Transmission Control for Spatial TDMA in Wireless Radio Networks

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Abstract- An attractive alternative for communications in areas in which there is little or no telecommunications infrastructure is to use Multi-hop packet radio networks (MPRNets). 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. High S-TDMA system capacities can be achieved by incorporating traffic load information into the MAC protocol design. Previous investigations into Traffic Controlled S-TDMA (TC S-TDMA) protocols used fixed transmission powers. Clearly, the application of power control to these systems could improve the spatial reuse factor. In this paper a suitable power control scheme has been applied to S-TDMA. As the cost of implementing power control is relatively small, and the performance gains are substantial, a prudent design should include power control. As would be expected the introduction of power control would markedly improved the delay performance of 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 (Multi-hop Ad hoc radio networks). 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: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. 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] due its numerous benefits.

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 power control to the uppers layer. Besides, 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. Furthermore, 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 has not been addressed. In this paper is presented, a suitable power 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 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 S-TDMA schemes. The power control issue is addressed in section IV. 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 introduces some implementational issues and section VII contains some the concluding remarks.

II. SYSTEM MODELS

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 $P_j = P_i \, (d_{ij})^{-\alpha}$. 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.

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, Γ_{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 γ_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 γ_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:

$$\Gamma_{ij} \geq \frac{P_i G_{ij}}{P \quad \underset{k \neq i}{} \quad k} = \frac{P_i G_{ij}}{Noise + \sum_{k \neq i} kj \; X \quad P_k} \qquad (2)$$

is greater than the threshold γ_0, otherwise the packet is lost. Here we have introduced the binary variable

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

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. 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 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 λ packets/time slot. We also assume the traffic load to be uniform, i.e. on the average each node

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

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

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

where T_{ij} are also the elements of the *Relative Traffic Load* matrix $\mathbf{T} = \{T_{ij}\}$. It should be noted that some $\lambda_{ij} = 0$ when the link (i, j) is not usable or unreliable. Moreover, we introduce *T(i)*, the estimated amount of traffic passing through each node i as:

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

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 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

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

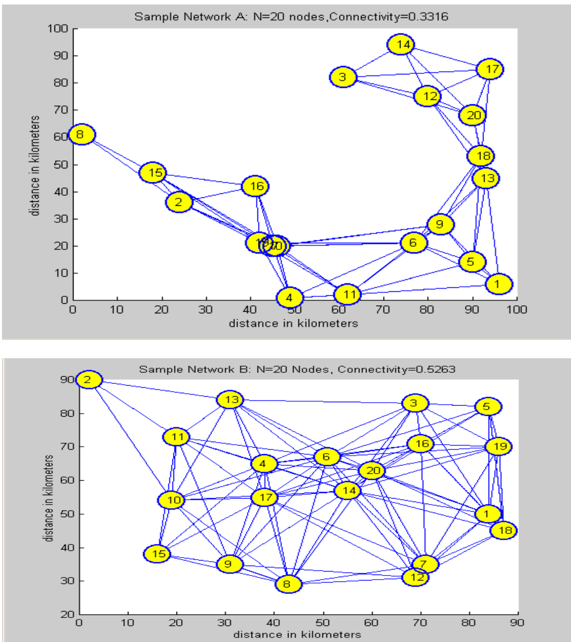

Fig. 1. Typical network realizations in a given area of 100 x 100 km^2. The number of nodes is N =20 . The lines represent the connections among the nodes. Above, the Sample Network A, and below the Sample Network B.

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 performance 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
Frequency	300 MHz
Data Rate	100 Kbps
External Packet Arrival	Poisson Distributed
Packet Destination	Uniform Distributed
Routing Algorithm	Minimum Hop Algorithm
Threshold path loss	138.3 dB
SIR Threshold (typical)	γ_0 = 10 dB
Equivalent Receiver Noise Bandwidth	100 KHz
Receiver Noise Figure	15 dB

III. S-TDMA for Multi-hop Networks

In S-TDMA, 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 Assignment* 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, **CM** = {cm_{ij}}, which is defined as [7]. In other words, each row in the **CM** corresponds to a maximal clique:

$$\mathbf{CM} = \begin{cases} 1 & \text{if arc } j \text{ can be activated in clique } i \\ 0 & \text{otherwise} \end{cases} \qquad (8)$$

High S-TDMA system capacities can be achieved by incorporating information from the matrix **T** into the MAC protocol design, this schemes are commonly referred as Traffic Controlled S-TDMA (TC S-TDMA) protocols. Previous investigations into TC S-TDMA systems used fixed transmission powers. 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 control to these systems could improve the spatial reuse factor. Therefore a combine power control & traffic-sensitive strategy can improved as well the system performance.

