A Distributed Routing Scheme with Mobility Handling in Stationless Multi-hop Packet Radio Networks*

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Abstract — **A mobile stationless multi-hop packet radio network consists of a set of mobile and geographically distributed nodes (e.g., computers, terminals, etc., equipped with radio units), called packet radio units (PRUs), which communicate using a shared broadcast radio channel without a central station control. In this paper we consider the routing in highly mobile stationless multi-hop packet radio networks. We provide a validation of the use of the tier-ring architecture, and we present a scheme for handling mobile packet radio units in stationless environment by the use of a link-traversal approach when a node (packet radio unit) is no longer in possession of an outgoing link to communicate with the rest of the network.**

INTRODUCTION

Packet radio networks offer the possibility of sharing a single channel rather than having a large number of channels with fixed (and mostly wasted) capacity. They are attractive solutions in mobile and geographically hostile environments where the telephone system is poorly developed or non-existent. They also provide a fairly good solution for local networks in urban areas (i.e., the University of Hawaii ALOHA system). In the past few years, packet radio networks have been developed for many purposes and have seen many radical changes in architectural designs and routing concepts.

The routing and flow control strategies used for forwarding and controlling the traffic to be carried are of utmost importance for efficient packet radio network operation. Routing is a problem distributed in space and time. Its task is *to best allocate the available* network resources to handle the network load, in the sense of minimizing average packet transmission time and or routing path length through the network, and to resolve *predictable and unpredictable* difficulties and obstacles, such as mobility, connectivity and loss of resources (packet radios, stations, or links). The specifications of routing procedures must, in some sense, be highly coupled with the specific implementations and the nature of the network. In fact, the few presently existing packet radio networks (PRnets) have totally different routing procedures, conception and design, essentially due to their nature and specifications. Examples of such nets include the PRNET of the Defense Advanced Research Projects Agency (DARPA) [1] , Advanced Mobile Phone Service (AMPS), Battlefield Information Distribution (BID) [2] , Ptarmigan [3] , Intra-Task Force (ITF) Network [4]. Each of these networks has many features in common with the others. Their architectural organizations are different, however, because each also has *unique* requirements and constraints. For example, the AMPS network is organized into cellular tessellations with a fixed local controller in each cell. On the other hand, military networks, such as BID and Ptarmigan , require a more adaptive structure. The architectural organization of the DARPA's PRNET has evolved from a central control (control and traffic) station to stationless packet radio networks. Experiments with multi-station packet radio networks [5, 6, 7] are being carried on extensively. Experiments with stationless [8] nets are also underway. Efforts to merge multi-station and stationless nets are also being made [9].

In this paper, we describe a distributed routing scheme in stationless mode. Our goal is two-fold. First, we attempt to validate the use of a tier-ring architecture for stationless nets and present a distributed routing algorithm that operates efficiently in a such mode. Second, we consider our algorithm as a distributed algorithm for the calculation of minimum directed shortest path trees at each node of the network where link weight depends on its endpoints and its direction. Such a weight measure is very appropriate for packet radio networks and can accommodate features such as quality of the link and signal strength.

In general, the routing algorithms in PRnets are typically concerned with optimization that minimizes the length of routing paths (i.e., number of hops), hoping that this will also minimize the delay. Nevertheless, this is not always true. So far, no provisions have been made to introduce any criteria that are concerned with minimum delay paths through a PRnet, although that delay is of utmost importance in packet radio networks and is often considered to be very important and critical in such communication media. The absence of attempts to explicitly minimize the delay in packet radio(PR) networks is primarily due to the fact that the topological organization of a PR network is plagued with enormous problems such as, frequent topological changes, quality of the links, hidden terminal problems, and particularly *the instability* of the routing information due to the mobility of the packet radios.

Presently, several routing algorithms for packet radio networks are defined; some of them implemented. Although all of these algorithms are coupled with and related to the architectural structures and constraint specifications, they have two common objectives:

a. assurance with high probability that a message launched into the network from an arbitrary point will reach its destination; and

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b. assurance that messages will be able to be transmitted through the network with an acceptable end to end delay.

Examples of such routing algorithms include, broadcast routing [10,11] , routing in a single station environment [12] , hierarchal routing [10,13] , directed broadcast routing, ARPANET-like routing with a distance vector [10] , incremental routing in multi-station PR networks [5,14,15,16,17,18,19] and [6] , flooding in multi-station routing [20] and routing in stationless PR networks [8].

Although noticeable progress is achieved in the design of packet radio networks and routing algorithms, crucial problems inherent to the nature of such networks still remain unaddressed, such as highly mobile environments where topological changes are frequent and have to be explicitly considered by the routing procedures. This paper also presents an approach to solve this problem.

