Opportunistic Scheduling with Power Control in Ad Hoc Wireless Networks

Reizel Casaquite[1], In-Yeup Kong[2], Myung-Hyun Yoon[3], Won-Joo Hwang[1]

[1]*Computer Networks Laboratory, Inje University, 607 Obang-dong, Gyeongnam, Gimhae*

[2]*Pusan National Universit, Geumjeong-gu, Busan, Korea*

[3]*Korea Electronics Technology Institute, Gyeongnam Local Office, Masan Gyeongnam, Korea*

rzl_16@yahoo.com,leafgirl@pusan.ac.kr, yoon@keti.re.fr, ichwang@inje.ac.kr

***Abstract* — To exploit the multiuser diversity in the CSMA/CA based wireless ad hoc networks, this paper proposes a new algorithm for opportunistic scheduling that will take advantage of both multiuser diversity and power control. The scheduling scheme is performed first before power control to further enhance throughput. The scheduling scheme ensures that the transmission is successful since a best candidate receiver is chosen for transmission and hence minimizes retransmissions. Likewise, the power control algorithm helps reduce interference between links and maximizes spatial reuse. In our study, we provided the scheduling scheme and the power control algorithm. We also showed optimal solutions for minimizing power consumption and maximizing net utility.**

***Keywords* — Opportunistic Scheduling, Power Control, Ad hoc Networks.**

1. Introduction

Scheduling has been extensively studied in various disciplines in wireline and wireless networks. These scheduling policies provide various degrees of performance guarantees including short-term and long-term fairness, as well as short-term and long term throughput bounds [1]. However, wireless communications systems have unique characteristics such as time-varying channel conditions and multiuser diversity. As a result, opportunistic scheduling was developed to achieve higher network performance by exploiting the channel conditions. The term opportunistic [7] denotes the ability to schedule users based on favorable channel conditions. Various opportunistic scheduling schemes have been studied and their common objective is to improve/maximize system performance or throughput under various fairness and QoS constraints. Most of the current researches on opportunistic scheduling focus on cellular systems, specifically the downlink side and there is less attention given to ad hoc networks. Hence, the researchers are motivated to explore opportunistic scheduling in ad hoc networks.

Most ad hoc wireless network systems attempt to form multi-hop networks without pre-configured network topologies and may contain nodes of various types, of which many can have limited power capabilities. Hence, power management in ad hoc networks is very important. There are certain issues in power management in ad hoc networks as posed by the authors in [10]. As the transmission power is reduced, the communication range is also reduced and there is a risk of loosing network connectivity. Likewise, as the communication range is reduced, the number of hops per packet may also increase and consequently, may increase system latency and decrease throughput. Finally, as the transmission power is being increased or decreased, more collisions may occur due to incorrect assumptions about the usage of the channel.

The IEEE 802.11 DCF (Distributed Coordination Function) mode is the most dominant MAC protocol for ad hoc networks. It follows the CSMA/CA with RTS/CTS (Request-To-Send and Clear-To-Send) handshake between the transmitter and receiver which reserve the floor for data transmission. These control packets and data packets are usually transmitted at a fixed or maximum power level to prevent all other potentially interfering nodes from starting their own transmissions. Any node that hears the RTS or CTS message defers its transmission to avoid collision. However, the fixed-power approach has a negative impact on channel utilization by not allowing concurrent transmissions to take place over the reserved floor. Also, the received power from a sender may be more than what is needed to achieve the required SINR, (signal-to-interference and noise ratio) and hence there is a waste of energy.

As a result, we study opportunistic packet scheduling with power control in ad hoc networks. One of the advantages of a power controlled protocol in ad hoc networks is that it allows a greater number of simultaneous transmissions which enhance spectral reuse. The study has the following objectives: 1. To design an opportunistic packet scheduling scheme and power control algorithm based on CSMA/CA framework; 2. To show that the proposed opportunistic scheduling and power control algorithm yields a higher throughput than IEEE 802.11; 3. To derive a mathematical analysis that shows if an optimal transmission power vector satisfying SINR constraints exists, it minimizes power consumption, and 4. To show that the power control algorithm maximizes utility.

