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CONNECTIVITY MONITORING IN MOBILE PACKET RADIO NETWORKS

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BY

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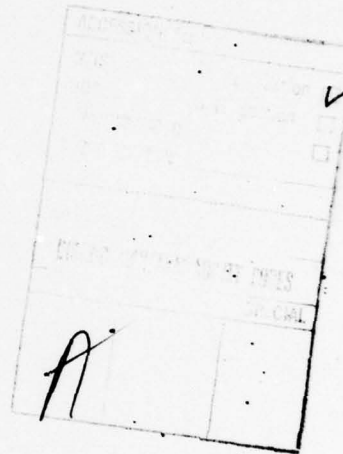Cambridge, Massachusetts 02139

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Knowledge of connectivity (i.e., what pairs of nodes can communicate directly) in a communication network is essential for the efficient and reliable operation of the network. In a packet radio network with mobile nodes, the connectivity varies with time and thus must in some way be monitored.

The problem of monitoring connectivity in mobile packet radio networks is considered. Two general methods for monitoring connectivity are developed and compared. It is found that each method has its respective advantages and disadvantages, and thus to

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Implementations of both monitoring methods in a terminal-oriented mobile packet radio network, where connectivity information is used for updating packet routes, are presented and compared. It is found that a particular implementation is the most flexible and in general uses the least amount of overhead. Its performance is analyzed in detail for a particular network model.

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IN MOBILE PACKET RADIO NETWORKS

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ABSTRACT

Knowledge of connectivity (i.e., what pairs of nodes can communicate directly) in a data communication network is essential for the efficient and reliable operation of the network. In a packet radio network with mobile nodes, the connectivity varies with time and thus must in some way be monitored.

The problem of monitoring connectivity in mobile packet radio networks is considered. Two general methods for monitoring connectivity are developed and compared. It is found that each method has its respective advantages and disadvantages, and thus to choose between them, one must examine both the specific type of packet radio in which one wishes to monitor connectivity and the specific use that is to be made of connectivity information in that network.

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PART I

<u>General Concepts</u>

CHAPTER 1

Introduction

1.1 Packet Radio Networks

A packet radio network is a type of data communication network.
In a general sense, one may view a data communication network as a
finite collection of nodes connected to each other by some form of
communication. Attached to some or all of the nodes are resources
(e.g., terminals, computers), and the purpose of the network is to
transport messages both reliably and efficiently between resources at
different nodes. A message is generally transported in the form of one
or more packets.* Each packet, in addition to message bits, contains
binary encoded control information (e.g., source and destination
addresses, error control bits). Much of this control information is
often located at the beginning of the packet in what is called the
packet header.

The main distinguishing feature between packet radio networks and
other data communication networks, specifically point-to-point packet
switching networks such as the ARPANET [2] or Tymnet [3], is the type
of communication used between nodes. Pairs of nodes in a point-to-point
packet switching network are connected by separate communication channels
(e.g., hardwire channels, microwave links). In contrast, the nodes of a
packet radio network are linked together by broadcast radio channel(s).
Specifically, the communication section of each node in a packet radio

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*See [1] for a discussion on the advantages of transporting data in the
form of packets.

network is a radio transceiver, with an omnidirectional antenna[*] and
finite transmission range, accessing one or more common broadcast channels.
Although seemingly simple, this one difference between packet radio net-
works and point-to-point packet switching networks leads to significant
differences in the operation of the two types of networks and in the ap-
plications for which each is suited.

Due to the broadcast nature of nodes in a packet radio network, a
packet may be received by all nodes within range of the transmitting node.
Thus, in contrast to a point-to-point network, a channel in a packet
radio network is not generally associated with only two nodes. This
implies the need for additional information in packet headers informing
the receiving nodes for whom a packet is or is not intended. This further
implies that if a node receives a packet in error, it may have no way of
knowing if the packet was intended for it and consequently, cannot re-
quest a retransmission. For this reason positive acknowledgements and
time-outs are used for error control in packet radio networks.

Channels in packet radio networks are generally shared by several
nodes. Various schemes (see [5], [6], [7] for examples) have been devised
which allow nodes to access these common channels. Studies (see above
references) have shown that for many applications, schemes which dynam-
ically share channel capacity (e.g., ALOHA) are more efficient than those
which assign fixed capacities to nodes (e.g., TDMA). Many of these
schemes which dynamically share channel capacity are referred to as

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[*]In certain situations it may be desirable for one or more of the nodes
to have directional antennas. See [4] pp. 221-223 for an example.

random access schemes. This is because with each of these schemes, the times at which nodes transmit packets are in some sense chosen at random. Hence, in using a random access scheme, two or more packet transmissions may overlap in time on the same channel, and thus interfere with each other at the receiving node. Consequently, the probability of a node receiving a packet in error in a packet radio network will not only be greater than in a point-to-point packet switching network, but will also be a function of the traffic level and the spatial topology of the nodes.

Packet radio networks are particularly well suited for applications which have one or more of the following properties. 1) The network resources are located in remote areas where hardwire connections are uneconomical, or in hostile locations where hardwire connections may not be feasible and where the capability of rapid deployment is essential. 2) The traffic characteristics of the resources are of a bursty nature (i.e., a high ratio of peak to average data rate), thus making the dynamic allocation of channel capacity a desirable feature. 3) Some or all of the resources are mobile, in which case a radio channel is essential.

1.2 Connectivity Monitoring

In a packet radio network, we say that a communication "link" exists from node i to node j if node j is within the transmission range of node i. Two nodes are said to be connected if such a communication link exists in at least one direction between them. The complete set of links in a network is referred to as the connectivity of the network.

Network control functions often require knowledge of connectivity. For example, directed routing is an efficient routing technique

in which a packet is directed from one node, say i, to another node within its transmission range, say j, by attaching the identity of node j to the packet header. All nodes other than j that receive the packet will ignore it, and only j will accept it and then either forward it on or keep it depending on the packet's final destination. There are various routing schemes which incorporate the use of directed routing. In one scheme, an ordered list of the nodes which are to relay a packet to its final destination is placed in the packet header by the node which originated the packet. In this way, a packet may be directed from node to node along its route with all the routing information contained in the packet header. In another scheme, each node maintains a table which pairs each of the possible destination nodes with a node within its transmission range to which it is to direct packets for that particular destination. In this scheme, each node determines the identity of the node to which it should direct a received packet by examining the packet header, determining the identity of the destination node, and then performing a table look-up. In Chapter 3 we describe a packet radio network in which the routing scheme is in some sense a combination of the above two schemes. In any event, we see that depending on the exact implementation, directed routing requires anywhere from a global knowledge of connectivity where every node knows the entire network connectivity, to a simple local knowledge where each node knows at least one node within its transmission range to which it may direct packets.

In packet radio networks with mobile nodes (e.g., a network for law enforcement may include patrol cars which would constitute mobile nodes), the network connectivity will be a function of an initial position

and the subsequent motions of the nodes. Since updated knowledge of connectivity is necessary for network control functions such as routing, the problem of how a packet radio network with randomly moving nodes monitors its connectivity is one which deserves study.

1.3 Outline of Thesis

The purpose of this thesis is to examine possible methods for monitoring connectivity in mobile packet radio networks. The thesis is divided into two parts. The first part includes, in addition to this introductory chapter, a chapter in which two general methods for monitoring connectivity are developed and compared. Throughout Part I, we keep the discussion as general as possible, making few if any assumptions about the type of packet radio network or the use that is to be made of connectivity information. In the second part of the thesis, however, we consider a specific type of packet radio network and a specific use of connectivity information. We begin Part II with a chapter on the description of this network. Next we discuss how the monitoring methods developed in Part I may be implemented in this network. We find that one monitoring implementation is the most flexible and in general uses the least amount of overhead. In order to gain a better understanding of the trade-offs associated with this implementation, in the fifth chapter we analyze its performance in greater detail. Finally, in the last chapter we make concluding remarks on connectivity monitoring and the results that we have obtained.

CHAPTER 2

Two Methods for Monitoring Connectivity

A method of determining if two nodes in a packet radio network
are connected is to simply test the communication channel between them
(i.e., try sending a packet from one node to the other). In this chapter,
two general methods for monitoring connectivity which employ this simple
testing idea are developed and compared.

2.1 Broadcast Method

Consider two nodes, say node i and node j, in a packet radio net-
work. Node j wishes to determine if a communication link exists from
node i to itself. One method for doing this is as follows. Node i will
transmit a special packet to node j. This special packet will contain
the unique identity of node i. If node j successfully receives this
packet, after examining the identity, node j will know that it is with-
in the transmission range of node i (i.e., a link exists from i to j).
If node j's transmission range is greater than or equal to node i's
transmission range, then node j will also know that it will be able to
successfully send packets to node i (i.e., a link also exists from j to
i). The monitoring extension of this method is to have node i transmit
these special packets at various points in time (e.g., periodically).
Each time node j receives one of these special packets, it will have up-
dated its knowledge of the connectivity from node i to itself.

Now consider all of the nodes in a packet radio network. One
approach to monitoring connectivity is to give each node the responsi-
bility of determining and then monitoring the connectivity between itself
and the other nodes in the network. Depending on the network control

functions (and their implementations) which require knowledge of connec-
tivity, this connectivity information may be needed elsewhere in the net-
work (e.g., a packet radio network may be set up so that one node in the
network determines the routing of packets for the entire network, and thus
would require knowledge of the entire network connectivity). In such
cases, after updating its knowledge of the connectivity between itself
and the other nodes in the network, each node could transmit this connec-
tivity information to those nodes within its transmission range which
require this information and/or are forwarding points to other nodes
which require this information.

A method in which each node may monitor the connectivity from the
other nodes in the network to itself follows from our discussion of the
two node case. Here each node at different points in time will broad-
cast a special packet containing its identity. Each node within range of
the transmitting node that receives one of these special packets will
know that a communication link exists from the transmitting node to
itself. In the case where every node in the network has the same trans-
mission range, the receiving node will also know a link exists from it
to the transmitting node. We call this the broadcast method of connec-
tivity monitoring, because each node simply broadcasts its identity to
all nodes within its transmission range.

With the broadcast method of connectivity monitoring, we see that
for a packet radio network with N nodes, only N transmissions are needed
in order for every node to determine the connectivity from the other nodes
to itself. Naturally, knowledge of connectivity cannot be perfect.
By the very nature of the schemes which are used to access the common

broadcast channel(s) in a packet radio network, packet errors will occur. Thus although a node may be within range of another node transmitting a special packet, it may not successfully receive that packet. So we see communication links may actually exist but not be detected.

To reduce the monitoring overhead associated with the broadcast method, one can take advantage of the connectivity information contained in regular message packets. If at each time a node transmits a packet (whether the node originated the packet or is simply forwarding it on from another node) it attaches to the packet header its identity,[*] all nodes within range of the transmitting node that receive the packet (even those to which it is not intended) can examine the packet header, determine the transmitting node, and update their knowledge of the con- nectivity from that node. In this way, a node need only broadcast a special packet when it has not transmitted a regular message packet for some length of time. Thus during heavy usage of the network by many nodes, one has a desirable reduction in the overhead needed for connec- tivity monitoring.

The broadcast method of connectivity monitoring is not, however, without its problems. With the broadcast method, a node which receives special monitoring packets from neighboring nodes is only informed of the connectivity from these nodes to itself. This knowledge of connec- tivity is in itself rather incomplete, in that without additional trans- missions, a node is aware of the neighboring nodes that may transmit

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[*] Depending on the details of packet routing, this identity may already be in the packet header, and thus need not be added.

packets to it, but does not in general know to which nodes it may transmit packets. If a node is to use connectivity information for routing packets, it is often necessary that that node be aware of the nodes to which it is connected in both directions. The outbound direction is necessary for sending message packets, and the inbound direction is necessary for receiving the acknowledgments for those packets. In packet radio networks where all nodes have the same transmission range, a test of connectivity between two nodes in one direction may be a sufficient test for both directions. In this situation, the broadcast method can be used to inform each node of its connectivity to and from the other nodes in the network. However, considering that transmission range is a function of transmitter power, such an assumption is not always realistic; possibly making the broadcast method of connectivity monitoring limited in its applications.

Another problem with the broadcast method is that each node must rely on the broadcasts of the other nodes in the network in order to monitor its inbound connectivity. For a mobile packet radio network, the rate at which a node must update its knowledge of connectivity will be a function of the characteristics of node mobility (e.g., velocity, randomness of motion) and the requirements (e.g., maximum average delay in packet delivery) placed upon that node by its associated resources. In general, an increase in node velocity and/or a decrease in the required average delay in packet delivery will require a higher monitoring rate. Suppose there is a large variance in the range of node velocities (e.g., a military packet radio network may include nodes moving by foot, motor vehicle, and aircraft), and/or a variety of network resources

which place different requirements upon the network (e.g., digitized voice communication may require a much smaller delay in packet delivery than say terminal-to-terminal communication). Although each node may have a different required rate of updating its knowledge of connectivity, with the broadcast method, the rate at which all nodes within a geographical area must broadcast special monitoring packets will have to be that needed by the node with the highest required updating rate. This can clearly result in excessive overhead for monitoring connectivity.

In the next section, we shall see that the problems associated with the broadcast method of connectivity monitoring are eliminated with the probing method. However, this is achieved only at the expense of an increase in network overhead.

2.2 Probing Method

Let us first consider just two nodes in a packet radio network. Node j wishes to determine if there exists both a communication link from it to node i and a communication link from node i to itself. Node j can do this by sending node i a probe packet, which if received by node i, instructs node i to send a response packet back to node j. If received by node j, this response packet informs node j that node i received the probe packet. Thus if after sending a probe packet to node i, node j receives a response, node j will know that it is connected in both directions to node i (i.e., a link exists from j to i and a link exists from i to j). The monitoring extension of this method is to have node j "probe" node i (i.e., send node i a probe packet) at various points in time, with each response packet received by node j

being an indication of a connection in both directions between nodes
i and j.

Now consider all of the nodes in a packet radio network. A
method in which each node may monitor the connectivity in both directions
between it and the other nodes in the network follows from the two node
case. Here each time a node wishes to update its knowledge of the connec-
tivity between it and the other nodes in the network, that node will
transmit a general probe packet. A general probe packet is simply a
probe packet addressed to all nodes in the network. Each node within
the transmission range of the probing node (i.e., the node which trans-
mitted the probe packet) that receives the probe packet will respond by
sending the probing node a response packet. This response packet will in
some way contain the unique identity of the responding node. Thus, each
response packet received as a reply to a probe packet, informs the
probing node of the existence of a connection in both directions between
it and the responding node. We call this the probing method of connec-
tivity monitoring, because each node probes (via probe packets) the
nodes within its transmission range in order to update its knowledge of
connectivity.

It is important to note that, as with the broadcast method, know-
ledge of connectivity gained via the probing method cannot in general be
perfect. For example, suppose each of two nodes is within the trans-
mission range of the other (i.e., the two nodes are connected in both
directions). If a probe packet sent by one node is received in error,
or if a probe packet sent by one node is correctly received but the
associated response packet sent by the other node is received in error,

then the connection between the two nodes will go undetected by the probing node. Consequently, as with the broadcast method, communication links in a network may actually exist but not be detected when using the probing method of connectivity monitoring.

It is also important to recognize that when a node transmits a general probe packet, some mechanism must be provided to prevent the nodes that receive that probe packet from sending response packets all at the same time on a common broadcast channel. If they did, it is possible that the response packets arriving at the probing node at the same time will destructively interfere with each other, and none of the response packets will be correctly received. To avoid this problem, one could assign to every node in the network a different time delay which each node will wait before responding to a general probe packet. The time delays should be assigned so that no two nodes could respond to a probe packet with response packets which overlapped in time. Alternatively, if the number of nodes in the network is large, one could make the time delay for each node a random variable. Although there still exists the possibility of a conflict of two or more response packets at a probing node, one could, with randomized time delays, reduce the time from when a probe packet is sent until all possible responses are received. This can simply be done by limiting the largest value of time that the time delay random variable associated with each node takes on nonzero probability.

The special monitoring packets used in the broadcast method, and the probe and response packets used in the probing method carry approximately the same amount of information. Thus we may assume that they

would be about the same length in bits if implemented in a packet radio network. Therefore, for the purpose of comparing these connectivity monitoring methods, we can use the number of packet transmissions involved in a particular monitoring method as a measure of the network overhead needed to implement that method.

Consider a packet radio network in which each node is connected in both directions to L other nodes. With the probing method of connectivity monitoring, it is clear that each node will require at most L+1 transmissions[*] to update its knowledge of the connectivity between it and the other nodes in the network. For an N node network, this comes to a total of at most $N(L+1)$ transmissions for all of the nodes to update their knowledge of connectivity. This number of transmissions is greater, by a factor of L+1, than the number of transmissions required by the broadcast method. However, one must keep in mind that the broadcast method only tests the communication channel between two nodes in one direction, whereas the probing method tests both directions. Also, the probing method is more flexible than the broadcast method. With the probing method, each individual node in a packet radio network may send a probe packet at whatever time it deems necessary. Consequently, each node has complete control over the rate at which it can update its knowledge of the connectivity between it and the other nodes in the network. Thus, in contrast to the broadcast method, a large variance in the required updating rates of the nodes in a packet radio network can be

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[*] One transmission of a probe packet, and a transmission of a response packet by each of the L nodes that correctly received the probe packet.

dealt with by the probing method in a very convenient manner. Specif-
ically, each node can simply send probe packets at its own required rate.

Depending on what knowledge of connectivity is needed by the net-
work, it may be that each node is not interested in monitoring the connec-
tivity between it and all of the other nodes in the network. For example,
we shall describe a packet radio network in Chapter 3 in which, at any
particular time, each node is interested in monitoring the connectivity
between it and only one other node in the network. In this case, each
node can transmit probe packets addressed only to that node between which
it is interested in monitoring connectivity, with only that specific node
responding to each received probe packet. Thus we see that at most only
2N transmissions are needed for all N nodes in the network to update that
knowledge of connectivity which is needed.

At this point it is clear that we cannot recommend the use of
one method of monitoring connectivity over another for packet radio
networks in general. Both the broadcast and probing methods have their
respective advantages and disadvantages. In choosing between them, one
must examine both the specific packet radio network in which one wishes
to monitor connectivity, and the specific use that is to be made of
connectivity information in that network.

PART II

Connectivity Monitoring in a Terminal-Oriented
Mobile Packet Radio Network

CHAPTER 3

Network Description

Up to this point we have only examined general ideas in monitoring connectivity. In Part II of this thesis, we narrow our view and examine connectivity monitoring in a specific type of mobile packet radio network. In this chapter we describe this network.

The packet radio network to be described is chosen for two reasons. First, this type of network is one that often arises in a terminal-oriented packet radio network, and is one which has already received considerable attention (see [8] for a discussion and further references). Secondly, we shall see that connectivity information is only used in this network for updating simple packet routes. Consequently, the connectivity monitoring needed in this network has relatively straightforward implementations which are amenable to analysis.

The packet radio network we now describe is one in which all nodes communicate with each other via some random access scheme on one common broadcast channel. For packet transportation, the network uses directed routing in which all traffic flows through a centralized node called a station. The packet routes are configured as a tree structure rooted at the station, where the branch nodes consist of relay devices called repeaters and the end nodes consist of end devices called terminals.* This structure implies that the same repeaters will be traversed by packets going in either direction between a particular device (terminal, repeater) and the station. Figure 3-1 illustrates a layout of

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*"Terminals" may include, for example, TTY-like and CRT terminals, computers, display printers, and unattended sensors.
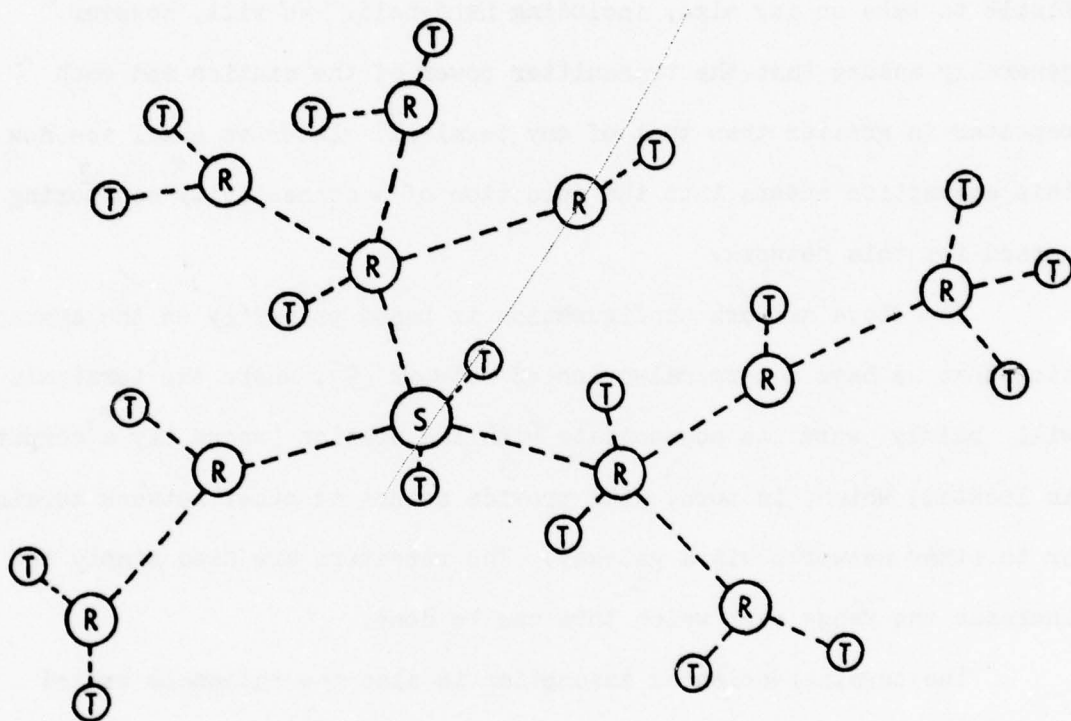
S   – station

R   – repeater

T   – terminal

The dashed lines between nodes indicate the
packet routes between the station and the
terminals and repeaters

<u>Figure 3-1</u> Packet radio network with tree-structured routes

tree-structured routes for this type of network. We allow the terminals to be mobile, however, for simplicity, we assume that the station and repeaters are stationary. Also, we place no lower limit on the transmitter power associated with each terminal, thus allowing the terminals to take on any size, including hand-held. We will, however, generally assume that the transmitter power of the station and each repeater is greater than that of any terminal. Later we shall see how this assumption enters into the selection of a connectivity monitoring method for this network.

The above network configuration is based primarily on the assumption that we have a terminal-oriented network [9], where the terminals will mainly want to communicate with the station (where say a computer is located) which, in turn, will provide access to other network terminals or to other networks via a gateway. The repeaters are used simply to increase the range over which this can be done.

The terminal-oriented assumption is also the rationale behind using "essentially fixed" routes between each terminal and the station. Since messages will generally be short, the overhead and complexity associated with variable routing outweigh its advantages. Naturally routes cannot be strictly fixed. Link failures due to device breakdowns, and more importantly due to terminal mobility, will necessitate that routes be changed. For efficiency reasons, when a route needs to be changed, the new route, selected from the set of available routes, will in some sense be the best available route (e.g., the minimum hop route, the minimum average delay route) at the time of selection.

Note that, in general, one may want to change routes in this

type of network not only because of changes in connectivity, but also
due to changes in traffic flow which result in a significant increase
in the delay in packet transportation. However, by choosing the "best"
available route after a change in connectivity necessitates that a new
route be selected, the network is automatically updating routes in an
attempt to improve traffic flow. Whether this updating alone is
sufficient, so that additional changes in routing are not needed, of
course depends on both the characteristics of terminal mobility
(e.g., average velocity and randomness of motion), and the characteristics
of traffic flow fluctuations (e.g., the frequency and magnitude of flow
changes). For the terminal-oriented network under consideration, we
assume that additional changes in routing for improved traffic flow will
be relatively infrequent compared to changes needed as the result of
terminal mobility.

Having described the structure of the routes in this network, we
now explain how a packet is directed along its route. The implementation
of directed routing in this network follows from our discussion in
section 1.2. Specifically, the first scheme discussed in section 1.2
is used for routing each outbound packet (i.e., a packet traveling from
the station to a particular terminal or repeater), and the second scheme
discussed in that section is used for routing each inbound packet (i.e.,
a packet traveling from a terminal or repeater to the station). That is,
when sending a packet to a terminal or repeater, the station includes in
the packet header an ordered list of the repeaters which are to relay
the packet to its destination. Thus each repeater along the route need
only examine the packet header in order to determine to whom it should

direct the packet. This form of directed routing is not, however, necessary for inbound packets. In particular, each device does not have to know the entire route to the station. It need only know the identity of the node (either a repeater or the station) to which it is to direct packets which are destined for the station. When a device, not within range of the station, wishes to send a packet to the station, it merely directs that packet to its "relaying repeater" which will then, in turn, forward the packet to the station.

There are of course other schemes for routing packets in a packet radio network (see [10] for examples). However, the scheme described above is of a rather simple nature. In particular, suppose that a terminal has moved out of range of its relaying repeater, and thus must obtain a new route to the station. With tree-structured directed routing, only that terminal and the station need to obtain new routing information. In fact, this new routing information need only consist of the identity of the terminal's new relaying repeater. The reason for this is that this identity is the only information needed by the terminal to send packets to the station; and by knowing the identity of the terminal's new relay repeater, the station can look up the route to that repeater and thus know the route to the terminal.