THE MODEL

Throughout the paper we consider the following:

a. *Multi-hop Packet Radio Network:* packets could be relayed over several hops before reaching their final destination.

b. *Stationless Mode:* the network contains no station. All the packet radio units (PRUs) are repeaters.

c. *Single Broadcast Channel:* all the PRUs transmit with fixed power on the same frequency band.

d. *Topology:* the network topology which is the set of PRUs along with their radio connectivity is changing frequently due to the mobility of the PRUs.

In such a multi-hop stationless packet radio network, where connectivity between PRUs is changing frequently, it is a formidable task for the routing to maintain *up-to-date* knowledge of the status of the net. Routing decisions based on old and inadequate information reports should be avoided. We thus need to find a *distributed* routing algorithm which :

a. does not swamp the network with control traffic messages;

b. reacts fast enough to provide routes;

c. assures with high probability that a packet launched into the network will reach its destination ;

d. delivers a large number of messages with a relatively small time delay; and

e. is also appropriate for *stationary* stationless multi-hop packet radio networks where all PRUs are fixed in space and connectivity changes are essentially caused by PRU failures.

Such a distributed routing algorithm must also be appropriate for packet radio networks and provide:

a. all the primary routes between all the source-destination PRUs in the network. A primary route between a source PRU and a destination PRU is defined to be the best path (i.e. shortest in number of hops,) between these two end-point PRUs. *A primary route does not have to be fixed and can change dynamically from one packet transmission to another**. More precisely, we define a primary route between two PRUs, *for a given packet*, as the set of links traversed by the previous packet to arrive at the destination. In the case of a stationary network and no PRU failure, all the primary routes between the PRUs will be stationary.

b. all the possible alternate routes between all the source-destination PRUs in the network to cope effectively with topological changes affecting previous primary routes. An alternate link *at a given PRU for a given destination PRU* is defined to be any outgoing link emanating from this PRU that has a link weight greater than that of the primary link (i.e., the one which belongs to the primary route). An alternate route between a source PRU and a destination PRU is a complete path that contains at least one alternate link. The weight of a link will be defined later. We define *for each PRU* in the network, the following:

1. Its identification number: ID#

2. A set of non negative integer values α^{d}_{ID} where d is any destination PRU ID# . We say that we have a link between PRU i and PRU j if and only if:

   a. PRU i and PRU j are neighbors, and

   b. $(i, \alpha_i^d) > (j, \alpha_j^d)$

$$\text{where } (i,\alpha_i^d) > (j,\alpha_j^d) \Leftrightarrow \alpha_i^d > \alpha_j^d \quad \text{OR} \quad \text{If } \alpha_i^d = \alpha_j^d \text{ Then } i>j \qquad (1)$$

We define the weight of a link between PRU i and PRU j for destination PRU d as follows :

$$\text{Weight [link: PRU i-->PRU j,For destination d]} = \alpha_j^d \qquad (2)$$

For simplicity we write (2) as :

$$\text{Weight [i--->j,d]} = \alpha_j^d \qquad (3)$$

It is obvious from this definition of the link weight that a link has different weights for different destinations. It is also worthwhile to note that this definition of link weight does not explicitly accommodate the link quality. We assume that link quality is included within the α^{d}_{ID} 's upon their assignments.

Let :

S_d = The network topology where PRU ID# d is the only possible destination.

Ψ = The network topology where any PRU can be destination.

Φ = the set of PRUs in the network.

Formally, S_d and Ψ can be defined as :

S_d = { (i,α_i^d,d) / i is a PRU ID#, α_i^d is the value associated with PRU i *for destination d*, d is a given PRU ID # }.

$\Psi = \{ S_d / d \in \Phi \}$

N = cardinality of Φ

PROPOSITION 1 :

For any $d \in \Phi$ we have :

S_d is an Acyclic Directed Graph (ADG) destination d oriented. That is S_d is a directed graph containing no directed cycle and for every PRU i in Φ there exists at least one directed path originating at this node and terminating at PRU d.

PROOF :

The proof can easily be seen from definition (3) and proposition 6.2 p. 28 reference [22].

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*In PRNET radio networks, say the multi-station mode, a complete path called the primary route is set-up between the source PRU and the destination PRU before any exchange of information packets. This primary route, once set-up, is fixed and might be refreshed only every half an hour [7,21]. In stationless mode, routes are also updated on an half hourly basis, when a new reporting PRU provides a route improvement.

Now working on the set Ψ we define the primary and the alternate routes in Ψ for all the source-destination pairs in the network. Due to the broadcast nature of the channel in packet radio networks, the transmitting PRU has to specify in the header of the packet to be transmitted, the identity of the receiving PRU. The set of receiving PRUs all along the route between the source PRU and the destination PRU defines the primary route taken by the packet. The receiving PRU of a packet, destined to the destination PRU d, is defined by the transmitting PRU,say PRU i, before transmission of the packet, according to the following :

Receiving PRU is ID# j if and only if (4)
Weight[i--->j,d] = $\min_{k \in \Phi}$ {Weight[i--->k,d]}
such that the link [i--->j,d] exists according to (1).

