Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2006, Article ID 63728, Pages 1–14
DOI 10.1155/WCN/2006/63728

A Power-Efficient Access Point Operation for Infrastructure Basic Service Set in IEEE 802.11 MAC Protocol

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Received 19 December 2005; Revised 1 May 2006; Accepted 26 May 2006

Recommended for Publication by Vincent Lau

Infrastructure-based wireless LAN technology has been widely used in today's personal communication environment. Power efficiency and battery management have been the center of attention in the design of handheld devices with wireless LAN capability. In this paper, a hybrid protocol named improved PCF operation is proposed, which intelligently chooses the access point- (AP-) assisted DCF (distributed coordinator function) and enhanced PCF (point coordinator function) transmission mechanism of IEEE 802.11 protocol in an infrastructure-based wireless LAN environment. Received signal strength indicator (RSSI) is used to determine the tradeoff between direct mobile-to-mobile transmission and transmission routed by AP. Based on the estimation, mobile stations can efficiently communicate directly instead of being routed through AP if they are in the vicinity of each other. Furthermore, a smart AP protocol is proposed as extension to the improved PCF operation by utilizing the historical end-to-end delay information to decide the waking up time of mobile stations. Simulation results show that using the proposed protocol, energy consumption of mobile devices can be reduced at the cost of slightly longer end-to-end packet delay compared to traditional IEEE 802.11 PCF protocol. However, in a non-time-critical environment, this option can significantly prolong the operation time of mobile devices.

1. INTRODUCTION

IEEE 802.11 [1]-based wireless LAN devices are being used more and more by portable computers and handheld devices as standard configuration. These devices are often powered by batteries or depletable sources of energy to achieve mobility and flexibility. Due to constraint of weight and volume, batteries can provide only a finite amount of energy. Extensive research and experiments suggest that excessive usage of the wireless interface can degrade the battery lifetime of handheld devices by a factor of 2 or 3 [2, 3]. Efficient use of battery power is now a significant consideration in designing mobile devices. IEEE 802.11 specifies the PCF mode to provide contention-free access which can guarantee a fair and predictable service for mobile stations. The PCF operation mode is aimed to be used for the infrastructure basic service set (BSS) that requires the presence of an AP which acts as a centralized coordinator for traffic control of all the mobile stations within its coverage area. Instead of communicating with each other directly using DCF protocol, all traffic of mobile stations must be routed through the AP in infrastructure BSS. AP can also act as the gateway between the local mobile network and the external network such as Internet. Our analysis shows that using IEEE 802.11 PCF protocol for the infrastructure network cannot achieve an optimal performance in such environments.

In this paper, modifications to the PCF operation of IEEE 802.11 protocol are proposed that reduce the energy consumption and increase the throughput. The proposed protocol improves the mobile-to-mobile traffic in the infrastructure network using DCF transmission mechanism assisted by the AP. The protocol behavior and performance of traditional IEEE 802.11 PCF are analyzed first especially in an environment where traffic is mostly mobile to mobile. The improved PCF operation is introduced to improve existing IEEE 802.11 protocol which adaptively selects between PCF and AP-assisted DCF transmission mechanism based on RSSI information of mobile stations for different traffic types. A two-phase polling mechanism is proposed.

(i) The first polling phase is utilized for traffic information collection and downlink traffic.
(ii) The second polling phase is utilized for uplink traffic and traffic routed by AP.

(iii) The contention-free period ends when AP sends the control frame of subtype CF-end, which piggybacks the explicit transmission scheduling information for DCF transmission [4] of the packets that have been announced in the first polling phase and have not been transmitted during the two polling phases.

(iv) An AP-assisted retransmission mechanism is also proposed in this paper. Mobile stations can pass their unsuccessfully transmitted packets in direct transmission phase to AP during next polling phase and AP can help to retransmit packets to the destination mobile stations.

(v) Furthermore, historical delay information and the request sending time are utilized to predict the end-to-end delay, which is then utilized to decide the waking up time of mobile stations efficiently in the proposed smart AP protocol. Stations will not wake up earlier from their power-saving state than the expected arrival time of the reply packets from the remote server in a client-server-based communication scenario.

Our proposed protocol operates in a hybrid mode by taking advantage of the capability of AP and the flexibility of AP-assisted DCF operation that is capable of providing service with reduced power consumption and increased throughput.

The rest of the paper is organized as follows. Section 2 briefly reviews the power-saving mechanism specified in IEEE 802.11 standard and related works that improve the AP operation. Section 3 presents the proposed enhancements to IEEE 802.11 PCF protocol to achieve energy efficiency and throughput improvement. Section 4 describes the simulation model and results which show the advantage of the proposed algorithm. Section 5 concludes the paper.

2. RELATED WORK

IEEE 802.11 PCF protocol [1] is a centralized polling-based access mechanism that requires the presence of an AP acting as point coordinator (PC). PCF is an extension that is based on the access rules defined in DCF mode. In order to integrate DCF and PCF together seamlessly, transmission time is divided into superframes in PCF mode. Each superframe consists of a contention period (CP) where DCF is used and a contention-free period (CFP) where PCF is used. Once the CFP started, the AP polls each station in its polling list (the high-priority stations) to grant them opportunity to access the wireless medium. A station being polled is allowed to transmit a data frame to mobile stations or the AP. However, transmission to mobile stations is not supported in the infrastructure BSS implementation. Without the knowledge of the destination's position, it is often impossible to deliver the packets with optimal power to destinations even they are within the radio coverage area of AP. Furthermore, under infrastructure BSS mode, stations are only allowed to send packets to AP using DCF during CP.

In [5], the authors propose an adaptive control algorithm to keep the aggregate throughput of AP close to the best capacity of both DCF and PCF modes based on various traffic requests. They use throughput as the feedback indicator to determine whether current dominant access method fits the traffic pattern. The throughput in PCF mode and in DCF mode are measured periodically using an estimation algorithm according to current traffic condition. Based on this information, the percentage of CFP duration within a superframe is actively controlled by AP to achieve an optimal aggregate throughput.

In [6], the authors propose a novel relay-enabled PCF (rPCF) to exploit the multirate capability of IEEE 802.11 WLANs. Based on the channel condition, rPCF may use multihop data transmission through MAC layer relay to improve the system performance. An intermediate relay node is used to forward traffic instead of direct transmission if the links from the sender to the relay node and from the relay node to the receiver can support higher data rate than direct link. In this protocol, the AP has to monitor and maintain the connection status (e.g., reachability, connection data rate, and congestion level, etc.) between all mobile stations and this can become a large overhead. The information can also get outdated since mobile stations move constantly. Furthermore since the two-hop relay transmission is used, it may increase the collision probability and the packet error rate.

The authors propose a bounded-slowdown (BSD) protocol in [7], which is an enhancement to power-saving mode of IEEE 802.11 protocol that dynamically adapts to network activity. Their goal is to minimize energy while limiting the observed round-trip time (RTT) of TCP connection to $(1 + p) * R$ in the existence of power-saving mode, where R is base RTT in the absence of PSM. After sending a request at time T_{request}, the mobile device has received no response at time T_{current}, then the network interface can go to sleep for a duration up to $(T_{\text{current}} - T_{\text{request}}) * p$. In the presence of beacon interval, the mobile device has to initially stay awake for $1/p$ beacon intervals after sending a request. In their example, given a 100-millisecond beacon interval and $p = 0.2$, the network interface has to stay active for 500 milliseconds. Their protocol aims to reduce the RTT while our protocol aims to conserve energy as much as possible. In our smart AP protocol, after sending a request, mobile station will not stay active in consecutive beacon intervals unless the expected reply is received by AP and it only stays active in specific beacon interval based on its own calculation of expected end-to-end delay.

