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Scheduling and Power Control Framework for Ad hoc Wireless Networks

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ABSTRACT

The wireless medium is known to be time-varying which could affect and result to a poor network's performance. As a solution, an opportunistic scheduling and power control algorithm based on IEEE 802.11 MAC protocol is proposed in this paper. The algorithm opportunistically exploits the channel condition for better network performance. Convex optimization problems were also formulated i.e. the overall transmission power of the system is minimized and the "net-utility" of the system is maximized. We have proven that an optimal transmission power vector may exist, satisfying the maximum power and SINR constraints at all receivers, thereby minimizing overall transmission power and maximizing net-utility of the system.

Keywords: Scheduling, Wireless ad hoc Networks, Power Control, Optimization

1. INTRODUCTION

A wireless ad hoc network is a collection of nodes communicating over a wireless channel and capable of self-configuration; however, ad hoc networks lack centralized control, have limited node capabilities, and the links are time-varying. Hence, different opportunistic scheduling schemes were developed to exploit the wireless medium's channel condition. The term *opportunistic* [1] denotes the ability to schedule users for transmission based on favorable channel conditions. Most research on opportunistic scheduling focused on cellular systems and less attention was given to ad hoc networks. Hence, we were motivated to explore opportunistic scheduling in ad hoc networks particularly under random access MAC protocols.

Random access MAC protocols can be more efficient and distributed by taking advantage of power control. As shown in Fig. 1, if nodes C and D transmit data packet to each other at a power level enough only to reach each other, without interfering the transmission between nodes A and B, nodes C and D can have their own transmission while nodes A and B can have their own transmission too, as long as A and B uses enough transmission power that do not interfere with C and D's transmission. Hence, power control could allow greater number of simultaneous transmissions which could enhance spectral reuse.

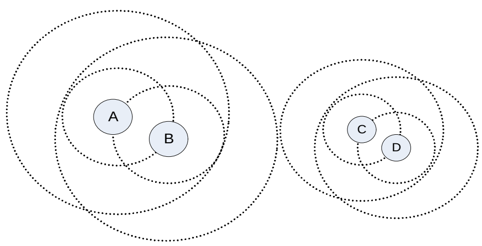

Fig. 1. Transmission powers with power control.

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The main contributions of our paper are as follows. We have formulated an energy-constrained convex optimization problem that finds an optimal transmission power vector that satisfies the maximum power and SINR constraints at all receivers such that the overall transmission power of the system is minimized and the network utility is maximized. We were able to design an opportunistic packet scheduling scheme with power control based on IEEE 802.11 MAC which exploits multi-user diversity in ad hoc networks, based on physical interference model or observed Signal to Interference plus Noise Ratio (SINR) at the link. For the power control algorithm, the wireless channel was modified and divided into two channels namely control and data channel. The control channel is where the RTS-CTS and the noise tolerance of the node are transmitted while data channel is where the data packets are transmitted. A NACK mechanism is proposed to be incorporated in the algorithm such that the receiver will just send NACK instead of ACK when the data is corrupted and needs retransmission.

2. RELATED WORKS

In wireless communication systems, channel quality is normally time-varying and independent across different neighbors; hence, a node has an opportunity to choose one of its neighbors with good channel quality to transmit data before those with bad channel quality. Presently, there are few studies of opportunistic scheduling in ad hoc networks and some of them are [2-4], and [5]. These papers exploit durations of high-quality channel conditions through rate adaptation while others exploit frequency diversity of multi-rate WLANs and multi-hop ad hoc networks.

For power control, several papers appeared in the context of cellular radio systems [6] and/or with TDMA/CDMA scheme [7,8]. The authors in [9] divided the data reception area of IEEE 802.11 DCF into two zones, based on the characteristics of wireless propagation model, namely decoding and carrier sensing zones. As the name implies, the decoding zone is the area where a node can receive and correctly decode a packet while a node within the carrier sensing zone can sense a signal but cannot decode it correctly. This data reception model is usually used for power control in ad hoc networks based on IEEE 802.11 RTS-CTS scheme like those in[9,10], and [11]. Hence, these decoding and carrier sensing zones were also taken into consideration in the power control scheme presented in this paper.