The rest of the paper is organized as follows. Section 2 reviews the related work. Section 3 describes the proposed opportunistic scheduling and power control algorithm. In section 4 we show through Lagrangian duality that if there exist an optimal transmission power that satisfies certain constraints it converges to an optimal or minimum overall transmission power. Since a trade-off exists between throughput and power consumption, we show that the net utility [3] of the system could be maximized.

2. Related Works

In ad hoc networks, it is usual that a node concurrently communicates with several neighbors. Since the channel quality is normally time-varying and independent across different neighbors, this provides the node 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], [3], [4], and [5]. Some of these papers exploit durations of high-quality channel conditions through rate adaptation while others exploit frequency diversity of multirate WLANs and multi-hop ad hoc networks.

There are several power control algorithms in the literature but most of them have appeared in the context of cellular radio systems. In the study made by authors in [10], they divided the data reception area of IEEE 802.11 DCF into two zones based on the characteristics of wireless propagation model. These zones are the decoding zones and carrier sensing zone as shown in the Figure 1 below. If node 3 is the sender, the nodes 2 and 4 are within the decoding zone while nodes 1 and 5 are within the carrier sensing zone only. As the name implies, the decoding zone is the area where a node can receive and correctly decode a packet. When a node is within the carrier sensing zone, it can sense a signal but cannot decode it correctly.

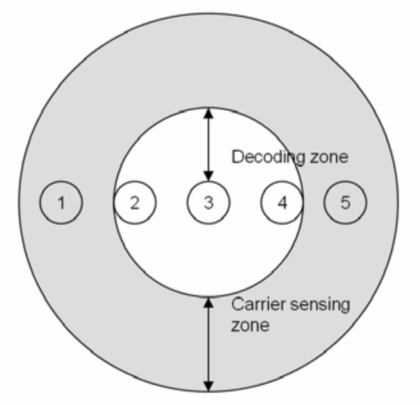


Figure 1. Data reception area of IEEE 802.11: decoding zone and carrier sensing zone.

In [8], they introduce PCM, a Power Control MAC protocol for ad hoc networks which is similar to BASIC scheme that uses maximum power level for RTS-CTS and minimum necessary transmit power for DATA-ACK. Only that during data transmission, the sender periodically raises the power level to the maximum level. In this way, the battery power is saved but the throughput is not totally enhanced. PCMA, a Power Controlled Multiple Access wireless MAC protocol within the collision avoidance framework was proposed in [9]. Their protocol generalizes the on/off collision avoidance into a flexible variable bounded power collision suppression. PCMA uses two channels, one for the packets and the other one for the busy tone. The busy tone is used to overcome the hidden terminal problem such that, while the node receives data packet, the node periodically sends a busy tone. The PCMAC on the other hand which is proposed by Lin et al [10] improves the handshake mechanism of IEEE 802.11 by adding a separate power control channel and a transmission table. In this way, they have tackled the asymmetrical link problem.

Liu et al, [6] studied the interference management in cellular networks through a joint scheduling and power allocation schemes. Using stochastic methods they solved an optimization problem in minimizing transmission powers and maximizing net utility. The authors in [12] propose a joint scheduling and power control for wireless ad hoc networks in TDMA and TDMA/CDMA systems. Their algorithm first determine the set of users who can attempt transmission simultaneously in a given slot and then specify the set of powers needed in order to satisfy SINR constraints at their respective receivers. This is done via scheduling and power control. The joint scheduling in [12] is in the context of unicast transmissions only, hence the authors in [13] proposes a distributed joint scheduling and power control algorithm for multicast traffic in TDMA/CDMA scheme.

