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Energy-efficient PCF operation of IEEE 802.11a WLANs via transmit power control

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Abstract

Transmit power control (TPC) has been recognized as one of the effective ways to save energy in wireless devices. In this paper, we demonstrate the energy-efficient point coordination function (PCF) operation of IEEE 802.11a wireless local-area networks (WLANs) via TPC and physical layer (PHY) rate adaptation. The basic idea is that the best transmit power level as well as the proper PHY rate are adaptively selected by a wireless station to transmit an uplink data frame, according to the up-to-date path loss condition between itself and the point coordinator, thus delivering data with minimum energy consumption. Evaluation results show that significant energy savings can be achieved by combining TPC with adaptive PHY rate selection. Note that a key requirement for a wireless station to realize the proposed energy-efficient PCF operation is the knowledge of the path loss, and we present a simple, novel, and effective path loss estimation scheme for this purpose. The results and conclusions presented in this paper should serve as a valuable guidance or reference for the design of future 5 GHz 802.11 WLAN systems.

Keywords: IEEE 802.11 MAC; IEEE 802.11a PHY; Point coordination function; Transmit power control; PHY rate adaptation

1. Introduction

For wide-area cellular systems, such as IS-95 code-division multiple access (CDMA) and the third generation (3G) wide-band CDMA (W-CDMA), transmit power control (TPC) is critically important in order to (1) ameliorate the near–far problem, specifically, for CDMA uplink systems; (2) minimize the interference to/from other cells, i.e., cochannel interference; and (3) improve the system performance on fading channels by compensating fading dips [1]. For wireless local-area networks (WLANs), which are mainly used in indoor home, office, and public access environments, TPC has not attracted enough attention as it was not considered as critical to success as in CDMA systems. However, since many WLAN devices such as laptops and palmtops are battery-powered, and extending the operation time of such

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devices is always desirable and important, applying TPC in WLAN systems in order to save the battery energy can be naturally an attractive idea. Moreover, in the multi-cell WLAN systems often found in office and public access environments, reducing the cochannel interference via TPC could be quite beneficial as well since it results in better error performance in a given area. In this paper, we demonstrate the energy-efficient data transmission in IEEE 802.11a WLANs by combining TPC with physical layer (PHY) rate adaptation.

1.1. Problem statement

The IEEE 802.11 standard [2] specifies two different medium access control (MAC) mechanisms in WLANs: the contention-based distributed coordination function (DCF), and the polling-based point coordination function (PCF). The IEEE 802.11a PHY [3] is the new high-speed PHY developed to operate IEEE 802.11 in the 5 GHz unlicensed national information infrastructure (U-NII) band, which provides eight PHY modes with data transmission rates ranging from 6 up to 54 Mbps.

In [4], we derived the goodput performance analytically for peer-to-peer communication in an IEEE 802.11a WLAN under the DCF, and proposed a link adaptation scheme to achieve goodput enhancement via both dynamic fragmentation and adaptive PHY mode (or equivalently, transmission rate) selection. In this paper, we address another important problem in the WLAN environment: how to minimize the energy consumption for data transmissions under the PCF? Obviously, in order to deliver a data frame, the higher the PHY rate, the shorter the transmission time and the less energy consumed in one transmission attempt, but more likely the transmission will fail, thus engendering re-transmissions. So, there is an inherent trade-off, and our idea is to combine TPC with adaptive PHY mode selection, so that the proper PHY rate as well as the best transmit power level can be adaptively selected to combat the path loss variation, thus delivering data with minimum energy consumption.

As described in [5], by simply allowing wireless stations to transmit at different power levels under the DCF, the number of hidden terminals is likely to increase because of the reduced transmission ranges, which, in turn, results in more collisions and re-transmissions due to the very nature of DCF's contention-based access mechanism, and hence, more energy is consumed eventually. See a companion paper [6] for details on how to apply TPC to save energy under the DCF while avoiding the possibility of having more hidden terminals. On the other hand, there is no "hidden nodes" problem under the PCF, since the access to the wireless medium is centrally controlled by the point coordinator (PC), or equivalently, the access point (AP), thus making the application of TPC to save energy under the PCF less hassle. Besides, the PC is normally located at a fixed position and connected to the power line, and therefore, the energy consumption at the PC for downlink (PC-to-station) data transmissions is usually not a critical issue. We are more concerned about energy savings by battery-operated wireless stations for uplink (station-to-PC) data transmissions.

One may think that the energy-efficiency optimization does not constitute the ultimate goal for the PCF operation since the PCF is typically used for isochronous real-time services. While this is a valid observation as real-time services require a timely delivery of traffic with less error, which may not result in energy-efficient operations, it should also be noted that the polling-based PCF could be used for non-real-time services as well. For example, the PCF is known to achieve a higher maximum throughput than the contention-based DCF [7], and hence one may want to use the PCF instead of the DCF in order to maximize the system throughput for data traffic. Our paper basically shows that one may also prefer the PCF with the proposed TPC to the DCF without TPC in order to minimize the energy consumption. We also consider a more typical PCF application in this paper, i.e., a streaming-like service that requires a sustained goodput level, and demonstrate the energy-efficient PCF operation with the minimum goodput requirement.

A WLAN device operates in one of the following modes: transmit mode, receive mode, or sleeping mode. Transmit mode results in the highest energy consumption, while sleeping mode consumes the least amount of energy. The TPC mechanism will be included in the upcoming IEEE 802.11h standard [8], which is an extension to the current 802.11 MAC and 802.11a PHY, and will allow a WLAN device to use one out of several available power levels in transmit mode. The results and conclusions presented in this paper should serve as a valuable guidance or reference for the future 802.11a/h WLAN system design.

1.2. Related work

In recent years, several power-management policies have been proposed to force a WLAN device to sleep adaptively at appropriate moments to save battery energy. In [9], the authors used the time-indexed semi-Markov decision process (TISMDP) model to derive the optimal policy for dynamic power management in portable systems. In [10], several application-specific policies were given to put an idle WLAN device into sleeping mode. However, both papers assumed a fixed transmit power level. Since TPC determines the best transmit power level to use in transmit mode, it is complementary to these power-management policies, which address how to switch between transmit/receive and sleeping modes.

The authors of [11] presented a scheme where the most battery energy-efficient combination of forward error correction (FEC) code and automatic re-transmission request (ARQ) protocol is chosen and adapted over time for data transmissions without, however, considering TPC.

1.3. Organization

The rest of this paper is organized as follows. Section 2 introduces the PCF of IEEE 802.11 MAC as well as the IEEE 802.11a PHY. The error probability analysis is presented in Section 3. Section 4 describes the details of the energy consumption analysis and the proposed energy-efficient PCF operation. Section 5 presents the evaluation results, and the implementation issues are discussed in Section 6. Finally, this paper concludes with Section 7.

