Power and Rate Control for Spatial TDMA in Wireless Radio Networks

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Abstract- A very attractive alternative for communications in areas in which there is little or lack of backbone telecommunications infrastructure is to use Multihop packet radio networks (MPRNet:s). One major design issue in MPRNets is the formulation of Medium Access Control (MAC) protocols. Spatial TDMA (S-TDMA) is a “conflict-free” multiple access for MPRNets, which ensures that a packet transmission, whenever made, is successful. S-TDMA is a link oriented scheduling. The availability of variable data rates in wireless radio networks raises the problem of controlling them in the most spectrally efficient way. In the radio channel, transmission rates are related to the Signal-to-Interference Ratios (SIRs), and the SIRs can be efficiently controlled by transmitter power. Therefore, it is natural to associate rate control with power control, which will be investigated in this paper.

The multihop ad hoc networks studied in this paper consist of a collection of twenty nodes, which have been randomly dispersed over the given area. We considered stationary networks with the nodes equipped with omnidirectional antennas and using a single frequency for the whole network. In order to build the S-TDMA schedule, we enabled a set of radio links, for each timeslot, that fulfill two conditions: a) They are prioritized accordingly to their traffic load and b) The SIRs commonly used as a measure of the link quality, is above certain thresholds named SIR target. In latter item, Power and Rate control can be used to increase the number of simultaneous transmissions while maintaining link quality.

For sample networks, we have obtained some results by means of discrete even simulations. In an attempt to improve network performance, a new scheduling algorithm, PR S-TDMA, STDMA with power and rate control was designed. The simulation results show an improvement average delay and the maximum throughput, for all traffic conditions, in comparison with the traditional S-TDMA.

I. INTRODUCTION

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 (Multihop Ad hoc networking). 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 Multihop Packet Radio Networks (MPRNet:s), 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:s 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. However, random MAC protocols exhibit comparatively poor performance in high load situations so "conflict-free" multiple schemes have been proposed to ensure that a packet transmission, whenever made, is successful. One of "conflict-free" MAC protocols for ad hoc multihop networks is Spatial TDMA (S-TDMA) [7]. When using S-TDMA as MAC protocol a link transmission schedule is created in advance. Scheduling algorithms are important components in the provision of guarantee quality of service parameters such as delay or throughput. Thus, the design of S-TDMA algorithms has received some attention in literature [2-4].

On the other hand, 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 variable transmitter power and adaptive antennas, for example. Previous results [8] show that controlling the transmitters power in wireless communication networks provides numerous benefits. It allows for efficient sharing of the same radio channel to achieved required quality of service levels, minimizing the power spent in the process. Furthermore, next-generation wireless systems such as multihop ad hoc networks will have to support multimedia services, which are characterized by different quality of service (QoS) requirements, such as maximum power and/or rate of transmission.

However, the impact of power and rate control in traffic-sensitive S-TDMA schemes has not been addressed. In this paper, a suitable power and rate control scheme has been applied to S-TDMA. The resulting delay performance is determined via network simulations. As would be expected the introduction of power and rate control markedly improved the delay performance of Traffic Sensitive S-TDMA. Here we will focus on a new scheduling algorithm PR S-TDMA (S-TDMA with power and rate control).

The paper is organized as follows. In Section II the system model is described, while Section III introduces S-TDMA schemes. The power and rate control issue is addressed in Section IV. Numerical examples (simulation results) are considered in Section V and concluding remarks are made in Section VI.

II. SYSTEM MODEL

A. *Link Quality and Connectivity Model*

We will refer to the collection of N nodes that form a particular network by an uppercase letter (e.g. Network A). It is assumed that the network is composed of identical nodes meaning that all nodes in the network have the same capability and that the only way to communicate between nodes is through the wireless medium using a single frequency band for transmission. It is also assumed that all antennas are isotropic. 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 radio propagation properties of the terrain where the network is deployed. The propagation effect is modeled by the radio propagation losses. We represent the path losses on link (i,j) by L_{ij}. The inverse of this quantity is commonly referred to as the link path gain, $G_{ij} = 1/L_{ij}$, and constitute the elements of the path gain matrix, **G**. Hence, the received power P_j at node j when node i transmits with power P_i is given by

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

To generate easily analyzed results the simple distance dependent propagation model is used. When using this model, equation (1) may be rewritten as $P_j = P_i (d_{ij})^{-a}$. Here d_{ij} is the distance between node i and node j, and α is the path loss exponent. A value of $\alpha = 3$ that may correspond to the rural scenario will be used to evaluate performance.

