An Energy-efficient MAC Protocol with Delay-bounded Downlink Traffic Scheduling Strategy for 802.11 Wireless LANs

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Abstract—**In the protocol, the access point (AP) schedules the downlink traffic with precise schedule information, which is appended in the redesigned traffic indication map (TIM). To reduce the overhead of control frames, only the schedule information of STAs that wake up at current Beacon interval (BI) is embedded in TIM. The mobile stations (STAs) learn their service time from TIM and choose an energy efficient way to retrieve the downlink data. The protocol is designed to meet different delay requirements of different applications, not just focused on minimizing the average delay of the network. And the Early Deadline First (EDF) strategy is applied on AP to guarantee the delay bound of data frames. We also find the maximal traffic load which the network can bear to guarantee that all the data flow can be scheduled within one schedule cycle. Through theoretical analysis and simulations, we demonstrate that our protocol presents a better performance than IEEE 802.11 and other protocols not only in energy efficiency but also in delay performance of data packets.**

Index Terms—**Energy-efficient, and MAC, 802.11, EDF**

I. INTRODUCTION

IEEE 802.11 wireless local area networks (WLANs) have been widely deployed in recent years. Meanwhile, many portable and mobile devices can enjoy the flexible and cost-effective solutions provided by the wireless network [1]. To support mobility, the devices are powered by batteries. Unfortunately, the limited mobile device battery lifetime is a major constraint for many wireless applications. Therefore, minimizing the energy consumption of a WLAN interface is an important design issue for mobile devices. On the other hand, different applications have diverse QoS (Quality of Service) requirements, which may vary based on the importance and urgency of the data generated by the applications and also sensitivity of the data to network delay. So how to meet different demands of QoS is another challenge for network designers.

To improve the energy efficiency, a power saving mode (PSM) is defined in the 802.11. A mobile station (STA) in PSM can power down the transceiver to save energy [2]. While in the sleep state, the radio is turned off and the STA cannot detect the radio signal, hence, unable to either receive or transmit data [3]. So the access point (AP) cannot communicate with the STAs in PSM all the time. The AP buffers data and announces its buffering status through the traffic indication map (TIM) contained in the beacon frames. The STAs wake up periodically to listen to the beacon frames. The time interval in which a station periodically wakes up to listen for beacons is called listen interval (LI). A listen interval equals to one or several beacon intervals. In the standard, when STAs wake up and TIM indicates that there are frames buffered in the AP, the STAs will send a power-saving poll (PS-poll) message to the AP to retrieve the buffered frames. When more than one STA have data buffered in AP, the simultaneously transmissions will result the problem of collisions [4], [5]. STAs that do not retain control of the medium access will stay awake to wait for their chance of transmission. So the idle listening time of STAs will be prolonged, which will waste more energy and increase the delay of data frames [6], [7].

A number of researchers have investigated the MAC issue [8], [9], proposing various solutions to minimize the energy consumption and delay of data frames. Stine and De Veciana [10] proposed a solution that extended the TIM frame and embedded the scheduling information into the beacon frames. In this case, STAs could listen to the beacon and receive frames in the pre-scheduled time. To minimize the total waiting time, Stine suggested AP should schedule with short-job-first (SJF) strategy. Further, Chao [11] improved the SJF scheduler by giving the highest access priority to the STA that occupied the minimal duration of the WLAN channel. Wu and Chen [12] combined the first-in-first-out (FIFO) with SJF to solve the starving problem. The difference of energy consumptions between FIFO and SJF was also evaluated in this paper. However, the modification of TIM element made those protocols hard to keep the backward compatibility with legacy devices. He and Yuan [20]

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proposed a backward compatibility scheme, that they scheduled packets transmission for PSM STAs using TDMA-like scheme that STAs were informed to retrieve buffered frames at precise timing slots. Their scheduling algorithm eliminated contentions and achieved near optimal power saving for the STAs. But this protocol did not give the detailed scheduled process about how to avoid the interference. Tsao [21] studied how the length of the beacon interval (BI) impacts the energy and the delay performance of wireless stations, and aimed to find the optimal length of BI. We also summarized the most popular energy-efficient MAC protocol in table 1[22].