The alternate routes between a source PRU and a destination PRU are defined to be the directed paths between these PRUs not including the primary route. Classification of alternate routes could be done according to the number of hops and quality of the links. We adopt the following classification. The nth ranked receiving PRU of a packet, destined to the destination PRU d, is defined by the transmitting PRU,say PRU i, before transmission of the packet, according to the following:

nth receiving PRU is ID# j if and only if (5)
Weight[i--->j,d] = nth $\min_{k \in \Phi}$ {Weight[i--->k,d]}
such that the link [i--->k,d] exists according to (1)

PROPOSITION 2 :

The primary routes in S_d from any PRU i in Φ to destination PRU d are minimum weight directed spanning trees. The primary routes in Ψ are minimum weight directed spanning trees routed at each node in Φ.

PROOF :

The proof of proposition 2 follows directly from definition (3), statement (4) and proposition 1.

We now seek to calculate and assign the α_{ID} 's to the PRUs ID # in a distributed fashion. Our task is then to calculate the α_{ID}^{d} for every d and ID in Φ . That is, form the sets S_d for every d in Φ to obtain the global set Ψ .
Consider figure (1) below and Let :

d : a given PRU ID # considered as a destination.
i : sender PRU ID #.
α_i^d : nonnegative integer value given to PRU i for destination PRU d.
h_d : number of hops separating PRU i from PRU d.
j : receiving PRU ID # to which an α_j^d has to be defined.
α_j^d : nonnegative integer value to be given to PRU j for destination PRU d.
T_{h_d} : number of PRUs at a distance of h_d hops from destination PRU d.

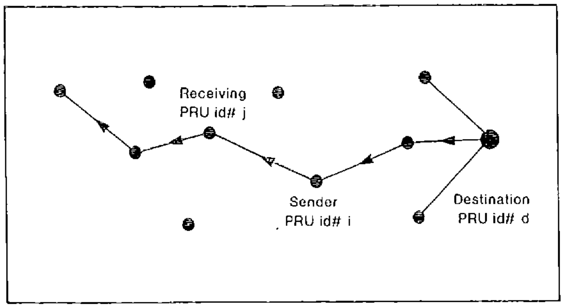

FIGURE 1
Definition of parameters

We therefore define the function α_j^d as follows :

$$\alpha_j^d = f\{ (i,\alpha_i^d),j,d,h_d,T_{h_d} \} \qquad (6)$$

According to (1) the function α_i^d has to satisfy the following relation :

$$\sum_{n=1}^{h_d-1} T_n < \alpha_i^d \leqslant \sum_{n=1}^{h_d} T_n \qquad (7)$$

Note that $\alpha_d^d = 0$.

We notice here that the parameter T_{h_d} is difficult to calculate accurately and is very dependent on the architecture of the network. Let us consider some examples to clarify the calculation of α_i^d and the meaning of the parameters defined above :
EXAMPLE 1 : TANDEM NET
Consider figure (2) below:

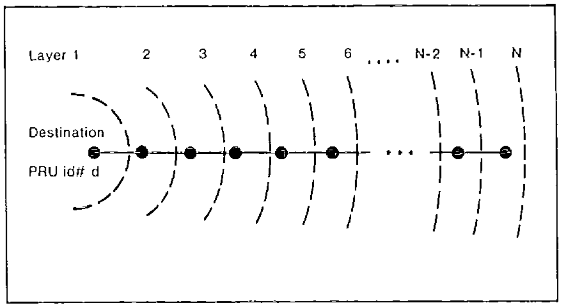

FIGURE 2
Tandem network

We thus have $T_{h_d} = 1$ for all h_d and relation (7) gives

$$(h_d - 1) < \alpha_i^d \leqslant h_d$$

which implies that $\alpha_i^d = h_d$ since it is an integer value.
EXAMPLE 2 : STAR NET (one hop only)
Consider figure (3) below.

We thus have $h_d = 1$, T_{h_d} = N-1; and relation (7) gives:

$$0 < \alpha_i^d \leqslant N\text{-}1$$

which implies that any numbering of the PRUs, such as α_i^d = i, would be acceptable.

