PCF: On Exploiting Spatial Reuse and Power Conservation Opportunities with Power Control and Fairness Mechanism for 802.11 WLAN

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Abstract—**Exploiting spatial reuse opportunities will allow more parallel transmissions and improve the throughput of wireless networks. Power control is one of the major mechanisms used to exploit both spatial reuse and power conservation opportunities. Increasing the transmitting power will prevent receiver from interference but consume power and create additional interference to other communicating nodes. On the contrary, reducing the transmitting power will reduce the interference to other communicating pairs and save sender's power consumption, but result a lower SNR (Signal to Noise Ratio) at receiver side. This article presents power control MAC protocol to exploit the spatial reuse and power conservation opportunities for 802.11 Wireless LAN. The proposed protocol evaluates the interference and adopts power control mechanism on both sender and receiver sides, trying to allow more communications proceeding simultaneously. In addition, a fairness control mechanism is also proposed to reduce the average communication delay and alleviate the packet lost phenomenon. Performance results reveal that the proposed protocol improves the throughput and power consumption of WLAN while the fairness among communicating pairs can be maintained.**

I. INTRODUCTIONS

802.11 wireless local area network(WLAN) has been widely used for providing mobile devices with capability of wireless communication. However, mobile devices are usually powered by batteries which constraint the use of energy. Therefore, techniques for energy conservation are of interest in last decade. One way to conserve energy is to use power saving mechanism, which allows a node to stay at doze state by powering off its wireless network interface [1][2][3][4]. Another alternative is to use power control scheme which controls the transmitting power to a proper level for reducing energy consumptions. In addition to providing energy conservation, power control can also potentially be used to improve spatial reuse of the wireless channel.

A number of power control mechanisms [5,6,7,8] have proposed modifications of IEEE 802.11 to incorporate power control. They use maximum transmission power for RTS-CTS and minimum required transmission power for DATA-ACK transmissions in order to save energy. The power control schemes proposed in [6][8] allow sender to indicate its current transmission power level in the transmitted RTS. On receiving RTS, the receiver evaluates the desired power level for maintaining required signal-to-noise ratio, and then indicates the desired transmission power level in the CTS sent back to sender. Sender then transmits data by using the specified power level in the CTS. Therefore, sender and receiver may exchange data and ack in transmitting minimal required power level while the required SNR could be maintained. Although these mechanisms use power control scheme to achieve power conservation and exploit spatial reuse opportunities, however, they did not consider the carrier sensing zone problem which creates collisions and increases overhead for retransmission.

Jung etcl. [9] take into consideration the effect of carrier sensing zone and propose a power control mechanism. The proposed PCM periodically increases the transmitting power during data transmission to inform nodes in the carrier sensing zone. However, interference from the other communicative pairs is not taken into consideration in the design of MAC protocol. Moreover, periodically increasing the transmitting power also consumes energy.

F. Ye, S. Yi and B. Sikdar [10] take into account the interference range of a communicative pair and improve the communication parallelism while the communicative nodes are very closed to each other. However, more general and specific discussions of interference raised from the other communicative pairs are required. Moreover, the proposed power control mechanism does not discussed incorporated with either power saving or fairness schemes.

This paper proposes a MAC power control protocol incorporated with the power saving mechanisms of 802.11 while the fairness is maintained. With overhearing the exchange of ATIM and ATIM-ACK packets in ATIM window, sender and receiver evaluate the required power for maintaining minimum required SNR and obtain the duration of communication time. In case that there is only one communicative pair, the distance between sender and receiver will be the key impact on the required power level. Alternatively, to allow more than one transmissions at the same time, interference raised by all the other communicative pairs will be another important impact on the required power level. During the ATIM window, the proposed power control MAC protocol takes into account the interference created from all the other communicative pairs and utilizes the overheard signal strength of ATIM and ATIM-ACK packets to evaluate the minimal required power. Then multiple communicative pairs may use the required power to simultaneously exchange data in data window. In addition to exploit the opportunities of power conservation and spatial reuse, the developed power control mechanism also involves the design of fairness mechanism. Performance results reveal that the proposed protocol exploits more opportunities for power conservation and spatial reuse and maintains the fairness among nodes, thus improving the throughput, lifetime, and maximum transmission delay of networks.

