On Constrained Power Control for Spatial TDMA in Multi-hop Ad Hoc Radio Networks

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Abstract- A very attractive alternative for communications in areas in which there is little or no telecommunications infrastructure is to use Multi-hop packet radio networks (MPRNet:s). One major design issue in MPRNet:s is the formulation of Medium Access Control (MAC) protocols. Spatial TDMA (S-TDMA) is a "conflict-free" multiple access for MPRNet:s, which ensures that a packet transmission, whenever made, is successful . Since the transmitter power is at a premium in wireless systems, it is important to utilize it in an efficient way. High STDMA system capacities can be achieved by incorporating traffic load information into the MAC protocol design. However, the impact of power control in traffic-sensitive Spatial TDMA schemes control has not received enough attention in the literature. A suitable power control scheme has been chosen and applied to S-TDMA. The resulting delay performance, as determined via network simulations, is presented in this paper. As would be expected the introduction of power control markedly improved the delay performance of Traffic Sensitive S-TDMA.

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. Furthermore, since usually in MPRNet there is an unbalanced traffic load on each node, the enhancement of the network performance has been considered in previous work [2-4], by means of incorporating traffic load measurements into the MAC protocol design.

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 [5][6] and CSMA. These random access protocols provide rather acceptable performance at low and moderate traffic loads. Random MAC protocols exhibit comparatively poor performance in high load situations so "conflict-free" multiple access has been proposed [7] to ensure that a packet transmission, whenever made, is successful. The design of S-TDMA algorithms has received some attention in the literature [2-4][6]. Generally speaking, in an S-TDMA system, time slots are assigned in a schedule, i.e. a repetitive pattern of time slots of finite length.

Thus, MAC protocols that exploit the capabilities of the physical layer need to be developed, so additional room for improvement of packet radio networks could be provided by the transmitter power and directional antennas. For instance, the physical layer may be capable of performing of power control to the uppers layer. Furthermore, previous results show that controlling the transmitters power in wireless communication networks provides multiple benefits. It allows interference links sharing the same radio channel to achieved required quality of service (QoS) levels, minimizing the power spent in the process. Moreover, by judiciously using the power to achieved QoS goals, interference is mitigated and the network capacity increases. Besides, since the transmitter power is at a premium in wireless systems, it is important to utilize it in an efficient way. However, the impact of power control in traffic-sensitive S-TDMA schemes have been not addressed. However, the impact of power control in traffic-sensitive Spatial TDMA schemes control has not received enough attention in the literature. A suitable power control scheme has been chosen and applied to S-TDMA. The resulting delay performance, as determined via network simulations, is presented in this paper. As would be expected the introduction of power control markedly improved the delay performance of Traffic Sensitive S-TDMA. Here we will focus on constrained power control for Traffic Controlled (TC) Spatial-TDMA (S-TDMA).

The paper is organized as follows: Section II describes the system models, while Section III introduces the power control issue. Section IV describes the power-sensitive TC S-TDMA protocols. In section V, the simulation results show that the “combined” strategy of TC S-TDMA with constrained power control improves the network performance in comparison with the traditional traffic-sensitive S-TDMA approach. Section VI contains some concluding remarks.

II. SYSTEM MODELS

A. Link Quality and Connectivity Model

In a given area 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} [8] G_{ij} denotes the power (propagation) gain on the link between node i and node j. For simplicity, the link gains through the wireless channel are assumed to be distance dependent where the link gain between node i and node j is given by $G_{ij} = d_{ij}^{-a}$, here d_{ij} denotes the distance between node i and node j, and α is the path loss exponent (in other words, received power falls off as an inverse power of distance). Thus, the received power P_j at node j when node i transmits with power P_i as

$$P_j = G_{ij} P_i \qquad (1)$$

By collecting all the possible link gains in the MPRNet we are able to have the link gain matrix $\mathbf{G}=[G_{ij}]$. We also assume that all the nodes are equipped with omnidirectional antennas, and a single frequency for the whole network is used. 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_i, 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 and the background noise 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:

$$\Gamma_{ij} \geq \frac{P_i G_{ij}}{P_{Noise} + \sum_{k \neq i} I_k} = \frac{P_i G_{ij}}{P_{Noise} + \sum_{k \neq i} G_{kj} X_k P_k} \qquad (2)$$

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

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

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 no 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, $j \in \{1,2,\dots,N\}$. In Figure 1, two random networks, denoted A, and B which were used in the simulations. 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.

B. 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

$$l_i = l/N \qquad i \in \{1, 2, .. N\} \qquad (4)$$

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:

$$l_{ij} = \frac{l}{N(N-1)} tm_{ij} \qquad (5)$$

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:

$$T(i) = \sum_{j=1,\, i \neq j}^{N} tm(ij) \qquad (6)$$

The routing scheme used is the Minimum Hop Routing Algorithm (MHA) [4], i.e. minimizing the number of hops in a multi-hop “connection”.

