research have improved energy efficiency in the IEEE 802.11 based WLANs by modifying the original power management scheme [4][5][6].

In our paper, we study how to optimally configure the parameters of the original power management in the IEEE 802.11 based infrastructure mode WLANs to achieve good energy efficiency without degrading system performance. We use the response time of a packet as one of the performance metrics. In an infrastructure network, when two stations communicate, the source station sends the packets to the AP first and the AP forwards the packets to the destination station. If the destination station is in the Doze state, the AP temporarily buffers the packets and forwards them later. The total response time of a packet consists of the time from the source to the AP, the delay in the AP and the time from the AP to the destination. Many research has analyzed the delay between a station and an AP [7][8]. In this paper, we focus on the delay that a packet spends in the AP buffer. We model the power management scheme of an infrastructure mode WLAN as a D/G/1 queue. We find the analytical results for the average response time of a packet and the percentage of time a station stays in the Doze state. Through analytical analysis and simulation, optimal parameters for energy efficiency are identified and discussed.

Our work is organized as following. Section II introduces the power management scheme specified in the IEEE 802.11 and defines the performance metrics in our study. An analytical $D/G/1$ model for the power management is proposed and discussed in section III. Section IV presents the simulation results and gives suggestions for power management configuration. The conclusion is drawn in section V.

2 POWER MANAGEMENT

In this section, we review the basic network structures and media access mechanism in WLANs first. Then, we introduce the power management specified in the IEEE 802.11 and analyze packet delay with power management. Finally, the performance metrics for evaluating the energy efficiency of WLANs are defined.

2.1 Review of the structures and the media access mechanism

The IEEE 802.11 standard [2] defines two types of network structures: the independent network and the infrastructure network. In an independent BSS (Basic Service Set), two stations communicate directly with each other. In an infrastructure BSS, two stations communicate through an AP. The source station sends the packets to the AP and the AP forwards the packets to the destination station.We focus on the infrastructure mode WLANs in this paper.

The basic media access method of the IEEE 802.11 standard is the distributed coordination function (DCF), which is known as the carrier-sense multiple access with collision avoidance (CSMA/CA). In order to avoid collisions, a station senses the medium status before its transmission. If the medium is idle, the station waits for some time and transmits. Otherwise, the station defers its transmission, waits for some time, then tries again. If a collision happens, the station undergoes a backoff procedure and retries. Our simulation applies the DCF.

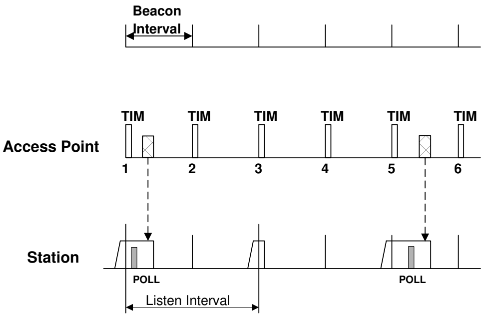


Fig. 1. Infrastructure BSS power management operation [2]

2.2 Power management in an infrastructure BSS

If the destination station is in the Doze state, the AP temporarily buffers the frames from the source station, then finds an appropriate time to forward them. The IEEE 802.11 standard uses beacons to schedule the transmission time for the buffered frames. Every beacon piggybacks a TIM (Traffic Indication Map) message that can identify the stations that have traffic buffered in the AP. A station stays in the Doze state when idle and listens for the beacons periodically. The time interval with which a station periodically wakes up to listen for beacons is called listen interval.

Fig.1 shows an example of the operation of the power management mechanism in an infrastructure BSS. The first TIM indicates that there is pending traffic in the AP destined for the station. The station stays awake and sends a poll message to retrieve the buffered traffic. After the station receives the traffic, it enters the Doze state. The station does not listen to the second TIM according to its power management scheme. From the third TIM, the station knows that there is no buffered traffic for it and enters the Doze state immediately.