TABLE I. COMPARATIVE STUDY OF ENERGY EFFICIENT MAC PROTOCOLS

Protocol	Schedule Scheme	Advantages& Disadvantages
SMAC [13]	Fixed duty cycle, Virtual Cluster, CSMA	Low energy consumption when traffic is low. Sleep latency, problem with broadcast
TMAC [14]	Adaptive duty cycle, overhearing, FRTS	Adaptive active time. Early sleeping problem.
BMAC [15]	LPL, Channel assessment software interface	Low overhead when network is idle, consumes less power. Overhearing, bad performance at heavy traffic.
WISE MAC [16]	Minimized preamble sampling	Energy consumption both at sender and receiver. Low power for low traffic, do not incur overhead due to synchronization.
TRAMA [17]	TDMA	Higher energy efficiency and throughput. Time is divided in to random access period.
DMAC [18]	Converge cast communication	Energy saving and low latency. Aggregate rate is larger
CMAC [19]	Aggressive ack. any cast, convergent packet forwarding	High throughput, low latency and consumes less energy

However, there are several flaws about the studies mentioned above. Firstly, they assumed that all downlink packets could be serviced within one BI. The assumption of single BI service time may be impracticable in real environment. Secondly, they introduced schedule strategies to minimize the average delay of all data frames. While in some scenarios different flows may have different delay constraints, and the minimized average delay cannot meet the requirement. Thirdly, they appended all the schedule information to the TIM including those in their PSM which introduced more control packet overhead. This paper aims to illustrate and emphasize on the design and implement of an energy-efficient MAC protocol that overcomes the above design issues. The proposed MAC protocol that schedules the buffered data frames with the Early Deadline First (EDF) strategy is applied on AP when schedules the buffered data frames to guarantee the delay of different flows. Each STA chooses an energy- efficient way to receive its downlink data according to the schedule information embodied in TIM element. The TIM element is also carefully redesigned to convey schedule information. To reduce the overhead of control frames, only the schedule information of STAs that wake up at current BI is embodied in TIM.

The rest of this paper is organized as follows. The proposed MAC protocol is illustrated in Sect.2. Sect.3 analyzes the performance of the proposed MAC protocol. Simulation results are shown in Sect.4 and conclusion is drawn in Sect.5.

II. PROPOSED PROTOCOL

A MAC protocol with proper design can minimize the transmission delay and enhance energy efficiency of STAs [23]. It also avoids the collisions caused by simultaneous transmission of STAs. So a good solution should wake up the STAs at proper time when communication, and power down the STAs to save energy when no data is to be received or transmitted [24]. In this section, we propose a PSM schedule scheme with EDF schedule strategy. It is based on the TDMA-like mechanism. The AP divides the BI into a fixed number of equal slots. Each STA that has data buffered in AP is assigned specific time slots by employing EDF schedule algorithm. The schedule time assigned to STAs is denoted as service time. The schedule information is attached with TIM in beacon frames. In our protocol, the schedule period is not limited in single BI, and the AP scheduler will seek vacant from the following BI when the current BI is full. STAs will get the schedule information from the redesigned TIM, and will decide whether to stay awake to wait for its turn or to switch to doze mode and wake up at proper time.

To ease the explanation, Fig. 1 illustrated the comparison of the Wise MAC [16] and our protocol. It shows that in our protocol, the receiver can choose the more energy-efficient way to receive the data. And the AP schedules the data using the EDF strategy to ensure that the time deadline can be guaranteed for each frame.

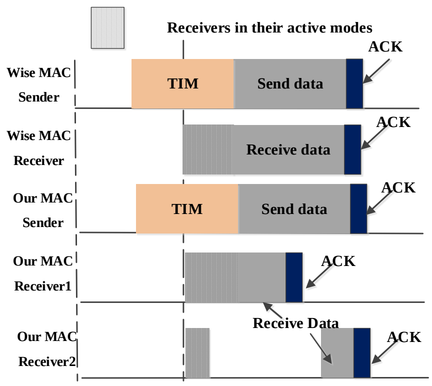

Figure 1. Comparison of Wise MAC, X-MAC, and our protocol

The explanation of our protocol is divided into three subsections: subsection 2.1 is the data structures used in our protocol, the AP operation of the protocol is described in subsection 2.2, and subsection 2.3 demonstrates the STA operation of the protocol.

A. Data Structure

In original standards, the part of partial virtual bitmap (PVB) within TIM element records whether the STAs have data frames buffered in the AP. If there are data frames buffered in AP, the bit associate with the AID (association identifier) of STA will be 1. Otherwise, the bit is 0. In order to achieve the mechanism proposed by this paper that AP has to inform the service time to STAs, the structure of TIM element is redesigned. Fig. 1 illustrates the modified TIM structure. The schedule information field which indicates the service time of STAs is appended to the end of the PVB. The schedule information field is constructed by schedule control field and schedule map field.

The schedule control field determines the number of slots in one BI and indicates the number of STAs scheduled in current BI. The value of slot count can be changed dynamically due to different network environments and different traffic conditions. A larger slot count means more precise control of time which will cost more energy to build a longer schedule information.

The schedule map field consists of a series of schedule information. The schedule information includes AID, BI offset and slot index. The value of BI offset is an integer that represents in which BI the STA can be scheduled. If the STA can be scheduled in current beacon the value of BI offset is to set 0. Otherwise, the offset value is to set as the number of BIs from data scheduled BI to current BI. The value of slot index represents the position of the first time slot of service time for STAs in scheduled BI. It is used for STAs to calculate the starting time of its service time.

