THE SURVIVABILITY OF THE PACKET RADIO NETWORK

BY

Dr. Kenneth S. Schneider
SIGCOM Engineering
134 Birchwood Park Drive
Jericho, N.Y. 11753

Dr. Yao H. Chu
Information Sciences
20 Blanchard Drive
Northport, N.Y. 11768

ABSTRACT

Survivability has always been an issue of consideration in the development of the Packet Radio Network. It has caused its development to evolve from the "Station Oriented Packet Radio" to the Stationless Packet Radio Concept. In this paper we begin by describing both concepts. This is followed by a comparison of the survivability of various aspects of network performance in both concepts. In particular, we look at the degradation of the population of radios supported, the number of hops required for route set-up and the capacity utilized for route set-up, as stations fail. Mechanisms for making Station Oriented Packet Radio more survivable are presented. Finally, we introduce an alternative packet radio concept which, from a survivability viewpoint appears more attractive than either of the other concepts.

INTRODUCTION

We assume the reader has some general familiarity with the techniques of packet switching and some specific familiarity with the packet radio network. Briefly, the network concept originated with DARPA. It is currently undergoing development jointly by DARPA and the U.S.Army. The packet radio network has the intended goal of providing reliable ground-to,ground and ground-to-air communications in the tactical environment. The essential focus of the network is the delivery of bursty messages. For the most part, the messages are expected to consist of data. However, there has been some effort at using packet radio to deliver digitized voice.

The packet radio network has a number of characteristic features and it will be worthwhile enumerating them. Its topological structure is strictly distributed. The network must have high capacity, be jam resistant and serve mobile users. Effective end-to-end reliability is to be attained by appropriate modulation/coding and the use of robust routing protocols. Needless to say, the issue of network survivability has always been of interest in the ferreting out of the network concepts.

On this last point we must say more. The above question of survivability has, in fact driven segments of the network development. Initially, there was what should be called "Station Oriented Packet Radio." Special network elements termed "stations" were utilized. The stations allowed the quick determination of attractive routing paths. However, the essentially hierarchical structure which stations seemed to imply posed problems with respect to network survivability. The stations were critical elements whose failure significantly affected network performance. There was a definite sacrifice of survivability for transport reliability. The unattractive survivability features of this packet radio concept led to the evolution of "Stationless Packet Radio." Here survivability improved but at the cost of an inefficient utilization of network capacity. This inefficiency translated into a lower throughput and a smaller population of packet radios supported.

In the sequel we shall describe in more detail Station-oriented Packet Radio and Stationless Packet Radio. This will be followed by a comparison of the survivability aspects of both of these concepts with respect to the number of radios supported, number of hops required for route set-up and the capacity overhead required for routing. Finally, we shall offer an alternative packet radio concept which we feel is more attractive than either of the previous two concepts, at least from a survivability/performance point of view.

Brevity does not allow us the opportunity to reference the plethora of excellent work which has been carried out in the development of the packet radio

CH1909-1/83/0000-0274$1.00©1983IEEE

network. Referencers 1-3 will have to suffice as representatives of the literature which we have used in preparation of this paper.

STATION ORIENTED PACKET RADIO

To be absolutely accurate, the correct term for this concept is "Multi-Station Packet Radio." However, we would like to emphasize more the station aspect than any pre-set label. In order to discuss this initial packet radio development we must describe the architecture and protocol structure associated with it.

Station Oriented Packet Radio had the following architectural features: network initialization and station entry, routing table and route determination, labeling and relabeling of packet radio elements, network expressway and direct linking of neighboring stations. Details are now given although we must be rather concise. In Station Oriented Packet Radio the radios initially announce their existence via transmission of "Radio-On-Packets" (ROP). Summary routing information tables reside at each station. "Neighboring" tables reside at packet radios. These allow a route set-up packet to gather end-to-end information and establish a route. Each station compares all possible routes and selects the one attractive candidate. Each station sends out labeling packets to the various packet radios. These allow the packet radios to determine connectivity to the different stations. Labeling information is time critical and consequently relabeling is executed on a regular basis. A network expressway consisting of a fixed or slowly changing path between stations allows station-to-station traffic to avoid the normal network route contention procedures. Neighboring stations can be directly linked on the expressway.