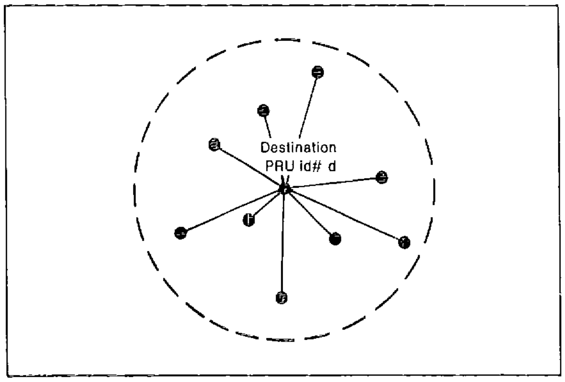

FIGURE 3
One hop star net

In general we can easily see that :

$$\max T_{h_d}=1 = N-1$$
$$\max T_{h_d}=2 = N-2$$
$$\vdots$$
$$\max T_{h_d}=i = N-i$$

and that for the particular case where :

T_{h_d} = T a fixed value for all hops h_d, we obtain :

$$T \leqslant N \text{ and } T * (h_d-1) < \alpha_j^d \leqslant T * h_d \quad \text{for all d in } \Phi . \qquad (8)$$

A very important case is when $T_{h_d} = N$. In this case (7) becomes:

$$N * (h_d-1) < \alpha_j^d \leqslant N * h_d \qquad (9)$$

which leads to our defining equation for the calculation of the α_j^ϕs for a given destination d :

$$\alpha_j^d = (h_d-1) * N+j \qquad (10)$$

For all j in Φ
and all d in Φ
with $\alpha_d^d = 0$

Let us now apply this algorithm to a general stationless multihop packet radio network.

Let :

$\Phi = \{1,2,3,4,5,6,7,8,9,10\}$
N = 10 PRUs distributed in space as shown in figure (4) below. The radio connectivity between these PRUs is represented by the dashed lines; two PRUs are in radio connectivity if there exists a dashed line connecting them.

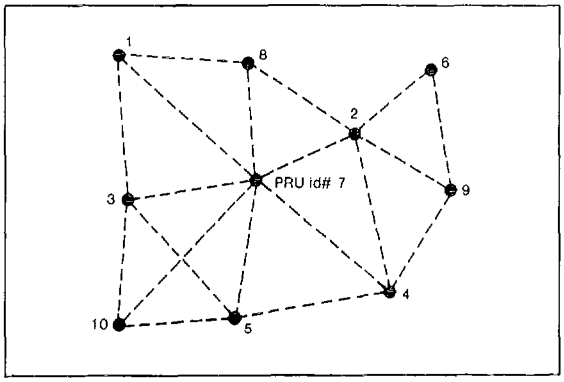

FIGURE 4
Stationless multi-hop PRnet

Let us first take PRU ID # 9 as a given destination and direct all the other PRUs in the network to it.

1. PRU 9 sends a packet called a mapping packet "MP" asking all the other PRUs in the net to direct themselves to it.

   "MP" = {originating PRU ID #, 0 ,originating PRU ID #}

   Figure (5) below sketches the propagation of the "MP" message generated by PRU 9. In this figure every PRU i is shown along with (i,α_i^9).

2. This broadcast packet will be received by all the neighbors of PRU ID #9, that is, PRU 6, PRU 2 and PRU 4. These PRUs perform the following actions:

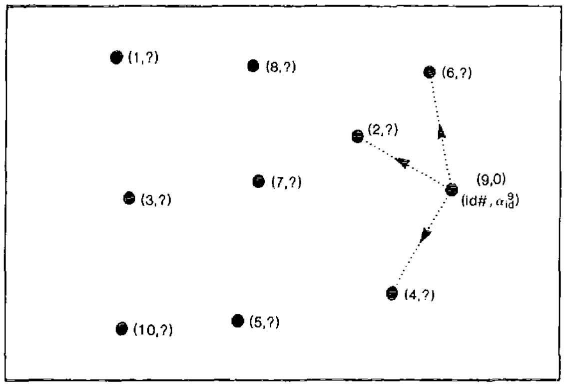

FIGURE 5
Generation of "MP" message

   a. Using equation (10) they compute their α_{ID}^9. Therefore, we have:
   $\alpha_6^9 = 0 \times 10 + 6 = 6$
   $\alpha_2^9 = 0 \times 10 + 2 = 2$
   $\alpha_4^9 = 0 \times 10 + 4 = 4$

   b. establish the links given by (1) as shown in figure (6) below:

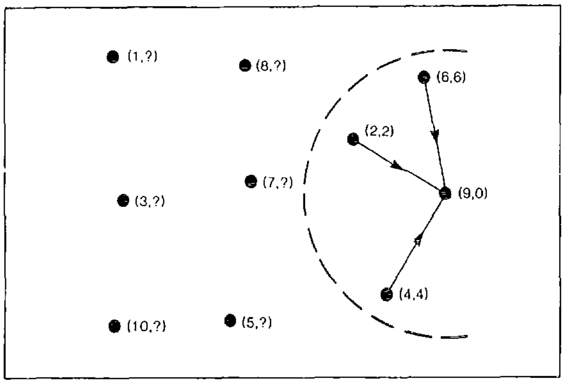

FIGURE 6
First establishment of layer 1 connectivity

   c. Upon defining its α_{ID}^9, a node broadcasts a routing packet defined as follows:
   "RP" = { sender PRU ID#, α_{ID}^9, destination PRU ID# }

   EXAMPLE :
   PRU 2, upon defining its $\alpha_2^9 = 2$ broadcasts the following "RP" = {2,2,9}. This packet will be received by all the neighbors of PRU ID # 2, that is, PRU ID #'s 9,6,4,7 and 8.

