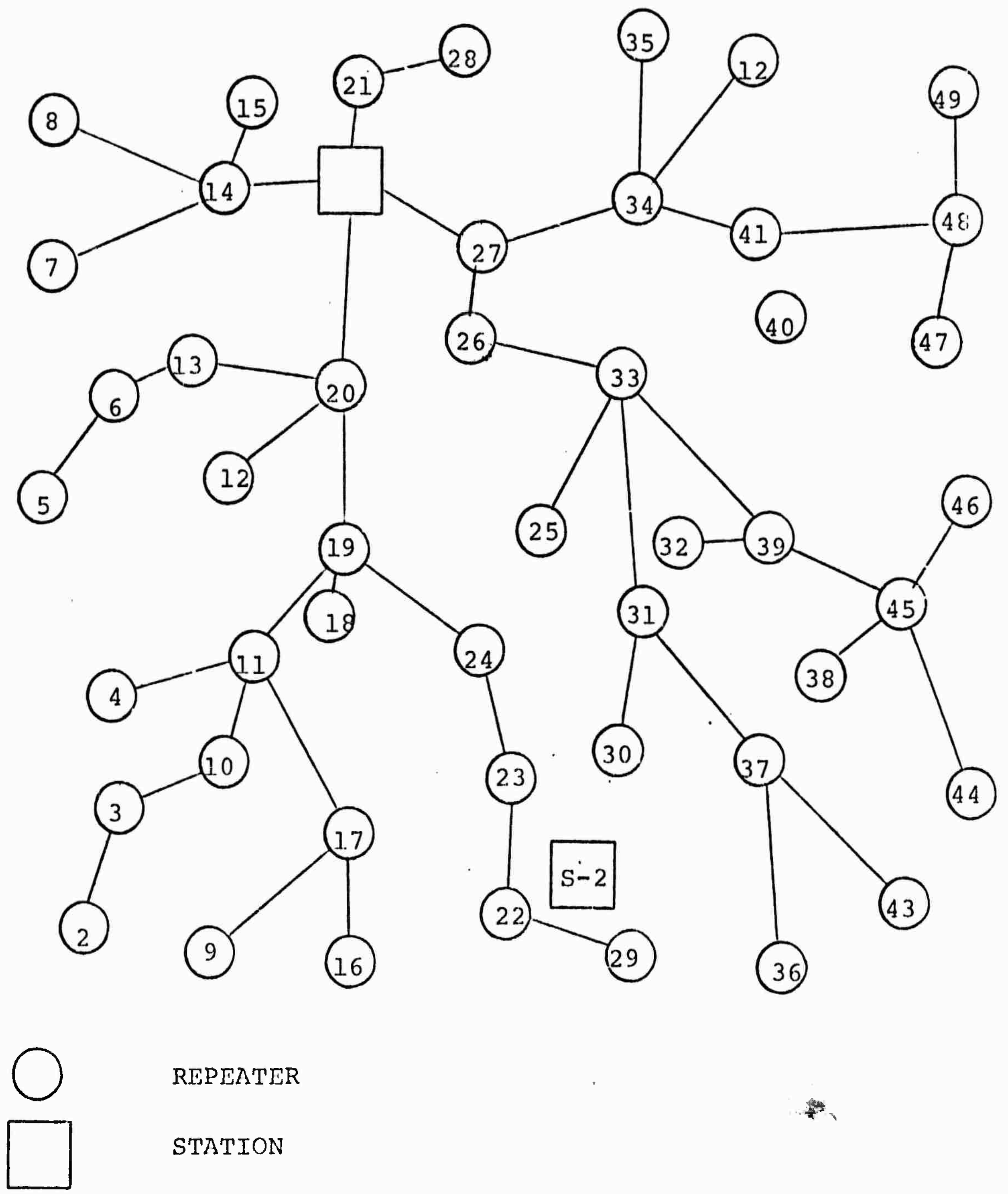


FIGURE 4.5: TREE STRUCTURE GENERATED BY LABELS ASSIGNED BY STATION S-1

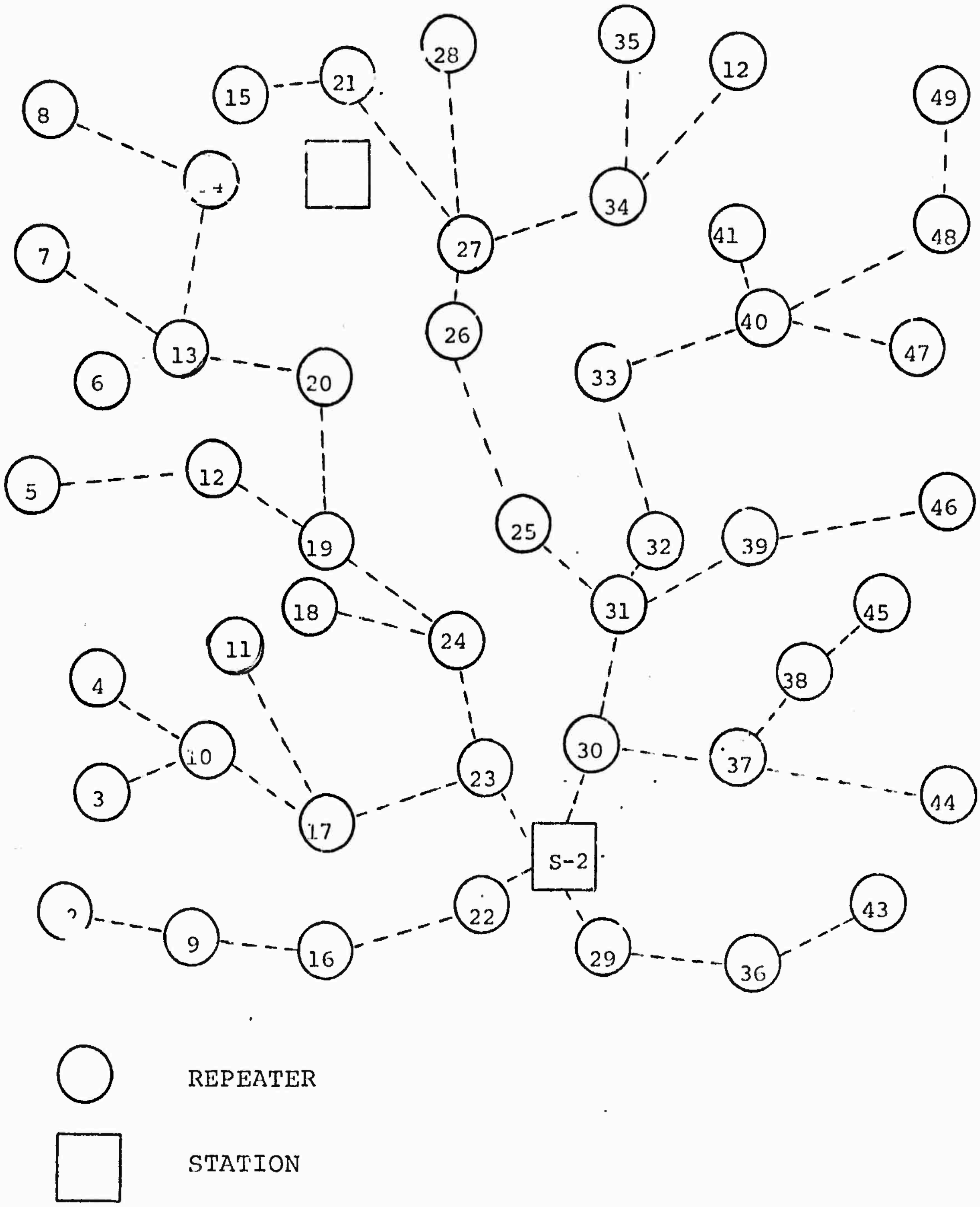


FIGURE 4.6: TREE STRUCTURE GENERATED BY LABELS ASSIGNED BY STATION S-2

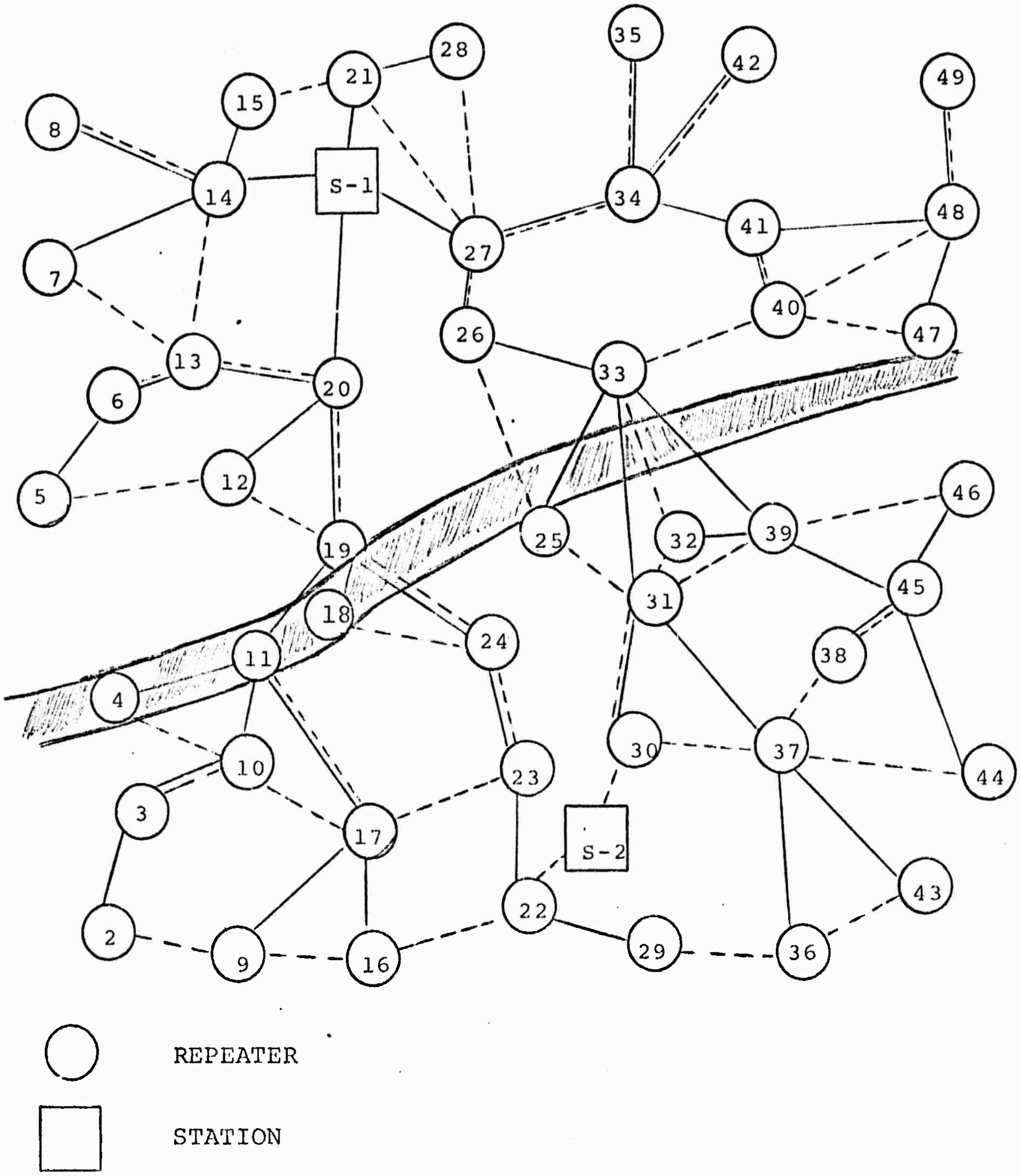


FIGURE 4.7: PARTITION OF REPEATERS TO PRIMARY AND SECONDARY STATION

of nodes which compete for the channel (using a random transmission scheme) when repeating the packet. To clarify the last point, consider a path traversed by a packet using the broadcast and hierarchical routing algorithms, respectively. The delay experienced when using the hierarchical algorithm will, on the average, be much smaller because only repeaters on the path transmit the packet. This results in a smaller probability of interference and thus a smaller number of transmissions per hop before success, and consequently a smaller delay per hop.

