Power control and fairness MAC mechanisms for 802.11 WLANs

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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 the receiver from interference but it will consume power and create additional interference to other communicating stations. On the contrary, reducing the transmitting power will reduce the interference to other communicating pairs and lessen the sender’s power consumption, but it will result to a lower signal to noise ratio (SNR) at receiver’s side. This article presents a power control MAC protocol that exploits the spatial reuse and power conservation opportunities for 802.11 Wireless LAN. The proposed protocol evaluates the interference and adopts a power control mechanism on both the sender and receiver sides to allow more communications to proceed simultaneously. In addition, a fairness control mechanism to reduce the average communication delay and alleviate the packet lost phenomenon is also proposed. Performance results reveal that the proposed protocol improves the throughput and power consumption of WLAN while the fairness among communicating pairs can also be maintained.

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1. Introduction

The 802.11 wireless local area network (WLAN) has been widely used for providing mobile devices with the capability for wireless communication. However, batteries that have constraints on the use of energy usually power mobile devices. Hence, techniques on energy conservation are of interest during the last decade. One way to conserve energy is the use of a power saving mechanism, which allows a station to remain in a state of hibernation by powering off its wireless network interface [1–4]. Another alternative is to use a power control scheme that controls the transmitting power to a proper level in order to reduce energy consumption. In addition to providing for energy conservation, power control can be used to improve spatial reuse of the wireless channel.

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

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

Ye et al. [10] took into account the interference range of a communicative pair and improved the communication parallelism while the communicative stations are very close to each other. However, more general and specific discussions of interference raised from other communicative pairs are required. Moreover, the proposed power control mechanism incorporated with either power saving or fairness schemes are not discussed.

As shown in Fig. 1, the power saving mechanism of 802.11 defines a beacon interval that starts with a beacon packet and consists of an ATIM window and a data window. All stations should remain awake in the ATIM window. To prevent the receiver from entering the doze mode in the data window, the sender initially sends an ATIM packet to the receiver in a contention-based manner. Upon receiving the ATIM packet, the receiver simply replies with an ATIM-ACK packet. Then those communicative pairs that have exchanged the ATIM and ATIM-ACK packets are allowed to exchange the DATA and ACK packets in the data window according to the 802.11 DCF standards. Stations that did not exchange the ATIM and ATIM-ACK packets in the ATIM window will enter the doze mode during the data window for power saving until the start of the next ATIM window.

This paper proposes a MAC power control protocol incorporated with the power saving mechanisms of the 802.11 while maintaining fairness. By overhearing the exchange of the ATIM and ATIM-ACK packets in the ATIM window, the sender and receiver evaluate the required power for maintaining the minimum required SNR and obtain the duration of the communication time. In case there is only one communicative pair, the distance between sender and receiver will be the key impact on the required power level. Alternatively, by allowing more than one transmission at the same time, interference raised by all the other communicative pairs will be another important factor 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 the ATIM and ATIM-ACK packets in order to evaluate the minimum required power. Then, multiple communicative pairs may use the required power to exchange data in the data window. In addition to exploiting the opportunities for power conservation and spatial reuse, the developed power control mechanism also involves the design of a fairness mechanism. Performance results reveal that the proposed protocol exploits more opportunities for power conservation and spatial reuse and maintains the fairness among stations. Thus, there are improvements in the throughput, lifetime, and maximum transmission delay of networks.

The remaining parts of the present paper are organized as follows. 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 the present work and gives some recommendations for future study.

2. Basic idea and preliminaries

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

Here, we assume that all stations are able to evaluate the interference impact on any receiver from the data transmission of any sender within their transmission range, and to maintain the interference impact information. This assumption could be achieved by exchanging the location information of all stations in a specific region. Another alternative to achieve the assumption is that all stations overhear the control packets and announce the interference impact from all the other stations within their communications range.

In the ATIM window, each sender will use maximum power level to compete with the other senders for sending the ATIM packet to its receiver. On receiving the ATIM packet, the receiver uses maximum power to reply with an ATIM-ACK packet that indicates the expected power of the sender and itself. This information can also be overheard by the other stations 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 the appropriate power in a specific space. Initially, there is only one communication group formed by the communicative pair.
that initially exchanges the ATIM and ATIM-ACK in the ATIM window. Subsequently, a new pair could join the group if its transmission maintains the minimum required SNR in itself and in all the pairs of 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 the sender and receiver sides would derive the 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 the group ID in the 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 the power conservation and throughput by power control, the proposed MAC protocol also involves a fairness mechanism to reduce the maximum delay of communicative pairs. With the distributed control of contention window for each sender, senders that are unable to transmit the ATIM packet in the ATIM window of previous beacon intervals will reduce their size of contention window to increase their priority for transmitting the ATIM packet. Therefore, the maximum delay of stations will be reduced and fairness among communicative pairs can be maintained.