2. System overview

2.1. PCF of IEEE 802.11 MAC

The centrally coordinated access mechanism of the IEEE 802.11 MAC, called the PCF, adopts a poll-and-response protocol to control the access to the shared wireless medium and eliminate contention among wireless stations. It makes use of the priority inter-frame space (PIFS) to seize and maintain control of the medium. The period during which the PCF is operated is called the contention-free period (CFP). [1] Once the PC has control of the medium, it may start transmitting downlink traffic to stations. Alternatively, the PC can also send contention-free poll (CF-Poll) frames to those stations that have requested contention-free services for their uplink traffic. During a CFP, a wireless station can only transmit after being polled by the PC. If a polled station has uplink traffic to send, it may transmit one frame for each CF-Poll received. Otherwise, it will respond with a NULL frame, which is a data frame without any payload. Besides, in order to utilize the medium more efficiently during the CFP, it is possible to piggyback both the acknowledgment (CF-Ack) and the CF-Poll onto data frames.

During the CFP, the PC sends a frame to a wireless station and expects the reply frame, either a CF-Ack or a data frame or a NULL frame in response to a CF-Poll, within a short inter-frame space (SIFS) that is shorter than PIFS. Consider an example of uplink data frame transmission. The PC first sends a CF-Poll to the wireless station and waits for an uplink data frame. As shown in Fig. 1, if a data frame is received correctly within SIFS time, the PC will send a CF-Ack + CF-Poll frame that allows the next uplink data frame transmission. If a data frame is received in error, determined by an incorrect frame check sequence (FCS), or equivalently, an incorrect cyclic redundancy check (CRC), the PC will send a CF-Poll asking for the re-transmission, as shown in Fig. 2.

[1] In an IEEE 802.11 WLAN, a CFP and a contention period (CP) alternate over time periodically, where the centrally coordinated PCF is used during a CFP, and the contention-based DCF is used during a CP.

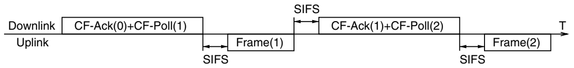

Fig. 1. Timing of successful uplink frame transmissions under the PCF.

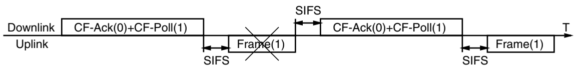

Fig. 2. CF-poll re-transmission due to an erroneous data frame reception.

However, if no reply frame is received within a SIFS interval possibly due to an erroneous reception of the preceding CF-Poll frame by the polled station, the PC will reclaim the medium and send its next CF-Poll after a PIFS interval from the end of the previous CF-Poll frame, as shown in Fig. 3. In this case, the PC will not be confused with the scenario where the polled station has nothing to transmit, because a NULL frame is expected under that circumstance. Therefore, the PC may choose to re-poll the same station instead of skipping to poll the next station on its polling list. Note that, in these figures, the blocks labeled with "CF-Ack(i)", "CF-Poll(i)", and "Frame(i)" represent the acknowledgment to, the CF-Poll to, and the uplink frame transmission from station i, respectively, and a crossed block represents an erroneous reception of the corresponding frame.

2.2. IEEE 802.11a PHY

The PHY is the interface between the MAC and the wireless medium, which transmits and receives data frames over the shared wireless medium. The frame exchange between MAC and PHY is under the control of the physical layer convergence procedure (PLCP) sublayer.

The OFDM has been selected as the modulation scheme for the IEEE 802.11a PHY, which is very similar to the modulation scheme adopted in Europe for HIPERLAN/2 PHY [12]. The basic principle of OFDM is to divide a high-speed binary signal to be transmitted over a number of low data-rate subcarriers. There are a total of 52 subcarriers, of which 48 subcarriers carry actual data and four subcarriers are pilots that facilitate phase tracking for coherent demodulation. Each low data-rate bit-stream is used to modulate a separate subcarrier from one of the channels in the 5 GHz band. The IEEE 802.11a PHY provides eight PHY modes with different modulation schemes and coding rates. Binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16-ary quadrature amplitude modulation (QAM), and 64-QAM are the supported modulation schemes. As listed in Table 1, the OFDM system provides a WLAN with capabilities of communicating at 6 to 54 Mbps. FEC is performed by bit interleaving and rate-1/2 convolutional coding. The higher code rates of 2/3 and 3/4 are obtained by puncturing the original rate-1/2 code.

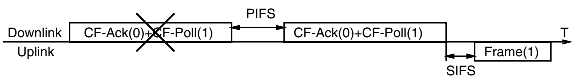

Fig. 3. CF-poll re-transmission due to CF-Poll failure.

Table 1
Eight PHY modes of the IEEE 802.11a OFDM PHY

Mode	Modulation	Code rate	Data rate (Mbps)	BpS
1	BPSK	1/2	6	3
2	BPSK	3/4	9	4.5
3	QPSK	1/2	12	6
4	QPSK	3/4	18	9
5	16-QAM	1/2	24	12
6	16-QAM	3/4	36	18
7	64-QAM	2/3	48	24
8	64-QAM	3/4	54	27

3. Error probability analysis

In this paper, we assume the additive white Gaussian noise (AWGN) wireless channel model and use the same error probability analysis as in [4]. For completeness, we briefly describe the analysis.

3.1. Bit error probability

The symbol error probability for an M-ary ($M = 4, 16, 64$) QAM [13] with the average signal-to-noise ratio (SNR) per symbol, r, can be calculated by

$$P_M(r) = 1 - [1 - P_{\sqrt{M}}(r)]^2, \tag{1}$$

where

$$P_{\sqrt{M}}(r) = 2\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3}{M-1} r}\right) \tag{2}$$

is the symbol error probability for the $\sqrt{M}$-ary pulse amplitude modulation (PAM). The Q-function is defined as

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-y^2/2} \, dy. \tag{3}$$

With a Gray coding, the bit error probability for an M-ary QAM can be approximated by

$$P_b^{(M)}(r) \approx \frac{1}{\log_2 M} P_M(r). \tag{4}$$

Note that 4-ary QAM and QPSK modulation are identical. For BPSK modulation, the bit error probability is the same as the symbol error probability, which is given by

$$P_b^{(2)}(r) = P_2(r) = Q(\sqrt{2r}). \tag{5}$$

The SNR (in dB) used above actually equals the output power level (in dBm) at the transmitter minus the path loss (in dB) and the white Gaussian noise level (in dBm) observed at the receiver. Therefore, the error performance of a modulation scheme varies with different transmit power levels and different path loss conditions.

3.2. Packet error probability

In [14], an upper bound was given on the packet error probability, under the assumption of binary convolutional coding and hard-decision Viterbi decoding with independent errors at the channel input. For an h-octet long packet to be transmitted using PHY mode m $(1 \leqslant m \leqslant 8)$, this bound is

$$P_e^m(h, r) \leqslant 1 - [1 - P_u^m(r)]^{8h}, \tag{6}$$

where the union bound $P_u^m(r)$ of the first-event error probability is given by

$$P_u^m(r) = \sum_{d=d_{free}}^{\infty} a_d P_d(r), \tag{7}$$

where d_{free} is the free distance of the convolutional code selected in PHY mode m, a_d is the total number of error events of weight d, and $P_d(r)$ is the probability that an incorrect path at distance d from the correct path being chosen by the Viterbi decoder. When the hard-decision decoding is applied, $P_d(r)$ is given by

$$P_d(r) = \begin{cases} \sum_{k=(d+1)/2}^{d} \binom{d}{k} \rho^k (1-\rho)^{d-k}, & \text{if } d \text{ is odd,} \\ \frac{1}{2}\binom{d}{d/2} \rho^{d/2} (1-\rho)^{d/2} \\ \quad + \sum_{k=d/2+1}^{d} \binom{d}{k} \rho^k (1-\rho)^{d-k}, & \text{if } d \text{ is even,} \end{cases} \tag{8}$$

where ρ is the bit error probability for the modulation scheme selected in PHY mode m, and is given by Eq. (4) or (5). The value of a_d can be obtained either from the transfer function or by a numerical search [15].

