Multi-hop Radio Networks in Rough Terrain: Some Traffic Sensitive MAC Algorithms

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Abstract

An exciting application of Multi-hop Packet Radio Networks (MPRNet) is to provide communication services in environments without suitable infrastructure. One key design issue in MPRNet is the formulation of Medium Access Control (MAC) protocols. In this paper, the performance of two MAC protocols, Slotted ALOHA (S-ALOHA) and Spatial TDMA (S-TDMA), are investigated. A finite number of buffered nodes were used in the evaluation of these MAC protocols. By definition, optimum network performance is achieved when the average packet delay is minimized.

For S-ALOHA, nodes transmit at random with some given probability *q*. We investigate the selection of *q*. Finding an assignment in terms of the traffic load and the connectivity, which yields a near optimal packet delay performance.

A novel systematic procedure to find transmission schedules in S-TDMA based on the connectivity is also described. The traffic-sensitive schedules show better performance in comparison to the classical S-TDMA.

1 Introduction

A very attractive alternative for communications in areas without telecommunication infrastructure is to use wireless ad-hoc networking. This is, a network formed without central administration which consists of nodes that use a wireless interface to send packet data. One type of wireless ad-hoc networks is a self-organizing store-and-forward packet radio system. Rural and emergency communications in developing countries, mobile users, and military tactical networks are typical examples of such systems. Such a network consists of a number of communicating radio units, nodes that are geographically spread out over a given area. In many MPRNet, not all packet radio nodes can communicate directly because of interference, range limitations, or natural obstacles. In this situation, a packet transferred between two distant nodes may have to be relayed by intermediate stations or nodes. In multi-hop packet radio systems[1], a message may travel long distances by means of the store-and-forward mechanism: a node transmits to another node, which in turn forwards the packet. This procedure is repeated until the packet arrives at its final destination.

Major design issues in these networks involve the "path finding" methods, i.e. routing algorithms, and the selection of the Medium Access Control (MAC) protocols (multi-access problem) that determine which nodes share the channel to transmit their packets. In this paper we will focus on the second issue, the multi-access strategy. Also, the transmitted power and directional antennas have been addressed as important parameters in the design of MPRNet [4][14].

The classic approach to multi-access in packet radio systems is to use “contention” or Random TDMA (Time Division Multiple Access) protocols such as ALOHA and CSMA[2-4]. In these schemes the nodes make independent and randomized transmission decisions for each packet transmission. The advantage of these schemes is mainly their simplicity. They require no other coordination between the nodes and provide rather acceptable performance at low traffic loads, i.e. when efficient resource utilization is not a major concern.

Since random MAC protocols exhibit comparatively poor performance in high load situations: "conflict-free" multiple access has been proposed [5-9] to ensure that a packet transmission, whenever made, is successful. In [5], the channel access protocol Spatial TDMA (S-TDMA) for multi-hop radio systems is proposed. The term spatial refers to the spatial reuse property of the radio networks, i.e. multiple nodes may be allowed to transmit simultaneously as long as they do not "interfere" with one another.

The design of S-TDMA algorithms has received some attention in the literature. Short (low delay) link schedules adapted to the traffic pattern have been discussed [6-10][14]. Distributed implementation of S-TDMA has also been proposed in [9]. Most early contributions in the field describe the network as a binary graph, i.e. two nodes are either connected and able to communicate reliable, or disconnected and not even able to disturb the transmissions of one another. Schedules were based on pairwise link compatibility. More realistic models incorporating radio propagation conditions have been proposed [3]. In radio environment, interference can be generated by a node that is beyond communicating range, hence the binary graph model is deficient. This shortfall has been overcome in [7][10]. In the latter two references, schedules for MPRNet in actual (or simulated) terrains were studied. In this paper we will investigate, the average delay associated with two multiple access schemes: S-ALOHA protocol and the S-TDMA strategy. We will evaluate the performance of the MPRNet, in a synthetic (random) terrain utilizing a detailed radio propagation model [11], which takes the terrain shadowing into account. The paper is organized as follows: Section 2 describes our simulation model and assumptions, while Section 3 illustrates the type of results obtained for multi-hop slotted ALOHA protocols using a novel transmission probability assignment scheme. Our simulation results show that the average delay can be decreased considerably by taking the traffic load and the connectivity into consideration in comparison with the classical approach. Section 4 is devoted to the spatial TDMA protocols, where new ways of creating transmission schedules are proposed. Finally, Section 5 contains some concluding remarks.