IV. POWER CONTROL for MPRNet:s

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 instant control of the entire power vector **P**. 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 well-known in a stationary MPRNet, here we consider a Centralized Constrained Power Control (CCPC) applied to Traffic Sensitive S-TDMA.

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 SIR. Let us assume that we draw from the schedule L nodes which are allowed to transmit in a particular timeslot. Let us describe all transmitter powers of the nodes in the network by the following power vector notation as:

$$\mathbf{P} = [P_1, P_2, P_3, .. P_N]^T \tag{9}$$

where the transpose of a vector […] is denoted as $[\ldots]^T$. This vector has clearly to be non-negative, i.e. $\mathbf{P} \geq 0$. We rewrite (2) as

$$\gamma_0 \geq \frac{P_i}{\dfrac{P_{Noise}}{G_{ij}} + \sum\limits_{k \neq i}^{L} \dfrac{G_{kj}}{G_{ij}} P_k} \tag{10}$$

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

$$H_{ik} = \begin{cases} 0 & \text{if } i = k \\ \dfrac{G_{kj}}{G_{ij}} \gamma_0 & \text{if } i \neq k \end{cases} \tag{11}$$

Furthermore, we define the Nx1 vector $\eta = (\eta_i)$ where $\eta_i = \gamma_0 (P_{Noise}/G_{ij})$ then rewriting the equation (10) using (11) in a matrix form results in (12)

$$\mathbf{AP} \geq \eta \tag{12}$$

where $\mathbf{A} = \mathbf{I} - \mathbf{H}$ and **I** denotes the identity matrix. From (12), it can be easily seen that the power vector **P** could be computed by the following expression

$$\mathbf{P} = (\mathbf{I} - \mathbf{H})^{-1} \eta \leq \mathbf{P}_{\mathbf{max}} \tag{13}$$

In this system there exist a transmission power ceiling, denote P_{max}, for every node in the network. Using (13) the transmitter powers of all nodes in a clique can be determined. If any elements of **P** > Pmax then the clique is not feasible.

C. The Algorithm of Creating a Power-Sensitive TC S-TDMA

In order to build the power-sensitive TC S-TDMA, we considered a simple distance dependence radio propagation model, which allows us to compute the Gain matrix for the network. The Minimum Hop Routing Algorithm (MHA) was used. In order to build the S-TDMA schedule, we enabled a set of links (called clique in the literature), for each timeslot, that fulfill two conditions: a) They are prioritized accordingly to their traffic load and b) The Signal-to-Interference-Ratio (SIR) is above the target SIR for every link. In the improved system power control was used to increase the number simultaneous transmissions. The calculation of the schedule for the power sensitive case is outlined in the flow chart in Fig. 2.

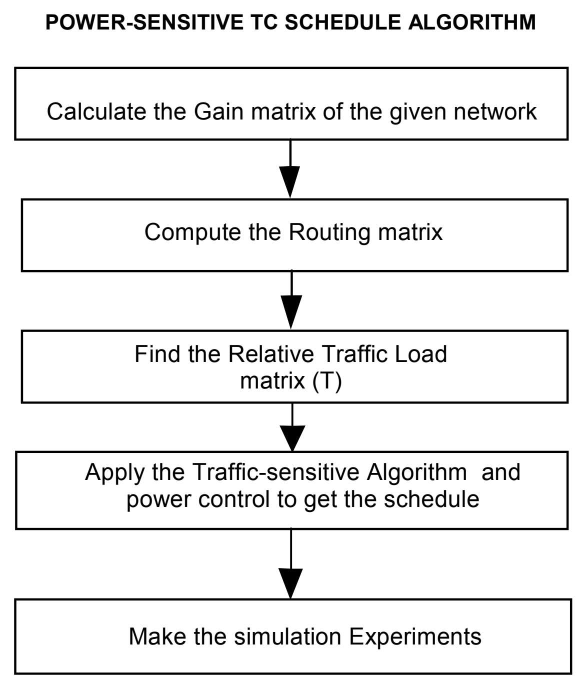

Figure 2. Flow diagram for creating the schedules in TC S-TDMA using power control.