To make it easy to understand the proposed protocol, the notations to be used in describing it are presented below:

- \( d_{ij} \) the distance of stations \( i \) and \( j \);
- \( P_i \) the transmitting power of station \( i \);
- \( \Delta P_{ij} \) the increasing power of station \( i \);
- \( C \) the communication group formed in the ATIM window which consists of a set of communicative pairs that are able to transmit data in parallel;
- \((x, y)\) the \( i \)th pairs of \( C \) in an order of ATIM/ATIM-ACK handshaking during the ATIM window;
- \( (u, v) \) the new communicative pair;
- \( a_i \) the acceptable interference of station \( x \);
- \( i_{uv,xx} \) the interference received at station \( x \) and created by station \( u \);
- \( i_{(u,v),xx} \) the interference received at station \( x \) and created by the communicative pair \((u,v)\);
- \( i_x \) the overall interference received at station \( x \).

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

\[
\text{SNR} = \frac{\text{received power}}{\text{interference power}} \geq \rho. \quad (1)
\]

This implies that the acceptable interference of receiver \( x \) could be derived from

\[
a_i \leq \frac{\text{received power}}{\rho}. \quad (2)
\]

Given a threshold \( \rho \), an arbitrary receiver \( x \) may derive the maximum interference it can afford. The signal strength received by the receiver depends on the distance between the sender and the receiver. Provided that the distance of stations \( u \) and \( v \) are communicative pairs, they will not send a packet at the same time. This implies that the communication of pair \((u,v)\) will create for \( x \) an interference \( i_{(u,v),xx} \) derived as follows:

\[
i_{(u,v),xx} = \max\{i_{ux}, i_{vx}\}
\]

Let the overall interference received at station \( x \) be denoted by \( i_x \). The overall interference \( i_x \) could be evaluated by

\[
i_x = \sum_{(u,v)} i_{(u,v),xx}, \text{ for all communicative pairs } (u,v) \quad (3)
\]

For instance, let pair \((s,r)\) be a communicative pair wherein \( n \) senders are transmitting data at the same time. Assume that the \( j \)th sender of the \( n \)-pair uses power \( P_j \) for data transmission and the distance of the \( j \)th sender and receiver \( r \) is \( d_{jr} \). According to expression (3), the overall interference at receiver \( r \) is:

\[
i_r = \sum_{j=1}^{n} \frac{P_j}{d_{jr}^2} \quad (4)
\]

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

\[
P_s \left( \sum_{j=1}^{n} \frac{P_j}{d_{jr}^2} \right)^{-1} \geq \rho
\]

This implies that

\[
p_s \geq \rho \sum_{j=1}^{n} \frac{P_j}{d_{jr}^2} \cdot d_{sr} \quad (5)
\]

Thus, a minimum required transmitting power can be derived.

In the following paragraphs, a formal definition of a safe state and an example is presented:
Definition 1 (Safe state). A communicative pair \((x, y)\) stays in a safe state if the signal quality received at the receiver side is higher than the threshold \(\rho\), which is the predefined minimum required SNR value.

Fig. 2 illustrates the criteria of safe transmission. There are two communicative pairs: \((A, B)\) and \((C, D)\). Assume that stations \(C\) and \(D\) have exchanged the ATIM and ATIM packets in the ATIM window, and pair \((A, B)\) intends to communicate in parallel with pair \((C, D)\). In the first place, both stations \(A\) and \(B\) will use expression (2) to derive the acceptable interferences \(a_A\) and \(a_B\), respectively. To evaluate the values of \(a_A\), station \(A\) estimates the received power by utilizing the information of the expected transmitting power of \(B\) and which could be found in the ATIM-ACK packet. Similarly, station \(B\) may estimate the value \(a_B\). With the overhead of the control packets from pair \((C, D)\) in the ATIM window, stations \(A\) and \(B\) may derive the overall interferences \(i_A\) and \(i_B\), respectively, by applying expression (3). The overall interferences in this example denote the expected interference from the communication of pair \((C, D)\) during the data transmission window. Both stations \(A\) and \(B\) should satisfy the inequalities \(i_A \leq a_A\) and \(i_B \leq a_B\) to guarantee that the communication of stations \(A\) and \(B\) is safe in the data transmission window. Moreover, to ensure the transmission quality of pair \((A, B)\), the communication of pair \((A, B)\) should guarantee that the transmission of pair \((C, D)\) is also safe. Both stations \(A\) and \(B\) will estimate the values of \(a_C\), \(a_D\), \(i_C\) and \(i_D\) by applying expressions (2) and (3). Both conditions \(i_C \leq a_C\) and \(i_D \leq a_D\) should be satisfied to guarantee that the communication of stations \(C\) and \(D\) is also safe in the data transmission window even if they suffer from the interference raised by the communication of pair \((A, B)\).

