Design Algorithms for Multihop Packet Radio Networks with Multiple Directional Antennas Stations

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***Abstract*—A new protocol called the simple tone sense (STS) protocol is designed for multihop packet radio networks (PRN's) with multiple directional antennas stations. The protocol can minimize transmission interference by using a group of tones to identify the active neighbors. A variation of the STS protocol called the variable power tone sense (VPTS) protocol is also designed to further reduce interference. Algorithms for assigning tones and for determining the orientation and broadcasting angles of the directional antennas are designed. Design examples are given. Simulation result shows that the STS protocol gives better throughput-delay performance than the BTMA protocol, especially when the traffic is heavy. The VPTS protocol gives still better throughput-delay performance than the STS protocol.**

I. Introduction

THE performance of channel access protocols for packet radio networks has improved tremendously over the past two decades. The first multiaccess protocol is known as the pure ALOHA [1] protocol. Due to the complete uncoordinating nature of this protocol packet collision on the channel is frequent and the channel utilization is low (0.18). However, pure ALOHA is superior to fixed assignment (such as frequency division multiple access and time division multiple access) when the user traffic is bursty and low packet delay is important. Later, a protocol in which users sense the channel before transmission is introduced in order to reduce the chance of collision. It is known as the carrier-sense multiple-access (CSMA) [2] protocol and can offer superior performance than the ALOHA protocol. But its performance starts to degrade in a multihop network environment. This is mainly due to the hidden station problem [3]. The busy tone multiple-access (BTMA) [3] protocol can be used to solve the hidden station problem. In BTMA, a station broadcasts a busy tone whenever it is receiving a packet and all stations within the transmission range of the receiving station can sense the busy tone and will remain silent during the presence of the busy tone. Collisions, therefore, can be avoided.

Omnidirectional antennas are used in the stations of the above systems. In other research works, directional antennas are used to increase the network throughput by spatially reusing the packet radio channel. An example of such protocols is the MTCD/MDA (multitone multiaccess with collision detection using multiple directional antennas) protocol [4]. In the MTCD/MDA protocol, when a station is busy in receiving packets each of its directional antennas broadcasts different busy tones. The orientation of the antennas must be the same for all stations and the number of antennas in each station must also be the same and be even.

With the use of directional antennas in multihop packet radio networks, a number of design issues arise. These include 1) number of antennas per station, 2) orientation and broadcasting angle of each antenna, 3) how to minimize the interference between neighboring stations, and 4) the design of efficient protocols to fully utilize the spatial frequency reuse advantage of directional antennas. In this paper, we design a new protocol called the simple tone sense (STS) protocol that can minimize transmission interference by using a group of tones to identify the neighboring stations that are receiving packets. A variation of the STS protocol called the variable power tone sense (VPTS) protocol is also designed to further reduce interference by using minimum required transmission power to reach the intended neighbor. In Sections III and IV we describe the multihop network environment and the new protocols to be used on it. Design algorithms for assigning tones and for determining the orientation and broadcasting angles of the directional antennas are presented in Section V. A network design example is given in Section VI and simulation results of the STS and VPTS protocols on four networks with various network size and density are given in Section VII.

II. Problems in the MTCD/MDA Protocol

In the MTCD/MDA protocol, when a station detects a packet addressed to it, it broadcasts different busy tones to its neighbors in different directions. All stations must have the same number of antennas and the antenna orientation for all stations must be the same. These two restrictions cause the following problems in a multihop network.

1) A large number of stations may be concentrated in certain transmission sectors, causing severe congestions in these sectors (Fig. 1).
2) Stations located near the quadrant boundaries are in the coverage of two antennas and suffered the interference from both antennas.

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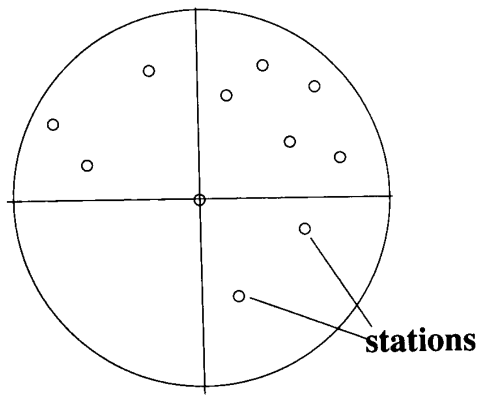


Fig. 1. Limitations of the MTCD/MDA protocol.

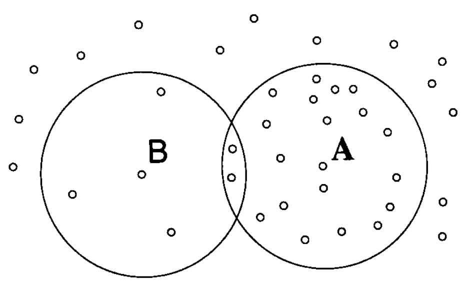


Fig. 2. A distributed multihop network.