Although the use of tree-structured routes simplifies the routing of packets in this network, it also, unfortunately, has its drawbacks. In particular, two problems result from having all traffic flow through the station. The first is that the station is a bottleneck to traffic flow, and the second is that if the station fails, packet transportation in the entire network will cease. The first problem may be partially

solved by using directional antennas at the station (see [4] pp. 221-
223). Also, the seriousness of the second problem may be reduced by
devising back up routing strategies which do not employ the use of
the station. Still, it is important to realize that the concept of a
packet radio network is a relatively new one, and that there are many
problems which need further study.

CHAPTER 4

Monitoring Methods

We are interested in the monitoring of connectivity for the purpose of updating routes in the network described in Chapter 3. Because the station and repeaters are assumed to be stationary, the connectivity between them will not, aside from infrequent repeater/station breakdowns, change with time. Thus, aside from infrequent repeater/station breakdowns and infrequent changes in routing for improved traffic flow, we assume that the route between each repeater and the station remains fixed. The terminals, however, are mobile and changes in connectivity between a terminal and the repeaters and station may necessitate that the route between that terminal and the station be changed. Thus we shall direct our attention to terminal-repeater and terminal-station connectivity monitoring for the purpose of updating the route between each terminal and the station.

For convenience, we refer to the node (either a repeater or the station) to which a device (terminal, repeater) directs packets which are destined for the station, as that device's <u>relaying node</u>. Note that with tree-structured routes, given the route between each repeater and the station, the route between any terminal and the station is completely specified by the identity of the terminal's relaying node. For this reason, we shall often times refer to a terminal obtaining a new route, as that terminal obtaining a new relaying node.

In this chapter we examine how the monitoring methods developed in Chapter 2 may be implemented, in the network we are now considering, for the specific task we have outlined above. We examine first the use of the broadcast method and then the use of the probing method.

4.1 Broadcast Method

Let us assume that the routes in the packet radio network
described in Chapter 3 have been initialized. For tree-structured
directed routing, this implies that each device knows the identity of
its relaying node and the station knows the complete route to every
device. With mobile terminals, changes in terminal-repeater and
terminal-station connectivity will occur, and thus the route between
each terminal and the station will have to be constantly changed.

4.1.1 First Implementation of the Broadcast Method

An implementation of the broadcast method for monitoring terminal-
repeater and terminal-station connectivity follows directly from our
discussion in section 2.1. Specifically, the repeaters and station
broadcast special monitoring packets. Recall that the identity of the
node broadcasting a special monitoring packet is contained in that
packet. For each special monitoring packet received, a terminal will
know that a communication link exists from the broadcasting node (in
this case either a repeater or the station) to itself. If the station
is given the function of updating routes, then the terminal will, at
various points in time (e.g., periodically and/or when the terminal
detects an important change in connectivity), send, via a relaying
node within its range, its updated knowledge of connectivity to the
station. There a decision is made as to whether the terminal should be
given a new route to the station. If a new route is to be assigned, the
station will send a packet to the terminal which informs that terminal

of its new relaying node. Another option is to give each individual
terminal the function of updating its own route to the station. In
this situation, it may be desirable to have each repeater include in its
special monitoring packet some measure of its ability to relay packets
to the station (e.g., number of hops to the station, expected delay to
reach the station, number of terminals already using that route to
the station). This way, after a terminal concludes a loss of con-
nectivity between it and its relay node (by not having received a
special monitoring packet from that node for some period of time),
the terminal may select, with some intelligence, a new relay node from
its updated list of available relaying nodes. After selecting a new
relay node, a terminal must of course inform the station of the ident-
ity of this relay node, so that the station will be able to send packets
to that terminal.

Unfortunately, the above use of the broadcast method suffers
from the problems that we have already discussed in section 2.1. Recall
that in Chapter 3 we made the assumption that the transmitter power of
the station and each repeater is greater than that of any terminal.
Hence the transmission range of the station and each repeater will be
greater than that of any terminal. Thus although a terminal can, from
the special monitoring packets, monitor its inbound connectivity, it
cannot in general be certain of its outbound connectivity. This lack of
connectivity information makes it nearly impossible for either the
terminal or the station to consistently select usable routes. Another,
possible less serious problem is the lack of control given to a termi-
nal in updating its knowledge of connectivity. A terminal must rely on

the broadcasts of the repeaters and station in order to update its knowledge of connectivity. Thus the rate at which the station and all the repeaters must broadcast special monitoring packets will have to be that needed by the terminal with the highest required updating rate. So for a network with a large range of required terminal updating rates, this implementation can clearly result in excessive overhead for monitoring connectivity.

However, if the network is such that the transmission range of each terminal is at least as great as that of the station and any repeater, and if each terminal has the same required rate of updating its knowledge of connectivity, then the problems associated with this first implementation of the broadcast method disappear. In addition, since only the station and repeaters are broadcasting special monitoring packets, very little overhead is generated in the monitoring process. Thus this first implementation of the broadcast method performs very well if the network is uniform in terms of transmission ranges and connectivity updating rates.

4.1.2 Second Implementation of the Broadcast Method

The problems associated with the first implementation of the broadcast method are eliminated in another, somewhat indirect implementation of the broadcast method. In fact, a form of this second implementation is used in an actual packet radio network that is currently being tested by ARPA (see [11] for details). In this second implementation of the broadcast method, for the purpose of monitoring terminal-repeater and terminal-station connectivity, rather than having

the repeaters and station broadcast special monitoring packets to the terminals, the terminals broadcast special monitoring packets to the repeaters and station. These special monitoring packets are called ROP's* and, as with other special monitoring packets, each ROP contains the identity of the terminal from which it was broadcasted. When a terminal broadcasts an ROP, any repeater with an assigned route to the station that receives the ROP will attach its identity to that ROP and then relay that ROP on to the station just as if it were a regular message packet. Thus when a terminal broadcasts an ROP, a set of associated ROP's are generated and relayed to the station. The station can then examine this received set of ROP's and update its knowledge of the terminal-repeater and terminal-station connectivity for the particular terminal which originated the ROP. The station can then use this and possibly other information (e.g., statistics on the delay in packet transportation for each route available to the terminal) to decide whether a new route should be assigned to that terminal, and if so, what route should be assigned. If a new route is selected, the station must of course send to the terminal a packet which informs that terminal of the identity of its new relaying node.

With this implementation of the broadcast method, we see that the problems associated with the first implementation have been eliminated. Specifically, the channel is now tested from each terminal to the repeaters and station. Since the transmission range of the station and each repeater is assumed to be greater than that of any terminal

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*For the purpose of this discussion, we may assume that "ROP" denotes "radio-on-packet."

(and this assumption is crucial), a test in the terminal to repeater (or station) direction is considered a sufficient test for both directions. We also see that a terminal has complete control over the times at which it broadcasts ROP's. Thus the implementation is flexible in that each terminal can broadcast ROP's, and thus initiate connectivity updates, at its own required rate.

In the next section we discuss an implementation of the probing method which not only overcomes the problems associated with the first implementation of the broadcast method, but is also more flexible and in many cases uses less overhead than the second implementation of the broadcast method.

4.2 Probing Method

Aside from the discussion in section 4.2.5, we once again assume that the routes in the network described in Chapter 3 have been initialized. We still direct our attention to the monitoring of terminal-repeater and terminal-station connectivity for the purpose of updating the route between each terminal and the station. In this section we examine the use of the probing method to do this monitoring.

4.2.1 An Implementation of the Probing Method

The implementation of the probing method which we now describe follows from our general description of probing in section 2.2. With the use of probe packets, each terminal assumes the responsibility for both initiating and determining an update in its knowledge of the connectivity between it and the repeaters and station. Specifically,

whenever a terminal deems it necessary, that terminal will transmit a general probe packet. When the station or any repeater with an assigned route to the station receives a general probe packet, it will respond by sending the probing terminal a response packet.[*] As before, the response packet informs the terminal that the responding node (either a repeater or the station) received the terminal's probe packet. Thus for each general probe packet transmitted, a terminal will obtain, from the received response packets, an update in its knowledge of the two directional connectivity between it and the repeaters and station. This connectivity information can then be transported to the station via the terminal's assigned route (if it is still usable) or via a route (i.e., a relaying node) selected from the terminal's updated knowledge of connectivity. As with the other implementations, the station can then make a decision as to whether a new route should be assigned. If a new route is selected, the station must then inform the terminal of this change.

At this point, let us compare this implementation of the probing method with the two implementations of the broadcast method discussed in section 4.1. To begin with, the two problems associated with the first implementation of the broadcast method have been eliminated with this implementation of the probing method. That is, this use of the probing method 1) tests the channel between a terminal and repeater (or station) in both directions, and 2) gives complete control to each

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[*] As mentioned in section 2.2, some mechanism must be provided to avoid the possibility of having two or more response packets arrive at the probing terminal at the same time.

terminal of the rate at which it may update its knowledge of connectivity.
As for the second implementation of the broadcast method, assuming
repeater/station transmission range is greater than terminal transmission
range, the end result of using either the second implementation of the
broadcast method or the above implementation of the probing method is
the same. That is, whether a terminal broadcasts an ROP or transmits a
general probe packet, the end result is that the station receives an up-
date in its knowledge of the connectivity between that terminal and the
repeaters and station. Although the end result is the same, the overhead
used by each of the two methods may be different. To illustrate this
point, let us determine the overhead, measured by the expected number of
transmitted overhead packets ($E[P]$), associated with each implementation
in order for a terminal to update its route to the station. Suppose that
the terminal we are considering is connected in both directions to L
relaying nodes. For simplicity, we assume that the route between the
terminal and the station via each of these relaying nodes consists of
H hops (i.e., there are H-1 repeaters along each route). Figure 4-1
illustrates the transmission of overhead packets for each of the two
implementations. Ignoring the possibility of channel errors and the
transmission of acknowledgements, the overhead associated with each imple-
mentation is given by

$$E[P \mid broadcast] = 1 + L(H-1) + H \cdot Pr\{new\ route\ assigned\} \qquad (4.1)$$

and

$$E[P \mid probing] = 1 + L + H + H \cdot Pr\{new\ route\ assigned\}$$

3. new route assigned

2. ROP's relayed to the station
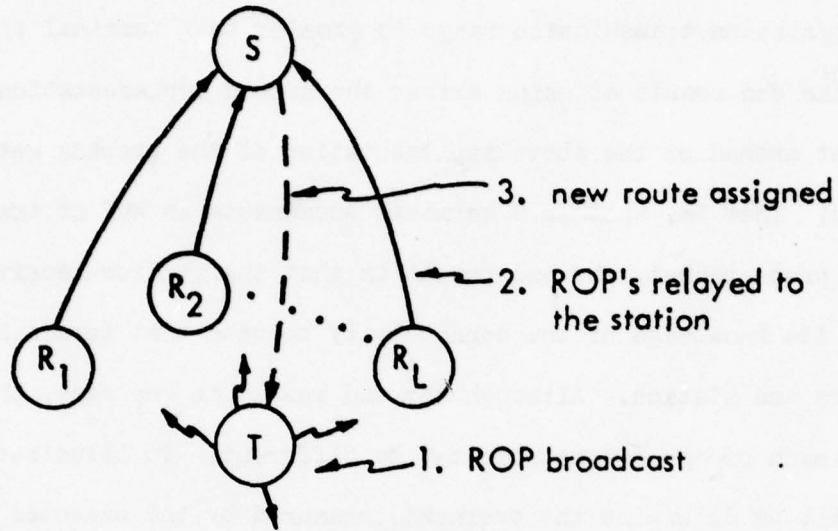
1. ROP broadcast

(a) Broadcast implementation (via ROP's)

4. new route assigned

3. connectivity information sent to the station

2. responses

1. general probe
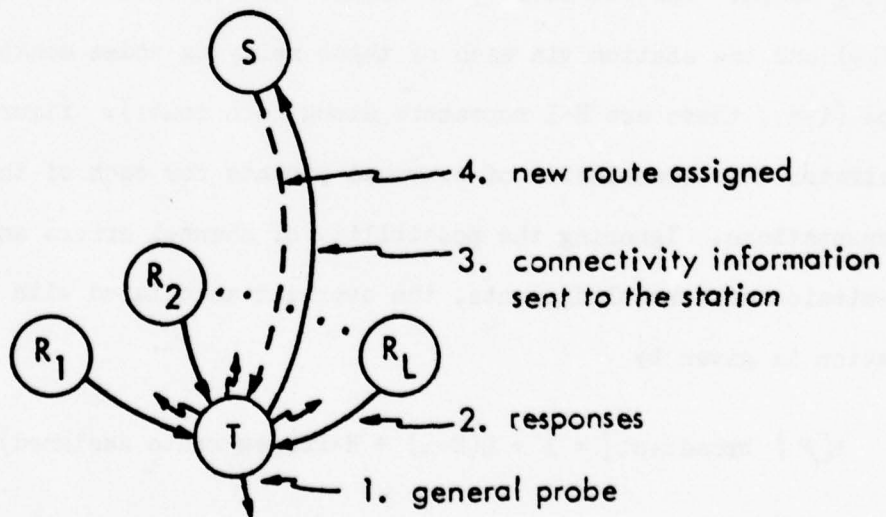
(b) Probing implementation

Figure 4-1 Illustration of the overhead packets associated with updating the route between a terminal and the station

From this analysis we see that the probing implementation is favored in the case where the terminal is far (i.e., several hops) from the station and surrounded by many repeaters. Whereas the broadcast implementation is favored in the case where the terminal is close (i.e., very few hops) to the station and surrounded by few repeaters. We can, however, take advantage of the properties of the network we are now considering in order to better refine the use of the probing method and thus reduce its associated overhead.

4.2.2 A Revised Implementation of the Probing Method

Before assigning to the station the responsibility for updating packet routes, one must be certain that either this is the only way or at least a reasonably efficient way for routes to be updated. Suppose that the route between a terminal and the station is changed only after that terminal experiences a loss of connectivity between it and its relaying node. In this case, we can revise the implementation of the probing method given in the previous section, so that less responsibility in updating routes is given to the station and more responsibility is given to the individual terminal, with the end result being a reduction in the associated overhead. Specifically, we give each terminal the responsibility for determining the loss of connectivity between it and its relaying node. A terminal may do this by transmitting a probe packet, at certain points in time, which is addressed only to its relaying node, with only that relaying node responding to each such received probe packet. Only when a terminal concludes that a loss of connectivity between it and its relaying node has occurred (by not having

received a response to one or more probe packets), will it then trans-
mit a general probe packet, and thus update its knowledge of the con-
nectivity between it and the repeaters and station. Two of the options
available to the terminal at this point are 1) send this connectivity
information to the station where a new route will be selected and
sent to the terminal, or 2) use this connectivity information, and
possibly other information sent in the received response packets, to
select its own route to the station, and then inform the station of
this new route. Suppose that the procedure used in selecting a new
route for a terminal is of the nature, "choose the route with the
minimum _____," where the blank, for example, is filled in by
"number of hops to the station," or "average delay to the station."
If the station and each repeater could maintain the required measure of
its ability to relay packets to the station, then this information
could be included in the response to each received general probe
packet. Thus a terminal could, just as well as the station, choose
its own route to the station and in so doing, not only reduce the over-
head associated with obtaining a new route to the station, but also
reduce the processing that is usually performed at the station.

Let us suppose that the procedure used for updating routes is
such that one may use the above revised implementation of the probing
method where each terminal is able to select its own route to the
station. We now determine the overhead associated with this imple-
mentation of the probing method, and compare it with that associated
with the ROP implementation of the broadcast method. Once again we
determine the expected number of transmitted overhead packets

associated with a particular terminal when it updates its route to the
station. We assume the terminal is connected in both directions to
L relaying nodes, where the route via each of these relaying nodes
consists of H hops. Figure 4-2 illustrates the transmission of over-
head packets associated with the revised implementation of the probing
method. Again ignoring the possibility of channel errors and the
transmission of acknowledgements, the overhead associated with the
revised probing implementation is given by

$$E[P \mid \text{revised probing}] = 2 \cdot \Pr\{\text{new route not selected}\}$$
$$+ (1+1+L+H) \cdot \Pr\{\text{new route selected}\}$$
$$= 2 + (L+H) \cdot \Pr\{\text{new route selected}\} \quad (4.2)$$

Comparing equations (4.1) and (4.2), we see that for the case
$\Pr\{\text{new route selected}\} \approx 0$, only when the terminal is within range
of the station with no surrounding repeaters (i.e., L=1, H=0) will
the broadcast implementation use less overhead than the probing
implementation. The case $\Pr\{\text{new route selected}\} \approx 1$ is the worst
case situation for using the probing implementation, but even in this
unlikely situation, the probing implementation is favored when 2L < 1+LH
(e.g., when L=2, H=2). Furthermore, one must keep in mind that when
using the ROP implementation of the broadcast method, not only does it
generally involve a greater number of transmitted overhead packets, but
even worse, most of these packets are being sent to the station which,
without the use of directional antennas, is already a bottleneck to
traffic flow. Also, by giving the station less responsibility in
monitoring connectivity and updating routes, one can reduce the

(a) Old route valid

1. probe   2. response

4. new route sent to the station

1. current relaying node probed

3. responses

2. general probe
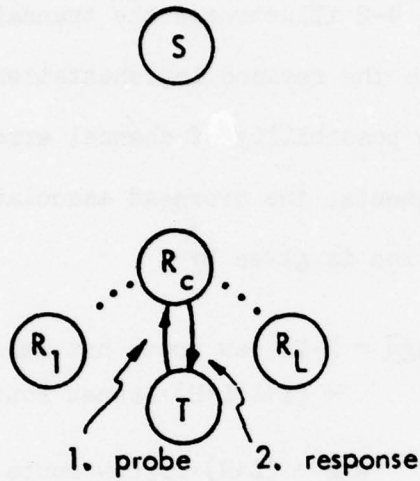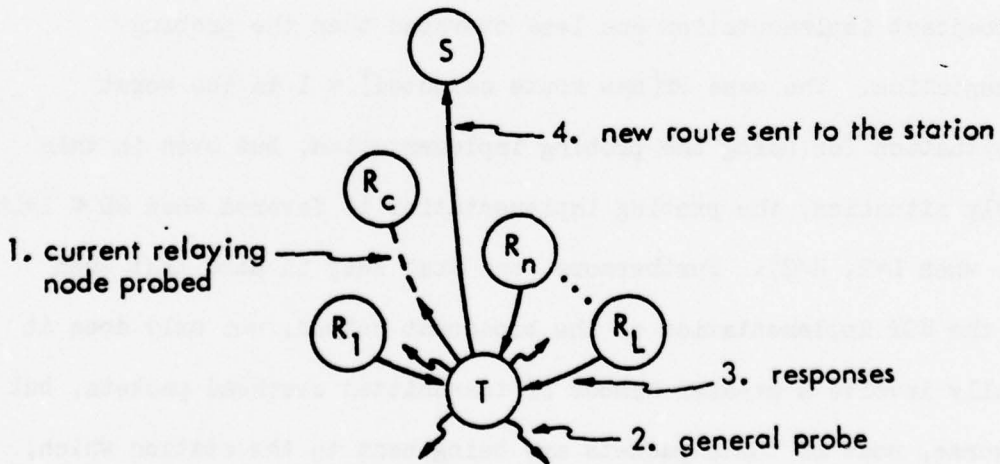
(b) New route selected

Figure 4-2 Illustration of the overhead packets associated with the revised probing implementation

processing capability needed at the station to perform these functions. Of course this implies the need for added processing capability at the terminals. However, a trend in technology has been toward decreasing the cost and increasing the capability of small processors. In an effort to improve network reliability and efficiency, a trend in the design of data communication networks has been to distribute the control of the network among its various nodes. The above implementation of the probing method is a step in this direction.

4.2.3 Probing via Message Packets

What makes the revised probing implementation even more attractive is its ability to easily incorporate the connectivity information obtained when regular message packets are transmitted, in order to further reduce its associated overhead. With this implementation of the probing method, each individual terminal is given the function of determining the loss of connectivity between it and its relaying node, and does this by probing its relaying node at certain points in time (e.g., periodically). This probing, however, is essentially performed each time the terminal sends a regular message packet to the station. Each packet a terminal wishes to send to the station is first sent to the terminal's relaying node. For each such packet received, the relaying node sends back to the terminal an acknowledgement which informs the terminal that the relaying node successfully received the packet. Thus, for the purpose of monitoring the connectivity between a terminal and its relaying node, a regular message packet acts as the probe packet and the acknowledgement for that packet acts as the response packet. In this way, a terminal

need only send a probe packet to its relaying node when it has not sent
a regular message packet for some length of time. Thus an increase in
the rate at which a terminal sends packets to the station will generally
result in a desirable decrease in the overhead needed for that terminal
to monitor the connectivity between it and its relaying node.

4.2.4 Choosing the Probing Times - Periodic Probing and Probing with Position Information

Given that the revised probing implementation is to be used, one
must determine the times at which a terminal should probe its relaying
node. A long period of an undetected loss of connectivity between a
terminal and its relaying node is undesirable in that it can result in
a significant increase in the delay experienced by packets traveling
from the station to a terminal. That is, as mentioned in the previous
section, a packet being sent from a terminal to the station acts as a
probe packet. Thus the added transportation delay for that packet, due
to a loss of connectivity between the terminal and its relaying node,
is only the delay associated with the terminal selecting a new relaying
node. However, when a terminal suffers a loss of connectivity between it
and its relay node, that terminal is effectively cut off from receiving
packets sent by the station. This loss of connectivity is only dis-
covered when the terminal attempts sending a packet (e.g., a probe or
message packet) to its relaying node. Thus, the added delay experi-
enced by an outbound packet, due to a loss of connectivity between
the destination terminal and its relaying node, can be significant.
Therefore, it is desirable for a terminal to learn of a loss of
connectivity between it and its relaying node soon after the loss

actually occurs.

One approach is to have each terminal periodically probe its
relaying node. The probing rate for a particular terminal will depend
on the mobility characteristics of that terminal, the network topology,
and the requirements (e.g., maximum duration of an undetected loss of
connectivity) the terminal is to satisfy. Of course a terminal will
not need to transmit probe packets in a strictly periodic manner. As
discussed in section 4.2.3, each time a terminal sends a message packet
to the station, it is effectively probing its relaying node. Thus, in
this situation, periodic probing implies that a terminal will probe its
relaying node at time t only if the last transmission of either a probe
or message packet was at time $t-T_p$, where T_p is the probing period.
By decreasing the probing period, a terminal can decrease the time of
an undetected loss of connectivity. However, this decrease in probing
period will generally result in an undesirable increase in the network
overhead.

A terminal could improve upon periodic probing if it could keep
track of its position relative to that of its relaying node. With
periodic probing, the probing period is the same regardless of where
the terminal is located relative to its relaying node. Ideally, the
probing period should be smaller at those locations where the terminal
is more likely to suffer a loss of connectivity between it and its
relaying node. Such a location may, for example, be in the outermost
region of the relaying node's transmission range.

If a terminal could continually monitor its position relative to
that of its relaying node (see [12] for a discussion of possible

methods), then it could use this information to vary the rate at which
it probes its relaying node. In fact, if position and connectivity
are highly correlated, then with the station and repeaters fixed in
position, a terminal would not even have to probe its relaying node.
The terminal could just select a new relaying node when, by the use
of position information, it anticipates a possible loss of connectivity
between it and its current relaying node. However, one must keep in
mind that to enable a terminal to continually monitor its position will
generally involve the use of hardware and radio spectrum other than that
which is provided in the basic packet radio network.

An alternative is to have each terminal obtain position infor-
mation only at each effective probing of its relaying node, and doing
so using only the radio channel already provided. For example, the
distance between two radio transceivers (e.g., a terminal and its re-
laying node) can be estimated by measuring the radio wave propagation
delay from one radio transceiver to the other. Thus a terminal can
estimate the distance to its relay node by taking the difference in the
time at which it transmits a probe(message) packet and the time at
which it receives the associated response(acknowledgement) packet, and
then subtracting off the processing time (which may be included in the
response(acknowledgement) packet) at the relaying node. With the addi-
tional use of directional antennas at the relaying node, angle can be
estimated at the relaying node and then sent back to the terminal in
the response(acknowledgement) packet (see [13] for related discussion).
With this information, the terminal can estimate its position relative to
its relaying node, and then use this information to decide when it would

be best to send the next probe packet. Furthermore, with this position information, a terminal can anticipate a possible loss of connectivity between it and its relaying node, and thus initiate rerouting before the loss occurs.

It would be reasonable to say that probing with position information is more efficient (i.e., less overhead for the same duration of an undetected loss of connectivity) than periodic probing. However, it is also more complex in that it requires the capability of determining position. In Chapter 5 we make use of analytical comparisons of the two probing schemes to determine under what conditions the increased efficiency of probing with position information might outweigh its complexity.

4.2.5 Using the Probing Implementation in a more General Network

In our discussion, in this chapter, of using connectivity monitoring for updating packet routes, we assumed that the packet routes in the network had been previously initialized and that the station and all repeaters are stationary. These assumptions, however, were only made to simplify both the discussion of the monitoring implementations developed in this chapter and the analysis performed in the next chapter. In this section we show that the implementation of the probing method discussed in section 4.2.2 can be generalized so as to incorporate both the initialization of packet routes and the mobility of the repeaters and station.