4. The energy-efficient PCF operation

In this section, we first analyze the average energy consumed by a wireless station when it is actively transmitting, receiving, or sensing the channel, i.e., when it is not in sleeping mode. The energy consumption is measured in *Joule per delivered data bit*. Then, we present the details of the energy-efficient PCF operation. The key idea is to combine TPC with adaptive PHY mode selection, so that the best transmit power level as well as the proper PHY rate can be adaptively selected by a wireless station to transmit an uplink data frame, according to the up-to-date path loss condition between itself and the PC, thus delivering data with minimum energy consumption.

4.1. Energy consumption model

Since we do not have access to the energy-consumption characteristic of any 802.11a-compliant product currently available in the market, we propose a WLAN card energy consumption model, as shown in Fig. 4, for our energy consumption analysis. It is based on the power characteristics of two 802.11b-compliant WLAN

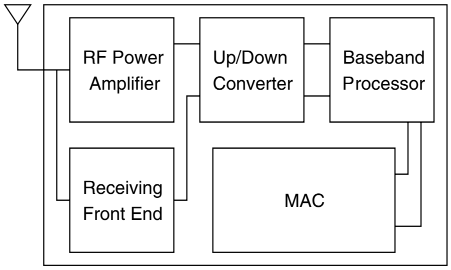

Fig. 4. Simplified block diagram of a WLAN card.

Table 2
Power characteristics of Agere ORiNOCO card

Receive mode	180 mA
Transmit mode	280 mA
Power supply	5 V
Nominal output power	15 dBm

Table 3
Power characteristics of Intersil Prism II card

Continuous receive mode	185 mA
Continuous transmit mode	300 mA
Power amplifier supply current	180 mA
Power supply	3.3 V
Nominal output power	18 dBm

devices, the Agere ORiNOCO (or formerly Lucent WaveLAN) card [16] and the Intersil Prism II card [17,18], which are listed in Tables 2 and 3, respectively. Note that the IEEE 802.11b PHY [19] is another high-speed physical layer extension to the IEEE 802.11, which provides data rates up to 11 Mbps in the 2.4 GHz band.

In general, the power consumption is different for receive mode and transmit mode, because different circuits are used in different modes. As shown in Fig. 4, the RF power amplifier (PA) is active in transmit mode only, while the receiving front end (e.g., the low noise amplifier in an Intersil Prism II card) is active only in receive mode.

The power conversion efficiency (η) of a PA is defined as the ratio of the actual signal power emitted from the antenna, or the output (transmit) power level ($\mathscr{P}_{\text{out}}$), to the total power consumed by the PA ($\mathscr{P}_{\text{pa}}$). Basically, η is a function of $\mathscr{P}_{\text{out}}$, and a PA presents the following non-linearity feature: it achieves very high efficiency at high output power levels, but the efficiency drops flat at low power levels. The *E–P* (efficiency vs. output power level) curve varies for different PA designs. Based on the *E–P* curves given in [20,21], we assume exponential *E–P* curves (see Fig. 7) for the 5 GHz power amplifiers used in the 802.11a-compliant WLAN devices. Since we are only interested in how to save energy by using PHY rate adaptation with TPC, not the exact amount of energy savings, this assumption has little impact on the results to be presented in Section 5.

Let $\mathscr{P}_{\text{rec}}$ denote the power consumption of the receiving front end. In general, $\mathscr{P}_{\text{rec}}$ is lower than $\mathscr{P}_{\text{pa}}$, and the difference becomes significant when the output power level is high. Converter, baseband processor, and MAC are considered to be the common components of both receive and transmit circuits, and they are assumed to consume the same amount of power ($\mathscr{P}_{\text{com}}$) in both receive and transmit modes. Let $\mathscr{P}_{r\_\text{mode}}$ and $\mathscr{P}_{t\_\text{mode}}$ be the total power consumption in receive and transmit modes, respectively. Then, we have

$$\begin{cases} \mathscr{P}_{r\_\text{mode}} = \mathscr{P}_{\text{com}} + \mathscr{P}_{\text{rec}}, \\ \mathscr{P}_{t\_\text{mode}}(\mathscr{P}_{\text{out}}) = \mathscr{P}_{\text{com}} + \mathscr{P}_{\text{pa}} = \mathscr{P}_{\text{com}} + \frac{\mathscr{P}_{\text{out}}}{\eta(\mathscr{P}_{\text{out}})}. \end{cases} \tag{9}$$

Furthermore, we assume that, when a WLAN card is sensing the channel, it presents the same power consumption as when it is in receive mode.

4.2. Energy consumption analysis

As shown in Fig. 5, in the IEEE 802.11 MAC, each MAC data frame, or MAC protocol data unit (MPDU), consists of the following components: [2] *MAC header*, variable-length information *frame body*, and FCS. The MAC overheads due to the MAC header and the FCS are 28 octets in total. The CF-Ack, CF-Poll, and CF-Ack + CF-Poll frames all use the same frame format as the data

[2] Actually, an additional field of "Address 4" appears in the wireless distribution system (WDS) data frames being distributed from one PC to another PC. However, since such WDS frames are rarely used, we do not consider the "Address 4" field in this paper. Besides, we do not consider the wired equivalent privacy option, which may introduce an extra eight-octet overhead.

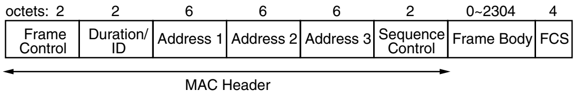

Fig. 5. Frame format of a data frame MPDU.

frames, but with zero frame body and different values in the *subtype* subfield of the *frame control* field.

During the transmission, a PLCP preamble and a PLCP header are added to an MPDU to create a PLCP protocol data unit (PPDU). The PPDU format of the IEEE 802.11a PHY is shown in Fig. 6, which includes PLCP preamble, PLCP header, MPDU (conveyed from MAC), tail bits, and pad bits, if necessary. The PLCP preamble field, with the duration of *tPLCPPreamble*, is composed of 10 repetitions of a short training sequence (0.8 μs) and two repetitions of a long training sequence (4 μs). The PLCP header except the SERVICE field, with the duration of *tPLCP_SIG*, constitutes a single OFDM symbol, which is transmitted with BPSK modulation and the rate-1/2 convolutional coding. The six "zero" tail bits are used to return the convolutional code to the "zero state", and the pad bits are used to make the resulting bit string to be a multiple of OFDM symbols. Each OFDM symbol interval, denoted by *tSymbol*, is 4 μs. The 16-bit SERVICE field of the PLCP header and the MPDU (along with six tail bits and pad bits), represented by DATA, are transmitted at the data rate specified in the RATE field. Table 4 lists the related characteristics for the IEEE 802.11a PHY.