2 System Models

2.1 Link quality modeling

Traditionally [5], the topology of MPRNet can be represented by a graph. The graph, G = (N, L), contains a set of nodes N and a set of radio links, L. Each radio link in L corresponds to an ordered pair of nodes, i.e. (i,j), and indicates that transmission from i can be heard with an adequate signal energy at j, or expressed concisely (i,j)$\in$ L. The connectivity, depends on many factors (e.g., the transmitted power). The networks studied in this paper consists of a collection N of nodes spread randomly over a (synthetic) terrain. The terrain height variations are modeled by a stationary two-dimensional random process, H(x,y), in the locations (x,y)

$$H(x,y) = \sum_{k=-x_0}^{x_0} \sum_{l=-y_0}^{y_0} \left| H^*(x-k, y-l) \right| \cdot p(k,l),$$

where H*(x,y) is a two-dimensional white Gaussian process with zero mean and variance σ (height parameter), and where p(x,y) can be seen as the impulse response of a filter given by:

$$p(x,y) = \begin{cases} 1+\cos\left(\pi\left(\dfrac{x^2}{(\rho+1)^2}+\dfrac{y^2}{(\rho-1)^2}\right)\right) & |x| \le (\rho+1), \quad |y| \le (\rho-1) \\ 0 \quad \mathit{otherwise} \end{cases}$$

where ρ is referred to as the smoothness parameter in meters. Figure 1 shows a realization of such a terrain.

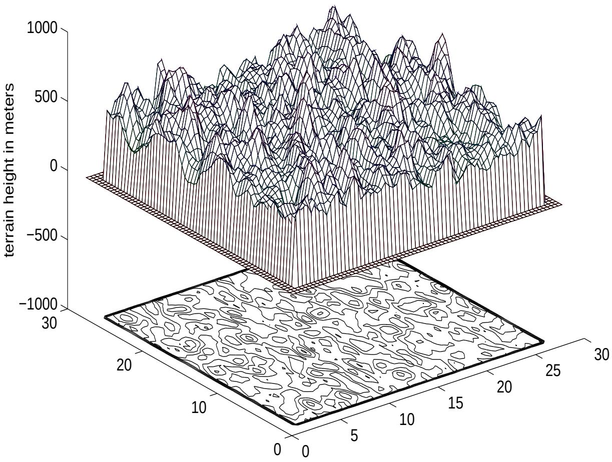

Figure 1**:** Plot of terrain realization. $\sigma = 40$ meters, $\rho = 3$ meters. Heights vary between 0 and 1200 meters, and the area is 28x28 km^2. (Vertical scale strongly exaggerated).

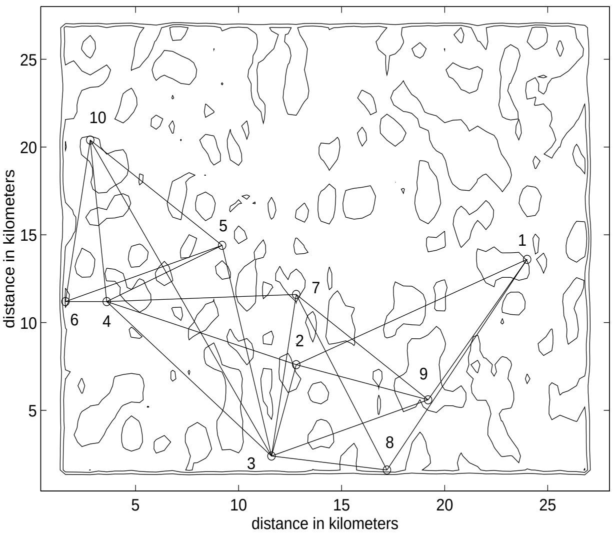

Figure 2: Typical network realization in terrain in fig 1. N=10. The lines represent the connections amomg the nodes.