2. There is a high probability that the packet will reach its destination, when taking into account alternate routing. The directionality of the algorithm also implies that the packet will arrive at only one station.

3. The only drawback of the algorithm is the need to maintain an updated set of labels. This, however, becomes a limitation only in a network with highly mobile nodes.

4.3.5 Discussion

Several possible generalizations of the hierarchical routing algorithm are possible, two of which are now discussed.

Generalization 1: This technique is based on the increase of transmission power when encountering blocking rather than using the "ALL" indicator, and enabling all repeaters on the path which are closer to the destination to accept the packets for switching. Specifically, suppose that repeater R of hierarchy level j + 1 transmits a packet towards a station. R addresses the packet to a repeater on the path at hierarchy level j. We now modify the rule to enable all repeaters along the path with a hierarchy level $\leq j$ to receive the packet. The advantage of this technique is that one can shorten the number of hops to the destination and bypass failed repeaters. The limitations are:

1. Duplicate copies of the packet are generated,

2. The increase in power results in interference with a larger number of repeaters, and

3. Difficulties may be encountered in the HBH ack scheme when the repeater which receives the packet for switching transmits it with a lower power than that used by its predecessor.

Generalization 2: This generalization involves the searches for an alternate repeater when encountering blocking. The search protocol involves the transmission of a search packet which specifies the class of repeaters sought and receiving a response from a repeater in that class; the response contains the hierarchical label of the responding repeater. The searching repeater substitutes the label of the responding repeater into the original packet and transmits the packet.

The essence of this technique is to define the class of repeaters sought. Consider a field from the hierarchical label. We stated two possible codes, a zero or an integer value which identifies a specific repeater. Now, we introduce another code for a field, the "ALL code", which addresses all repeaters in that hierarchy level. Thus, the class of repeaters sought by the search packet can be defined by the specific fields in the label which contain an ALL code. Figure 4.8 shows the label of a search packet which defines the class of repeaters in hierarchy level 2, 3, or 4, associated with the particular station defined by the first field.

The class of repeaters sought can be progressively increased as necessary.

The advantage of this technique is that no duplicate copies of the packet are generated along the path. The entire packet is always transmitted to a unique repeater. This technique requires, however, two hierarchical labels in the packet header when routing from the station (towards a repeater); one which may be replaced as a result of the search protocol, and the other which defines the path and enables routing of the packet back onto it after departure. An additional requirement is the search protocol.

4.4 DIRECTED BROADCAST ROUTING ALGORITHM

The development of the hierarchical routing algorithm was based on the assumption that the radio network is used for local collection and distribution of traffic. Furthermore, the stations were assumed to have directories of destinations and accounting capabilities, so that every packet had to pass through a station even when destined to a device in the radio network. These assumptions implied a centralized network architecture, and when traffic requirements and reliability considerations were taken into account, it resulted in a set of overlaid centralized networks.

We now consider a different set of assumptions. Specifically, suppose that: (1) the traffic requirements are uniform, that is, any pair of nodes (repeaters and stations) in the network, (2) that the traffic origination device knows (or can obtain) the ID of the destination repeater, and (3) that accounting per packet or per message is not needed. These assumptions imply a distributed network architecture. The concept is applicable to cases in which most of the resources are on the radio network. It is characteristic of cases in which the network resources and users belong to the same entity, such as in military applications. The hierarchical routing can still be used; however, a distributed routing approach in which a packet is routed directly to the destination repeater may be more appropriate, and is presented in this section.

It is still assumed that the capabilities of repeaters are limited and that stations will perform all the tasks not directly related to packet switching, as well as acting as repeaters. The main task of a station in a distributed radio network is as an observer and controller. Specifically, the station will perform the following:

1. Network initialization: This is the same function needed when using hierarchical routing. The station

FIELD 1	2	3	4	5		H
SPECIFIC CODE	ALL CODE	ALL CODE	ALL CODE	ZERO CODE	. . . .	ZERO CODE

FIGURE 4.8: THE LABEL OF A SEARCH PACKET WHICH DEFINES A CLASS OF REPEATERS

maps the network topology, determines labels to be assigned to repeaters and initializes repeaters.

