Energy Consumption Optimization under Multi-link Target Wake Time scheme in WLANs

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***Abstract*—Since the stations (STAs) are usually powered by batteries in the wireless local area network (WLAN), the energy consumption of STAs is of great importance. The target wake time (TWT) mechanism is designed to save energy in the WLAN. Besides, the multi-link operation (MLO) technology is proposed recently to achieve the extremely high throughput transmissions in the WLAN. In this paper, we study the TWT with the newly proposed MLO. We analyze the impact of TWT and MLO both on the energy consumption of STAs. We optimize the TWT and MLO jointly with the goal of energy minimization for STAs. Through adjusting the LI parameter in TWT and the traffic allocation in MLO, we balance the tradeoff among energy consumption, transmission delay, queueing stability, as well as multi-link scheduling in WLANs. We formulate this energy optimization problem as a mixed-integer non-convex problem, and design a multi-link optimal algorithm to optimally solve it. Simulation results show that the proposed scheme has a great advantages in terms of energy consumption.**

***Index Terms*—Energy Consumption, Multi-link Operation, Target Wake Time**

I. INTRODUCTION

Wireless local area networks (WLANs) have been ubiquitously deployed recently due to the high flexibility. In a WLAN, an access point (AP) provides low-cost broadband wireless Internet access for stations (STAs). To support user mobility, STAs are usually portable and powered by batteries, such as smartphones, laptops and tablets. Therefore, the energy consumption performance of STAs is of significant importance, and it attracts great attention not only in WLAN but many other wireless communication networks. In cellular system and Internet of Things (IoT), many techniques have been introduced to save the energy consumption of devices [1], [2]. And in WLAN, the power saving mode (PSM) technology is introduced to save energy and has received great attentions [3], [4]. The PSM allows a STA to power down transceiver temporarily to reduce energy. When a STA wakes up, it sends a power-saving poll (PS-Poll) frame to notify AP its awake state and meanwhile retrieve buffered traffic from AP. When the number of STAs becomes large, contention may happen since multiple STAs transmit PS-Poll frames simultaneously [5].

To deal with the serious contention problem of PSM in the dense user environment, the target wake time (TWT) mechanism is further proposed in 802.11ax. The main idea behind TWT is the following. Through a negotiation between STAs and AP, AP could know in advance the periods when STAs are awake. Thus, the PS-Poll frames are not necessary, and the contention among STAs is relieved [6].

There are two types of TWT in 802.11ax: the individual TWT and broadcast TWT. In individual TWT, the STA will negotiate the next service period (SP) with AP in every transmission. In the broadcast TWT, it determines a periodic SP in the negotiation stage and can share the SP with other STAs. We mainly focus on the broadcast TWT in this paper. In the broadcast TWT scheme, a STA first negotiates with AP two parameters: the first target beacon (FTB) and listening interval (LI). Through this negotiation, STA determines which beacon frames to wake up and listen. The beacon frame a STA chooses to listen is defined as the target beacon frame. FTB indicates the position of the first target beacon. LI is the time interval between successive target beacon frames, which indicates the frequency of target beacons. By listening to the target beacons, the STA gets the SP information. The SP information indicates the periods when the STA should wake up and communicate with AP. Besides the target beacon frames and SPs, the STA could keep doze and power down its transceiver to save energy.

Therefore, LI is a key parameter to control the frequency of target beacon frames and influence the energy performance of a STA. A short LI means a frequent target beacon listen, which causes too much energy on listening beacons without data transmission. However, larger LI means less transmission opportunities for STAs. This may cause too much traffic accumulated in the buffer of STAs, and result in large transmission delay and severe buffer overflow. Obviously, for a STA in WLANs with broadcast TWT, by adjusting LI parameter, there is a tradeoff among energy consumption, transmission delay and queue stability.