V. NUMERICAL RESULTS ON S-TDMA

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. In Figure 3, Diagram 1, we can see that the average delay of Network A can be decreased considerably by taking into account the traffic load and power control in comparison with the non-power-sensitive TC S-TDMA. Similar results have been obtained with the network B and these are illustrated in Figure 3, Diagram 2.

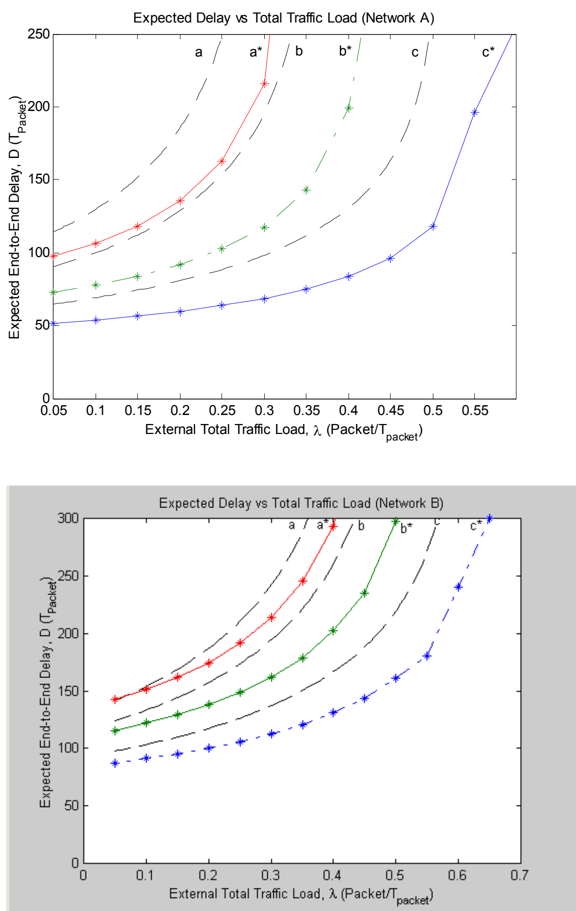

Fig. 3. Packet Delay vs. Traffic load. MAC Protocol: TC S-TDMA. Diagram 1 (Above). Network A. Without power control: a) γ_0 =15dB, b) γ_0 =10dB, c) γ_0 =5dB. With power control: a*) γ_0 =15dB, b*) γ_0 =10dB, c*) γ_0 =5dB . Diagram 2 (Below). Network B. Without power control: a) γ_0 =15dB, b) γ_0 =10dB, c) γ_0 =5dB. With power control: a*) γ_0 =15dB, b*) γ_0 =10dB, c*) γ_0 =5dB .

VI. IMPLEMENTATIONAL ISSUES

An important issue in practical systems design is the sensitivity to implementational imperfections. Here the effects of limited transmitter power dynamic range has been studied as well as the effect of quantization. Figure 4 show some numerical examples from the sample networks. It was found that a dynamic range of 20 dB achieves almost all the gain that is available by the power control. Figure 4 indicates that rather coarse power steps still provide adequate results.

VII. CONCLUSIONS

In this paper the addition of power control to TC S-TDMA was investigated. A new scheduling algorithm, TC S-TDMA with power control significantly improves network performance in MPRNet:s. The simulation results show an improvement of up to 60% of the *maximum* *throughput*, for high traffic load, 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 control is relatively small, and the performance gains are substantial, a prudent design should include power control.

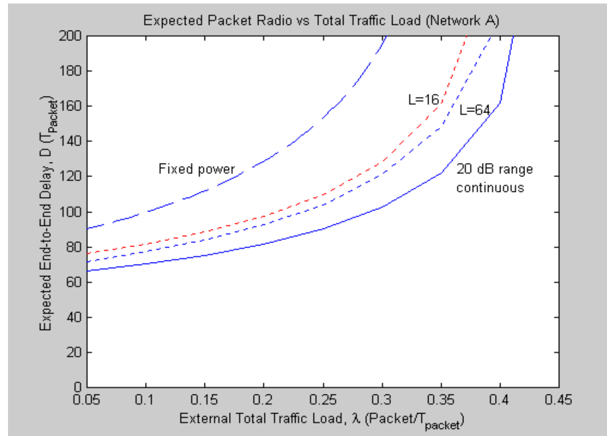

Fig. 4. Packet Delay vs. Traffic load. MAC Protocol: TC S-TDMA. γ_0 =10dB. Lower curves from the top: steps L=16, steps L=64, 20 dB range continuous. Dynamic range 20 dB.

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