3. Upon defining its value for a given destination ID # , each PRU broadcasts an "RP". Thus upon defining its α_2^9 , PRU ID #2 broadcasts an "RP" which will be received by all its neighbor PRUs; and likewise for PRU ID #'s 4 and 6. At this point, all the links at a distance of one hop denoted by layer 1, from the destination d are defined. See figure (7) below:

4. In the same manner layer 2 is defined as shown in figure (8) below. Note that the hop number is not sent in the routing packet but instead could be calculated at the receiving PRU by the following formula:

$$h_d = (\alpha^{d}_{senderID\#} - \text{sender PRU ID \#}) / N + 2 \qquad (11)$$

For example, PRU 7 upon receiving an "RP" message from PRU 2, its h_d is then:

$$h_d = (2\text{-}2)/10 + 2 = 2$$

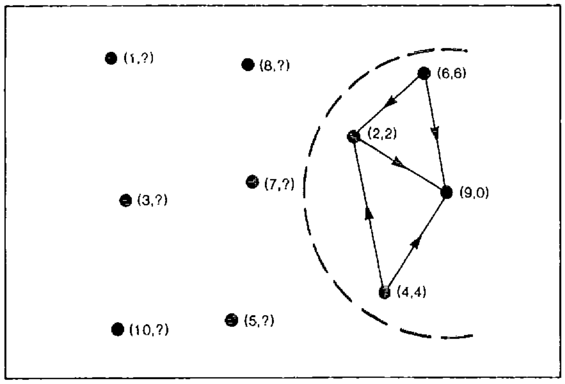

FIGURE 7
Establishment of layer 1 connectivity

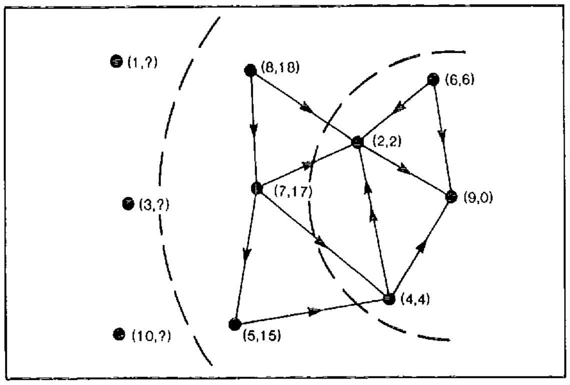

FIGURE 8
Establishment of layer 2 connectivity

5. Finally, when PRU ID #'s 1,3,and 10 broadcast "RP" the set $S_{d=9}$ will be completely defined. Figure (9) below shows the set S_9 .

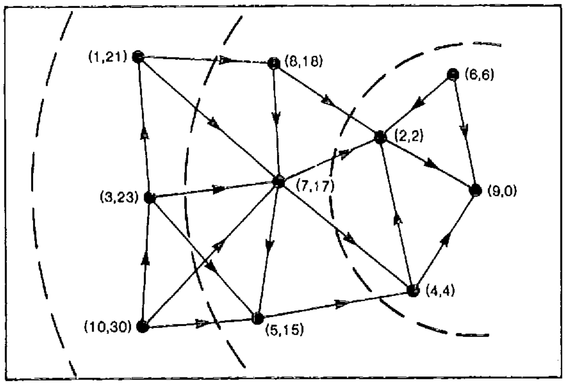

FIGURE 9
Establishment of the topology S_9

We notice a very nice property of this algorithm. It layers the set S_d, for every d in Φ into tier-rings centered at PRU d. Our goal is to define the whole set Ψ. This is obtained by letting each PRU ID # i in Φ sends an "MP" to direct the rest of the network to itself and thus obtain S_i. In general the algorithm is stated as follows:

ALGORITHM : *(12)*

1. All the α^{d}_{ID} for all d and ID in Φ are initialized to infinity.
2. Every PRU in Φ sends an "MP"
3. Upon receiving an "MP" or an "RP" for a given destination PRU d, a PRU performs the following actions :
   a. Using equation (10) it computes its corresponding value α^{d}_{ID} for this destination d , and retains (i.e., updates) it if it is better (smaller) than the one it already has for that destination.
   b. Using (1) it establishes the links.
   c. Broadcasts an "RP" for that destination PRU d if its α^{d}_{ID} is updated.

As mentioned earlier, once we have the set Ψ we define the primary routes in Ψ for all the source-destination pairs in the network according to formula (4). The alternate routes between a source PRU and a destination PRU are defined to be the directed paths between these PRUs not including the primary routes. Classification of alternate routes could be done according to the number of hops and quality of the links.