This network concept utilizes a protocol structure essentially operating as follows. The packet radios are assumed interrupt driven. Generally, this is accomplished by two (2) types of external events: either by a packet received via the radio path or a packet received over the 1822 (host) interface. The interrupt can also be driven by an internal event, a " time out."

Station Oriented Packet Radio has a number of advantages balanced by disadvantages. On the positive side the multi-station operation provides redundancy among functionally identical stations in packet radio labeling. Knowledge about stations is transparent to end-user devices. The packet radio element is simple, with stations having to assume the major responsibilities and intelligent functions. On the negative side, survivability, in terms of the presence of critical nodes and links, appears to be unattractive. The protocol which is utilized (CAP 6) contains too many special purpose packets, thus contributing to excess network overhead. (Ref. 4) Likewise, this overhead compromises network survivability by "burning up" capacity. Link quality between stations and packet radios is critical for adequate network operation. At the same time station-to-radio links are critical, thus presenting an obvious weakness from the viewpoint of survivability. The multi-station network protocol has to interface with strayed packet radios which have not been labeled. In total, Station Oriented Packet Radio presents simple and robust operation at the cost of obvious "survivability" weaknesses.

STATIONLESS ORIENTED PACKET RADIO

As with Station Oriented Packet Radio, we describe the associated architecture and protocol structure.

In contrast to Station Oriented Packet Radio, Stationless Packet Radio has an absolutely non-hierarchical structure. All of the radios are identical in both their hardware and software complements. All radios have equal status: each radio has the same degree of control over network operation. An immediate consequence of this structure is the absence of critical nodes in stationless packet radio. This, of course, is an attractive network survivability feature. Route finding is accomplished in the following manner. A route set-up packet is sent out only via a broadcast mode. The route set-up packet propogates through the network with copies of it multiplying with the propogation. This continues until one or more copies of this packet reaches the intended destination. As the selected packet travels back to the source from its destination it enters into enroute-PR memories, the "route history." This method of route determination is in marked contrast to Station Oriented Packet Radios. We elaborate on this below.

Stationless Packet Radio is able to execute routing without the prior knowledge of the global network connectivity needed in Station Oriented Packet Radio. Again, this is another positive feature with respect to network survivability.

We must emphasize though, that the route set-up packet is utilized in both Station Oriented and Stationless Packet Radio. The key difference is that in the former the route set-up packet utilizes pre-stored information at the stations (prior knowledge). In the later, this pre-stored information is absent. Yet, in both cases the route set-up packet reverses its direction of propagation and always returns to the source with the needed routing information.

Stationless Packet Radio utilizes a protocol (CAP 7) structure which differs considerably from that employed by Station Oriented Packet Radio. Now packets are received only via the radio path. While the interrupt can still be driven by an internal time out, we now do not have "stations." Consequently, there is no 1822 (host) interface. Stationless Packet Radio does not employ the "prior knowledge" utilized in Station Oriented Packet Radio. As a consequence, the incidence of packet collision is much higher. The protocol structure must, of necessity, be more complex in order to resolve the greater chance of collision.

SURVIVABILITY TRADEOFFS

We are now in a position to consider the survivability of Station Oriented Packet Radio versus that of Stationless Packet Radio. It is best to start by admitting that the term "survivability" is in itself, ambiguous. As a result, the consideration of survivability is difficult to approach from the general analytical view where quantitative results are usually desired. We have not been able to avoid this dilemma. Our approach has been to hypothesize at the outset that any universal measure of network survivability (as bit error rate is a universal measure of transmission integrity) is beyond our ability. Hence, we cannot quantify conclusions by means of a single figure of merit. Instead, we have deemed it fit to focus on several different aspects of network performance and phrase these accepted performance measures in terms of survivability criteria. Our approach to the entire issue of survivability will be that of focusing on three specific aspects of performance. We will consider how each of these aspects survive the failure of the critical elements in Station Oriented Packet Radio; namely the stations. This surviving performance will be compared to that of Stationless Packet Radio, which is supposedly more robust with respect to failure. The three (3) performance aspects to be considered are:

1) The number of packet radios that can be supported, 2) the number of hops required for route set-up, and 3) the capacity utilization required for route set-up.