3) Increasing the number of transmission sectors requires a corresponding increase in the number of tones.
4) Since the number of antennas is the same for all stations, the station with more neighbors cannot have more antennas and the station with very few neighbors cannot have less. This problem is illustrated in Fig. 2. Station A has 20 neighboring stations while station B has only five.

A new protocol is proposed here that can avoid the above problems. The main idea is that each station is assigned a tone which is unique to its neighbors (We will describe how these tones are assigned in Section V). When a station receives a packet, it broadcasts its tone immediately for a period of time so that its neighbors can identify its presence and avoid transmitting to its direction. With this arrangement, the orientation and broadcasting angles of the directional antennas are not required to be the same for all stations and the orientation of antennas can be chosen to make the neighboring stations as far away from the boundary of the transmission sectors as possible. Moreover, the broadcasting angles of the antennas should be so chosen as to make the number of stations in each sector as evenly distributed as possible (Fig. 3). Also, a station with more neighbors can be equipped with more directional antennas so that a particular antenna will not be too heavily loaded.

III. The Simple Tone Sense (STS) Protocol

System Descriptions

Let there be N stations in the packet radio network and let all station locations be fixed. Each station is assigned

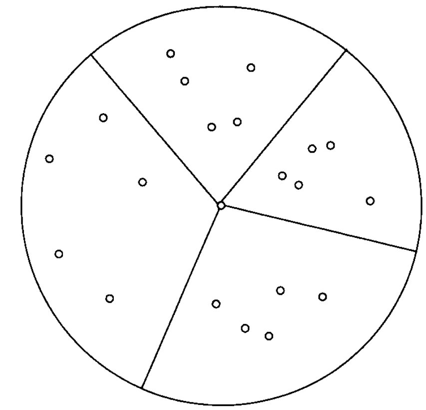


Fig. 3. The number of stattions in each sector is equal.

a tone and a station-number. A tone is just a sinusoidal wave at a certain frequency. The station-number is globally unique, but the tone frequency is unique only in each station's neighborhood. The maximum transmission range R is assumed to be the same for all stations and the propagation delay across distance R be a.

Each station maintains five arrays to store the network status information. Consider a local station which has m directional antennas and n neighboring stations with station-numbers $1, 2, \ldots, n$.

a) Path array $P = (p_1, p_2, \cdots, p_N)$ where p_j is the station-number of the neighboring station that will lead to destination station j. For example, $p_{13} = 7$ means that a packet destined for station 13 is to be sent via station 7.
b) Antenna array $A = (a_1, a_2, \cdots, a_n)$ where a_k denotes the directional antenna for transmitting packets to station k. For example, $a_4 = 3$ means that station 4 is in the coverage of the directional antenna 3 of the local station.
c) Neighbor status array $S = (s_1, s_2, \cdots, s_n)$ shows the busy/idle status of the neighbors of the local station. Thus, $s_6 = 0$ and $s_{10} = 1$ indicate that stations 6 and 10 are idle and busy, respectively.
d) Antenna status array $B = (b_1, b_2, \ldots, b_m)$ shows the busy/idle status of the m directional antennas of the local station with a 0 indicating idle and a 1 indicating busy.
e) Sector status array $C = (c_1, c_2, \ldots, c_m)$ shows the busy/idle status of the m transmission sectors of the local station. The value of c_i is determined from the busy/idle status of the stations (i.e., the array S) covered by directional antenna i. For example, $c_3 = 0$ means that all stations in sector 3 (covered by directional antenna 3) are idle while $c_3 = 1$ means that one or more stations in sector 3 are currently receiving packets.

Tone signaling serves both as an explicit destination to source acknowledgment and as a busy signal to alert other stations that a successful packet reception is ongoing. As soon as a station detects a packet destined to it, the station broadcasts its assigned tone for T_1 s to all its neighbors. As an example of the signaling and acknowledging process, consider the case in Fig. 4. Here, A (or station A) is transmitting a packet to B, C knows that D's sector is idling and transmits

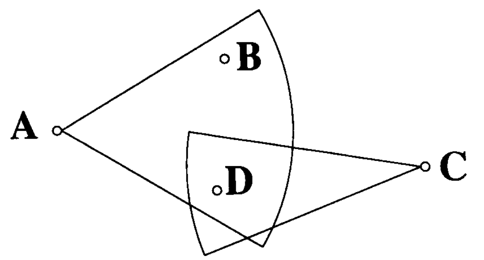


Fig. 4. An example of signaling and acknowledging in STS.

a packet to D. But D cannot receive the packet because it is being interfered by A's transmission. Therefore, C stops its transmission as soon as the expected tone from D is not received in a time out period of T_o seconds. Here T_o must be at least the round-trip propagation delay $2a$ plus the header detection time.