If we allow the repeaters and station to be mobile, then changes in connectivity between a repeater and the network's other repeaters

and station may necessitate that the route between that repeater and
the station be changed. Just as would a terminal, this repeater can
use probe and message packets to monitor the connectivity between it
and its relay node (either another repeater or the station). When a
repeater concludes a loss of connectivity between it and its relaying
node, that repeater could then transmit a general probe packet and, from
the received response packets, update its knowledge of the connectivity
between it and the network's other repeaters and station. Just as in
the case of a terminal, the repeater could send this connectivity in-
formation to the station where a new route will be selected, or if the
routing procedure allows it, the repeater could select its own route
to the station. Thus we see that for the purpose of updating routes,
each repeater could function just as though it were a terminal. Of course
when a repeater does conclude a loss of connectivity between it and its
relaying node, until it obtains a new route to the station, that repeater
will not respond to any received probe packet nor acknowledge any
received message packet. In this way, a terminal or repeater to which
this repeater is acting as a relaying node will not receive a response nor
an acknowledgement after sending a probe or message packet, respectively.
Thus that terminal or repeater will assume a loss of connectivity
between it and this repeater, and will then initiate obtaining a new
route to the station. The idea here is that for the purpose of routing,
each device, terminal or repeater, only concerns itself with having a
usable route to the station. We see that the process of updating routes,
even with the station and each repeater mobile, is relatively simple,
because, with the use of tree-structured routing, a route to the station

is specified by the identity of a relaying node, and to change a route, a device simply changes its relaying node.

The initialization of packet routes follows from the above discussion of updating routes with the repeaters and station mobile. When the network is first started (or restarted), no device has a route to the station. Thus each device begins transmitting general probe packets. Since only those relaying nodes with routes to the station will respond to received general probe packets, initially only the station will be responding to received general probe packets. Thus each device with a connection in both directions between it and the station will eventually receive a response to a transmitted general probe packet, and will subsequently obtain a route to the station which involves sending its packets directly to the station. After obtaining this route, each of these devices which is a repeater will then begin responding to general probe packets transmitted by other devices to which it is connected in both directions. Each of these other devices will eventually receive a response to one of its general probe packets, and will subsequently obtain a two-hop route to the station. This process then continues on for devices which are three hops and further from the station, until the packet routes for the entire network have been initialized.

CHAPTER 5

Analysis of the Probing Implementation*

In Chapter 4 we found that the implementation of the probing
method devoloped in section 4.2.2 is more flexible and in general uses
less overhead than the implementations of the broadcast method developed
in section 4.1. However, we have left some questions concerning this use
of the probing method unanswered. For example, we have not yet deter-
mined how the characteristics of terminal mobility affect the perfor-
mance of this implementation, nor have we determined how much better is
probing with position information than periodic probing. In this
chapter we examine these and other aspects associated with the use of
the probing implementation.

In the analysis in this chapter, we generally consider just
one terminal as it moves within the region covered by a packet radio
network. For reasons of clarity, and without loss of generality, we
assume that this terminal always sends(receives) packets to(from) the
station via at least one repeater. In this way, the terminal's re-
laying node will in fact always be a repeater.

5.1 Performance Criterion

In this section we establish the criterion that will be used
to evaluate the performance of the probing implementation. To
motivate the choice of criterion, let us consider a terminal as it
moves within the region covered by a packet radio network. For

_____

*
In this chapter, the words "probing implementation" implicitly refer
to the revised probing implementation (discussed in section 4.2.2)
where each terminal selects its own relaying node.

simplicity, we ignore the possibility of channel errors. Figure 5-1

illustrates a path taken by the terminal. Each location marked by X

denotes a point along the path where the terminal probed its relaying

repeater and received a response. Each location marked by ▧ denotes

a point where the terminal probed its relaying repeater, but did not

receive a response due to a loss of connectivity between it and that

repeater. So at each of these locations, the terminal also transmitted

a general probe packet and, from the received response packets, selected

a new relaying repeater. The terminal's i^{th} (i=1,2,...) selected re-

laying repeater is denoted as R_i. The transmission range of the

terminal and all repeaters are assumed equal. Thus, only after the

terminal exits the transmission range of its current relaying repeater,

does it then experience a loss of connectivity between it and that

repeater. The portions of the path marked by a solid line indicate

that the terminal is connected to its current relaying repeater, and

the portions marked by a broken line indicate that the terminal is not

connected to its current relaying repeater. As mentioned in section

4.2.4, it is desirable that a terminal learn of a loss of connectivity

between it and its relaying repeater soon after the loss occurs. Thus

it is desirable to reduce that fraction of the path marked by broken

lines in Figure 5-1. However, we note that to do so would require that

the terminal probe its relaying repeater more often.* This illustrates

that there is a fundamental trade-off between the fraction of time a

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*At least the terminal would have to probe its relaying repeater more
often as it approaches the outermost region of its relaying repeater's
transmission range.
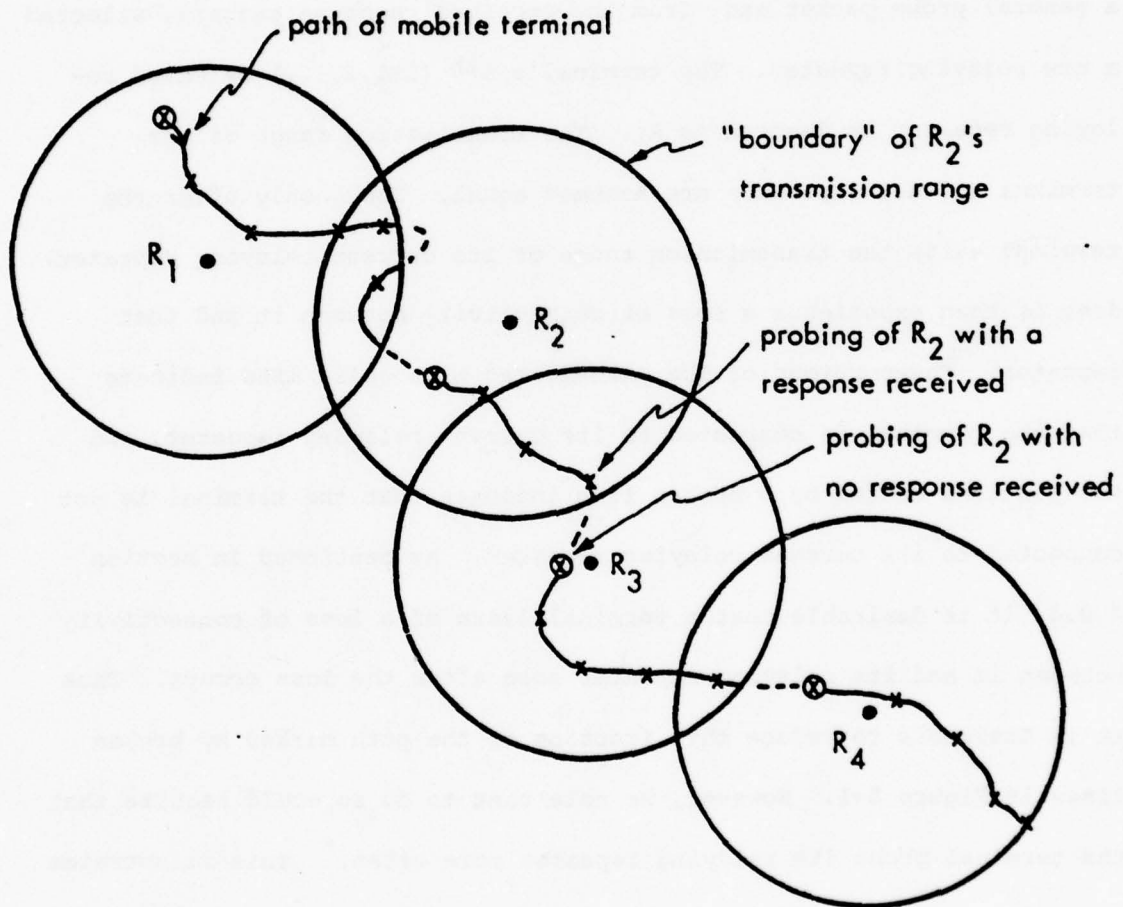
Figure 5-1 Illustration of the probing implementation

terminal has a usable route to the station and the associated probing

rate (and thus the network overhead). It follows that a reasonable

method for evaluating the performance of the probing implementation is

to examine how well the probing implementation is able to trade off these

quantities. Thus, we use as the performance criterion, the fraction of

time a terminal has a usable route to the station for a given asso-

ciated average transmission rate of overhead packets. The first quan-

tity will be referred to as the fraction of time connected (FTC)[*], and

the second quantity will be referred to as the average transmission

rate (ATR). Being more precise about these quantities, we define

T_i = the duration of time between the terminal's $(i-1)$th and ith probing

TC_i = the total time that the terminal is connected to its current relaying repeater between probing i-1 and i

P_i = the number of transmitted overhead packets associated with the routing update at the time of the ith probing

With these definitions, we may now express FTC and ATR as

$$FTC = \lim_{M \to \infty} \frac{\sum_{i=1}^{M} TC_i}{\sum_{i=1}^{M} T_i} \tag{5.1}$$

---

* The word "connected" refers to the terminal being connected to its current relaying repeater and thus, in a sense, to the network itself.

and

$$ATR = \lim_{M \to \infty} \frac{\sum\limits_{i=1}^{M} P_i}{\sum\limits_{i=1}^{M} T_i} \tag{5.2}$$

if the limits exist.

5.2 Network Model

In order to evaluate the performance of the probing implementation, we must formulate both a model of terminal mobility and a model of network topology. Our objective in the analysis is not so much to obtain specific quantitative results, but rather to obtain qualitative results which indicate trends associated with using the probing implementation. Thus our mobility and topology models will have to be realistic enough to correctly indicate trends, and yet simple enough to allow the use of analytical techniques.

In the analysis, we consider just one terminal. We model this terminal's mobility as a constrained random walk characterized by a homogeneous, discrete-time, discrete-state Markov process. Specifically, the terminal is constrained to move along the path shown in Figure 5-2. The path is considered to extend in each direction for an infinite distance. At intervals of s units of distance along the path are locations identified by consecutive integers below the path. These locations correspond to the states of the Markov process. The terminal's movement between these states is defined as follows. If the terminal enters state i at time t, at time $t+T_s$ it will move to state $i+1$ with
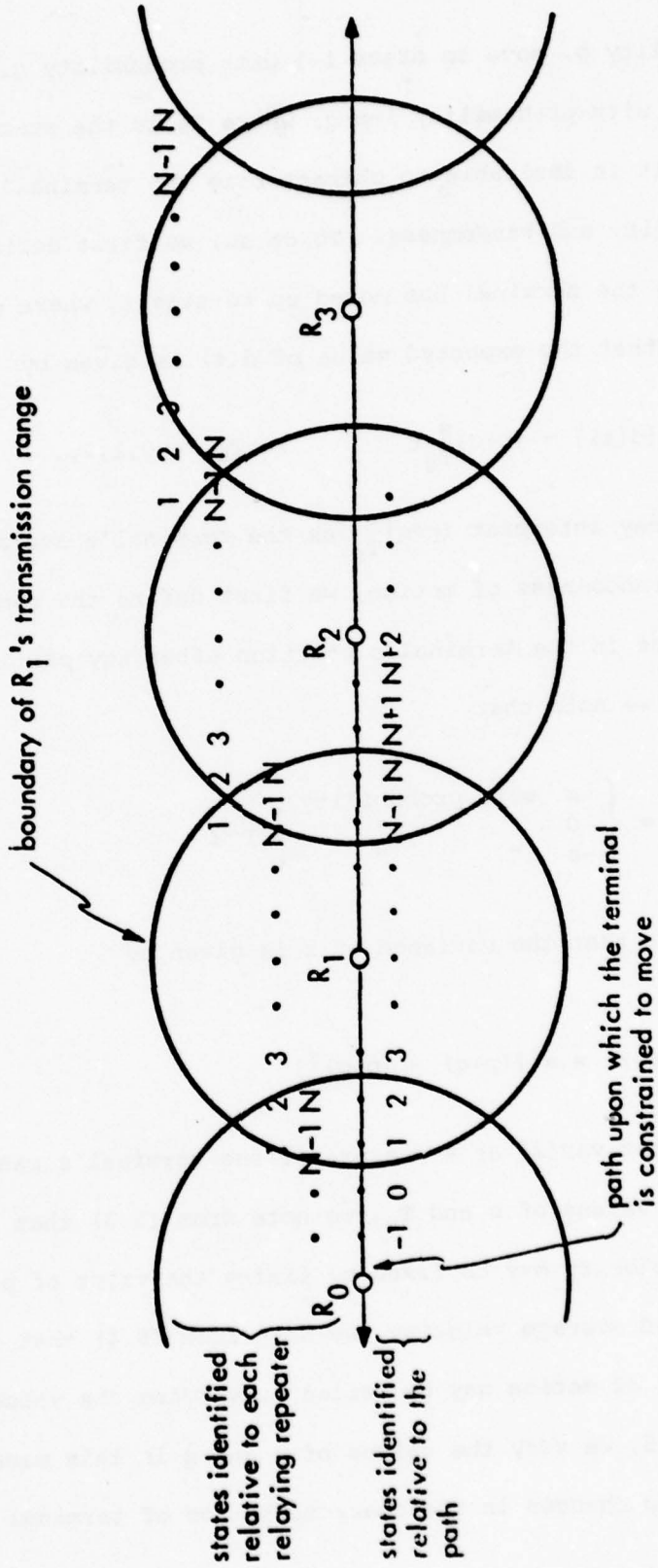
Figure 5-2 Illustration of the mobility and topology models

probability p, move to state i-1 with probability q, or remain in state i with probability 1-p-q; where T_S is the state transition time.

It is desirable to characterize the terminal's motion in terms of velocity and randomness. To do so, we first define d(t) as the total distance the terminal has moved up to time t, where d(0) = 0. It follows that the expected value of d(t) is given by

$$E[d(t)] = (p+q)\frac{s}{T_S}t \qquad t=nT_s, \ n=0,1,2,\ldots \qquad (5.3)$$

Thus we may interpret $(p+q)\frac{s}{T_S}$ as the terminal's average velocity. As for the randomness of motion, we first define the random variable z as the change in the terminal's position after any particular transition. As such, we note that

$$z = \begin{cases} s & \text{with probability p} \\ 0 & \text{"} \qquad \text{"} \qquad 1\text{-p-q} \\ -s & \text{"} \qquad \text{"} \qquad q \end{cases}$$

It follows that the variance of z is given by

$$var[z] = s^2[(p+q) - (p-q)^2] \qquad (5.4)$$

We interpret var[z] as a measure of the terminal's randomness of motion. For given values of s and T_s, we note from (5.3) that the terminal's average velocity may be fixed by fixing the value of p+q. Furthermore, for a fixed average velocity, we note from (5.4) that the terminal's randomness of motion may be varied by varying the value of p-q. In section 5.5, we vary the values of p and q in this manner in order to examine how changes in the characteristics of terminal mobility affect

the performance of the probing implementation.

As for the network topology, shown in Figure 5-2 are repeaters which are equally spaced along the path. Each of these repeaters may act as the terminal's relaying repeater during one of more segments of time. The transmission range of each of these repeaters is shown to encompass N consecutive states along the path. The states relative to each repeater are identified by the integers 1 through N. For simplicity, we assume that the terminal and the repeaters along the path each have the same transmission range.* Also, we assume that the repeaters are spaced so that each state along the path is within the transmission range of at least one repeater. Not shown in Figure 5-2, but nevertheless present, are other network repeaters and the station.

In the derivation of FTC and ATR in section 5.4, it is necessary to distinguish between a state relative to the path and a state relative to the terminal's current relaying repeater. To do so, we use the notation $s(n)=j$ to denote the event that immediately after the nth transition (i.e., at time nT_s), the terminal is in state j (j an integer) relative to the path. Also, where appropriate, we use the notation $s_r(n)=j$ to denote the event that immediately after the nth transition, the terminal is in state j ($j=1,2,\ldots,N$) relative to its current relaying repeater.

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*In the actual analysis, it is only necessary that the repeaters along the path have the same transmission range.

5.3 Probing and the Selection of a New Relaying Repeater

In the analysis of the probing implementation, we assume that the terminal's knowledge of the connectivity between it and its relaying repeater is only updated each time the terminal sends its relaying repeater a probe packet. That is, we do not directly incorporate in the analysis the terminal's effective probing of its relaying repeater each time it sends a message packet to the station. Also, aside from the discussion in section 5.6, we ignore the possibility of packet errors. In particular, if the terminal and a repeater are each within the transmission range of the other, then a probe packet sent from the terminal to the repeater and the associated response packet sent from the repeater back to the terminal will each be received correctly. These assumptions are made to simplify the mathematical analysis. We shall, however, comment on the expected changes in the obtained results when each of these assumptions is removed.

With the model of terminal mobility described in section 5.2, we note that the connectivity between the terminal and its relaying repeater does not change from the end of one transition time until the beginning of the next. Thus the best times for the terminal to probe its relaying repeater are immedicatly after transitions. However, the question is, after which particular transitions should the terminal probe its relaying repeater? As mentioned in section 4.2.4, we examine two schemes for choosing these probing times. The first scheme is periodic probing in which the terminal probes its relaying repeater immediately after every n^{th} (n=1,2,...) transition and consequently, nT_s is the probing period.

The second scheme is probing with position information. With this scheme, at each probing while within the transmission range of its relaying repeater, the terminal learns of its position relative to that repeater. If at a probing the terminal is out of the transmission range of its relaying repeater, then through the process of obtaining a new relaying repeater, the terminal learns of its position relative to that new relaying repeater. In either case, the terminal uses this position information to determine when (i.e., after how many more transitions) to send the next probe packet to its relaying node.

Before proceeding with the derivation of FTC and ATR, there is one other aspect associated with the probing implementation that must be mentioned. In the discussion in section 4.2.2, we stated that when a terminal selects a new relaying repeater, it bases its choice on the relative relaying abilities of the available repeaters. For the model described in section 5.2, we assume that a repeater's position along the path is uncorrelated with its ability to relay packets to the station. Thus, choosing a new relaying repeater on the basis of relaying ability will, as far as the analysis is concerned, correspond to choosing a repeater at random from the set of available repeaters. However, it is also desirable to examine the performance of the probing implementation when the choice of a new relaying repeater is based on other criteria. In section 5.5, besides examining the use of a random choice of a new relaying repeater, we also examine the use of basing the choice of a new relaying repeater on the terminal's position relative to each of the available relaying repeaters. The motivation for doing this comes from equation (4.2). We note from (4.2) that the largest amount of overhead is used in the updating process when a terminal must select a new

relaying repeater. Thus it is desirable to maximize the time between needed changes in the terminal's relaying repeater. One method for doing this is to have the terminal base its choice of a new relaying repeater on its position relative to each of the available relaying repeaters. In section 5.5 we discuss and evaluate two uses of position information for choosing a new relaying repeater.

5.4 Derivation of FTC and ATR

To incorporate in the performance analysis both the use of periodic probing and probing with position information, we associate with the ith $(i=1,2,\ldots,N)$ state relative to each repeater the waiting time τ_i (τ_i a positive integer). Furthermore, we define the associated waiting time vector $\underline{\tau} = (\tau_1,\tau_2,\ldots,\tau_N)$. The significance of $\underline{\tau}$ is as follows. If at a probing the terminal is in state i relative to its current relaying repeater, then the terminal will wait τ_i transition times before again probing its relaying repeater. If at a probing the terminal is out of the transmission range of its current relaying repeater, but is in state i relative to its newly selected relaying repeater, then the terminal will wait τ_i transition times before probing its new relaying repeater.*

For periodic probing, it is clear that $\tau_1=\tau_2=\ldots=\tau_N=k$, where k takes on values 1,2,3,... for probing periods $T_s,2T_s,3T_s,\ldots$, respectively. For probing with position information, $\underline{\tau}$ should be selected so as to optimize the performance of the probing implementation. Later (in section 5.5) we shall discuss both the selection of $\underline{\tau}$ and what is meant by the optimal performance of the probing implementation.

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* We assume that the time delay from when the terminal detects a loss of connectivity between it and its relaying repeater until it selects a new relaying repeater is very small compared to the transition time T_s.

For now, let us assume that a value for $\underline{\tau}$ and values for p and q have been selected along with a strategy for choosing a new relaying repeater. On the route to deriving expressions for FTC and ATR, we define

$$\psi_{ij} = Pr\{s_r(\tau_i+m) = j \mid s_r(m) = i\} \quad i,j=1,2,\ldots,N; \; m=0,1,2,\ldots$$

where state j is taken to be relative to the terminal's current or newly selected relaying repeater if, immediately after transition τ_i+m, the terminal is, respectively, within range or out of range of its current relaying repeater. In words, ψ_{ij} is the probability that the next probing will take place while the terminal is in state j relative to its relay repeater, given that the last probing took place while the terminal was in state i relative to its relaying repeater at that time. We may express ψ_{ij} in terms of the n-step transition probability $\phi_{ij}(n) \overset{\Delta}{=} Pr\{s(n) = j \mid s(0) = i\}^*$ of the Markov process which characterizes the terminal's motion along the path. In doing so, we obtain

$$\psi_{ij} = \phi_{ij}(\tau_i) + \sum_{\substack{k>N \\ k<1}} \phi_{ik}(\tau_i) \cdot Pr \left\{ \begin{array}{l} \text{state k relative to the path} \\ \text{is the same location as state} \\ \text{j relative to the newly selected} \\ \text{relaying repeater} \end{array} \right\} \quad (5.5)$$

The first term on the right-hand side of (5.5) is the probability that, immediately after transition τ_i+m, the terminal is in state j relative to its current relaying repeater, given $s_r(m) = i$. The second term is the probability that, immediately after transition τ_i+m, the terminal

---

* Equation (A.1) defines a recursive method for calculating $\phi_{ij}(n)$ for any finite state Markov chain. See Appendix C for details on how one may compute $\phi_{ij}(\tau_i)$ for the Markov chain under consideration.

is outside of the range of its current relaying repeater and is in state j

relative to its newly selected relaying repeater, given $s_r(m) = i$. The

second probability term within the summation in (5.5) is of course a

function of the strategy used for selecting a new relaying repeater. We

note that the associated N×N matrix Ψ with elements ψ_{ij} is stochastic,

and thus may be viewed as representing the transition probabilities of

a discrete-time Markov chain. Furthermore, we note that p+q < 1 is

a sufficient condition for this Markov process to be ergodic.* Assuming

this condition to hold, from the discussion in Appendix A, we can

determine the steady-state probabilities

$$\tilde{\pi}_i = \lim_{m \to \infty} \tilde{\pi}_i[m] \qquad i=1,2,\ldots,N$$

where

$$\tilde{\pi}_i[m] \overset{\Delta}{=} \Pr \left\{ \begin{array}{l} \text{the m}^{th} \text{ probing is made while the terminal is} \\ \text{in state i relative to its current or newly} \\ \text{selected relaying repeater} \end{array} \right\}$$

by solving the set of equations given by

$$\tilde{\pi}_i = \sum_{k=1}^{N} \tilde{\pi}_i \psi_{ik} \qquad i=1,2,\ldots,N$$

$$1 = \sum_{i=1}^{N} \tilde{\pi}_i$$

(5.6)

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*With p+q < 1, the process is an irreducible, aperiodic, finite Markov chain and is thus ergodic (see [14] section 15.7). If p+q = 1, then there are certain cases (e.g., τ_i=1 for all i and relaying repeaters spaced such that there is no overlap of their transmission ranges) in which the Markov chain defined by Ψ is periodic and thus not ergodic.

We now express (5.1) and (5.2) in the forms given by

$$FTC = \lim_{M \to \infty} \frac{\frac{1}{M} \sum_{i=1}^{M} TC_i}{\frac{1}{M} \sum_{i=1}^{M} T_i} = \frac{\lim_{M \to \infty} \frac{1}{M} \sum_{i=1}^{M} TC_i}{\lim_{M \to \infty} \frac{1}{M} \sum_{i=1}^{M} T_i} \qquad (5.7)$$

and

$$ATR = \lim_{M \to \infty} \frac{\frac{1}{M} \sum_{i=1}^{M} P_i}{\frac{1}{M} \sum_{i=1}^{M} T_i} = \frac{\lim_{M \to \infty} \frac{1}{M} \sum_{i=1}^{M} P_i}{\lim_{M \to \infty} \frac{1}{M} \sum_{i=1}^{M} T_i} \qquad (5.8)$$

Since the Markov chain defined by Ψ is ergodic, from (5.7) and (5.8) we obtain, respectively,

$$FTC = \frac{E[TC]}{E[T]} \qquad (5.9)$$

and

$$ATR = \frac{E[P]}{E[T]} \qquad (5.10)$$

where, under steady-state conditions, $E[T]$ is the expected time between two consecutive probings, $E[TC]$ is the expected time between two consecutive probings that the terminal is connected to its current relaying repeater, and $E[P]$ is the expected number of overhead packet transmissions associated with a probing and the resulting possible change in the route to the station. For notational convenience, we normalize $T_s = 1$. From the definition of expectation, we may write

$$E[T] = \sum_{i=1}^{N} \tilde{\pi}_i \tau_i \qquad (5.11)$$

Defining the conditional expectation

$$E[TC^i] = E[TC \mid \text{the first of the two consecutive probings is made} \\ \text{while in state i relative to the relaying repeater}]$$

we may write

$$E[TC^i] = \sum_{k=1}^{N} E[\text{time the terminal occupies state k, starting from} \\ \text{when a probing is made while in state i until just} \\ \text{before the next probing}]$$

$$= \sum_{k=1}^{N} \sum_{n=0}^{\tau_i - 1} \phi_{ik}(n) \qquad (5.12)$$

Thus from (5.12), we obtain

$$E[TC] = \sum_{i=1}^{N} \tilde{\pi}_i \sum_{k=1}^{N} \sum_{n=0}^{\tau_i - 1} \phi_{ik}(n) \qquad (5.13)$$

We define ℓ as the expected number of additional overhead packets transmitted when, at a probing, the terminal must obtain a new route to the station. It follows that

$$E[P] = 2 + \ell \cdot \Pr\{\text{new relaying repeater selected}\}$$

$$= 2 + \ell \sum_{i=1}^{N} \tilde{\pi}_i \left[1 - \sum_{k=1}^{N} \phi_{ik}(\tau_i) \right] \qquad (5.14)$$

Thus substituting (5.11) and (5.13) into (5.9) yields

$$\text{FTC} = \frac{\sum\limits_{i=1}^{N} \tilde{\pi}_i \sum\limits_{k=1}^{N} \sum\limits_{n=0}^{\tau_i-1} \phi_{ik}(n)}{\sum\limits_{i=1}^{N} \tilde{\pi}_i \tau_i} \qquad (5.15)$$

Likewise, substituting (5.11) and (5.14) into (5.10) yields

$$\text{ATR} = \frac{2 + \ell \sum\limits_{i=1}^{N} \tilde{\pi}_i \left[1 - \sum\limits_{k=1}^{N} \phi_{ik}(\tau_i) \right]}{\sum\limits_{i=1}^{N} \tilde{\pi}_i \tau_i} \qquad (5.16)$$

Equations (5.15) and (5.16) are the expressions we had set out to derive in this section.

