Traffic Sensitive MAC Algorithms in Multi-hop Radio Networks

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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. In many MPRNet, the traffic load can vary considerably from link to link. We considered improving the network performance by incorporating traffic load information into the MAC protocol design. In S-ALOHA, nodes transmit at random with some specified probability q. By defining q in terms of traffic load and connectivity near optimum performance was achieved. For S-TDMA the design of transmission schedules was considered. A systematic procedure, for generating schedules, based on the connectivity is described and this procedure was enhanced considerably by utilizing traffic load information. The resulting traffic-sensitive schedules markedly improved network performance.

I. INTRODUCTION

A very attractive alternative for communications in areas in which there is little or no telecommunication infrastructure is to use Multi-hop Ad hoc radio networks. Ad hoc Networks are a collection of wireless stations forming a (temporary) network without the use of any existing infrastructure or centralized administration. One type of Ad Hoc networks is a self-organizing store-and-forward packet radio system. Rural communications in developing countries, and military tactical networks are typical applications. These networks usually carry packets of data between nodes equipped with radio transceivers and omnidirectional antennas. In many Multi-hop Packet Radio Networks (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 [1]. 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 that determine how nodes share the channel to transmit their packets. Besides, since usually in MPRNet there is an unbalanced traffic load on each node, we considered improving the network performance by incorporating traffic load measurements into the MAC protocol design. In this paper we will focus on traffic-sensitive multiple access for two study cases: S-ALOHA (Slotted ALOHA) and S-TDMA (Spatial TDMA).

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 [2][3] and CSMA. These random access protocols provide rather acceptable performance at low and moderate traffic loads. Since random MAC protocols exhibit comparatively poor performance in high load situations so "conflict-free" multiple access have been proposed [4] to ensure that a packet transmission, whenever made, is successful. The design of S-TDMA algorithms has received some attention in the literature [4-7]. Most early contributions [4-5] 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. In radio environment, a node that is beyond communicating range can generate interference, hence the binary graph model is deficient. This shortfall has been overcome in [6][7].

In this paper, we evaluated the performance of the MPRNet, in a synthetic (random) terrain utilizing a detailed radio propagation model [8], which takes the terrain shadowing into account. The paper is organized as follows: Section II describes our simulation model and assumptions, while Section III contains simulation results obtained for multi-hop S-ALOHA protocols using a novel transmission probability assignment scheme. Section IV is devoted to the S-TDMA protocols, where new ways of creating transmission schedules are proposed. The simulation results show that traffic controlled S-TDMA improves the network performance in comparison with the non traffic-sensitive traditional approach. Finally, Section V contains some concluding remarks.

II. SYSTEM MODELS

A. Terrain Model

The networks studied in this paper consist of a collection N of nodes spread randomly over a given (synthetic) terrain. The terrain height variations are generated by means of a two-dimensional white Gaussian process, $H^*(x,y)$ with zero mean

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and variance s (height parameter with units in meters). The absolute value of $H^*(x,y)$ is filtered to yield the terrain heights:

$$H(x,y) = \sum_{k=-x_0}^{x_0} \sum_{l=-y_0}^{y_0} \left| H^*(x-k, y-l) \right| \cdot p(k,l) \quad (1)$$

i.e. $p(x,y)$ is the response of the smoothing filter, defined as:

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

we can refer to r as the smoothness parameter with units in meters. Figure 1 shows a realization of such a terrain. In our simulations, only one realization, of the random process above, was used. In Figure 2, two random networks, denoted A, and B which were used in the simulations.

B. Link Quality and Connectivity Model

In the given terrain a network of N randomly uniformly distributed nodes will be considered. Nodes i and j, with $i, j \in \{1,2,...,N\}$ are either connected by a link or disconnected, depending on the propagation loss between the nodes. The propagation effect is modeled by the link gains G_{ij} [7] which are derived from the terrain model. G_{ij} denotes the power (propagation) gain on the link between nodes i and node j. We also assume that all the nodes transmit with constant power level P_t, a single frequency for the whole network is used, and they are equipped with omnidirectional antennas. Furthermore, 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, G_{ij} , when node i transmits with power P_t, to node j. In order to have a reliable link a minimum SIR is required, referred to as the SIR threshold g_0. 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 g_0 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:

$$\Gamma_{ij} \ge \frac{P_t G_{ij}}{P_{Noise} + \sum_{k \ne i} I_k} = \frac{P_t G_{ij}}{P_{Noise} + \sum_{k \ne i} G_{kj} X_k P_t} \quad (3)$$

is greater than the threshold g_0, otherwise the packet is lost. Here we have introduced the binary variable

$$X_k = \begin{cases} 1 & \text{node } k \text{ transmits} \\ 0 & \text{node k does not transmit} \end{cases} \quad (4)$$

where I_k is the interference power of station k and P_{Noise} is the background noise power level at j. If packets can be successfully transmitted between two nodes while there is not interference from any other node then those two nodes are connected. A path is a set of links connecting a set of nodes sequentially. A network is said to be connected if there is exists a path between node i and node j for every $i, j \in \{1,2,\ldots,N\}$.