In the forthcoming IEEE 802.11e protocol [8], a direct link protocol (DLP) is proposed. Direct link refers to the ability to exchange data directly between two stations in the network, without being routed through the AP. The traditional 802.11 MAC specifies that stations can only communicate with APs in an infrastructure BSS. This is to ensure that communication is possible between all stations, even if they are out of range with each other. But this reduces the available bandwidth for station-to-station communication by possibly more than one half. DLP in 802.11e provides a mechanism to allow direct station-to-station communication in the case where the stations are in range of each other. In our proposed approaches, the tradeoff between a direct link transmission and the AP routed transmission is determined based on the

RSSI information of mobile stations. A direct transmission is used only if it conserves energy compared with a routed transmission. An AP-assisted retransmission mechanism is also proposed that passes the unsuccessfully delivered packets to AP to conserve energy and reduce channel collision possibility.

3. ENHANCED PCF OPERATION OF ACCESS POINT

In this section, detailed description as how the traditional IEEE 802.11 PCF protocol can be modified to achieve a better performance is given. The original IEEE 802.11 is analyzed to show that PCF is not suitable for the environment where most traffic is between mobile stations in an infrastructure BSS. Then our improved PCF operation is introduced, which is a hybrid protocol using AP-assisted DCF operation for mobile-to-mobile traffic in an infrastructure-based wireless LAN environment. Experiments of signal strength measurement are also conducted. It shows that the overheard signal strength information, that is used as an important metric in our protocol, is sufficient to determine the tradeoff between direct and routed transmissions. Furthermore, an end-to-end delay estimation method is introduced for traffic between mobile stations and a remote server attached to AP through wired link. The delay estimation is used to efficiently determine the waking up time of mobile stations, which reduces unnecessary energy consumption when mobile stations stay in idle state without transmitting or receiving any data. Since the upper-layer protocol may significantly affect the delay, historical delay information is used for our estimation. Furthermore, only the stations that are expecting their reply packets in current contention-free period stay in active state, which shortens the length of the polling list of AP. This also reduces the end-to-end packet delay and increases the throughput of traffic between mobile stations and AP.

3.1. Problem analysis of IEEE 802.11 PCF

IEEE 802.11 PCF mode is a centralized polling scheme, which uses AP as a coordinator for all communications within its coverage. The benefit of using the AP is obvious: it will guarantee a contention-free transmission period through the centralized polling. However, it also has the following drawbacks in an infrastructure BSS.

(1) During each CFP, the AP will issue polls to a subset of the stations on the polling list in ascending order of association identifier (AID) value. During the CFP, if all CF frames have been delivered and all STAs on the polling list have been polled, the AP may generate one or more CF polls to any station on the polling list. However, this is often not possible when the number of mobile stations is large and the traffic intensity is high. If it is assumed that mobile stations can only be polled once during each beacon interval, the average delay between two consecutive transmissions of a mobile station is the length of the superframe. Although it aims to maintain fairness for all stations, the mobile stations are expected to experience long-packet end-to-end delay if the number of stations is very large.

(2) The AP serves as a bridge between the mobile stations and the wired network (internet, etc.). Extra buffering and processing delay are expected at the AP side for the mobile-to-mobile traffic which is routed through the AP.

(3) In an infrastructure BSS, all the packets will go through the AP. This is not efficient for mobile-to-mobile communication.

   (i) Each data packet is required to be transmitted twice: mobile → AP then AP → mobile. This increases the collision probability and also increases channel utilization time.
   (ii) As wireless transmission is subjected to higher bit error rate (BER), two-hop transmission will encounter a higher overall error rate than that for a single-hop transmission.
   (iii) The AP will buffer packets from the source station until the time the destination station is polled. So data packets are expected to have longer end-to-end delay. This delay can be as long as the whole length of a superframe if AP polls the destination station earlier than the source station.
   (iv) The two-hop transmission may consume more energy than a direct single-hop transmission as illustrated in Figure 1. It is assumed that the receiver uses constant power for receiving a packet. A scheme that has been used in our proposed protocol to dynamically adjust transmission power of mobile stations is described in the latter section, in which the overheard RSSI information of control frames is used to estimate the minimal required power for packet transmission to other mobile stations. The AP is at a fixed known position and always transmits with fixed power. The transmission power required

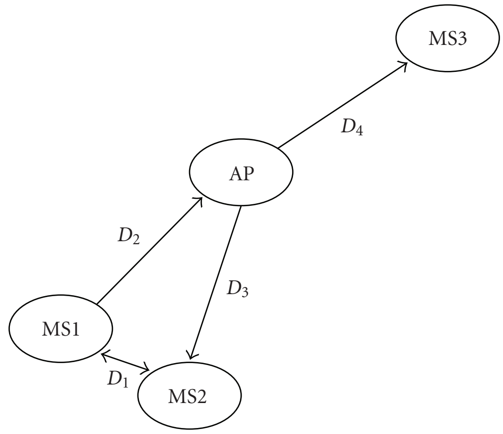

Figure 1: Choose the transmission method based on position information.

for mobile stations to maintain an acceptable signal-to-noise ratio (SNR) at AP can also be estimated based on the RSSI information of polling message from AP, which can be used by mobile stations to dynamically adjust their transmission power to AP. According to the basic theory of radio communication, the received signal strength is inversely proportional to some power of distance between the sender and the receiver. To guarantee a fixed SNR at the receiver side, transmitted power should be adjusted proportional to D^{λ} ($2 \le \lambda \le 4$ for outdoor transmission), where D is the distance between sender and receiver.

It is assumed that the power required at mobile station 1 for direct transmission is $P_{1\to 2}$ and for the transmission routed by AP is $P_{1\to \mathrm{AP}}$. So $P_{1\to \mathrm{AP}}$ is much larger than $P_{1\to 2}$ as shown in (1), if $D_2 > D_1$ given that $2 \le \lambda \le 4$. As in this particular example, a direct transmission (MS1 → MS2) is more power-efficient than the transmission routed by AP (MS1→ AP →MS2),

$$\frac{P_{1\to \mathrm{AP}}}{P_{1\to 2}} = \left(\frac{D_2}{D_1}\right)^{\lambda}. \qquad (1)$$

(v) The transmission MS1 → AP → MS2 will occupy the shared wireless channel almost twice longer than a direct transmission MS1 → MS2. Both sender and receiver have to wait longer time in an idle state, which is considered as a waste of energy.

(4) Under PCF mode, there exists an option for mobile stations to reply the contention-free poll from AP by sending a frame to other mobile stations. However, due to the lack of the position information and operating state (in PS state) of destination, such transmission is not guaranteed and sometimes not even possible. So it is not actually implemented in most of the wireless LAN devices under an infrastructure BSS setup. As shown in Figure 1, MS3 is either out of the transmission range of MS1, or requires much more energy than using AP as router to forward traffic.

3.2. *Proposed improved PCF operation*

Based on the above analysis, modifications to the PCF are necessary to achieve higher performance. In traditional PCF protocol of IEEE 802.11, right after the beacon transmission AP will poll the registered stations within the service set one by one in a round-robin fashion. Upon reception of the polling message (without payload if there is no downlink data for the specific station), the station will return its uplink packets if there is any or will return a packet without payload which indicates that it has no uplink packet. The modified version operates in two polling phases.