On the other hand, each node has a quality of service (QoS) and also power and rate constraints. 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 (i,j) a minimum SIR is required, referred to as the SIR threshold $g_{0,ij}$. 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 $g_{0,ij}$ dB. A set L of links is said to be supported if

$$\Gamma_{ij} = \frac{P_i G_{ij}}{P_{Noise} + \sum_{k \neq i} G_{kj} P_k} \geq g_{0,ij} \;\; \forall \, ij \in L \qquad (2)$$

is greater than the threshold $g_{0,ij}$, otherwise the packet is lost. Here, 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. Figure 1 shows two networks realizations, which were used in the simulations as a sample networks. 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. *Connectivity* is defined as the fraction of nodes in the network that can be reached by a node, in one hop, on average, i.e. $M/N(N-1))$, where M is the number of directed (unidirectional) radio links in the network .

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. Besides, packet arrivals at a node are of two classes (1) external and (2) internal. Furthermore, it is assumed that the traffic load is evenly distributed. Thus, external arrivals to node i are assumed are generated accordingly to the following expression

$$l_i = l/N \qquad i \in \{1, 2, .. N\} \qquad (3)$$

Moreover, internal packets arrive from other nodes and can further be classified as: transit packets that must be retransmitted to others nodes after they are received, and terminal packets that are destined to the node and therefore need not be relayed. The initial source (S) and final destination (D) of a packet is denoted by an (S,D) pair. Due to store-and–forward mechanism, packets between (S,D) pairs may travel through intermediate nodes. Therefore, the

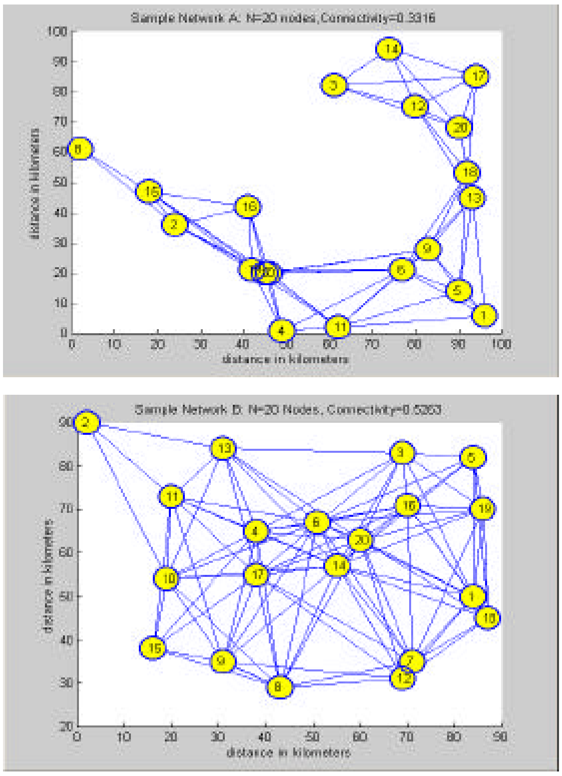

Fig. 1. Typical network realizations over an area of 100 km x 100 km. The number of nodes is *N* =20. The lines represent the connections among the nodes. Above, the Sample Network A, and below the Sample Network B.

average traffic load l_{ij} going through a link (i,j) is the result of external and internal traffic [2]. We can easily see that the traffic in link (i,j) is:

$$l_{ij} = \frac{l}{N(N-1)} T_{ij} \qquad (4)$$

where T_{ij} are the elements of the *Relative Traffic Load* matrix $\mathbf{T} = \{T_{ij}\}$ given by

$$T_{ij} = \sum (S,D) \textit{ routed through link } (i,\, j) \qquad (5)$$

It should be noted that some $l_{ij} = 0$ when the link (i, j) is not usable or unreliable. The routing scheme used is the Minimum Hop Routing Algorithm (MHA) [4], i.e. minimizing the number of hops in a multihop "connection".