3. PROBLEM FORMULATION

3.1 System Model

An ad hoc network can be generally represented by a graph G(V,L) where V denotes the set of all nodes and L is the set of links between those nodes. We assume that there are M numbers of active direct communication pair (i, j) where i is the transmitting node and j is the receiving node, and $(i, j) \in L$. We let $\mathbf{P} = (P_1, P_2, \cdots P_M)$ as the power vector where P_i is the transmit power of node i. We also denote $N_j = \eta_o B_T$ as the noise signal at the receiver node, where η_o and B_T denotes the noise density and bandwidth respectively and the noise power vector for every source destination pair is defined as $\mathbf{N} = (N_1, N_2, \cdots N_M)$. We let G_{ij} be the link gain of transmitter i and its intended receiver j and G_{kj} as the link gain of an interfering node k at the receiver node j. The link gain of transmitter node i and its intended receiver j can be computed as $G_{ij} = 1/d_{ij}^{\beta}$ where β is a path loss exponent and d_{ij} is the distance between nodes i and its intended receiver j. A transmitter node i can only have a successful transmission to node j if the corresponding SINR, $\Gamma_j(\mathbf{P})$ at the link is greater than or equal to a given threshold γ_j as given by

$$\Gamma_j(\mathbf{P}) = \frac{P_i G_{ij}}{\sum_{i \neq k} P_k G_{kj} + N_j} \geq \gamma_j \qquad (1)$$

The interference made by simultaneous transmissions are treated as noise and we let Pn_j be the total noise observed at the receiver node where $Pn_j = \sum_{i \neq k} P_k G_{kj} + N_j$.

The assumptions and constraints of the algorithm are as follows. The channel gain between two nodes is approximately the same in both directions. We define $RX_{REQ} > RX_{THRESH}$ and $\gamma_{REQ} > \gamma_j$ where RX_{THRESH} is the minimum required signal power to receive a valid packet. RX_{REQ} and γ_{REQ} were incorporated to take transmission reliability into account i.e. the values should be larger than the thresholds. The bandwidth is divided into two: control and data channels. The power control channel has no interference with the data channel and both of them share the same propagation gain.

3.2 Minimizing Transmission Powers

We have formulated the power control problem as a linear programming (LP) problem given by (2)-(5). It aims to find an optimal transmission power vector that minimizes the overall transmission power of the system, while satisfying the SINR requirements and power constraints at all receiver nodes.

$$\text{Minimize} \quad \sum_{i=1}^{M} \alpha_i P_i \tag{2}$$

$$\text{Subject to} \quad 0 \le P_i \le P_i \max \tag{3}$$

$$\frac{P_i G_{ij}}{\sum_{i \neq k} P_k G_{kj} + N_j} \ge \gamma_j \quad = 1, 2, \ldots, M \tag{4}$$

Equation 2 is the objective of the problem where α is introduced as a cost or weight assigned for each transmission power P_i.

In addition $\alpha_i \ge 0$ and $\sum_{i=1}^{M} \alpha_i = 1$. The constraint (3) is the maximum power constraint where the transmit power of any node should be within [0, $P_i$max] or upper bounded by a maximum power level, $P_i max$. The second constraint (4) is the SINR constraint where the observed SINR at a link should satisfy the given threshold γ_j. The constraint (4) can be written in the form of $A\mathbf{P} \ge b$, where A (a receiver by transmitter matrix) and b are given below.

$$\mathbf{A} = \begin{bmatrix} 1 & \frac{-\gamma_1 G_{12}}{G_{11}} & K & -\frac{\gamma_1 G_{1M}}{G_{11}} \\ \frac{-\gamma_2 G_{21}}{G_{22}} & 1 & K & \frac{-\gamma_2 G_{2M}}{G_{22}} \\ M & M & O & M \\ \frac{-\gamma_M G_{M1}}{G_{MM}} & \frac{-\gamma_M G_{M2}}{G_{MM}} & K & 1 \end{bmatrix} \qquad \mathbf{b} = \begin{bmatrix} \frac{\gamma_1 N_1}{G_{11}} \\ \frac{\gamma_2 N_2}{G_{22}} \\ M \\ \frac{\gamma_M N_M}{G_{MM}} \end{bmatrix}.$$

The optimization problem can be formally written as

$$\text{Minimize} \quad {}_{P_i \in [0, P_i \max]} \alpha^T \mathbf{P} \tag{5}$$

$$\text{Subject to} \quad A\mathbf{P} \ge \mathbf{b} \tag{6}$$

The power control problem aims to find an optimal transmission power vector that satisfies the SINR requirement as well as the transmission power constraints at all receiver nodes. There may or may not exist a power vector **P** that satisfies the constraints. However, if an optimal solution exists, the objective function converges [12] to a minimum power vector such that the total power expenditure of the system is minimized. An optimal solution to the problem in (2) exists if and only if there is a solution to the constraints given by equations (3) to (4) i.e. there is at least one set of transmission powers which ensures successful reception at all receiver nodes which at the same time satisfies node's maximum transmission power and SINR constraints. Observe that, the transmit power is bounded by $P_i$max for all nodes; hence, an optimal solution exists by virtue of Theorem 3.4 in [13]. The optimal solution or minimizer ($\mathbf{P}^*$) can be solved using simplex method or any other simple means.