2. Monitoring network connectivity and changing repeaters labels as necessary.

3. Global flow control functions and controlling operating parameters of repeaters.

4. Gateway: All traffic to destinations not in the radio network must go through a station.

5. Supervisor: Extra capabilities needed by a terminal or by a repeater will be requested from a station. For example, the directory of resources which changed locations.

4.4.1 The Repeater Label

The label contains similar information to that available to IMP's in the ARPANET [Fultz, 1971, Gertz, 1973]. In the ARPANET, node i has a table A of $(N-1) \times L_i$ entries, where N is the number of nodes in the network and L_i is the number of outgoing point-to-point channels (links) from node i. An entry a_{kj} indicates the distance (or delay) from node i to node k when using outgoing link j.

The notion of point-to-point link is meaningless in broadcast radio networks. A repeater is assigned a label in the form of a distance vector. Repeater i, R_i, will be given the vector $\underline{d}_i = (d_{ij})$, where d_{ij} is the minimum number of hops from R_i to

R_j. We propose a convention that stations will be numbered from 1 to S, where S is the number of stations, and repeaters from S + 1 on; so that if a repeater requires extra capabilities from a station, it can select an arbitrary number from 1 to S, as its destination, providing the distance to the one selected is finite.

If we assume that there are N nodes in the network (repeaters) and stations), the maximum distance is N - 1 hops. In addition, it is necessary to represent a distance of ∞.* Thus, one needs a total of $N\log_2 N$ bits for storing the vector $\underline{d}_i$.

Note that R_i is not provided with the ID's of its neighbors; in fact, its own ID (R_i) is not explicitly known to it; the latter is implicitly given by the fact that $d_{ij} = 0$.

4.4.2 The Routing Algorithm

Figure 4.9 shows the information carried in the packet header for use by the directed broadcast algorithm. The handover number is used for flow control to limit the number of hops that a packet traverses. The destination ID and the distance to it from the transmitting device are used for the HBH ack and for determining the devices that need to accept the packet for switching.

Essentially, the rule for accepting a packet for switching is that the receiving device is closer to the destination than the transmitting device. The destination device identifies that a packet is for it by noticing that its distance to the destination is zero. We now outline the processing done by a repeater along the path.

Suppose that R_k transmits a packet which is defined to R_i; the

*The distance of ∞ can be used by a station to prevent communication between a repeater and a set of repeaters, for partitioning the repeater network among the stations, or possibly for turning a repeater off, when all entries apart from d_{ii} are ∞.

HANDOVER NUMBER	DESTINATION ID (R_i)	DISTANCE OF TRANSMITTING REPEATER TO DESTINATION (d_{ki})	UNIQUE PACKET IDENTIFIER (UPI)

FIGURE 4.9: HEADER SECTION FOR PACKET TRANSPORTATION USING DIRECTED BROADCAST ROUTING

1. If packet is received in error, discard packet, go to (7);

2. If packet is a HBH ack, discard packet received and packet acknowledged, go to (7);

3. If handover number equals zero, discard packet received, go to (7);

4. If $d_{ji} \geq d_{ki}$, discard packet received, go to (7);

5. (a) Decrement handover number,

   (b) Set d_{ji} into packet header;

6. Initialize packet for transmission;

7. End.

In Step 2, the received packet is a HBH ack to a stored packet if it has the same UPI and if $d_{ji} > d_{ki}$. The only change in the header needed for routing is the substitution of d_{ji} into the packet header.

When encountering blocking, a repeater may increase its transmission power, thus increasing the number of potential receivers. This, however, may result in some difficulties in obtaining a HBH ack, as discussed in Section 4.3.5. As a last option, the repeater may send a control packet to a station to resolve the difficulty.

4.4.3 Properties

1. The algorithm enables direct (i.e., not via a station) routing to any repeater or station in the radio network.

2. There is a high probability of reaching the destination node. In fact, if we ignore traffic overload, then if there is a path to the destination, the packet will "find" it. The packet is routed to a single destination.