B. AP Operation

In this section we describe the AP operation when the proposed protocol executes. To avoid contention with STAs, the AP will gain control of the medium after the wireless channel has been sensed idle for a DIFS time. Assume that the number of PSM STAs within the coverage area of the AP, N, is fixed. The data buffered in AP can be cataloged into N flows, and each flow is destined to one STA. The protocol requires AP to estimate the length of transition time for each flow, and determine the order of each service time (st). The AP then prepares and sends the TIM in the first time slot of the BI. Assume that AP knows the listen intervals of all STAs. This can be done by attaching the information in association and re-association frames at the time of entering a new AP. The sequence of wake-up STAs is recorded in awake-list. The AP informs STAs their service time through redesigned TIM element, and this approach minimizes the idle listening time of STAs. So the AP can choose a proper schedule strategy to meet different delay requirement instead of just focusing on the minimization of energy consumption. To achieve this purpose, we introduce EDF strategy when scheduling data frames. The EDF is a dynamic priority strategy which assigns higher priority to data that has earlier deadline. It performs well when applied to wireless networks [25].

Fig. 2 is the algorithm which presents how the data frames are scheduled at AP. The schedule information is recorded in schedule-list. When new data frame arrives at AP, the length of service time of the data frame will be

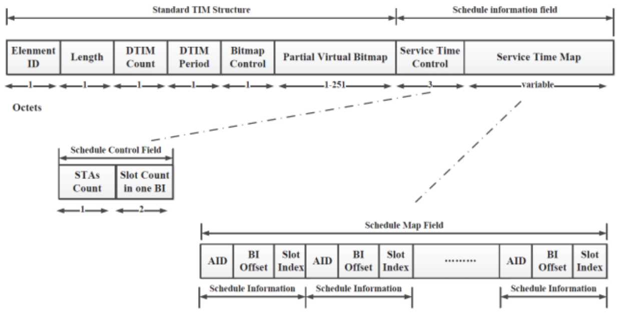

Figure 2. Modified TIM data structure

Algorithm 1

$Schedule\_List\{BI_{index}, data, BI_{offset}, Slot_{index}\}$:the array recording the transmission information of data

$awake\_list\{BI_{index}, AID\}$: the array recorded the BI index of each wake-up STA

$Data\_Buffer\{AID, data, D_{max}\}$: all of new data destined to PSM STAs buffered in AP

$data\_item\{AID, data, D_{max}\}$:an item implemented in this algorithm

T_{item} :the time for transmitting data frame

$T_{overhead}$:the overhead time of transmit a frame, include the time of transmit PS-Poll frame, ACK and SIFS

$T^{index}_{remained-interval}$:remained interval in BI_index

D_{item} :the tolerant delay of data frame

st_j :the length of service time for flow i

ST_{prio} : the total service time needed by frames that has higher priority than current data

T_{st} : the service time needed by frame

while($Data\_buff \,!= NULL$)

$data\_item \leftarrow dequeue(Data\_buffer)$

$T_{st} \leftarrow T_{item} + T_{overhead}$

$BI_{index} \leftarrow seekBI(AID, awake\_list)$

$D_{item} \leftarrow data\_item.D$

$ST_{prio} \leftarrow \sum_{D_j < D_{item}} st_j$

$T_{remaind-interval} \leftarrow T_{BI} - ST_{prio}$

If($T_{st} < T_{remaind-interval}$)

$BI_{offset} \leftarrow 0$

$Slot_{index} \leftarrow getslotindex(item, BI_{index})$

Else

$BI_{vacant} \leftarrow seek\_Vacant\_BI(T_{st}, schedule\_list)$

$BI_{offset} \leftarrow BI_{vacant} - BI_{index}$

$Slot_{index} \leftarrow getslotindex(item, BI_{vacant})$

End if

$enquene(schedule\_list, BI_{index}, data, BI_{offset}, Slot_{index})$

End while

Figure 3. Algorithm applied on AP

calculated. The AP checks the awake-list to get the awake information of the STA that the data frame aimed to. Assume the STA that data frame aimed to wakes up at the j^{th} BI. Then the AP checks the delay deadline, Di, of the incoming data frame and calculates the schedule information for the incoming frame using EDF strategy.

AP calculates the total service time of frames that have earlier deadlines than D_i. If the remained time slots of j^{th} BI is larger than the service time of new arrival frame, the AP will allocate time slots for data frame within the j^{th} BI. Otherwise, there are no enough time slots to accommodate the new arrival data. The AP will seek vacant time slots in the following BI and arrange the schedule order within the BI that has enough spare time slot. The difference between the j^{th} BI and BI that has spare time slots will be recorded as BI offset. In order to guarantee each STA can get the correct schedule information, only those data that has not be broadcasted in TIM will be redistributed service time when EDF strategy is applied. The schedule-list updates when new schedule information is added. At the beginning of each BI, AP will generate TIM according to the schedule-list, only the schedule information of STAs that wake up at current BI will be appended to TIM.