(1) AP will poll all stations at least once. During the first polling phase, AP follows the traditional PCF operation, while stations will return the following information of their pending traffic instead of actual data packets:

 (i) number of pending packets for AP;
 (ii) number of pending packets for other mobile stations;
 (iii) the destination address of mobile stations;
 (iv) the location information (calculated based on the RSSI information of the poll from AP).

 So after this polling phase, all the downlink packets have been transmitted.

(2) AP will send a broadcast message to all mobile stations after the first polling, which enables those mobile stations with no pending packets to or from AP and other mobile stations to switch to the power-saving state until next beacon period.

(3) Then AP will poll the stations that are still in the active state again.

 (i) It will first poll the stations that only have pending packets for AP based on the traffic announcements received in the last polling phase. The packet transmission procedure will be according to the original PCF mode. Upon reception of the polling message, stations will acknowledge the polling by returning their uplink packets. After the transmission, stations without any pending packets for other mobile stations can switch to the power saving state until next beacon period.
 (ii) If the location information of mobile stations can be obtained from a location service [9], mobile stations can utilize the distance information between each other to dynamically adjust their transmission power. In case such location service is not available, mobile stations can use RSSI measurements [1, 10–12] based on the overheard control frames to estimate the minimal necessary power for desired destination mobile stations. In our proposed protocol, as shown in Figure 1, MS1 has data packets for MS2. During the first polling phase, if MS1 is polled first, MS1 will announce its pending data packets as a reply to the poll. MS2 can then overhear the announcement which has MS2's AID as the destination address and calculate the RSSI from MS1. The RSSI value between MS1 and MS2 is transmitted to AP as piggyback information when MS2 is polled. If MS2 is polled first, MS2 will reply a frame without payload to AP since it does not have pending packets. MS1 can actively overhear the transmission and transmit the RSSI value between MS1 and MS2 to AP when it is polled.

The signal strengths between AP and mobile stations are monitored by AP constantly, while the signal strength information between different mobile stations is collected by mobile stations and reported to AP when polled. The mean of the most recent 20 signal strength values is then used in our proposed algorithm. Based on the RSSI information between

Table 1: Scheduling stack.

Transmission order	Source address	Destination address	Number of pending packets
1, 2, 3, ...	4 bytes	4 bytes	2 bytes

different mobile stations and the traffic condition (mobile to mobile), AP will calculate the power required for routed transmission (mobile to AP to mobile) and direct transmission (mobile to mobile) as described previously. It will choose the transmission method based on the comparison. Stations that can only use AP to forward their mobile-to-mobile traffic (either because the source and destination are out of transmission range, or the direct transmission is not power-efficient, e.g., MS1 to MS3) will be polled by AP for their pending packet subsequently. After the transmission, stations without any pending packets for mobile stations can switch to the power-saving state until the next beacon period.

After all the stations that satisfy the above-mentioned criteria have been polled, AP will signal the end of the contention-free period by transmitting a control frame of subtype CF end. If there is any mobile-to-mobile traffic pending, AP will piggyback the transmission order information [4] to schedule the AP-assisted DCF transmission period to reduce any possible collision. The transmission order information as shown in Table 1 includes the source and destination address of mobile stations, the number of pending packets, and the scheduled transmission time. The variable packet length can also be incorporated in the schedule stack. For example, if the length of a single packet is considered to be 1024 bytes, a packet with length equal to 2048 bytes is considered as two units of a packet, which are scheduled together. Stations operating in the contention period must follow the explicitly announced transmission order by AP, which can minimize the contention when multiple stations with pending packets try to access the channel simultaneously. The detailed procedure for AP and mobile station operation are illustrated in Figures 2 and 3.

(4) During the direct transmission, if a specific packet has not been correctly acknowledged by the destination, the source mobile station will transmit the packet to AP during its next polling round as its uplink packet. AP will then retransmit the packets to the destination. It operates in the following manner. Suppose that A has a series of packets to be directly transmitted to B with sequence numbers 1, 2, 3, 4 and after the transmission of packet 2 to B, A has not received ACK from B within the ACK timeout. In this case, the transmission error is probably caused by random noise. In our proposal, A will try to retransmit packet 2 only once. If the retransmission is successful, then remaining packets will be transmitted as usual. If the retransmission is not acknowledged either, A will stop the direct transmission and pass all the remaining packets to AP during the next polling. (In this case, the destination may be in deep fading, out of range, or subject to interference.) The detailed procedure for this mechanism is illustrated in Figure 4.

3.3. Signal strength measurement of mobile stations

In our proposed algorithm, the energy consumption of the routed transmission through AP and the direct transmission are compared based on the RSSI information between mobile stations and AP. Since we are not interested in the exact location of mobile stations, we do not have to use complex location system such as GPS [13, 14] or signal triangulation and probability-based approaches [15, 16]. Mobile stations can actively measure the signal strength of other mobile stations (by overhearing their transmissions when they are polled by AP) or AP (by measuring the signal strength of AP when receiving polls from AP). In this section, experimental results of RSSI measurement are given to show that in practical scenarios, the RSSI-based method is able to provide sufficient and accurate information which can be used in our proposed algorithm to determine the tradeoff between direct transmission and routed transmission.

In the experiment, we try to get the signal strength values of wireless connection from a single AP which is located approximately in the center of our CeMNet Research Laboratory. The signal strength values have been obtained at 15 locations within CeMNet, and they are illustrated as a dotted line in Figure 5. The distance between consecutive locations is approximately 3 meters. The laptop computer which is equipped with a wireless LAN card is placed at a higher position, so there is no significant obstacle in the line-of-sight between each testing point and the antenna of the AP. At each testing point, 100 signal strength values are collected at the intervals of 0.5 second. During the post-data processing, we notice that there are significant data variations at the beginning of each test. The reason for this behavior is probably that the wireless card is not in the fully working condition during the switching between idle state and passive reception state [17]. So the later 80 values are used in our analysis. Figure 6 shows the signal strength variation at different locations. In this figure, the relationship between the location and the received signal strength values is illustrated clearly. Even in the indoor environment, the received signal strength changes significantly when distance between sender and receiver changes, but at a fixed location the signal strength tends to remain at a rather constant level. So the source mobile station can dynamically adjust its transmission power based on the RSSI information to guarantee a constant and acceptable SNR at the destination.