3.3 Maximizing "Net-Utility"

The second objective of the power control problem is to maximize utility. We adopt the definition of *"net utility"* in [6] which was defined as the difference between the value of the achievable data rate and the cost of the power consumption. According to Shannon, the capacity of an additive white Gaussian noise channel under average or peak power constraints with bandwidth W is given by

$$R_i(\mathbf{P}) = W \log_2(1+\Gamma_j(\mathbf{P})) \tag{7}$$

We let $R_i(\mathbf{P})$ as the achievable instantaneous data rate or capacity of link (i,j) under the maximum transmission power and SINR constraints. To maximize throughput, nodes should transmit at a high power as possible since the SINR, $\Gamma_j(\mathbf{P})$ is an increasing function of transmit power P_i. However, high transmit power could cause interference to other nodes; thereby, a trade off is necessary between opposite constraints since adding power increases the rate and reliability of transmission, but on the other hand, more power means more interference which may reduce the global throughput of the network.

We let $C_i(\mathbf{P})$ be the cost of the power consumed by node i's transmission to node j and similar to [6], we denote $R_i(\mathbf{P})-C_i(\mathbf{P})$ as the "net utility" of node i and $T_i(\mathbf{P})$ as the average "net utility" of user i. The objective is to maximize the net utility subject to a receiver's minimum data rate requirement and maximum transmission power constraint. We have formulated the maximization problem as

$$\text{Maximize}_{P_i \in [0, P_i \max]} \sum_{i=1}^{M} T_i(\mathbf{P}) \tag{8}$$

$$\text{Subject to } R_i(\mathbf{P}) \geq X_j \tag{9}$$

The constraint (9) simply says that the achievable data rate of node i associated with its transmission power P_i must satisfy the data rate requirement of the receiver node, denoted by X_j. An optimal solution to the problem (8) exists if there exists a transmit power that maximizes the data rate and minimizes the interference generated while transmitting the packets. Note that (9) is a function of SINR, which in turn is determined by the power levels at all active transmitters. Since the optimization problem (8) is convex, it could be easily solved using the techniques in convex optimization[14].

4. PROPOSED ALGORITHM

Motivated by the multicast RTS and priority-based CTS mechanism of OSMA (Opportunistic Packet Scheduling and Media Access Control) protocol [2], we proposed an opportunistic packet scheduling with power control scheme based on IEEE 802.11 MAC protocol. The following sections discuss our joint scheduling and power control algorithm in more detail.

4.1 Scheduling Framework

The scheduling framework of OSMA protocol [2] was adopted in the study. A multicast RTS and prioritized CTS mechanisms were implemented to exploit the multi-user diversity of the system. The main focus is on the next neighborhood transmission which is sending packet traffic to the specified neighbors while meeting the SINR constraints at the intended receivers. If the sender node has several packets in its queue waiting for transmissions, the scheduler will choose a set of receivers based on weight of the HOL (head of line) packet. As shown in Fig. 2, one separate queue for each next hop is maintained at the sender node.

In our proposed algorithm, a transmission is only successful if the received SINR, $\Gamma_j(\mathbf{P})$ at the receiving node is above the preset threshold γ_j. Firstly, the node will check if the channel is not busy else, the transmitting node will double its back off window and defer its transmission. This

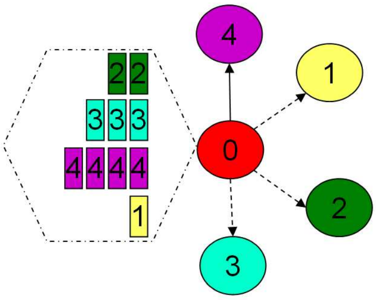

Fig. 2. Scheduling Framework.

back-off algorithm is similar to that of IEEE 802.11. If the channel is idle for a duration equal to DIFS (Distributed Inter Frame Spacing), NAV (Network Allocation Vector) is zero and the power received/observed (Pr_i) at sender is less than the carrier sensing range threshold, $Pr_i < CS_{THRESH}$, node i can send a multicast RTS at a power level P_i.