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

\[
\begin{align*}
&i_x \leq a_x \quad \text{and} \quad i_y \leq a_y, \quad \text{for all} \ (x, y) \in C; \\
&i_u \leq a_u \quad \text{and} \quad i_v \leq a_v;
\end{align*}
\]

(6)

In the other words, if the total interference derived by (3) at stations \(u\) and \(v\) is smaller than the acceptable interference values, the SNR values received at stations \(u\) and \(v\) will be higher than the minimum requirement \(\rho\).

However, in the case where the evaluation of \(i_x\) is bigger than \(a_x\), during the negotiation of the ATIM and ATIM-ACK packets, station \(v\) should ask station \(u\) to increase its power \(\Delta P_u\) to prevent the interference from all pairs \((x, y)\) in the existing communication group \(C\). The increased power \(\Delta P_u\) could be evaluated by

\[
\Delta P_u = i_x - \rho \cdot d_{u,v} - P_u
\]

(7)

Station \(u\) should use a new power \(\Delta P_u + P_u\) to transmit the data packet in order to meet the minimum requirement \(\rho\) of SNR at station \(v\). Similarly, in the case when \(i_u\) is bigger than \(a_u\), station \(u\) will ask station \(v\) to use an increased power \(\Delta P_v + P_v\). The next section presents a power control MAC protocol based on the above-mentioned analysis.

3. Power control MAC protocol

This section proposes a power control MAC protocol incorporated with the power saving mechanisms of 802.11. As defined in the 802.11 spec., the beacon interval consists of the ATIM window and the data transmission window. As shown in Fig. 3, each beacon interval starts with a beacon. Then all senders compete to send an ATIM packet to the receiver and asking the corresponding receiver to wake up during the data transmission window. A contention window will be controlled to maintain the fairness among communicative pairs. The details of the fairness mechanism will be presented in the next section. As shown in Fig. 3, pairs \((A, B), (H, G), (C, E), (I, J)\) and \((D, F)\) will exchange ATIM and ATIM-ACK packets in order, according to the fairness control.

Upon receiving the ATIM packet, the receiver will reply with an ATIM-ACK packet as a confirmation of being awake during the data transmission window. In the ATIM window, the negotiation of the ATIM and ATIM-ACK packets will be used for the 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 the ATIM and ATIM-ACK packets to evaluate the minimum required power and to guarantee that all existing pairs would be safe during their future communications. Afterwards, multiple communicative pairs can use the required power to exchange data simultaneously in the data window.

![Fig. 2. An example to illustrate the criteria of safe transmission.](image)

![Fig. 3. An example of five communicative pairs in the ATIM window.](image)
As shown in Fig. 3, the communicative pair \((A, B)\) is the first pair to exchange the ATIM and ATIM-ACK packets according to a certain fairness policy. This pair will organize a communication group \(C_1\). Any station that intends to communicate with stations \(A\) or \(B\) cannot compete in sending the ATIM packet at this time since stations \(A\) and \(B\) are scheduled to exchange data with each other in the future and are unable to communicate with the other stations.

Fig. 4 shows that pair \((H, G)\) subsequently evaluates the minimum 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, station \(H\) estimates the overall interference \(i_{H}^{}\) according to expression (3). Afterwards, sender \(H\) sends an ATIM packet with the indication of the value \(i_{H}^{}\) to receiver \(G\). Upon receiving the ATIM packet, receiver \(G\) estimates the value of \(i_{G}^{}\). Subsequently, station \(G\) 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 the ATIM-ACK packet in reply to sender \(H\) and is overheard by every station. Moreover, to include the values of \(P_{H}\) and \(P_{G}\), receiver \(G\) will check in advance if criteria (6) is satisfied by substituting \((x, y)\) with \((A, B)\) and \((u, v)\) with \((H, G)\). In case criteria (6) is satisfied, pair \((H, G)\) can join group \(C_1\), so that \((A, B)\) and \((H, G)\) can proceed with their communications in parallel in data transmission window. Otherwise, station \(G\) may either request station \(H\) to enlarge its transmitting power by setting a larger value in \(P_{H}\) or creates a new group. The resultant decision will be made according to the rules illustrated in function Safe and will be discussed later. In this example, pair \((H, G)\) exchanges ATIM and ATIM-ACK packets in the ATIM window and joins group \(C_1\).