The remaining parts are organized in below. Section 2 introduces the model of communication and interference. The power control MAC protocol and fairness mechanisms are presented in Sections 3 and 4, respectively. Section 5 examines the performance of the proposed protocols. Section 6 concludes this work and give some future study.

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II. BASIC IDEA AND PRELIMINARIES

This paper proposes a power control MAC protocol for 802.11 based wireless networks. The proposed protocol considers power control mechanism incorporated with the power saving DCF of 802.11 to exploit spatial reuse and power conservation opportunities and maintain the fairness among communicative pairs. With the overheard ATIM and ATIM-ACK packets from other pairs exchanged in ATIM window, each communicative device evaluates its minimal required power and the time starting for data communication in data window.

Some assumptions should be made in the proposed power control mechanism. All nodes are assumed to be directly communicatable by using maximal transmitting power. In addition, all nodes have maintained the information or are able to evaluate the interference impact on any receiver from data transmission of any sender. This assumption could be achieved by exchanging location information of all nodes in a specific region. Another alternative to achieve the assumption is that all nodes overhear control packets and announce the interference impact from all the other nodes.

In ATIM window, each sender will use maximal power level to compete with the other senders for sending ATIM packet to its receiver. On receiving ATIM packet, the receiver uses maximum power to reply an ATIM-ACK packet which indicates the expected power of sender and itself. This information also can be overheard by the other nodes and is useful for determining their expected power. Let a *communication group*, say C, denote the communicative pairs that are capable of communicating at the same time by transmitting appropriate power in a specific space. Initially, there is only one communication group that is formed by the communicative pair that firstly exchanges ATIM and ATIM-ACK in ATIM window. Subsequently, a new pair could join the group if its transmission maintains the minimum required SNR of itself and all pairs in the group. More specifically, for a new communicative pair that intends to be included in an existing communication group, the sender and receiver should evaluate the interference by overhearing the ATIM and ATIM-ACK packets exchanged by all pairs in the group. Then both sender and receiver sides would derive a minimum required power so that the minimum required SNR of the new pair can be satisfied and all pairs in the existing communication group can suffer from the interference created by the new pair. This will guarantee the signal quality for all parallel transmissions of a communication group. A new communicative pair that cannot join the existing communication groups will construct a new communication group by declaring its MAC address as group ID in ATIM and ATIM-ACK negotiation. Followed the ATIM window, all communication groups will in turn transmitting data in data window according to the order the communication group formed in ATIM window.

In addition to improve power conservation and throughput by power control, the proposed MAC protocol also involves fairness mechanism to reduce the maximum delay of intended communicative pairs. With the distributed control of contention window for each sender, senders that unable to transmit ATIM packet in ATIM window of previous beacon intervals will reduce their size of contention window to increase their priority for transmitting ATIM packet. Therefore the maximum delay of nodes will be reduced and fairness among communicative pairs can be maintained.

To make easy understanding the proposed protocol, some notations that will be used in describing the proposed protocol are introduced in below.

$d_{i,j}$: the distance of nodes i and j;
P_i : the transmitting power of node i;
ΔP_i : the increasing power of node i;
C : the communication group formed in ATIM window that consists a set of communicative pairs that are able to transmit data in parallel;
(x_i, y_i): the ith pairs of C in an order of handshaking during ATIM window;
(u, v): the new communicative pair;
a_x : the acceptable interference of node x;
$i_{u\to x}$: the interference received at node x and created by node u
$i_{(u,v)\to x}$: the interference received at node x and created by communicative pair (u,v)
i_x : the overall interference received at node x

To guarantee the signal quality at receiver side, the signal to noise ratio(SNR) should be maintained larger than a minimum value, say ρ, as the basic requirement. Therefore, we have

$$SNR = \frac{\textit{received power}}{\text{interference power}} \geq \rho. \tag{1}$$

This implies the acceptable interference of receiver x could be derived from

$$a_x \leq \frac{\textit{received power}}{\rho}. \tag{2}$$

Given a *threshold* ρ, an arbitrary receiver x may derive the maximal interference it can afford.

