A Multi-Station Packet-Radio Network

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A new structure for packet-radio networks, called the multi-station network, is suggested and analyzed. We describe the salient features of this structure that consists of a large number of nodes and several stations. We then focus on one of the main problems within the suggested structure, the problem of forwarding packets from the nodes to the stations through a shared radio channel. Two basic forwarding schemes are investigated and compared. The classical slotted ALOHA is considered as an access scheme to the shared channel.

Keywords: Multi-Station Network, Packet-Radio, Multiple Access, Slotted ALOHA, Forwarding Schemes.

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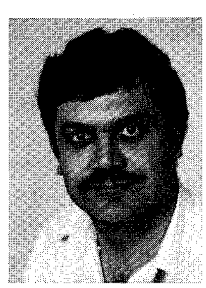
1. Introduction

In this paper we consider an hierarchical packet-radio network that consists of a large number of nodes and several stations. Nodes are geographically distributed, possibly mobile, share a common radio channel and have limited transmission range. Hierarchical structures are natural in many communication systems with mobile users and can be found in numerous civil and military applications where the mobile users (nodes) communicate with or through centers (police patrol cars with their headquarters, ambulances with hospitals, etc.).

We propose a multi-station configuration as an efficient solution for hierarchical packet-radio networks. In the multi-station model the nodes of the network are originators of data and they transmit their data through the shared channel to the stations. The stations might be the final destinations for some packets and can act as repeaters for other packets by forwarding them to their respective destinations (other stations or nodes). Accordingly, we distinguish between the following three communication problems: (i) the node-to-station communication; (ii) the interstation (station-to-station) communication; (iii) the station-to-node communication. Note that the three problems need not be handled within the same domain and by using the same protocols.

We focus mainly on the first communication type, i.e. the mechanism used by the nodes to



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forward their packets to the stations. For the latter two communication types we assume that they are treated somehow by respective protocols that do not interfere with the node-to-station communication protocols. In this paper we assume that the station-to-node communication is conflict free. For instance, in practical situations, when the number of stations is comparatively small, the interstation communication might be solved by preassigning the channel between stations (FDMA, TDMA), as they are concentrators and their traffic is not bursty. In this case, the same preassigned radio channels can be used for the station-to-node communication (hence the conflict-free mode of operation) by allowing nodes to listen to the interstation communication (and thus receive and transmit on different channels). In other practical situations when the stations are not mobile, they can be interconnected by physical links, thus forming a point-to-point backbone network. Still, for the station-to-node communication, the channel can be preassigned to the stations.

The advantages of the multi-station configuration over the single station configuration (ALOHA) [1,2,10] are that the former allows for lower-power transmitters at the nodes, results in better utilization of the common radio channel due to spatial reuse of that channel, and allows distribution of control between several stations. It has also advantages over the standard multihop model [3,4,6,12,13,14] mainly because it simplifies both the design and the analysis of the network, it simplifies nodal protocols and it is also adequate for a large number of naturally structured hierarchical networks.

We focus on the problem of how the nodes forward their packets to the stations. This problem includes both the known issue of access to a shared channel (which is more complex than in the single-station models), and the novel issue of selecting the stations to which packets should be forwarded. The forwarding issue arises because a node might be heard by more than one station, due to the broadcast nature of its transmissions. We suggest and analyze two basic forwarding schemes. In the first scheme the sending node regards a packet as received correctly only if it is received by a predetermined fixed station, and in the second scheme if it is received correctly by any station. The advantages and disadvantages of each scheme are discussed in Section 2.

The paper is organized as follows. In Section 2 we give a detailed description of multi-station packet-radio networks and of the two basic forwarding schemes. In Sections 3 and 4 we analyze the performance of the network with the two forwarding schemes and also give several examples. To simplify the presentation we assume that the nodes of the network use the slotted ALOHA access policy. Other policies can be analyzed similarly. In Section 5 we compare the performance of the two schemes in different situations. Section 6 summarizes the content of the paper.

2. General model—a multi-station network

Let N be the set of all nodes and S the set of all stations of a packet-radio network in which all nodes share a common radio channel. Each node originates data and transmits it to one or more stations that forward it towards its destination.