Based on the above analysis, to transmit a frame with ℓ octets data payload over the IEEE 802.11a PHY using PHY mode m and transmit power level $\mathscr{P}_{\text{out}}$, the energy consumption is

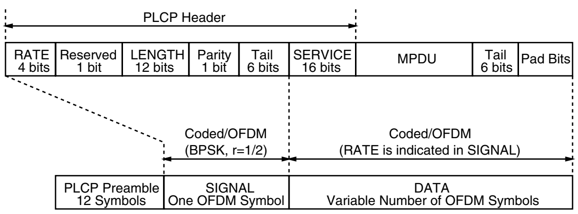

Fig. 6. PPDU frame format of the IEEE 802.11a OFDM PHY.

Table 4
IEEE 802.11a OFDM PHY characteristics

Characteristics	Value (μs)	Comments
tSlotTime	9	Slot time
tSIFSTime	16	SIFS time
tPIFSTime	25	PIFS = SIFS + Slot
tPLCPPreamble	16	PLCP preamble duration
tPLCP_SIG	4	PLCP SIGNAL field duration
tSymbol	4	OFDM symbol interval

$$\mathscr{E}_{\text{data}}(\ell, m, \mathscr{P}_{\text{out}}) = T_{\text{data}}(\ell, m)\mathscr{P}_{t\_\text{mode}}(\mathscr{P}_{\text{out}}), \tag{10}$$

where the data transmission duration, $T_{\text{data}}(\ell, m)$, is given by

$$\begin{aligned} T_{\text{data}}(\ell, m) &= \mathit{tPLCPPreamble} + \mathit{tPLCP\_SIG} \\ &\quad + \left\lceil \frac{28 + (16+6)/8 + \ell}{\text{BpS}(m)} \right\rceil \mathit{tSymbol} \\ &= 20\ \mu\text{s} + \left\lceil \frac{30.75 + \ell}{\text{BpS}(m)} \right\rceil 4\ \mu\text{s}. \end{aligned} \tag{11}$$

Note that BpS(m), the bytes-per-symbol information for PHY mode m, is given in Table 1. The energy consumed to receive the corresponding CF-Ack(+ CF-Poll) frame is

$$\mathscr{E}_{\text{ack/poll}}(m) = T_{\text{ack/poll}}(m)\mathscr{P}_{r\_\text{mode}}, \tag{12}$$

where the CF-Ack(+ CF-Poll) frame is assumed to be transmitted at the same rate as the data frame it is acknowledging, and the CF-Ack(+ CF-Poll) transmission duration is

$$T_{\text{ack/poll}}(m) = T_{\text{data}}(0, m). \tag{13}$$

Besides, We use $\mathscr{E}_{\text{sifs}}$ and $\mathscr{E}_{\text{pifs}}$ to denote the energy consumptions of a wireless station being idle for SIFS time and PIFS time, respectively, and they can be calculated by

$$\mathscr{E}_{\text{sifs}} = \mathit{tSIFSTime}\mathscr{P}_{r\_\text{mode}} = 16\ \mu\text{s}\mathscr{P}_{r\_\text{mode}}, \tag{14}$$

and

$$\mathscr{E}_{\text{pifs}} = \mathit{tPIFSTime}\mathscr{P}_{r\_\text{mode}} = 25\ \mu\text{s}\mathscr{P}_{r\_\text{mode}}. \tag{15}$$

4.3. The energy-efficient PCF operation

Assume that a wireless station is ready to transmit an uplink frame with ℓ octets data payload using PHY mode m with transmit power level $\mathscr{P}_{\text{out}}$. Besides, assume that the CF-Ack(+CF-Poll) frames are transmitted by the PC at the maximum power ($\mathscr{P}_{\max}$) to reduce the possibility of CF-Ack/CF-Poll failures. One can do this because the PC is normally connected to the power line, and thus the energy consumption at the PC for downlink transmissions is not critically important. Moreover, let s and n denote the path loss between the wireless station and the PC and the background noise level, respectively.

In the IEEE 802.11 MAC, a frame transmission is considered successful only upon receiving the corresponding acknowledgment correctly. Therefore, the probability of a successful uplink frame transmission can be calculated by

$$\begin{aligned} P_{s,\text{xmit}}(\ell, m, \mathscr{P}_{\text{out}}, s, n) = {} & [1 - P_{e,\text{ack/poll}}(m, s, n)] \\ & \times [1 - P_{e,\text{data}}(\ell, m, \mathscr{P}_{\text{out}}, s, n)], \end{aligned} \tag{16}$$

where $P_{e,\text{data}}$, the data transmission error probability, and $P_{e,\text{ack/poll}}$, the CF-Ack(+CF-Poll) transmission error probability, are given by

$$\begin{aligned} & P_{e,\text{data}}(\ell, m, \mathscr{P}_{\text{out}}, s, n) \\ & \quad = 1 - [1 - P_{\text{e}}^{1}(24/8, \mathscr{P}_{\text{out}} - s - n)] \\ & \qquad \times [1 - P_{\text{e}}^{m}(28 + (16+6)/8 + \ell, \mathscr{P}_{\text{out}} - s - n)] \\ & \quad = 1 - [1 - P_{\text{e}}^{1}(3, \mathscr{P}_{\text{out}} - s - n)] \\ & \qquad \times [1 - P_{\text{e}}^{m}(30.75 + \ell, \mathscr{P}_{\text{out}} - s - n)], \end{aligned} \tag{17}$$

and

$$P_{e,\text{ack/poll}}(m, s, n) = P_{e,\text{data}}(0, m, \mathscr{P}_{\max}, s, n), \tag{18}$$

respectively. Here, $P_{\text{e}}^{1}\ (3, \mathscr{P}_{\text{out}} - s - n)$ is the error probability of the PLCP SIGNAL field, because it is 24-bit long and always transmitted with BPSK modulation and rate-1/2 convolutional coding, i.e., PHY mode 1. $P_{\text{e}}^{1}(\cdot)$ and $P_{\text{e}}^{m}(\cdot)$ are calculated by Eq. (6).