3.4. Proposed smart AP protocol

In this section, a smart AP protocol is introduced by utilizing the results from our analysis of the expected reply delivery time of traffic between mobile stations and a remote server attached to AP through wired line. The smart AP protocol aims at enhancing the proposed improved PCF operation to reduce the end-to-end delay of traffic between AP and mobile stations through a waking-up-time estimation using historical delay information. Furthermore, smart AP protocol also reduces energy consumption of mobile stations, since mobile stations stay in active state in specific beacon interval only if

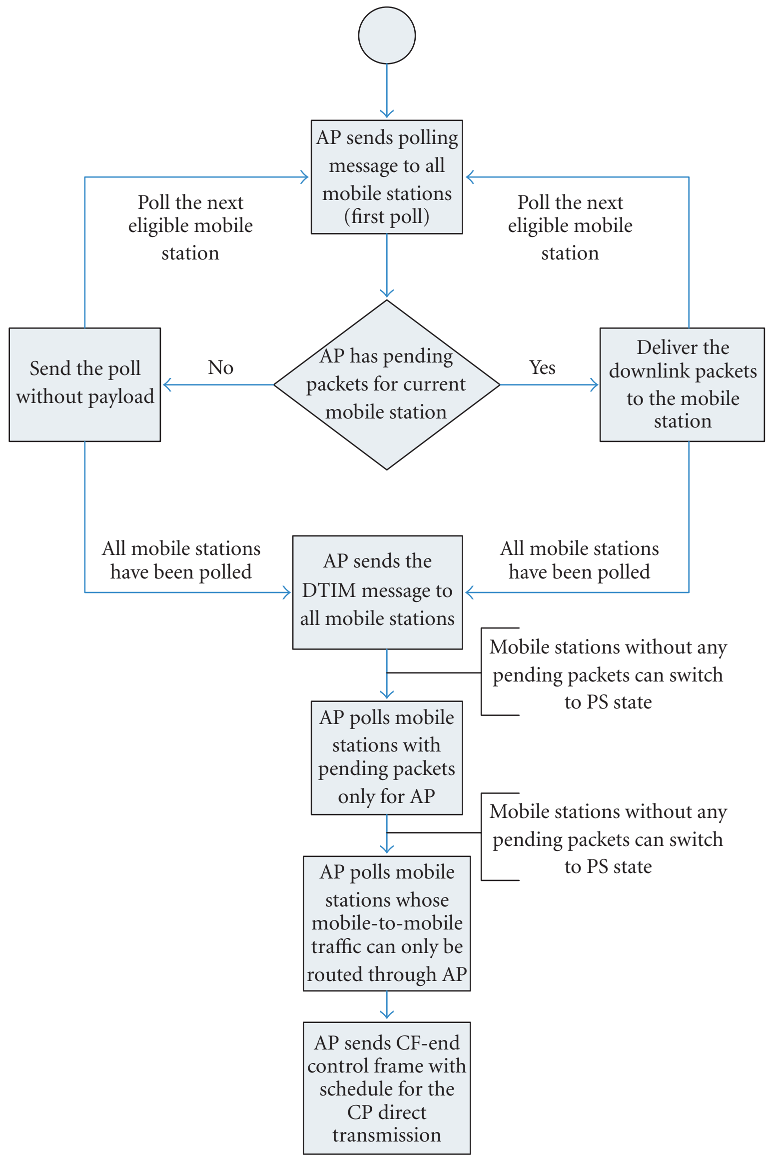

Figure 2: AP operation procedure of the enhanced PCF protocol.

they have packets for AP or the replies from remote server are already buffered at AP and ready to be transmitted to mobile stations. Using the proposed protocol, mobile stations stay in power-saving state for a longer period of time and not all mobile stations are required to stay in active state in every beacon interval. The number of mobile stations that have to be polled by AP in every beacon interval is reduced, which reduces the end-to-end delay and increases the throughput of the traffic between AP and mobile stations.

3.4.1. *Analysis of the expected reply delivery delay for waking-up-time determination of mobile stations*

In order to further extend the improved PCF operation, analysis and experimental results of end-to-end delay in a client-server communication scenario are presented. A smart AP protocol is proposed on top of the improved PCF operation as an extension, which determines the waking up time of mobile stations in the power-saving mode using models derived from the expected reply delivery time analysis. In our analysis and simulations, we assume an infrastructure-based wireless LAN environment with a single AP and mobile stations within its coverage area. The AP is connected to a remote server with wired link. Mobile stations send request to the remote server and wait for the reply message. In this scenario, the request has to be transmitted to AP first, which acts as a common gateway between mobile stations and external network. The AP forwards the request to the remote server and buffers the reply from it. The buffered information will be transmitted to the desired mobile station when it is in active state and polled by AP.

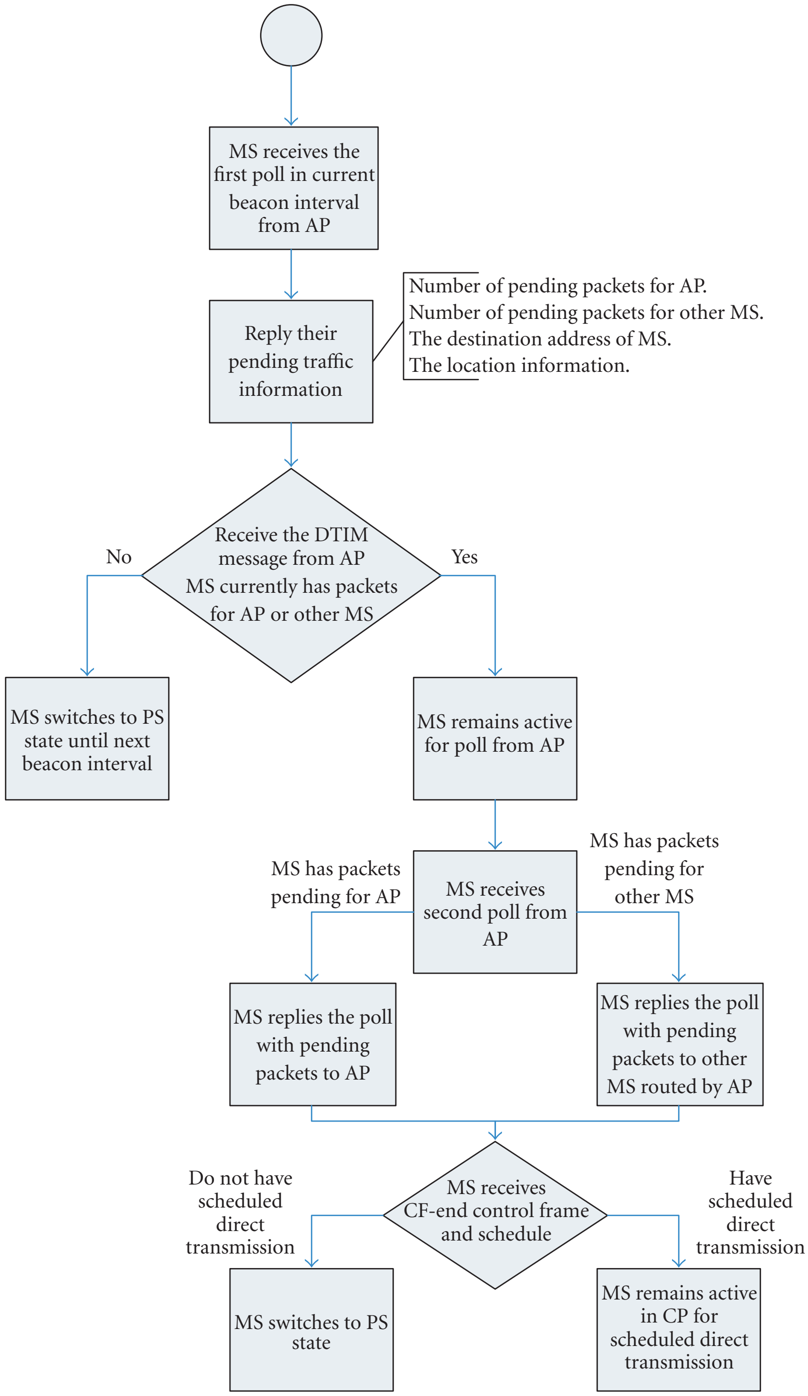

Figure 3: Mobile station operation procedure of the enhanced PCF protocol.