The first aspect of network performance so considered is that of "graceful" degradation. To be specific, suppose that there are a total of "P" packet radios and a total of "S" stations in Station Oriented Packet Radio. "P" and "S" are both powers of 2. The following question is now asked. What is the number of "p" packet radios that can be supported when only "s" stations have survived. We ask this question both for Station Oriented Packet Radio and Stationless Packet Radio. We also note that survival here may be after an attack (physical or electromagnetic) or after some non-hostile reliability problem (e.g. lightning).

Clearly, for Stationless Packet Radio, the number of radios that can be supported is independent of the number of stations surviving (they do not exist anyway in the system). Yet if we are careful and put an equal throughput constraint on both packet radio concepts, we should in fairness have the constant value of p less than the Station Oriented maximum P, and instead equal to some smaller value P' that is,

$$p \neq P \quad \text{but} \quad p = P'$$

for all s where

$$P' < P$$

With Station Oriented Packet Radio an analysis of how p varies with s depends upon the way in which radios are assigned to stations and on the sequence in which stations "fail." Clearly, the possibilities are endless. We have decided to consider three representative station assignment rules in assessing survivability. These rules will be referred to a "Linear," "Duplicate" and "M-Group." The survivability results for each are provided below.

Linear-Here each radio is assigned to one and only one station. Furthermore, exactly P/S radios are assigned to each station. For simplification in the sequal we can identify the radios assigned to station J, J = 1...S by the symbols

$$R_{J1}, R_{J2}, \ldots R_{JN} \qquad (1)$$

where N = P/S

Ignoring the integer problem for p and s, the reader may clearly note that

$$p \approx (P/S)\, s \qquad (2)$$

independently of the sequence in which stations fail. This is plotted in Figure 1.

Duplicate-Here each radio is assigned

to two (2) different stations. In order to make the analysis most transparent we now assume that radios

$$R_{J1}, R_{J2}, \ldots R_{JN} \qquad (3)$$
$$R_{(J+1)1}, R_{(J+1)2}, \ldots R_{(J+1)N}$$

are assigned jointly to stations J and J + 1, where J = 1, 3,...S-1. From the point of view of survivability there will be a "best" and "worst" "p" vs "s" curve depending upon the failure sequence. The best curve results when the first (S-1)/2 stations to fail are given by labels J = 1,3,...S-1, or some permutation of them or some permutation of some station set formed by increasing each label by 1. With such a failure sequence we have

$$p \approx P, \text{ for } s \geq S/2$$
$$p \approx 2s\,P/S, \text{ for } s \leq S/2 \qquad (4)$$

That is the redundancy offered by the duplicate assignment helps , provided network performance is not really affected by failure. The worst curve results when the station failure sequence is given by J = 1,2,3...S or some permutation thereof where pairs J,J+1 (J odd) are carried in the permutation. With such a failure sequence "we lose" 2 P/S radios with each pair of stations lost. The relation is then

$$p \approx \left(\frac{P}{S}\right) s, \text{ for all } s \qquad (5)$$

This is the same as the result with the linear assignment rule. The "best" and "worst" curves bound performance and are shown in Figure 2.

M-Group-This is merely a direct generalization of the Duplicate rule. Here each radio is assigned to M different stations where, M is an integer. Again, in order to make the analysis most transparent, we assume that radios

$$R_{J1}, \ldots, R_{JN}$$
$$R_{(J+1)1}, \ldots, R_{(J+1)N} \qquad (6)$$
$$\vdots$$
$$R_{(J+M)1}, \ldots, R_{(J+M)N}$$

are jointly assigned to stations J,J+1...J+M, where J=1, J=M+1, J=2M+1...