By referring to Fig. 1, each successful uplink frame transmission duration is equal to the data transmission time, plus the acknowledgment transmission time, and plus two SIFS times. However, whenever the frame transmission fails, the PC has to wait for a SIFS time or a PIFS time before it reclaims the medium (see Figs. 2 and 3). Therefore, the expected total energy consumption, $\mathscr{E}_{\text{total}}$, for an uplink data frame delivery can be calculated by

$$\begin{aligned} \mathscr{E}_{\text{total}}(\ell, m, \mathscr{P}_{\text{out}}, s, n) = {} & \mathscr{E}_{\text{ack/poll}}(m) + \mathscr{E}_{\text{sifs}} \\ & + \mathscr{E}_{\text{data}}(\ell, m, \mathscr{P}_{\text{out}}) + \mathscr{E}_{\text{sifs}} \\ & + \sum_{i=1}^{\infty} P[n = i]\, i\, \overline{\mathscr{E}}_{\text{re-xmit}} \end{aligned} \tag{19}$$

where $\overline{\mathscr{E}}_{\text{re-xmit}}$ is the expected energy consumed for each re-transmission attempt and given by

$$\begin{aligned} \overline{\mathscr{E}}_{\text{re-xmit}} = {} & \frac{P_{e,\text{ack/poll}}(m, s, n)}{1 - P_{s,\text{xmit}}(\ell, m, \mathscr{P}_{\text{out}}, s, n)} \\ & \times [\mathscr{E}_{\text{ack/poll}}(m) + \mathscr{E}_{\text{pifs}}] \\ & + \frac{[1 - P_{e,\text{ack/poll}}(m, s, n)] P_{e,\text{data}}(\ell, m, \mathscr{P}_{\text{out}}, s, n)}{1 - P_{s,\text{xmit}}(\ell, m, \mathscr{P}_{\text{out}}, s, n)} \\ & \times [\mathscr{E}_{\text{ack/poll}}(m) + \mathscr{E}_{\text{sifs}} + \mathscr{E}_{\text{data}}(\ell, m, \mathscr{P}_{\text{out}}) + \mathscr{E}_{\text{sifs}}]. \end{aligned} \tag{20}$$

$\mathscr{E}_{\text{data}}(\cdot)$, $\mathscr{E}_{\text{ack/poll}}(\cdot)$, $\mathscr{E}_{\text{sifs}}$, and $\mathscr{E}_{\text{pifs}}$ are given by Eqs. (10), (12), (14), and (15), respectively, and

$$\begin{aligned} P[n = i] = {} & [1 - P_{s,\text{xmit}}(\ell, m, \mathscr{P}_{\text{out}}, s, n)]^{i} \\ & \times P_{s,\text{xmit}}(\ell, m, \mathscr{P}_{\text{out}}, s, n) \end{aligned} \tag{21}$$

is the probability of i consecutive unsuccessful transmission attempts before the successful delivery. The average energy consumption can then be approximated by

$$\begin{aligned} & \mathscr{J}(\ell, m, \mathscr{P}_{\text{out}}, s, n) \\ & \quad = \frac{\mathscr{E}_{\text{total}}(\ell, m, \mathscr{P}_{\text{out}}, s, n)}{8\ell} \ \text{(Joule per Bit)}. \end{aligned} \tag{22}$$

Consequently, the most energy-efficient combination of PHY mode and transmit power level for a wireless station to transmit an uplink data frame with ℓ octets data payload, when the path loss between the wireless station and the PC is s and the background noise level is n, and the corresponding minimum average energy consumption are, respectively,

$$\begin{aligned} & \{m^{*}(\ell, s, n), \mathscr{P}_{\text{out}}^{*}(\ell, s, n)\} \\ & \quad = \arg\min_{\{m, \mathscr{P}_{\text{out}}\}} \mathscr{J}(\ell, m, \mathscr{P}_{\text{out}}, s, n), \end{aligned} \tag{23}$$

and

$$\mathscr{J}^{*}(\ell, s, n) = \mathscr{J}(\ell, m^{*}, \mathscr{P}_{\text{out}}^{*}, s, n). \tag{24}$$

Similarly, the expected transmission duration of an uplink data frame, $\mathscr{D}_{\text{total}}$, can be calculated by

$$\mathscr{D}_{\text{total}}(\ell, m, \mathscr{P}_{\text{out}}, s, n) = T_{\text{ack/poll}}(m) + tSIFSTime + T_{\text{data}}(\ell, m) + tSIFSTime + \sum_{i=1}^{\infty} P[n = i] i \overline{\mathscr{D}}_{\text{re-xmit}} \quad (25)$$

where $\overline{\mathscr{D}}_{\text{re-xmit}}$ is the expected time spent on each retransmission attempt and given by

$$\overline{\mathscr{D}}_{\text{re-xmit}} = \frac{P_{e,\text{ack/poll}}(m, s, n)}{1 - P_{s,\text{xmit}}(\ell, m, \mathscr{P}_{\text{out}}, s, n)} \times [T_{\text{ack/poll}}(m) + tPIFSTime] + \frac{[1 - P_{e,\text{ack/poll}}(m, s, n)] P_{e,\text{data}}(\ell, m, \mathscr{P}_{\text{out}}, s, n)}{1 - P_{s,\text{xmit}}(\ell, m, \mathscr{P}_{\text{out}}, s, n)} \times [T_{\text{ack/poll}}(m) + tSIFSTime + T_{\text{data}}(\ell, m) + tSIFSTime]. \quad (26)$$

The average goodput is

$$\mathscr{G}(\ell, m, \mathscr{P}_{\text{out}}, s, n) = \frac{8\ell}{\mathscr{D}_{\text{total}}(\ell, m, \mathscr{P}_{\text{out}}, s, n)} \text{ (Mbps)}. \quad (27)$$

Hence, the most energy-efficient combination of PHY mode and transmit power level to transmit an uplink data frame while meeting the target goodput requirement $\mathscr{G}_{\text{target}}$ is

$$\{m^{**}(\ell, s, n), \mathscr{P}^{**}_{\text{out}}(\ell, s, n)\} = \arg\min_{\{m, \mathscr{P}_{\text{out}}\}} \mathscr{J}(\ell, m, \mathscr{P}_{\text{out}}, s, n) \quad (28)$$
$$\text{subject to } \mathscr{G}(\ell, m, \mathscr{P}_{\text{out}}, s, n) \geqslant \mathscr{G}_{\text{target}}.$$

The corresponding average energy consumption and achieved goodput are, respectively,

$$\mathscr{J}^{**} = \mathscr{J}(\ell, m^{**}, \mathscr{P}^{**}_{\text{out}}, s, n) \quad (29)$$

and

$$\mathscr{G}^{**} = \mathscr{G}(\ell, m^{**}, \mathscr{P}^{**}_{\text{out}}, s, n). \quad (30)$$

5. Evaluation results and discussion

As specified in the IEEE 802.11 standard [2], the length of a MAC service data unit (MSDU), which is a data unit conveyed from the higher logic link control sublayer to the MAC, can be up to 2304 octets (see Clause 6.2.1.1.2 in [2]). The maximum transmit power ($\mathscr{P}_{\max}$) is limited to 200 mW (i.e., 23 dBm) [22] for the middle band of the 5 GHz U-NII band, which is suitable for indoor environments. Clearly, the PA reaches the maximum power conversion efficiency ($\eta_{\max}$) when the output power level is 23 dBm. In this paper, we assume that all the MSDUs are 2304-octet long and transmitted without fragmentation. Furthermore, as mentioned in Section 4.1, we assume an exponential *E–P* curve for the PA, where the power conversion efficiency is 0.02 when the output power level is 0 dBm ($\eta_0 = 0.02$). Table 5 summarizes the power characteristics we used to obtain the evaluation results, and Fig. 7(a) and (b) show the *E–P* curves of a low-efficiency PA ($\eta_{\max} = 0.1$) and a high-efficiency PA ($\eta_{\max} = 0.5$), respectively.

