# SCHEDULING FOR VARIABLE POWER AND RATE CONTROL FOR SPATIAL TDMA IN WIRELESS AD HOC NETWORKS

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**ABSTRACT**

Multihop ad hoc wireless networking is alternative for the communications in areas where there is a scarcity of telecommunications infrastructure. A major design issue in such networks is the formulation of the Medium Access Control (MAC) protocols. Spatial TDMA (S-TDMA) is a “conflict-free” MAC protocol thus enabling high spectral utilization, however the scheduling is required. In link oriented S-TDMA the schedule specifies when particular radio links will be activated. In most wireless networks simultaneous link activation or “reuse” is possible. An efficient schedule is critical to network performance.

This paper investigates power and rate control in an S-TDMA ad hoc wireless networks. We present EPR S-TDMA (S-TDMA with enhance power and rate control) scheduling algorithm, that substantially improves throughput performance, when compared to fixed power and rate. The algorithm presented can provide shorter schedule frame duration in comparison with Traffic-sensitive S-TDMA algorithm.

## 1. 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 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. Moreover, the impact of power and rate control in traffic-sensitive S-TDMA has been shown in [11] to improve throughput and delay performance. In this paper, we extend those results by incorporating the power and rate selection into the traffic-sensitive scheduling algorithm proposed in [3]. We call this new algorithm EPR S-TDMA (S-TDMA with enhance power and rate control). The resulting delay performance is determined via network simulations.

The paper is organized as follows. In Section 2 the system model is described, while Section 3 introduces S-TDMA schemes. The power and rate control issue is addressed in Section 4. Numerical examples (simulation results) are considered in Section 5 and concluding remarks are made in Section 6.

## 2. SISTEM MODEL

### 2.1. Link Quality andConnectivity

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

$$P_j = G_{ij} P_i \tag{1}$$

To generate easily analyzed results the simple distance dependent propagation model is used. When using this model, equation (1) may be rewritten as $P_j = P_i\ (d_{ij})^{-\alpha}$. Here $d_{ij}$ is the distance between node i and node j, and $\alpha$ 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, $\Gamma_{ij}$ , 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 $\gamma_{0,ij}$. Thus, 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 $\gamma_{0,ij}$ dB. In the sequel, we will assume that the rate assignment and target SIRs are related as the well-known expression:

$$R_{ij} = BW \log_2(1+\gamma_{o,ij}) \tag{2}$$

where $R_{ij}$ is rate assigned to link (i,j). The slot length is $1/R_b$, $R_b$ is the rate used in the TC S-TDMA. Thus, a set $\mathcal{L}$ of links is said to be supported if

$$\Gamma_{ij} = \frac{P_i G_{ij}}{P_{Noise} + \sum_{k \neq i} G_{kj}\ P_k} \geq \gamma_{0,\mathrm{ij}} \quad \forall\, \mathrm{ij} \in \mathcal{L} \tag{3}$$

is greater than the threshold $\gamma_{0,ij}$, otherwise the packet is lost. Here, $P_{Noise}$ is the background noise power level at receiving node $j$. 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 as a sample networks, which were used in the simulations. In each network $N$ nodes have been randomly dispersed over the given area. 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 .

### 2.2. Traffic and Routing

We assume that packets are of constant length and arrived according to a Poisson process with total (external) arrival rate $\lambda$ packets/time slot. One packet can be transmitted in a slot using rate $R_b$, two packets using $2R_b$ etc. 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:

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

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

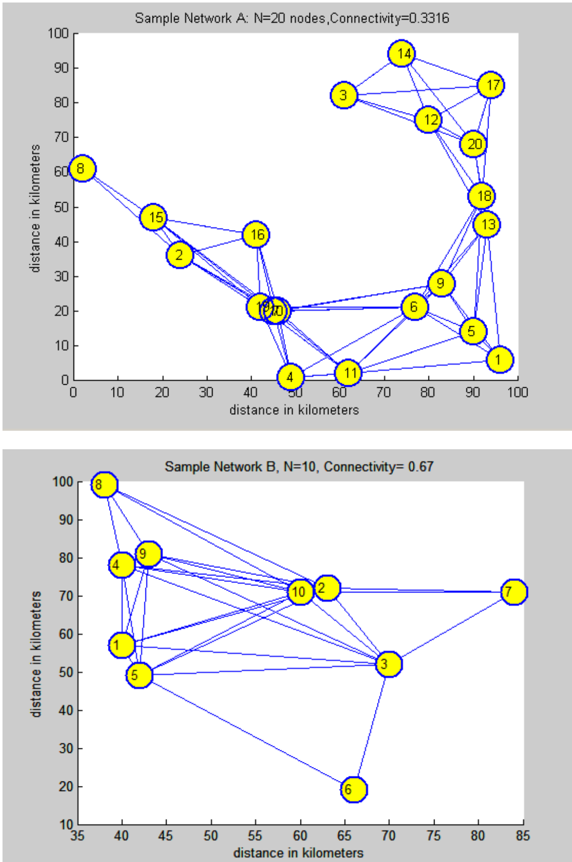


Fig. 1. Typical network realizations over an area of 100 km x 100 km. The number of nodes is $N$ =20 and $N$=10 Nodes. The lines represent the connections among the nodes. Above, the Sample Network A, and below the Sample Network B.

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 average traffic load $\lambda_{ij}$ 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:

$$\lambda_{ij} = \frac{\lambda}{N(N-1)} T_{ij} \tag{5}$$

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

$$T_{ij} = \sum (S,D) \textit{ routed through link } (i,j) \tag{6}$$

It should be noted that some $\lambda_{ij} = 0$ 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".

### 2.3. 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

$$E[D] = \sum_{\forall \text{ link } (i,j)} \frac{T_{ij}}{N(N-1)} E[D_{ij}] \tag{7}$$

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

Discrete-event simulations have been used to evaluate the expected packet delay since MPRNet:s are hard to track analytically [7]. Some simulation parameters are displayed in Table I.

TABLE I
SIMULATION PARAMETERS USED FOR THE PERFORMANCE EVALUATION.

| Parameter | Value |
|---|---|
| Number of Nodes ($N$) | 20 and 10 |
| Maximum radio range | 40 km |
| Propagation constant ($\alpha$) | 3 |
| Bandwidth | 100 KHz |
| Maximum Transmitter Power | 0.806 W |
| Minimum Transmitter Power | 0.0806 W |
| External Packet Arrival | Poisson Distributed |
| Packet Destination | Uniform Distributed |
| Routing Algorithm | Minimum Hop Algorithm |
| Maximum path loss ($L_{max}$) | 138.06 dB |
| Data Rates | 100 Kbps, 200 Kbps, 300 Kbps, & 400 Kbps |
| Target SIRs | $\gamma_{0, li} = 1, 3, 7, 15$ |
| $P_{Noise}$ | 1.26 X $10^{-14}$ W |

## 3. S-TDMA FOR MULTIHOP NETWORKS

In S-TDMA, transmission schedules are coordinated in such a way that no conflicts occur. S-TDMA 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 2, 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 uilize 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.

## 4. POWER AND RATE CONTROL FOR MULTIHOP AD HOC NETWORKS

### 4.1. 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.

### 4.2. Power and Rate Control for S-TDMA

The transmitted power clearly affects the link signal quantity and the interference environment in the MPRNet. Equation (3) provides us with an expression for the SIR. Let us assume that we draw from the schedule $N'$ ($0 < N' \leq N$) 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:

$$\mathbf{P} = [P_1, P_2, P_3, ..P_{N'}]^T \tag{8}$$

where $[\ldots]^T$ denotes the transpose of a vector $[\ldots]$. This vector has clearly to be non-negative, i.e. $\mathbf{P} \geq 0$. We rewrite (3) as

$$\frac{P_i}{\dfrac{P_{Noise}}{G_{ij}} + \displaystyle\sum_{k \neq i}^{N'-1} \frac{G_{kj}}{G_{ij}} P_k} \geq \gamma_{0,ij} \tag{9}$$

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 $\mathbf{\Gamma_0}$ as the diagonal matrix whose elements are $\gamma_{0,ij}$. The $\gamma_{0,ij}$ is dependent on what rate we transmit with on that a particular link (in next section we explain how the rates are chosen).