5.5 Performance Results

In this section we evaluate and compare the performances associated with periodic probing and probing with position information, along with those associated with the random and position based selections of a new relaying repeater. This is done as the values of p and q are varied in order to model changes in the terminal's average velocity and randomness of motion. Initially we select both a value for the number of states within the transmission range of each repeater along the path, and a value for the spacing between the repeaters along the path. Later we examine the affects on the obtained results when each of these two parameters is changed.

As illustrated in Figure 5-3, N is chosen to be 11 and a repeater is located every 5 states along the path. In the analysis,
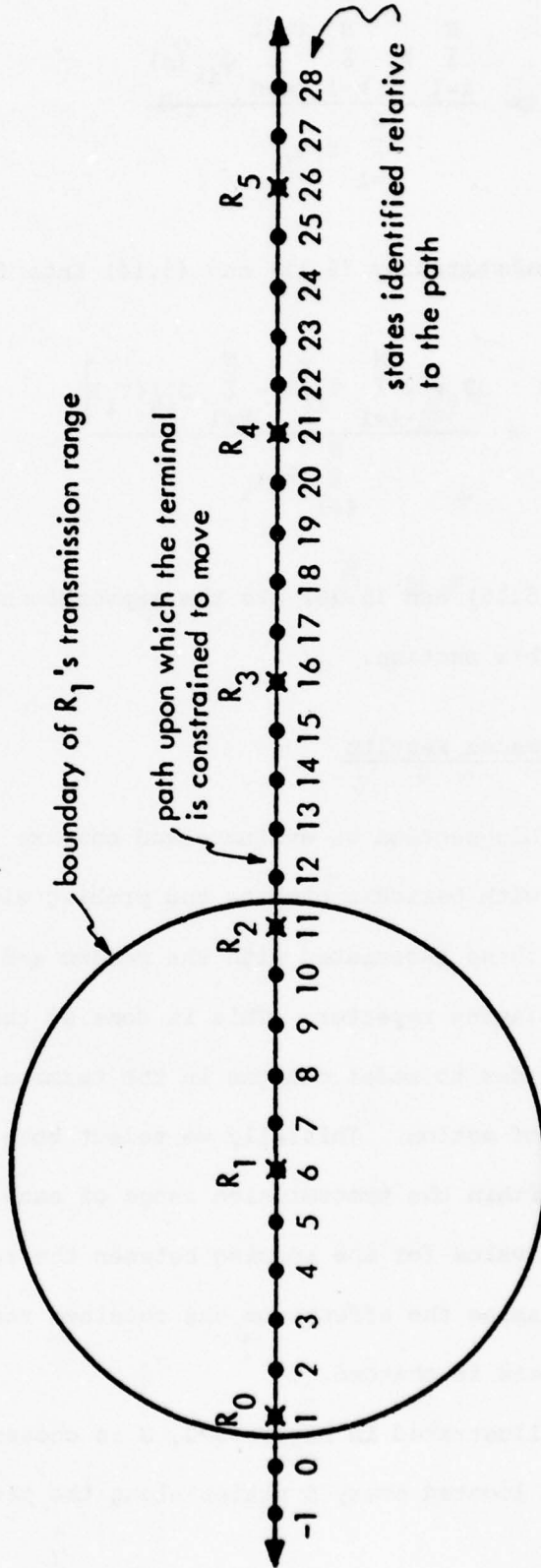
Figure 5-3 Network model for N = 11 and repeater spacing = 5s

we examine average velocities corresponding to p+q = 0.8 and 0.4. To give some physical significance to these values, if we choose s = 1 km, then each repeater's transmission range will be approximately 11 km and a repeater will be spaced every 5 km along the path. Moreover, if we choose T_s = 30 seconds, then for p+q = 0.8 and 0.4, the terminal's average velocity will be, respectively, 96 and 48 km/hour.

We examine three methods for selecting a new relaying repeater. With the first method, the terminal selects at random its new relaying repeater from the set of available repeaters. This corresponds to the situation where position information is not available and/or where the choice of a new relaying repeater is based only on the relative relaying abilities of the available repeaters. With the second method, the terminal selects the nearest repeater as its relaying repeater. This corresponds to the situation where the terminal is aware of its distance to each of the available repeaters and uses only this information, in what seems to be a reasonable way, to select a new relaying repeater. Finally, with the third method, the terminal selects the repeater for which the expected time to first exit that repeater's transmission range (E[TE]) is a maximum.[*] With this last method, the terminal bases its choice both on its position relative to each of the available repeaters and on its mobility characteristics (i.e., the type of motion and the values of p and q). Later we comment on whether this use of position information is optimal.

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[*] See Appendix C for an expression that may be used to compute the conditional expectation $E[TE_i] = E[TE|s_r(0)=i]$ for i=1,2,...,N.

5.5.1 Periodic Probing

We first examine periodic probing. Let us, for the present time, assume that the route between the station and each repeater along the path consists of two hops. It follows that the expected number of additional overhead packets transmitted when, at a probing, the terminal must select a new relaying repeater is given by

$$\ell = E[\text{number of hops along the route between the terminal and the station}]$$
$$+ E[\text{number of repeaters within range of the terminal at the time of selection}]$$
$$= 3 + 2 + \Pr\{\text{terminal is within range of 3 repeaters at the time of selection}\} \quad (5.17)$$

The probability term in (5.17) may be computed via a straightforward summation on $\tilde{\pi}_i \phi_{ij}(\tau_i)$. Using (5.17) along with the results of section 5.4, values for FTC and ATR were computed for p=0.8, q=0; p=0.6, q=0.2; and p=0.4, q=0.4 and are plotted in Figures 5-4, 5-5, and 5-6, respectively. For each of the three methods for selecting a new relaying repeater (i.e., random, nearest, and max E[TE]), the probing period is increased and the corresponding points (ATR, FTC) are plotted. The consecutive points for each selection method are connected by straight line segments in order to indicate values of FTC and ATR that can be achieved if one were to time-share between the points which define each line segment. Time-sharing in this case means that for fraction θ ($0 \leq \theta \leq 1$) of the time the value of $\underline{\tau}$ associated with one point is used, and for fraction $1-\theta$ the value of $\underline{\tau}$ associated with the other point is used. The proof of this time-sharing result is given in Appendix B.
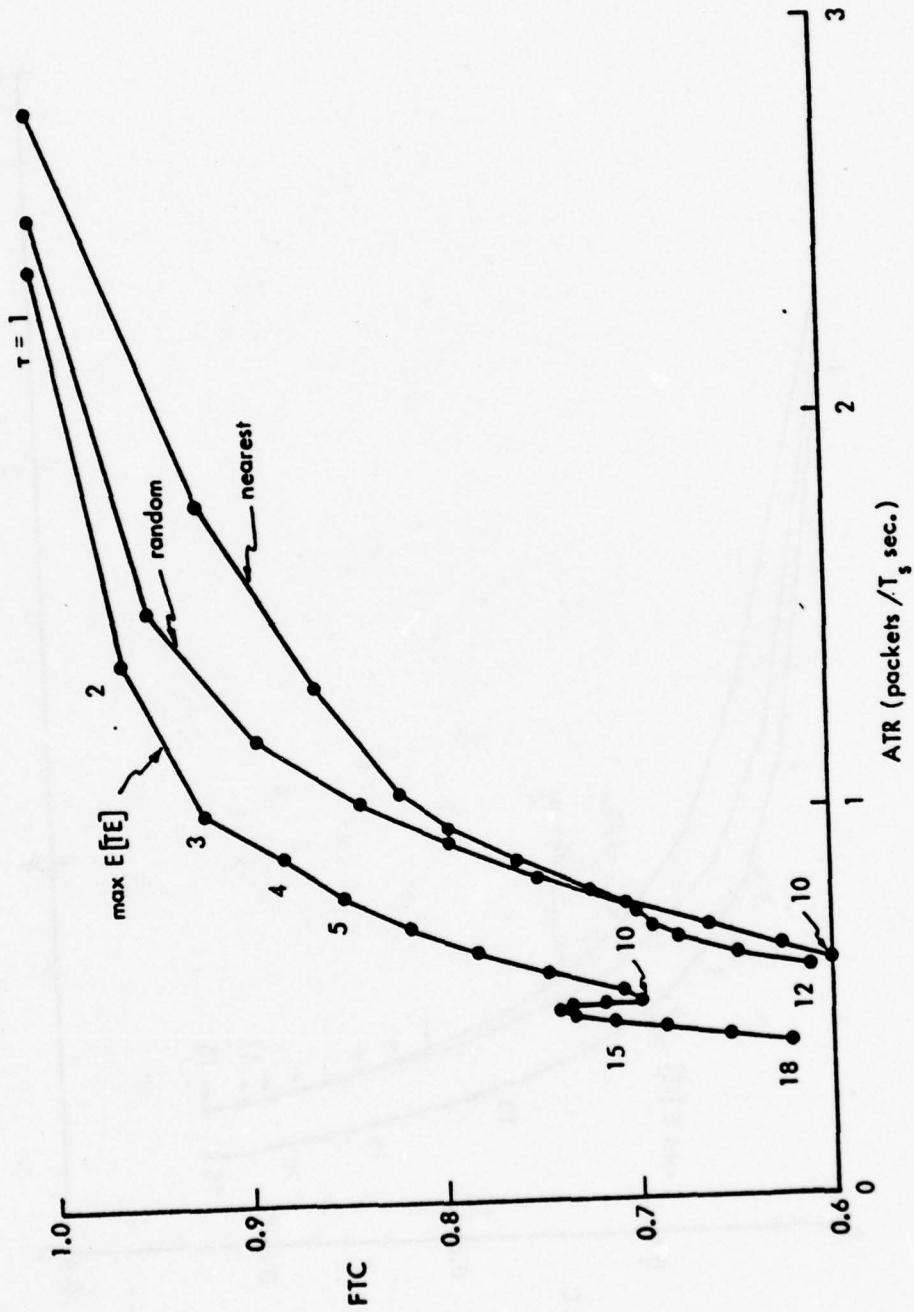
Figure 5-4 FTC vs. ATR for periodic probing with p=0.8, q=0

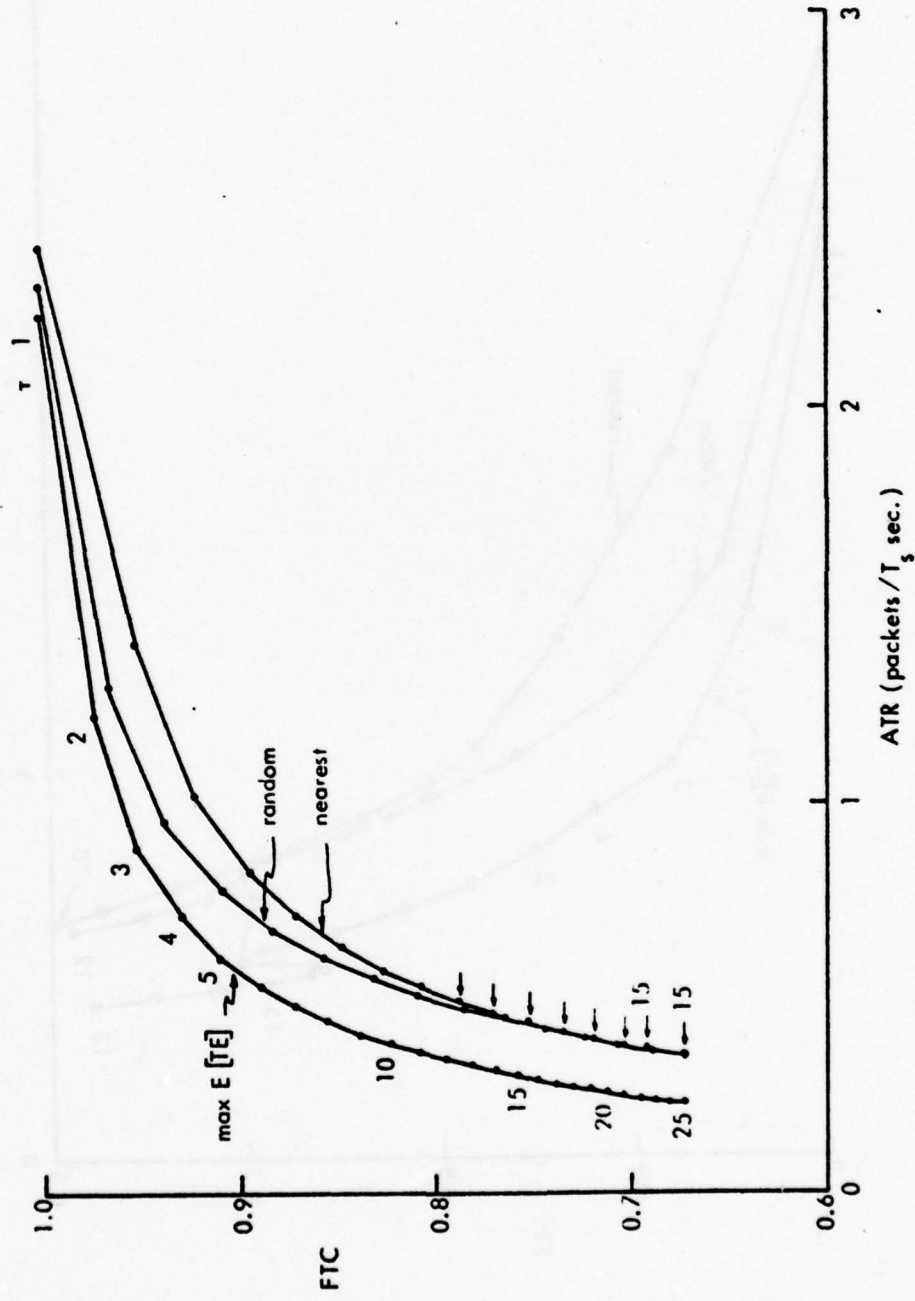Figure 5-5 FTC vs. ATR for periodic probing with p=0.6, q=0.2

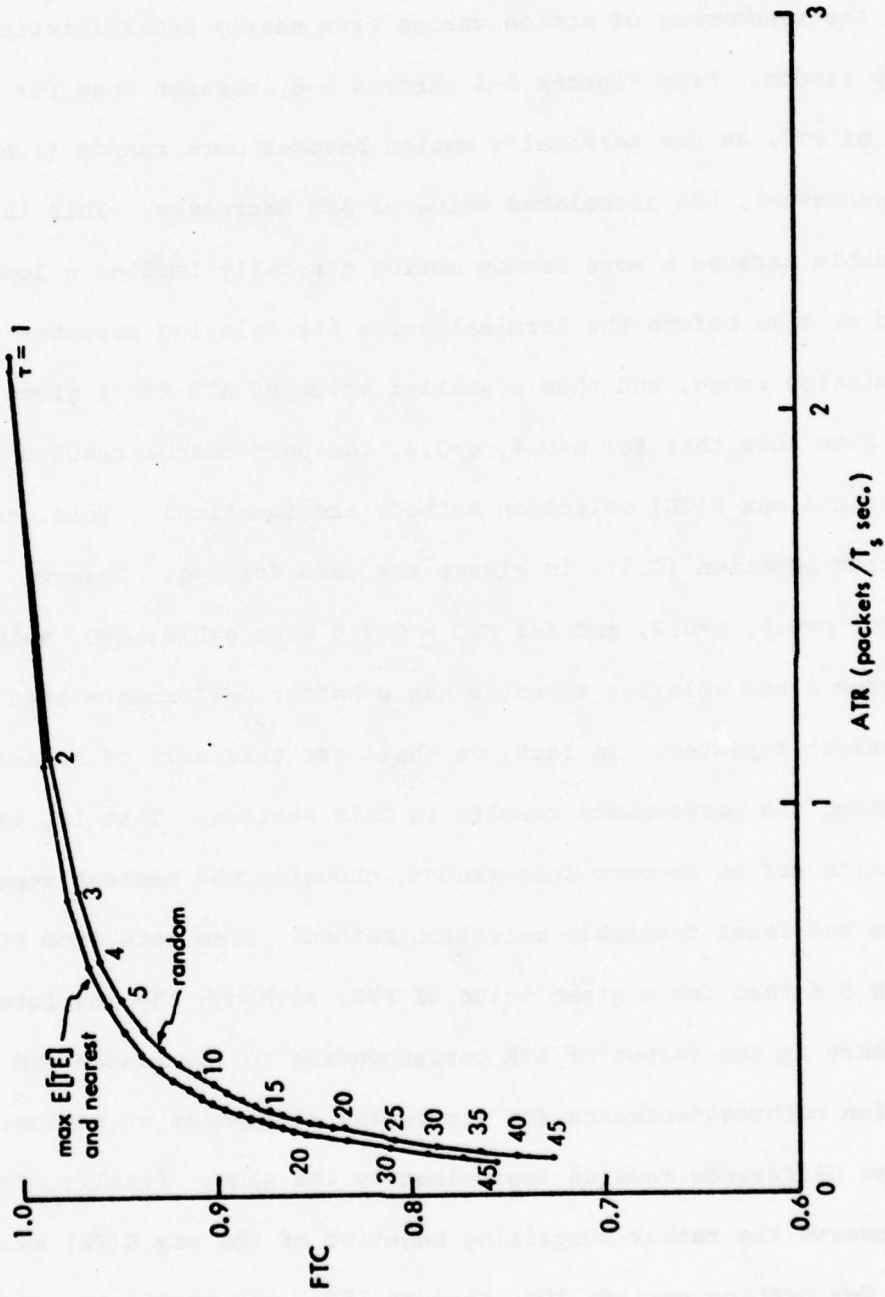<u>Figure 5-6</u> FTC vs. ATR for periodic probing with p=0.4, q=0.4

Note that the values of p and q corresponding to Figures 5-4 through 5-6 represent the same average velocity (i.e., p+q=0.8), but where the randomness of motion varies from nearly deterministic to highly random. From Figures 5-4 through 5-6, observe that for a given value of FTC, as the terminal's motion becomes more random (i.e., as p-q decreases), the associated value of ATR decreases. This is reasonable because a more random motion generally implies a longer period of time before the terminal exits its relaying repeater's transmission range, and thus a smaller value of ATR for a given value of FTC. Also note that for p=0.4, q=0.4, the performance results for the nearest and max E[TE] selection methods are identical. This, as can be seen from equation (C.1), is always the case for p=q. Observe, however, that for p=0.6, q=0.2, and for FTC $\geq$ 0.716 when p=0.8, q=0, selecting at random a new relaying repeater has a better performance than selecting the nearest repeater. In fact, we shall see this sort of behavior throughout the performance results in this section. That is, as the terminal's motion becomes less random, choosing the nearest repeater becomes the least desirable selection method. Also note from Figures 5.4 through 5.6 that for a given value of FTC, although the absolute difference in the values of ATR corresponding to the random and max E[TE] selection methods decreases for increasing randomness of motion, the relative difference remains approximately the same. Finally, for p=0.8, q=0, observe the rather surprising behavior of the max E[TE] selection method for probing periods $10T_s$ through $15T_s$. In particular, note that the terminal can obtain a higher value of FTC at a lower value of ATR by probing with period $13T_s$ as opposed to $10T_s$. This behavior, which is not

exhibited elsewhere in the performance results, is thought to be due to the terminal having a higher probability of being in a "good" state (i.e., a state for which max E[TE] is large) at the time at which it selects a new relaying repeater, when the probing period is $13T_s$ rather than $10T_s$.

Still considering periodic probing, we now examine the affects on the performance when the terminal's average velocity is changed. Specifically, Figures 5-7 through 5-9 indicate the changes in performance for, respectively, Figures 5-4 through 5-6 when the terminal's average velocity is reduced by one half (i.e., p+q=0.4), but where the conditional probability (conditioned on moving to another state) of moving left or right along the path remains the same. As expected, the lower average velocity results in an increase in the time between needed changes in the terminal's relaying repeater, and thus a decrease in ATR for a given value of FTC. The percent decrease in ATR is not, however, the same for all values of FTC. For example, in the case being examined, with a decrease in the average velocity by one half, for FTC = 1.0, 0.9, and 0.7, the percent decrease in ATR is, respectively, on the order of 10, 45, and 50 percent. However, we observe that for a given value of FTC < 1.0, the probing period ($\tau \cdot T_s$) associated with the low velocity case is approximately twice that associated with the high velocity case. This is reasonable since one would expect that in order to remain at the same value of FTC, a particular change in velocity would require a proportional change in the probing rate. Finally, note that both the high and low velocity cases represent the same basic qualitative differences between the performances associated with the three methods for selecting a new relaying repeater.
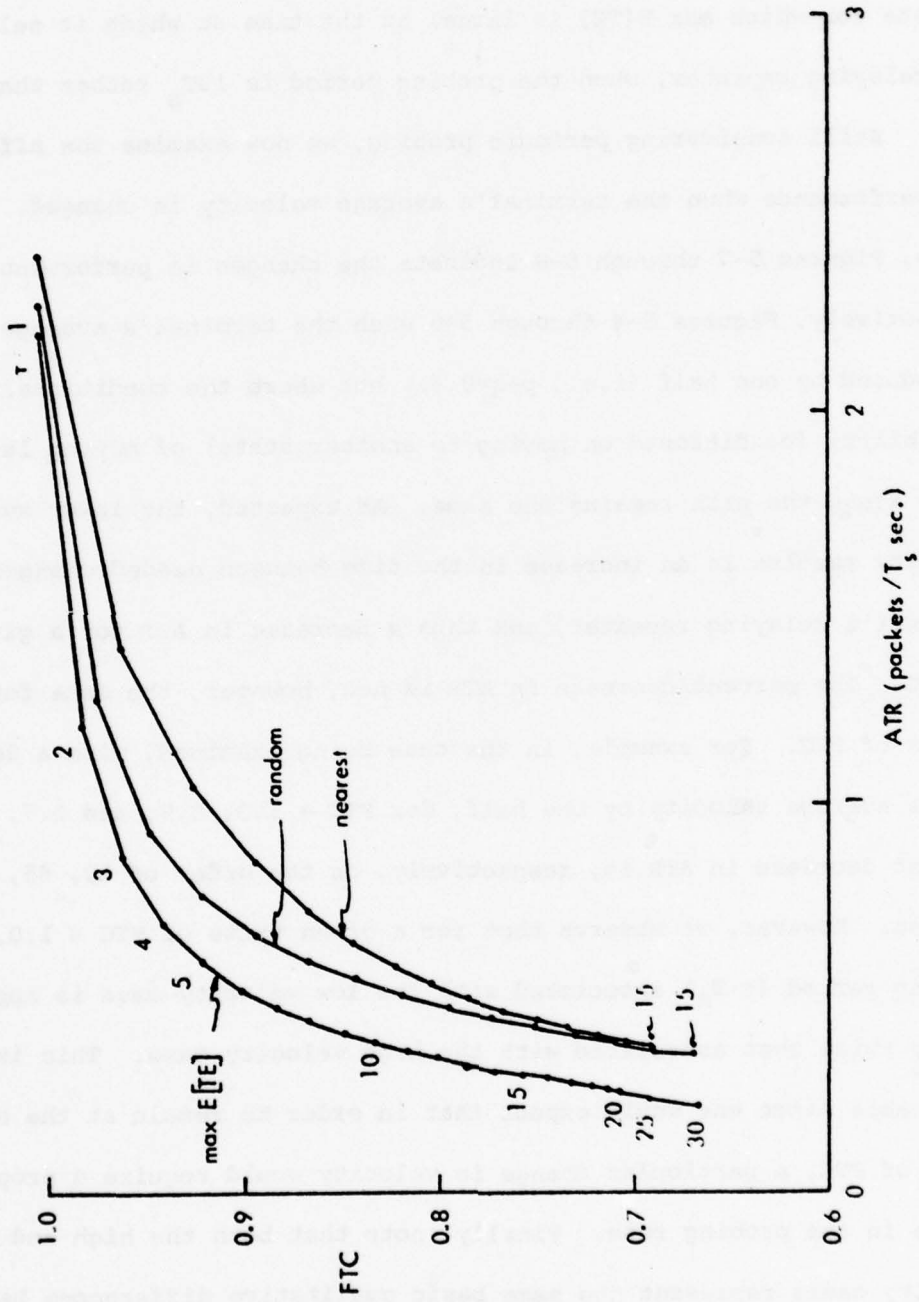
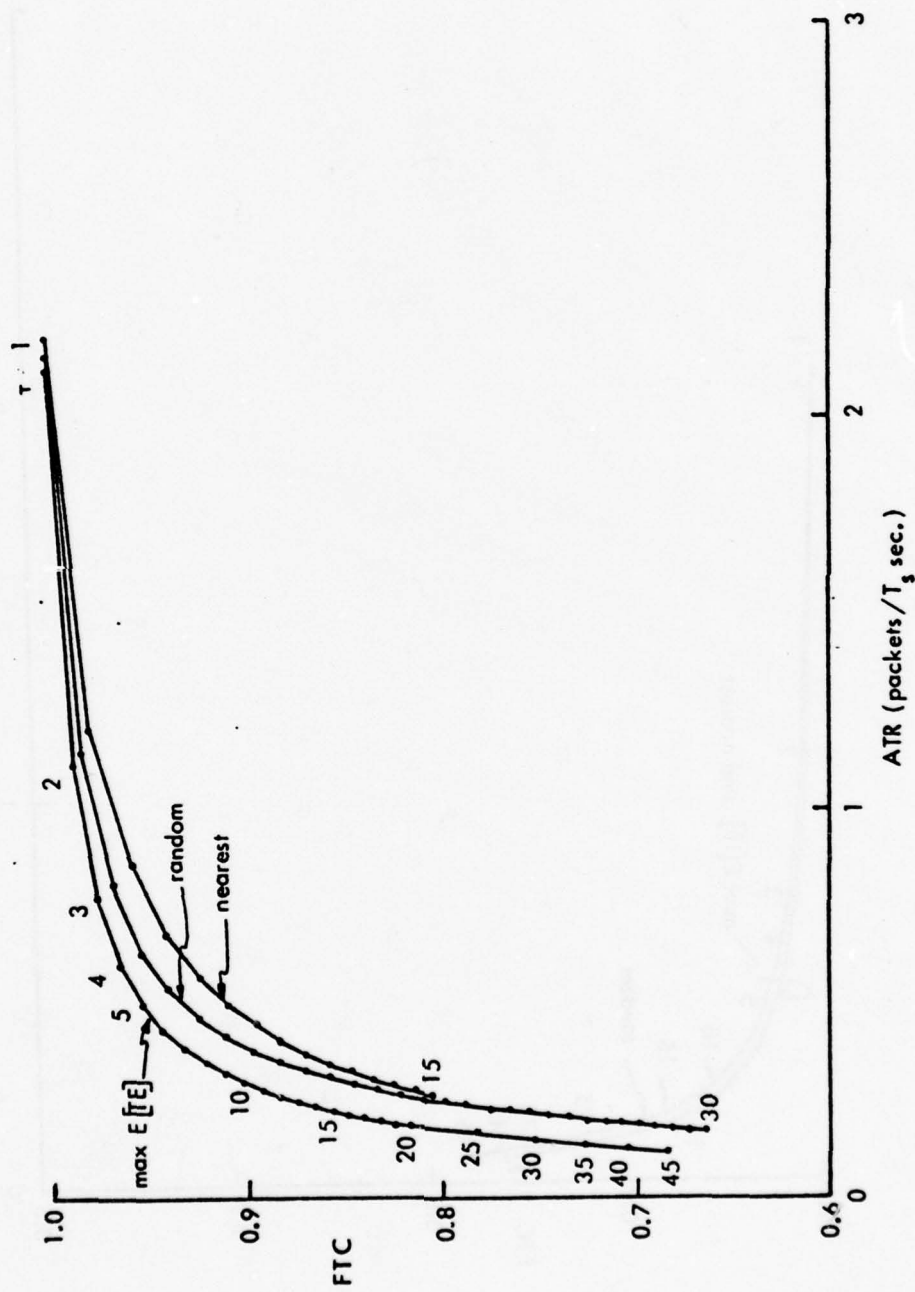**Figure 5-7** FTC vs. ATR for periodic probing with p=0.4, q=0