To ease the explanation, we show an example of the AP schedule process in Fig. 3. Assume that there are four STAs and one AP. There are data frames Data1 Data2 Data3 and Data4 buffered in AP. Three of the four STAs wake up at the first BI and ST A1 wakes up at the second BI. AP will schedule data using the EDF discipline with the consideration of the awake-list. Assume that the BI is divided into 16 slots. Though the ST A2 wakes up at the first BI, the service time for Data2 is assigned at the second BI because there are not enough spare slots for Data2 at the first BI. The BI offset of Data2 is set 1 in schedule map field to inform ST A2 that it should receive data frame in the next BI. Since ST A1 wakes up at the second BI, the schedule information of Data1 is not append in the current TIM to reduce the control overhead.

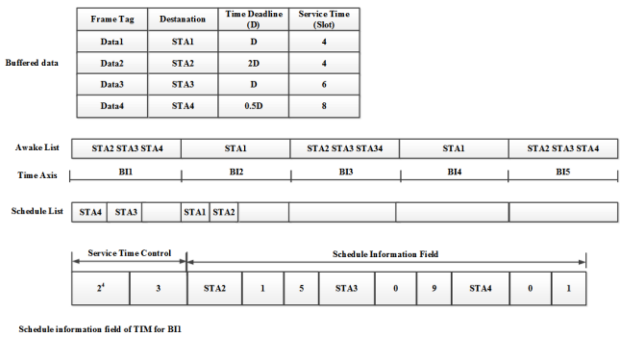

Figure 4. An example of AP schedule method

C. STA Operation

We assume that the PSM STAs wake up at the beginning of BI to listen to the TIM. Fig. 4 is the algorithm applied in STAs. Each time a beacon is received, STA checks the TIM frame to see whether it has downlink data to receive. If the bit corresponding to its AID is 0, STA will switch to doze mode immediately and wake up at the beginning of next listen interval. If the bit corresponding to its AID is 1, it then goes further into the schedule map field to find its schedule sequence. STAs will decide whether to stay awake to wait for the incoming downlink data or to switch to doze mode and wake up at proper time.

Algorithm 2

$TIM[]$:the array recording the transmission order
AID : the number of the AP
$slot_{count}$:the number of slots within one BI
BI_{offset} : difference between current BI and BI when to receive data
$Slot_{index}$:the first time slot to receive data in BI
p_{idle} :the power consumption in idle mode in one slot
p_{trans} :the energy consumption when a STA changes its state

```
p ← 0
If( TIM[AID] != 0 )
    slot_count ← TIM[].slot_count
    BI_offset ← TIM[AID].BI_offset
    slot_index ← TIM[AID].slot_index
    p ← p_idle × (BI_offset × slot_count + slot_index)
    If( p < 2 × p_trans )
        stay awake to receive data
    Else
        switch to doze mode and wake up at
            slot_index th slot of BI_offset th BI
    End if
End if
```

Figure 5. Algorithm applied on STAs

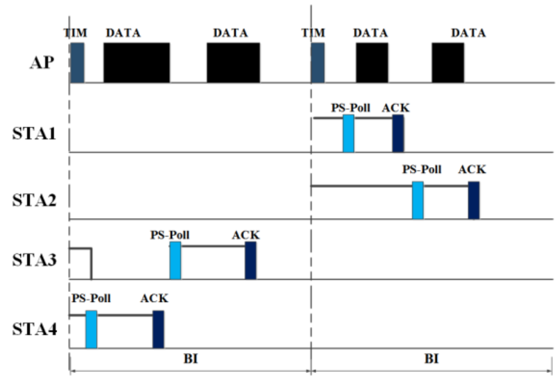

Figure 6. STAs retrieve buffered data

Without loss of generality, we assume that the power consumption in idle mode, p_{idle}, is equal to the power consumption in receive mode, p_{RX}, and it takes one unit of energy consumption one time slot. The energy consumption when a STA changes its state is defined as p_{trans}. We neglect the power consumption in doze mode.

When $p_{idle} \cdot (n_{slot} + BI_{offset} \cdot slotcount) \geq p_{trans} \cdot 2$ STA will change to doze mode and wake up at the n_{slot} th slot of BI_{offset} BI to receive its data. Otherwise, STA will stay awake till it completes the data reception. Fig. 5 is the retrieval process of buffered frames for the example mentioned in section 2.2. At the beginning of each listen interval, STAs wake up to receive the TIM, and get the schedule information of the downlink traffic. Then STAs choose an energy-efficient way to retrieve data. In this scenario, STA3 stays awake till the completion of the data retrieval process, while STA2 changes to doze mode and wakes up at the scheduled time slot.