Meanwhile, with the evolvement of WLAN technology, 802.11be, the next generation of 802.11ax, is investigated from 2019 [7]. The goal of 802.11be is to further improve the data rate, transmission reliability and latency performances for WLAN. So that it can accommodate to more modern applications, such as augmented reality, virtual reality, and online gaming. One of key technologies introduced in 802.11be is multi-link operation (MLO), which expands the frequency bands from traditional 2.4GHz and 5GHz to 6GHz. STAs could adopt these multiple bands to establish multiple links and achieve an extremely high throughput transmission [8].

Besides the throughput improvement with MLO, the energy performance is also impacted by considering TWT and MLO

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jointly. On the one hand, for a STA under broadcast TWT, it can obtain faster transmission rate through MLO when it is awake, meaning that more traffic could be sent out within the awake period. This implies the MLO could support larger LI for a STA, and thus save energy on beacon listening. However, when multiple links are awake simultaneously, multiple radio frequency (RF) chains are operating and conversely increasing the energy consumption. To this end, LI and MLO should be optimized jointly in terms of energy consumption for a STA.

In summary, in this paper we investigate the energy performance of STAs in WLANs. By jointly considering broadcast TWT scheme and MLO, we optimize the energy when a STA performing uplink transmission to the AP. We adjust the LI parameter and MLO together, and balance the tradeoff among energy consumption, transmission delay, queue stability, as well as multi-link scheduling. We formulate this energy optimization problem as a mixed-integer non-convex problem, and then we design a multi-link optimal (ML-opt) algorithm to optimal solve it. The contributions of this paper could be summarized as follows:

- We consider the broadcast TWT and MLO jointly in WLANs. We analyze how the LI and MLO design jointly impact the energy, delay and queuing performances. Then we formulate the optimization problem with the goal of energy minimization as well as delay and queuing stability constraints.
- Since the formulated problem is mixed-integer and non-convex, we propose a ML-opt algorithm, which mathematically transforms the problem into several linear subproblems. Then the ML-opt algorithm solves the problem optimally with a low complexity.
- Through extensive simulations, we compare the proposed ML-opt scheme with other schemes and investigate its performance. The numerical results show the advantage of the proposed scheme in terms of energy consumption.

II. Related Work

Many works have been focused on the energy consumption issue of STAs in WLANs. Specifically, under the PSM technology, [5], [9], [10] aim to reduce the energy consumption by mitigating the competition among STAs when they are awake. [11]–[13] study the relationship between energy and delay. By adaptively changing LI according to the STA traffic, the sleep duration is prolonged as much as possible to save energy while meeting the delay requirement. Other studies, such as [14] and [15], use machine learning to classify STA traffic and develop better sleep strategies for STAs. There are also some research works on the TWT design. In [16], high energy efficiency is achieved by further dividing time slots according to the proportional fairness and maximum rate in TWT SP. [17] improves the transmission process of trigger frames in TWT and combines it with a wake-up radio, which significantly reduces the energy consumption. [18] dynamically selects STAs to be served and assigns the TWT interval based on the traffic and channel conditions of STAs.

Although there are many well-performing power saving designs in WLANs, the MLO is newly proposed in 802.11be, hence not too many studies focusing on the combination between broadcast TWT and MLO. In this paper, we consider the broadcast TWT and MLO jointly, and analyze how the LI and MLO design impact the energy, delay and queuing performances for a STA. This may help to further improve the energy performance in next generation WLANs.

III. Broadcast TWT Mechanism with MLO

In this section, we introduce the detail of the broadcast TWT mechanism in WLANs over one link, and then discuss the issue extended into MLO case. As shown in Fig.1, in the TWT negotiation phase a STA first negotiates TWT parameters with the AP. The TWT parameters mainly include two parts: first target beacon (FTB) and listening interval (LI). The target beacon is the beacon frame a STA should wake up and listen. Each target beacon contains the instruction of the service period (SP), including the start time and duration of a SP within this beacon interval. With the SP instruction, the STA could know the specific time period when to wake up and communicate. The FTB parameter is the first target beacon frame the STA starts to wake up. LI parameter is the time interval between successive target beacons, which is in unit of beacon interval. LI indicates the frequency of target beacon frames.