This paper differs from related works in the following ways. Our paper exploits multiuser diversity in ad hoc networks considering the physical condition in the case there is a transmitter node which has several packets to send to a set of receivers. The best candidate receiver based on channel conditions is chosen for data transmission. The power control algorithm is based on CSMA/CA mechanism. We have made some modifications such that the system uses two channels: control channel and data channel. The control channel is where the RTS-CTS and the noise tolerance of the node are transmitted. Instead of ACK, the receiver will just send a NACK if the data is corrupted and need retransmission. The details of the algorithm will be described in Section 3.

3. Proposed Algorithm

3.1 System Model

In a system there are M nodes. Let $\mathbf{P} = (Pt_1, Pt_2, ..., Pt_M)$ be a power vector where Pt_i is the transmit power of user i.
Let N_i be the noise signal at node i, $N_i = \eta_O B_T$ where η_O is the noise density with bandwidth B_T. Then, we can define a noise power vector $\mathbf{N}=(N_1, N_2, ..., N_m)$, for every node i. Let G_{ik} be the link gain between the receiver of node i and transmitter k. Let $\Gamma_i(\mathbf{P})$ be the SINR of node i and γ_i is its target SINR.

$$\Gamma_i(\mathbf{P}) = \frac{Pt_i}{I_i(\mathbf{P})} \tag{1}$$

where $I_i(\mathbf{P})$ is the effective interference of node i and is defined as

$$I_i(\mathbf{P}) = \frac{\sum_{i \neq k} G_{ik} Pt_k + N_i}{G_{ii}}$$

and let Pn_i be the total noise observed at the receiver of node i.

$$Pn_i = \sum_{i \neq k} G_{ik} Pt_k + N_i$$

The assumptions and constraints of our algorithm are as follows:

1. The transmit power of any node is upperbounded by a maximum power level denoted as P_{MAX} and it must be in the range, $0 \le Pt_i \le P_{MAX}$.
2. The transmission from node i is successful if the received SINR $\Gamma_i(\mathbf{P})$ at the intended receiver j is not less than the minimum required SINR threshold, γ_i .
3. The channel gain between two nodes i approximately the same in both directions. The propagation gain incorporates the effects of link loss phenomena such as fading and shadowing. The gain between nodes can be computed as ratio between the received power from node i over the transmission power of node i.
4. Let $P_{THRESH}<P_{REQ}$ and $\gamma_i < \gamma_{REQ}$. P_{THRESH} is the minimum received signal power needed for receiving a valid packet. The reason that the values should be larger than the threshold is to take the transmission reliability into account.
5. The bandwidth is divided into two channels: data and control channels. The power control channel has no interference with the data channel and both of them share the same propagation gain and the transmission ranges are same if using the same power level.

3.2 Scheduling Framework

The framework given in [1] will be adopted in the study. In order to exploit the multiuser diversity, a multicast RTS and a prioritized CTS mechanism will be implemented as proposed by Wang et al. The focus will be on the next neighborhood transmission which is sending packet traffic to the specified neighbors while meeting constraints on the SINR at the intended receivers.

At the sender node, one separate queue is maintained for each next hop. If the sender 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. The WFQ (Weighted Fair Queuing) algorithm will be used instead of Round-robin policy. By default, WFQ schedules low-volume traffic first, while letting high-volume traffic share the remaining bandwidth. This is handled by assigning a weight to each flow, where lower weights are the first to be serviced.

3.3 Opportunistic Packet Scheduling with Power Control

Power control mechanisms remain a challenge in ad hoc networks. As shown in Figure 1, if a power control mechanism is implemented such that only enough transmission power is used as long as it maintains network connectivity and reduces interfernce, spatial reuse could be maximize.