III. Performance Analysis

In this section, we analyze the proposed protocol in three aspects: backward compatibility, energy-efficiency and delay performance of frames.

A. Backward Compatibility

The challenge is whether or not the new schedule scheme can cooperate with legacy STAs. When a legacy STA receives a modified TIM, it can parse the PVB field up to its own AID and ignore the other fields. It also ignores the newly added fields which indicate the schedule information. So the modified TIM can be correctly parsed by legacy STAs.

The original standard is contention-based, STAs that have data buffered in AP contend for medium access. If the medium is busy, an STA sets its network allocation vector (NAV) with the value carried in the duration field of the overheard frame [26]. When the protocol executes, the AP will restrain the medium access. Legacy STAs can update their NAV when new protocol executes. So the legacy STAs will not disturb the scheduled order and will gain the medium access through contention window. So the new designed protocol is backward compatible.

B. Analysis of Energy Efficiency

In [28], the major sources of energy waste of shared medium wireless networks were listed as follows: collision, overhearing, control packet overhead, and idle listening.

As for TDMA-like schedule, transmission collisions can be eliminated. Overhearing means that a STA receives and decodes packets that are not destined to it. The way to mitigate overhearing problem is to reduce the number of simultaneously awake STAs. The following theorem shows that the number of simultaneously awake STAs in our protocol is upper bounded.

Theorem 1: The number of simultaneously awake STAs during the retrieval process of buffered frames is upper bounded by $\left\lceil \frac{C}{2\times p_{trans}} \right\rceil$, where $C=(\frac{SIZE_{PS}+SIZE_{ACK}}{datarate}+SIFS\times 2)\times p_{idle}$, $SIZE_{PS}$ is the data size of PS-Poll frame. $SIZE_{ACK}$ is the data size of ACK frames. datarate is the data process speed of STA.

Proof: The time for a STA to receive its data can be expressed as

$$t_{RX}=\frac{SIZE_{PS-poll}+SIZE_{ACK}}{datarate}+SIFS\cdot 2+st \quad (1)$$

Since $\frac{SIZE_{PS-poll}+SIZE_{ACK}}{datarate}+SIFS\times 2$ is constant for a specific network, we define it as C. So

$$t_{RX}=C+st \quad (2)$$

The t_{RX} is proportional to st. So the minimal time a STA receiving downlink data is C when the size of downlink data goes to zero. Recall the STA operation described in section 2.3. Only when the energy consumption of idle listening is less than that of mode switch the STA will stay awake to receive the downlink data. Define the maximal number of receiving time a STA can wait as N_{max}. Then the constraint holds:

$$C\times p_{idle}\times N_{max}\le p_{trans}\times 2 \quad (3)$$

Then:

$$N_{max}\le \left\lceil \frac{C}{2\times p_{trans}} \right\rceil \quad (4)$$

N_{max} is also the maximal number of STAs that stay awake simultaneously. Idle listening is another important source that affects the energy efficiency. In our protocol, the energy consumption of idle listening before a STA receiving down- link data cannot exceed $2\cdot p_{trans}$. This is more efficient than those schemes in which STAs keep sensing the state of channel to gain the medium access. Also, no more control packets are introduced in our protocol. The protocol reduces the energy consumption of collisions, overhearing and idle listening at the expense of longer TIM. Considering the energy consumption model shown in Table 1 adopted in [13], it is beneficial to trade a little extra energy for the introduction of schedule information.

C. Analysis of Downlink Delay

As illustrated in section 2, the proposed protocol minimizes the idle listening time of the whole network and introduces EDF strategy to schedule flows. In this section, we try to find the constraints to guarantee the tolerant delay of each flow. Recall the description of flow in section 2.2. Conveniently, we use an array (l_i, P_i, D_i) to describe frames of flow i (0<i<= N). Suppose the frame length of flow i, l_i, is constant. Pi is the period of flow i, that when flow i is acyclic it denotes the minimal interval between successive frames. D_i is the tolerant delay of the frame. Assume all flows share the same frame loss ratio ρ and link speed of AP v. Then the estimated transmission time for one frame of flow i is given by:

$$st_i=(\frac{l_i}{v}+SIFS+\frac{ACK}{v})\cdot\frac{1}{1-\rho} \quad (5)$$

In our protocol, the schedule information is not limited in one BI, so we introduce the concept of schedule cycle (SC) which is several consecutive BIs. Assume that one SC contains k BI. Suppose all the data can be scheduled within one SC, then every STA will, at least, wakes up once per SC. LI_i denotes listen interval length of STA i. Assume that the longest listen interval of all STAs is LI_{max}, then $P_{SC}\ge LI_{max}$ should be satisfied. The data length of flow i accumulate in one SC can be educed as $L_i=l_i\cdot\left\lceil \frac{P_{sc}}{p_i} \right\rceil$ The time allocated to flow i in one SC should be:

$$ST_i=\left\lceil \frac{P_{sc}}{P_i} \right\rceil\bullet st_i \quad (6)$$

If all the data can be scheduled within one SC, then the constraint holds:

$$\sum_{i=1}^{N} ST_i \le P_{SC} \tag{7}$$

To simply the illustration, we define U_i as the channel utilization of flow i, where $U_i = \frac{st_i}{P_i}$. Then the total channel utilization of all flows is:

$$U = \sum_{i=1}^{N} U_i \tag{8}$$

U describes the traffic load of the network. A large value of U means heavy traffic load of the network. The following theorem shows that there exists a limit value of U to guarantee that all the data flow can be scheduled within one SC.

Theorem 2: If the total channel utilization of all flows satisfies the following condition, all flows can be scheduled within one SC.

$$U \le \frac{\lceil P_{sc} / p_{max} \rceil - 1}{\lceil P_{sc} / p_{max} \rceil} \cdot (1 - \frac{\varphi}{P_{SC}}) \tag{9}$$

Proof: $f(x) = \frac{x-1}{x}$, $f'(x) = \frac{1}{x^2} > 0$, so f(x) is an increasing function. $P_{sc} / p_{max} \le P_{sc} / p_i$, so

$$\begin{aligned} U &\le \frac{\lceil P_{sc} / p_{max} \rceil - 1}{\lceil P_{sc} / p_{max} \rceil} \cdot (1 - \frac{\varphi}{P_{SC}}) \\ &\le \frac{\lceil P_{sc} / p_i \rceil - 1}{\lceil P_{sc} / p_i \rceil} \cdot (1 - \frac{\varphi}{P_{SC}}) \\ &\le \frac{\lceil P_{sc} / p_i \rceil}{\lceil P_{sc} / p_i \rceil} \cdot (1 - \frac{\varphi}{P_{SC}}) \end{aligned} \tag{10}$$

If there exists a p_u, which minimizes the $\frac{P_{sc} / p_i}{\lceil P_{sc} / p_i \rceil}$, combined equations (8) and (10),

$$\sum_{i=1}^{N} U_i \cdot \frac{\lceil P_{sc} / p_u \rceil}{P_{sc} / p_u} \le 1 - \frac{\varphi}{P_{SC}} \tag{11}$$

Then

$$\sum_{i=1}^{N} U_i \cdot \frac{\lceil P_{sc} / p \rceil_i}{P_{sc} / p_i} \le \sum_{i=1}^{N} U_i \cdot \frac{\lceil P_{sc} / p_u \rceil}{P_{sc} / p_u} \le 1 - \frac{\varphi}{P_{SC}} \tag{12}$$

Combined equations (6) and (12),

$$\sum_{i=1}^{N} ST_i \cdot \frac{p_i \cdot U_i}{st_i} \le P_{SC} - \varphi \tag{13}$$

$p_i \cdot U_i = st_i$, then

$$\sum_{i=1}^{N} ST_i \le P_{SC} - \varphi \tag{14}$$

So all the flows can be scheduled in one SC.

IV. PERFORMANCE EVALUATION

In this section, we develop a simulation model to investigate the performance of the proposed power conservation scheme. The simulation modeled a network consisting of an AP and 50 STAs. The radio range is set large enough to guarantee the connectivity between any two stations. The length of frames is randomly assigned from 128 to 1000 bytes with uniform distribution. The energy consumption model shown in Table 2 adopts the specifications suggested in [20] and [13]. Each result is

TABLE II. ENERGY CONSUMPTION MODEL

Parameters	Value
Idle mode	1150mW
Transmit mode	1650mW
Receive mode	1400mW
Sleep mode	45mW
Mode transition	50mJ

TABLE III. THE SIMULATION PARAMETERS

Parameters	Value
The number of AP	1
The number of STAs	50
Beacon interval	100ms
SIFS	10 μ s
PS-poll size	160bit
ACK size	112bit
slot time	20 μ s
Transmission rate	11 Mbps

The average of 10 times simulation and each simulation runs 5s. And some other parameters used in simulation is shown in Table 3.

A. Protocol Performance against Length of LI

First, we investigate the impacts of the length of listen interval on the power performance and delay performance of the proposed protocol. The Beacon interval is 100ms. The period of flows in the network is randomly assigned from 100ms to 500ms with uniform distribution. The tolerant delay of each flow equals to its period. In each scenario we compare the overtime ratio, which is the ratio of frames that missed their time deadline, to evaluate the ability of delay guarantee.