All stations when detecting a tone of duration T_1 will change the status of the station corresponding to the received tone to busy. After a station has received a packet correctly, it acknowledges the source station by broadcasting its assigned tone for T_2 seconds. All stations when detecting a tone for T_2 s will change the status of the corresponding station to idle. We will discuss how to determine the tone durations T_1 and T_2 in Section V.

Transmission Protocol

1) Look up the path array to decide which neighbor the packet is to be forwarded.
2) Look up the antenna array to decide the appropriate directional antenna to be used and denote it as antenna k.
3) If $b_k = 1$ or antenna k is being used at that moment, wait until it becomes idle.
4) If $c_k = 1$ or some other station in sector k is receiving a packet, recheck after a random delay. If $c_k = 0$, transmit the packet immediately.
5) If the expected tone of duration T_1 is detected before the time out period, continue the transmission. Otherwise, stop transmission immediately, wait for a random delay and go to (4).
6) After the whole packet is transmitted, if the expected tone of duration T_2 is detected before the time out period, the packet is assumed to be correctly received. Otherwise, retransmit the packet immediately and go to 5).

Reception Protocol

1) When the header of an incoming packet is detected without error, broadcast the assigned tone to all neighbors for T_1 s.
2) After receiving the whole packet and no error is detected, broadcast the assigned tone for T_2 s.

IV. The Variable Power Tone Sense (VPTS) Protocol

In order to increase the spatial-reuse advantage, a station uses only the minimum required power to send the packet to the destination station. However, the assigned tones are still broadcasted to cover a range of R.

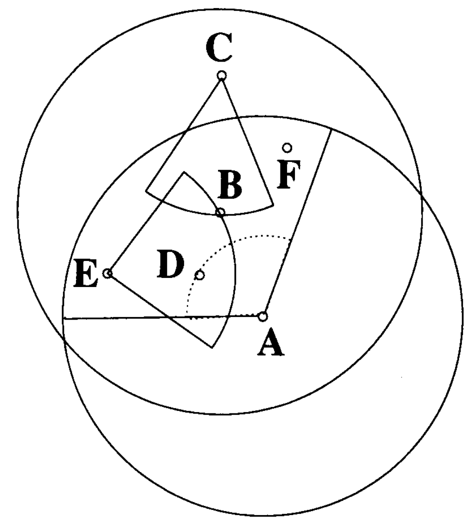


Fig. 5. Variation of transmission power.

To illustrate the advantage of using variable power, consider the case in Fig. 5. Here C transmits a packet to B with the minimum required power. B then broadcasts its tone for T_1 s. A detects the tone from B and will refrain from sending packets to stations B, D, E, and F if the simple tone sense protocol were used. But in reality, A could transmit a packet to D using the minimum required power without interfering B's packet reception. Now suppose E transmits a packet to B. A detects B's tone and realizes that B is far enough away from D. Therefore, A might transmit a packet to D. But here, since D is in the transmission range of E, a collision will occur. However, A's transmission cannot reach B, therefore, B's packet reception is not affected. Thus, the VPTS protocol can in some cases improve the network throughput but in no case will it degrade the throughput.

For each station, two additional arrays besides the five required by the STS protocol are maintained as follows.

a) Distance array $D = (d_1, d_2, \ldots, d_n)$ where d_j is the distance between the local station and its jth neighbor.
b) Range array $E = (r_1, r_2, \ldots, r_m)$ where r_k is the current allowable transmission range in sector k.

The range array is updated as follows.

1) Initially, all r_k's are set to R_o which is an arbitrary number larger than R.
2) When the local station detects a tone of duration T_1 from neighbor j located in sector k, it replaces r_k by d_j if $d_j < r_k$.
3) When the local station detects a tone of duration T_2 from its neighbor located in sector k, it determines from arrays S and D the nearest neighbor (if any) in sector k which is still receiving a packet and denote it as neighbor i. Set r_k to d_i.
4) If no station in sector k is currently receiving a packet, r_k is set to R_o.

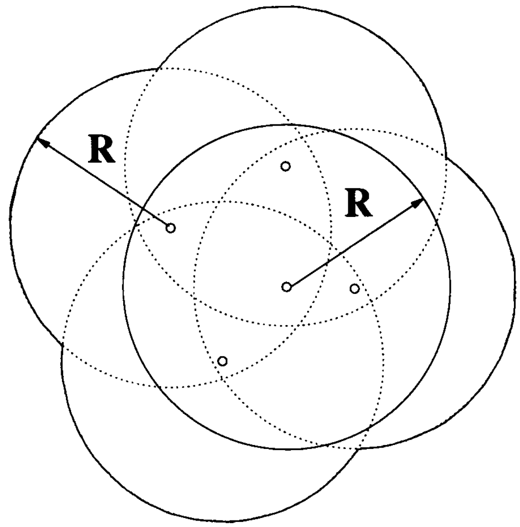


Fig. 6. The local range.