The single strength received by receiver depends on the distance between sender and receiver. Providing that the distance of nodes x and u is $d_{u,x}$, node x will receive an interference power $i_{u\to x}$ from node u if u uses transmitting power P_u to communicate with another node, say v. More specifically,

$$i_{u\to x} = \frac{p_u}{d_{u,x}^{\ \alpha}},$$

where α is an pathloss exponential and its value is ranging from 2 to 5 in our experimental environment. However, since nodes u and v are communicative pair, they will not send packet at the same time. This implies that the communication of pair (u, v) will create to x an interference $i_{(u,v)\to x}$ derived in below.

$$i_{(u,v)\to x} = \max\{i_{u\to x}, i_{v\to x}\}$$

Let the overall interference received at node x is denoted by i_x. The overall interference i_x could be evaluated by

$$i_x = \sum i_{(u,v)\to x}\text{, for all communicative pairs } (u, v) \tag{3}$$

For instance, let pair (s, r) be a communicative pair but there are n senders transmitting data at the same time. Assume that the jth sender of n-pair uses power p_j for data transmission and the distance of jth sender and receiver r is $d_{i,r}$. According to expression (3), the overall interference at receiver r is:

$$i_r = \sum_{j=1}^{n} \frac{p_j}{d_{j,r}^{\ \alpha}} \tag{4}$$

Putting expressions (1) and (4) together, to ensure that the signal quality at receiver r could be maintained higher than threshold ρ, sender s should transmitting data with minimum power P_s, where P_s satisfies:

$$\frac{P_s}{d_{s,r}^{\alpha}}\left(\sum_{j=1}^{n}\frac{p_j}{d_{j,r}{}^{\alpha}}\right)^{-1} \geq \rho$$

This implies

$$p_s \geq \rho \cdot \sum_{j=1}^{n}\frac{p_j}{d_{j,r}{}^{\alpha}} \cdot d_{s,r}{}^{\alpha} \tag{5}$$

Therefore, a minimal required transmitting power can be derived.

In the following, a formal definition of *safe* state and an example is presented to illustrate the criteria of *safe* state.

Definition: ***Safe state***

A communicative pair (x, y) is stay in ***safe*** state if the signal quality received at receiver side is higher than the *threshold* ρ, which is the predefined minimum required SNR value.

Let (u, v) be a new communicative pair. Pair (u, v) that intends to communicate simultaneously all communicative pairs $(x, y) \in C$ in existing communication group C should satisfy the following criteria:

$$\begin{cases} i_x \leq a_x \text{ and } i_y \leq a_y, \text{ for all } (x, y) \in C; \\ i_u \leq a_u \text{ and } i_v \leq a_v; \end{cases} \tag{6}$$

In the other words, if the total interference derived by equation (3) at nodes u and v are smaller than the acceptable interference values, the SNR values received at nodes u and v will be higher than the minimum requirement ρ.

However, in case that the evaluation of i_v is bigger than a_v, during the negotiation of ATIM and ATIM-ACK packets, node v should ask node u to increase its power Δp_u to prevent the interference from all pairs (x, y) in existing communication group C. The increased power Δp_u could be evaluated by

$$\Delta p_u = i_v \cdot \rho \cdot d_{u,v}{}^{4} - p_u \tag{7}$$

Node u should use a new power $\Delta p_u + p_u$ to transmit data packet to meet the minimum requirement ρ of SNR at node v. Similarly, in case that i_u is bigger than a_u, node u will ask node v to use a increased power $\Delta p_v + p_v$. The next section presents a power control MAC protocol based on the above analysis.

III. POWER CONTROL MAC PROTOCOL

This section proposes a MAC power control protocol incorporated with the power saving mechanisms of 802.11. As defined in 802.11 spec., the beacon interval consists of ATIM window and data transmission window. As shown in Fig. 1, each beacon interval starts with a beacon. Then all senders compete to send an ATIM packet to receiver, asking the corresponding receiver to wake up during data transmission window. A contention window will be controlled to maintain the fairness among communicative pairs. The detail of fairness mechanism will be presented in the next section. As shown in Fig. 1, according to the fairness control, pairs (A, B), (H, G), (C, E), (I, J), (D, F) will exchange ATIM and ATIM-ACK in order.