C. *Performance Measures*

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 End-to-end delay for all source-destination pairs is given by

$$E[D] = \sum_{\forall \text{ link } (i,\, j)} \frac{T_{ij}}{N(N-1)} E[D_{ij}] \qquad (6)$$

Moreover an important performance measure is the *maximum throughput*, which it can be defined as the largest input traffic λ^* giving bounded average packet delay.

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

TABLE I
SIMULATION PARAMETERS USED FOR THE PERFORMANCE EVALUATION

Parameter	Value
Number of Nodes (N)	20
Maximum radio range	40 km
Propagation constant (α)	3
Bandwidth	100 KHz
Data Rate with $\gamma_0 = 10$	346 Kbps
Maximum Transmitter Power with $\gamma_0 = 10$ dB	8 W
External Packet Arrival	Poisson Distributed
Packet Destination	Uniform Distributed
Routing Algorithm	Minimum Hop Algorithm
Maximum path loss (L_{max})	138.3 dB
Target SIRs	$\gamma_{0,\, li} = 3, 5, 7, 10$ dB
Receiver Noise Figure	15 dB
P_{Noise}	1.26 X 10^{-14} W

III. S-TDMA for Multihop Networks

In STDMA, transmission schedules are coordinated in such a way that no conflicts occur. STDMA defines a repeating transmission schedule (*frame*) that contains a fixed number of slots, with each slot being assigned to a unique set of non-conflicting links. This paper considers *Link Assignment* schedules, when the network gain matrix and some information about the load matrix are taken into account. Throughout the paper, we use the term arc to refer to a unidirectional radio link. In general, from the radio propagation path loss and connectivity models in Section

II, it is possible to determine in which combination arcs can be used simultaneously without causing any packet loss. 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 that contains all arcs in the radio network. All the relevant information about the S-TDMA schedule is collected in the so-called Compatibility matrix (**CM**) [7].

High S-TDMA system capacities can be achieved by incorporating information from the matrix **T** into the MAC protocol design; these schemes are commonly referred as Traffic Controlled S-TDMA (TC S-TDMA) protocols [2-4]. Previous investigations into TC S-TDMA systems used fixed transmission powers and fixed transmission rates. However, this view yields a pessimistic compatibility matrix since some nodes might utilize more transmitted power than they need to deliver their packets to the destination site. Clearly, the application of power and rate control to these systems could improve the spatial reuse factor as well as the network performance.

IV. POWER and RATE CONTROL for MPRNet:s

A. Introduction

One controllable radio resource closely related to the network capacity is the transmitter power. Centralized algorithms for power control require instantaneously controls of the entire transmitted power vector of all the nodes in a wireless radio network. It is assumed that the information (in particular the gain matrix **G**) about all of the nodes in the network is collected 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. Since the **G** matrix is known in a stationary MPRNet, here we consider a Centralized Constrained Power Control (CCPC) applied to TC S-TDMA.

B. Centralized Constrained Power and Rate 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 SIR. Let us assume that we draw from the schedule N´ (0 < N´ ≤ N) nodes which are allowed to transmit in a particular timeslot. Let us describe all transmitter powers of the active nodes in the network in a timeslot by the following power vector notation as:

$$\mathbf{P} = [P_1, P_2, P_3, ..P_{N'}]^T \qquad (7)$$

where […]^T denotes the transpose of a vector […]. In the sequel, we will assume that the rate assignment and target SIRs are related as the well-known expression:

$$R_{ij} = BW \log_2(1 + g_{o,ij}) \qquad (8)$$

where R_{ij} is rate assigned to link (i,j).