The major difference between improved PCF operation and smart AP protocol is the beacon transmission procedure. In our proposed smart AP protocol, when AP transmits the beacon at the beginning of each beacon interval, it also piggybacks the traffic indication message (TIM) [1] to the original beacon. The TIM is generated based on all the reply packets that have been received from the remote server by AP and have not been transmitted to mobile stations. The stations with their addresses listed in the TIM will stay active to receive the pending reply packets forwarded by AP in the first polling phase after the beacon transmission. Other stations with their addresses not listed in the TIM can switch to power-saving state if they do not have data packets to send. Based on our improved PCF operation, two-phase polling mechanism is used and the first polling phase is utilized for downlink traffic and collection of traffic information.

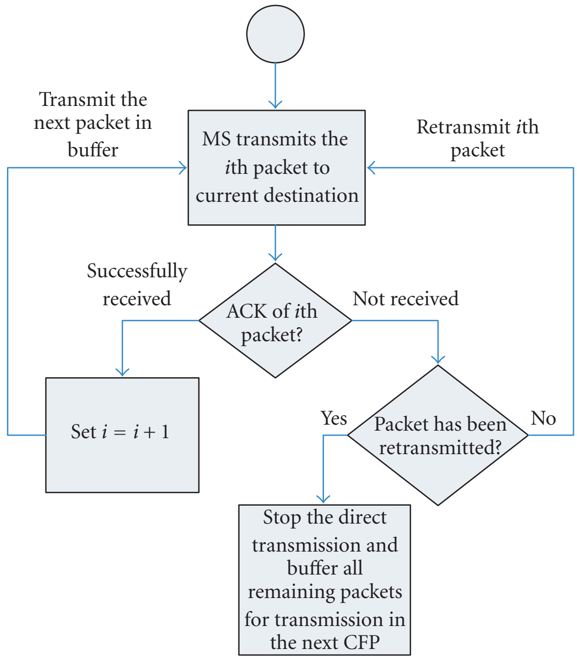

Figure 4: The AP-assisted retransmission mechanism.

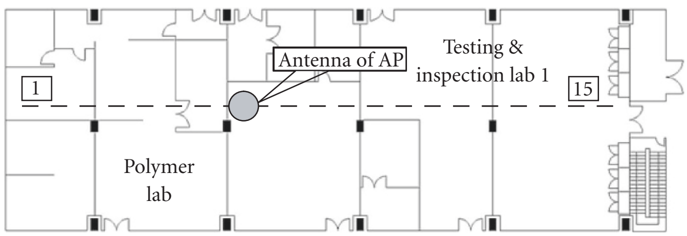

Figure 5: CeMNet floor plan with illustration of the experiment setup.

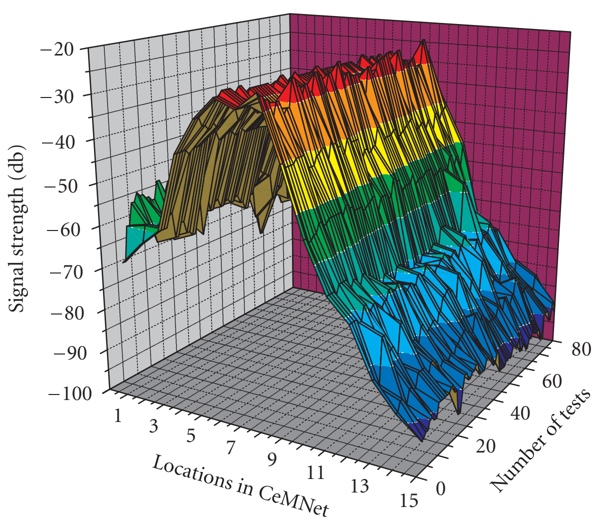

Figure 6: 3D Map of received signal strength variation at different locations.

So stations with pending mobile-to-mobile or mobile-to-AP traffic are still required to stay in active state and report information of their pending traffic as the reply to AP's poll using the procedure described in previous sections. Using the TIM, the stations that have transmitted requests in previous beacon intervals and still wait for their replies from the remote server to be received by AP have a chance of switching to PS state after reception of the beacon. Hence, these stations will not be polled by AP in current beacon interval if they do not have packets pending to send. If other stations still have pending packets for these stations, the packets are transmitted to AP and buffered, which can be delivered to the destination mobile stations in the following beacon intervals by notifying them using TIM.

Based on the above description, we derive the following analysis to the expected reply delivery delay of the traffic between mobile stations and the remote sever.

(1) Fixed wired line delay.
The round-trip time (RTT) between the AP and remote server is a fixed value (an approximated value) D.

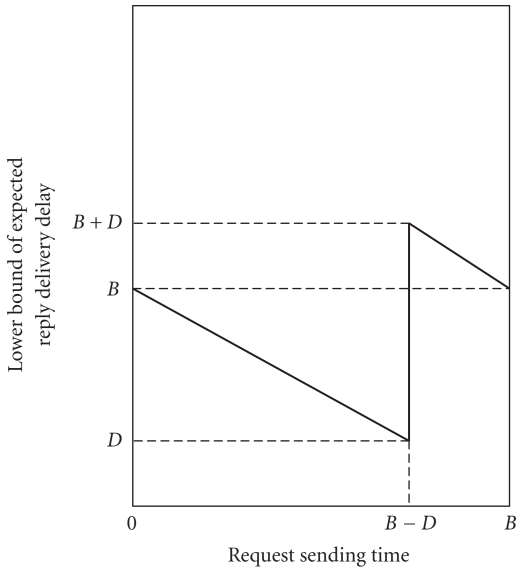

FIGURE 7: Lower bound of the expected reply delivery delay time with $0 < D < B$.

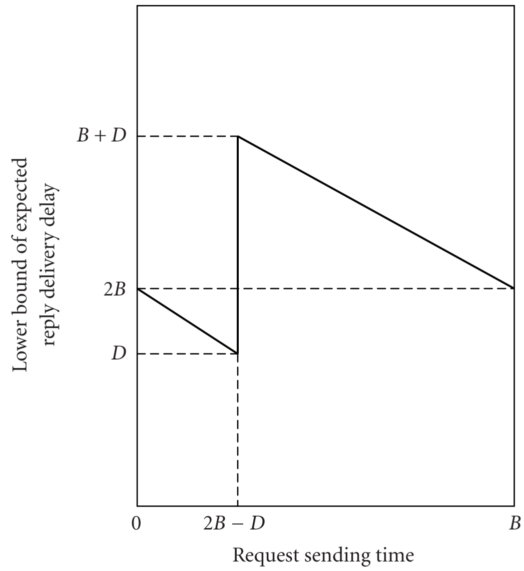

FIGURE 8: Lower bound of the expected reply delivery delay with $B < D < 2B$.

This represents the scenario where the remote server is connected with AP through reliable connections such as LAN. It is assumed that the processing time of the request at remote server is negligible compared with the transmission delay. So the expected end-to-end (mobile to remote server) reply delivery delay is also D, if the propagation delay between mobile stations and AP is also neglected. However, transmission time is divided into a series of beacon intervals and in our proposed smart AP protocol, the downlink packets are delivered during the first polling phase at the beginning of each beacon interval. To consider the lower bound of the reply delivery delay, it is assumed that AP will transmit the buffered reply to the destination immediately at the beginning of a beacon interval if it has received the reply for designated destination in previous beacon interval. So the reply packets can be delivered to mobile stations in a specific beacon interval only if they have already been received by AP during previous beacon interval. Furthermore, if a request packet is generated at a specific mobile station before the station is polled, the packet may be transmitted to AP in current beacon interval when the station is polled. On the other hand, if the request packet is generated after the station is polled, it has to wait until the station is polled by AP in the next beacon interval.