Once again, due to the broadcast nature of the channel in packet radio networks, the transmitting PRU has to specify in the header of the packet to be transmitted the identity of the receiving PRU. The sequence of receiving PRUs along the path between the source and the destination PRUs defines the primary route to be taken by the packet. This primary route is then the best route between the source and destination PRUs according to our metric defined by formula (3). Note that this metric assures that the primary routes are the shortest routes to the destinations. Nevertheless, others practical considerations could be introduced in this metric to account for other specifications.

EXAMPLE :

Let us take our previous stationless multi-hop packet radio network example. Figure (10) below shows the set of primary and alternate routes in S_9 between the different source-destination pairs in Φ. The primary routes are shown by heavy links .

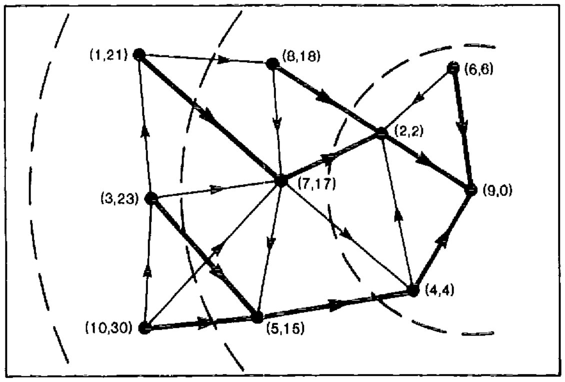

FIGURE 10
Primary and alternate routes in S_9

Let :

$S_{d,primary}$ denote the tree in S_d formed by the union of primary routes in S_d

And $\Psi_{primary} = \{ S_{i,primary} \; / \; \text{PRU ID \# } i \in \Phi \}$

PROPOSITION 3 :

$\Psi_{primary}$ forms the set of minimum weight directed shortest path trees and minimum weight directed spanning trees in Ψ.

PROOF :
The proof of proposition (3) follows directly from proposition (2) and statement (4).

PROPOSITION 4 :

The tier-ring routing algorithm defined by (11) is optimal for stationary networks.

PROOF :
If the network is stationary, it is easy to see that (12) is optimal according to equation (3).

We notice that the algorithm defined by (12) has a complexity (i.e; number of "MP" and "RP" messages) of the order of $O(N^2)$ which is the same order of magnitude as what it takes to construct any N arborescences. Algorithm (12) is a distributed algorithm appropriate for packet radio networks that gives the minimum weight directed shortest path arborescences according to the metric given by (3) and also provides all the possible alternate routes in the network between the different source-destination PRU pairs. Note also that control messages (i.e., "MP" and "RP") exchanged between PRUs are very short messages and that the algorithm is very simple.

NETWORK IN OPERATION WITH MOBILITY HANDLING

So far we have defined a distributed algorithm that gives us the network topology Ψ (i.e., the set of PRUs along with their radio connectivities). We have seen that Ψ is formed by the superposition of the N subsets S_d where d is a PRU in Φ. Every subset S_d is represented in a tier-ring fashion, where the PRU d is the center of these tiers. Our task, now, is to maintain a *useful knowledge* of the topology Ψ during the network operation where connectivity changes are frequent and any PRU in Φ can be mobile. We believe that maintaining a *complete and exact* knowledge of Ψ at any time is impractical, that is, maintaining constantly a complete knowledge of the layers in each S_d, for every d in Φ is virtually impossible. Moreover, trying to maintain a complete and exact knowledge of Ψ by relying on periodic routing information reports is ridiculous in such an environment where topological changes are frequent. Periodic routing reports can describe the status Ψ of the network at the end of the last period, but not *the actual status.* Decreasing the period length only results in jamming the network. Nevertheless, having an accurate knowledge of a *subset* of Ψ is enough to operate the network as far as this subset of Ψ is an irreducible directed graph. A graph is said to be an irreducible directed graph if every PRU in Φ has at least one directed path to every other PRU in Φ. We denote by Ψ_{irr} any irreducible directed subgraph of Ψ .
We notice the following :

1. We say that $\Psi_{irr,1}$ is included in $\Psi_{irr,2}$ if and only if $\Psi_{irr,1}$ is an irreducible directed subgraph of $\Psi_{irr,2}$. In this case we say also that $\Psi_{irr,2}$ is a *better knowledge* of Ψ than $\Psi_{irr,1}$.

2. It may happen that during the network operation for some period of time that a subset of PRUs Φ_{idle} of Φ are not addressed (i.e., as source or destination) or involved (i.e., as intermediate repeaters) in the traffic handling. It is therefore obvious that exact knowledge of the connectivity of these PRUs is of no concern for the network operation during that period of time. What we need then, is an Ψ_{irr} where only the PRUs in (Φ - Φ_{idle}) are considered. We denote this Ψ_{irr} by Ψ'_{irr}.