Afterwards, sender \(C\) of pair \((C, E)\) would intend to compete in sending the ATIM packet. By executing 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, the communication of pairs \((C, E)\) will raise the interference that may change some pairs in group \(C_1\) from the safe to unsafe state. Thus, pair \((C, E)\) will organize a new group, say \(C_2\). Next, pair \((I, J)\) would also intend to compete for the communication opportunity. This pair evaluates the required transmitting power by the exchange of ATIM and ATIM-ACK packets and then join group \(C_1\). Then pair \((D, F)\) joins group \(C_2\) if the created interference still maintains the minimum required SNR of itself and pair \((C, E)\). With the overhearing of the negotiations in the ATIM window, pairs in group \(C_2\) maintain the maximum duration of pairs in \(C_1\). Hence, all pairs in \(C_1\) will communicate at the same time while all pairs in group \(C_2\) will communicate simultaneously during the data transmission window.

Fig. 5 shows the schedule of the example in Fig. 3. The proposed power control mechanism not only saves on power consumption but also improves the throughput by allowing a maximum number of parallel transmissions. The scheduled data transmission also saves the RTS and CTS negotiations in the data transmission windows.

Let \(U\) be all the pairs that intend to communicate in the current beacon interval. As shown in Fig. 6, each sender \(u\) of pair \((u, v)\) in \(U\) will perform the MacProtocol as shown in Fig. 7, to check if its communication is safe for all pairs in the existing communication groups. Fig. 6 depicts the scenario of a pair \((u, v)\) that intends to participate in a communication group in the ATIM window. Let us suppose that pair \((u, v)\) intends to join the existing communication groups. Stations \(u\) and \(v\) will check if they are in the safe state. That is, stations \(u\) and \(v\) will check if \(i_{u}^{}\leq a_{u}\) and \(i_{v}^{}\leq a_{v}\) are satisfied, respectively. In case that any one of the conditions is not satisfied, they will ask the corresponding station to increase the transmitting power according to Eq. (7). This also causes the value of the count to increase by one, which denotes that there is a pair of stations adjusting their transmitting power. The do-while loop continuously determines which of the communication groups would pair \((u, v)\) join. Function Safe\((C, (u, v))\) returns a Boolean value representing whether or not pair \((u, v)\) can join the communication group \(C\). In case pair \((u, v)\) is unable to have communication in parallel with all the other pairs in group \(C\), it will perform the next interaction of the loop until it can join some communicative group \(C\) or create a new group.

Fig. 8 presents the implementation details of Safe\((C, (u, v))\). Since the communication of pair \((u, v)\) would create interference to any pair in \(C\), it should maintain a safe state for any pair in \(C\). At first, stations \(u\) and \(v\) will evaluate their transmitting power according to the
overheard information from the ATIM and ATIM-ACK packets exchanged by all pairs of set $C$. Then pair $(u,v)$ will check the impact of increased interference on any communicative pair in $C$. In case there exists any communicative pair, say pair $(x,y)$, which changes its state from safe to unsafe, pair $(x,y)$ will try to adjust its transmitting power and prevent the increased interference from pair $(u,v)$.

The adjustment of transmitting power at pair $(x,y)$ will maintain the minimum required SNR at the receiver side. A further check for all communicative pairs belonging to set $C' = C \cup \{(u,v)\}$ is required. In case the interference created by pair $(u,v)$ and pair $(x,y)$ causes the SNR value of any other pair in $C'$ to be smaller than the threshold $\rho$, any other adjustment of transmitting power will
With the check of expressions (2) and (3), conditions and 
whether the increased interference is acceptable at stations 
raise additional interference to pair $(u, v)$ in $C$.