This vector has clearly to be non-negative, i.e. **P** ≥ 0. We rewrite (2) as

$$\frac{P_i}{\frac{P_{Noise}}{G_{ij}} + \sum_{k \neq i}^{N'-1} \frac{G_{kj}}{G_{ij}} P_k} \geq g_{0,ij} \qquad (9)$$

Let us introduce the N´ x N´ normalized link gain matrix $A_{k,ij} = (a_{k,ij})$ such that $a_{k,ij} = G_{kj}/G_{ij}$ for $k \neq i$ and $a_{k,ij} = 0$ for k= i. We define the matrix G_0 as the diagonal matrix whose elements are $\gamma_{0,ij}$. Furthermore, we also define the N´x1 vector h = (η_i) where $\eta_i = \gamma_{0,ij}\,(P_{Noise}/G_{ij})$ then rewriting the equation (9) in a matrix form results in

$$(\mathbf{I} - \mathbf{G}_0\,\mathbf{A})\mathbf{P} \geq ? \qquad (10)$$

where **I** denotes the identity matrix. From (10), it can be easily seen that the power vector **P** could be computed by the following expression

$$\mathbf{P} \quad (\mathbf{I} - \mathbf{G}_0\mathbf{A})^{-1} ? \quad \mathbf{P}_{\max} \qquad (11)$$

In this system there exist transmission power ceilings, denote $P_{max,i}$, for every active node i in a particular timeslot. In other words, $P_{max,i}$ is the required transmission power to achieve a given $g_{0,ij}$ while at the same time overcoming the a maximum propagation path loss, L_{max}, so we may have

$$Pmax,i = g_{0,ij}\, P_{Noise}\, L_{max} \qquad (12)$$

Using (11) the transmitter powers of all active nodes in a timeslot can be determined. In the case that P_i > Pmax,i in that timeslot then the link (i,j) is not admitted into that particular clique.

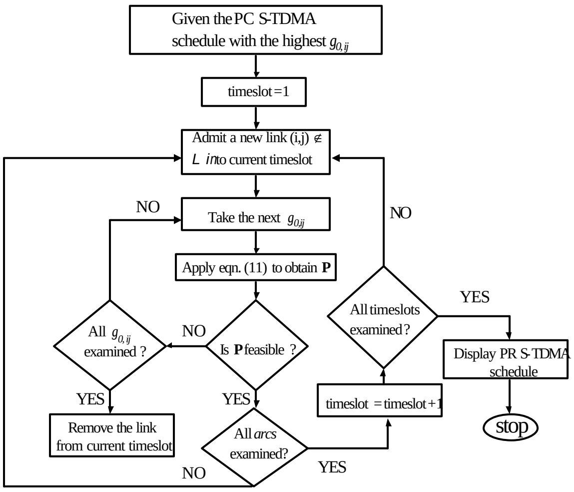

Fig. 2. Flow diagram for creating the schedules with the PR S-TDMA algorithm.

C. *The Algorithm of Creating the Power and Rate S-TDMA (PR S-TDMA) schedule*

The algorithm for creating the PR S-TDMA schedule relies on prior simpler scheduling algorithms. The PR S-TDMA algorithm uses the Power-Sensitive S-TDMA (PC S-TDMA)[9] scheduling algorithm which is built on the Traffic Controlled S-TDMA (TC S-TDMA)[3-4] which in turn is an improvement on the basic scheduling algorithm.

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 ≤ N² (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 [4]. The procedure for the creation of the BS 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.

The TC-S-TDMA algorithm builds the schedule from the CM using knowledge of the expected relative traffic load in each link. This algorithm adds cliques to the schedule giving priority to links with a high relative traffic load. The TC S-TDMA algorithm also ensures that all links are activated during a frame as does the basic scheduling algorithm. The PC S-TDMA algorithm only differs from TC S-TDMA in how the CM is constructed. In PC S-TDMA (TC S-TDMA with Power Control) is used to check compatibility when creating the cliques in the CM as well as setting the transmit powers Pi.