The transmission protocol of VPTS is identical to STS except that Step 4) is replaced by the following.

4) If $r_k > d_j$ where j is the intended receiving neighbor, transmit the packet immediately. Otherwise, recheck after a random delay.

This protocol assumes that stations can make continuous adjustment of transmission power, we call it the continuous range VPTS protocol. A discrete range version of the VPTS protocol can similarly be defined.

V. Network Design Algorithms

Tone Assignment Algorithm

Each station is assigned a tone for identifying itself from the neighboring stations. Since the identifying tones are local in nature, beyond a certain range, which we call it the local-range for convenience, they can be reused. A tone-group is just a group of stations that use the same tone for identifying themselves in their neighborhood. The size of the local-range depends on the transmission range *R* and the distribution of neighboring stations. The local-range of a particular station is formed by the perimeters of the transmission ranges of the station's neighbors (Fig. 6).

The algorithm for assigning tones to stations is as follows:

1) $j := 1$.
2) Select an unassigned station and denote it as S_o.
3) Assign tone$j$toS_o.
4) $S := S_o$.
5) Mark all the stations in the local-range of station *S*.
6) If all unassigned stations are marked, go to 9).
7) Assign tone *j* to one of the unmarked stations *S*'.
8) $S := S'$; go to 5).
9) If all stations are assigned, stop. Otherwise unmark all unassigned stations.
10) $j := j + 1$; go to 2).

Directional Antenna Assignment Algorithm

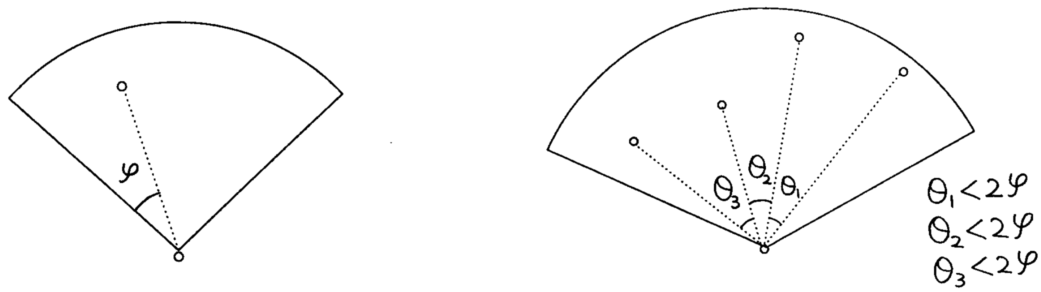
Each station may have a different number of directional antennas and each antenna can have a different broadcasting angle. The orientations and the broadcasting angles of the directional antennas are so chosen as to make the number of stations in each transmission sector as even as possible. Increasing the number of the directional antennas in the stations can improve the network throughput without increasing the number of tones required.

To avoid interference, let φ be the minimum angular separation required between a neighboring station and the boundaries of the transmission sector [Fig. 7(a)]. Also let the nominal number of stations covered by an antenna be n_o. The neighboring stations are assigned to the appropriate antennas according to the following three criteria.

1) If two adjacent neighboring stations have angular separation smaller than 2φ, both are assigned to the same antenna [Fig. 7(b)]. This will ensure that all stations are at least φ degrees away from the antenna transmission boundaries.
2) The number of stations in each sector should be as even as possible and should normally not exceed n_o except when the neighboring stations are very close together.
3) A minimum number of directional antennas is preferred.

The algorithm for determining the beam width and the orientation of the directional antennas of any station, say station *A*, is as follows.

1) Rank the neighbors of station *A* according to their bearings.
2) Calculate the angles $\theta_1, \theta_2, \ldots$ between all adjacent neighbors of station *A* [Fig. 7(b)].
3) Partition the neighboring stations into groups such that the angular separation between a station and its "closest" (i.e., with the smallest angular separation) group



(a) (b)

Fig. 7. Antenna assignment.

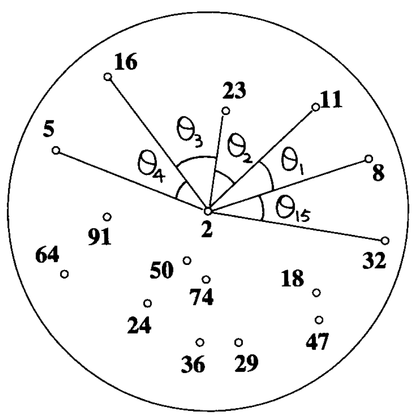


Fig. 8. Station 2 and its neighbors.

member is less than 2φ.