Let $H(i)$ be the set of all nodes that are heard by station s_i. (An example of a network is depicted in Fig. 1.) The shared radio channel is of collision type, i.e. when two or more nodes that belong to $H(i)$ transmit during the same slot, none of the packets can be correctly received at station s_i and those nodes whose packets were not correctly received must retransmit their packets again at some later time. The specific access policy used by the nodes might be based on one of the many multi-access schemes proposed in the literature for single-station networks, such as the slotted ALOHA scheme [1,2,10], CSMA and BTMA schemes [11,15], etc. It is assumed that the corresponding stations inform the nodes whether their

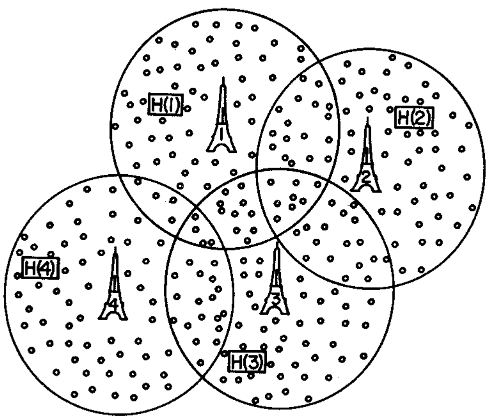

Fig. 1. A multi-station packet-radio network.

transmission was successful or not via a collision-free feedback channel. Practically, the feedback channel is part of the station-to-node communication that has been discussed in the introduction.

Regarding the general model of a multi-station packet-radio network, we distinguish between two basic schemes for forwarding packets from the nodes to the stations. The first will be called the Fixed-Forwarding Scheme (FFS) and the second the Random-Forwarding Scheme (RFS).

In the Fixed-Forwarding Scheme we assume that a node in the network always forwards its packets to a fixed single predetermined station. Let the set of all nodes that forward their packets to station s_i be denoted by $B(i)$. Clearly, for FFS, $B(i) \cap B(j) = \emptyset \ \forall i \neq j$ and $H(i)$ includes $B(i)$. Notice that, according to the FFS, a node that belongs to $B(i)$ must follow only the feedback channel of station s_i and that the transmission of a node that belongs to $B(i)$ might be interfered by all nodes of $H(i)$.

In the Random-Forwarding Scheme a packet transmitted by a node is considered as successfully forwarded to a station when it is first received correctly by any station of the network. Let N_k be a set of nodes that is heard by the same set of stations, where the subscript k enumerates all possible sets. Potentially there are $2^s - 1$ such sets (s is the number of stations in the network). With the RFS, a packet might be received correctly by more than one station and no specific restriction is imposed on the identity of the receiving stations. Note that with the RFS a node that belongs to $H(i)$ must follow the feedback channel of station s_i. This implies that some nodes should follow the feedbacks of more than one station. If the stations employ a TDMA scheme for transmission (as described in the introduction) this requirement does not pose any problem.

As we show, the channel might be utilized more efficiently with RFS than with FFS. The price paid for the improved efficiency is twofold. Firstly, more than one copy of the same packet might exist within the network with RFS, while with FFS it is guaranteed that only one copy will reside in the network. Secondly, with FFS we can control which of the stations will receive a packet from a node, while with RFS the stations that receive a packet are randomly chosen, and their choice depends on which ones are the transmitting nodes during each slot. The choice between FFS and RFS depends, in general, on the cost of using the shared channel (efficiency) and on the cost of routing packets through the interstation communication system. In addition, there are circumstances (mobile nodes) where the FFS is not applicable.

To simplify the presentation, we will assume in the sequel that the nodes of the network use the slotted ALOHA policy for accessing the shared channel. For that purpose the time axis is assumed to be slotted into segments whose durations are equal to the transmission time of a packet, and all nodes are synchronized and start transmissions at the beginning of a slot. Other access schemes, slotted and unslotted, can be also considered within the multi-station model. For instance, in [7], the application of CSMA and BTMA in a two-station network has been studied. The application of collision resolution algorithms in a multi-station network has been suggested in [8] and analyzed in [5].