In our proposed algorithm, using the physical model, transmission is successful if the received SINR of a node $i, \Gamma_i(\mathbf{P})$ is above the preset threshold γ_i . If the channel is busy, the node will double its back off window and defer transmission. If the channel is idle for a duration equal to DIFS (Distributed Inter Frame Spacing), NAV (Network Allocation Vector) is zero and the received power (Pr_i)of sender i is less than the carrier sensing range threshold, $Pr_i<CS_{THRESH}$ as shown in Figure 1, then node i can send the multicast RTS at a power level Pt_i .The multicast RTS will include the noise level, Pn_i at the sender's node and its transmission power Pt_i at which RTS is transmitted. Also, it includes a duration which is used to specify the time that the channel will still be occupied. The terminals in the neighborhood could adjust their NAVs upon receiving the multicast RTS as shown in Figure 2.

Frame Control	Pn_i	Pt_i	RA(1)	Duration	...	RA(N)	Duration	TA	FCS

Figure 2. Multicast RTS

Upon receiving the RTS, the receivers will then analyze the channel condition by computing the SINR of the link from that transmitter to the receiver itself. The received power at the receiver must be at least equal to P_{THRESH} which denotes the minimum received signal power for receiving a valid packet. The candidate receiver with SINR above its SINR threshold, $\Gamma_i(\mathbf{P}) \ge \gamma_i$ is allowed to access the channel and will reply CTS at a power level Pt_j in order to satisfy the both minimum power threshold and the SINR threshold.

$$Pt_j = \max\left\{\frac{P_{REQ}}{G_{ij}}, \frac{\gamma_{REQ} Pn_i}{G_{ij}}\right\} \tag{2}$$

If there is more than one receiver that will be 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 [1]. 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 media and hence the high priority to reply CTS first.

The receiver will include in the CTS (Figure 3) the minimum transmission power P_{DATA}, needed by the sender to transmit the data successfully. The duration included in each frame presume the time it would take for the sender to receive an ACK frame from the receiver.

$$P_{DATA} = \max\left\{\frac{P_{REQ}}{G_{ij}}, \frac{\gamma_{REQ} Pn_j}{G_{ij}}\right\} \tag{3}$$

Frame Control	Duration	Receiver Address	P_{DATA}	FCS

Figure 3. Prioritized CTS

Before the sender node i transmit data to its destined receiver at the required power level, sender i should perform collision computation [10] at a nearby receiver, say k. If it satisfies the constraint below then it could send the data. This will ensure whether node *i's* transmission might cause collision at nearby current receiver. The symbol λ is a coefficient that will ensure that the power level is slightly below the threshold.

$$G_{jk} Pt_i \leq \lambda \left(\frac{\Pr_k}{\gamma_k} - Pn_k \right) \qquad (4)$$

The left hand side of the above equation denotes the noise given by node i to node k while the right side is the noise tolerance of node k.

When receiver begins to receive data packet, it estimates the signal and noise strength, computing the noise level it can still endure by

$$\frac{\Pr_j}{\gamma_j} - Pn_j \qquad (5)$$

and then broadcast this information through the power control channel at the normal level.

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, else the channel will return into idle mode.

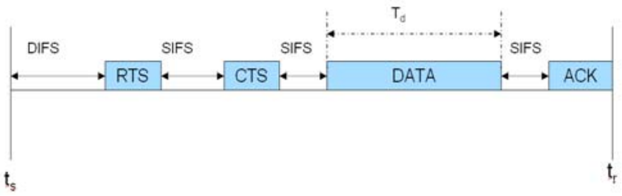
The power control algorithm is summarized in Figure 4 where node i is the sender and node j is the receiver.

One of the objectives of power control is to maximize spatial reuse of bandwidth. To measure the effectiveness of bandwidth spatial reuse, an end to end throughput could be an appropriate metric. Hence, we can say that spatial reuse of bandwidth is maximized if we can show that throughput is also maximized. The throughput capacity is the average number of bits transmitted per unit time by every node to its destination. Hence, throughput is concerned of the transmission rate per node.