4) Let P be the initial grouping after partitioning. Let the number of groups in P be p.
5) Let G be the desirable grouping of the neighbors and g be the number of groups in G.
6) $G := P$ and $g := p$.
7) $k := 1$.
8) $k' := k$.
9) If the total number of stations in group k' and its adjacent group $k'+1 (\text{mod } k)$ is less than or equal to n_o, combine the two groups and call it group $k'+1$.
10) If $k' \neq k - 1 (\text{mod } k)$, $k' := k' + 1$ and go to (9).
11) Denote the new grouping of neighbors as H and the number of groups in H as h. Let the number of stations in these groups be $n_1, n_2, \ldots, n_h$ and let Var (H) be the variance of the ni's, or $\text{Var}(H) = \sum_{i=1}^{h} n_i^2 - \left(\sum_{i=1}^{h} n_i\right)^2$.
12) If $(h < g)$ OR $(h = g$ and $\text{Var}(H) < \text{Var}(G))$ then $G := H$ and $g := h$.
13) If $k < p, k := k + 1$ and go to (8).
14) If $k = p$, the assignment is complete.

As an example, consider Fig. 8 which shows station 2 and its neighbors. The neighbors are ordered as 8, 11, 23, 16, 5, 91, 64, 24, 50, 36, 74, 29, 47, 18, 32 according to their bearings from station 2. The angular separation θ's for all neighbor pairs are computed. Here, θ_1 and θ_2 are less than 2φ, but θ_3 and θ_15 are greater than 2φ. Hence, stations 8, 11, and 23 are assigned to the same group (group 1). The other groups can be obtained similarly and the grouping are shown as follows:

Group number	Station number	Number of stations in the group
1	8, 11, 23	3
2	16	1
3	5, 91	2
4	64	1
5	24, 50, 36, 74, 29	5
6	47, 18	2
7	32	1

The number of initial groups $p = 7$ and the number of stations in groups 1 to 7 are 3, 1, 2, 1, 5, 2, and 1, respectively. Suppose the nominal number of stations in an antenna zone n_o is four. Starting from group 1, we obtain the total number of stations in groups 1 and 2 is four, which is equal to n_o. So we combine the two groups and denote it as group 2. After that we check the total number of stations in groups 2 and 3 and find that it is $4 + 2 = 6$ which is greater than n_o. So, groups 2 and 3 are not combined. The entire grouping process starting from group 1 is shown as follows:

Step	Grouping						
-	3	1	2	1	5	2	1
1		4	2	1	5	2	1
2		4	2	1	5	2	1
3		4		3	5	2	1
4		4		3	5	2	1
5		4		3	5	2	1
6		4		3	5		3

The result of the grouping is $H = [4, 3, 5, 3]$ and the number of groups h is 4. The same steps are performed starting from different initial groups. The result of all possible grouping is shown as follows:

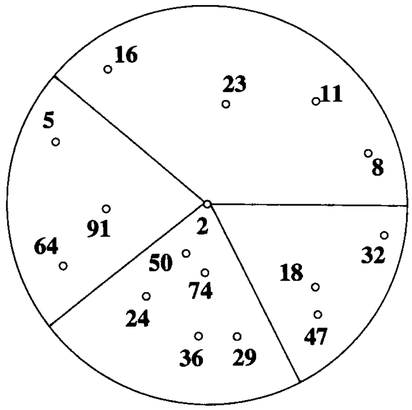


Fig. 9. The orientation and broadcasting angles of the antennas.

Starting group	Resultant sequence						
1	-	4	-	3	5	-	3
2	3	-	-	4	5	-	3
3	-	4	-	3	5	-	3
4	-	4	-	3	5	-	3
5	-	4	-	3	5	-	3
6	-	4	-	3	5	-	3
7	4	-	-	4	5	2	-

Since the minimum number of groups g is 4, the grouping G that we choose for station 2 is [4, 3, 5, 3] (which has a smaller variance compared with the grouping [4, 4, 5, 2]). The final orientation and broadcasting angles of the antennas are shown in Fig. 9.

Routing Strategy

In a distributed multihop PRN, the choice of a routing algorithm is essential. We choose, for our design, the minimum hop routing rule for simplicity. When there are multiple minimum hop paths between two stations, one of them is chosen arbitrary. Let $p_{i,j}$ be the next station on the routing path from station i to station j. The routing path can be uniquely determined by the $N \times N$ path matrix $P = [p_{i,j}]$.