C. 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, the expected value $E[D_{ij}]$ is used to measure performance. The average expected delay for all source-destination pairs is given by

$$\overline{D} = \frac{1}{\binom{N}{2}} \sum_{j=1}^{N} \sum_{i=j+1}^{N} E[D_{ij}] \tag{7}$$

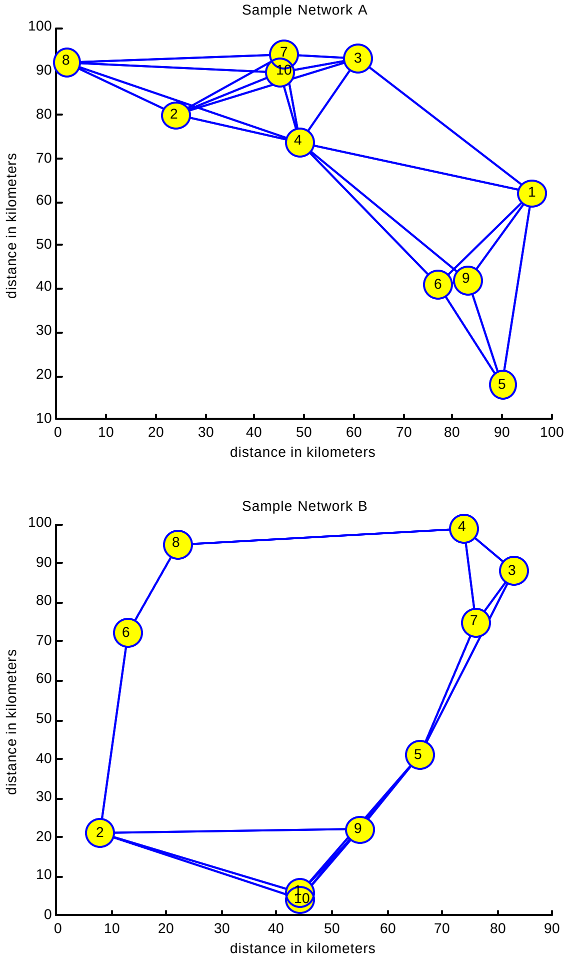

Fig. 1. Typical network realizations in a given area of 100 x 100 km^2. The number of nodes is $N = 10$. The lines represent the connections among the nodes. Above, the Sample Network A, and below the Sample Network B.

Simulations have been used to evaluate the expected packet delay since MPRNet are hard to track analytically. Ten nodes have been randomly dispersed over the given area until a connected network was found, see Figure 1. Discrete event simulations were performance using the models described in section II. The some simulation parameters are displayed in Table I.

III. POWER CONTROL for MPRNet

A. Introduction

Power control for wireless networks comes in many different forms. One important distinction for the algorithms is that between centralized and distributed power control. Centralized algorithms require instantaneously controls of the entire vector **P**. It is assumed the collection of global information (in particular the gain matrix **G** is known) about of the nodes in the network at a single location or central controller. This controller then distributes the power decisions throughout the network. Usually this approach implies high complexity. Centralized power control algorithms are used as a benchmark or upper bound on the network performance. Here we consider a Centralized Constrained Power Control (CCPC) applied to Traffic Sensitive S-TDMA.

TABLE I

SIMULATION PARAMETERS USED FOR THE PERFORMANCE EVALUATION

Parameter	Value
Number of Nodes (N)	10
Minimum Transmitted Power	0.625 W
Maximum Transmitted power	1 W
Propagation constant (α)	3
Frequency	300 MHz
Antenna Gains (G_t, G_r)	3 dB
Packet Size	40 Bytes
Data Rate	100 Kbps
External Packet Arrival	Poisson Distributed
Packet Destination	Uniform Distributed
Routing Algorithm	Minimum Hop Algorithm
Threshold path loss	133 dB
SIR Threshold	γ_0 = 10 dB
Equivalent Receiver Noise Bandwidth	100 KHz
Receiver Noise Figure	15 dB

B. Centralized Constrained power control for S-TDMA

The transmitted power clearly affects the link signal quantity and the interference environment in the MPRNET. Equation (2) provides us with an expression for the signal to interference ratio. Let us assume that we draw from the schedule L nodes which allowed to transmit in a particular timeslot. Let us introduce the following vector notation to describe all transmitter powers of the nodes,

$$\mathbf{P} = [P_1, P_2, P_3, ..P_N]^T \tag{8}$$

This vector has clearly to be non-negative, i.e. $\mathbf{P} \geq 0$. We rewrite (2) as

$$\gamma_0 \geq \frac{P_i}{\frac{P_{Noise}}{G_{ij}} + \sum_{k \neq i}^{L} \frac{G_{kj}}{G_{ij}} P_k} \tag{9}$$

let us introduce the N x N matrix **H** such that

$$H_{ik} = \begin{cases} 0 & \text{if } i = k \\ \dfrac{G_{kj}}{G_{ij}}\gamma_0 & \text{if } i \neq k \end{cases} \qquad (10)$$