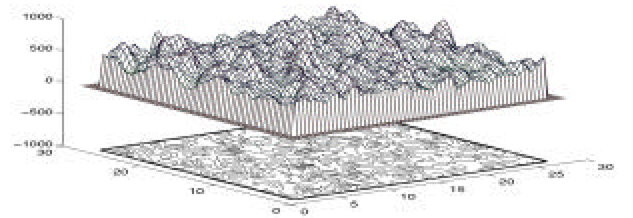

Fig. 1: Plot of terrain realization. $s = 40$ m , ρ = 3 m. Heights vary between 0 and 1200 meters, and the area is 28x28 km^2. (Vertical scale in meters).

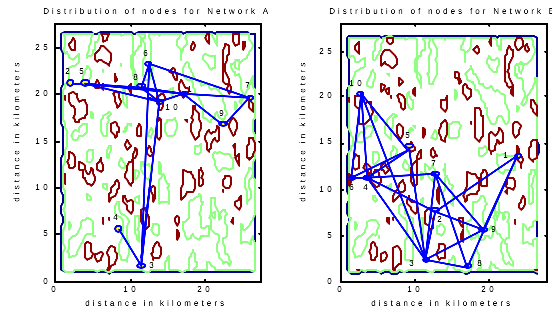

Fig. 2: Typical network realizations in terrain in Fig 1. N =10 nodes. The lines represent the connections among the nodes.

The study was confined to connected networks, i.e., networks where every node can be reached from another one with a finite number of hops. Furthermore, nodes are assumed to have infinite buffer size for intermediate storage of packets. Network connectivity $\overline{N}$ is defined as the average number of neighbors.

C. Traffic and Routing

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

$$l_i = l/N \qquad i \in \{1, 2, .. N\} \quad (5)$$

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

$$l_{ij} = \frac{l}{N(N-1)} tm_{ij} \quad (6)$$

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

$$T(i) = \sum_{j=1, i \ne j}^{N} tm(ij) \quad (7)$$

The routing scheme used is the Minimum Hop Routing

Algorithm (MHA), i.e. minimizing the number of hops in a multi-hop "connection.

D. 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 node and the end of the slot in which it 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

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

Simulations have been used to evaluate the expected packet delay since MPRNet are hard to track analytically. Ten nodes have been randomly dispersed over this terrain until a connected network was found, see Fig. 2. Discrete event simulations were performance using the models described in section II. The simulation parameters are displayed in Table I.

TABLE I
SIMULATION PARAMETERS USED FOR THE PERFORMANCE EVALUATION

Parameter	Value
Number of Nodes (N)	10
Transmitter Power (P_t)	-5 dBW
Frequency	300 MHz
Antenna Gains (G_t, G_r)	3 dBi
Antenna height	20 m
Packet Size	40 Bytes
Data Rate	100 Kbps
External Packet Arrival	Poisson Distributed
Packet Destination	Uniform Distributed
Routing Algorithm	Minimum Hop Algorithm (MHA)
Threshold path loss	130 dB
SIR Threshold	γ_0 = 10 dB
Equivalent Receiver Noise Bandwidth	100 KHz
Receiver Noise Figure	15 dB
Number of simulated arrival events	10,000
Warm-up period (slots)	1,500
Number of independent runs	100

III. NUMERICAL RESULTS ON S-ALOHA

Slotted ALOHA [4][5] is a random access protocol, where nodes are allowed to transmit packets only at the start of a time slot. In S-ALOHA [5] the nodes transmit their packets with a certain probability *q* in every timeslot, whenever there is one ready for transmission. 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) survives if the SIR is above the SIR target. S-ALOHA for multi-hop packet radio 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.

A. 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* [9]**.** Description of what the strategies do is the following:

1. Strategy *I*: It is an assignment policy where the transmission probability (*q*) is a linear function in λ. Every node uses the same *q*. The numbers used, in Strategy *I*, were derived by means of the simulation of 50 random networks with different traffic loads. Then, we collected the optimal *q* (q*), which is the *q* that minimizes the packet delay $\overline{D}$. Additionally, we approximated q using linear regression of data gathered.