In IEEE 802.11 unicast packet transmission sequence, the throughput [11] could be measure using the equation below.

$$TP = \frac{S}{t_r - t_s}$$

where S is the packet size of the packet
t_s is the time stamp that packet is ready
t_r is the time stamp that ACK has been received



$$T_{TOTAL} = DIFS + \frac{S_{RTS}}{BW} + SIFS + \frac{S_{CTS}}{BW} + SIFS + \frac{S_{DATA}}{BW} + SIFS + \frac{S_{ACK}}{BW}$$

The total transmission time needed in IEEE 802.11 is given by T_{TOTAL}. In the proposed algorithm however, DIFS duration is allotted for scheduling scheme. Wherein upon transmitting multicast RTS a DIFS duration is given to the set of candidate receivers in order to choose the best receiver to reply the CTS.

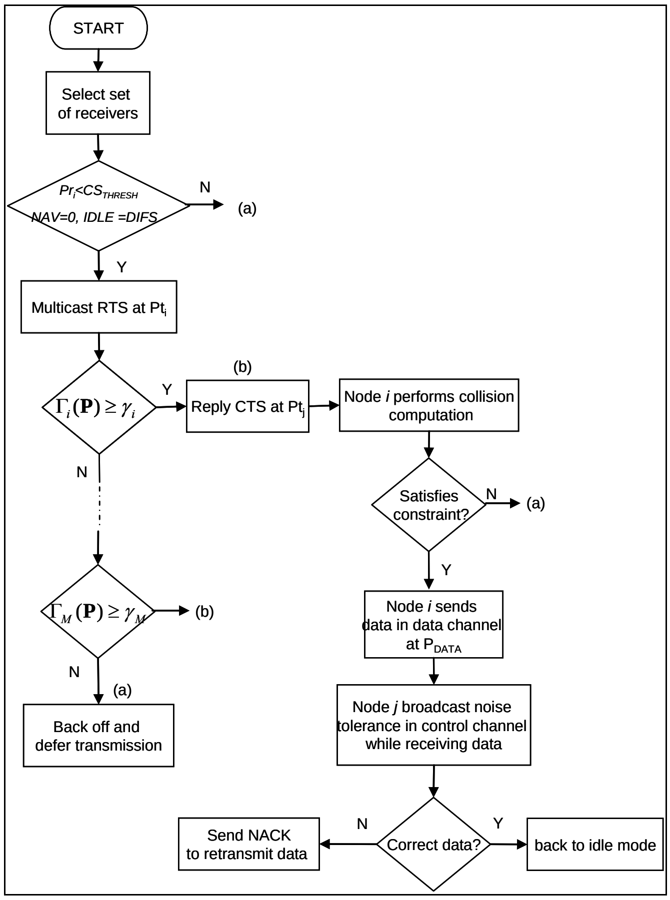
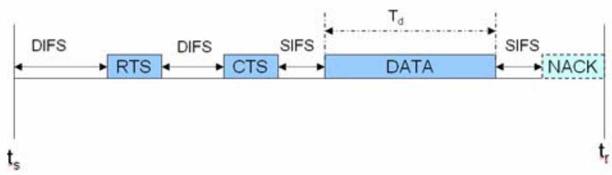


Figure 4. Flowchart of the proposed opportunistic packet scheduling with power control.

If we let S be the size of the packets, then the total time for a node's transmission is



$$T_{TOTAL} = DIFS + \frac{S_{RTS}}{BW_{CH1}} + DIFS + \frac{S_{CTS}}{BW_{CH1}} + SIFS + \frac{S_{DATA}}{BW_{CH2}} + SIFS + \left(\frac{S_{NACK}}{BW_{CH2}} \right)$$

where

Control channel bit rate = BW_{CH1}
Data channel bit rate = BW_{CH2}
Total bit rate of the channel bandwidth BW_{CH} = BW_{CH1}+BW_{CH2}

Based from the equations, we can say that the IEEE 802.11 has a shorter time for transmission than the proposed protocol. However, as already known, there are problems in hidden and exposed terminals in IEEE 802.11 MAC. We must show then that though the total time for transmission for IEEE 802.11 is shorter than our proposed protocol, IEEE 802.11 is more prone to collision and retransmissions; hence, there is a drawback on the throughput. Unlike, the proposed protocol, the joint scheduling and the power control yields a higher throughput due to spatial channel reuse and interference avoidance.