We can see that the length of the beacon interval (B) and the time the request is sent (T) within current beacon interval are two major factors that affect the expected reply delivery time significantly. Figures 7, 8, and 9 are used to describe the expected reply delivery delay for the fixed wired line delay scenario. The x-axis is the request sending time within current beacon interval and the y-axis is the expected reply delivery delay.

(i) Delay range $0 < D < B$: Figure 7 can be used to describe the expected reply delivery delay at destination mobile station. Therefore, if a request is transmitted to AP (as a reply to AP's poll) at time $B_i + T$ in current beacon interval B_i with the length of the beacon interval equal to B, the mobile station is expected to receive the reply from the remote server in the beginning of next beacon interval B_{i+1} at time B_{i+1}, if $T + D < B$ (which means that AP receives the reply from remote server within beacon interval B_i). If $T + D > B$ (which means that AP receives the reply from remote server within beacon interval B_{i+1}), the mobile station is expected to receive the reply in the beginning of next beacon interval B_{i+2} at time B_{i+2}. The lower bound of expected reply delivery time to destination mobile stations is described using the following equations:

$$\text{delay} = \begin{cases} B_i + B & \text{if } T + D < B, \\ B_i + 2B & \text{if } T + D > B. \end{cases} \quad (2)$$

(ii) Delay range $B < D < 2B$: Figure 8 can be used to describe the expected reply delivery delay at destination mobile station. The lower bound of expected reply delivery time to destination mobile stations is described using the following equations:

$$\text{delay} = \begin{cases} B_i + 2B & \text{if } T + D < 2B, \\ B_i + 3B & \text{if } T + D > 2B. \end{cases} \quad (3)$$

(iii) In general cases $kB < D < (k+1)B$: Figure 9 can be used to describe the expected reply delivery delay at destination mobile station.

The lower bound of expected reply delivery time to destination mobile stations is described using the

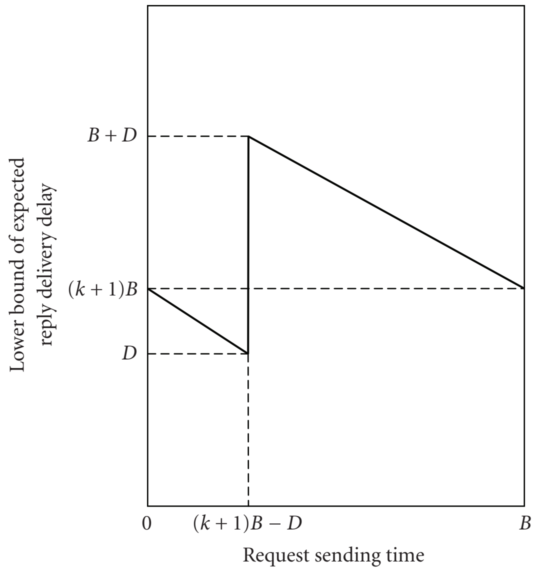

Figure 9: Lower bound of the expected reply delivery delay with $kB < D < (k+1)B$.

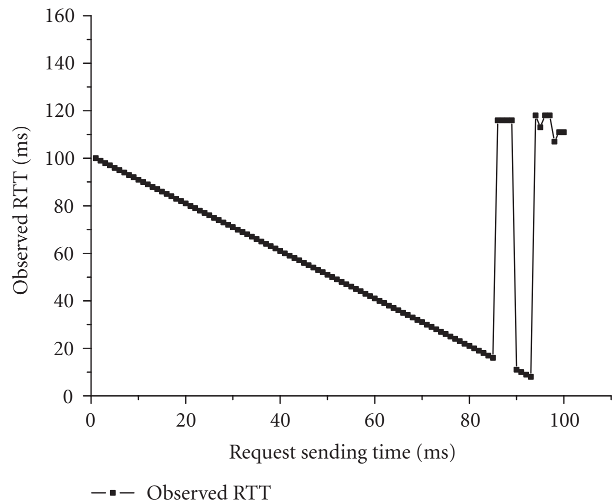

Figure 10: Expected reply delivery delay with delay range [0, 20].

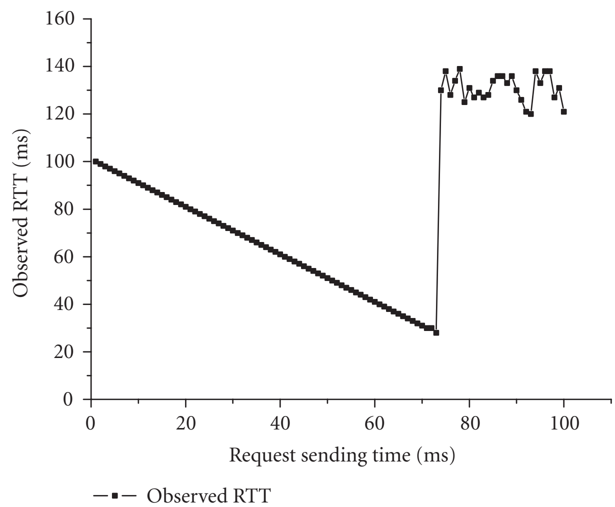

Figure 11: Expected reply delivery delay with delay range [20, 40].

following equations:

$$\text{delay} = \begin{cases} B_i + kB, & T + D < (k+1)B, \\ B_i + (k+1)B, & T + D > (k+1)B. \end{cases} \quad (4)$$

Using the expected reply delivery time, the power state transition pattern of mobile stations that have transmitted the request can be easily determined. Therefore, mobile stations can decide when to switch to power-saving state and when to stay in active state to receive the buffered data from the AP based on the time they have transmitted the request.

(2) Variable wired line delay.
The RTT between the AP and remote server is not a fixed value but a random value P_{rtt} uniformly distributed within the range of [$\text{Delay}_{\text{lowbound}}$, $\text{Delay}_{\text{highbound}}$]. This represents the scenario where the remote server is connected with AP through unreliable connection such as Internet. We provide the simulation results of the expected reply delivery delay with a simulation program. The simulation program uses the similar assumption that we have described previously.

Figures 10, 11, 12, 13, and 14 show the relationship between expected reply delivery delay and request sending time. The beacon interval is 100 milliseconds in the simulation, and we simulate a scenario that there is a request every 1 millisecond. The queuing time and contention within the service area are currently ignored and the transmission time between mobile stations and AP is also neglected.