Furthermore, define the Nx1 vector $\boldsymbol{\eta} = (\eta_i)$ where $\eta_i = \gamma_0 (P_{Noise}/G_{ij})$ then rewriting the equation (9) using (10) in a matrix form we end up as follows

$$\mathbf{AP} \geq \boldsymbol{\eta} \qquad (11)$$

for $\mathbf{A} = \mathbf{I\text{-}H}$ where I denotes the identity matrix. From (11), it can be easily seen that the power vector **P** could be computed by the following expression

$$\mathbf{P} = (\mathbf{I}-\mathbf{H})^{-1}\boldsymbol{\eta} \leq \mathbf{P}_{\mathbf{max}} \qquad (12)$$

here we denote the maximum transmitter power by P_{max}. In addition, we are also constrained by a minimum transmitter power P_{min}= 0.625 W, this value is derived from $P_{min} = (P_{Noise*}\gamma_0/G_t{*}G_r{*}G_{ij})$, see Table I. Using the approach suggested in [8] we are able to try to achieve the **P*** (optimum power vector) and γ^* (the largest SIR possible with **P***) in the MPRNet. Given some enabled links, in particular time slot, If the $\gamma^* \geq \gamma_0$ we applied the CCPC to the construction of the schedule otherwise we just keep the traffic-sensitive scheme.

IV. S-TDMA for Multi-hop Networks

A. Traffic Controlled S-TDMA (TC S-TDMA)

S-TDMA for multi-hop packet radio networks is a generalization of TDMA for single-hop networks. In these schemes, transmission schedules are coordinated in such a way that no conflicts occur. S-TDMA defines a repeating transmission schedule (*frame*) which contains a fixed number of slots, with each slot being assigned to a unique set of non-conflicting links. This paper considers link allocation schedules, when the network gain matrix and some information about the load matrix are taken into account. When we incorporate the load matrix to make the transmission schedules, we say that we have a traffic-sensitive S-TDMA [2-4]. In general, from the radio propagation path loss and connectivity models (see section II) it is possible to determine in which combination arcs can be used simultaneously without causing any lost of packet. Furthermore, we introduce the term *clique* as a set or group 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". Generally speaking, the schedule is a set of maximal cliques which contains all arcs in the radio network. All the relevant information about the S-TDMA schedule is collected in the so-called Compatibility matrix. Let us consider L enabled links in the network. Then the compatibility between arc i and arc j is represented by the element "cm_{ij}" in the L x L binary matrix, $\mathbf{CM} = \{cm_{ij}\}$, which is defined as [7]. In other words, each row in the **CM** corresponds to a maximal clique:

$$\mathbf{CM} = \begin{cases} 1 & \textit{if arc j can be activated in clique i} \\ 0 & \text{otherwise} \end{cases} \qquad (13)$$

The traditional approach in S-TDMA for multi-hop networks usually only consider the transmitted power of the node to be a at constant level. However, this view yields a pessimistic compatibility matrix since some nodes might utilize more transmitted power than they needs to deliver their packets to the destination site. So, including some "power control" in traffic-sensitive S-TDMA frame, it may help. However, it has not been shown which approach that is preferable.

B. The Algorithm of creating a power-sensitive TC S-TDMA

The calculation of the schedule for the power sensitive case is outlined in the flow chart in Fig. 2. This method can be summarized in the following four steps.

Step 1: Calculate the gain matrix (**G**).
Step 2: Create a list of arcs which contains all the arcs of the MPRNet. Find the routing matrix.
Step 3: Compute the traffic load matrix (**TM**).
Step 4: Construct the schedule utilizing a CM which come from the combination of the TC S-TDMA protocol proposed in [3], together with the power control strategy in (12).

V. NUMERICAL RESULTS ON S-TDMA

In order to evaluate performance, two networks A and B composed by 10 nodes are generated accordingly to the random process described in section 2 over a geographical area of 100 x 100 km^2. In the following analysis, we also assume that the location of the nodes in the service area and the requirements are known. In Figure 3, we can see that average delay of Network A, can be decreased considerably by taking into the account the traffic load and power control in comparison with the non-power-sensitive TC S-TDMA (Traffic Controlled S-TDMA). In order to run the simulations for S-TDMA, we first use the TC Spatial TDMA without power control using all the nodes a constant transmitted power of 1 W, then we introduce in the construction of schedule not only the influence of the Traffic load matrix but the power control as well. See Table

I for the simulation parameters. Similar results have been obtained with the network B.