The analysis parallels that of the Duplicate rule. There is a "best" curve and a "worst" curve. We leave out the details of the analysis for brevity sake. The "best" curve is given by

$$p \approx P, \text{ for } s \geq S/M$$
$$p \approx M\,P/S, \text{ for } s \leq S/M \qquad (7)$$

The "worst" curve is the performance of the linear rule given by (8)
These bounding curves are shown in Figure 3.

$$p \approx (P/S)\,s, \text{ for all } s \qquad (8)$$

By observing Figures 1 through 3, we can draw some ready conclusions regarding the survivability of Station Oriented Packet Radio versus that of Stationless Packet Radio. To begin with, in the "worst" circumstances the redundancy used by the M-Group type rules may not be able to improve survivability at all. The bounding "worst" curves are the same as the performance of the Linear. Consequently, the additional protocol structure which represents the "expense" of the M-Group rules for Station Oriented Packet Radio may buy nothing in terms of improved survivability. However, the conditions for improvement as measured against the guaranteed P' for Station Oriented Packet Radio depend so much on the exact values of P, P' and the value of s, that no definitive argument can be made for the cost burden on the basis of survivability. The final line on this issue is that Stationless Packet Radio has to be considered more attractive from a survivability point of view, than even a more complex Station Oriented Packet Radio.

As a second issue we consider survivability from the view of the amount of time required for route set-up. In both Station Oriented Packet Radio and Stationless Packet Radio this is generally equated to the number of hops that a route set-up packet must traverse during the set-up procedure.

Consider, the situation with Station Oriented Packet Radio. Suppose a route is to be set-up between some originating node and some destination node. We assume, that all stations are present (have survived) between these nodes and in fact that the number of these stations is equal to s"-1. The situation is illustrated in Figure 4. In this situation the number of hops required for route set-up, Hs, grows as

$$H_s \sim 2s'' \qquad (9)$$

Here, the factor of 2 accounts for the return path of the packet to the originating node.

Now consider the same situation but with Stationless Packet Radio. Stations aren't present. Yet, we can consider the totality of packet radios as having been grouped into what might have been previously classed as station service areas, there being s" such areas in the example of present interest. We assume that in route set-up the packet traverses, on average $\approx n$ packet radios per serving area. The number of hops required for route set-up, H_L, grows here

$$H_L \sim 2 n s'' \qquad (10)$$

An obvious comparison of equation (9) and (10) indicates the advantage of Station Oriented Packet Radio over Stationless Packet Radio in route set-up time. Now let us examine what happens with this advantage as the critical elements of Station Oriented Packet Radio, the stations, fail. That is, let us see what happens to the survivability of this performance advantage.

For the purposes of simplifying the discussion, direct attention to Figure 4. Assume that the station failures enroute are isolated. In other words, consecutive stations do not fail. Furthermore, let us assume that when a station does fail, the route set-up packet traverses the station serving area in the same manner by which it does in the Stationless case. In this situation if Q stations survive we have:

$$H_S \sim 2\left(Q + (s''-Q)n\right) \qquad (11)$$

The reader may verify from (11) that when Q = s", i.e., complete station survivability, that performance is the same as given by (9). On the other hand when Q = 0, i.e., no stations surviving, the performance is the same as given by (10). What we have is a graceful degradation of Station Oriented Packet Radio to Stationless Packet Radio, as stations fail. Consequently, we have to consider Station Oriented Packet Radio more attractive here from a survivability viewpoint. It can adapt its performance to the dynamic changes in network connectivity. Stationless Packet Radio cannot.

As a final issue in this section we consider the overhead required for route set-up in Station Oriented Packet Radio and Stationless Packet Radio. Both packet radio concepts use up network capacity in order to execute their routing protocols. The utilization of capacity, and consequently network efficiency, is affected by the "survivability" of the network.

In Station Oriented Packet Radio, route set-up is carried out by the transmission of a routing packet on the direct link between adjacent stations on the fixed route. Using our previously introduced nomenclature, suppose a route being set-up traverses s" stations. Suppose furthermore, that with each of these stations present (surviving) a total of "C" units of capacity is used up on each direct station-to-station link in transmittal of the routing protocol. The total network capacity, C_S then used up in route set-up grows as

$$C_S \sim 2 s'' C \qquad (12)$$

We have allowed here for the return of the routing packet to the originating radio.