The maximal period of flows is quintuple of BI. So we compare the simulation results of five situations, 1) LI_i = BI, 2) LIi ∈ [BI, 2BI, 3BI], 3) LI_i ∈ [BI, 2BI, 3BI] with the constraint that LI_i ⩽ Di, 4) LI_i ∈ [BI, 2BI...6BI], 5)LI_i ∈ [BI, 2BI...6BI] with the constraint that LI_i ⩽ D_i.

Fig. 7 shows the energy efficiency (bytes per joule) versus the length of the LI mentioned above. As we can see from figure 7, there is a significant gap in the aspect of energy efficiency between uniform LI and distributed LI. The reason is that the energy consumption to listen to the TIM at each BI dominates the total energy consumption when LI equals to BI. When LI_i = BI, STAs need to wake up at every BI to receive TIM and check if they have data buffered in AP. The energy consumption of overhearing and state conversion increases as STAs waking up frequently, which hinders the energy efficiency of our protocol. For distributed BI, note that when the channel utilization is low, the energy efficiency is less sensitive to the choice of length of BI. However, as the channel utilization increases, energy efficiency is more and more sensitive to the choice of length of BI. The main reason is that many STAs cannot retrieve their buffed data at their awake BI when channel utilization is larger, and more STAs have to be reactive beyond its awake BI to receive their packets, which increases the energy consumption.

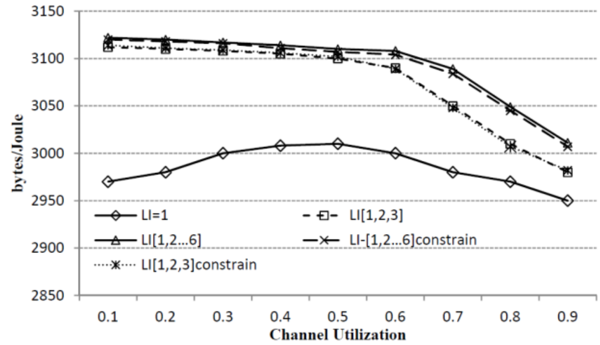

Figure 7. Energy efficiency versus channel utilization

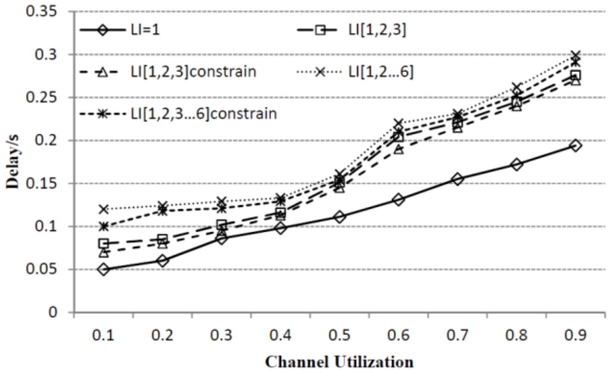

Figure 8. Average delay channel utilization

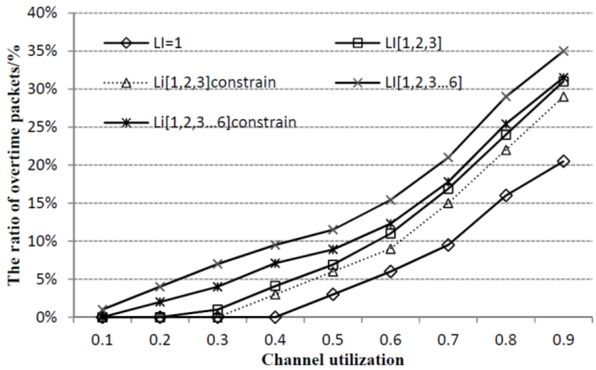

Figure 9. Overtime ratio versus channel utilization

In Fig. 8 and Fig. 9, we investigate the impact of length of LI on the delay performance. As shown in Fig. 8, the average delay of networks with shorter LI is smaller than those with longer LIs, which conforms the intuitive judgment. Flows aimed to STAs with longer LI are buffered at AP longer time, which increase the average delay. There is no notable difference whether the LI is constrained within the tolerant delay. However, the constraints improve the overtime ratio. Since the maximal tolerant delay of flows is 500ms, when the LI is distributed among [BI, 2BI...6BI] some packets become overtime easily.

Above all, we find that when the length of LI is distributed among the tolerant delay with the constraint that $LI_i \leq D_i$ the energy efficiency and delay performance is optimal. So we choose $LI_i \in$ BI, 2BI, 3BI] with the constraint that $LI_i \leq D_i$.