Strategy I: $q^I = 0.54 - 0.17\lambda\ \overline{N}$ (9)

2. Strategy *II*: It is an assignment policy where the transmission probability (*q*) is an inverse function of number of neighbors of node *i*, N^i. Every node may use a different *q*. Let us denote the transmission probability of node i, q^i

Strategy II: $q^{II} = q^i = 1/N^i$ (10)

3. Strategy *III*: It is an assignment policy where the transmission probability (*q*) is a function of relative traffic handled by a node. Here the node *i* uses a particular *q, denote* q^i accordingly to (11)

Strategy III: $q^{III} = q^i = k\,T(i)/\,\overline{T}\,N^i$ (11)

where *k* is a constant, $\overline{T}$ is the average amount of traffic passing through the nodes of the network, and $T(i)/\overline{T}$ is the normalized traffic load handled by node *i*. In the third Strategy we weighted each node transmitting probability using the information of the load matrix introduced in Section II.C. Optimal network performance is achieved when the average packet delay is minimized.

The simulation results for S-ALOHA using the three strategies under consideration are shown in Figures 3 and 4. See Table I for the simulation parameters. In those figures, the network delay is depicted for the three assignments policy mentioned above. The Strategy I yields the highest performance. The simulation results in Strategy II show the poorest network performance.

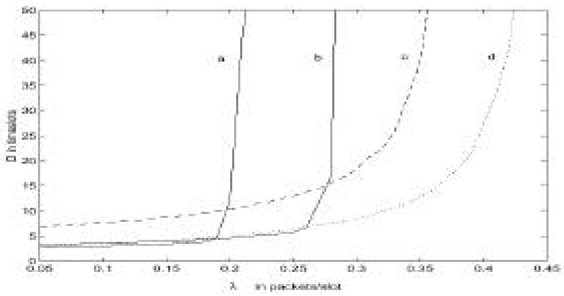

Fig. 3: Packet Delay vs. traffic load (Network A, s = 40m, r =3m). S-ALOHA. Strategy III a: k =1.75, b: k =1.50. Strategy II: curve c, Strategy I: curve d. The network connectivity is $\overline{N}$ = 3.2.

Generally speaking, the Strategy III exhibits slightly better or similar performance than Strategy I for low load traffic. This is probably due to the fact the Strategy III is more adaptive for low traffic load than 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 network connectivity.

IV. 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 Figure 5.a a linear network of four nodes is depicted, with all possible radio links indicated by lines connecting the nodes, and it will be used for illustration. In this network it would, e.g., seem feasible to reuse the time slots used for communication on the unidirectional links (so-called 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. As a matter of fact, S-TDMA defines a period of arcs transmissions, called *schedule* (a repetitive pattern of time-slots of finite length) in such a way that no conflicts occur. Figure 5.b illustrates the schedule for the given linear 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 the schedule. Then the schedule for the network under study is: $S = \{arc\ 1\ \&\ arc\ 4, arc\ 2,\ arc\ 3\ \&\ arc\ 6, arc\ 5\}$.

In general, from the path loss and connectivity models it is possible to determine in which combination arcs can be used simultaneously without conflicts. Furthermore, we introduce the term clique as a set of arcs allowing all its members to simultaneously transmit successfully. A maximal clique is one in which no additional arcs can be added without creating a conflict. The compatibility between arc i and arc j is

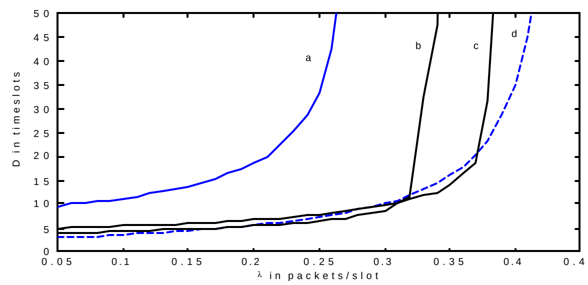

Fig. 4: Packet Delay vs. traffic load (Network B, s = 40m, ρ=3 m). S-ALOHA. Strategy II: curve a. Strategy III b: k =1.50, c: k =1.25, Strategy I: curve d. The network connectivity is $\overline{N}$ = 4.2.