Furthermore, we also define the $N'$x1 vector $\boldsymbol{\eta} = (\eta_i)$ where $\eta_i = \gamma_{0,ij}\,(P_{Noise}/G_{ij})$ then rewriting the equation (9) in a matrix form results in

$$(\mathbf{I} - \mathbf{\Gamma_0 A P}) \geq \boldsymbol{\eta} \tag{10}$$

where $\mathbf{I}$ denotes the identity matrix. From (10), it can be easily seen that the power vector $\mathbf{P}$ could be computed by the following expression:

$$\mathbf{P} = (\mathbf{I} - \mathbf{\Gamma_0 A})^{-1} \boldsymbol{\eta} \geq P_{max} \tag{11}$$

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

$$P_{max} = \gamma_c \, P_{Noise} \, L_{max} \tag{12}$$

In the examples we set $\gamma_c$ to the minimum SIR of 0 dB. Using (11) the transmitter powers of all active nodes in a timeslot can be determined. In the case that $P_i > P_{max}$ in that timeslot then the link (i,j) is not admitted into that particular clique.

### 4.3. The EPR S-TDMA Algorithm

The EPR S-TDMA algorithm combines scheduling the variable Power and Rate [11] with the algorithm which is built on the Traffic Controlled S-TDMA (TC S-TDMA)[3-4]. The EPR-S-TDMA algorithm incorporates the options of rate and power control into TC-S-TDMA algorithm. It starts by assigning an arc with highest rate to a time slot. Then it tries to add others arcs at successively lower rates until a feasible clique is found. The variables used for describing the EPR S-TDMA algorithm are as follows: t is current time slot, The link priority is set totiTij where ti is the number of slots that have passed since the link was previously allocated a time slot, hi denote the number of slots in the schedule, Yt is the clique in the timeslot t, xi is the current arc, ri is the new help variable, Rate=ri*Rb where Rb is the lowest rate and 4*Rb the highest data rate, kmax=4 (Max. data rate(4Rb)/Rb). The procedure for the creation of the EPR S-TDMA is the following, which is a modified version of the algorithm in [3, pages 25-28]:

Step 1 Initialize

1.1 Enumerate the links

1.2 Create a list, A, containing all the links and and empty list B.

1.3 Set $t$ to zero.

1.4 Calculate the number of time slots each link is to be guaranteed and set $h_i = T_{ij}$.

1.5 Set $\tau_i$ to zero.

1.6 Reorder lists A according to link priority $\tau_i$Tij highest priority first.

Step 2 Repeat until list A is empty :

Step 2.1 Set $t \leftarrow t + 1$ and $Y_t \leftarrow \emptyset$.

Step 2.2 For each link $x_i$ in list A:

2.2.1 Set $Y_t \leftarrow Y_t \cup x_i$.

2.2.2 $r_i = \min$ (hi, kmax).

2.2.3 While $r_i > 0$

If $Y_t$ can transmit simultaneously:

- $h_i = h_i - r_i$, $\tau_i = 0$, and set $r_i = 0$.
- If $h_i = 0$ then move arc $x_i$ from list A and add to list B.

2.2.4 If $Y_t$ cannot transmit simultaneously, set

- $r_i = r_i - 1$.
- If $r_i = 0$, $Y_t \leftarrow Y_t \setminus x_i$, and set $\tau_i = \tau_i + 1$.

Step 2.3 For each link xi in list B but not in $Y_t$:

2.3.1 Set $Y_t \leftarrow Y_t \cup x_i$.

2.3.2 If $Y_t$ can transmit simultaneously:

- Set $\tau_i$ to zero.