VI. CONCLUSIONS

In this paper one MAC protocol in an MPRNet was investigated: TC S-TDMA with power control. The two major contributions were:

1) An S-TDMA multiple access that exploits the capabilities of the physical layer are proposed, so additional room for improvement of packet radio networks could be provided by the transmitter power.
2) A new scheduling algorithm for TC S-TDMA which significant improves network performance in MPRNet. The simulation results show an improvement of up to 60% in comparison with the traditional traffic-sensitive scheduling. 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 distributed traffic controlled S-TDMA has not yet been addressed in a "realistic radio environment". Hence further enhancements are possible.

VII. ACKNOWLEDGEMENT

The author is grateful to Tim Giles for his comments.

REFERENCES

[1] Kahn, R. E., "The Organization of Computer Resources into a Packet Radio Network", *IEEE Trans Comm, vol. COM-25*, No.1, Jan 1977.

[2] Robertazzi, T., Shor, J., "Traffic Sensitive Algorithms and Performance Measures for the generation of Self-Organizing Radio Network Schedules", *IEEE Trans Comm, vol. COM-41*, no. 1, Jan 1993.

[3] Grönkvist, J.,"Traffic Controlled Spatial TDMA in multihop radio networks", *PIMRC 98*, Oct 1998.

[4] Somarriba, O.,"Traffic-sensitive MAC protocols in multihop radio networks", *Globecom 2001*, Nov 2001.

[5] Abramsson, N., "The throughput of packet broadcast channels", *IEEE Trans Comm, vol. COM-25*, No.1, Jan 1977.

[6] Roberts, L.G., "ALOHA Packet System With or Without Slots and Capture", Computer Communication Review, vol. 5, 1975.

[7] Nelson, R., Kleinrock, L., "Spatial-TDMA, A collision –free multihop channel access protocol", *IEEE Trans. Comm., vol. COM-23*, no. 9, Sept. 1985.

[8] Zander, J., "Transmitter power control for co-channel Interference Management in Cellular Radio Systems", in Proc. Fourth WINLAB Workshop on Third Generation Wireless Information Networks, pp. 241-247, 1993.

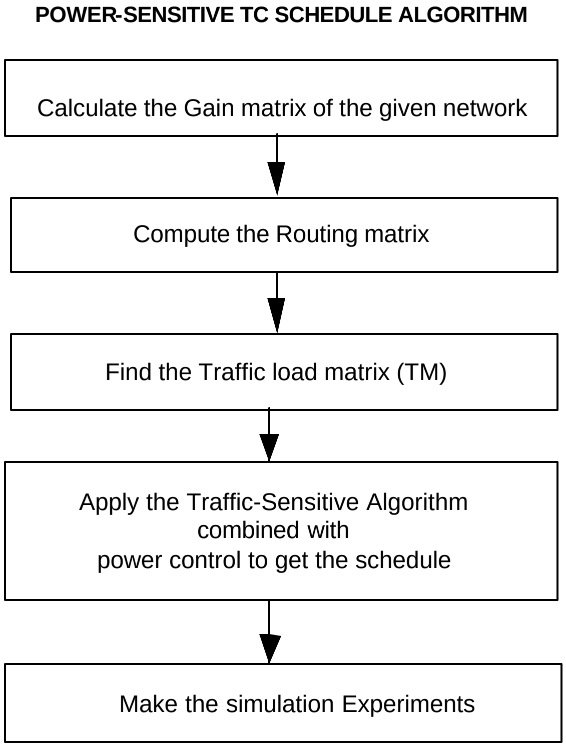

Figure 2. Flow diagram for creating the schedules in S-TDMA using power control.

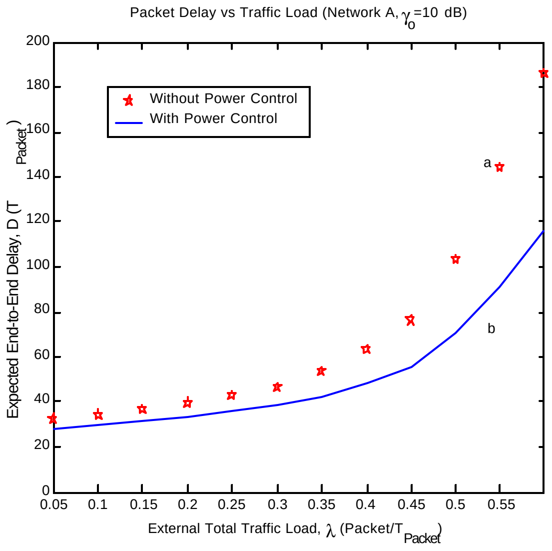

Fig. 3. Packet Delay vs. Traffic load. Network A. MAC Protocol: TC S-TDMA. a: Without power control, b: With power control.