EXAMPLE :

Let us consider a stationless multi-hop packet radio network with one mobile PRU and the rest of the PRUs are stationary. It is obvious that if this mobile PRU is not addressed or involved in the traffic handling for a certain period of time, we don't need to capture its movement. As soon as this mobile PRU is involved , we have to establish its connectivity with the rest of the network.

Our task is to provide at any time of the operation of the net the best possible Ψ'_{irr} and to react fast enough in a distributed fashion to account for the connectivity of mobile PRUs *when and only when* they are involved in the traffic handling, *without jamming* the network with control traffic.

We have defined for each PRU i in Φ for every destination PRU the set of non negative integer values, that is α_i^d for all d in Φ. We have also defined for each PRU i in Φ the set of the different routes to every destination PRU in the network. Thus for PRU ID # i we defined the list* :

$$\begin{array}{cccc} y^i_{11} & y^i_{12} & \dots & y^i_{1k1} \\ & & \vdots & \\ & & \vdots & \\ & & \vdots & \\ y^i_{j1} & y^i_{j2} & \dots & y^i_{jkj} \\ & & \vdots & \\ & & \vdots & \\ & & \vdots & \\ y^i_{N1} & y^i_{N2} & \dots & y^i_{NkN} \end{array}$$

Where entry j in this list gives *the ordered set* of neighbors of PRU ID #i to construct the routes from PRU ID # i to destination PRU ID #j. That is y^i_{j1} is the first node on the primary route from PRU ID # i to PRU ID # j, y^i_{jn} is the first on the nth ranked alternate route from PRU ID # i to destination PRU ID # j. We note that kj defines the number of helpers for PRU ID # i toward destination PRU ID #j. These helpers are a subset of the neighbor PRUs of PRU ID # i.

Let :
$H_{i,d}$ denote the number of helpers of PRU ID # i for the destination PRU ID # d.
X_i denote the number of neighbor PRU 's for PRU ID # i.

In general we have : $H_{i,d} \leqslant X_i$ and

If $H_{i,d} = X_i$ then PRU ID # i has no *incoming* link in the topology S_d.

If $H_{i,d} = 0$ then PRU ID # i has no *outgoing* link in the topology S_d and cannot either transmit or relay a packet to destination PRU ID # d. If PRU i is in (Φ - Φ_{idle}), Ψ'_{irr} is no longer irreducible and *an immediate action* has to be taken.

Given these sets of information, every node in the network has enough information to operate and communicate with the rest of the network. At any time a given link (outgoing link) can be declared down if communication over that link becomes impossible or if the other endpoint PRU of that link (the neighbor) acquires a higher rank value such that the link becomes incoming instead of outgoing link for our tagged PRU . At any time, if a PRU i upon transmitting or forwarding a packet, finds itself without outgoing links, that is $H_{i,d} = 0$, it undergoes a reversal action of all its incoming links. We next describe the reversal action by using two methods first mentioned in [12] for the case of central (control and traffic) station packet radio networks.

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*We are not considering the data structure of this list.

Full reversal method : *(13)*

1. For each S_d, d in Φ,

2. At each iteration, each PRU i in Φ other than PRU d, such that $H_{i,d} = 0$ reverses the directions of all its incoming links in S_d

This algorithm provides a sequence of Acyclic Directed Graphs (ADGs) and terminates when an ADG destination d oriented is obtained for every PRU d in Φ. Figure (11) below gives an example of the sequence of the successive iterations of this algorithm. We mark by R the nodes that reverse at each iteration.

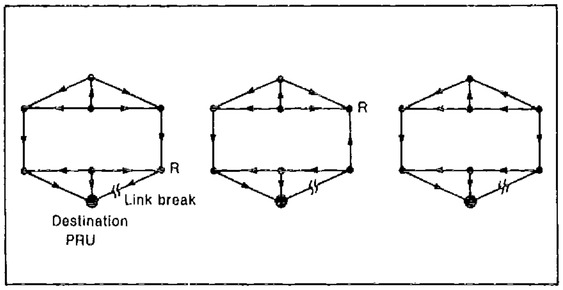

FIGURE 11
Full reversal method

Partial reversal method : *(14)*

For each S_d, d in Φ,

1. Every PRU i other than d keeps a list of its neighbor PRU j that has reversed the direction of the corresponding link (i,j) in S_d .

2. At each iteration, each PRU i that has no outgoing link in S_d reverses the direction of links (i,j) in S_d for all j that do not appear on its lists and empties the lists. If no such j exists, PRU i reverses the direction of all incoming links in S_d and empties the lists. Figure (12) below gives an example of the sequence of successive iterations of this algorithm, starting with empty lists.