In case the following conditions are satisfied, pair $(A, B)$ to use expression (5) in order to evaluate the required 
increment in their transmitting power. However, the 
increasing power of pair $(A, B)$ to further result again in 
letting pair $(C, E)$ to remain in an unsafe state. Hence, function $Safe(C_1, (C, E))$ returns with a value 0, so that pair $(C, E)$ cannot join set $C_1$. Afterwards, pair $(C, E)$ will execute the second interaction of the do loop, calling 
$Safe(C_2, (C, E))$ to construct a new communication set $C_2$. The other communicative pairs can evaluate the transmitting 
power and either join an existing communication 
group or construct a new group in a similar way.

4. Fairness mechanism in power control MAC protocol

Exploiting spatial reuse opportunities will increase the 
number of safe transmissions proceeding at the same time 
and thus, enhance the throughput. However, some communicative pairs may not be granted for transmission if their 
communication raises the interference and causes some pairs 
in the existing groups to be unsafe. In the ATIM window, 
senders that intend to communicate with another station will 
compete for transmitting the ATIM packet and then wait for 
the ATIM-ACK packets from the receiver. According to the 
order of exchange of the ATIM and ATIM-ACK packets 
and the overheard signal strength, all pairs evaluate the 
proper group $C_i$ for participation in order to guarantee that 
all pairs belonging to same group can proceed with their 
communication in parallel during the data transmission 
window. The former pairs that exchange the ATIM and 
ATIM-ACK packets will be granted for transmission and

construction groups, resulting in the latter communicative pair to have strict constraints granted for transmission in parallel with some groups since their transmission should maintain the safe state of all pairs belonging to the groups. In the worst case, a pair may have infinite delays if there are always some other communicative pairs that have a smaller back-off time than this pair. To resolve the starvation problem while the high throughput could still be maintained, a fairness control mechanism is proposed herein by adaptively adjusting the contention window of communicative pairs. Before the description of the fairness control mechanism, some definitions used in describing the mechanism are introduced.

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

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

$$cw'_x = \begin{cases} cw_x & \text{if } f = 0 \\ \max \left\{ \left[ \frac{dur}{dur} \cdot \frac{1}{f} \cdot cw_x \right], cw_{\text{min}} \right\} & \text{if } f \neq 0 \text{ and } l = 0 \end{cases}$$

(8)

The number of unsuccessful attempts for sending the ATIM packet will have an impact on the size of the contention window. In the case of $f = 0$ and $l = 0$, the ATIM packet is successfully transmitted by station $x$ in the previous beacon interval so that the contention window of station $x$ is unchanged. However, in the case of $f \neq 0$ and $l = 0$, the increasing number of unsuccessful attempts for sending the ATIM packet will decrease the size of the contention window and increase the priority of station $x$. Another factor that is involved in the fairness control is the packet size. A big packet size results to a larger value of $dur_x/dur$, and thus, making the other communicative pairs acquire a bigger delay. Hence, the size of the contention window of $x$ would be enlarged to make the other communicative pairs gain more opportunities by sending earlier the ATIM packet within this beacon interval.

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

5. Performance study

This section examines the performance of the proposed power control protocol. The experimental environment is described below. There are fifty stations randomly deployed in a space sized at 1000*1000 while the signal communication range of each station is at the most 250 U. The Constant Bit Rate (CBR) Model is used to generate the traffic load for each communication pair and the traffic arrival rate is 100 kbps. The experiment result is obtained from the average of 50 runs and the communicative pairs are randomly generated. Environmental parameters are listed in Table 1.

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

Figs. 9 and 10 compare the efficiencies of the proposed protocol PC, 802.11 MAC, and PCM. The proportion of successful transmissions over the number of communicative pairs that intend to communicate measures the efficiency. Fig. 9 compares the efficiency of the proposed protocol PC, 802.11 and PCM. In general, the increase in the number of intended communication pairs reduces the efficiency. However, the PC exploits the reuse opportunities, allows

| Table 1 |
|-----------------|------------------|
| **Simulation parameters** | **Value** |
| ATIM window | 20 ms |
| Data transmission | 80 ms |
| Contention window | 31–1023 |
| SIFS | 10 μs |
| ATIM packet | 20 μs |
| ATIM-ACK | 20 μs |
| Packet size | 1024 byte |
| SNR threshold: $\rho$ | 10 |
more communicative pairs to transmit data in parallel, and outperforms 802.11 and PCM.

Fig. 10 compares the efficiency by varying path-loss exponential. The increasing interference will reduce the received SNR and thus, there is a need to enlarge the transmitting power to maintain the threshold $\rho$. As shown in expression (4), the interference from other transmissions is mainly determined by the exponential distance of the receiver and sender of the other communicative pairs. In case the interference factor is set at 2, it means that the received signal at the receiver side is proportional to the square of the distance between the receiver and any other sender. The increasing pathloss exponential will increase the interference among the communicative pairs and thus, reduce the efficiency as observed in all schemes. However, when considering the interference impacts, the curve of the proposed PCF drops slower than the 802.11 and PCM schemes.