3. Slotted ALOHA—Fixed-Forwarding Scheme

3.1. Feasibility region

Let the nodes of a multi-station network with the Fixed-Forwarding Scheme apply the slotted ALOHA access policy, in which a packet transmission is synchronized to the start of a slot, and in case of a collision the node retransmits the packet after some random delay. To analyze the slotted ALOHA policy with FFS, assume that the nodes of $B(i)$ generate new packets according to a Poisson distribution with rate t_i packets per slot, and that the combined traffic of new and retransmitted packets from nodes of $B(i)$ is also Poisson with rate $\lambda_i \geqslant t_i$ packets per slot. Let G_i be the total average number of packets heard at station i per slot, and let ϕ_{ji} be the fraction of the total traffic of nodes of $B(j)$ that is heard also by station i. ϕ_{ji} is referred to as an interference factor, since it indicates the fraction of traffic destined to station j that interferes the transmission of traffic destined to node i. These definitions imply that

$$G_i = \sum_{j=1}^{s} \phi_{ji} \lambda_j, \quad 1 \leqslant i \leqslant s, \tag{1}$$

where by definition $\phi_{ii} = 1$, $1 \leqslant i \leqslant s$, and $s = |S|$.

At equilibrium the Poisson assumptions yield

$$t_i = \lambda_i \, e^{-G_i}, \quad 1 \leqslant i \leqslant s. \tag{2}$$

Relation (2) implies that when $\{\lambda_i\}_{i=1}^s$ is given, then $\{t_i\}_{i=1}^s$ is uniquely determined. However, when $\{t\}_{i=1}^s$ is given, then there might or might not exist sets of $\{\lambda_i\}_{i=1}^s$ that satisfy (2). We define $\{t_i\}_{i=1}^s$ to be a *feasible* rate distribution (feasible, in short) if for that $\{t_i\}_{i=1}^s$, (2) has a solution (not necessarily unique). Note that whenever $\{t_i\}_{i=1}^s$ is feasible and $\{\lambda_i\}_{i=1}^s$ is chosen as a solution of (2), then t_i, $1 \leqslant i \leqslant s$, represents the throughput (average number of successfully received packets per slot) at station i. For a given set of interference parameters $\{\phi_{ji}\}$, $1 \leqslant j,i \leqslant s$, the *feasibility region* for FFS is defined as the region containing all feasible rate distributions. Note that the special $\phi_{ji} = 1 \; \forall j,i$ has been analyzed in [2].

In the following we present a simple necessary condition for $\{t_i\}_{i=1}^s$ to be feasible. Then we give an iterative algorithm for checking whether $\{t_i\}_{i=1}^s$ is feasible or not and introduce a monotonous property of the feasibility region. The proofs of the subsequent propositions are simple and therefore omitted.

3.1. Proposition. *$\{t_i\}_{i=1}^s$ is feasible only if $t_i \leqslant e^{-(1+\Sigma_{j\neq i}\phi_{ji}t_j)}$, $1 \leqslant i \leqslant s$.*

Note that the proposition implies that t_i should not exceed e^{-1}.

To check whether $\{t_i\}_{i=1}^s$ is feasible or not we show in Proposition 3.2 that the following iterative procedure can be used [3]:

$$\lambda_i(0) = t_i, \qquad 1 \leqslant i \leqslant s, \tag{3a}$$

$$\lambda_i(n+1) = t_i \, e^{\Sigma_{j=1}^s \phi_{ji}\lambda_j(n)}, \quad n = 0, 1, 2, \ldots, \quad 1 \leqslant i \leqslant s. \tag{3b}$$

3.2. Proposition. *$\{t_i\}_{i=1}^s$ is feasible if and only if the iterative procedure* (3) *converges to some $\{\lambda_i^*\}_{i=1}^s$.*

It is also easy to see that when (3) converges, it converges to the smallest $\{\lambda_i\}_{i=1}^s$ that satisfies (2). We also observe that $\lambda_i^* \leqslant 1$, $1 \leqslant i \leqslant s$.