4. Mathematical Analysis

4.1 Minimizing Transmission Powers

The power control problem aims to minimize the overall transmission powers while satisfying the SINR requirements of all nodes. The first objective of the power control problem aims to find an optimal transmission power, satisfying the SINR requirement of all users. The power control problem is a linear programming problem where the objective function could be formally stated as

$$\text{minimize} \quad \sum_{i=1}^{M} Pt_i \tag{6}$$

$$\text{subject to} \quad 0 \le Pt_i \le P_{\max} \tag{7}$$

$$\frac{G_{ij} Pt_i}{\sum_{i \ne k} G_{ik} Pt_k + N_i} \ge \gamma_i \tag{8}$$

The second constraint (8) can be written in the form of $A\mathbf{P} \ge b$, where A is the channel gain matrix. The first goal of the minimization of power is to find a feasible transmission power that satisfies the given constraints. According to the theorem as cited by [2], there is a power vector which guarantees the successful reception at all receiver nodes, which satisfies the constraints (7) and (8). Hence, there exists a feasible solution for the LP problem in (8). Likewise, there exists a feasible region R_f which contains the feasible solution that satisfies the given constraints.

$$\text{minimize} \quad \sum_{i=1}^{M} Pt_i$$

$$\text{subject to} \quad 0 \le Pt_i \le P_{\max}$$

$$\mathbf{A} Pt_i \ge \mathbf{b}$$

We consider the primal problem above and we let Pt_i^* as the optimal solution and $g(c)$ be its optimal cost. Using the Lagrange multiplier or price vector υ ,where $\upsilon \ge 0$ we introduce a relaxation problem in which the constraint $\mathbf{A} Pt_i \ge \mathbf{b}$ is penalized and replaced by $\upsilon(\mathbf{b} - \mathbf{A} Pt_i)$. For the price variable υ the cost of transmission power of each transmitter associated with the constraint, we can introduce the problem

$$\text{minimize} \sum_{i=1}^{M} Pt_i \; + \upsilon(\mathbf{b} - APt_i)$$

$$\text{subject to} \quad Pt_i \in R_f$$

and denote its optimal cost as $g(\upsilon)$ where $g(\upsilon) = \min \sum_{i=1}^{M} (Pt_i \; - \upsilon APt_i) + \upsilon \mathbf{b}$. Hence, the dual problem [14] is obtained as

$$\text{maximize} \quad g(\upsilon)$$

$$\text{subject to} \quad \upsilon \ge 0$$

Lemma 1. If the problem in (6) has an optimal solution and if $\upsilon \ge 0$, then $g(\upsilon) \le g(c)$.

Proof: Let Pt_i^* denote the optimal solution to the LP problem in (6) then $\mathrm{b} - \mathrm{APt}_\mathrm{i}^* \le 0$, and therefore using the definition above

$$g(\upsilon) = \min \sum_{i=1}^{M} (Pt_i^* \; - \upsilon APt_i^*) + \upsilon \mathbf{b}$$

$$\le \sum_{i=1}^{M} Pt_i^*$$

$$\le g(c)$$

Therefore, $g(\upsilon) \le g(c)$, where $g(\upsilon)$ is the lower bound of the optimal cost. This completes the proof.