Tone Detection Time and Packet Length

When two or more stations transmit packets simultaneously to the same destination, the destination will experience a collision. Hence, a busy tone should be broadcast only after the destination has not sensed a collision for a seconds. As collision is detected by checking the CRC code in the packet header, packet header transmission time T_h must be longer than a, or

$$T_h > a. \tag{1}$$

To make the protocol more efficient, packet transmission time T_p should be longer than the busy tone duration T_1 plus

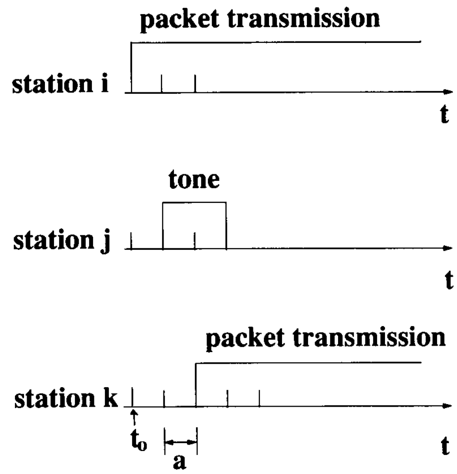


Fig. 10. Determination of T_1.

the round-trip propagation delay $2a$ or

$$T_p > T_1 + 2a \tag{2}$$

because otherwise gaps will always appear between successive packet transmissions and the acknowledgment tone will interfere with the busy tone.

To determine T_1 and T_2, consider the following cases. Let station i transmits a packet to station j at t_o. Then station j can receive the packet on or before $t_o + a$ and broadcast the assigned tone immediately. This tone can reach all of station j's neighbors before $t_o + 2a$. Hence, if a neighboring station transmits a packet towards station j's direction in $[t_o, t_o + 2a]$, a collision will occur.

Let us say in the worst case, one of station j's neighboring stations transmits a packet at $t_o + 2a - \epsilon$ (ϵ is arbitrarily small) or just before the tone arrives. That packet will reach station j at $t_o + 3a$ and cause a collision. To make sure that this collision can be detected, the tone duration T_1 must be at least $(t_o + 3a) - (t_o + a) = 2a$ s (Fig. 10) or

$$T_1 > 2a. \tag{3}$$

To distinguish T_2 from T_1, T_2 needs only be longer than T_1 or

$$T_2 > T_1. \tag{4}$$

As an example, let the transmission range R be 3 Km and the data rate be 500 Kbps. Then $a = 0.01$ ms and the header length need only be longer than 5 bits. If we choose T_1 to be 2 ms which satisfies constraint (3), then the minimum packet size from constraint (2) is 2.02 ms, or 1010 bits.

Note that a tone is just a pure sine wave at a certain frequency and theoretically occupies zero bandwidth. But the turning-on and turning-off of a busy tone make the tone signal look like an on–off keying signal. The shortest duration of a tone in our case is T_1. So the tone bandwidth is about $2/T_1$ Hz. To minimize the bandwidth occupied by the tone, T_1 therefore should be as large as possible. For a data rate of 500 Kbps, the data bandwidth is 1 MHz. If T_1 is chosen as 2 ms, the tone bandwidth is only 1 KHz. For a system using 20 tones, the tones occupy a bandwidth of 20 KHz. The total bandwidth needed is therefore only 1.02 MHz.

VI. Network Design Example

Consider a PRN with 20 randomly located stations on a 20 km $\times$ 20 km square area. Let the transmission range R be 8 km. A particular sampling gives the following station locations:

Station-number	1	2	3	4	5	6	7	8	9	10
X coordinate	8.4	16.1	13.9	3.2	1.6	3.2	18.6	14.5	14.3	17.8
Y coordinate	3.3	15.4	18.8	17.8	13.5	3.1	0.2	15.1	14.2	0.4

Station-number	11	12	13	14	15	16	17	18	19	20
X coordinate	1.0	16.5	13.1	16.3	7.8	5.7	4.6	15.4	5.5	18.8
Y coordinate	13.1	8.0	17.1	9.2	9.0	18.0	13.9	10.9	19.5	6.8

The tone assignment according to the algorithm is as follows:

Station-number	1	2	3	4	5	6	7	8	9	10
Tone-number	1	1	2	1	2	3	1	3	4	2

Station-number	11	12	13	14	15	16	17	18	19	20
Tone-number	4	5	6	7	8	5	7	9	10	10

Next, the nominal number of stations covered by a directional antenna and the angular interference margin φ are set to be three and 0.2 radian, respectively. Following the antenna assignment algorithm, the antenna coverage matrix $A = [a_{ij}]$ is determined. Here, $a_{ij} = k$ means that station j is in the coverage of the directional antenna k of station i and $a_{ij} = 0$ means station j is not a neighbor of station i. The matrix A therefore also contains the full connectivity information of the network.