On receiving the ATIM packet, the receiver will reply with an ATIM-ACK packet, as the approval of being awake during the data transmission window. In ATIM window, the negotiation of ATIM and ATIM-ACK packets will be used for sender and receiver to evaluate the required power for maintaining the minimum SNR of all existing communicative pairs. Taking into account the interference created from the other communicative pairs, a new communicative pair will utilize the signal strength of ATIM and ATIM-ACK packets to evaluate the minimum required power and to guarantee that all existing pairs could be safe in their future communications. Then multiple communicative pairs may use the required power to simultaneously exchange data in data window.

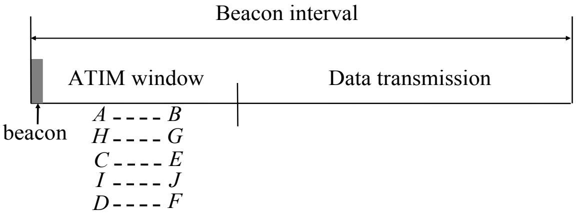

Fig.1. An example of five communicative pairs in ATIM window.

As shown in Fig.1, communicative pair (A, B) is the first pair to exchange ATIM and ATIM-ACK packet according to some fairness policy. This pair will organize a communication group C_1. Any node that intends to communicate with nodes A or B can not compete for sending ATIM packet at this moment, since nodes A and B are scheduled to exchange data with each other in the future and unable to communicate with the other nodes.

Then pair (H, G) evaluates the minimal transmitting power to satisfy the minimum required SNR value of pairs (A, B) and (H, G) while the two pairs communicate at the same time. To achieve this, node H estimates the overall interference i_H according to expression (3). After that, sender H sends to receiver G an ATIM packet with indication of value i_H. On receiving the ATIM packet, receiver G estimates the value of i_G. Subsequently, node G utilizes the values i_H and i_G to estimate the values of P_H and P_G according to expression (5). The values of P_H and P_G will be included in ATIM-ACK packet which is replied to sender H and is overheard by every nodes. In addition to include the values of P_H and P_G, receiver G will check in advance if the criteria (6) is satisfied by substituting (x, y) with (A, B) and (u, v) with (H, G). In case that criteria (6) is satisfied, pair (H, G) can join group C_1, thus (A, B) and (H, G) can proceed their communications in parallel in data transmission window. Otherwise, node G may either request node H to enlarge its transmitting power by setting a larger value in P_H or creates another new group. The resultant decision will be made according the rules. In this example, pair (H, G) exchanges ATIM and ATIM-ACK packets in ATIM window and join group C_1.

After that, sender C of pair(C, E) intends to compete for sending ATIM packet. By executing the similar operations done by pair (H, G) as described above, pair (C, E) will evaluate whether they can join group C_1 or not. However, communication of pairs (C, E) will raise the interference which may change some pairs in group C_1 from safe to unsafe state. Therefore, pair (C, E) will organize a new group, say C_2. Next, pair (I, J) also intends to compete the communication opportunity. This pair evaluates the required transmitting power by the exchange of ATIM and ATIM-ACK packet and then join group C_1. Then pair (D, F) join group C_2 if the created interference still maintain the minimum required SNR of itself and pair (C, E). With the overhearing of the negotiations in ATIM window, pairs in group C_2 maintain the maximum duration of pairs in C_1. Therefore, all pairs in C_1 will communicate at the same time and then all pairs in group C_2 will in turn communicate at the same time during data transmission window.

Figure 2 demonstrates the schedule of this example. The proposed power control mechanism not only saves power consumption but also improves the throughput by allowing maximum number of parallel transmissions. The scheduled data transmission also saves RTS and CTS negotiations in data transmission windows.

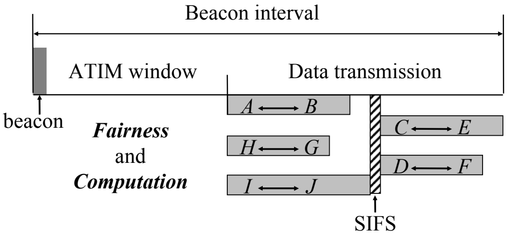

Fig.2. Schedule of the proposed power control mechanism for example in Fig.1.