2.3 Packet delay with power management

Many research have evaluated the performance of WLANs [9][10][11], especially saturation throughput and delay analysis. With power management, in addition to the delay between stations and an AP, a packet may experience extra delay in the AP buffer. we call the transmission from a station to an AP as upload and the transmission from an AP to a station as download. Fig.2 shows the transmission of upload and download. We denote the average packet delay of upload and download as D_{up} and D_{down} respectively. We refer Bianchi's result [9] to calculate D_{up} and D_{down}. Bianchi studied saturation throughput of IEEE 802.11. The average packet delay under saturation condition is easily obtained as $D = \frac{P}{S}$, where D denotes the average packet delay, P denotes the packet length, and S denotes the saturation throughput. The saturation throughput is (Because of page limitation, please refer [9] for the derivation),

$$S = \frac{P_s P_{tr} E[P]}{(1 - P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1 - P_s)T_c} \tag{1}$$

where P_s is the probability that a transmission occurring on the channel is successful, P_{tr} is the probability that there is at least one transmission in the considered slot time

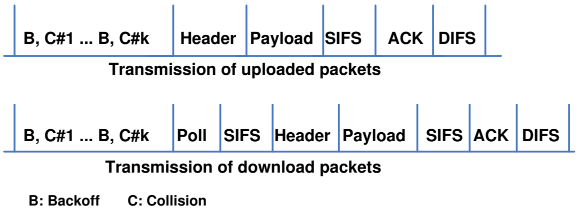


Fig. 2. Transmission of upload and download packets

and σ is the duration of an empty slot time. P_s, P_{tr} and σ remain the same as in the paper. We use constant packet length in our study, E[P]=P. T_s and T_c needs to be modified for our study. T_s is the average time the channel is sensed busy. T_c is the average time the channel is sensed busy by each station during a collision.

The number of packets that go up and down is the same, so the modified T_s is,

$$\begin{aligned} T_{s_{up}} &= H + P + SIFS + \sigma + ACK + DIFS + \sigma \\ T_{s_{down}} &= Poll + SIFS + \sigma + T_{s_{up}} \\ T_s &= (T_{s_{up}} + T_{s_{down}})/2 \end{aligned} \tag{2}$$

Where $H = Header = PHY_{header} + MAC_{header}$, $P = Payload$.

We only consider the collisions between two packets as an approximation. The collision can happen between two upload packets, two download packets and a upload and a download packets, each case has 1/3 probability. We obtain the modified T_c,

$$\begin{aligned} T_{c_{uu}} &= T_{c_{up}} = H + P + DIFS + \sigma \\ T_{c_{dd}} &= Poll + DIFS + \sigma \\ T_c &= (T_{c_{uu}} + T_{c_{ud}} + T_{c_{dd}})/3 \end{aligned} \tag{3}$$

Thus, we find the packet delay between stations and an AP under saturation condition.

$$\begin{aligned} D_{up} &= P/S \\ D_{down} &= P/S + Poll + SIFS + \sigma \end{aligned} \tag{4}$$

We will analyze the performance of power management based on the packet delay under saturation condition. This means we will obtain the worse-case performance. Our analytical model will focus on the delay in the AP.

2.4 Performance metrics for evaluating energy efficiency

We use two performance metrics to evaluate the energy efficiency in WLANs.

PTD (Percentage of Time a station stays in the Doze state): We use PTD to measure the energy efficiency of a power management scheme. The larger the PTD is, the more energy efficiency a power management scheme can achieve.

FRT (Response Time of a Frame): In the power management scheme, a station in the Doze state may not be able to respond to some traffic requests immediately, which brings in extra delay. We want to save energy without degrading the system performance. Therefore, we choose FRT as another performance metric for our study. In an infrastructure network, FRT is defined as the time interval between the instant that a source station tries to send a packet and the instant that the destination station receives it.

3 ANALYTICAL MODEL

In this section, we propose a D/G/1 model for the power management first. Then, based on the analytical results, we obtain the average FRT and PTD, which are controlled by the listen interval. Finally, we propose to select the largest listen interval under response time requirement to improve energy efficiency in an infrastructure WLAN.

3.1 Analytical model for the power management in an infrastructure BSS

In an infrastructure BSS, we view an AP as a server. The buffered packets form the queue of the server. We call a packet is served when it is downloaded by a station from the AP. In order to model the system, we make the following assumptions:

- There are m stations and all the stations have the same priority.
- The traffic is generated evenly from all the stations in the BSS. The total traffic arrives at the AP with a Poisson process with parameter λ and equally destined for all the stations in the BSS.
- The packet length is constant and the traffic is transmitted with a single rate.