The format of the multicast RTS is given in Fig. 3 where additional parameters were added: Pn_i is the total noise observed at node i, RA is the receiver's address, TA as transmitter's address and FCS as Frame Check Sequence. The transmission power P_i at which RTS is transmitted and the duration at which channel will still be occupied are also included in the header of the multicast RTS. Upon receiving the RTS, the candidate receivers will analyze the channel condition by computing the SINR from the transmitter to the receiver itself. The other nodes in the neighborhood would just adjust their NAVs upon hearing the multicast RTS not intended for them. Only the candidate receiver with SINR above its SINR threshold is allowed to access the channel and will reply CTS first at a power level F_j given by (10). The RTS/CTS mechanism is facilitated by the scheduling framework (Fig. 2).

Frame Control	Pn_i	P_i	RA(1)	Duration	...	RA(M)	Duration	TA	FCS

Fig. 3. Multicast RTS.

4.2. Power Control Algorithm

Similar to the power control algorithm in [8], the transmit power F_j, used to transmit CTS, includes the total noise observed at the transmitter, Pn_i as given by the equation

$$P_j = \max\left\{\frac{RX_{REQ}}{G_{ij}}, \frac{\gamma_{REQ} Pn_i}{G_{ij}}\right\} \tag{10}$$

Similar to OSMA protocol [2], if there are more than one receiver qualified to transmit CTS, different IFSs (Inter-Frame Spacings) will be employed such that the IFS of the ith receiver will be IFS = SIFS+(n-1)×time-slot where n is the number of candidate receivers. The order of the receivers in the candidate receiver's list will be the basis of prioritization. The closer the receiver address to the top of the receiver list, the higher the priority to access the medium and to reply CTS. The receiver will include in the CTS (Fig. 4) the minimum transmission power P_{DATA}, needed by node i to transmit the data successfully to node j. The duration included in each frame, predefined the time it would take for node i to receive an ACK from its receiver.

$$P_{DATA} = \max\left\{\frac{RX_{REQ}}{G_{ij}}, \frac{\gamma_{REQ} Pn_j}{G_{ij}}\right\} \tag{11}$$

Before node i transmits data to node j at a required power level P_{DATA}, node i should perform collision computation [9] first at a nearby current receiver node, say k. This will ensure whether node i's transmission to its intended receiver j might cause collision to other nearby receivers. The symbol δ is a constant that ensures that the power level of i is slightly below the noise tolerance of other receiver node k.

Frame Control	Duration	RA	P_{DATA}	FCS

Fig. 4. Prioritized CTS.

$$P_i G_{ik} \le \delta\left(\frac{\Pr_k}{\gamma_k} - Pn_k\right) \tag{12}$$

The left side of the above equation denotes the noise caused by node i to a nearby receiver node k while the right side is the noise tolerance of node k. If node i satisfies the constraint above, it could send the intended data for its receiver. Otherwise, it should defer the transmission. When the receiver node j begins to receive data packet from node i, it estimates its signal and noise strength by computing the noise level it can endure by

$$\frac{\Pr_j}{\gamma_j} - Pn_j \tag{13}$$

and broadcast this information through the power control channel at a normal power level. This will inform other nodes that a transmission is going on and other nodes must perform collision computation first before initiating a transmission. This will ensure that the current transmission is not interfered. This mechanism may solve the asymmetrical link problem observed in IEEE 802.11 DCF.

If the receiver has not received the correct data packet within a time period, the receiver will send NACK to let the sender initiate retransmission. If the data packets are received successfully, the channel will return into IDLE mode. The joint opportunistic scheduling and power control is summarized in Fig. 5.

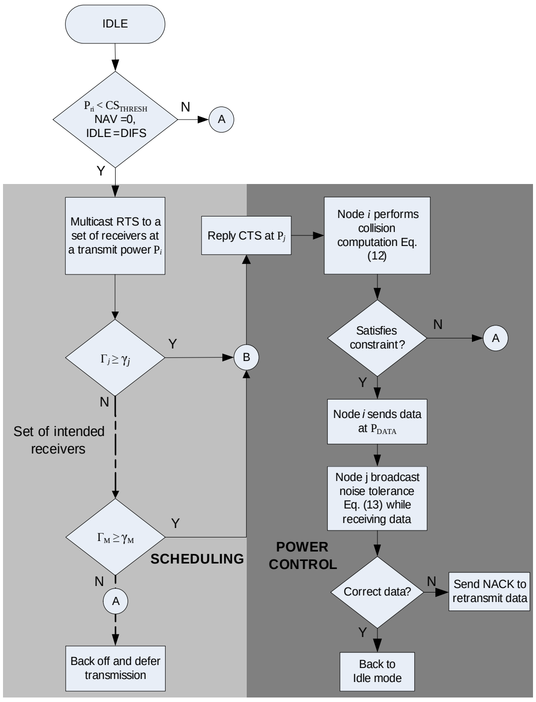

Fig. 5. Flowchart of the proposed opportunistic packet scheduling with power control.