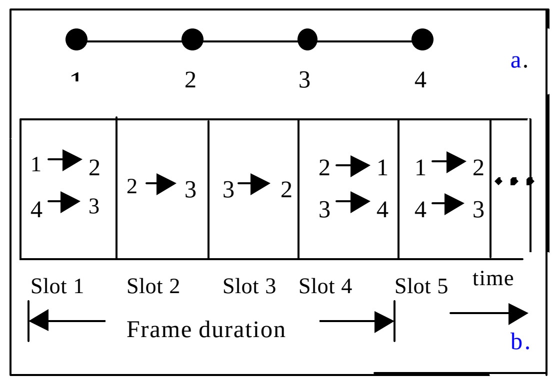

Fig. 5: Basic terms used in S-TDMA a. A linear network of four nodes. b. Schedule of the network. 2→3: node 2 transmits and node 3 receives.

represented by the element "cm_{ij}" in the so-called Compatibility Matrix, **CM = {**cm_{ij}**}**, which is defined as [6]:

$$\mathbf{CM} = \begin{cases} 1 & \textit{if arc j can be activated in clique i} \\ 0 & \text{otherwise} \end{cases}$$

As a matter of fact, each row in the **CM** corresponds to a maximal clique, e.g., Figure 6 shows the Compatibility Matrix for the linear network under study.

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

Fig. 6: Compatibility matrix of the linear network in Fig. 5.

Let us introduce two algorithms of creating the schedule: the Basic Schedule and the Enhanced Schedule.

A. The Algorithm of Creating S-TDMA Basic Schedule

The Basic Schedule (BS) is a link-activation schedule, which is based on the following approach: If we let C_i denote the ith clique (the ith row in **CM**). Then we can form a schedule BS = $\{C_1, C_2,...,C_h\}$ where the index $h \le N^2$ (N = number of nodes) and where each arc of network is included in at least one member of S. We need this schedule as a benchmark in order to compare other scheduling algorithms and it is straightforward procedure to create the S-TDMA schedule [6]. The procedure for the creation of the BS is:

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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.

B. *Traffic Sensitive Spatial TDMA*

Utilizing traffic-sensitive S-TDMA schedules, where the slot assignment is dependent on the estimated amount of traffic $T(i)$, in each node i, it has been shown to improve network performance [5]. Since the relative traffic load per link in the network is unbalance, traffic controlled S-TDMA systems assign more slots to the links with the heavy traffic load. The traffic sensitive S-TDMA schedule will be termed Enhanced Schedule (ES). The algorithm we propose to create this kind of schedule as follows:

Step 1: Compute the BS of the net under study. Obtain F_d. For each node i obtain $T(i)$. Select the maximum $T(i)$, we name it, T_{max}. Choose M_{max} = number of neighbors of the node with the T_{max}. Reckon the Node Factor (*NF*) associated with node i:

$$NF(i) = \lceil T(i)M_{max}/T_{max} \rceil \quad (12)$$

where $\lceil x \rceil$ denotes the smallest integer greater or equal to x. The Node Factor is the number of slots a node needs to handle its relative traffic load.

Step 2: Compute the traffic-sensitive frame duration, expressed in slots, and it will be termed F_{ES} using (13) as:

$$F_{ES} = \sum_{i=1}^{N} NF(i) \quad (13)$$

Step 3: Extra slots = F_{ES}-F_d. These are the *resultant or extra slots* that could be added to the BS. Calculate the slots needed for each arc as follows:

$$\text{Slots needed by link } (i,j) = T_{ij}NF(i)/T(i) \quad (14)$$

Step 4: Assign the "*extra timeslots*" (Step 3) to the arcs that need to complete their slots needed according to (14). Add those cliques that contain the selected arc into the BS to have the *ES*. In Figure 7, we can see that average delay (Network C is a slight variation of Network A), can be decreased considerably by taking into the account the traffic load in comparison with the BS. In order to run the simulations for S-TDMA, we first use the BS and next the ES. See Table I for the simulation parameters.

V. CONCLUSIONS

In this paper two MAC protocols in MPRNet in rough terrain were investigated: S-ALOHA and S-TDMA. The two major contributions were:

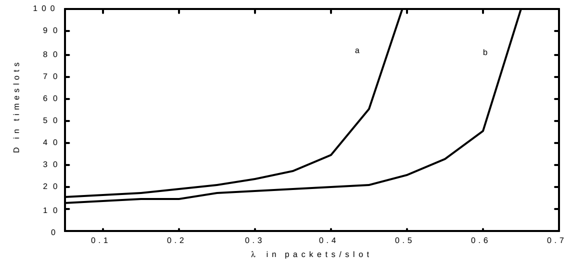

Fig. 7: Packet Delay vs. traffic load. (Network C, σ = 40m, ρ =3 m. S-TDMA. a: BS, b: Enhance Scheduling. Network C is similar to Network A minus two radio links: one link between nodes 6 & 7 and second one between nodes 9&10 are both disconnected.

1) A simple and novel transmission probability assignment (*Strategy I*) for multi-hop S-ALOHA that improved the network delay performance. Two other strategies for adjusting the 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 performed best. The transmission probability was based on the average number of neighbors and the total traffic load.

2) 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 BS. 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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