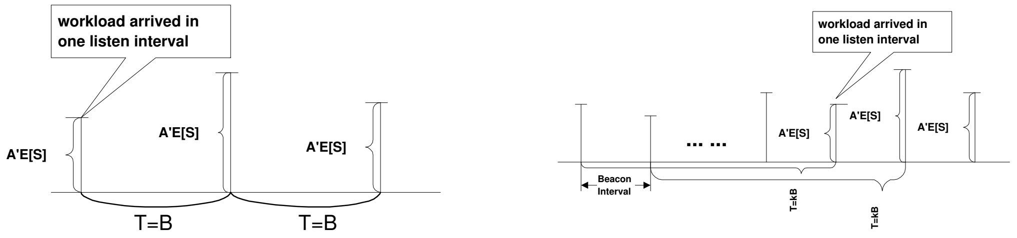
Here are some notations we are going to use for the model. We denote the beacon interval in the system by B; the listen interval of a station by T, where $T = kB,\ k = 1, 2, 3, \ldots$; the service time of a packet by S. If there is only download activity over the wireless channel, $E[S]$ is equal to D_{down}. Because the upload and download traffic are balanced, we approximately assume that when a packet is downloaded, the channel will upload a packet as well. Therefore, $E[S] = D_{up} + D_{down}$. The total time a packet stays in the modeled system, which is the summation of the waiting time in the queue and S, is equal to the FRT. We denote the maximum number of packets that can be transmitted by the AP during a listen interval by L. Given the physical capacity of the media, we obtain $L = \lfloor \frac{T}{E[S]} \rfloor$. In the following, we propose our analytical model according to the length of a listen interval.

Single-beacon model ($T = B$): We view all the traffic arrived within one listen interval as a batch. Our model is developed based on the behavior of the batches. We model the system as a $D/G/1$ queue.

The earliest time to serve a batch is at the beginning of the next listen interval. So the beginning of the next listen interval can be treated as the arrival instant of a batch. Therefore, batches arrive with the constant interval B. The service time of a batch is the summation of the service time of all the packets arrived within a listen interval. The "1" in the model stands for that only one batch is permitted to transmit each time.

Fig.3(a) illustrates the $D/G/1$ queue model. The batches arrive with the constant interval T. A batch consists of all the traffic arrived within one listen interval. We denote the number of packets arrived in one listen interval by A'. The service time of a batch is $A'E[S]$.

Multiple-beacon model ($T = kB$): We look at the system when a listen interval equals multiple beacon intervals, i.e., $T = kB$, where $k > 1$. We assume the listen intervals of the stations are configured such that at the beginning of each beacon interval, the number of stations that wake up is approximately the same. In other words, if the number of the



(a) D/G/1 Queue Model with single-beacon

(b) D/G/1 Queue Model with multiple-beacon

Fig. 3. D/G/1 Queue Model

stations in the system is m, the number of the stations that wake up at the beginning of each beacon interval is m/k.

We still model the system as a $D/G/1$ queue. A batch arrives at the beginning of each beacon interval. In the single-beacon model, the packets in a batch arrive in one beacon interval with the rate λ; while in the multiple-beacon model, the packets in a batch arrive in k beacon intervals with the rate $\frac{\lambda}{k}$. The number of packets arrived in a listen interval is Poisson distributed with parameter $\frac{\lambda}{k} * kB = \lambda B, \quad k = 1, 2, 3, \ldots$, which is independent of the length of the listen interval. Therefore, we obtain the same D/G/1 model. The single-beacon model is a special case of the multiple-beacon interval.

Fig.3(b) shows the multiple-beacon model. The batches arrive with the constant interval B. The packets arrive with the rate $\frac{\lambda}{k}$ in k beacon intervals forms one batch and are eligible for transmission at the beginning of the next listen interval (the $(k+1)th$ beacon interval).

3.2 Performance evaluation

We calculate the average FRT and derive the bounds of the average PTD.

FRT: We divide the total waiting time of a packet into three phases.

W_1: The time between the arrival of a packet in the original system and the arrival of the batch in the $D/G/1$ queue model.

W_2: The waiting time experienced by a batch in the $D/G/1$ queue. Since a packet is in a batch, it also experiences this part of waiting time.

W_3: The waiting time caused by other packets in the same batch.