Based on the above analysis and simulations, the actual request sending time and the length of the beacon interval decide the time that mobile stations are expected to receive their replies. If mobile stations do not have any uplink packets to AP, they should not stay in active state earlier than the time the replies are expected to be ready at the AP side, otherwise mobile stations wait in idle state and waste their energy. Furthermore, AP has to poll the active mobile stations even if they do not have any uplink and downlink packets, which also reduces the available bandwidth. In our proposed smart AP protocol, mobile stations use the average of the last five observed reply delivery delays to estimate the actual end-to-end delay and use the models described above to determine the actual time they have to stay in active state instead of staying active for every beacon interval. If mobile stations wake up and the replies

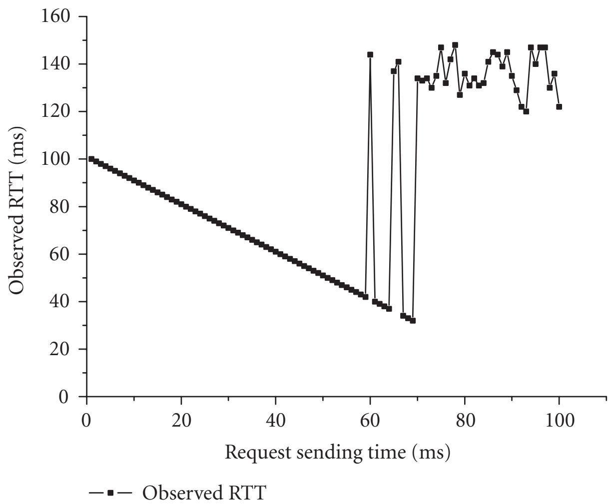

FIGURE 12: Expected reply delivery delay with delay range [20, 50].

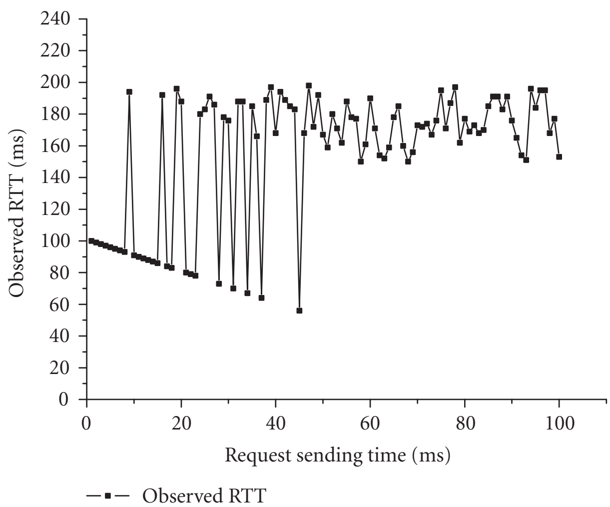

FIGURE 13: Expected reply delivery delay with delay range [50, 100].

have not been received by AP yet, they are instructed to switch to power-saving state using TIM by AP unless they have other mobile-to-mobile or mobile-to-AP packets waiting.

4. SIMULATION AND ANALYSIS

In order to verify our proposed algorithm as it is incorporated into existing IEEE 802.11 protocol and provide comparison results, we used the well-known network simulator NS-2 Version 2.1b8 [18] with contributed PCF model provided by Lindgren et al. [19], which has a detailed simulation of the MAC/PHY layer characteristics and infrastructure-based operation of IEEE 802.11. We implemented our proposed modifications on top of the existing model. In the

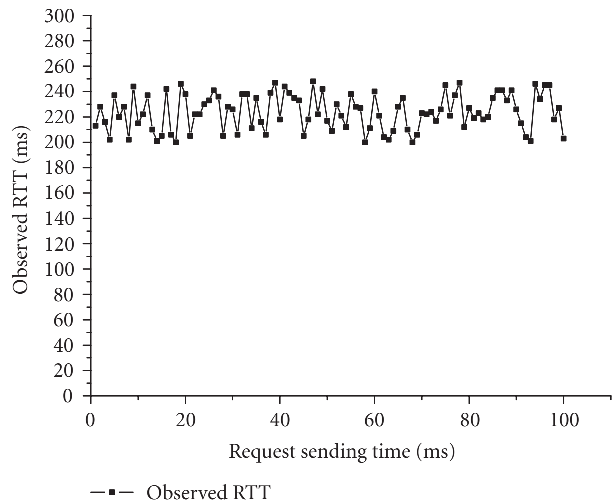

FIGURE 14: Expected reply delivery delay with delay range [100, 150].

simulation, we set up a wireless LAN environment with AP and mobile stations. The physical layer is modeled as the 2 Mbps wireless medium as widely used in most of the IEEE 802.11 compatible devices. The physical data rate does not significantly affect the results, since the MAC-level protocol operates basically in the same way for different data rates and we only make modifications on MAC level. The simulation area is a flat square ($500 \times 500\,\text{m}^2$), and the AP is a special node with infinite energy and fixed position which is located in the center (250, 250) of the simulation area. The total number of mobile stations in the simulation area is 20 and they are randomly deployed within the area. We use the constant bit rate traffic with fixed-length packet size of 1024 bytes. The beacon interval is set to be 1 second and the maximum duration of the CFP is 0.8 second for PCF mode. The default energy consumption model is described in Table 2. We assume that mobile stations use fixed energy level for receiving, idle and power-saving states. The transmission power is adjustable and only applicable for data packets. As a result, mobile stations use maximum transmission power ($P_{\text{transmitting}}$) for communication during the first polling phase and control packets. Based on the estimated distance (D_{est}) between sender and receiver, we use (5) to obtain the minimal required energy (P) for the transmission,

$$P = P_{\text{transmitting}} \times \left(\frac{D_{\text{est}}}{D_{\text{range}}}\right)^{\lambda}. \quad (5)$$

We use UDP traffic at each source with constant packet generation rate at 4 packets per second. The connection patterns are randomly generated. In Figures 15, 16, and 17, the x-axis "number of stations polled by AP" means the number of stations that are communicating with each other using the AP as the router, in which the traffic sinks are at the destination stations (mobile stations). It should be noted that all other stations communicating with AP have their

TABLE 2: Energy-consumption model.

Operation mode	Energy
Idle	1.15 W
Power-saving mode	0.045 W
Receiving	1.4 W
Transmitting ($P_{\text{transmitting}}$)	1.65 W
Transmission range (D_{range})	250 m

destination addresses of UDP traffic set at a remote server attached to AP. The simulation time is 200 seconds and all UDP traffic start at 7 seconds together. In the simulation, we compare the traditional IEEE 802.11 protocol with our proposed modifications: the improved PCF operation and smart AP protocol. In our protocols, the mobile stations take advantage of the AP-assisted DCF transmission mechanism for direct transmission between each other without routing through AP if certain criteria are met. Mobile stations do not have to stay active in every beacon interval owing to the waking-up-time estimation and announcement of TIM through beacon transmission. In the simulation, IEEE 802.11 PCF protocol has the minimum end-to-end delay as shown in Figure 15. The average delay calculation includes stations with packets targeted for remote server and mobile stations. Suppose that a total of N packets have been received successfully, then the average delay can be calculated as described by

$$\text{average\_delay} = \frac{\sum_{i=1}^{N} (\text{rcv\_time}_i - \text{gen\_time}_i)}{N}, \tag{6}$$

where rev_time_i represents the time ith packet is successfully received, and gen_time_i is the generation time of ith packet.

There are several reasons that affect the results. In IEEE 802.11 PCF, stations will stay active for the entire beacon period. After all the stations in the polling list have been polled, AP can poll any station that has downlink data packets pending. Packets that are generated or received during the polling period can still be transmitted to mobile stations if the contention-free period is not over. Furthermore, in our proposed algorithm, we use two-phase polling mechanism during which the first polling period is utilized for traffic information collection. So the average time that a station with pending data is polled is larger than that in the traditional IEEE 802.11 PCF protocol, especially when the number of stations in the polling list of AP is very large. Our smart AP operation has a performance gain over the optimized PCF, since an estimation of the wake up time is used to decide the stations' power state transition. Stations only stay in active state at specific polling period during which the reply from the remote server is expected to be received. So the number of stations that wake up during each contention-free period is reduced, which reduces the length of polling list. So the average time that a station with pending data is polled is less than that in the improved PCF protocol.