Table 5
Power characteristics used for the evaluation

$\mathscr{P}_{\text{com}}$	500 mW
$\mathscr{P}_{\text{rec}}$	50 mW
$\mathscr{P}_{\text{out}}$	−19 to 23 dBm
noise_level	−93 dBm
η_0	0.02
$\eta_{\max}$	0.1 or 0.5

In order to evaluate the energy-consumption performance of a transmission scheme quantitatively, we introduce a new measure called the *energy consumption ratio*. It is defined as the ratio

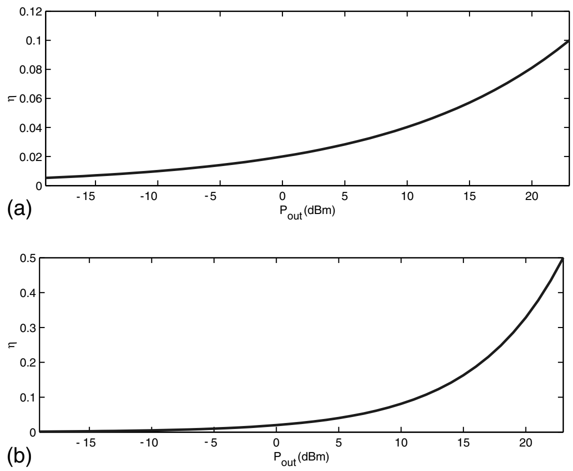

Fig. 7. *E–P* (efficiency vs. output power level) curves of 5 GHz PA. (a) Low efficiency PA with $\eta_{\max} = 0.1$, (b) high efficiency PA with $\eta_{\max} = 0.5$.

of the energy consumption, when the referred scheme is used, to the energy consumption, when the adaptive PHY mode selection and TPC with 15 power levels are used (as shown in Fig. 8(c)). This measure presents how a particular scheme performs, in terms of the energy consumption, relative to the adaptive scheme of dynamic PHY mode selection and TPC with 15 power levels that we originally proposed in [23].

5.1. Data transmission with minimum energy consumption

First, we investigate the problem of selecting the best combinations of PHY mode and transmit power level to achieve energy-efficient uplink data transmissions for non-real-time applications (e.g., FTP-like services).

Fig. 8 shows the energy-consumption performance when there are 15 transmit power levels (with 3 dBm steps) and when the PA presents a low power conversion efficiency ($\eta_{\max} = 0.1$). The best combinations of PHY mode and transmit power level, which achieve the most energy-efficient uplink data transmissions, under different path loss conditions are shown in Fig. 8(a) and (b), and the corresponding average energy consumptions are shown in Fig. 8(c), respectively. For example, when the path loss is 100 dB, this figure reads that, by using PHY mode 4 at the transmit power level of 17 dBm, the uplink data is transmitted with minimum energy consumption (about 0.08 mJ per information bit).

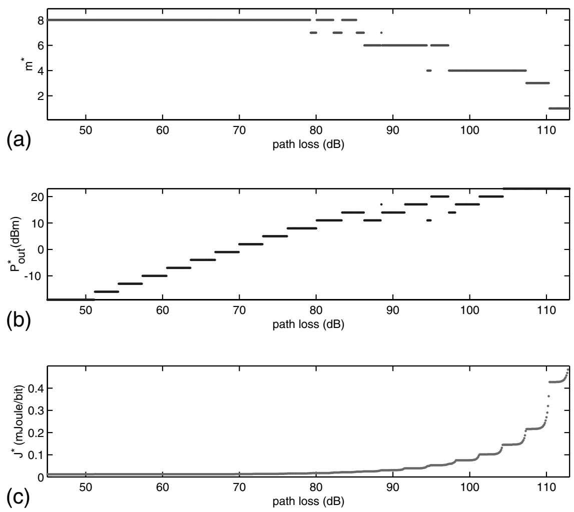

Fig. 8. 15 power levels with low-efficiency PA. (a) PHY mode selection, (b) transmit power level selection and (c) average energy consumption.

Basically, we have two more observations from Fig. 8. First, when the path loss is large, the lower PHY modes are preferred since they are more robust and have better error performances. On the other hand, when the path loss is small, higher PHY modes are used to save energy since the duration of a single transmission attempt is shorter. Note that even with TPC, PHY mode 2 (BPSK modulation with rate-3/4 coding) is not part of the optimal selection due to its longer transmission time but only comparable error performance to PHY mode 3 (QPSK modulation with rate-1/2 coding) under most SNR conditions, which is consistent with a similar observation in [4], where the link adaptation idea was studied in order to maximize the system goodput. Second, a low transmit power level does not necessarily result in low energy consumption. This is because, for the same PHY mode, adopting a lower transmit power level may lead to less energy consumption in a single transmission attempt, but the consequent low SNR may cause more re-transmissions and greater total energy consumption.

The key idea is to select the best *mode-power pair*, rather than the PHY mode or the transmit power level itself, to minimize the energy consumption for each path loss value. Moreover, due to the discreteness of the available PHY modes (8) and transmit power levels (15), under a certain PA model, it is possible that the combination of a higher PHY mode with stronger transmit power results in lower energy consumption than the combination of a lower PHY mode with rather weaker transmit power. As shown in Fig. 8, when the path loss is about 80 dB, PHY mode 7 is selected with the transmit power of 8 dBm, while for the path loss of slightly higher than 80 dB, PHY mode 8 is used again, however, with a higher power level at 11 dBm. Similar switch-backs can also be observed at other path loss ranges in the figure. In comparison, when the transmit power level is fixed (see Figs. 10 and 11), the PHY mode

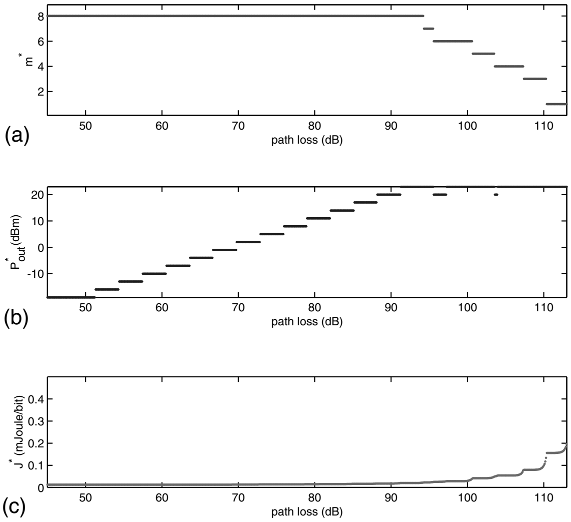

Fig. 9. 15 power levels with high-efficiency PA. (a) PHY mode selection, (b) transmit power level selection and (c) average energy consumption.

selection becomes a non-increasing function of the path loss.