Finally, we state the following intuitive monotonous property of the feasibility region.

3.3. Proposition. *Let $\{t_i\}_{i=1}^s$ be feasible for some interference parameters $\{\phi_{ji}\}$. Then $\{t_i'\}_{i=1}^s$ is feasible for all interference parameters $\{\phi_{ji}'\}$, where $t_i' = t_i - \epsilon_i$, $\phi_{ji}' = \phi_{ji} - \delta_{ji}$, and $0 \leqslant \epsilon_i \leqslant t_i$, $0 \leqslant \delta_{ji} \leqslant \phi_{ji}$, $1 \leqslant j,i \leqslant s$.*

To see that the feasibility region is not empty for any set of interference parameters $\{\phi_{ji}\}$, let $\phi_{ji} = 1$, $1 \leqslant j,i \leqslant s$. If $\Sigma_{i=1}^s t_i = e^{-1}$, then (2) has always a solution ($\lambda_i = e t_i$). By Proposition 3.3, (2) has a solution whenever $\Sigma_{i=1}^s t_i \leqslant e^{-1}$ and for any $\{\phi_{ji}\}$.

3.2. Global performance measures

If one is interested in having a single measure that globally captures the performance of the network, the first one to come to mind is the total throughput. For any feasible $\{t_i\}_{i=1}^s$ the total throughput of the network is

$$t = \sum_{i=1}^{s} t_i = \sum_{i=1}^{s} \lambda_i \, e^{-G_i}. \tag{4}$$

To determine the maximal total throughout one should solve the optimization problem

$$\max_{\{\lambda_i\}_{i=1}^s} t \quad \text{subject to } \lambda_i \geqslant 0, \quad 1 \leqslant i \leqslant s, \tag{5}$$

that, in general, is not a simple problem. Moreover, the total throughput of the network has a major drawback as a measure of performance for the system, because its maximum value might be achieved at the expense of nullifying the throughputs at some stations (as we will show in an example), which is a very undesirable property.

To overcome the above drawback and difficulties, we propose here a new global performance measure that we call the *product throughput.* For any feasible $\{t_i\}_{i=1}^s$ the product throughput of the network is

$$\pi = \prod_{i=1}^{s} t_i = e^{-\Sigma_{i=1}^s G_i} \prod_{i=1}^{s} \lambda_i. \tag{6}$$

That the product throughput has a maximum is obvious since $\pi \geqslant 0$ and $\pi \to 0$ when $\lambda_i \to 0$ and also when $\lambda_i \to \infty$ (for any i). To determine the maximal product throughput we calculate,

$$\frac{\partial \pi}{\partial \lambda_j} = -\sum_{i=1}^{s} \phi_{ji} \, e^{-\Sigma_{i=1}^s G_i} \prod_{m=1}^{s} \lambda_m + e^{-\Sigma_{i=1}^s G_i} \prod_{m=1}^{s} \lambda_m / \lambda_j = 0, \quad 1 \leqslant j \leqslant s. \tag{7}$$

Since (7) has a single solution

$$\lambda_j = 1 / \sum_{i=1}^{s} \phi_{ji}, \quad 1 \leqslant j \leqslant s, \tag{8}$$

it follows that it achieves the maximum. Intuitively, (8) states that if the traffic destined to station j causes large interference, its rate should be slowed down.

Beside the simplicity in obtaining the λ_i's that lead to its maximal value, the product throughput has the appealling property that when maximized, no throughput of any station can be significantly small. In other words, maximizing the product throughput also implies some fairness among the stations.

3.3. Examples

3.3.1. Symmetric network

Let us consider a symmetric network in which $\phi_{ji} = \phi$ for all $i \neq j$. The boundary of the feasible region for a two-station symmetric network with $\phi = 0, 0.3, 1$ is plotted in Fig. 2. In a network with s stations, assuming that $G_i = G$ we obtain that $\lambda = 1/[1 + (s-1)\phi]$ maximizes both the total throughput and the product throughput, and the maximal throughput per station is $t_i = e^{-1}/[1 + (s-1)\phi]$. The latter is plotted in Fig. 3 for a two-station network.