Figure 5-8   FTC vs. ATR for periodic probing with p=0.3, q=0.1
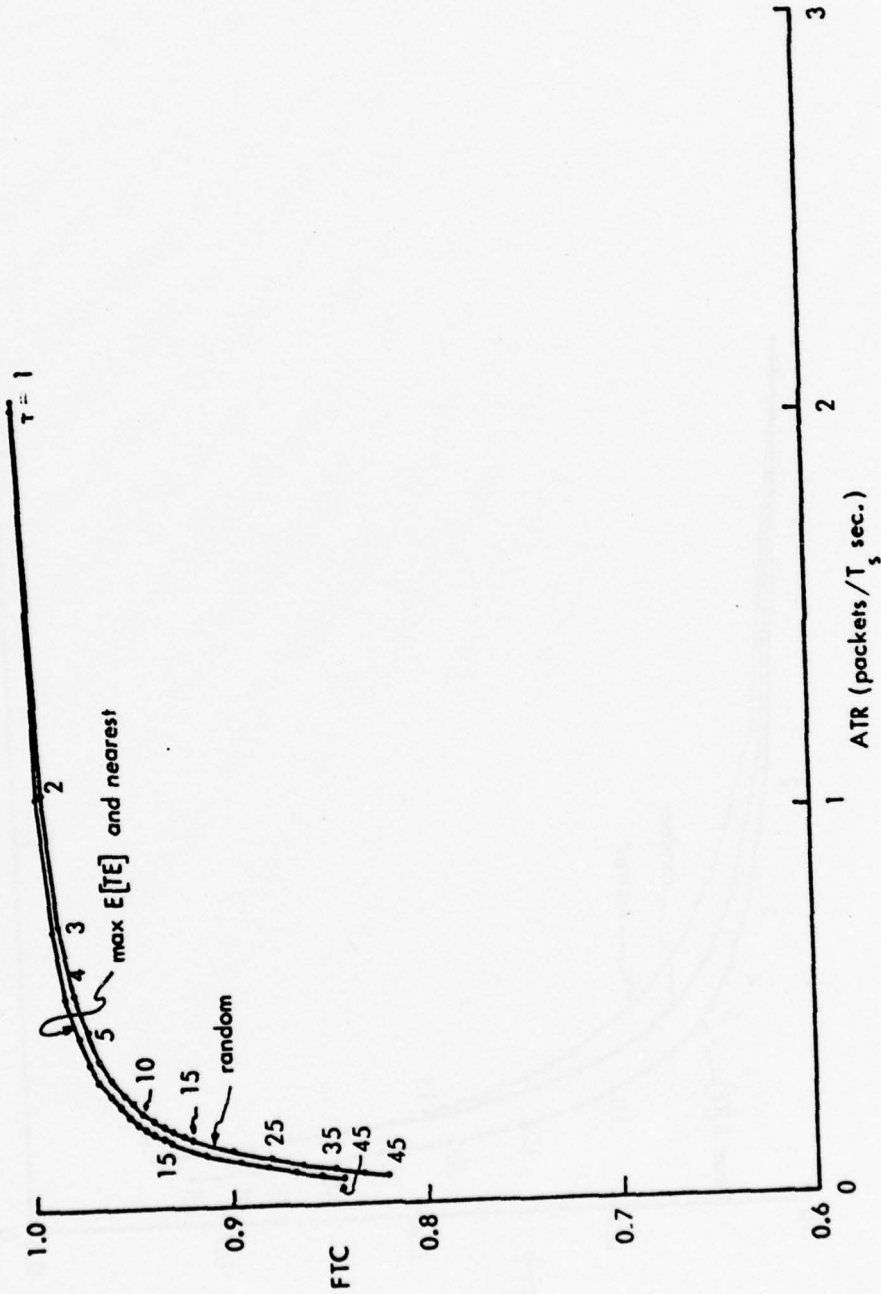
Figure 5-9 FTC vs. ATR for periodic probing with p=0.2, q=0.2

5.5.2 Probing with Position Information

Up to this point we have not stated how the waiting time vector $\underline{\tau}$ should be chosen when using probing with position information. Having gained insight from the performance results of periodic probing, we are now in a better position to define the optimal values of $\underline{\tau}$. Note that for given values of p and q and a method for selecting a new relaying repeater, each possible choice of $\underline{\tau}$ (where τ_i is a positive integer, i=1,2,...,N) is mapped via equations (5.15) and (5.16) on to a point on the FTC vs. ATR graph. We define the set of optimal points on FTC vs. ATR (corresponding to the optimal values of $\underline{\tau}$), as that subset of possible points which lie on the left boundary of the smallest convex region containing all points. That is, if the consecutive points, in the optimal set, corresponding to decreasing values of FTC are connected by straight line segments, the resulting curve will be convex with all nonoptimal points lying to the right of it. For the network model being considered, the optimal selection of $\underline{\tau}$ corresponding to FTC = 1.0 is for p and q > 0,

$$\tau_i = \begin{cases} i & \text{for } i=1,2,\ldots,\left\lceil\frac{N}{2}\right\rceil \\ N+1-i & \text{for } i=\left\lceil\frac{N}{2}\right\rceil+1,\ldots,N \end{cases}$$

and for p or q = 0,

$$\tau_i = \begin{cases} i & \text{for } i=1,2,\ldots,N \text{ and } p=0 \\ N+1-i & \text{for } i=1,2,\ldots,N \text{ and } q=0 \end{cases}$$

Because these are the largest possible values of the τ_i's for which FTC = 1.0, it follows that the selection is optimal. Unfortunately,

equations (5.15) and (5.16) are of sufficient complexity that the task
of determining the optimal values of $\underline{\tau}$ for FTC < 1.0 seems to be one of
extreme difficulty. For this reason, we turn to a heuristic approach
for selecting the values of $\underline{\tau}$ to be used in evaluating the performance of
probing with position information. Before describing this heuristic
approach, it is appropriate to mention that the max E[TE] method for
selecting a new relaying repeater is not in general an optimal use of
position information. Determining the optimal selection of a new relay
repeater seems to be on the same order of difficulty as determining the
optimal values of $\underline{\tau}$ for FTC < 1.0. Thus the max E[TE] method was chosen
for its good heuristic qualities.

The heuristic approach we use for selecting values for $\underline{\tau}$ is as
follows. For various values of the variable γ, where $0 \leq \gamma < 1$, we
determine for each i (i=1,2,...,N) the minimum value of τ_i such that

$$\Pr\{s(\tau_i) > N \text{ or } s(\tau_i) < 1 \mid s(0) = i\} = \sum_{\substack{k>N \\ k<1}} p_{ik}(\tau_i) > \gamma$$

That is, for each state i relative to the terminal's current relaying
repeater, we assign the waiting time to be the smallest value of τ_i
for which the probability that the terminal has exited its current re-
laying repeater's transmission range, τ_i transition times after probing
while in state i, is greater than γ. Figures 5-10 through 5-12
illustrate the performance of this use of position information, and
Tables 5-1 through 5-3 give for each selected value of γ, the corres-
ponding value of $\underline{\tau}$. Comparing Figures 5-10 through 5-12 with Figures
5-4 through 5-6 (i.e., the periodic probing counterparts), we see that

Figure 5-10 FTC vs. ATR for probing with position information with p=0.8, q=0

Y	τ_1	τ_2	τ_3	τ_4	τ_5	τ_6	τ_7	τ_8	τ_9	τ_{10}	τ_{11}
0.0	11	10	9	8	7	6	5	4	3	2	1
0.15	12	11	10	8	7	6	5	4	3	2	1
0.35	13	12	10	9	8	7	6	4	3	2	1
0.55	14	12	11	10	9	7	6	5	4	2	1
0.6	14	13	11	10	9	8	6	5	4	2	1
0.65	14	13	12	10	9	8	6	5	4	3	1
0.7	15	13	12	11	9	8	7	5	4	3	1
0.75	15	14	12	11	10	8	7	6	4	3	1
0.8	15	14	13	11	10	9	7	6	4	3	2
0.85	16	14	13	12	10	9	7	6	5	3	2
0.9	16	15	13	12	11	9	8	6	5	4	2
0.95	17	16	14	13	12	10	9	7	6	4	2

Table 5-1   The value of $\underline{\tau}$ corresponding to each point plotted in Figure 5-10 where p=0.8, q=0

Figure 5-11 FTC vs. ATR for probing with position information with p=0.6, q=0.2

Y	τ_1	τ_2	τ_3	τ_4	τ_5	τ_6	τ_7	τ_8	τ_9	τ_{10}	τ_{11}
0.0	1	2	3	4	5	6	5	4	3	2	1
0.05	1	12	11	10	8	7	5	4	3	2	1
0.1	1	14	13	11	9	8	6	4	3	2	1
0.15	1	16	14	12	10	8	7	5	3	2	1
0.2	19	17	15	13	11	9	7	5	3	2	1
0.25	20	18	16	14	12	10	8	6	4	2	1
0.3	21	19	17	15	13	11	9	6	4	2	1
0.35	23	20	18	16	14	11	9	7	5	2	1
0.4	24	22	19	17	15	12	10	8	5	3	1
0.45	25	23	20	18	15	13	11	8	6	4	1
0.5	26	24	21	19	16	14	11	9	6	4	1
0.55	28	25	23	20	17	15	12	10	7	4	1
0.6	29	27	24	21	19	16	13	11	8	5	3
0.65	31	28	25	23	20	17	14	12	9	6	3
0.7	32	30	27	24	21	19	16	13	10	7	3
0.75	34	32	29	26	23	20	17	14	11	8	4
0.8	37	34	31	28	25	22	19	16	13	9	5
0.85	40	37	34	31	28	24	21	18	15	11	7

Table 5-2   The value of τ corresponding to each point plotted in Figure 5-11 where p=0.6, q=0.2
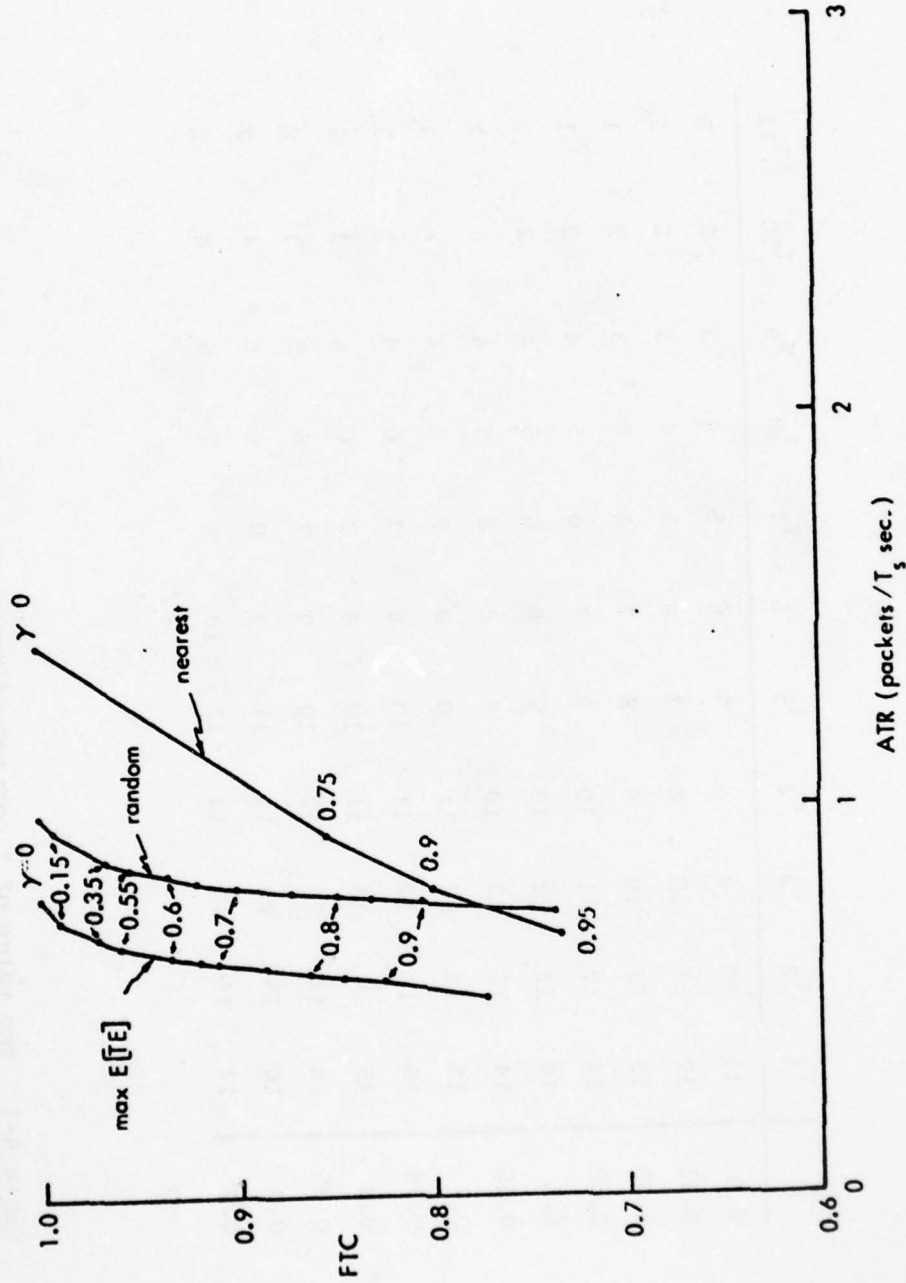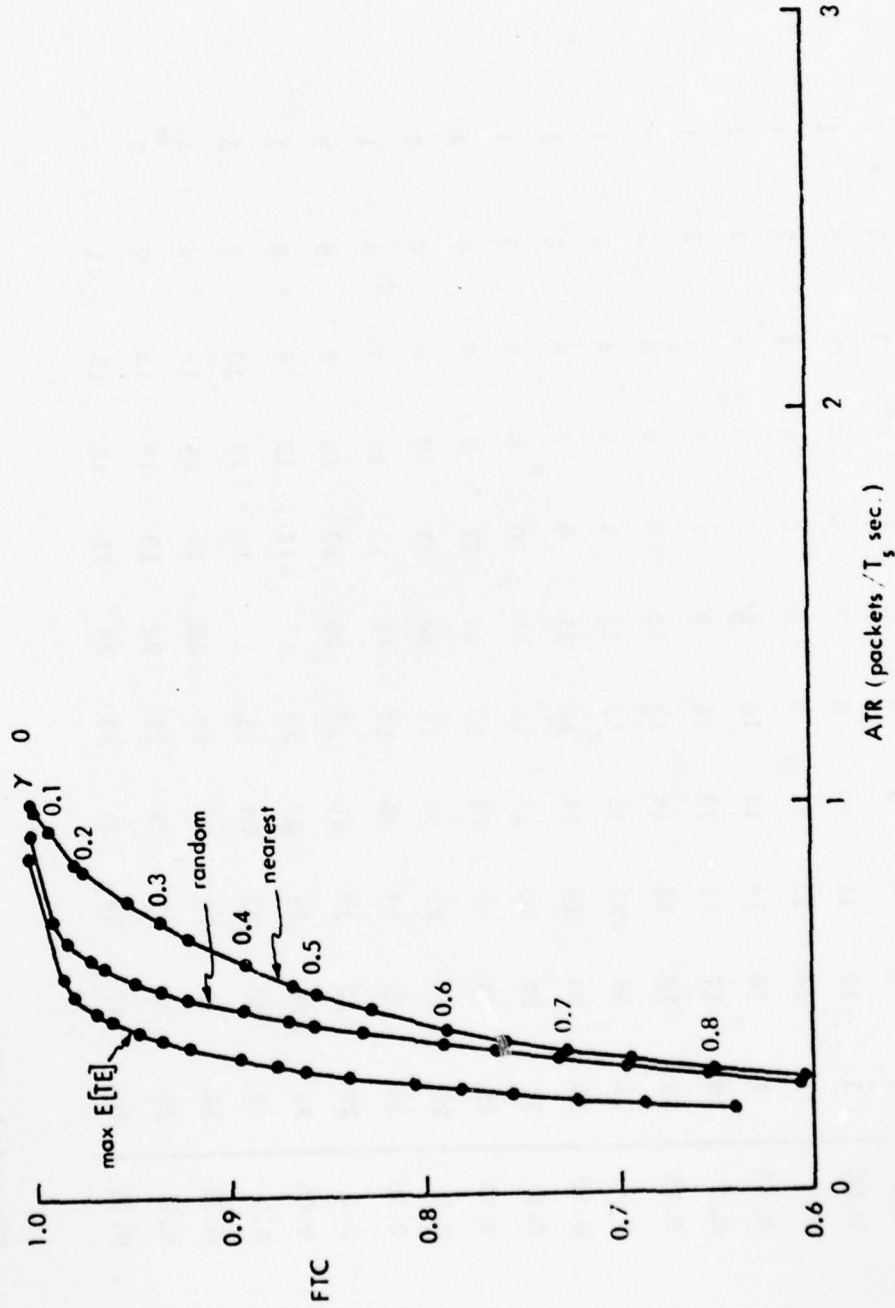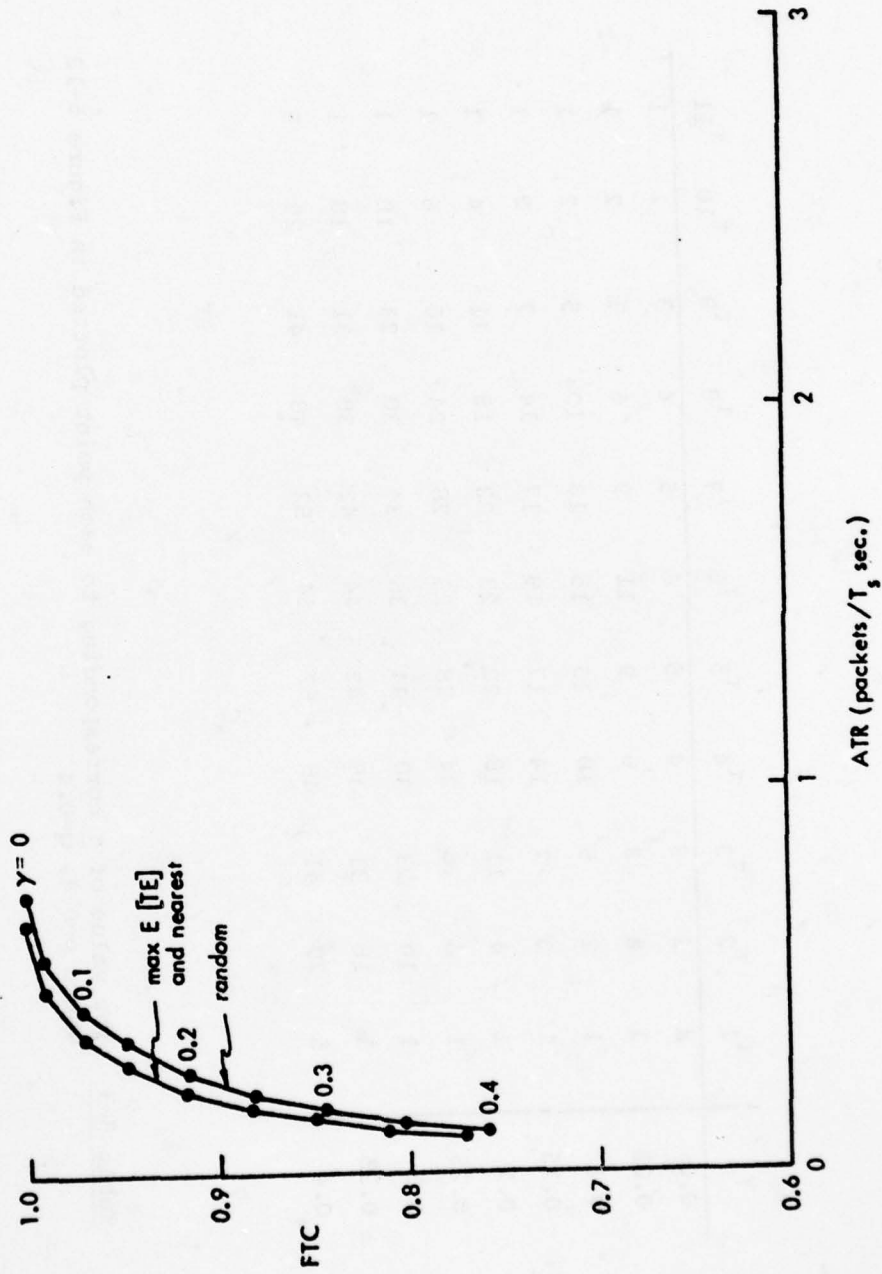
Figure 5-12 FTC vs. ATR for probing with position information with p=0.4, q=0.4

Y	τ_1	τ_2	τ_3	τ_4	τ_5	τ_6	τ_7	τ_8	τ_9	τ_{10}	τ_{11}
0.0	1	2	3	4	5	6	5	4	3	2	1
0.05	1	2	3	6	9	11	9	6	3	2	1
0.1	1	2	5	10	13	15	13	10	5	2	1
0.15	1	2	7	14	17	19	17	14	7	2	1
0.2	1	4	11	18	22	23	22	18	11	4	1
0.25	1	6	16	24	28	29	28	24	16	6	1
0.3	1	10	23	30	34	36	34	30	23	10	1
0.35	1	18	31	38	42	44	42	38	31	18	1
0.4	5	29	41	48	52	54	52	48	41	29	5

Table 5-3   The value of τ corresponding to each point plotted in Figure 5-12 where $p=0.4$, $q=0.4$

the same basic qualitative differences between the performances of the
three methods for selecting a new relaying repeater are present in both
probing schemes. Observe, however, that for values of FTC in the vicinity
of 1.0, the value of ATR associated with probing with position information
is less than one half of the corresponding value associated with periodic
probing. The two values of ATR do, however, converge as FTC decreases,
and are in fact generally very close for FTC < 0.8.

In order to get an indication of how close the performance
curves generated by the heuristic method for choosing the values for $\underline{\tau}$
are to the optimal curves, the values of $\underline{\tau}$ corresponding to the points
plotted in Figure 5-12 were perturbated and then used to obtain new
values of FTC and ATR. It was found that for those perturbations which
resulted in an improvement, the improvement was very slight and in many
cases would not have been shown to be an improvement if a smaller incre-
ment had been chosen for γ. Thus, although it is not strictly proven,
the pertubation analysis seems to indicate that the performance of the
heuristic method for choosing values for $\underline{\tau}$ is not significantly differ-
ent from that of the optimal.