Fig. 9 shows the energy-consumption performance with a high-efficiency PA ($\eta_{\max} = 0.5$). We can see that the two observations from Fig. 8 also hold, and additionally, the higher power levels are more likely to be selected due to the higher power conversion efficiency of the PA. Due to space limitations, we will present other evaluation results only for the low-efficiency PA, but the same trends are actually found to hold for the high-efficiency PA as well.

The energy-consumption performances with the transmit power level fixed at 15 dBm (the nominal value of Agere ORiNOCO card) and 23 dBm (the maximum allowed in the 5 GHz middle band) are plotted in Figs. 10 and 11, respectively. As expected, we observe from Figs. 10(c) and 11(c) that the schemes with fixed power levels consume more energy in general. Note that the larger the energy consumption ratio, the less energy-efficient. In Fig. 10, energy consumptions close to the optimum—corresponding to the energy consumption ratio one—can only be observed at the path loss range between 85 and 100 dB, where the transmit power level of 15 dBm is part of, or close to, the best selection (see Fig. 8(b)). When the path loss is smaller

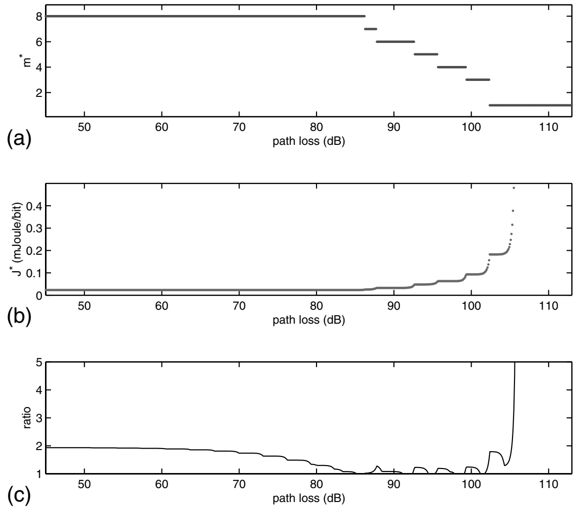

Fig. 10. Fixed power level at 15 dBm with low-efficiency PA. (a) PHY mode selection, (b) average energy consumption and (c) energy consumption ratio.

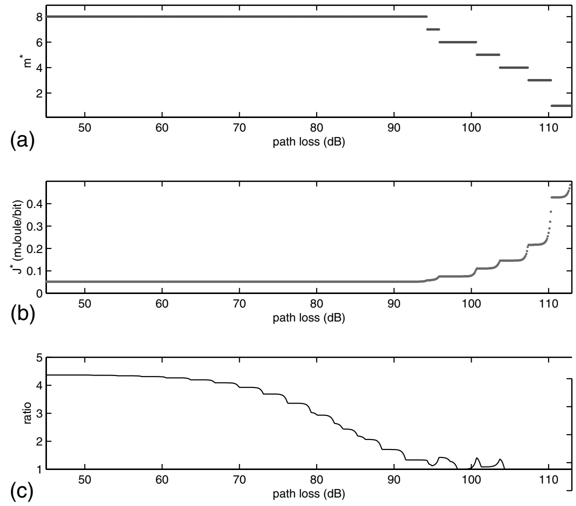

Fig. 11. Fixed power level at 23 dBm with low-efficiency PA. (a) PHY mode selection, (b) average energy consumption and (c) energy consumption ratio.

than 80 dB, the scheme consumes more energy because the frames are transmitted using a higher power level than necessary over a relatively short distance. When the path loss is larger than 105 dB, the energy consumption goes up drastically (to infinity), meaning that even with the most robust PHY mode, the transmit power level of 15 dBm is still not high enough to combat the high path loss, and thus transmission never succeeds. On the other hand, if the fixed power level is increased to the maximum, i.e., 23 dBm, such a scheme works fine under high path loss conditions, as shown in Fig. 11. However, significantly more energy is consumed at the low path loss range, as an undesirable side effect. Based on the above observations, we draw the following conclusion: by simply adjusting the PHY mode while fixing the transmit power level, we will inevitably suffer either limited operating (path loss) range or much higher energy consumption.

Finally, we increase the number of transmit power levels from 15 (with 3 dBm steps) to 85 (with 0.5 dBm steps) and show the energy-consumption performance in Fig. 12. Compared to Fig. 8, we observe smoother PHY mode transitions and power level transitions due to finer power levels. However, the results in Fig. 12(d) suggest that the energy gain may not be significant.

5.2. Energy-efficient data transmission with goodput constraint

Now, we consider the problem of selecting the best combinations of PHY mode and transmit power level to achieve energy-efficient uplink data transmissions with additional goodput constraints (e.g., streaming-like services). The objective is to meet the minimum goodput requirement while saving as much energy as possible. Obviously, different results are expected from those in Section 5.1.

Fig. 13 shows the results when 15 transmit power levels are used and the target goodput is set to 35 Mbps. We have three observations. First, when the path loss is smaller than 86 dB, the 35 Mbps goodput target can be achieved with minimum energy consumption. The rationale is that there is no conflict between the energy-saving requirement and the goodput requirement when the station is close to the PC. Second, when the path loss is between 86 and 95 dB, more energy than minimum is required to achieve the target goodput. We can see that PHY modes 7 and 8 are used at this path loss range, although they are not part of the optimal selections from a pure energy saving point of view (see Fig. 8(a)). This is because PHY modes 7 and 8 are the only two modes that may be able to achieve goodput equal to, or higher than, 35 Mbps. Consequently, higher power levels have to be selected at this path loss range, such that the

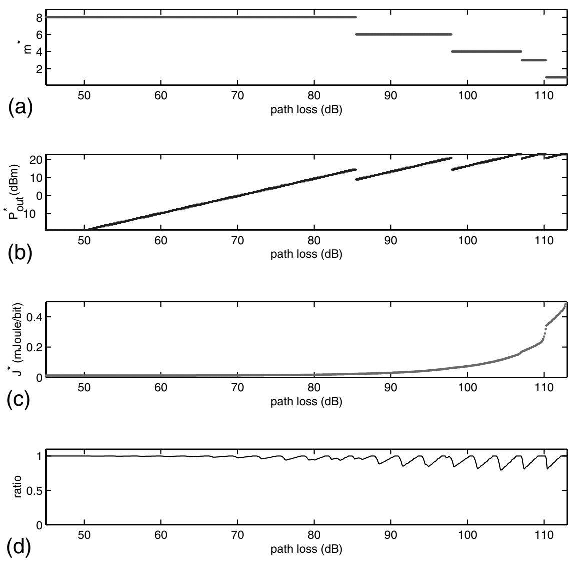

Fig. 12. 85 power levels with low-efficiency PA. (a) PHY mode selection, (b) transmit power level selection, (c) average energy consumption and (d) energy consumption ratio.