The PR-S-TDMA algorithm tries to make improvements on the schedule provided by the PC-S-TDMA algorithm. It examines every time-slot in the PC S-TDMA schedule and tries to add extra links using equation (11) to check for compatibility. For each link the algorithm checks successively lower rates. If any rate if feasible it then adds this link to the timeslot, This procedure is illustrated in the flow chart of Figure 2.

V. NUMERICAL RESULTS ON S-TDMA WITH POWER and RATE CONTROL

In order to evaluate performance, two networks A and B composed by 20 nodes are generated accordingly to the random process described in Section II over a geographical area of 100 x 100 km^2. Then, we compute the PR STDMA scheduling accordingly to Section IV.C. Here it is assumed that a radio link can support four target SIRs, 3 dB, 5dB, 7 dB and 10 dB, these correspond accordingly to equation (8) to four data rates, 158 kbps, 205 kbps, 258 kbps and 346 kbps, respectively. The resulting delay performance is determined via network simulations. In Figure 3, Diagram 1, we can see that the average delay of Network A (curve c) can be decreased considerably by taking into account the power and rate control in comparison with the traditional TC S-TDMA schemes (curve a). Curve b shows the evaluation of the average delay for the case when only the transmitted power is varied. Similar results have been obtained with the network B and these are illustrated in Figure 3, Diagram 2. The PR S-TDMA algorithm initially assigns the highest data rate to the most heavy loaded links during a particular timeslot, and then it may eventually lower the available data rates for the remainder arcs to add another feasible link(s) into the skeleton schedule, utilizing any excess capacity that the radio network can provide.

VI. CONCLUSIONS

In this paper the addition of power and rate control to TC S-TDMA was investigated. A new scheduling algorithm, (PR S-TDMA) Traffic Controlled S-TDMA with power and

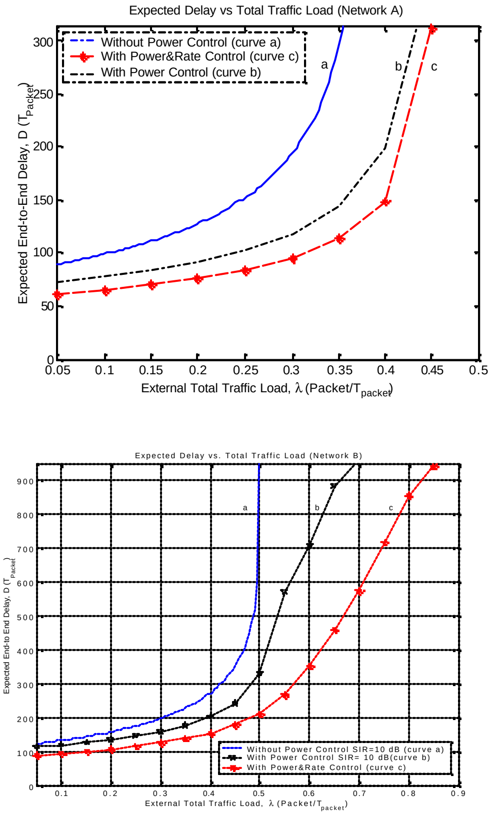

Fig. 3. Packet Delay vs. Traffic load. MAC Protocol: TC S-TDMA. Diagram 1 (Above). Network A. Without power control: a) γ_0 =10dB, b) With Power Control using γ_0 =10dB c) With Power and Rate Control. Diagram 2 (Below). Network B. Without power control: a) γ_0 =10 dB, b) With power control using γ_0 =10 dB, c) With Power and Rate Control.

rate control significantly improves network performance in the test networks. The simulation results show an improvement of the maximum throughput (λ*) and lower average delay for all traffic conditions in comparison with the traditional TC S-TDMA. This improvement is achieved by utilizing interference and knowledge of the expected the traffic load. As the cost of implementing power and rate control is relatively small, and the performance gains are substantial, a prudent design should include these features. Future work will be focused on the minimum total transmitted power and the maximum total rate conditions [10]. It will be interesting to address the problem of power control and resource management as a constrained optimization problem in the power and the data rates, applied to S-TDMA.

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