3. It is claimed that the algorithm has the property of shortest path routing. This is due to the HBH ack scheme used, which eliminates repeaters on the basis of distance to the destination, rather than the number of hops that the packet traversed.

4. The algorithm does not have the property of point-to-point routing. It enables the generation of copies of the packet along the path. This implies that its efficiency, in terms of processing capacity at nodes and channel utilization will be less than that of the hierarchical routing algorithm, for repeater to station paths.

5. The main limitation of the algorithm is in the need of maintaining an updated set of labels. The algorithm, in the form presented, is suitable for stationary network nodes. That is, when the local connectivity of a single device is changed, it affects the labels of other devices in the network. In this case it may not be efficient to have the stations initialize repeaters and monitor network connectivity. If the application implies a distributed architecture and the network elements (repeaters and stations) are mobile, the task of updating distance vectors should be distributed. This will require more capabilities in the repeaters.

4.5 CONCLUDING REMARKS

Three routing algorithms for broadcast radio networks were described in this chapter. The algorithms take advantage of the properties of radio networks in minimizing the utilization of network resources for packet transportation.

The Broadcast Routing Algorithm is the least efficient; however, devices need not be initialized beforehand. The comparison between the Hierarchical Routing Algorithm and the Directed Broadcast Algorithm is not obvious. The directed broadcast algorithm seems to be better from the reliability point of view because of the feature of being a non point-to-point algorithm in which more than one receiver may accept the packet for switching. The reliability is further enhanced if an adaptive power mechanism is available in repeaters. Note also that the efficient HBH ack scheme should cancel out many of the possible paths, in particular when the packet approaches the destination. However, given a path between a repeater and a station, it is apparent that the directed broadcast algorithm will utilize more network resources than the hierarchical routing algorithm.

Another point for comparison, which may become major, is the flexibility of expanding the network and the overhead of updating repeater labels. In this regard the hierarchical routing algorithm is preferable to the directed broadcast algorithm. When a new repeater is added, it is necessary to change all the labels of existing repeaters in the directed broadcast technique; whereas when using the hierarchical algorithm it is only necessary to initialize the new repeater. Furthermore, the fact that all packets are routed via a station, in the hierarchical algorithm, enables easy monitoring of network connectivity (by the stations) and faster updating of labels.

An analytic comparison of the algorithms is rather difficult. The broadcast and hierarchical algorithms were simulated and extensively tested, some results appear in [Frank, 1975]; the directed broadcast algorithm has not yet been experimentally evaluated.

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Network Analysis Corporation Beechwood, Old Tappan Road Glen Cove, N.Y. 11542	UNCLASSIFIED
	2b. GROUP None

3. REPORT TITLE

Fifth Semiannual Technical Report, August, 1975, for the Project "Local, Regional, and Large Scale Integrated Networks"

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Fifth Semiannual Technical Report, August 1975

5. AUTHOR(S) (First name, middle initial, last name)

Network Analysis Corporation

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
August 1975	175	15

8a. CONTRACT OR GRANT NO. DAHC-73-C-0135	9a. ORIGINATOR'S REPORT NUMBER(S) Semiannual Report 5B
b. PROJECT NO. ARPA Order No. 2286	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) None
d.	

10. DISTRIBUTION STATEMENT

Approved For Public Release, Distribution Unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
NONE	Advanced Research Projects Agency, Department of Defense

13. ABSTRACT

This report summarizes principal technical accomplishments during the reporting period as well as tasks in progress. The body of the report describes detailed results in the area of Packet Radio. Extensive descriptions of procedures for Packet Radio Network initialization, connectivity monitoring, and stability control are given. These issues are addressed at two levels:

1) Procedures proposed for implementation in the Experimental Packet Radio Local Area Demonstration System, and

2. Extensions and additions for application in second generation DOD systems.

Keywords: data transmission systems; Communication and Radio Systems; wave path

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Large Scale Networks						
Local Access						
Packet Switching						
Packet Radio						
Network Stability						
Random Access						
Packet Routing						
Network Control						