On the other hand, Stationless Packet Radio carries out route set-up in a broadcast mode. In a "pessimistic" case, the route set-up packet could "visit" every radio in the network, thus using up a capacity C_L which grows as:

$$C_L \sim 2PC \qquad (13)$$

In an optimistic case one might be able to modify the routing protocol so that broadcast only occurs in the "station areas" covered by the s" stations, if present. There are $(P/S)s''$ radios in these areas in which case we would have:

$$C_L \sim 2\,(P/S)\,s''\,C \qquad (14)$$

Putting the above together, one could set the following limits to

$$2P\frac{s''}{S}C \le C_L \le 2PC \qquad (15)$$

Combining this with the case of Station Oriented Packet Radio, with all stations surviving we have:

$$\frac{P}{S} \le \frac{C_L}{C_S} \le \frac{P}{s''} \qquad (16)$$

Since, P in general would exceed "S" by well above a factor of 2, the above inequality shows the essential capacity inefficiency of Stationless Packet Radio as compared to Station Oriented Packet Radio for route set-up when all stations survive.

Now let us change the situation and assume that only Q of the s" stations do survive. We will make the situation somewhat easy to address and assume that the stations are isolated (not adjacent or otherwise contiguous). Route set-up for Station Oriented Packet Radio does not fail completely in such a situation. Rather, one could use the Stationless Packet Radio type broadcast mode to carry the routing packets back and forth across the failed station service area. With such a "survivability" mode in the routing protocol, we have:

$$C_S \sim 2QC + 2(s''-Q)(P/S')C \quad (17)$$

and consequently...

$$\frac{P\, s''/S'}{Q+(s''-Q)P/S'} \le \frac{C_L}{C_S} \le \frac{P}{Q+(s''-Q)P/S'} \quad (18)$$

Here we see as expected, that when Q=s" we obtain the same result as with total survivability of the stations. This is expected. However, notice the behavior as $Q \longrightarrow 0$. C_L/C_S always exceeds unity. This indicates that the capacity efficiency of Station Oriented Packet Radio as compared to Stationless Packet Radio survives the failure of the critical stations. Here Station Oriented Packet Radio is more attractive from the survivability aspect of network efficacy.

The last two performance aspects, namely number of hops and capacity utilization for route set-up become more crucial in a relatively highly mobile and dynamic network environment. Frequent reestablishment of a route is necessary to provide adaptive routing for data packets. Any route being discovered by the route set-up packet is only useful in the absense of rapid change in the network topology during the travel time of the route set-up packet. Therefore, the time required in setting up packet route has to be much less than the characteristic time of the network. The characteristic time is the amount of time that segments of the network remain mostly unchanged. This time is short in a highly mobile environment, especially with some air-packet radios. This is why we stress the importance in the trade-off analysis of route set-up requirements.

ALTERNATIVE CONCEPT

We will present the alternative concept to the present Multi-Station and Stationless architectures in this section. But before doing that we would like to summarize the advantages and disadvantages of each type as analyzed in the previous section.

Station Oriented Packet Radio is less attractive when one considers the issue of degradation with respect to the number of packet radios supported. As the number of surviving stations go down, the number of supported radios go down in an immediate and proportional manner. Stationless Packet Radio, via its protocol scheme, can be supported independent of the number of stations surviving. On the other hand, Station Oriented Packet Radio is more efficient from the consideration of route set-up, both with respect to set-up delay and capacity utilization. Its survivability can "degrade" gracefully to that of Stationless Packet Radio. Because of the labeling information stored at the stations, the route finding procedure does not have to resort only to the broadcast mode. The broadcast mode is an inefficient way of utilizing network capacity. This problem is even more pronounced if the topology of the network changes rapidly.

We propose an alternative concept which seems to be more attractive than either of the two previous architectures. A description of the attributes of the alternative approach follows:

Identical Radios: There are no "stations" in this approach. All the radios are identical units. This has the advantage from the "survivability" criterion because any radio can thus perform the functions or substitute for other radios.

Pack Leader and Pack Member: Each radio can be either a pack leader or a pack member. The difference between a pack leader role and a pack member role is that a pack leader collects network connectivity information and provides useful routing information to its labeling members.