3.3.2. Nonsymmetric network

Let us consider a two-station antisymmetric network. In this network we assume that $\phi_{12} = 1$ and $\phi_{21} = 0$. The boundary of the feasibility region in this case is plotted in Fig. 2. The maximal total throughput in this case is obtained when $\lambda_1 = 1 - e^{-1}$ and $\lambda_2 = 1$, hence $t_1 = 0.336$ and $t_2 = 0.195$. The maximal product throughput is obtained when $\lambda_1 = 0.5$ and $\lambda_2 = 1$, hence $t_1 = 0.303$ and $t_2 = 0.220$ in this case.

In a larger network with $s \geqslant 4$ stations and $\phi_{ij} = 0$ $\forall i \neq j$ except that $\phi_{1j} = 1$ for $1 \leqslant j \leqslant s$, we obtain the following. The maximal total throughput is obtained when $\lambda_1 = 0$ and $\lambda_j = 1$ for $2 \leqslant j \leqslant s$, hence $t_1 = 0$ and $\lambda_j = e^{-1}$ for $2 \leqslant j \leqslant s$. The maximal product throughput is obtained when $\lambda_1 = 1/s$ and $\lambda_j = 1$ for $2 \leqslant j \leqslant s$, hence $t_1 = e^{-1/s}/s$ and $\lambda_j = e^{-1-1/s}$ for $2 \leqslant j \leqslant s$. This example demonstrates very clearly the fairness property of the product throughput.

3.3.3. Symmetric ring network

Let us consider a network where each node is either heard by a single station or by two stations.

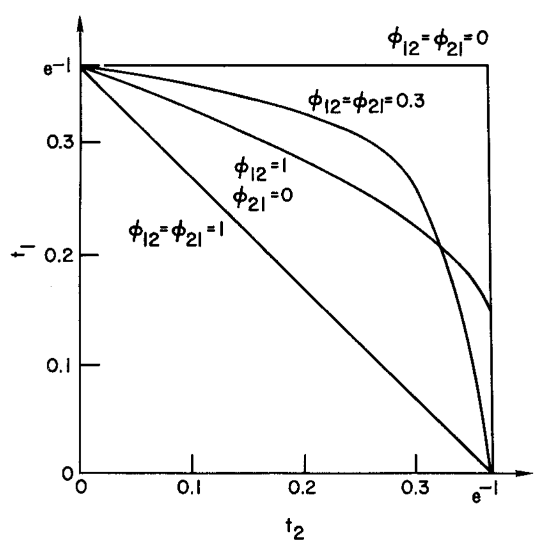

Fig. 2. A two-station network: Feasibility region: FFS.

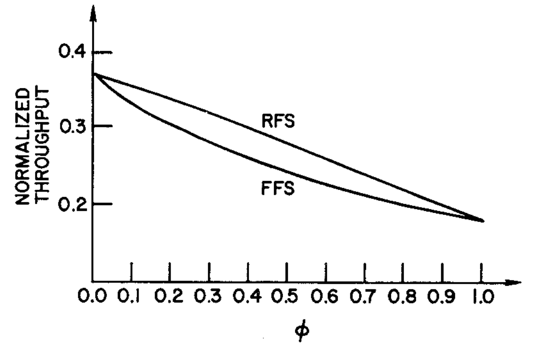

Fig. 3. A two-station symmetric network: Slotted ALOHA.

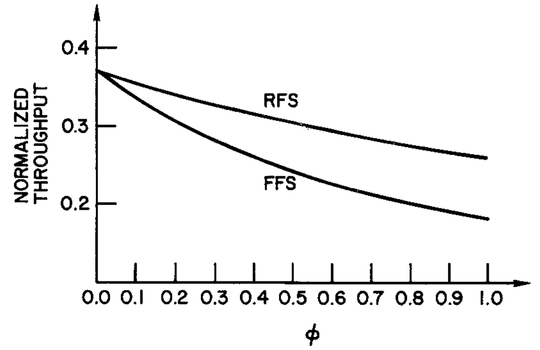

Fig. 4. A symmetric ring network: Slotted ALOHA.