IV. FAIRNESS MECHANISM IN POWER CONTROL MAC PROTOCOL

Exploiting spatial reuse opportunities will increase the number of safe transmissions proceeding at the same time and hence enhance the throughput. However, some communicative pairs may not be granted for transmission if their communication raises interference and cause some pair in existing group unsafe. In ATIM window, senders that intend to communicate with another nodes will compete for transmitting ATIM packet and then wait for receiving the ATIM-ACK packets from receiver. According to the order of exchange of ATIM and ATIM-ACK packets and the overheard signal strength, all pairs evaluate the proper group C_i to join to guarantee that all pairs belonging to same group can proceed their communication in parallel during data transmission window. The former pairs that exchange ATIM and ATIM-ACK packets will be granted for transmission and construct group. The latter communicative pair thus has a strict constraints to be granted for transmission in parallel with some group because that their transmission should maintain the safe state of all pairs belonging to the group. In worst case, a pair may have infinite delay if there always exist some other communicative pairs have a smaller backoff time than this pair. To resolve the starvation problem while the high throughput still could be maintained, a fairness control mechanism is proposed herein by adaptively adjusting the contention window of communicative pairs to resolve the starvation problem. Before the description of fairness control mechanism, some definitions used in describing the mechanism are introduced.

dur_x: the duration of data transmission of sender x;
$\overline{dur}$: the average duration of successful transmission in the previous becon interval;
f: The number of continuous unsuccessful attempts for sending ATIM packet;
l The number of collisions for sending ATIM packet
cw_{min}: Minimal value of contention window;
cw_x: contention window of x in previous beacon interval;
cw_x' : contention window of x in current beacon interval;

To prevent ATIM packets from collision, sender x that intends to send ATIM packet should wait for an interval of time slots which is randomly selecting a number from contention window cw_x as the backoff interval. As the backoff counter is decreased to a value of zero and the medium is idle, sender may exchange ATIM and ATIM-ACK with receiver. To maintain the fairness, a control in contention window is involved in the design of the power control MAC protocol. Initially, all nodes have the same contention window as defined in 802.11. Only those nodes that have unsuccessful attempts for sending ATIM packet will invoke the fairness control mechanism to determine the new contention window. The new contention window is determined by expression (8) as defined in the following.

$$cw_x' = \begin{cases} cw_x & \text{if } f = 0 \\ \max\left\{ \left\lceil \frac{dur_x}{\overline{dur}} \cdot \frac{1}{f} \cdot cw_x \right\rceil, cw_{\min} \right\} & \text{if } f \neq 0 \end{cases} \quad \text{and } l=0 \qquad (8)$$

The number of unsuccessful attempts for sending ATIM packet will impact the size of contention window. In case of f=0 and l=0, the ATIM packet is successful transmitted by node x in the previous beacon interval, thus the contention window of node x is unchanged. However, in case of $f \neq 0$ and l=0, the increasing number of unsuccessful attempts for sending ATIM packet will decrease the size of contention window, raising the priority of node x. Another factor that is involved in the fairness control is the packet size. A big packet size will result a larger value of $dur_x / \overline{dur}$, making other communicative pairs have a higher delay. Therefore the size of contention window of x would be enlarged to make the other communicative pairs have more opportunities earlier sending the ATIM packet in this beacon interval.

However, in case of $l \neq 0$, the number of senders probably exceeds the size of contention window. The phenomenon should be alleviated by reducing the number of attempts for competitions. As designed of RTS_Retransmit_Counter in 802.11, a value ATIM_Retransmit_Counter should be maintained in each node. Node will quit for competing the medium access if the ATIM__Retransmit_Counter achieves an ATIM_Retransmit_Limit which is predefined in system. This rule will help to resolve the number of communicative pairs exceeds the length of contention window. Thus the contention window will be unchanged. Through the control of contention window, the fairness could be maintained among communicative pairs.

V. PERFORMANCE STUDY

This section examines the performance of proposed power control protocol. The experimental environment is described. There are fifty nodes randomly deployed in a space sized 170*170 while the signal communication range of each node is 250 units at maximal. Environmental parameters are listed in Table I.

ATIM Window	20ms
Data Tansmission	80ms
Contention Window	31~1023
SIFS	10µs
ATIM Packet	20µs
ATIM ACK	20µs
Packet Size	1024byte
SNR threshold: ρ	10

Table I. Simulation parameters.

The proposed power control protocol without/with fairness mechanism (referred as PC and PCF respectively) is compared with 802.11 MAC protocol and power control mechanism PCM[9]. Performance measures considered here include throughput, power conservation, average delay time, and the fairness.