Pack Leader Declaration: Each radio periodically transmits leader candidate requests along with its Radio-On-Packet (ROP). Any other radio connected with this radio will acknowledge, upon receipt of the message. However, a pack leader or a pack member status is sent along with the reply packet. Only a certain percentage of the packet radios are designated pack leaders. In other words, whether a packet radio can be designated a leader depends on a) a minimum number of packet radios replying, (This ensures the candidate pack leader serves a minimum number of members) and b) the ratio of the total number of replying radios to those that are also pack leaders. This ratio shall not be less than a certain critical number, e.g. 4. (This inplies that on the average no more than one quarter of the population can be pack leaders.) A packet radio is then elected a pack leader when

the above two conditions are met. This packet radio will then carry this information in its Radio-On-Packet (ROP).

Pack Leader Expiration: The pack leader is timed out after a predetermined interval. This interval can be set to reflect the characteristic time of the network, however defined. We do not have to be concerned about the expiration of a pack leaders status because new pack leaders are elected whenever the network needs additional leaders.

With these definitions presented the operation of this alternative concept, "The Pack Leader Concept," can be described quite readily. Basically, it operates in exactly the same manner as Station Oriented Packet Radio but with 1) pack leaders executing the station functions 2) any radio being able to take on the role of pack leader, and 3) a temporal variation in the designation of which radios are labeled pack leaders with such variations being driven by network connectivity conditions.

The reader may readily grasp that Pack Leader Oriented Packet Radio immediately has all of the advantages of Station Oriented Packet Radio from both a throughput and survivability viewpoint. Specifically, Pack Leader Oriented Packet Radio has a graceful degradation of its survivability (as pack leaders fail) with respect to the number of hops required for route set-up and for capacity utilization during route set-up. However, Pack Leader Oriented Packet Radio surpasses Station Oriented Packet Radio with respect to the population of packet radios supported, as pack leaders fail. When stations fail, the population of radios that can be supported decreases in proportion to the number of stations surviving. However, when pack leaders fail, we do not have this proportional decrease in the population of packet radios that can be supported since new pack leaders can be designated to take the place of the ones that have failed. With Station Oriented Packet Radio, equations (2), (4), (5), (7) and (8) provided the relationships between the population of radios supported and the number of stations surviving. With Pack Leader Oriented Packet Radio we can make "p" essentially constant independant of s, the limiting case of M-Group assignment, for high "M". (Of course, this may not hold for all scenarios, but we beleive it to be generally true).

The cost of Packet Leader Oriented Packet Radio is in the increased and identical software/firmware complement for each radio. However, this should be well in the direction of cost improvements through technological trends.

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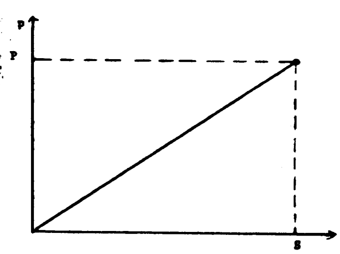

Figure 1: p versus s for the Linear Assignment

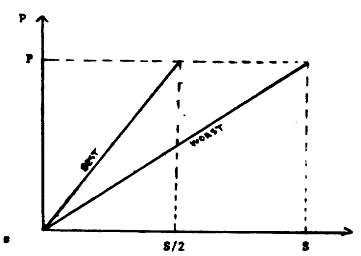

Figure 2: p versus s for the Duplicate Assignment

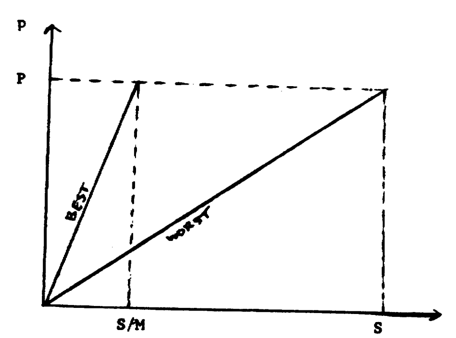

Figure 3: p versus s for the M-Group Assignment Rule

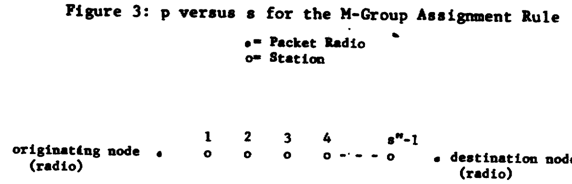

Figure 4: Station Oriented Case s" stations enroute and all surviving