2.2 Connectivity model

In the terrain a network of N randomly uniformly distributed nodes will be considered. Nodes i and j, with i, j$\in \{1,2,\ldots,N\}$ are either connected by a link or disconnected, depending on the propagation loss between the nodes. The propagation effect is modeled by link gains where G_{ij} [7] denotes the power (propagation) gain on the link between nodes i and node j, and is derived from the terrain model. Note that even though the network, in principle, is fully connected, many links can be characterized by a very low gain (high loss) and establishing a communication link may not be possible if an adequate signal energy at the receiver is required. In the follows, we assume a simple connectivity model where if the propagation loss in a given link (i,j) is larger than some *threshold path loss G_o*, communication cannot be sustained, i.e., no connection exists along the link between node i and j. We will assume G_0 = -130dB [14]. Using this criterion the connectivity diagram for a sample networks is shown in Figure 2. The study was confined to connected networks, i.e., networks where every node can be reached.

On other hand, the Signal-to-Interference-Ratio (SIR) is commonly used as a measure of the link quality. For a link (i,j) we introduce the SIR, Γ_{ij}, when node i transmits with power P_t, to node j:

$$\Gamma_{ij} = \frac{P_t G_{ij}}{N_r + I} = \frac{P_t G_t G_r}{(N_r + I) L_b} \tag{1}$$

w[illegible] gain at the transmitter site, G_r is the antenna gain at the receiver site, L_b is the transmission path-loss between node i and node j, N_r is the noise power, and I is the interference power.

In order to have a reliable link a minimum SIR is required, referred to as the SIR threshold γ_0 or the SIR target. Thus, in order to model the effect of the interference at a given receiving site, we consider a packet to be correctly received if its received signal exceeds the sum of the power of the other colliding packets by at least γ_o dB (capture property). When we consider the capture effect, a slotted access scheme is assumed and a packet from node i is successfully received at node j if the SIR from Eqn. 1:

$$\Gamma_{ij} = \frac{P_t G_{ij}}{N + \sum_{k \neq i} I_k} = \frac{P_i G_{ij}}{N + \sum_{k \neq i} G_{kj} X_k P_k} \tag{2}$$

is greater than the threshold γ_o, otherwise the packet is lost. Here we have introduced the binary variable

$$X_k = \begin{cases} 1 & \text{node k transmits} \\ 0 & \text{node k does not transmit} \end{cases} \tag{3}$$

2.3 Traffic & Routing [6] [12]

We assume that packets are of constant length and arrived according to a Poisson process with total (external) arrival rate λ packets/time slot. Furthermore we assume the traffic load to be even, i.e. on the average each node

$$\lambda_i = \lambda/N \qquad i \in \{1, 2, .. N\} \tag{4}$$

The traffic originated at node i destined to node j, is denoted μ_{ij}. Assuming the destinations to be random and uniformly distributed, we have

$$\mu_{ij} = \begin{cases} \dfrac{\lambda_i}{N-1} & i \neq j \\ 0 & i = j \end{cases} \tag{5}$$

Furthermore, we might consider the number of paths using a particular available link. Denote the number of paths that use the link (i,j) as $P^{(ij)}$, in a connected network. We can easily see that the traffic in link (i,j) is:

$$\lambda_{ij} = \frac{\lambda}{N(N-1)} P^{(ij)} \tag{6}$$

It should be noted that some λ_{ij} = 0 when the link (i,j) is not usable or unreliable. Thus, our ”load matrix” is defined as $\mathrm{P} = \{P^{(ij)}\}$, where $P^{(ij)}$ is also an undirected measure of the amount of traffic load that can be expected to transverse the link (i,j). Moreover, we introduce $P^{(i)}$, the estimated amount of traffic passing through each node i as:

$$P^{(i)} = \sum_{j=1,\, i \neq i}^{N} P^{(ij)} \tag{7}$$

The routing scheme used is the Minimum hop Routing Algorithm (MHA), i.e. minimizing the number of hops in a multi-hop “connection”. The routing is static, and is independent of the MAC protocol and the actual traffic flows. Nodes are assumed to have infinite buffer size for intermediate storage of packets. The average number of neighbors $\overline{N}$ goes under the name network connectivity.