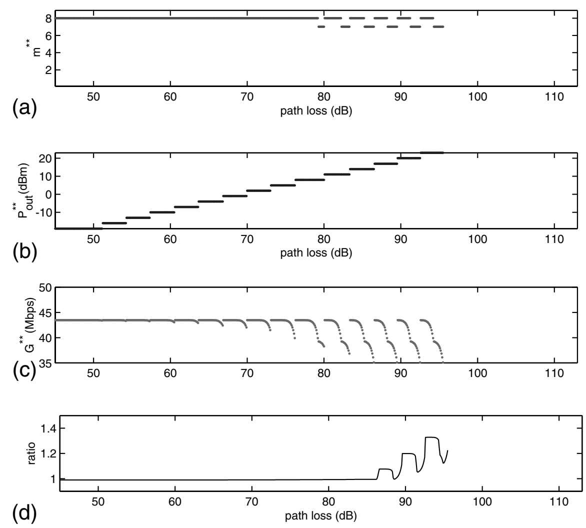

Fig. 13. 15 power levels with target goodput of 35 Mbps. (a) PHY mode selection, (b) transmit power level selection, (c) achieved goodput and (d) energy consumption ratio.

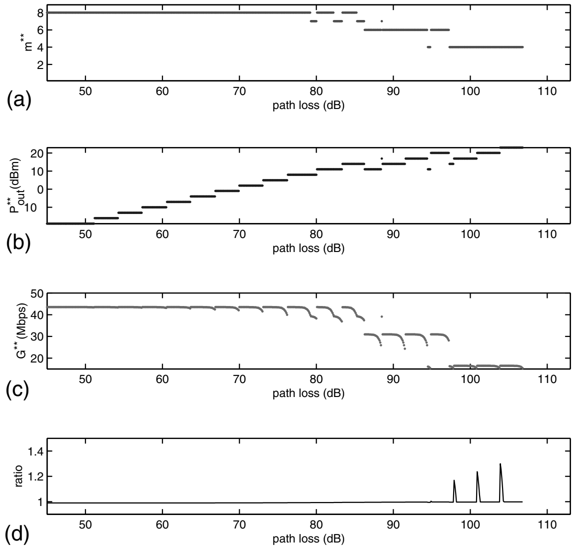

Fig. 14. 15 power levels with target goodput of 15 Mbps. (a) PHY mode selection, (b) transmit power level selection, (c) achieved goodput and (d) energy consumption ratio.

error performances of PHY modes 7 and 8 can be improved enough to achieve the target goodput. Third, when path loss is larger than 95 dB, the 35 Mbps goodput target cannot be achieved due to limitation of the maximum transmit power level. Similar trends are observed for the target goodput of 15 Mbps, as shown in Fig. 14.

An alternative way to determine the mode-power pair to meet the target goodput requirement and save energy is as follows. The maximum transmit power is first assumed in determining the proper PHY mode to meet the target goodput. Once the PHY mode is selected, the transmit power is then reduced as much as possible while still meeting the target goodput. One problem with such a scheme is that it only gives a *sub-optimal* pair of PHY mode and transmit power level, because it divides the two-dimensional optimization problem into two one-dimensional problems without proper de-coupling process.

6. Implementation issues

In order to realize the proposed energy-efficient PCF operation, a wireless station has to estimate the path loss between itself and the PC. We have developed a simple and novel scheme [23] as one of the possible solutions, and the main idea is to convey the transmit power level information in the SERVICE field of the PPDU.

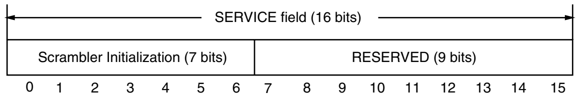

Fig. 15. Standard SERVICE field bit assignment.

As shown in Fig. 6, the DATA field of the IEEE 802.11a PPDU contains the 16-bit SERVICE field. The standard bit assignment of the SERVICE field is shown in Fig. 15. Bits 0–6 are set to zero and are used to initialize the de-scrambler at the receiver. The remaining nine bits (7–15) of the SERVICE field are reserved for future use. As defined in the IEEE 802.11 standard [2], TXPWR_LEVEL is one of the TXVECTOR parameters, which are passed from MAC to PHY, in order to initiate a MAC frame transmission. Other parameters in the TXVECTOR include the transmission rate (i.e., PHY mode) and the frame length. Currently, TXPWR_LEVEL is defined from 1 to 8, where the mapping between a TXPWR_LEVEL value and the actual power is implementation-dependent.

We propose to redefine TXPWR_LEVEL from 1 to 15, and standardize the mapping between a TXPWR_LEVEL value and the actual power level (in dBm) so that the receiver of a PPDU can identify the transmit power level (in dBm) of the received PPDU. The 15 transmit power levels are from −19 to 23 dBm with 3 dBm steps in the middle band of the 5 GHz U-NII band as used in Fig. 8. Fig. 16 illustrates our proposal to revise the SERVICE field bit assignment, which would use bits 7–10 to convey the TXPWR_LEVEL information. We also propose to add one parameter, which is TXPWR_LEVEL extracted from the SERVICE field in the PPDU being received, into

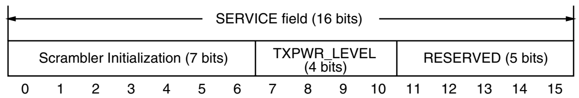

Fig. 16. Revised SERVICE field bit assignment.

the RXVECTOR. Note that an RXVECTOR is passed from PHY to MAC via the PHY-RXSTART.request(RXVECTOR) service primitive when the PHY starts conveying the received frame bit stream to the MAC.

With the above proposed changes, it becomes possible for a wireless station to estimate the path loss between itself and the PC easily. That is, with the knowledge of the received signal strength (in dBm) via the receive signal strength indicator (RSSI) as well as the transmit power level (in dBm) via TXPWR_LEVEL found in the received frame's (e.g., CF-Ack or CF-Poll) SERVICE field, a wireless station can calculate the path loss (in dB) by doing the simple subtraction. Note that RSSI is one of the RXVECTOR parameters, which is measured by the physical layer and indicates the energy observed at the antenna used to receive the current PPDU. Basically, the path loss calculated in this manner can be used by the wireless station to determine the best transmission strategy for its next uplink frame. For example, one can look up Fig. 8 to select the best combination of PHY mode and transmit power level for an FTP service, while referring to Fig. 13 for a data streaming service with the target goodput of 35 Mbps. This approach is reasonable since with 802.11 WLANs, the same frequency channel is used for all transmissions in a time-division duplex manner, and hence, the channel characteristics in terms of path loss for both directions between two stations are likely to be similar.

7. Conclusion

In this paper, we investigate and demonstrate the energy-efficient PCF operation of IEEE 802.11a WLANs via TPC and PHY rate adaptation. The key idea is that the best transmit power level as well as the proper PHY rate are adaptively selected by a wireless station to transmit an uplink data frame, according to the up-to-date path loss condition between itself and the PC, thus delivering data with minimum energy consumption. Evaluation results suggest that, by combining TPC with adaptive PHY mode selection, significant energy savings can be achieved compared to those schemes that only adapt the PHY mode but fix the transmit power level. We also present a novel, simple, and effective way for a wireless station to estimate the path loss and realize our approach.

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