It is worth mentioning that another heuristic approach for
generating values for $\underline{\tau}$ was also examined. This alternate heuristic is
as follows. For various values of the variable δ, where $\delta \geq 0$, we
determine for each i (i=1,2,...,N) the minimum value of τ_i such that

$$\tau_i - E[TC^i] > \delta$$

That is, for each state i relative to the terminal's current relaying

repeater, we assign the waiting time to be the smallest value of τ_i
for which the expected time the terminal is outside of its current
relaying repeater's transmission range, during the τ_i transition times
after probing while in state i, is greater than δ. The performance of
this heuristic was determined for the same parameters as represented in
Figures 5-10 through 5-12. The corresponding performance curves
generated by each heuristic were found to lie very close to each other,
however, more often than not, the curve generated by the second heuristic
was to the right of the corresponding curve generated by the first
heuristic. For this reason, the results of the second heuristic are not
presented here.

At this point, one might comment that a reduction of ATR by at
most a little more than one half of that corresponding to periodic
probing is not sufficient to warrant the complexity and expense
associated with being able to determine position at each probing. How-
ever, before jumping to this conclusion, one must take into consideration
the fact that the obtained performance results are based on a discrete
model of terminal motion. That is, the terminal is assumed to move only
at discrete instances of time corresponding to the transition times of a
Markov process. Because of this, to achieve FTC = 1.0 with periodic
probing, the terminal need only probe its relaying repeater immediately
after each transition time. In an actual mobile packet radio network,
the motion of each terminal is continuous. In this situation, in order
to achieve FTC $\simeq$ 1.0 with periodic probing, a terminal would have to
probe its relaying repeater nearly continuously, implying an extremely
large value of ATR. Moreover, considering the finite capacity of the

broadcast channel, this value of ATR may not even be allowable. However,

in using probing with position information in a situation where a terminal's

motion is continuous, as long as the terminal's velocity is bounded and

the transmission range of its relaying repeater is well defined, FTC = 1.0

is achievable at values of ATR not significantly different from those

associated with the discrete model of motion. The reason for this is

twofold. First, by knowing its position at the last probing and by keeping

track of its velocity since that probing, a terminal can send the next

probe packet just before there is a nonzero probability that it will

have exited its current relaying repeater's transmission range. Secondly,

with position information, the terminal is able to anticipate a possible

loss of connectivity between it and its current relaying repeater and thus

select a new relaying repeater before the loss can occur. Hence, FTC = 1.0

is clearly achievable without a significant increase in the value of ATR

associated with the discrete model. In the performance analysis, a

discrete model of terminal motion was chosen in order to facilitate the

derivation of FTC and ATR. In fact, except in the vicinity of FTC = 1.0,

the performance curves obtained by using the discrete model of motion may

be considered to be a good approximation to those which would be obtained

with a similar, but continuous model of motion. Thus we see that the

main advantage of using probing with position information is when the

terminal's motion is continuous in nature and when the required value of

FTC is close to 1.0. In this situation, the value of ATR associated with

periodic probing can be reduced significantly by switching to probing

with position information.

5.5.3 Sensitivity Analysis

The performance results obtained thus far have been based on the assumption that the route between the terminal and the station consists of three hops. Let us now examine the changes in performance as the number of hops between the terminal and the station is increased. Although the same behavior exists for either probing scheme and each of the three methods for selecting a new relaying repeater, Figure 5-13 illustrates the changes in performance for periodic probing (p=0.6, q=0.2) with the random selection of a new relaying repeater. Note that the essential characteristics of the performance curve are not changed, only shifted to higher values of ATR as the number of hops between the terminal and station is increased.

Suppose we maintain the same repeater transmission range and spacing (e.g., 11 and 5 km, respectively), and we require that the terminal's average velocity remain the same. However, we wish to increase the number of states N within the transmission range of each repeater along the path. We can do this by making the changes $s' = \theta s$ and $T_s^l = \theta T_s$, where $0 < \theta < 1$. It follows from equation (5.4) that the variance in the terminal's position is proportional to s^2/T_S. Thus by increasing N in this manner, we are decreasing the terminal's randomness of motion and consequently, we expect to see the same sort of change in performance as when we increased the value of p-q. Moreover, this increase in N makes for a better approximation to a continuous form of terminal motion. Thus, as mentioned above, the advantages of using probing with position information for FTC $\simeq$ 1.0 will become more evident.
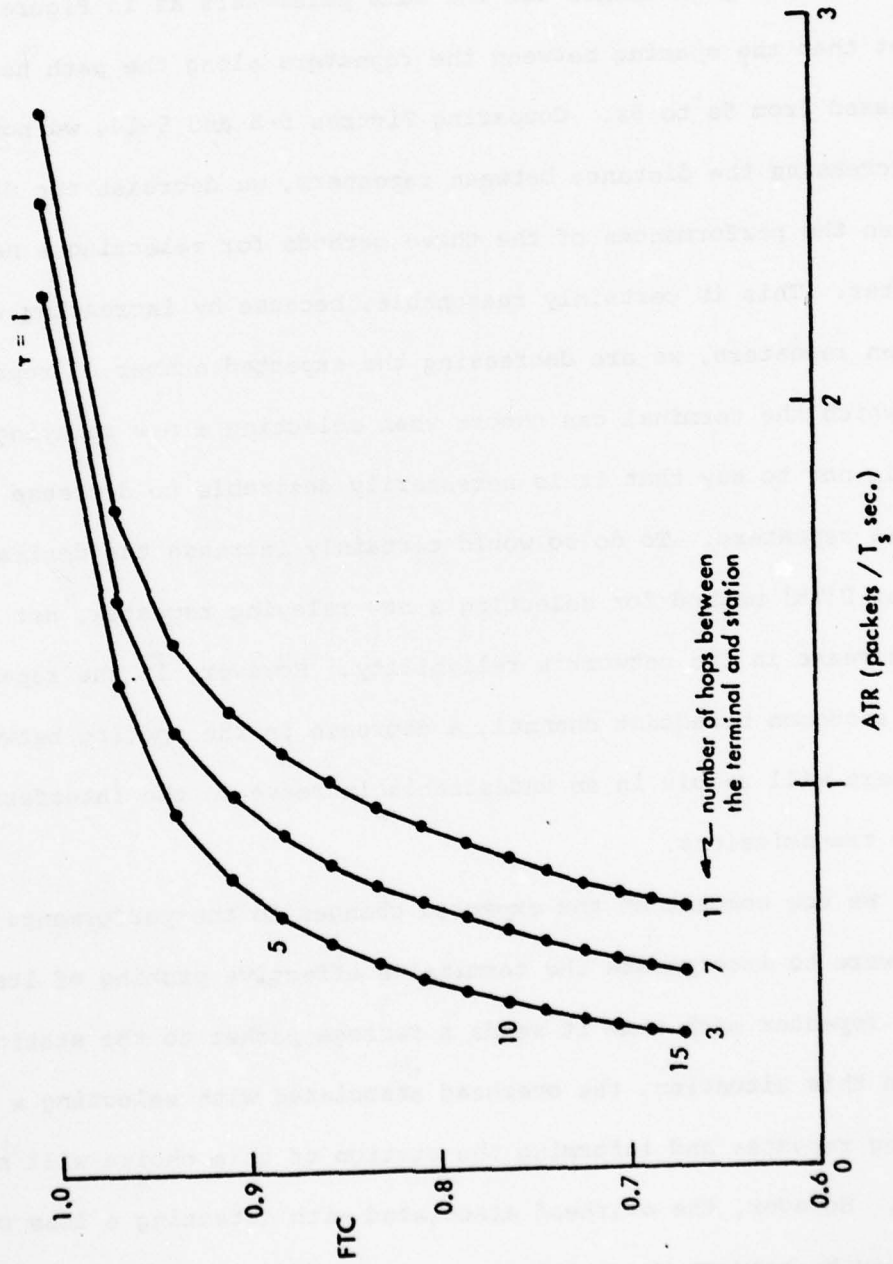
Figure 5-13 FTC vs. ATR for periodic probing (p=0.6, q=0.2) with the random selection of a new relaying repeater

Now suppose we maintain the same values for s, T_s, and N, but increase the spacing between the repeaters along the path. Figure 5-14 represents the performance for the same parameters as in Figure 5-5, except that the spacing between the repeaters along the path has been increased from 5s to 8s. Comparing Figures 5-5 and 5-14, we note that by increasing the distance between repeaters, we decrease the difference between the performances of the three methods for selecting a new relaying repeater. This is certainly reasonable, because by increasing the spacing between repeaters, we are decreasing the expected number of repeaters from which the terminal can choose when selecting a new relaying repeater. This is not to say that it is necessarily desirable to decrease the spacing between repeaters. To do so would certainly increase the desirability of the max E[TE] method for selecting a new relaying repeater, not to mention the increase in the network's reliability. However, if the repeaters share a common broadcast channel, a decrease in the spacing between repeaters will result in an undesirable increase in the interference of packet transmissions.

We now comment on the expected changes in the performance results if we were to incorporate the terminal's effective probing of its re-laying repeater each time it sends a message packet to the station. Note that in this situation, the overhead associated with selecting a new relaying repeater and informing the station of this choice will not change. However, the overhead associated with detecting a loss of connectivity between the terminal and its relaying repeater will de-crease. To see how this decrease affects the performance results, let us suppose that the terminal's motion is of a continuous nature, and
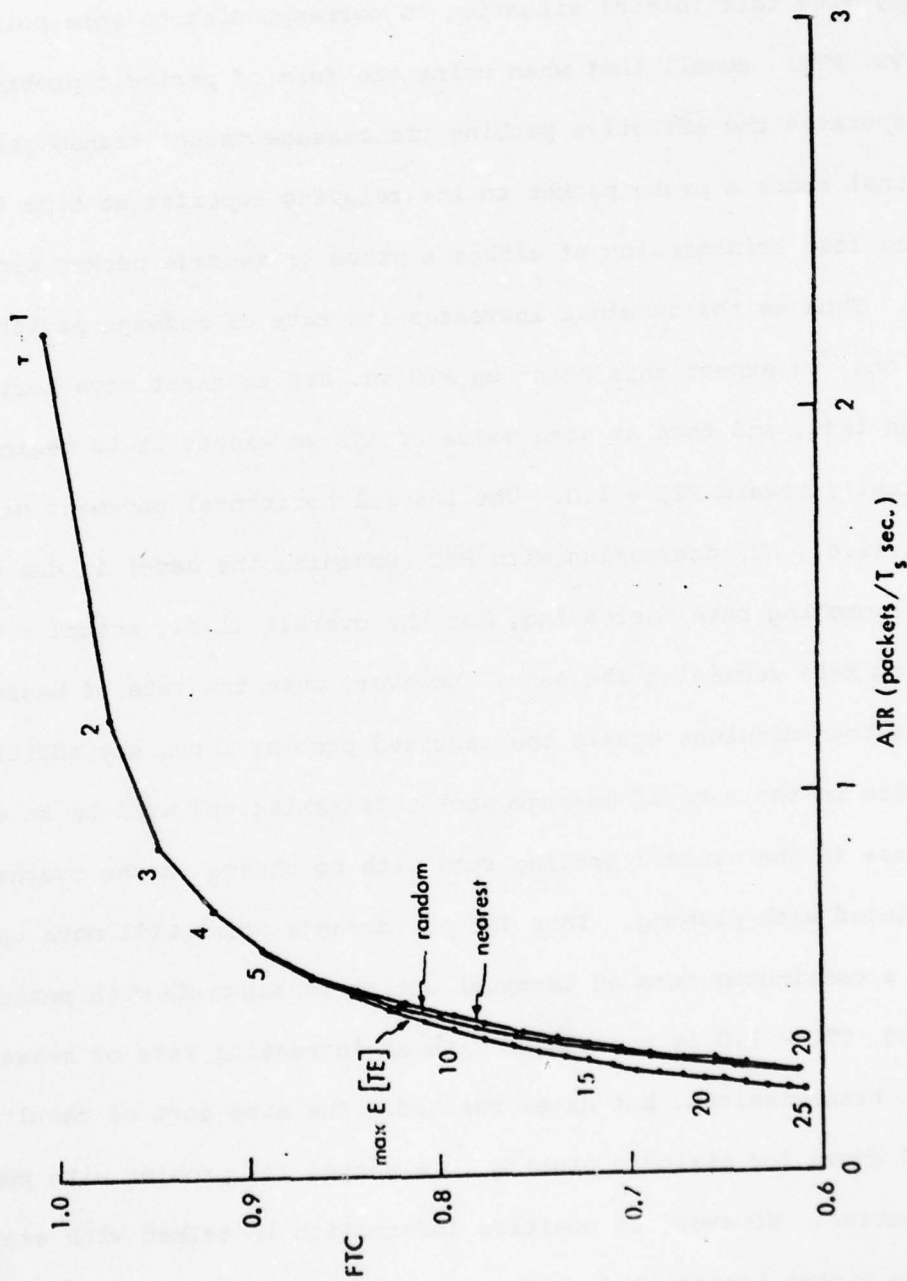
Figure 5-14 FTC vs. ATR for periodic probing with p=0.6, q=0.2, and with a repeater located every 8 states along the path

that it is using periodic probing with probing period T_p. Also, let us assume that initially the terminal is sending no messages to the station. We may view this initial situation as corresponding to some point on FTC vs. ATR. Recall that when using the form of periodic probing which incorporates the effective probing via message packet transmissions, the terminal sends a probe packet to its relaying repeater at time t, only if the last transmission of either a probe or message packet was at time $t-T_p$. Thus as the terminal increases its rate of message packet transmissions, we expect this point on FTC vs. ATR to first move horizontally to the left, and then at some value of ATR we expect it to begin moving vertically toward FTC = 1.0. The initial horizontal movement of the point (i.e., ATR decreasing with FTC remaining the same) is due to the actual probing rate decreasing, but the overall (i.e., actual + effective) probing rate remaining the same. However, when the rate of message packet transmissions equals the required probing rate, any additional increase in the rate of message packet transmissions will be an effective increase in the overall probing rate with no change in the overhead associated with probing. Thus the performance point will move upward. Since a continuous form of terminal motion is assumed, with periodic probing, FTC = 1.0 is approached with an increasing rate of message packet transmissions, but never reached. The same sort of result as stated above for periodic probing is expected for probing with position information. However, if position information is gained with each message packet transmitted, FTC = 1.0 is eventually reached for some finite rate of message packet transmissions. This is because, as we previously stated, with position information, the terminal is able to

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anticipate a possible loss of connectivity between it and its relaying
repeater and thus select a new relay repeater before the loss can occur.

Finally, we comment on the expected changes in the performance
results if we allow the possibility of packets being received in error.
We expect two basic changes in the performance curves. First, the
number of transmitted overhead packets associated with informing the
station of a change in the terminal's relaying repeater will increase
(due to necessary retransmissions) with increasing error probability.
Thus the performance curves will move to the right in the same fashion
as illustrated in Figure 5-13. Secondly, when the terminal sends out
a general probe packet, it will not necessarily receive responses from
all of the repeaters within its transmission range. Consequently, its
choice of a new relaying repeater will be based on incomplete information.
As such, we expect the difference in the performance curves associated
with the three selection methods to decrease. As a final comment, note
that when a terminal probes its relaying repeater, it may not receive a
response due to either the probe or response packet being received in
error. Thus in this situation, the terminal may conclude that a loss of
connectivity between it and its relaying repeater has occurred, when in
fact there is no loss. In the next section we examine the desirability
of having the terminal probe its relaying repeater one or more additional
times before concluding that a lack of a response is due to a loss of
connectivity.

5.6 Probing and Packet Errors

If a terminal receives a response to a probe packet that it sent to its relaying repeater, then the terminal will know that a connection exists in both directions between it and that repeater. If the terminal does not receive a response, then the terminal will know that either there has been a loss of connectivity between it and its relaying repeater, or the probe or response packet was received in error and thus ignored. If the amount of overhead associated with obtaining a new route to the station is large and/or if the error probability on the channel is sufficiently high, then at a routing update, it may be desirable to have the terminal probe its relaying repeater one or more additional times before concluding that the lack of a response is due to a loss of connectivity. This section is in some sense a departure from sections 5.1 through 5.5 in that we do not concern ourselves with the performance of the probing implementation in terms of FTC and ATR. Rather, we now assume the possibility of packet errors and consider the question, at a routing update, what is the maximum number of times a terminal should probe its relaying repeater without receiving a response, before concluding that a loss of connectivity between it and that repeater has occurred?

The situation where a terminal will, at any particular routing update, send up to k (k=0,1,2,...) probe packets before concluding that a loss of connectivity has occurred, will be referred to as probing policy k. Also, we define the optimal probing policy as that selection of k which minimizes the expected number of transmitted overhead packets

($E[P]$) associated with a routing update. To determine this optimal value of k (k_{opt}), we begin by deriving an expression for the conditional expectation $E[P_k]$, which is the expected number of transmitted overhead packets associated with a routing update, given probing policy k is adopted. We first define the following events:

c - at the time of a routing update, the terminal is connected in both directions to its relaying repeater

r - given event c, the terminal receives a response to a probe packet sent to its relaying repeater

We also define the following probabilities:

ε = Pr{a packet sent over the broadcast channel is received in error}[*]

α = Pr{$\bar{r}$}[**]

Noting that with probability ε a probe packet will be received in error, and with probability $(1-\varepsilon)\varepsilon$ the probe packet will be received correctly but the response packet will be received in error, it follows that

$$\alpha = \varepsilon + (1-\varepsilon)\varepsilon \qquad (5.18)$$

Finally, we define the following expectations:

β = E[number of transmitted overhead packets associated with a probing | $\bar{r}$]

λ = E[number of transmitted overhead packets associated with selecting a new relaying repeater and informing the station of this choice]

_____

[*] We assume that packets transmitted over the broadcast channel are received with or without error independently of each other.

[**] The notation "$\bar{r}$" means "not r."

It follows that

$$\beta = (\epsilon + 2(1-\epsilon)\epsilon)/\alpha = 1 + (1-\epsilon)\epsilon/\alpha \tag{5.19}$$

Later we shall derive an expression for λ. For now, note that if the terminal is not connected in both directions to its relaying repeater, then with probing policy k, the terminal will, at a routing update, send a total of k probe packets to its relaying repeater without receiving a response. In addition, an average of λ overhead packets will be transmitted in order for the terminal to obtain a new route. Thus we may write

$$E[P_k \mid \bar{c}] = k + \lambda \tag{5.20}$$

If the terminal is connected in both directions to its relaying repeater, then for $k = 0$, it follows that $E[P_0 \mid c] = \lambda$. For $k > 0$, with probability $(1-\alpha)\alpha^{i-1}$, the terminal will receive a response to the ith ($i = 1, 2, \ldots, k$) probe packet sent to its relaying repeater. With probability α^k, the terminal will not receive a response after sending k probe packets to its relaying repeater. Thus, it follows that

$$E[P_k \mid c] = \begin{cases} \lambda & k=0 \\ \sum_{i=0}^{k-1} (2 + i\beta)(1-\alpha)\alpha^i + (k\beta + \lambda)\alpha^k & k=1,2,\ldots \end{cases} \tag{5.21}$$

Noting that

$$\sum_{i=0}^{k-1} \alpha^i = \frac{1 - \alpha^k}{1 - \alpha}$$

and

$$\sum_{i=0}^{k-1} i\alpha^i = \frac{\alpha(1-\alpha^k)}{(1-\alpha)^2} - \frac{k\alpha^k}{1-\alpha}$$

we may rewrite (5.21) as

$$E[P_k \mid c] = 2 + \frac{\beta\alpha}{1-\alpha} + (\lambda - 2 - \frac{\beta\alpha}{1-\alpha})\alpha^k \quad k=0,1,2,\ldots \quad (5.22)$$

Thus from (5.20) and (5.22), we obtain

$$E[P_k] = Pr(\bar{c})\{k + \lambda\}$$
$$+ Pr(c)\left[2 + \frac{\beta\alpha}{1-\alpha} + (\lambda - 2 - \frac{\beta\alpha}{1-\alpha})\alpha^k\right] \quad k=0,1,2,\ldots(5.23)$$

We now determine k_{opt} (i.e., the value of k which minimizes $E[P_k]$). For the case where $\lambda \leq 2 + \beta\alpha/(1-\alpha)$, we see by inspection of (5.23) that $E[P_k]$ is minimized when k = 0. For the case where $\lambda > 2 + \beta\alpha/(1-\alpha)$, it is easily shown that $E[P_k]$ is a convex function of k. Solving for k_o ($k_o \in$ reals) in the equation

$$E[P_{k_o}] = E[P_{k_o+1}]$$

yields

$$k_o = \frac{\ln\{Pr(\bar{c})/[Pr(c)[(\lambda-2)(1-\alpha) - \beta\alpha]]\}}{\ln \alpha} \quad (5.24)$$

It follows that

$$k_{opt} = \begin{cases} \lceil k_o \rceil \text{ and } \lfloor k_o+1 \rfloor & \text{for } \lceil k_o \rceil \geq 0 \\ 0 & \text{for } \lceil k_o \rceil < 0 \end{cases}$$

Note from (5.24) that as λ and/or $Pr(c)$ increases, the value of k which minimizes $E[P_k]$ is nondecreasing. This is certainly an intuitively pleasing behavior.

Before one can actually use the above procedure for determining k_{opt}, one must determine a value for λ. We may write

$$\lambda = \lambda_s + \lambda_i \tag{5.25}$$

where

    λ_s = E[number of transmitted overhead packets associated with selecting a new relaying repeater]

and

    λ_i = E[number of transmitted overhead packets associated with informing the station of a change in relaying repeater]

Recall that a terminal bases its choice of a new relaying repeater on the responses that it receives after transmitting a general probe packet. We assume that only in the case where a terminal does not receive at least one response to a general probe packet will it then transmit another general probe packet. Note that if the terminal is connected in both directions to L (L=1,2,...) available repeaters, then the probability that exactly i (i=0,1,...,L) of these repeaters will correctly receive the terminal's transmitted general probe packet is given by $\binom{L}{i}\varepsilon^{L-i}(1-\varepsilon)^i$ (i.e., i successes in L trials). Furthermore, given that i repeaters correctly receive the terminal's general probe packet, with probability ε^i, the terminal will not receive any of the i corresponding response

packets. Thus it follows that

$$\lambda_s = 1 + \sum_{i=0}^{L} (i + \lambda_s \varepsilon^i)\binom{L}{i}\varepsilon^{L-i}(1-\varepsilon)^i \qquad L=1,2,\ldots \tag{5.26}$$

Rearranging the terms in (5.26), we obtain

$$\lambda_s\left[1 - \varepsilon^L \sum_{i=0}^{L} \binom{L}{i}(1-\varepsilon)^i\right] = 1 + \sum_{i=0}^{L} i\binom{L}{i}\varepsilon^{L-i}(1-\varepsilon)^i \tag{5.27}$$

Noting that

$$\sum_{i=0}^{L} \binom{L}{i}(1-\varepsilon)^i = (2-\varepsilon)^L$$

and

$$\sum_{i=0}^{L} i\binom{L}{i}\varepsilon^{L-i}(1-\varepsilon)^i = L(1-\varepsilon)$$

we may rewrite (5.27) as

$$\lambda_s[1 - (\varepsilon(2-\varepsilon))^L] = 1 + L(1-\varepsilon) \tag{5.28}$$

Noting that $\alpha = \varepsilon(2-\varepsilon)$, and solving for λ_s in (5.28), we obtain

$$\lambda_s = \frac{1 + L(1-\varepsilon)}{1-\alpha^L} \qquad L=1,2,\ldots \tag{5.29}$$