2.4 Performance measure

The main performance measure of interest is the average expected end-to-end packet delay. The end-to-end packet delay is defined as the time between the arrival of a packet at the buffer of the originating station and the end of the slot in which is successfully received at the final destination. In a network of *N* nodes, in general, a randomly selected packet to be transmitted from node i to node j has the delay D_{ij}, expressed in timeslots. Since D_{ij}, is a random variable, one must resort to make statistical interference of D_{ij} by means of its expected value $E[D_{ij}]$.The average expected delay for all source-destination pairs is given by

$$\overline{D} = \frac{1}{\binom{N}{2}} \sum_{j=1}^{N} \sum_{i=j+1}^{N} E[D_{ij}] \tag{8}$$

In general, $\bar{D}$ is a function of the traffic load and the terrain parameters, which influence the connectivity of the network. Simulations have been used to evaluate the expected packet delay in the same terrain that with a varying height scale to simulate different terrain roughness. 10 nodes have been randomly dispersed over this terrain until a connected network was found, i.e., a network where every node is reachable at least in a finite number of hops. Three such random networks, denoted A, B, C are used in the numerical examples below.

Furthermore, given the matrix gain, a sample network and a simple routing policy (MHA), we can now examine the multi-hop MAC protocols under study. We also assume that all the node transmit with constant power level P and they are equipped with omnidirectional antennas.

3 Numerical Results on S-ALOHA

Slotted ALOHA [2][3][4] is a random access protocol, where nodes are allowed to transmit packets only at the start of a time slot. We assume that a node will try to transmit whenever it holds a packet in its queue, and that the node transmits a packet according to a Bernoulli process with parameter q in a slot. The term q goes under the name *transmitting probability*. Since there is no coordination among the nodes, collision (overlapping in time at the receiver of packets sent by two or more different nodes) can occur. However, when two or more packets arrive at the receiver at the same time, either a collision occurs (i.e. no packet can be successfully detected) or the strongest packet, (i.e. the packet with largest received power) can survive if the SIR is above a SIR target. Nodes can detect collisions by various mechanisms, e.g., a node transmitting a packet is advised of the correct reception by explicit acknowledgment message sent by the receiving node. If the transmitter does not receive this acknowledgment after an appropriate interval, it presumes that a collision has taken place. Here, the time that a node takes to receive an acknowledgment is neglected, such that each node is assumed to know immediately after it transmitted its packet whether the reception was successful or not. Once the transmitting station detects a collision, it retransmits the packet after a random amount of time and continues to do so until the packet has been successfully received. Conversely, when the node receives an acknowledgment the packet under transmission is removed from the queue.

We are also reminded that the single-hop S-ALOHA can be considered as a fully connected network. This can be considered to be equivalent to the case where all nodes transmit packets over a common broadcast radio channel to a central receiver. If a packet is successfully receive at the central node an acknowledgment is sent to the transmitting node. On the other hand, in a multi-hop S-ALOHA system, nodes are allowed to transmit to each other directly, i.e. there is no central receiver which ”repeats” packet to the intended node. However, the multi-hop topology adds another possibility for packet collisions. This might occur when a node transmits to another node, which is also transmitting in the same slot. S-ALOHA for networks can be seen a generalization of S-ALOHA for single-hop networks. Unless otherwise stated here, the term S-ALOHA refers to the multi-hop S-ALOHA.

3.1 Traffic Sensitive Slotted ALOHA

In the design of an S-ALOHA network, it is valuable to find a simplified way of choosing a proper value of q. In seeking a coherent policy for assigning transmission probabilities with this protocol, we investigate a few possible candidates in order to estimate a "good" q[10]:

- Strategy I: $q^{I} = 0.54 - 0.17\lambda\ \bar{N}$ (9)
- Strategy II: $q^{II} = q^{i} = 1/N^{i}$ (10)
- Strategy III: $q^{III} = q^{i} = f_{d} P^{(i)} / N^{i}\bar{P}$ (11)

First, in Strategy I, we consider the assignment of the same transmission probability (q) to every node in the network. A straightforward procedure that comes to ones mind is to utilize the inverse of the average number of neighbors ($\bar{N}$) in a network as a "good guess" value for q. Unfortunately, the policy $q = 1/\bar{N}$ seems to give a rather poor estimates of the q*, which is the q that minimizes the packet delay $\bar{D}$.