Fig. 11 compares the throughput of the PC, 802.11 and PCM. Six and 12 communicative pairs are included in the environment setting. The normalized traffic load denotes the rate of the number of stations intending to communicate over the number of total communicative pairs. In general, the throughput is increased with the traffic load as the load gets smaller than 0.6. Since the proposed PC allows more transmissions to proceed in parallel, its throughput is higher than the PCM and 802.11. However, as the traffic load gets larger than 0.6, the extensive competitions reduce the throughput of the three mechanisms.

Fig. 12 investigates the power conservation of the three mechanisms. The proposed PC mechanism is developed in the power saving mode. Since more pairs can transmit their data in parallel, they can enter the doze mode earlier and save in power consumption. This is the main reason why the proposed PC has a better performance than the 802.11 and PCM in power conservation.

Figs. 13 and 14 compare the average delay in varying the number of communication pairs. In Fig. 13, the average delay is lower for the proposed PC than for 802.11 and PCM, indicating better performance in terms of delay.
delay increased with the number of communicative pairs. However, the proposed PC allows multiple transmissions to proceed at the same time, and thus has a lower delay than the other two mechanisms.

Fig. 14 examines the average delay in varying interference factors ranging from 2 to 5. The increasing value in interference factor will cause each communicative pair to transmit a higher power in order to maintain the SNR threshold, thus reducing the number of transmissions communicating in parallel and resulting into long delays of data transmissions.

Figs. 15–17 show the effectiveness of the fairness mechanism. The fairness control mechanism can prevent a station from a long transmission delay. However, under certain conditions there should be a tradeoff between fairness and throughput. By introducing the fairness mechanism, the average delay time and throughput matrix are examined. Fig. 15 compares the average delay time of the proposed power control protocol with and without the fairness control involved. The average delay time increases with the number of intended communicative pairs. With the fairness control, the intended communicative stations that fail to send the ATIM packet in the previous beacon intervals will reduce the contention window in the ATIM window, by giving a higher priority to exchange the ATIM and ATIM-ACK packets with the receiver. Thus, the proposed power control protocol with the fairness control has on the average a smaller delay time than the protocol without the fairness control.

Fig. 16 shows the change in the average delay time of the power control protocol with and without fairness control at varying interference factor ranging from 2 to 5. As the interference factor increases, the communicative pair uses a higher transmitting power to maintain the SNR threshold, and hence, reducing the number of other communicative pairs transmission in parallel. Thus, the increasing interference factor will increase the average delay. In general, the average delay increases with the interference factor, regardless of whether the fairness control mechanism is involved or not. However, the power control protocol with the fairness control has a smaller average delay than the one without fairness control.

Fig. 17 presents the impact of fairness on the throughput. The station that fails in the transmission during the previous beacon interval will have a higher priority in the ATIM window. However, the earlier transmission of the failed communicative pair can have a long distance between the sender and the receiver or a short duration, hence causing the communication group to have fewer
members or a short duration for data transmission. Thus, the power control protocol with fairness control has a lower throughput than the one without fairness control.

The proposed power control MAC protocol exploits the opportunities for simultaneous data transmissions and thus, improves the efficiency, reduces the average delay, and increases the throughput over 802.11 MAC and PCM [9] protocols. Although the power control MAC protocol with fairness design has a lower throughput than the one without involving any fairness design, considering fairness when designing the power control MAC protocol reduces the average delay and prevents the communicative pair from starvation.

6. Conclusions

The present article proposes a power control and fairness MAC mechanisms for the 802.11 WLAN. Based on the interference measurements, the proposed protocol uses a power control in trying to allow a maximum number of parallel transmissions. To avoid the starvation problem, a fairness mechanism is proposed to control the contentions window for those intended communicative stations that failed to exchange the ATIM and ATIM-ACK packets in the ATIM window. It is well-known that power conservation can be achieved by both power control and a power saving mechanism. The proposed power control protocol is incorporated with the power saving protocol originally defined in the 802.11 spec., to achieve the goal of power conservation in the MAC layer. Experimental study reveals that the proposed PCF protocol saves on power consumption, reduces the average delay and increases the throughput. Future work will consider the development of power control and fairness mechanisms for a multi-channel environment.

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