$$A = \begin{matrix}
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 2 & 2 & 0 & 0 & 3 & 1 & 3 & 0 & 0 & 0 & 3 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 1 & 2 & 0 & 1 & 0 \\
0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 2 & 1 & 0 & 2 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 3 & 2 & 3 & 0 & 0 & 0 & 3 & 0 & 0 \\
0 & 1 & 2 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 3 & 2 & 3 & 0 & 0 & 0 & 3 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 1 & 1 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 2 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 2 \\
0 & 1 & 1 & 0 & 0 & 0 & 0 & 3 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 3 & 2 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 2 \\
1 & 0 & 0 & 0 & 2 & 1 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 2 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 1 & 0 & 0 & 0 & 2 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 & 2 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 2 & 1 & 0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 3 & 1 & 3 & 2 & 0 & 0 & 0 & 0 & 3 \\
0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 2 & 0 & 0 & 2 & 2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 2 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0
\end{matrix}$$

Finally, the path matrix P is constructed according to the routing rule as follows:

$$P = \begin{matrix}
0 & 15 & 15 & 15 & 15 & 6 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 \\
18 & 0 & 3 & 13 & 18 & 8 & 12 & 8 & 9 & 12 & 18 & 12 & 13 & 14 & 18 & 13 & 13 & 18 & 13 & 14 \\
9 & 2 & 0 & 13 & 13 & 3 & 8 & 8 & 9 & 8 & 13 & 8 & 13 & 8 & 13 & 13 & 13 & 8 & 13 & 2 \\
17 & 16 & 19 & 0 & 5 & 1 & 19 & 19 & 16 & 11 & 11 & 16 & 19 & 11 & 11 & 16 & 17 & 19 & 19 & 11 \\
15 & 19 & 16 & 4 & 0 & 15 & 15 & 15 & 16 & 15 & 11 & 15 & 16 & 15 & 15 & 16 & 17 & 15 & 19 & 15 \\
1 & 15 & 15 & 15 & 15 & 0 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 & 15 \\
20 & 10 & 20 & 20 & 20 & 20 & 0 & 20 & 20 & 10 & 20 & 10 & 20 & 20 & 20 & 20 & 20 & 20 & 20 & 20 \\
18 & 2 & 3 & 13 & 13 & 18 & 18 & 0 & 9 & 12 & 18 & 12 & 13 & 14 & 18 & 13 & 18 & 18 & 13 & 12 \\
18 & 2 & 3 & 13 & 13 & 18 & 18 & 8 & 0 & 12 & 18 & 12 & 13 & 14 & 18 & 13 & 18 & 18 & 13 & 12 \\
12 & 12 & 12 & 20 & 12 & 12 & 7 & 12 & 12 & 0 & 12 & 12 & 20 & 20 & 12 & 20 & 20 & 20 & 20 & 20 \\
15 & 19 & 19 & 4 & 5 & 15 & 15 & 16 & 19 & 15 & 0 & 15 & 19 & 15 & 15 & 16 & 17 & 15 & 19 & 15 \\
18 & 2 & 2 & 18 & 18 & 18 & 20 & 8 & 9 & 10 & 18 & 0 & 2 & 14 & 18 & 8 & 18 & 18 & 18 & 20 \\
18 & 2 & 3 & 16 & 19 & 18 & 18 & 8 & 9 & 9 & 16 & 18 & 0 & 8 & 18 & 16 & 19 & 18 & 19 & 18 \\
18 & 2 & 9 & 8 & 18 & 18 & 20 & 8 & 9 & 12 & 18 & 12 & 8 & 0 & 18 & 6 & 18 & 18 & 2 & 20 \\
1 & 18 & 18 & 17 & 5 & 6 & 18 & 18 & 18 & 18 & 11 & 18 & 18 & 18 & 0 & 11 & 17 & 18 & 11 & 18 \\
17 & 13 & 13 & 4 & 5 & 17 & 13 & 13 & 13 & 13 & 11 & 13 & 13 & 13 & 17 & 0 & 17 & 13 & 19 & 13 \\
15 & 19 & 16 & 4 & 5 & 15 & 15 & 15 & 16 & 15 & 11 & 15 & 16 & 15 & 15 & 16 & 0 & 15 & 19 & 15 \\
15 & 2 & 8 & 13 & 15 & 15 & 20 & 8 & 9 & 20 & 15 & 12 & 13 & 14 & 15 & 13 & 15 & 0 & 13 & 20 \\
5 & 13 & 13 & 4 & 5 & 11 & 13 & 13 & 13 & 13 & 11 & 13 & 13 & 13 & 11 & 16 & 17 & 13 & 0 & 13 \\
18 & 18 & 18 & 18 & 18 & 18 & 7 & 12 & 18 & 10 & 18 & 12 & 18 & 14 & 18 & 18 & 18 & 18 & 18 & 0
\end{matrix}$$