Next, we turn our attention to another type of transmission probability assignment, namely where the transmission probability for each node can be different. This approach seems interesting since some studies [13] suggest that throughput optimization for S-ALOHA is achieved by an adaptive node transmission probability assignment policy. Then, our second strategy could be to assign the transmitting probability for node i as, $q^{i} = 1/N^{i}$, where N^{i} is the number of neighbors of node i. Moreover, in Strategy III we can weight each node transmitting probability using the information of the load matrix introduced in Section 2.3. In other words, we may add the impact of the load matrix in the selection of the node transmitting probabilities, assuming that q^{i} is proportional to the estimated traffic that passes through each node. In equation (11), we have introduced the scaling factor f_q, which may ”tune” the node transmission probability to the traffic load variation.

Figures 3 and 4, the network delay is depicted for the three assignment policies mentioned above. In our sample networks, the simulation results show that Strategy II performs poorly in comparison with the Strategy I (curve d) as illustrated in Figures 3 and 4.

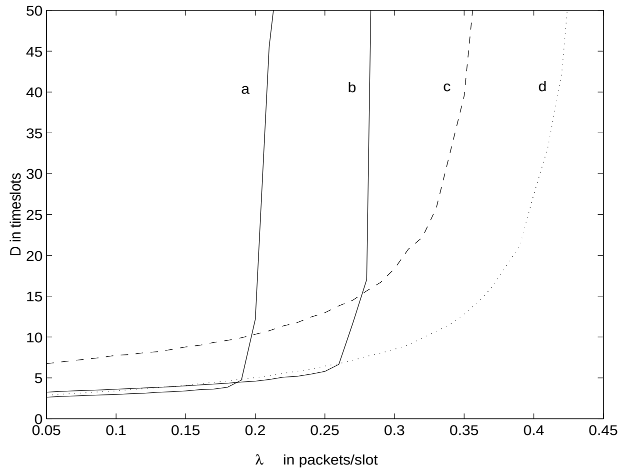

Figure 3: Packet Delay vs. traffic load (Network A, $\sigma = 40$ m, $\rho = 3$ m. γ_o = 10dB). S-ALOHA. Strategy III a: f_q =1.75, b: f_q =1.50. Strategy II: curve c , Strategy I: curve d.

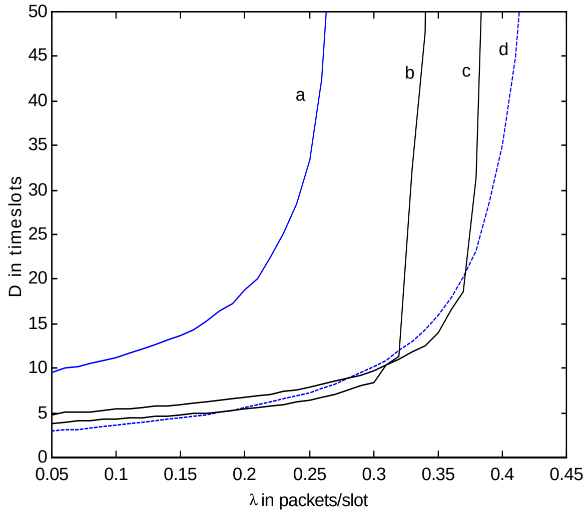

Figure 4: Packet Delay vs. traffic load (Network B, $\sigma = 40$ m, $\rho = 3$ m. γ_o = 10dB). S-ALOHA. Strategy II: curve a. Strategy III b: f_q =1.50, c: f_q =1.25, Strategy I: curve d.

This is because Strategy II does not take into account the traffic load situation at all. Besides, we can see that the Strategy II performance is usually inferior to the other approaches. Generally speaking, the Strategy III whether exhibits slightly better or similar performance than Strategy I for low load traffic load. This is probably due to the fact the Strategy III (we may suggest f_q = 1.25**)** is more adaptive to the for low traffic load situation in comparison with Strategy I. However, in our sample networks, we have achieved better overall network performance with Strategy I, because this is an integrated approach which includes the traffic load (λ) and the connectivity $\overline{N}$. Moreover, the Strategy I has been obtained in a more general basis, there is a specific procedure [10] to calculate the near q^*, and it is more robust and stable then. Of course, an optimal adaptive transmission probability policy should always be better than Strategy I. Moreover, we may see Strategy I as a sort of "envelope" of the Strategy III.