Figure 5-15 is a plot of λ_s vs. ε for various values of L. As for λ_i, if the terminal's newly selected route to the station involves H hops, then the expected number of transmitted overhead packets associated with in-
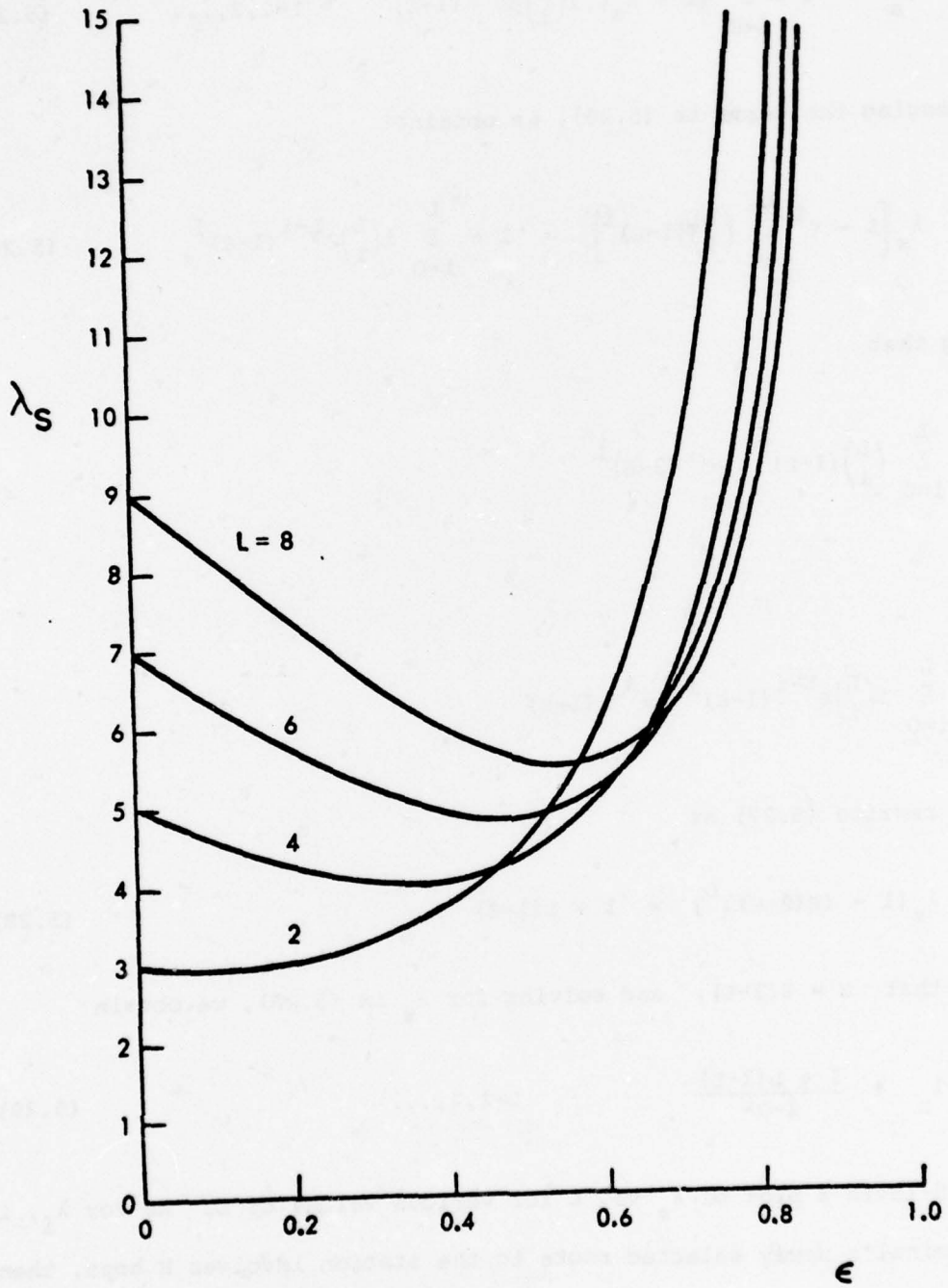
Figure 5-15 λ_s vs. ε

forming the station of this new route is simply given by

$$\lambda_i = \frac{H}{1-\epsilon} \tag{5.30}$$

Figure 5-16 is a graph of λ_i vs. ϵ for various values of H. Finally, substituting (5.29) and (5.30) into (5.25), we obtain

$$\lambda = \frac{1 + L(1-\epsilon)}{1-\alpha^L} + \frac{H}{1-\epsilon} \tag{5.31}$$

Thus for given values of ϵ, $Pr(c)$, L, and H, using (5.31) and the procedure for determining the optimal probing policy, we can compute k_{opt}. Figures 5-17, 5-18, and 5-19 are graphs of k_{opt} vs. ϵ for various values of, respectively, $Pr(c)$, H, and L. Note that in each case, as ϵ increases, k_{opt} increases to a peak and then falls rapidly to zero. This implies that for sufficiently large ϵ, the terminal should, at a routing update, select a new relay repeater without even probing its current relaying repeater.
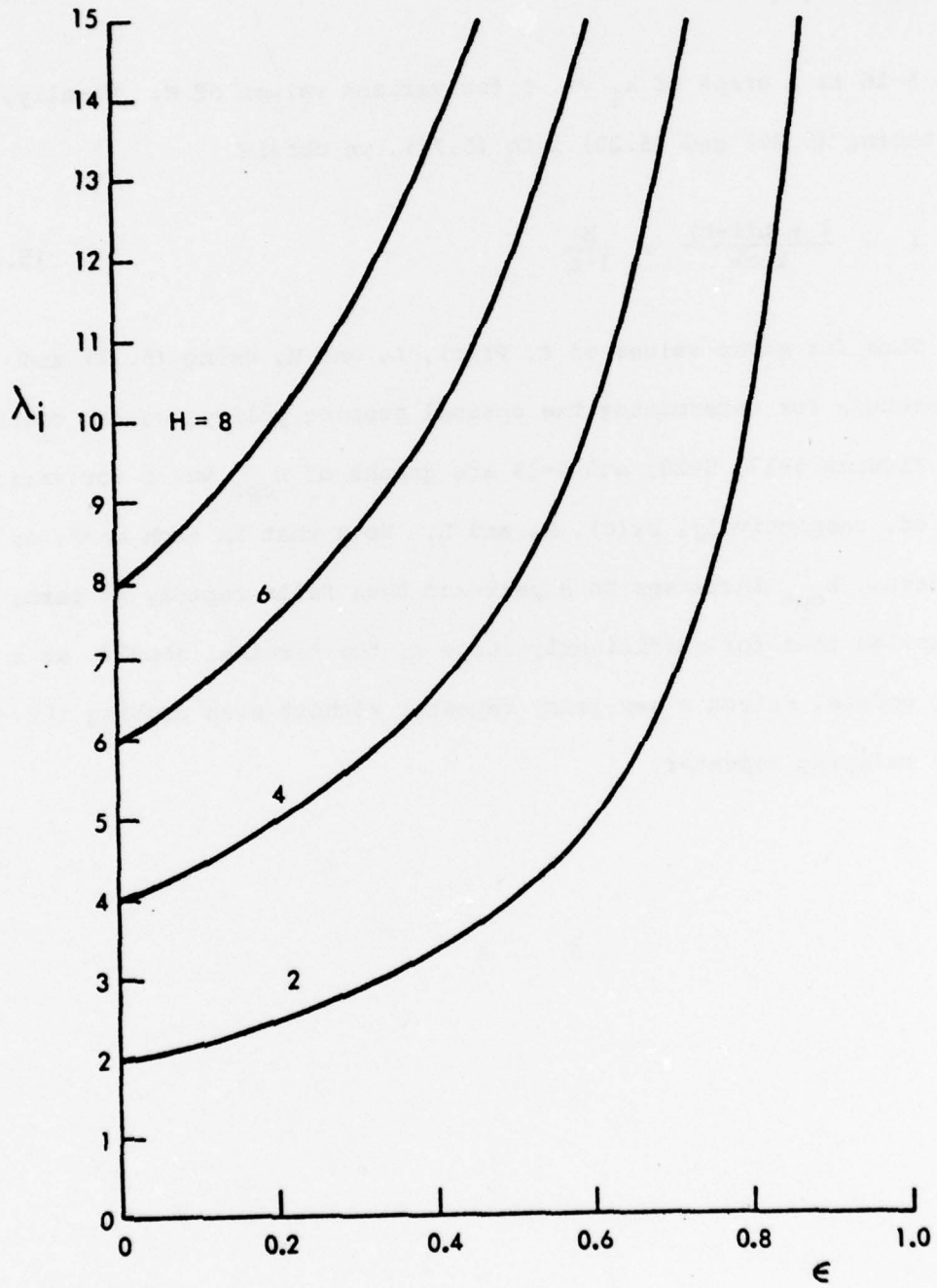
Figure 5-16 λ_i vs. ϵ
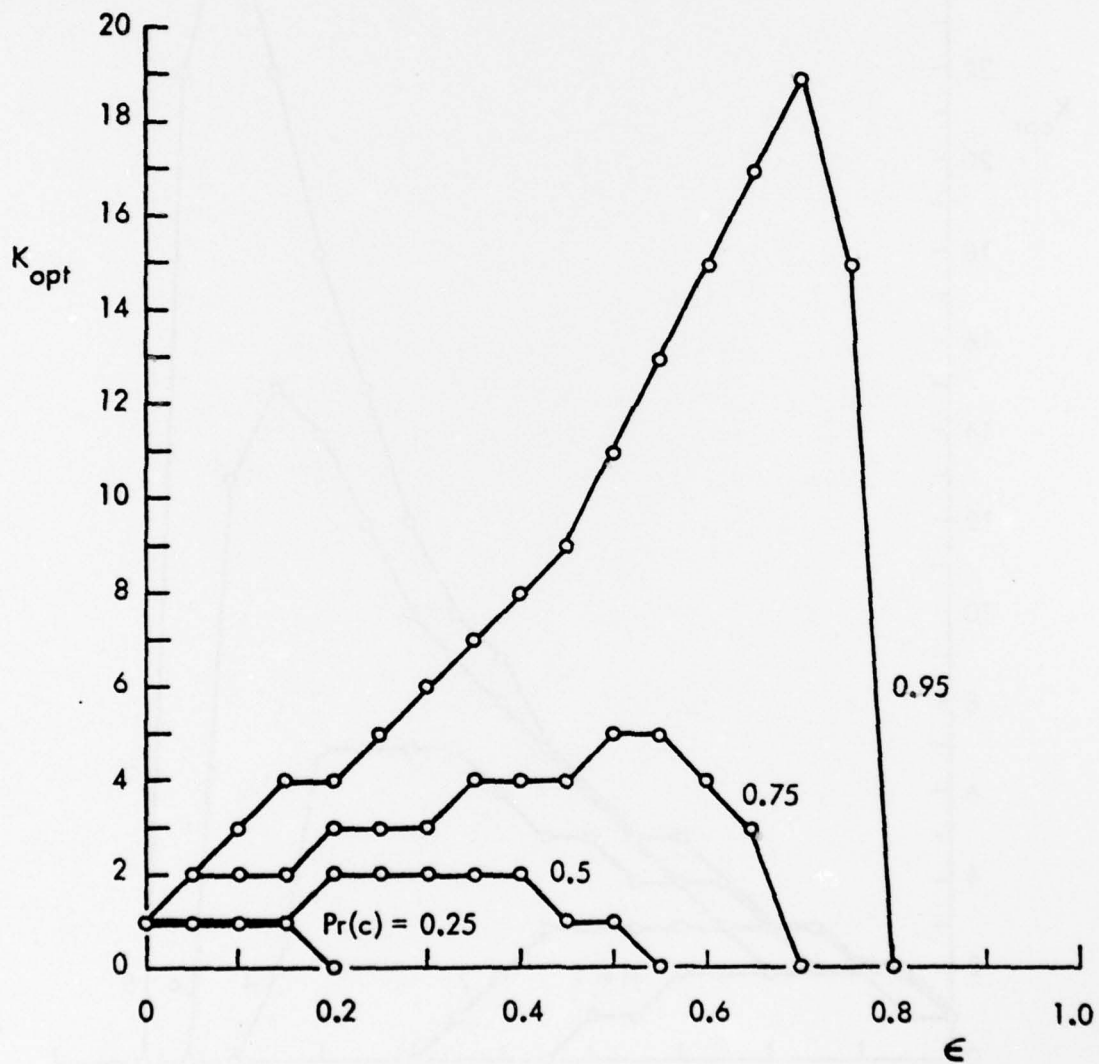
Figure 5-17 k_{opt} vs. ϵ with H = 3 and L = 3
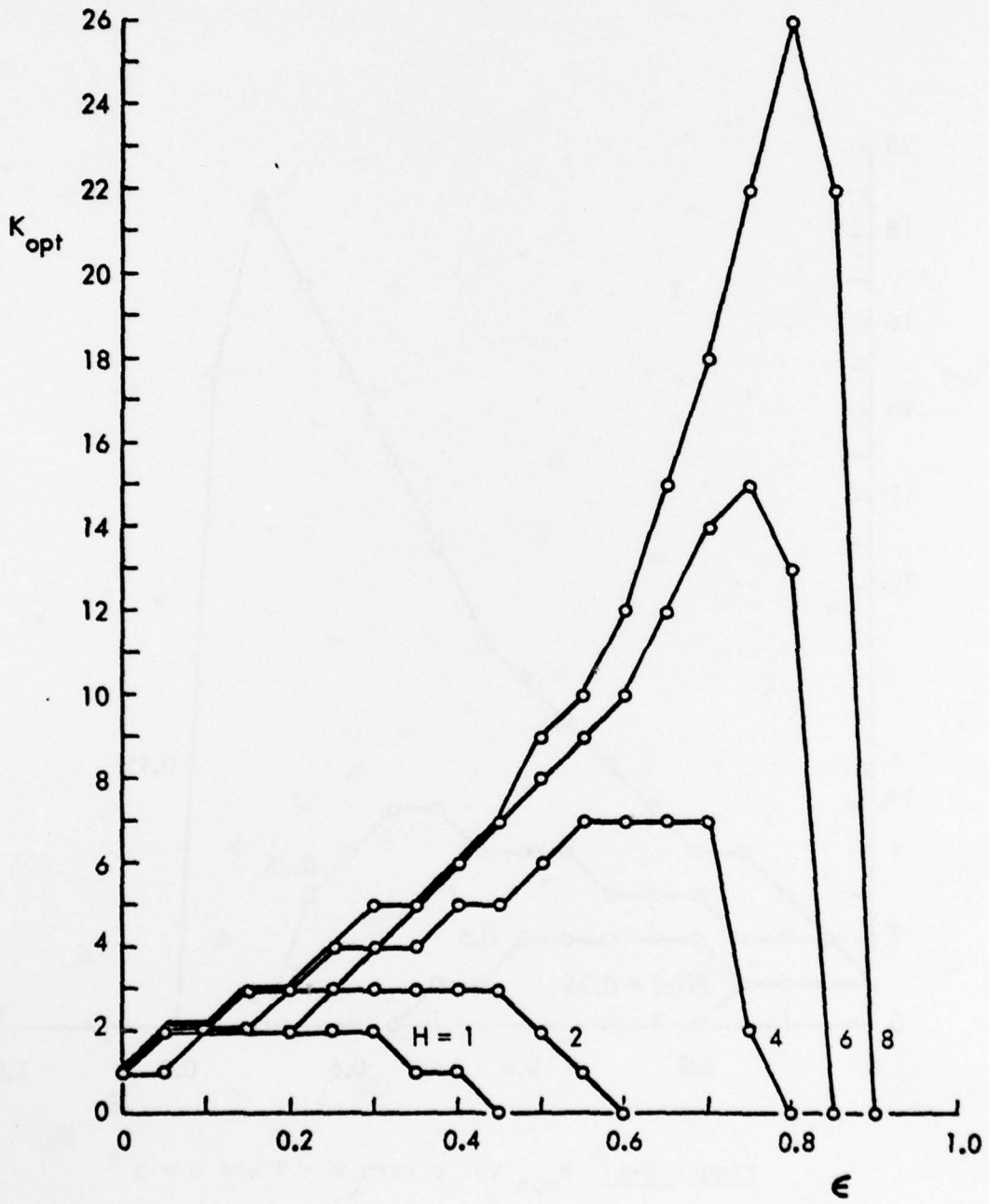
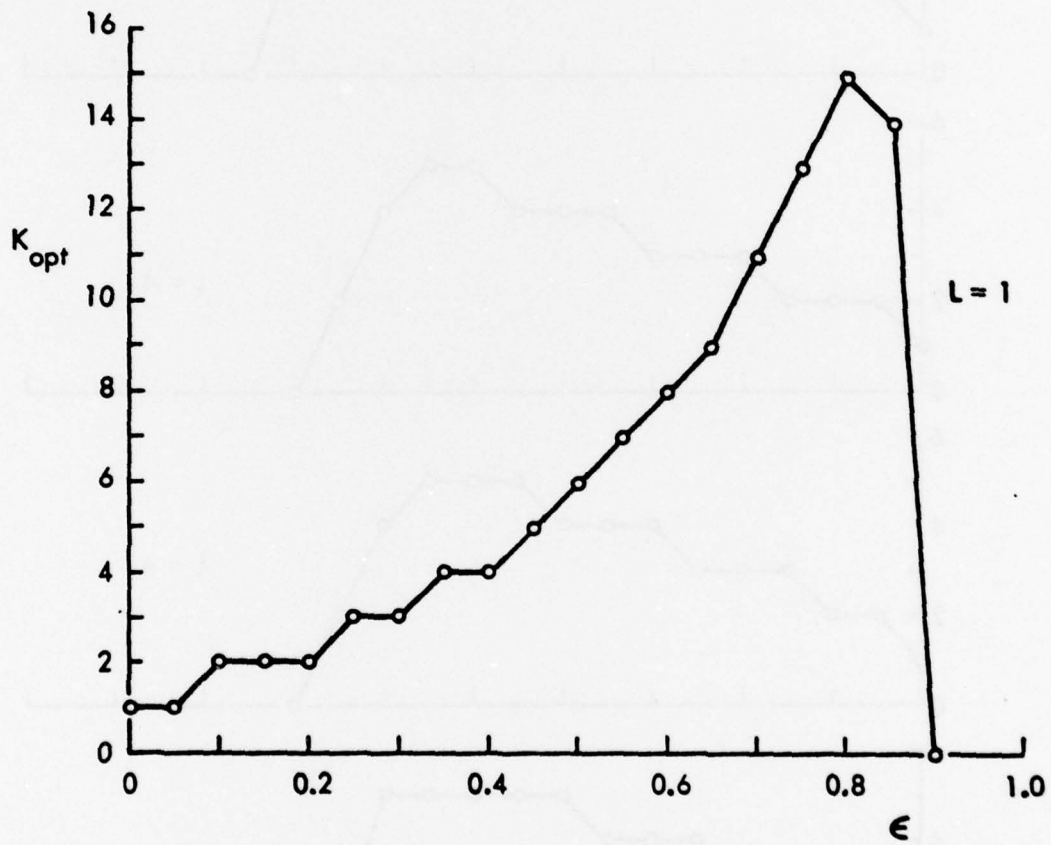Figure 5-18 k_{opt} vs. ε with Pr(c) = 0.75 and L = 3

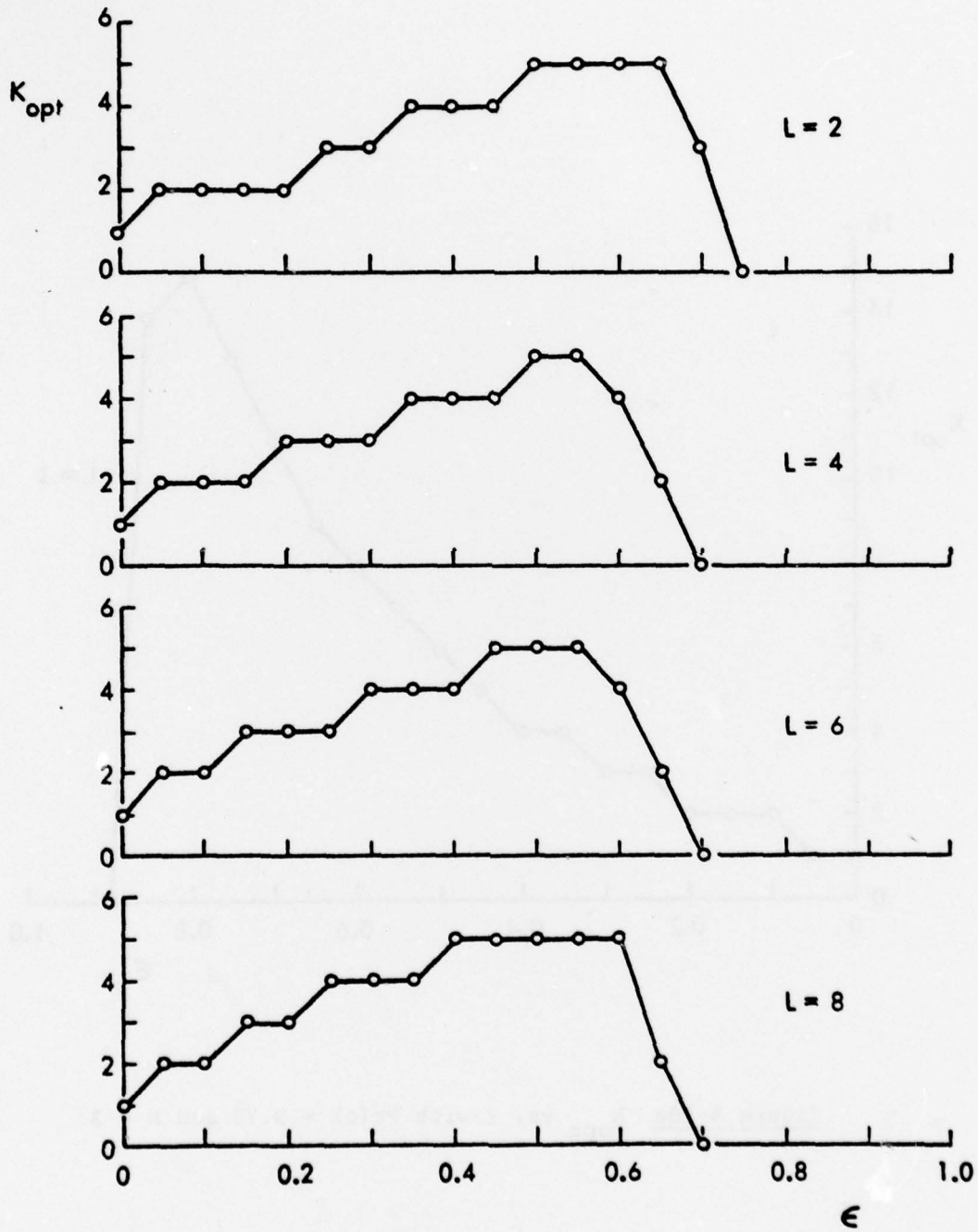Figure 5-19a k_{opt} vs. ε with Pr(c) = 0.75 and H = 3

Figure 5-19b k_{opt} vs. ε with $Pr(c) = 0.75$ and $H = 3$

CHAPTER 6

Summary and Conclusions

This thesis has been concerned with the problem of monitoring connectivity in mobile packet radio networks. The initial approach to this problem was to make as few assumptions as possible about the type of mobile packet radio network and the use that the network is to make of connectivity information. Considering just two nodes, we presented two monitoring methods, the broadcast method and the probing method. These two methods were generalized so that each node in a packet radio network could monitor the connectivity between it and the other nodes in the network. It was found that in this situation, there is little overhead associated with the broadcast method. However, unlike the probing method, the broadcast method does not test the connection between two nodes in both directions, and is not efficient when there is a large range in the required connectivity updating rates of the nodes in the network. Thus we concluded that there are trade-offs associated with each method and that to choose between them, one must examine both the specific type of packet radio network in which one wishes to monitor connectivity, and the specific use that is to be made of connectivity information.

In the second part of this thesis, we examined connectivity monitoring in a terminal-oriented mobile packet radio network. This network uses a tree-structured form of routing in which all traffic flows through a centralized node called a station. Each of the other nodes in the network is classified as either a repeater or a terminal. We allowed the terminals to be mobile, however, for simplicity, we required the station and repeaters to be stationary. We examined how

the broadcast and probing methods may be implemented in this network
for the purpose of updating the route between each terminal and the
station.

Two implementations of the broadcast method were first pre-
sented. The first implementation, a direct application of the broad-
cast method, consists of the repeaters and station broadcasting special
monitoring packets to the terminals. Unfortunately, we found that it
suffered from the two problems that are generally associated with the
broadcast method. Thus, although possibly suitable for a network in
which the repeaters and station have the same transmission range as
the terminals, we considered it an unsuitable choice for the network
under consideration. The second implementation, a form of which is
currently in use in an actual packet radio network, is a somewhat in-
direct application of the broadcast method which does not suffer the
problems associated with the first implementation. The second imple-
mentation consists of each terminal broadcasting special monitoring
packets called ROP's. Any repeater with an assigned route to the
station which receives an ROP attaches its identity to that ROP and
then forwards it to the station. The station can then update its
knowledge of the terminal-repeater and terminal-station connectivity
for the particular terminal which originated the ROP, and then if
needed, assign that terminal a new route to the station.

Next we presented an implementation of the probing method.
This implementation consists of each terminal updating, via probe
packets, the two-directional connectivity between it and the repeaters
and station. This connectivity information is then forwarded to the

station where a decision is made as to whether the terminal should
be assigned a new route. We found that although the end result of
using either this probing implementation or the ROP broadcast
implementation is the same, the overhead associated with each may be
different. In particular, we found that if a terminal is close to
the station and surrounded by few repeaters, the ROP broadcast
implementation is favored, whereas if the terminal is far from the
station and surrounded by many repeaters, the probing implementation
is favored. However, in the situation where 1) a terminal's route
is only changed when necessitated by a change in connectivity, and
2) the terminal is able to select its own route to the station, we
found that by revising the probing implementation, the associated
overhead can be reduced significantly, and thus make the probing
implementation a clear choice over the ROP broadcast implementation.
In addition, we found that this revised implementation can easily
make use of transmitted message packets in order to further reduce its
associated overhead, and that it can be generalized for the situation
where the repeaters and station are mobile.

The revised probing implementation was next analyzed in greater
detail. We chose as our measure of performance, the trade-off between
FTC and ATR. After formulating a network model, we derived expressions
for FTC and ATR. These were then used to evaluate the performance of
the revised probing implementation for variations in a terminal's
average velocity and randomness of motion, for two methods for choosing
the probing times (i.e., periodic probing and probing with position in-
formation), and for three methods for selecting a new relaying repeater

(i.e., random, nearest, and max E[TE]). The form of the results for
variations in a terminal's average velocity and randomness of motion is
illustrated in Figure 6-1(a). The comparison of the performances of
periodic probing and probing with position information is illustrated
in Figure 6-1(b). Here we found that the complexity and expense
associated with determining position may well be worth it if the
required value of FTC is in the vicinity of 1.0. As for the methods for
choosing a new relaying repeater, two points are of importance. First,
we found that basing the choice of a new relaying repeater on complete
position information (i.e., the max E[TE] method) had a somewhat better
performance than choosing a repeater at random. However, the improvement
is not necessarily significant enough to warrant basing the choice of a
new relaying repeater on position rather than on ability to relay packets
to the station. Secondly, we found that one must be careful about using
incomplete position information (e.g., distance information only) when
choosing a new relaying repeater, because in some situations, the per-
formance is actually worse than that associated with choosing a repeater
at random. Finally, we examined the problem of probing in the presence
of transmission errors. Specifically, we determined the optimal number
of times a terminal should attempt probing its relaying repeater before
concluding that a loss of connectivity between it and that repeater
has occurred.