The interference factors associated with this network are

$$\phi_{ij} = \begin{cases} 1, & j = i, \\ \phi/2, & j = i+1 \bmod(s) \\ & \text{or } j = i-1 \bmod(s), \\ 0, & \text{otherwise.} \end{cases} \quad (9)$$

This network can be visualized as a ring network. Assuming a symmetric situation, where $\lambda_i = \lambda$ for $1 \leqslant i \leqslant s$, we find that both the total and the product throughput are maximized when $\lambda = 1/(1+\phi)$ and the throughput per station is given by:

$$t_i = e^{-1}/[1+\phi], \quad 1 \leqslant i \leqslant s. \quad (10)$$

The latter is plotted in Fig. 4.

4. Slotted ALOHA—Random-Forwarding Scheme

4.1. Feasibility region

Assume that the nodes apply the slotted ALOHA scheme with the Random-Forwarding Scheme and that the nodes of N_k (recall that the set N_k contains all nodes that are heard by exactly the same group of stations) generate new packets according to a Poisson distribution with rate t_k packets per slot. Further assume that the combined traffic of new and retransmitted packets from nodes of N_k is also Poisson with rate λ_k packets per slot. We call the total traffic generated by nodes in N_k a stream k.

Remembering that with RFS a packet is considered as successfully forwarded when it is first received by some station, we have that

$$t_k = \text{Prob}\left\{ \bigcup_{s_k^j \in S_k} A_{kj} \right\} \quad (11)$$

where A_{kj} denotes the event that a packet from stream k is successfully received by station s_j. S_k is the set of stations that hear the transmissions of nodes in N_k and $s_k^1, s_k^2, \ldots, s_k^{l_k}$ are the elements of S_k (so S_k contains l_k elements).

Let $S_k^m(h)$ be a subset of h elements from

$$S_k, \quad 1 \leqslant m \leqslant \binom{l_k}{h}.$$

Let $\Lambda_k^m(h) = \Sigma_p \lambda_p$, where the sum is carried over all streams p heard by stations that belong to $S_k^m(h)$ and $p \neq k$. At equilibrium these definitions with the Poisson assumption yield

$$\text{Prob}\left\{ \bigcap_{s_k^j \in S_k^m(h)} A_{kj} \right\} = \lambda_k e^{-\lambda k} e^{-\Lambda_k^m(h)}, \quad (12)$$

so using (11), (12) and the inclusion-exclusion principle we obtain

$$t_k = \lambda_k e^{-\lambda_k} \sum_{h=1}^{l_k} (-1)^{h-1} \sum_{m=1}^{\binom{l_k}{h}} e^{-\Lambda_k^m(h)},$$
$$1 \leqslant k \leqslant 2^s - 1. \quad (13)$$

As in Section 3.1 we define $\{t_k\}_{k=1}^{2^s-1}$ to be a *feasible* rate distribution if for that $\{t_k\}_{k=1}^{2^s-1}$, (13) has a solution (not necessarily unique).

We state here similar propositions to those in Sections 3.1.

4.1. Proposition. *Let $T_k^m(h) = \Sigma_p t_p$, where the sum is carried over all streams p heard by stations that belong to $S_k^m(h)$ and $p \neq k$. Then* (11) *has a solution only if*

$$t_k \leqslant e^{-1} \sum_{h=1}^{l_k} (-1)^{h-1} \sum_{m=1}^{\binom{l_k}{h}} e^{-T_k^m(h)}, \quad 1 \leqslant k \leqslant 2^s - 1.$$

To check whether $\{t_k\}_{k=1}^{2^s-1}$ is feasible or not, the following iterative procedure should be used:

$$\lambda_k(0) = t_i, \quad 1 \leqslant k \leqslant 2^s - 1, \quad (14a)$$

$$\lambda_k(n+1) = t_k e^{\lambda_k} / \sum_{h=1}^{l_k} (-1)^{h-1} \sum_{m=1}^{\binom{l_k}{h}} e^{-\Lambda_k^m(h)},$$
$$n = 0, 1, 2, \ldots, \quad 1 \leqslant k \leqslant 2^s - 1. \quad (14b)$$