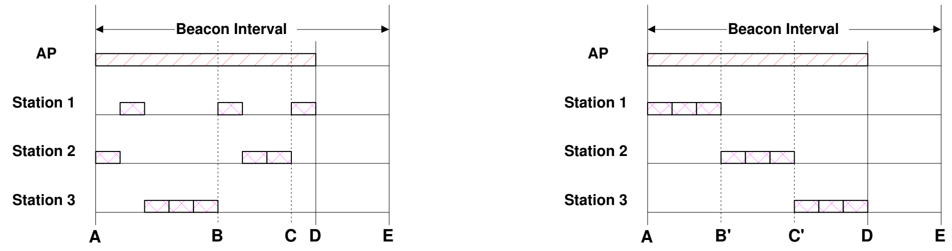
Calculation of the average waiting time W_1:

Since the packet arrival is Poisson process, the arrival instant of each packet is uniformly distributed in the listen interval $(0, kB)$. Thus, $E[W_1]$ is $\frac{kB}{2}$.

Calculation of the average waiting time W_2:

The average waiting time of a $D/G/1$ queue with no vacation was deduced by Servi in [12]. It is,

$$-\frac{N(N-1) - G''(1)}{2(N - G'(1))} + \sum_{r=1}^{N-1} \frac{1}{1 - z_r} \tag{5}$$



Note: The shadow area shows that the medium is busy.

Note: The shadow area shows that the medium is busy.

(a) Stations retrieve packets from the AP under DCF

(b) Stations retrieve packets from the AP station by station

Fig. 4. Packet transmission order from the AP to stations

where, N is the quantized length of the interarrival time of the customers to the queue; $G(z)$ is the z-transform of the service time; $z_1, z_2, \ \ldots, z_{N-1}$ are the unique roots of $z^N - G(z) = 0$ that are on or within the unit circle but not equal to 1.

Here, we quantize the beacon interval by the service time of a packet E[S]. Thus, the interarrival time of the batches is L. In the quantized time frame, the service time of a packet is $E[S]/E[S] = 1$. We calculate the z-transform of the batch service time.

$$G(z) = e^{-\lambda B(1-z)}, \ G'(1) = \lambda B, \ G''(1) = \lambda B)^2 \tag{6}$$

Therefore,

$$E[W_2] = \big(- \frac{L(L-1) - G''(1)}{2(L - G'(1))} + \sum_{r=1}^{L-1} \frac{1}{1 - z_r} \big) * E[S] \tag{7}$$

Calculation of the average waiting time W_3:

We've denoted the number of arrivals within a listen interval by A'.

$$E[W_3] = \sum_{i=1}^{\infty} \Big(\frac{(i-1)}{2} E[S] * \frac{iP(A'=i)}{\sum_{i=1}^{\infty} iP(A'=i)} \Big) = \frac{\lambda B}{2} E[S] \tag{8}$$

Therefore,

$$E[FRT] = E[W_1] + E[W_2] + E[W_3] + E[S] = \frac{kB}{2} + E[W_2] + E[W_3] + E[S] \quad where, \ k = 1, 2, 3, \ldots. \tag{9}$$

PTD: The average PTD depends on the transmission order of the buffered packets from the AP to stations, which is controlled by the DCF [2]. Fig.4(a) shows an example of the transmission sequence. Because the retrieving sequence can change from beacon interval to beacon interval, it is difficult to obtain a fixed value as the average PTD.

We develop a lower bound and an upper bound for the average PTD. In Fig.4(b), all stations are in the Doze state during the time interval DE, which is the idle time of the AP. We take the average idle time of the AP as the lower bound of the average PTD.

$$E[PTD]_{lower\ bound} = \frac{kB - \frac{\lambda}{k}kBE[S]}{kB} = 1 - \frac{\lambda E[S]}{k} \quad where\ k = 1, 2, 3, \ldots \tag{10}$$

The upper bound is developed by assuming the buffered traffic is transmitted exclusively station by station. It means that one station reserves the medium and continuously retrieve all its packets, then enters the Doze state. The other stations repeat the process. The upper bound of the average PTD is,

$$E[PTD]_{upper\ bound} = \frac{kB - \frac{\lambda}{k}kBE[S] + \frac{\frac{\lambda BE[S]}{m/k}\,\frac{\frac{m}{k}(\frac{m}{k}-1)}{2}}{m/k}}{kB} = 1 - \frac{\lambda E[S]}{2k} - \frac{\lambda E[S]}{2m} \tag{11}$$

Where, $k = 1, 2, \ldots$; m is the number of stations in the system.

3.3 Suggestion for the selection of the listen interval

Both E[FRT] and E[PTD] increases with the increase of the variable k. In other words, when the listen interval increases, the energy efficiency gets better, but the response time becomes worse. Therefore, we suggest to select the largest listen interval under the response time requirement.