4.2 Maximizing Utility

One of the objectives of the power control problem is to maximize throughput. According to Shannon capacity formula [16], the capacity or the maximum rate at which data can be transmitted over a given communication path or channel with bandwidth W under the power vector **P** is given by

$$R_i(\mathbf{P}) = \mathrm{W}\log_2(1 + \Gamma_i(\mathbf{P}))$$

To maximize throughput, the nodes should transmit at high power as possible since $\Gamma_i(\mathbf{P})$ is an increasing function of $\mathrm{Pt_i}$. However, transmission power could cause interference within the nodes, so we should consider power consumption just what the authors in [3] did.

They introduce the notion of “net utility” which is defined as the difference between the value of the throughput and the cost of power consumption. Let $R_i(P)$ be the achievable instantaneous data rate of node i under the maximum transmission power constraint $0 \le Pt_i \le P_{\max}$ and SINR constraint. $R_i(P)$ denotes the instantaneous capacity of the system associated to Pt_i. Let $C_i(\mathbf{P})$ be the power cost of node i and then let $R_i(\mathbf{P}) - C_i(\mathbf{P})$ be defined as the net utility of node i.

Also let $T(\mathbf{P}) = \frac{\sum_{i=1}^{M} R_i(\mathbf{P}) - C_i(\mathbf{P})}{M}$ be the average net utility of user i.

The objective is to maximize the net utility given the maximum power constraint and the data rate requirement constraints. Hence, the maximization problem can be written as

$$\text{maximize} \quad T(\mathbf{P}) \tag{9}$$

$$\text{subject to} \quad 0 \le Pt_i \le P_{\max} \tag{10}$$

$$R_i(\mathbf{P}) \ge Dr_i \tag{11}$$

The second constraint (11) simply says that the achievable data rate of node i associated with its transmission power Pt_i must be greater than of equal to the required data rate of node i which is denoted by Dr_i.

Using the Lagrange multiplier η , we can have the Lagrangian function in the form of

$$L(\mathbf{P},\eta)=T(\mathbf{P})+\eta(Dr_i-R_i(\mathbf{P})) \tag{12}$$

For $\eta_i \geq 0$, the Lagrangian relaxation problem is given by

$$g(\eta)=\max L(\mathbf{P},\eta) \tag{13}$$
$$\text{subject to } \mathbf{P}\in R_f$$

Using the Lagrangian duality, the dual problem is obtained by making the Lagrangian relaxation as strong as possible.

$$\text{minimize } g(\eta)$$
$$\text{subject to } \eta \geq 0$$

Lemma 2: If z(**P**) is the optimal value of the problem (9) and $\eta \geq 0$, then $g(\eta)\geq z(\mathbf{P})$.

Proof: Suppose $\mathbf{P}^*$ satisfies the maximum transmission power constraint and data rate constraint and $\eta \geq 0$ then

$$\begin{aligned} g(\eta) &= \max\left[T(\mathbf{P}^*)+\eta(Dr_i-R_i(\mathbf{P}^*))\right] \\ &\geq T(\mathbf{P}^*)+\eta(Dr_i-R_i(\mathbf{P}^*)) \\ &\geq T(\mathbf{P}^*) \\ &\geq z(\mathbf{P}) \end{aligned}$$

and $g(\eta)$ denotes as the upperbound of the optimal cost. This completes the proof.

5. Conclusion and Future Works

In this paper we have proposed an opportunistic packet scheduling and power control algorithm in ad hoc networks based on CSMA/CA framework. In our study, we provided the scheduling scheme and the power control algorithm. The scheduling scheme ensures successful transmission since a best candidate receiver is chosen for transmission and hence minimizes retransmissions. Likewise, the power control algorithm helps reduce interference between links and maximizes spatial reuse. We have also shown that there exist optimal solutions for minimizing power consumption and maximizing net utility. However, due to limited time and other resources we were not able to simulate our proposed opportunistic packet scheduling with power control and compare it to other algorithms.