2.3.3 If $Y_t$ cannot transmit simultaneously, set

- $Y_t \leftarrow Y_t \setminus x_i$, and set $\tau_i = \tau_i + 1$.
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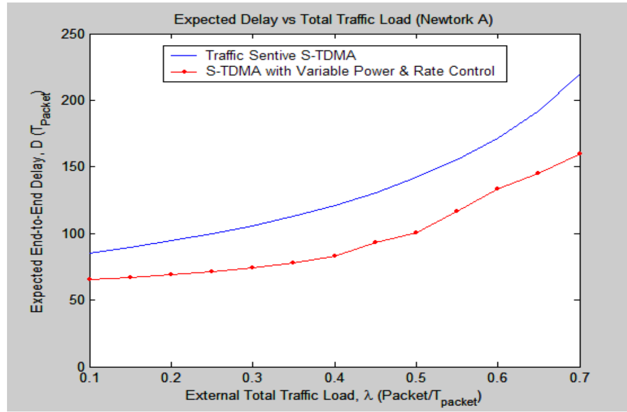
Step 2.4 Reorder lists A and B according to link priority $\tau_i$Tij highest priority first.



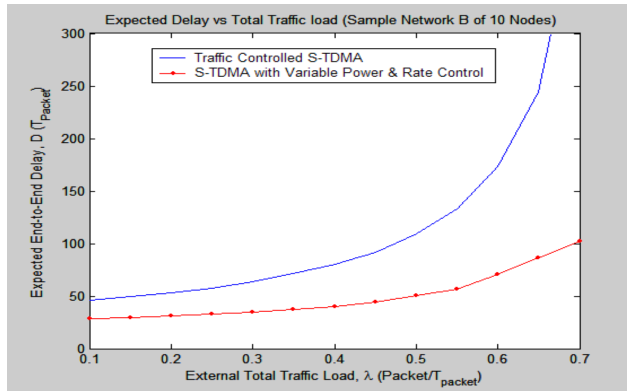




Fig. 2. Packet Delay vs. Traffic load. MAC Protocol: TC S-TDMA. Diagram 1 (Above). Network A. a) TC S-TDMA, b) TC S-TDMA with Power and Rate Control. Diagram 2 (Below). Network B. a) TC S-TDMA, b) TC S-TDMA with Power and Rate Control.

In EPR S-TDMA we assume that the minimum or basic data rate $R_b$ is equal to inverse of the packet duration. In [12] it is described a method to compute more precisely the data rates based on the packet size selected (information block size).

## 5. NUMERICAL RESULTS

In order to evaluate performance, two networks A and B composed by 20 and 10 nodes respectively are generated accordingly to the random process described in Section 2 over a geographical area of 100 x 100 $km^2$. Then, we compute the EPR S-TDMA scheduling accordingly to Section 4.3. Here it is assumed that a radio link can support four target SIRs, 1, 3 , 7 and 15 , these correspond accordingly to equation (2) to four data rates, 100 kbps, 200 kbps, 300 kbps and 400 kbps, respectively. The resulting delay performance is determined via network simulations. In Figure 2, Diagram 1, we can see that the average delay of Network A (lower curve) can be decreased considerably by taking into account the power and rate control in comparison with the traditional TC S-TDMA schemes (upper curve). Similar results have been obtained with the network B and these are illustrated in Figure 2, Diagram 2. In the simulation for TC S-TDMA our SIR target is minimal SIR of the EPR S-TDMA algorithm. The EPR 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. Finally, we have observe that EPR S-TDMA algorithm decreased the frame size in comparisson with TC S-TDMA.

## 6. CONCLUSIONS

The availability of power control and variable data rates in S-TDMA wireless networks raises new problem in schedule design. In this paper the addition of power and rate control to TC S-TDMA was investigated. A new scheduling algorithm, Traffic Controlled S-TDMA with enhance power and rate control (EPR S-TDMA) significantly improves network performance in the test networks. The simulation results show an improvement of the maximum throughput ($\lambda^*$) and lower average delay for all traffic conditions in comparison with the traditional TC S-TDMA. High maximum throughput is desirable in wireless networks, so including power and rate control in an S-TDMA ad hoc network is advisable. This improvement is achieved by utilizing variable power and rate control and knowledge of the expected the traffic load. 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. Also combining scheduling, routing and power allocation in ad hoc networking is an interesting problem.

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