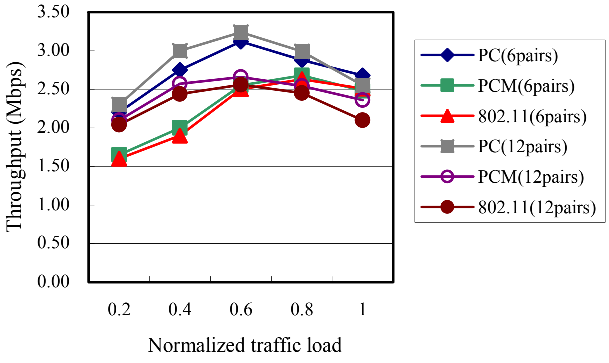

Fig.3. Throughput vs. normalized density

Figure 3 compares the throughput of PC, 802.11 and PCM. Six and twelve communicative pairs are included in the environment setting. The normalized traffic load denotes the rate that number of nodes that intends for communication over the number of total communicative pairs. In general, the throughput is increased with the traffic load as the load smaller than 0.6. Since the proposed PC allows more transmissions proceeded in parallel, its throughput is higher than PCM and 802.11. However, as the traffic load larger than 0.6, the extensive competitions reduce the throughput of the three mechanism.

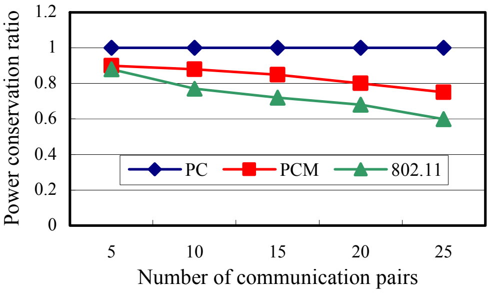

Fig.4. Power conservation ratio vs. the number of communication pairs.

Figure 4 investigates the power conservation of three mechanisms. The proposed PC mechanism is developed in power saving mode. Since more pairs may transmit their data in parallel, they can earlier enter doze mode for saving the power consumption. This is the main reason that the proposed PC has a better performance than 802.11 and PCM in power conservation.

Figures 5 investigate the effectiveness of fairness mechanism. The fairness is control mechanism may prevent a host from delay for a long time. However, in some condition there should be a tradeoff between fairness and throughput. With the introduced fairness mechanism, the average delay time and throughput matrix are examined. Figure 5 compares the average delay time of the proposed power control protocol with and without the fairness control involved. The average delay time is increased with the number of intended communicative pairs. With the fairness control, the intended communicative hosts that fail to send ATIM packet in previous beacon intervals will reduce the contention window in ATIM window, having a higher priority to exchange the ATIM and ATIM-ACK packets with the receiver. Thus the proposed power control protocol with fairness control has fewer delay time in average than the protocol without fairness control.

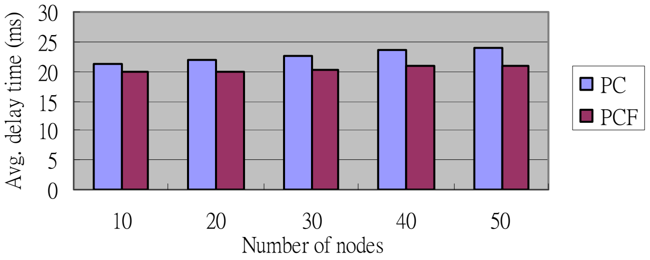

Fig.5. Fairness under number of nodes which have packets to transmit.

VI. CONCLUSIONS

This article proposes a power control and fairness mechanisms for 802.11 WLAN. Based on the interference measurement, the proposed protocol use power control trying to allow maximal number of parallel transmissions. To prevent the starvation problem, a fairness mechanism is proposed to control the contention window for those intended communicative nodes that are fail to exchange the ATIM and ATIM-ACK packets in ATIM window. It is well known that power conservation can be achieved in both power control and power saving mechanism. The proposed power control protocol is incorporated with the power saving protocol originally defined in 802.11 spec., to achieve the goal of power conservation in MAC layer. Experimental study reveals that the proposed PCF protocol saves power consumption, reduces the average delay and increases the throughput. Future work will consider the power control and fairness mechanisms developed for multi-channel environment.

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