Concerning the network model used in the performance analysis,
it is important to recognize that, conceptually, we could have just as
easily used a two-dimensional Markov model of terminal mobility. The
only requirements that the model must satisfy are 1) the positions of
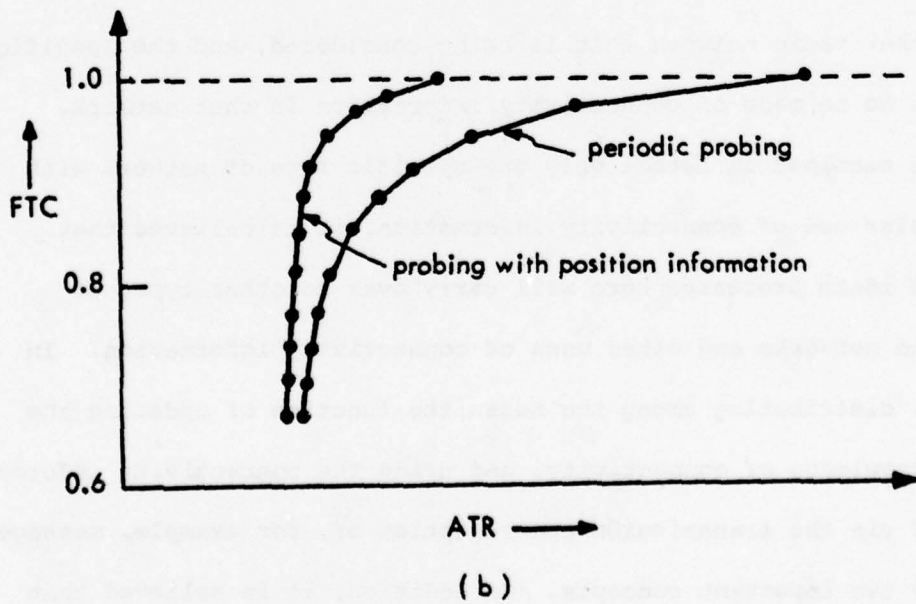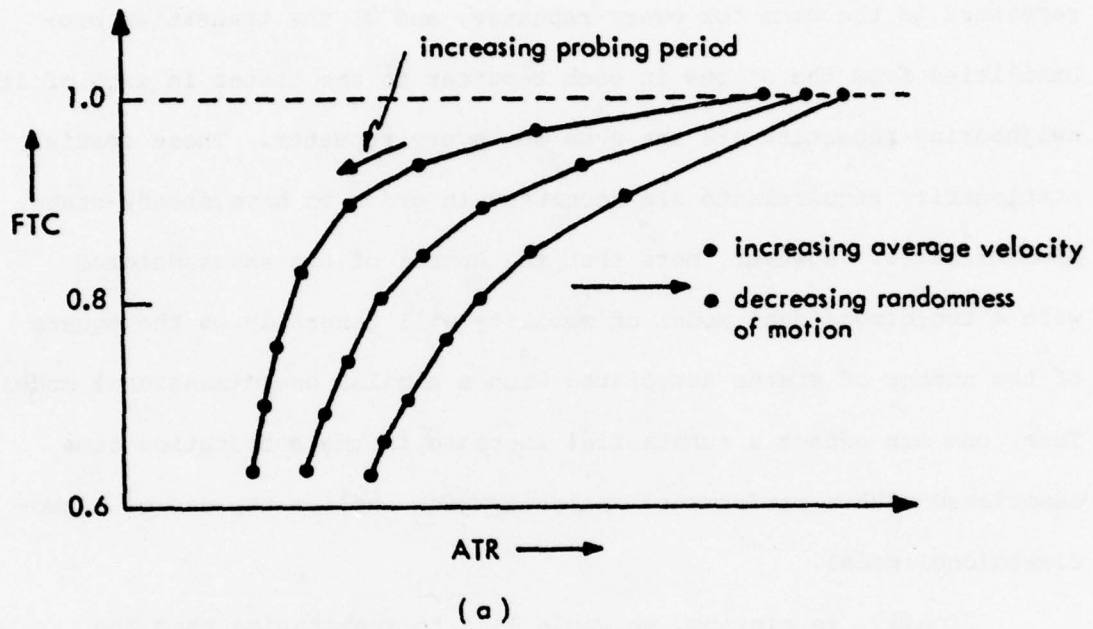
Figure 6-1 Form of the results for (a) variations in a terminal's average velocity and randomness of motion, and (b) the use of periodic probing and probing with position information

the states and the transition probabilities between the states within
the transmission range of each repeater are the same for every repeater,
2) the position of each repeater relative to each of its neighboring
repeaters is the same for every repeater, and 3) the transition pro-
babilities from the states in each repeater to the states in each of its
neighboring repeaters are the same for every repeater. These spatial
stationarity requirements are necessary in order to have steady-state
probabilities. However, note that the number of states associated
with a two-dimensional model of mobility will generally be the square
of the number of states associated with a similar one-dimensional model.
Thus, one can expect a substantial increase in the computation time
associated with a performance analysis which employs the use of a two-
dimensional model.

Finally, in closing, we would like to reemphasize that the
choice of a monitoring method is highly dependent on both the specific
type of packet radio network that is being considered, and the specific
use that is to be made of connectivity information in that network.
Although we examined in detail only one specific type of network with
one particular use of connectivity information, it is believed that
many of the ideas presented here will carry over to other types of
packet radio networks and other uses of connectivity information. In
particular, distributing among the nodes the function of updating the
network's knowledge of connectivity, and using the connectivity informa-
tion gained via the transmission and reception of, for example, message
packets are two important concepts. In addition, it is believed that
the results in Appendix A on Markov processes with observations could
be useful in the performance analysis of other monitoring implementations.

APPENDIX A

Markov Processes with Observations[*]

We consider an arbitrary, finite state, discrete-time, homo-geneous Markov process.[**] For notational convenience, we assume that the Markov process has N states which are identified by the integers 1 through N, and that state transitions occur at integer times. Also, we use the notation $s(n) = j$ to denote the event that the process is in state j at time n. The Markov process is completely characterized by its state transition probability matrix P (where element $p_{ij} \overset{\Delta}{=}$ $Pr\{s(n)=j|s(n-1)=i\}$ for i,j=1,2,...,N and n=1,2,...) and its initial state probability vector $\underline{\pi}(0)$ (where component $\pi_i(n) \overset{\Delta}{=} Pr\{s(n)=i\}$ for i=1,2,...,N and n=0,1,2,...). Associated with the process is an "observer" and a waiting time vector $\underline{\tau}$. The function of the observer is to observe the state of the Markov process. Observations are made at discrete instances of time. The time at which each successive observation is made is determined by $\underline{\tau}$ and the state of the process at the most recent observation. Specifically, τ_i, the ith (i=1,2,...N) component of $\underline{\tau}$, is a positive integer associated with state i. If state i is observed at time m, the observer will wait until time $m+\tau_i$ before again observing the state of the process. If at time $m+\tau_i$ state j is observed, the observer will wait until time $m+\tau_i+\tau_j$ before making the next observation. This continues for all subsequent observations.

_____

[*] As related to the derivation of FTC and ATR in section 5.4, observations and probes are equivalent. The word "observation" is used here to lend some generality to the results that are derived.

[**] See [15] for a more detailed discussion of this type of Markov process.

We would like to determine, probabilistically, at which times and in which states observations are made. We start by defining the indicator random variable

$$x(n) = \begin{cases} 1 & \text{if an observation is made at time n} \\ 0 & \text{if an observation is } \underline{\text{not}} \text{ made at time n} \end{cases} \quad n=0,1,2,\ldots$$

We now define two conditional probabilities that are of interest.

$$\phi_{ij}(n) = \Pr\{s(n)=j \mid s(0)=i\} \qquad i,j=1,2,\ldots,N; \; n=0,1,2,\ldots$$

$$\rho_j(n) = \Pr\{s(n)=j, \; x(n)=1 \mid x(0)=1\} \qquad j=1,2,\ldots,N; \; n=0,1,2,\ldots$$

The first conditional probability, $\phi_{ij}(n)$, is well known in the study of Markov processes and is often called the n-step transition probability. It may be evaluated recursively by using a simple form of the Chapman-Kolmogorov equation given by

$$\phi_{ij}(n) = \begin{cases} \displaystyle\sum_k \phi_{ik}(n-1)p_{kj} & n=1,2,\ldots \\ \delta_{ij} & n=0 \end{cases} \qquad \text{(A.1)}^*$$

Note that $\phi_{ij}(n)$ is independent of the observation process. The second conditional probability, $\rho_j(n)$, is dependent on the observation process and in words, is the probability that at time n the Markov process will be in state j and an observation will be made, given that at time 0 an observation was made. An equation similar to (A.1) may be used to eval-

---

*All summations without labeled indices implicitly run from 1 to N

(i.e., $\displaystyle\sum_k$ is used to denote $\displaystyle\sum_{k=1}^{N}$), and $\delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$.

uate $\rho_j(n)$ recursively. This equation and its proof are as follows:

$$\rho_j(n) = \begin{cases} \sum_k \rho_k(n-\tau_k)\phi_{kj}(\tau_k) & n=1,2,\ldots \\ \pi_j(0) & n=0 \\ 0 & n=-1,-2,\ldots \end{cases} \qquad (A.2)$$

Proof of Equation (A.2):

We assume that the first observation is made at time 0, thus it follows that $\rho_j(n)=0$ for $n < 0$. Also, from the definition of $\rho_j(n)$ and $\pi_j(n)$, it is clear that $\rho_j(0) = \pi_j(0)$. We begin the proof for $n > 0$ by noting that, given $x(n)=1$ and $s(n)=j$, the set of paired events $\{s(n-\tau_k)=k, x(n-\tau_k)=1\}$ $k=1,2,\ldots,N$ forms a mutually exclusive and collectively exhaustive set. Thus, from the definition of $\rho_j(n)$, we may write

$$\rho_j(n) = \sum_k \Pr\{s(n)=j, x(n)=1, s(n-\tau_k)=k, x(n-\tau_k)=1 \mid x(0)=1\}$$

$$= \sum_k \Pr\{s(n)=j, x(n)=1 \mid s(n-\tau_k)=k, x(n-\tau_k)=1, x(0)=1\}$$
$$\cdot \Pr\{s(n-\tau_k)=k, x(n-\tau_k)=1 \mid x(0)=1\} \qquad (A.3)$$

The first term within the summation of (A.3) may be rewritten as

$$\Pr\{s(n)=j, x(n)=1 \mid s(n-\tau_k)=k, x(n-\tau_k)=1, x(0)=1\}$$

$$= \Pr\{x(n)=1 \mid s(n)=j, s(n-\tau_k)=k, x(n-\tau_k)=1, x(0)=1\}$$
$$\cdot \Pr\{s(n)=j \mid s(n-\tau_k)=k, x(n-\tau_k)=1, x(0)=1\}$$

$$= 1 \cdot \phi_{kj}(\tau_k) \qquad (A.4)$$

Furthermore, the second term within the summation of (A.3) is by definition $\rho_j(n-\tau_k)$. Using this fact and substituting (A.4) into (A.3), we obtain the desired result

$$\rho_j(n) = \sum_k \rho_k(n-\tau_k)\phi_{kj}(\tau_k)$$

Q.E.D.

We now use the above result to investigate the steady-state behavior of a Markov process with observations. We begin by defining

$$\tilde{\pi}_j(n) = \Pr\{s(n)=j \,|\, x(n)=1, \, x(0)=1\} \qquad j=1,2,\ldots,N; \; n=0,1,2,\ldots$$

From the definition of conditional probability, as long as $\Pr\{x(n)=1\,|\,x(0)=1\} \neq 0$, we may write

$$\tilde{\pi}_j(n) = \frac{\Pr\{s(n)=j, \, x(n)=1 \,|\, x(0)=1\}}{\Pr\{x(n)=1 \,|\, x(0)=1\}}$$

$$= \frac{\rho_j(n)}{\sum_i \rho_i(n)} \qquad \text{for } \sum_i \rho_i(n) \neq 0 \tag{A.5}$$

Summing, with respect to j, both sides of (A.2), we obtain

$$\sum_j \rho_j(n) = \sum_j \sum_k \rho_k(n-\tau_k)\phi_{kj}(\tau_k)$$

$$= \sum_k \rho_k(n-\tau_k) \sum_j \phi_{kj}(\tau_k)$$

$$= \sum_k \rho_k(n-\tau_k) \tag{A.6}$$

Substituting (A.2) and (A.6) into (A.5), we obtain

$$\tilde{\pi}_j(n) = \sum_k \frac{\rho_k(n-\tau_k)}{\sum_i \rho_i(n-\tau_i)}\phi_{kj}(\tau_k)$$

$$= \sum_k \tilde{\pi}_k(n-\tau_k)\phi_{kj}(\tau_k) \qquad \text{for } \sum_i \rho_i(n) \neq 0 \tag{A.7}$$

Suppose that at time n the mth observation is made. We can say that for

some k (k=1,2,...,N), at time $n-\tau_k$ the $(m-1)^{th}$ observation was made while in state k. Using the notation $\tilde{\pi}_j[m]$ to denote the conditional probability that, given x(0)=1, the process is in state j at the time of the mth observation, we may rewrite (A.7) as

$$\tilde{\pi}_j[m] = \begin{cases} \sum_k \tilde{\pi}_k[m-1]\phi_{kj}(\tau_k) & m=1,2,\ldots \\ \\ \tilde{\pi}_j(0) & m=0 \end{cases} \qquad (A.8)$$

Note that (A.8) is of the same structure as the familiar (see [15] section 1.3) equation

$$\pi_j(n) = \begin{cases} \sum_k \pi_k(n-1)p_{kj} & n=1,2,\ldots \\ \\ \pi_j(0) & n=0 \end{cases}$$

Recall from basic Markov theory that if the stochastic matrix P represents an ergodic Markov process (e.g., an irreducible aperiodic, finite Markov chain), then the limiting probabilities

$$\pi_j = \lim_{n\to\infty} \pi_j(n)$$

always exist and are independent of the initial state probability distribution. Furthermore, these limiting probabilities are uniquely determined by the following equations:

$$\pi_j = \sum_i \pi_i p_{ij}$$

$$1 = \sum_i \pi_i$$

Thus, if we interpret the stochastic matrix Φ, with elements $\phi_{kj}(\tau_k)$, as representing the transition probabilities of a Markov process, and if Φ is such that the associated Markov process is ergodic, then the limiting probabilities

$$\tilde{\pi}_j = \lim_{m \to \infty} \tilde{\pi}_j[m]$$

always exist, are independent of $\tilde{\pi}_j[0]$, and may be uniquely determined by

$$\tilde{\pi}_j = \sum_i \tilde{\pi}_i \phi_{ij}(\tau_i)$$

$$1 = \sum_i \tilde{\pi}_i \tag{A.9}$$

Equation (A.9), in a slightly different form, is used in the derivation of FTC and ATR in section 5.4.

APPENDIX B

Time-Sharing on FTC vs. ATR

Given any two points, say Q_1 and Q_2, on FTC vs. ATR corresponding to two different sets of parameters (e.g., two different values of $\underline{\tau}$ with all other parameters the same), we show that with time-sharing, any point lying on the straight line segment connecting Q_1 and Q_2 is achievable. By time-sharing we mean that for fraction θ ($0 \le \theta \le 1$) of the time the parameter set associated with one of the two points is used, and for fraction $1-\theta$ the parameter set associated with the other point is used.

Let us assume that for fraction θ of the time the parameter set associated with Q_1 is used, and for fraction $1-\theta$ the parameter set associated with Q_2 is used. For notational convenience, we define

a_i = E[TC] for the parameter set associated with Q_i (i=1,2)

b_i = E[P]   "   "   "   "   "   "   "   "

c_i = E[T]   "   "   "   "   "   "   "   "

Using these definitions and equations (5.7) and (5.8), we may write

$$FTC(\theta) = \frac{\theta a_1 + (1-\theta)a_2}{\theta c_1 + (1-\theta)c_2} \qquad (B.1)$$

and

$$ATR(\theta) = \frac{\theta b_1 + (1-\theta)b_2}{\theta c_1 + (1-\theta)c_2} \qquad (B.2)$$

Let us define point Q as that point corresponding to FTC(θ) and ATR(θ). To prove that point Q is on the line segment connecting points Q_1 and Q_2, it is sufficient to show that the slope of the line connecting Q_1 and Q is independent of θ for $0 \le \theta < 1$. Following this line of proof, we write

$$\text{slope}(Q_1, Q) = \frac{FTC(\theta) - FTC(1)}{ATR(\theta) - ATR(1)} \qquad (B.3)$$

Substituting (B.1) and (B.2) into (B.3), we obtain

$$
\begin{aligned}
\text{slope}(Q_1, Q) &= \left[\frac{\theta a_1 + (1-\theta)a_2}{\theta c_1 + (1-\theta)c_2} - \frac{a_1}{c_1} \right] \bigg/ \left[\frac{\theta b_1 + (1-\theta)b_2}{\theta c_1 + (1-\theta)c_2} - \frac{b_1}{c_1} \right] \\[2mm]
&= \frac{c_1[\theta a_1 + (1-\theta)a_2] - a_1[\theta c_1 + (1-\theta)c_2]}{c_1[\theta b_1 + (1-\theta)b_2] - b_1[\theta c_1 + (1-\theta)c_2]} \\[2mm]
&= \frac{(1-\theta)a_2 c_1 - (1-\theta)a_1 c_2}{(1-\theta)b_2 c_1 - (1-\theta)b_1 c_2} \\[2mm]
&= \frac{a_2 c_1 - a_1 c_2}{b_2 c_1 - b_1 c_2}
\end{aligned}
$$

Q.E.D.

Thus we have shown that, with the use of time-sharing, any point on the line segment connecting Q_1 and Q_2 can be achieved by an appropriate choice of θ.

APPENDIX C

Some Computational Details

Computing $\phi_{ij}(\tau_i)$

The computation of FTC and ATR as defined by, respectively,
equations (5.15) and (5.16) incorporate (directly, and indirectly through
the computation of $\tilde{\underline{\pi}}$) the quantity $\phi_{ij}(\tau_i)$ for i=1,2,...,N and
j = {all integers}. Although the recursive method for computing $\phi_{ij}(n)$,
as defined by equation (A.1), is only valid for a Markov process with a
finite number of states, by limiting the value of τ, we may view the in-
finite state Markov process which defines the terminal's motion along the
path as having a finite number of states. We define

$$\tau_{max} = \max_{i} \tau_i$$

As such, we note that for i=1,2,...,N

$$\phi_{ij}(\tau_i) = 0 \quad \text{for } j > \tau_{max} + N \text{ or } j \leq -\tau_{max}$$

Thus for our purposes, we need only consider the Markov process to have
$N + 2\tau_{max}$ states, and hence we may use equation (A.1) to compute $\phi_{ij}(\tau_i)$.

There are, however, more efficient means for computing FTC and
ATR other than first computing $\phi_{ij}(\tau_i)$ in this manner and then making a
direct substitution into equations (5.5), (5.15), and (5.16). To see
this, let us consider the network model illustrated in Figure 5-3 where
N = 11 and a repeater is located every 5 states along the path. Let us
suppose the restriction $\tau_{max} \leq 14$ has been imposed. Note from Figure
5-3 that state 0 and state 25 both represent the same position relative

-122-

to the repeaters whose transmission ranges encompass each. The same is true for states -1 and 24, -2 and 23, all the way up to and including states -13 and 12. After examining the methods for selecting a new relaying repeater (see section 5.5), one realizes that in so far as choosing a new relaying repeater is related to the computation of ψ_{ij} in equation (5.5), these paired states are equivalent. That is, the term within the summation on the right hand side of (5.5) is the same for k equal to either of the paired states. Thus the logical thing to do is to combine each of these paired states, but doing so in such a way that the values of $\phi_{ij}(\tau_i)$ (i,j=1,2,...,N) used directly in equations (5.15) and (5.16) are unaffected. We may do this by modifying the current Markov chain so that it is of the form illustrated in Figure C-1. The transition probabilities for moving one state in the clockwise direction, moving one state in the counterclockwise direction, and remaining in the current state are, respectively, p, q, and 1-p-q. Note that as long as $\tau_{max} \leq 14$, the values of $\phi_{ij}(\tau_i)$ (i,j=1,2,...,N) used directly in equations (5.15) and (5.16) are the same for either the modified or unmodified Markov chain. This type of modification of the Markov chain can of course be made for any τ_{max}, N, and repeater spacing. One must only make certain that the paired states are indeed equivalent and that N_s, the total number of states in the modified Markov chain, is greater than or equal to $N+\tau_{max}$. As a final note, in computing the n-step transition probability $\phi_{ij}(n)$ for a Markov chain of the form illustrated in Figure C-1, recognize that

$$\phi_{ij}(n) = \phi_{[(i+k)\,MOD\,N_s]+1,\ [(j+k)\,MOD\,N_s]+1}(n) \quad \begin{array}{l} i,j=1,2,\ldots,N_s \\ k,n=0,1,2,\ldots \end{array}$$
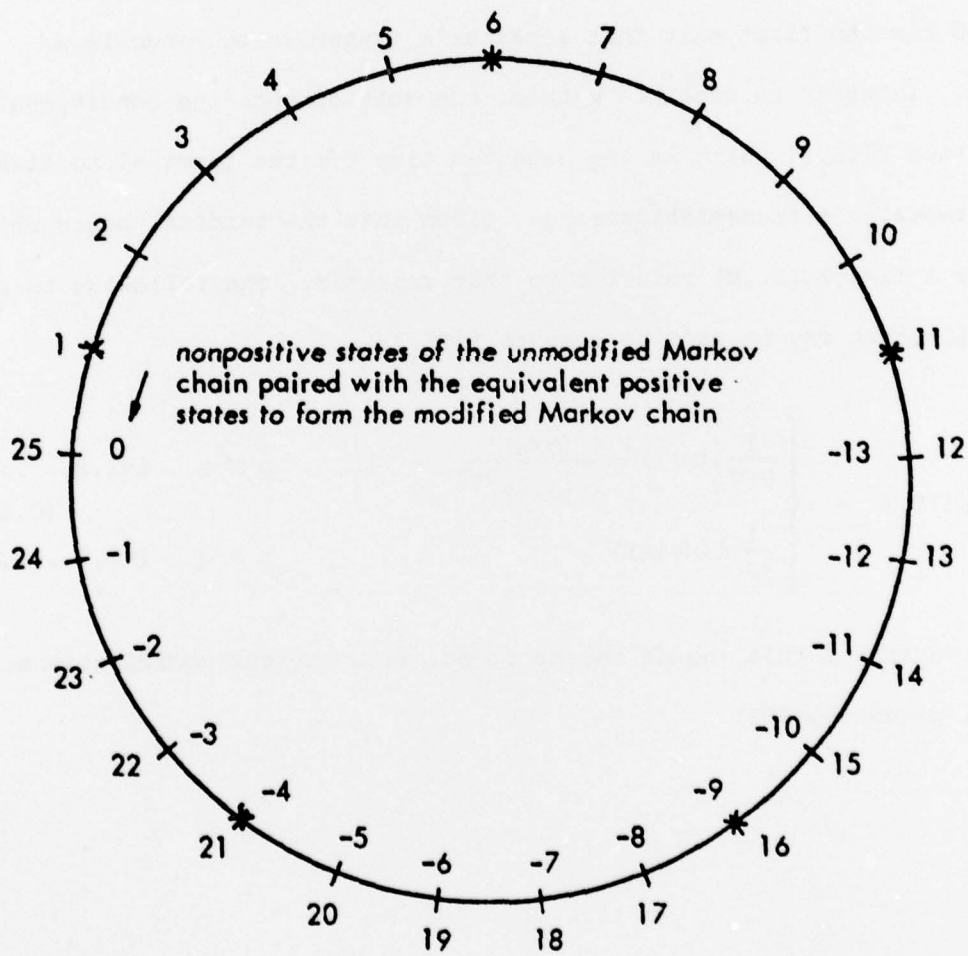
Figure C-1 Modified Markov chain for $\tau_{max} \leq 14$, $N = 11$, and repeater spacing = 5s

Thus to determine $\phi_{ij}(n)$ for $i,j=1,2,\ldots,N_s$, one need only actually com-

pute $\phi_{ij}(n)$ for one value of i and $j=1,2,\ldots,N_s$.

Computing $E[TE_i]$

In section 5.5, one method discussed for choosing a new relaying

repeater consisted of the terminal selecting the repeater for which the

expected time to first exit that repeater's transmission range is a

maximum. In order to use this method, one must compute the conditional

expectation $E[TE_i]$, which is the expected time for the terminal to first

exit a repeater's transmission range, given that the terminal began while

in state i ($i=1,2,\ldots,N$) relative to that repeater. The following is an

expression that may be used to compute $E[TE_i]$:

$$E[TE_i] = \begin{cases} \dfrac{1}{p-q}\left[(N+1)\dfrac{1 - (q/p)^{i}}{1 - (q/p)^{N+1}} - i\right] & p \neq q, \quad i=1,2,\ldots,N \\ \\ \dfrac{1}{2p}\, i(N+1-i) & p = q \quad i=1,2,\ldots,N \end{cases} \tag{C.1}$$

The derivation of this result may be found, with obvious modifications,

in [15], pages 460-462.

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