4.2. Proposition. *$\{t_k\}_{k=1}^{2^s-1}$ is feasible if and only if the iterative procedure* (14) *converges to some $\{\lambda_k^*\}_{k=1}^{2^s-1}$.*

4.3. Proposition. *Let $\{t_k\}_{k=1}^{2^s-1}$ be feasible. Then $\{t'_k\}_{k=1}^{2^s-1}$ is feasible, where $t'_k = t_k - \epsilon_k$ and $0 \leqslant \epsilon_k \leqslant t_k$, $1 \leqslant k \leqslant 2^{s-1}$.*

Finally, the total throughput is obtained by summing up the throughputs of all the streams, i.e.,

$$t = \sum_{k=1}^{2^s-1} t_k = \sum_{k=1}^{2^s-1} \lambda_k e^{-\lambda_k} \sum_{h=1}^{l_k} (-1)^{h-1} \sum_{m=1}^{\binom{l_k}{h}} e^{-\Lambda_k^m(h)}. \quad (15)$$

4.2. Examples

4.2.1. Two-station network

In a two-station network we have in general three streams. Let streams 1 and 2 be heard by stations 1 and 2, respectively, and stream 3 be heard by both stations. Then from (13) we have that:

$$t_1 = \lambda_1 e^{-\lambda_1} e^{-\lambda_3}, \quad t_2 = \lambda_2 e^{-\lambda_2} e^{-\lambda_3}, \tag{16a}$$

$$t_3 = \lambda_3 e^{-\lambda_3}(e^{-\lambda_1} + e^{-\lambda_2}) - \lambda_3 e^{-\lambda_3} e^{-(\lambda_1+\lambda_2)}. \tag{16b}$$

Let us consider the symmetric case, where $\lambda_1 = \lambda_2 = \lambda(1-\phi)$ and $\lambda_3 = 2\lambda\phi$. Notice that ϕ is an interference factor. In this case the total throughput is given by

$$t = 2\lambda(1+\phi) e^{-\lambda(1+\phi)} - 2\lambda\phi e^{-2\lambda}. \tag{17}$$

By taking the derivative of t in (17) with respect to λ and equating it to zero we obtain the maximal throughput. The normalized maximal throughput is plotted in Fig. 3 as a function of ϕ.

4.2.2. Symmetric ring network

Similarly to the symmetric ring network of Section 3 we consider here the following ring network. Each station in the ring hears three streams, two with rates $\phi\lambda$, that are also heard by the nearest stations in the ring, and the third with rate $(1-\phi)\lambda$ is heard only by itself. Now the total throughput is given by

$$t = s\left[(1+\phi)\lambda e^{-(1+\phi)\lambda} - \phi\lambda e^{-\lambda(2+\phi)}\right]. \tag{18}$$

The maximal throughput in (18) is obtained from $\partial t/\partial\lambda = 0$. The normalized maximal throughput is plotted in Fig. 4 as a function of ϕ.

5. Performance comparison between the forwarding schemes

In terms of maximal throughput and feasible rate distributions, the FFS is never better than the RFS. In the examples of Figs. 3 and 4 we see that the RFS might be significantly better than the FFS in terms of maximal throughput. However, to have fair comparison of the two forwarding schemes, one should take into account both the throughput and the load on the interstation and the station-to-node communication. The reason is that with RFS the load on the stations is higher compared to FFS. The comparison will depend on the actual structure of the interstation and the station-to-node communication. Here we assume that the stations forward traffic to the nodes without conflicts (by employing TDMA for instance). In addition, we use a simplified assumption that each station is heard by all nodes (but not vice versa). This implies that each packet arrives to its destination (either a station or another node) in at most two hops. Let $1-f$ be the fraction of packets transmitted by the nodes whose final destinations are the stations and f be the fraction of packets that have to be forwarded by the stations to the nodes.