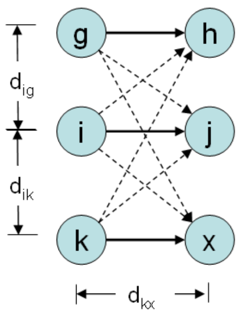

Fig. 6. Parallel Links.

5. Numerical Examples

Three parallel links as shown in Fig. 6 was investigated to explain the power control over interfering links. The three parallel links transmit in the same direction: g → ı, i → , k → ĸ. The active transmissions are indicated by the bold lines while the dashed lines are the transmissions made by the interfering nodes. We set d_{kx}=d_{ij}=d_{gh} and d_{ig}=d_{ik} and to avoid collisions between nodes, we also set d_{ig} > d_{kx}. In this example, we varied d_{ig} and d_{ik} where d_{kx} is fixed and is equal to 50meters. The optimal transmission power vector at each link was solved using MATLAB and the relationship of the optimal transmission power with increasing distance is plotted in Fig. 7. As can be seen in the graph, if same target SINR is assumed for all users, and when the distance between parallel links is less than twice the distance between each source-destination pair, the transmission power is increasing. However, as the distance between parallel links is greater than 100 meters, the transmission power decreases continuously. For the parallel links in our example, we can say that 100 meters is a threshold distance. If the links are near to each other, there is more interference generated in the network and therefore more power is needed to overcome the interference and satisfy the SIR requirement at the receiving nodes. The relationships between these parameters are quite obvious, hence, we can say that as distance between active links and interfering links increases, less interference will be generated and less transmit power is needed to have a successful transmission. Note that this optimal transmit power has satisfied the maximum transmission power and SINR constraints given in (3) and (4) respectively.

Still using the parallel links in Fig. 6, we fixed d_{kx}=50meters and d_{ig}=80 meters and we determine the optimal transmission power but at this time, the SINR requirements at each receiver were varied. As can be seen in Fig. 8, as the SINR requirement of the receiving nodes increases, the optimal transmission power needed for successful transmission also increases.

From the above example, the farther the distance of the current transmitter from interfering nodes, the lower is the optimal transmission power needed for a successful transmission which at the same time satisfies the maximum transmission power constraint and SINR constraint. Hence, a lower transmission power could be used if the two nodes are just close to each other and away from other interfering nodes. This way, the power consumption of the node is minimized and this further enhances spatial reuse of the bandwidth. The ideas obtained from our examples are important consideration in our power control and scheduling scheme, since we consider a valid transmission only if the nodes satisfies the SINR constraints in the first place.

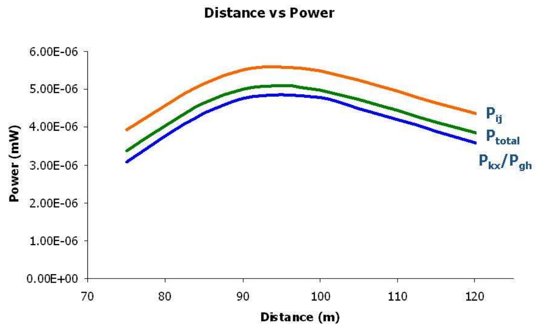

Fig. 7. Optimal transmission power as the distance between parallel links is varied. ($d_{kx}=d_{ij}=d_{gh}$=50meters)

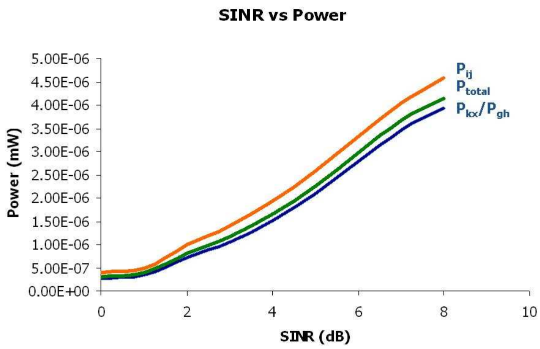

Fig. 8. Optimal transmission power at each active link as the SINR requirement at each receiving node is varied.

6. CONCLUSIONS

We have proposed an opportunistic packet scheduling and power control algorithm in ad hoc wireless networks based on IEEE 802.11 MAC protocol. If power control is implemented such that a node only uses enough transmission power to transmit data packets to other nodes, spatial reuse could be maximized. We have provided convex optimization problems where there may exists an optimal transmission power vector satisfying the maximum power constraint and SINR constraints of all nodes, which minimizes the overall transmission power and maximizes the utility of the system. For our future work, further simulation of our proposed algorithm and a comparison to other protocols will be conducted.

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