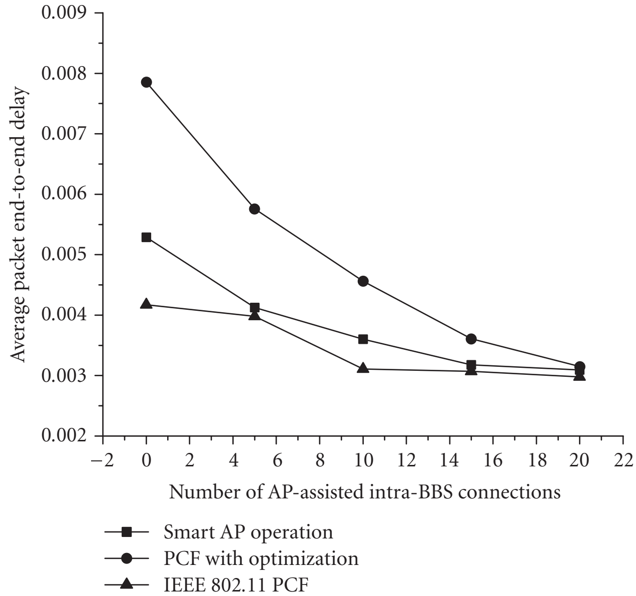

FIGURE 15: Average packet end-to-end delay.

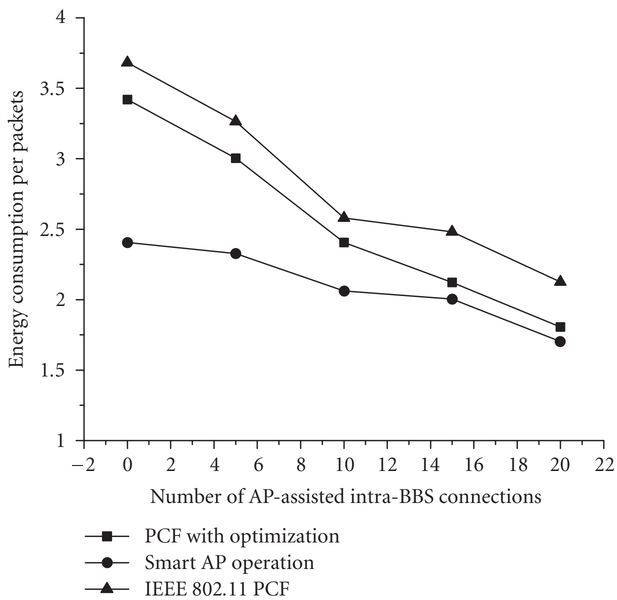

FIGURE 16: Energy consumption per packet.

Energy consumed per packet is computed for each packet received at the destination, which accounts for the average energy consumed by each successfully received packet. It can be described by

$$\text{energy\_per\_packet} = \frac{\text{total\_energy\_consumed}}{\text{total\_packet\_received}}. \tag{7}$$

The proposed protocols lead to less energy consumption per packet than IEEE 802.11 PCF, which may prolong the battery

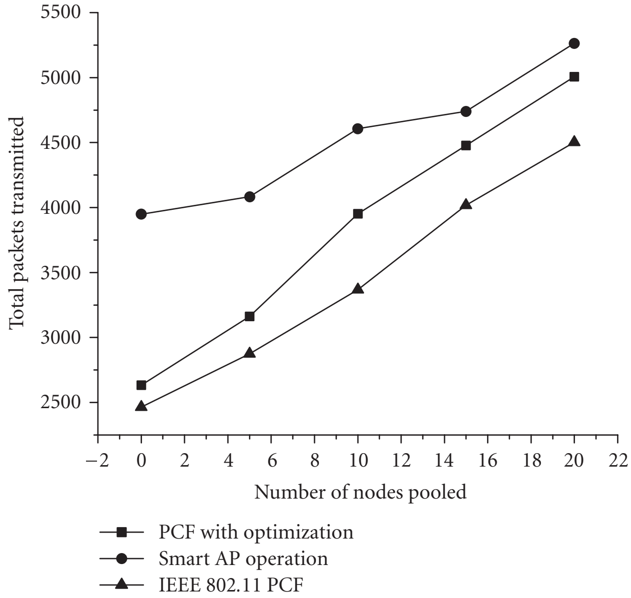

Figure 17: Total packets transmitted during the simulation time.

lifetime up to 35% in the best scenario as shown in Figure 16. Stations do not have to stay active for the entire contention-free period unless they have set up schedule with AP during the first polling period, otherwise energy is wasted since stations wait in an idle state without receiving or sending any data packets. The two-hop transmission is also reduced to a single-hop direct transmission if necessary for power efficiency. Stations can switch to power-saving mode after receiving the first poll, if they do not have packets to transmit or receive. Stations can also switch to power-saving mode after the second poll, if they have finished the packets transmission and no direct transmission (AP-assisted DCF) is scheduled by AP. If there is only traffic between the mobile stations and remote server (number of nodes polled equals 0), the energy saving can be maximized using smart AP operation. Stations do not have to wake up earlier than the time that the expected reply reaches the access point, which shortens the time that stations wait in idle state without receiving or sending any data packets.

Figure 17 shows the number of data packets that has been transmitted and successfully received by the destinations. Since all the simulations run for the same amount of time and the traffic arrival rate, more packets transmitted suggests higher bandwidth utilization. Our proposed protocol utilizes the beacon interval as long as possible for the two-phase polling if most traffic is between AP and mobile stations. When most traffic is between different mobile stations, our scheme will enable them to be directly transmitted during contention period. Furthermore, the two-hop transmission is reduced to a single-hop direct transmission without contention, which reduces the channel utilization and possibility of collision. Hence there will be more time in each contention-free period for stations that actually have pending data packets, which increases the throughput significantly. The smart AP operation has a noticeable performance gain over the improved PCF operation mainly due to the estimation of the waking up time through the implementation of the TIM. Mobile stations use the historical traffic information and the delay model to estimate the expected reply delivery delay. Based on the estimation and the time that a request is sent, mobile stations are able to get approximate time at which the replies are expected to be received. Using this information, stations can be instructed efficiently to stay in active state at specific contention-free period, which reduces the energy consumption. Since stations do not have to stay in active state during every contention-free period, the length of the polling list of AP is also reduced. So there will be more time in each contention-free period for stations that actually have pending data packets, which increases the throughput significantly.

5. CONCLUSION

In this paper, enhancements to the traditional IEEE 802.11 PCF protocol are proposed. Simulation results show that using the proposed protocols energy consumption of mobile devices can be reduced while the end-to-end packet delay is slightly longer than traditional IEEE 802.11 PCF protocol. The throughput is increased significantly due to the reduction of channel utilization through the direct transmission and waking-up-time estimation. The proposed protocol is a hybrid of AP-assisted DCF and PCF operation, which is more flexible and fault-tolerant, and can be readily reverted to the traditional IEEE 802.11 protocol for compatible reason when required.

ACKNOWLEDGMENT

This work was supported by the research grant of Nanyang Technological University.

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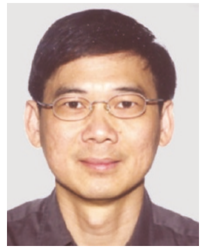

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