4 Numerical Results on S-TDMA

S-TDMA for multi-hop packet radio networks is a generalization of TDMA for single-hop networks. Its aim is to provide a conflict-free transmission schedule that gives each link at least one slot. In order to explain better how S-TDMA works, we need a set of proper terms. The terms we will use are: *arc*, *clique*, and *schedule* [5, 9]. Arc represents one-way radio communication between two nodes. Furthermore, a clique allows all its member arcs (unidirectional links) to simultaneously transmit successfully. A maximal clique is one in which no additional arcs can be added.

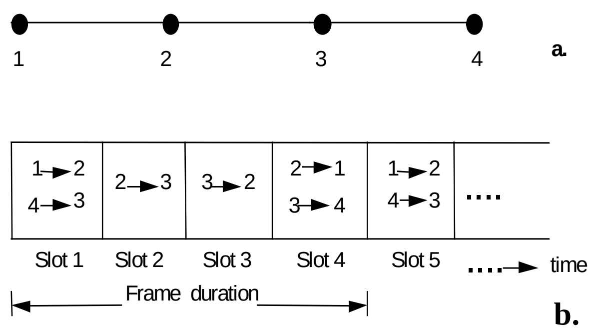

Figure 5: Basic terms used in S-TDMA a. A tandem network of four nodes. b. Schedule of the tandem network. 2→3: node 2 transmits and node 3 receives.

There is two ways of slot allocation strategies for TDMA: node assignments and link assignments. We will focus on the latter one. Slots can be assigned to transmitter (transmitter scheduling) or individual (unidirectional) links (link scheduling). Figure 5.a illustrates a tandem network of four nodes with all possible radio links indicated by lines connecting the nodes. In this network it would, for example, seem feasible to reuse the time slots used for communication on the links (arcs) 1→2 and 4→3, whereas 2→1 and 4→3 would probably not be able to share the same slot.

In this example, we assume that the transmission range from a node is just enough to "reach" each one of its one-hop neighbors. In general, S-TDMA defines a period of arcs transmissions, called *schedule* (a repetitive pattern of time-slots of finite length.*)* in such a way that not conflicts occur. Figure 5.b illustrates the schedule for the given tandem network. The frame duration, expressed in slots, will be termed F_d (Figure 5.b). In this case F_d = 4 slots, so in the slot number five the same cycle starts once more. If an arbitrary number is assigned to the arcs in

Fig. 5, we might represent them as: arc 1: 1-->2; arc 2: 2-->3; arc 3: 3-->4; arc 4: 4-->3; arc 5: 3-->2; arc 6: 2-->1. We denote by S_x the schedule of network x. The schedule of the tandem network, S_{tandem} corresponding to Figure 5.b is:

$S_{tandem} = \{arc\,1\,\&\,\text{arc } 4, \text{arc } 2, \text{ arc } 3\,\&\,\text{arc } 6, \text{arc } 5\}$

In general, from the path loss and connectivity models is possible to determine in which combination arcs can be used simultaneously without conflicts. The compatibility between arc i and arc j is represented by the element $cm^{(ij)}$ in the so-called Compatibility Matrix (CM), which is defined as [5]:

$$cm^{(ij)} = \begin{cases} 1 & \textit{if arc j can be activated in clique i} \\ 0 & \text{otherwise} \end{cases}$$

Figure 6 shows the compatibility matrix for the tandem network under study.

$$CM = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}$$

Figure 6: Compatibility matrix of the tandem network in Figure 5.

When designing S-TDMA algorithms, scheduling delays of arcs should be made as small as possible. This could be achieved by *minimizing the cycle length* of transmission schedule. Thus, in the classical approach, the objective is to find a link-activation schedule of *"minimum-length"* that satisfies the specified communication requirements.

4.1 The Algorithm of creating S-TDMA Basic Schedule (BS)

The procedure for the creation of the Basic Schedule is:

Step 1: Calculate the compatibility matrix (CM) using the Gain matrix and the routing. BS is the empty set.

Step 2: Create a list of arcs which contains all the arcs of the MPRNet.

Step 3: Add the row of the CM corresponding to first element of the list of arcs to the BS. This row contains a clique which includes the arc that can be activated simultaneously from the list of arcs.

Step 4: Remove all arcs of the list which are now listed in the BS.

Step 5: Repeat from Step 3 until the list of arcs is empty.