The total average number of packets per slot received successfully by all stations is called the *stations load* (SL). For FFS we have that the stations load is just the total throughput, i.e. $SL_{FFS} = t_{FFS}$. For RFS we have

$$SL_{RFS} = \sum_{k=1}^{2^s-1} \lambda_k e^{-\lambda_k} \sum_{m=1}^{l_k} e^{-\Lambda_k^m(1)}, \tag{19}$$

because a packet of stream k is successful at station s_k^j, $1 \leqslant j \leqslant l_k$, if it is the only packet of stream k, and no packets of streams heard by station s_k^j are transmitted. Note that $SL_{RFS} \geqslant t_{RFS}$.

Let BW_1 and BW_2 be the number of slots per unit of time needed to successfully forward one packet per unit of time for the node-to-station traffic and for the station-to-node network traffic, respectively. The number of slots per unit of time that are required to forward one packet per unit of time from a node to a station is $1/t$ on the average. Since the station-to-node communication is assumed to be conflict free, then exactly one slot per unit of time is needed to forward a single copy of a packet from a station to a node. The expected number of copies of a packet in the stations is SL/t. Hence,

$$BW_1 = \frac{1}{t}, \quad BW_2 = \frac{fSL}{t}. \tag{20}$$

Note that the sum $BW = BW_1 + BW_2$ reflects the total number of slots per unit of time needed to successfully forward one packet per unit of time from its source to its destination. We compare the FFS and the RFS according to BW.

The example network that we use is the two-

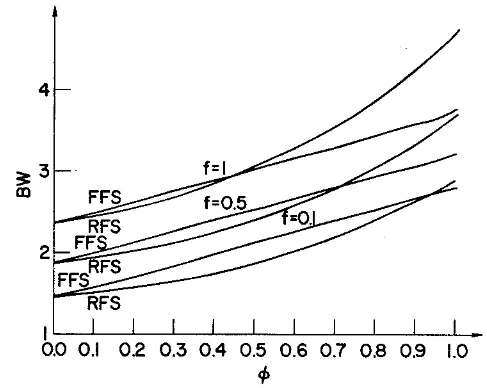

Fig. 5. BW versus ϕ for a two-station symmetric network.

station symmetric network. For this network,

$$BW_{FFS} = \frac{(1+\phi)\,e}{2} + f,$$

$$BW_{RFS} = \frac{1 + 2f\lambda(1+\phi)\,e^{-\lambda(1+\phi)}}{2f\lambda(1+\phi)\,e^{-\lambda(1+\phi)} - 2\lambda\phi\,e^{-2\lambda}}, \quad (21)$$

where ϕ is the interference factor. For each forwarding scheme we find the minimal BW required for different values of the interference factor ϕ and the fraction f. The results for $f = 0.1$, 0.5, and 1 are depicted in Fig. 5.

As we see from Fig. 5 BW increases as ϕ increases. We notice that the FFS outperforms the RFS for large values of ϕ. The reason is that for large ϕ the chances of multiple receptions of a single packet (costly to RFS) are increased. The value of ϕ where the FFS turns to be better than the RFS depends on the fraction f. Generally, for small values of f, the RFS is better even for high values of ϕ. As f increases this value of ϕ for which the RFS is better, decreases.

If all stations can hear each other, it is possible for all stations to detect whenever a specific packet is transmitted, and therefore transmissions of duplicates can be inhibited. This can be accomplished if TDMA is used by the stations' network. In such a case $SL_{RFS} = t$ and the RFS will always be better than the FFS (since $t_{FFS} \leqslant t_{RFS}$, as depicted in Fig. 3).

6. Summary

A new architecture called the multi-station packet-radio network has been introduced and analyzed. We described the various features of this network that consists of a large number of nodes and several stations. Focusing on the issue of forwarding packets from the nodes to the stations through a shared radio channel, we investigated and compared two basic forwarding schemes, the FFS and the RFS. We found out that if channel utilization is the performance measure, then RFS should be used. When packets forwarding to their destinations by the stations is taken into account, there are circumstances (high interference, large amount of forwarding) where FFS is better.

A lot of interesting research topics related with the multi-station network configuration are still to be explored. For instance, checking its performance under different access schemes, investigating the routing problems in these networks, etc.

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