In fact, it is quite intuitive that the largest listen interval with the satisfaction of the response time should be selected. However, no analytical model supports this intuitive result. We propose to use the $D/G/1$ queue to model the power management in the IEEE 802.11 and claim the result based on our analysis. Furthermore, given an infrastructure BSS, we can calculate the average FRT and the bounds of the average PTD analytically.

4 SIMULATION

This section studies the energy efficiency in WLANs by simulation.

4.1 Simulation environment and configuration

The simulation is carried out in the Arena platform [13]. We simulate a single BSS with an AP and 10 stations. We assume that the traffic is evenly distributed among them. The arrival to an AP is modeled as a Poisson process and the packet length of 3000 bits is used in the simulation. The system load 50% is simulated.

The system parameters used in the simulation are configured based on the IEEE 802.11 recommendation [2]. For the backoff procedure parameters, the Backoff Slot Time is $50\mu s$ and the contention window is between 32 and 256. For the basic access parameters, the SIFS (short interframe space) is $28\mu s$ and the DIFS (distributed coordination function interframe space) is $128\mu s$. The max propagation time is $1\mu s$. The length of the PHY (physical layer) header is set to 128 bits. The length of a beacon interval is set to 100 milliseconds.

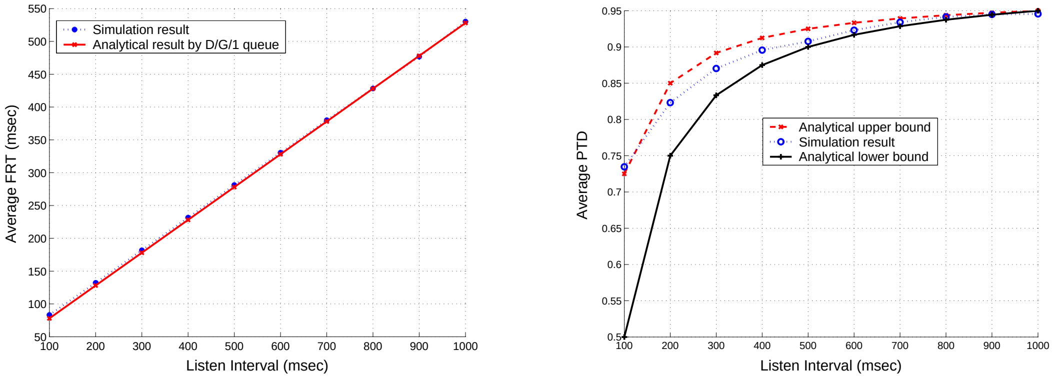
4.2 Simulation results and suggestions

The power management of the IEEE 802.11 puts a station into the Doze state when it is idle to save energy. The duration of the time that a station stays in the Doze state is scheduled by the power management parameters. The power management parameter for an infrastructure network is a listen interval. We want to optimally configure the listen interval to achieve good performance metrics, which means to maximize the average PTD of stations with the satisfaction of the average FRT requirement.

Here, we present the results of the power management in an infrastructure BSS when stations retrieve messages from the AP. The listen interval that equals 1∼10 beacon intervals are selected as the control variable.

Fig.5(a) shows the influence of the listen interval over the average FRT. The average FRT increase linearly with the increase of the listen interval. We observe the good match between the simulation result and the analytical result.

Fig.5(b) shows the impact of the listen interval over the average PTD. The dotted curve is our simulation result, which locates between the analytical lower bound and the analytical upper bound. Also, the trend of simulation result is similar with that of the analytical bounds. They all increase with the increase of the listen interval, which indicates that the larger listen interval leads to good energy efficiency.



(a) FRT increases with listen intervals

(b) PTD increases with listen intervals

Fig. 5. Simulation results

Therefore, a larger listen interval gives better energy efficiency, but poorer response time. The simulation results also suggest selecting the largest listen interval under the requirement of the response time. The simulation results support our analytical results.

5 CONCLUSION

This study aims to find optimal parameters for the power management scheme in the IEEE 802.11 based infrastructure WLANs. We use response time as one of the performance metrics. With power management, there is extra delay in the AP. We emphasis on this and model the power management scheme by a $D/G/1$ queue. From the analytical results, we propose to select the largest listen interval when the response time requirement is satisfied in order to achieve good energy efficiency. Our simulation results support the analytical model.

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