4.2 Traffic Sensitive Spatial TDMA

Utilizing traffic-sensitive S-TDMA schedules [6], where the slot assignment is dependent on the amount of traffic $P^{(i)}$ in each node i, is one way to further improve network performance. The approach suggested in this work is a combination of the basic S-TDMA protocol proposed in [5], together with some extra slots allocated to the heavier loaded arcs to a great extend similar to the study in [6]. Besides, the traffic sensitive S-TDMA schedule will be termed Enhanced Schedule (ES). The algorithm we propose to create this kind of schedule has 7 steps:

Step 1**:** Compute the Basic Schedule (BS) of the net under study (Obtain F_d). For each node i obtain $P^{(i)}$.

Step 2**:** Select the maximum $P^{(i)}$, we name it, P_{max}. Choose M_{max} =# of neighbors of the node with the P_{max}.

Step 3**:** Reckon the Node Factor (NF) associated with node i, NF (i) = $\left\lceil \frac{P^{(i)} M_{max}}{P_{max}} \right\rceil$ where $\lceil x \rceil$ denotes the smallest integer greater or equal to x.

Step 4: Compute the duration of the traffic-sensitive frame as $F_{ES} = \sum_{i=1}^{N} NF(i)$

Step 5: Subtract F_{ES} - F_d. These are the *resultant or extra slots* that could be added to the BS.

Step 6: Calculate the slots needed of each arc as follows: Slots needed by link (i,j) = $P^{(ij)}$ NF(i) / $P^{(i)}$

Step 7: Assign the "*extra timeslots"* (Step 5) to the arcs who need to complete their slots needed according to the traffic load. Add those cliques (with highest number of additional arcs as it is possible) which contain to the selected arc into the BS to have the *ES*.

In Figure 7, we can see that average delay (Network C) can be decreased considerably by taking into the account the traffic load in comparison with the BS.

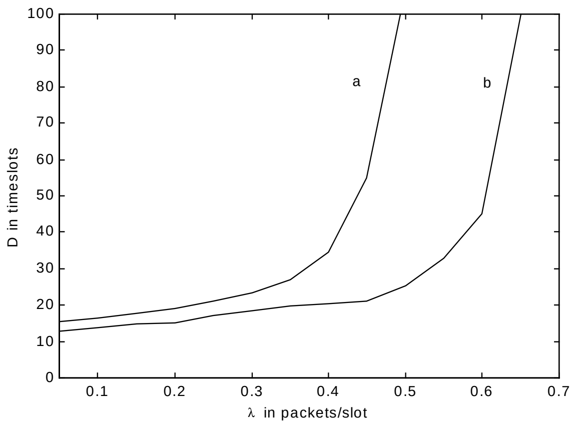

Figure 7: Packet Delay vs. traffic load. (Network C, $\sigma = 40$ m, $\rho = 3$ m. $\gamma_o =$ 10 dB. S-TDMA. a: Basic Scheduling S_C, b: Enhance Scheduling, S_C^{ES} .

5 Conclusions

In this paper two different kinds of channel access protocol in multi-hop packet radio network in rough terrain have been investigated: S-ALOHA and S-TDMA. In some sense these two protocols are extremes among all the MAC protocols. We use a fixed routing strategy, the Minimum Hop Algorithm and network topologies of 10 nodes.

A non-binary connectivity, that includes a detailed radio propagation model which takes the interference screening of the terrain obstacles into account, together with a simple model of queues in each node were the basis of the evaluation of the two MAC protocols. Thus, we mainly study through computer simulations the effect of various factors (terrain profile, propagation model, transmission probabilities/schedules and traffic load) on the *average expected delay*.

The two major contributions were:

- Two simple strategies that adjust S-ALOHA transmission probability, for each node, based on the number of neighbors and current traffic load failed to improve network performance. The strategy assigning the same value of transmission probability for every node performs best. The transmission probability was based on the average number of neighbors and the total traffic load.
- A new scheduling algorithm for S-TDMA which significant improves network performance in MPRNet. The simulation results show an improvement of up to 30% in comparison with the Basic Schedule. This improvement is achieved by utilizing interference and the traffic load knowledge.

Thus far interference and traffic load have been considered in S-TDMA scheduling, however power control and routing have not yet been addressed. Hence further enhancements are possible.

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