VII. Simulation Results

Four network samples are generated on which the performance of various protocols are compared. The stations in the network are randomly located within a 20 km × 20 km square region. The transmission range is 4 km. The nominal number of stations covered by a directional antenna and the angular interference margin are 5 and 0.2 radian, respectively. The packet generation rates are the same for all stations and the packet destinations are equally probable for all stations, excluding the source station. Let the packets be of fixed length and let the arrivals to each station be a Poisson process. The characteristics of the networks generated are summarized as follows:

Cases / Network parameters	1	2	3	4
No. of stations	80	80	40	40
ave. no. of neighbors per station	8.31	8.38	4.05	5.45
max. no. of neighbors per station	15	12	7	11
ave. no. of antennas per station	2.10	1.89	1.23	1.55
max. no. of antennas per station	4	3	2	3
No. of tones required	21	15	9	14

The protocols compared include slotted ALOHA with single omnidirectional antenna (SA), slotted ALOHA with multiple directional antennas (SA/MDA), busy tone multiple access with omnidirectional antenna (BTMA), simple tone sense (STS) and variable power tone sense (VPTS) protocols. Minimum hop routing rule is used. The normalized network throughput, or the average number of packets reaching destinations per packet transmission time is measured in the simulation. This throughput measure is different from the one-hop throughput usually given in some studies because most packets have to travel two or more hops before reaching their destinations. We assume the total bandwidth occupied by the busy tones is 2% of the total bandwidth for STS and VPTS protocols. The throughput η shown for these two protocols is the effective network throughput, which is the network throughput multiply by $(1-0.02)$. The average end-to-end delay as a function of network throughput for cases 1 and 3 are plotted in Figs. 11 and 12, respectively. The throughput-delay characteristics of cases 2 and 4 are similar and so are not shown. The maximum network throughput attained for the four station distributions (or the four cases) are obtained as shown at the top of the following page.

The maximum network throughput attained by STS has 30 to 45% improvement over BTMA on the 80 node networks. This improvement is primarily due to the use of additional directional antennas. But on the 40 node networks there is no significant improvement. Therefore, it seems that when the stations are not densely located, adding additional directional antennas does not significantly improve the network throughput. But the delay for STS and VPTS is always smaller than BTMA. When compare VPTS with STS, there is a throughput

Protocols \ Cases	1	2	3	4
SA	0.50	–	0.35	–
SA/MDA	0.71	0.69	0.40	0.39
BTMA	1.09	1.08	0.78	0.79
STS	1.42	1.57	0.79	0.80
VPTS	1.57	1.74	0.98	0.88

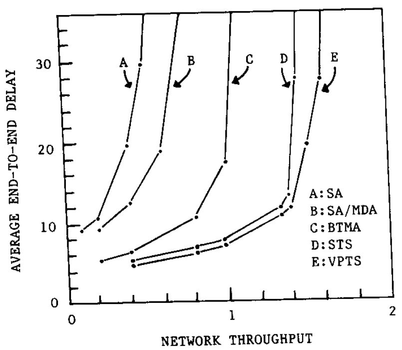


Fig. 11. Delay versus throughput for an 80 node network.

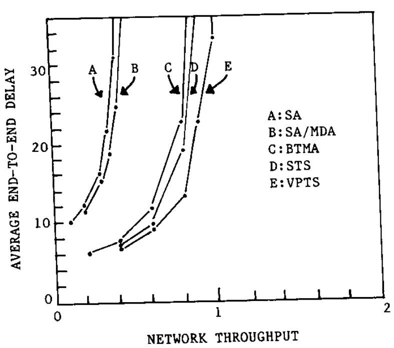


Fig. 12. Delay versus throughput for a 40 node network.

improvement around 10% on the 80 node networks. On the 40 node networks, the improvement in network throughput is 24% for case 3 and 10% for case 4. VPTS always has a smaller delay than STS.

VIII. Conclusion

Due to bandwidth limitation, throughput efficiency is of primary concern in the design of multihop PRN's. This paper is an attempt to give a design methodology as well as two efficient transceiving protocols, the STS and VPTS, for PRN. Algorithm for assigning tones and for determining the orientation and broadcasting angles of the directional antennas are also designed. Simulation result shows that the STS protocol performs better than the BTMA protocol, especially when the traffic is heavy. But VPTS gives still better throughput-delay performance.

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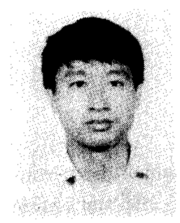

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