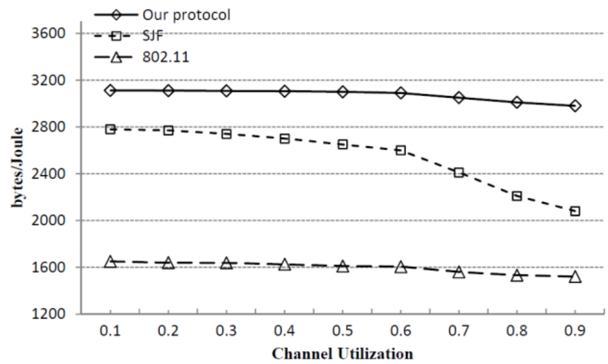

Figure 10. Energy efficiency versus channel utilization

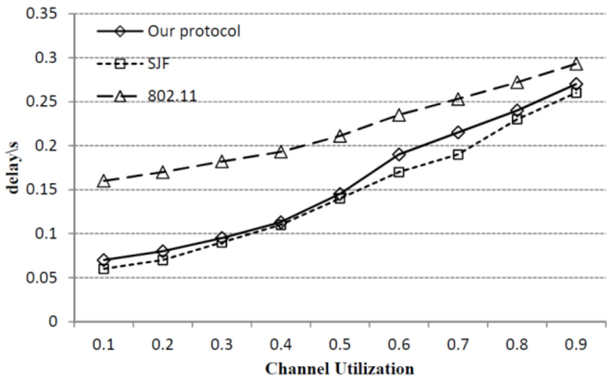

Figure 11. Average delay versus channel utilization

B. Compared with SJF and 802.11

In the following, we compare the simulation results of the protocols SJF introduced in [12], protocol proposed in this paper, and 802.11(IEEE 802.11 standard) from three aspects, the energy efficiency, the average transmission delay, and the overtime ratio of frames. In Fig. 10, the IEEE 802.11 is the worst one because the frames collisions and the back off delay will cause the energy wastage. As to the other two, our protocol is always superior to SJF. The reason is that in our protocol STAs wake up just when they receive downlink frames which minimize the idle listening time and then the consumption of energy. Moreover, another interest scenario is the gap between our protocol and SJF becomes wider while the channel utilization becomes higher. SJF lets the smallest frame transmits first to minimize the total waiting time. When the channel utilization becomes higher, the larger frames have to wait long time to be transmitted which increases the total idle listening time and depresses the energy efficiency. Our protocol is less sensitive to the channel utilization. Some STAs may be reactive when the service time arranged to them is beyond their awake BI, which is the only extra energy usage when channel utilization is high.

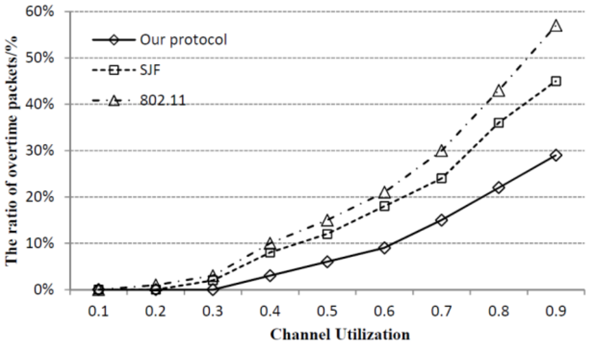

Figure 12. Overtime ratio versus channel utilization

Fig. 11 shows that the sequence of the average delay is 802.11>ourprotocol>SJ F. The back off delay and the retransmission delay incurred in IEEE 802.11 makes its average delay the largest. The goal of SJF is designed to minimize the total waiting time of the whole network, so its average delay is the lowest. While our protocol aims to meet the deadline of each flow, the EDF strategy always schedules the packet with the earliest deadline first. Fig. 12 shows the overtime ratio of three protocols versus channel utilization. Despite that the SJF performs the best in average delay, our protocol outperforms SJF in the aspect of overtime ratio. SJF only concerns on the transmission time of buffered frames and pays no attention on the tolerant delay of each frame. Not all the short frames should be arranged with high priorities to transmit. Some longer frames may have a rigorous delay constraint. So the EDF strategy is better to meet different delay constraints than other two protocols.

V. CONCLUSIONS

In this paper, we have designed a power-saving MAC protocol with EDF schedule strategy in IEEE 802.11 Wireless LANs. The proposed protocol has three main contributions. First, the energy consumption is suppressed by scheduling the STAs with precise service time. We redesigned the TIM to convey the schedule information. Second, the schedule period is not limited in one BI in our protocol, which is more practicable in real environment. Third, as our scheduling strategy, we employ EDF to meet different requirements of delay constraints. We also have studied the impact of the length of the LI on the energy and delay performance characteristics. The results showed that when the length of LI is distributed among the tolerant delay with the constraint that $LI_i \leqslant D_i$ the energy efficiency and delay performance is optimal. Both theoretical analysis and simulation validations are conducted to evaluate the effectiveness of the proposed protocol. The mathematic analysis and simulation results show that our power-saving MAC protocol possesses a better performance than SJF and IEEE 802.11 not only in energy efficiency but also in overtime ratio of data frames.

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