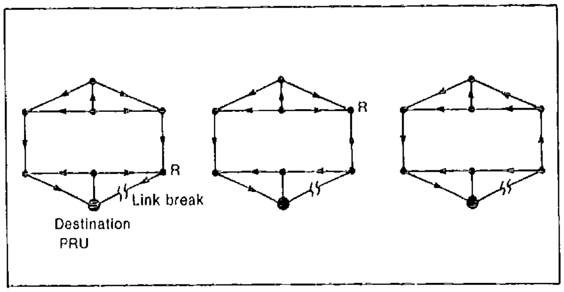

FIGURE 12
Partial reversal method

These two methods have some very nice properties :

1. If the graph (i.e; topology) S_d is connected then the reversal process will terminate after a finite number of iterations at a destination d oriented ADG.

2. The directed graph generated at each iteration is acyclic.

3. The direction of any link in S_d between two PRUs that have a directed path to the destination PRU ID # d in the initial S_d will never be reversed.

The proof of these properties for both methods is given in [12]... The third property indeed makes the reversal action very powerful in packet radio network environments. It shows an important stability property and states that regions not affected by topological changes never participate in the reversal action. More precisely, a PRU i such that $H_{i,d}$ is non-zero for a destination PRU d will never undergo a reversal action in S_d, and if for all d in Φ, $H_{i,d}$ is non-zero then PRU i never undergoes a reversal action in Ψ. The reversal action is an asynchronous action that can be taken at any time by a PRU i when it runs out of outgoing links in any S_d for any destination PRU d. This allows us to establish and reinitialize routes when and only when needed.

In this paper, we consider only the full reversal method for the reversal action.
Let us now state this reversal action formally :

REVERSAL ACTION : *(15)*

a. A PRU ID # i has no outgoing link in the set S_d, d in Φ if and only if for all PRU ID # j neighbors of PRU ID# i we have :

$$(i,\alpha_i^d) < (j,\alpha_j^d)$$
i different from j
that is $H_{i,d} = 0$

b. Any PRU ID #i, i in Φ, before transmitting or forwarding a packet, destined for PRU d has to undergo step c if its $H_{i,d} = 0$

c. At the kth iteration such a PRU ID # i increases* its $\alpha_i^d(k)$ to:

$$\alpha_i^d(k+1) = \max\{\alpha_j^d(k) \ / \ j \text{ is a neighbor of } i\} + 1$$

Finally, we require that every PRU broadcasts periodically a short packet to indicate its existence. This could be of a great help to update and maintain the network topology Ψ .

CONCLUSION

We have defined a distributed routing algorithm that is appropriate for stationless multi-hop packet radio networks. This algorithm has a complexity (i.e; number of control messages) of the order of $O(N^2)$ where N is the number of PRUs in the network. It provides the minimum weight directed shortest path trees rooted at each node in the network and gives all the possible alternate routes between all the source-destination PRUs. These alternate routes are very important to cope effectively with link failures and route breaks. The algorithm also has the nice property of layering and presents the network for a given destination PRU as a set of tier-rings centered at this destination PRU. This tier-ring structure is optimal for stationary networks.

Moreover, this algorithm, along with the reversal action algorithm, presents an efficient method to handle PRU mobility and frequent topological changes, and has the following properties :

1. A new coming PRU ID# n is easily connected to the network. It only needs to broadcast a mapping packet "MP" and initialize its $H_{n,d}$ to zero for all PRUs d in the network.

2. A PRU undergoes the reversal action for a given destination only when it runs out of outgoing links for that destination. Routes are established only when needed. The

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* $\alpha_i^d(k)$ represents the α_i^d at the kth iterattion.

reversal action is, in fact, rarely performed by PRUs due to the multitude of alternate routes and the dynamic behavior of the primary routes between any source-destination PRUs. Stationary regions of the network, where directed paths to the destinations exist, will never participate in the reversal action algorithm. This gives an important stability property to our algorithm. In particular, if the network is stable, with no topological changes and no PRU failures, the reversal action algorithm will never be performed.

3. The algorithm is very reliable in the sense that it assures that a packet launched into the network will reach its destination as long as the network does not become disconnected (i.e., PRU without neighbors).

4. The algorithm is also applicable to station and multi-station packet radio networks. A central (control and traffic) station network can be viewed as a stationless network where the central station is the only destination. Labeling the PRUs by stations and communication between subnets in a multi-station environment could be easily and effectively performed by the algorithm. This provides us potential features for merging stationless and multi-station networks.

Further studies and simulations have to be carried on to evaluate and characterize the behavior of the algorithm with changing degrees of PRU mobility and network topology constraints. The link weight, although open to accommodate any PRU connectivity features, has to explicitly include and reflect practical considerations such as link qualities, degree of mobility of the PRUs, neighborhood congestion, etc., to best ranck the different outgoing links emanating from a PRU toward a given destination in the network. The partial reversal method, although requires more storage and parameters computation than the full reversal method and needs less control traffic exchange between PRUs, could result in larger average path lengths. Studies to compare the efficiency of the full reversal and partial reversal methods in such mobile packet radio networks are being investigated.

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