As a supplement, based from previous studies, power controlled MAC achieves higher throughput than IEEE 802.11 MAC protocol since interference with other nodes is avoided. Unlike in IEEE 802.11 hidden and exposed nodes exist. Moreover, the opportunistic scheduling scheme proposed by [2] obtains throughput gains several times better as compared to 802.11 MAC. Hence, we are confident that our proposed scheduling and power control scheme will perform better than IEEE 802.11 MAC. Merely that, a comparison between our proposed protocol with other protocols is needed. This is for further implementation.

References

[1] X. Liu, Chong, E.K.P, Shroff, N.B., "Optimal Opportunistic Scheduling in Wireless Networks," *Vehicular Technology Conference*, 2003. Volume 3, 6-9 Oct. 2003 P1417 – 1421.

[2] J. Wang, H. Zhai, and Y. Fang., "Opportunistic Packet Scheduling and Media Access Control for Wireless LANs and Multi-hop Ad Hoc Networks," *Wireless Communications and Networking Conference*, 2004. Volume 2, 21-25 March 2004 Page(s) 1234.

[3] J. Wang, H. Zhai, Y. Fang, and Y. M.C., "Opportunistic Media Access Control and Rate Adaptation for Wireless Ad hoc Networks," *IEEE International Conference on Communications*, Volume 1, 20-24 June 2004 Page(s):154 - 158 Vol.1.

[4] V. Kanodia, A. Sabharwal, and E. Knightly, "MOAR: A multi-channel Opportunistic Auto-rate Media Access Protocol for Ad Hoc Networks," *Proceedings First International Conference on Broadband Networks*, 2004 Page(s):600 – 610.

[5] B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly, "Opportunistic Media Access for Multirate Ad hoc Networks," in *Proceedings of ACM MOBICOM* 2002.

[6] X. Liu, E.K.P. Chong, and N.B. Shroff, "Joint Scheduling and Power-Allocation for Interference Management in Wireless Networks," *Proceedings of Vehicular Technology Conference*, 2002. IEEE 56th Volume 3, 24-28 Sept. 2002 Page(s):1892 – 1896.

[7] A.I. El-Osery, D. Baird and S. Bruder, "Transmission power management in ad hoc networks: issues and advantages," *IEEE Proceedings of Networking, Sensing and Control* 2005, 19-22 March 2005 Page(s):1043 – 1048.

[8] E. Jung and N. H. Vaidya "A Power Control MAC Protocol for Ad Hoc Networks" Mobicom 2002, September 23-28, 2002 Atlanta, Georgia, USA

[9] J. Monks, V. Bharghavan and W. Hwu. "A Power Controlled Multiple Access Protocols for Wireless Packet Networks", INFOCOM 2001. Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings.IEEE Volume 1, 22-26 April 2001 Page(s):219 - 228 vol.1

[10] X. Lin, Kwok, Y. and V. Lau "Power Control for IEEE 802.11Ad Hoc Networks: Issues and A new Algorithm" Proceedings of the 2003 International Conference on Parallel Processing (ICPP'03)

[11] S. Shah, H., K. Chen and K. Nahrstedt, "Dynamic Bandwidth Management for Single-hop Ad Hoc Wireless Networks", Proceedings of the first IEEE International Conference on Pervasive Computing and Communications (PerCom'03) 2003.

[12] T. Elbatt and A. Ephremides "Joint Scheduling and Power Control for Wireless Ad-hoc Networks". IEEE INFOCOM 2002

[13] K. Wang, C. Chiasserini, R. Rao, and J. Proakis "A Distributed Joint Scheduling and Power Control Algorithm for Multicasting in Wireless Ad Hoc Networks" IEEE International Conference on Communications, 2003

[14] Bertsimas D. and J. Tsitsiklis. Introduction to Linear Optimization. Massachusetts Institute of Technology. Belmont, Mass. 1997.

[15] Stallings William, Data and Computer Communications. 7th Edition Pearson Prentice Hall, NJ. 2004.