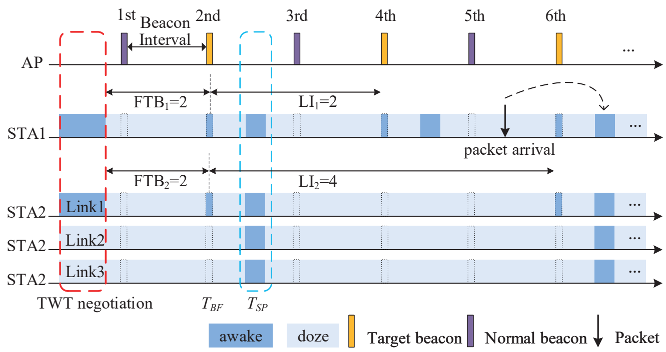

Fig. 1. An example of Broadcast TWT.

For example, in Fig.1, after negotiation, the $FTB = 2$ and $LI = 2$ of STA1, meaning that STA1 will wake up at the second, fourth, sixth beacon frames, and so on. These target beacon frames are yellow in Fig.1. After receiving target beacons, STA1 goes to sleep until the corresponding SP begins. During each SP, STA1 wakes up and communicates with AP. The SPs are circled with a blue dotted line in Fig.1.

We can see that the STA wakes up in two periods: the target beacon frames and the SPs. Waking in the target beacons is to obtain the information about SP, and waking in the SPs is to complete data transmission with AP. From the view of effective data transmission, the energy consumed within target beacons is a waste, since no transmission happens. Thus it is better to reduce the frequency of target beacons and design a larger LI. However, a large LI may cause too many traffic generated and buffered. If the buffered traffic can not be transmitted in time, the delay and queueing performance will be impacted. Therefore, the length of LI should be optimized in terms of the tradeoff among energy, delay and queueing performances.

Moreover, the STA2 has MLO ability in Fig.1. With multiple links, the transmission rate is greatly improved. More data can be sent out in time within a SP. Therefore, the frequency of target beacons could be low in order to save energy, i.e., the LI=4 for STA2 in Fig.1. But operating on multiple links also causes more RF chain power consumption. As a result, the LI parameter and MLO should be jointly optimized to balance the tradeoff among energy consumption, delay, queueing and multi-link scheduling performances.

IV. System Model

We consider a WLAN with broadcast TWT and MLO. Let f and l denote the FTB and LI respectively. Then the STA will wake up at $(f + k * l)$-th beacon frame, where $k = 1, 2, \cdots$. We denote the time length of a beacon interval as T_{BI}, and thus the time length of the LI is $T_{LI} = lT_{BI}$. The time length of a service period is T_{SP}. The transmission time of a beacon frame is T_{BF}. Since the energy of the STA is concerned in this work, we only focus on the uplink transmission from STA to AP. We assume that the packet generation follows a Poisson arrival process with rate λ. Each packet contains $Mbits$. The total traffic arrived and accumulated during the LI period can be calculated as $D = M \cdot \lambda \cdot lT_{BI} bits$.

There are three links in the WLAN. We use $j = 1, 2, 3$ to indicate the link over 2.4GHz, 5GHz and 6GHz frequency band, respectively. When multiple links transmit simultaneously, the total traffic D is divided among them. The traffic divided over link j is

$$D_j = \alpha_j D, \forall j, \tag{1}$$

where $0 \leq \alpha_j \leq 1$ is the portion over link j. Note that $\alpha_j = 0$ means the link is not adopted, while $\alpha_j = 1$ degrades into a single link case where only link j is adopted.

The transmission rate over link j is denoted as R_j, and R_j can be calculated as follows.

$$R_j = B_j log_2(1 + \frac{P_j |h_j|^2}{N_0 B_j + I_j}), \forall j, \tag{2}$$

where B_j is the bandwidth of link j. P_j is the transmission power of link j. h_j is the channel gain, and I_j is the wireless interference power over link j. The additive noise is modeled as i.i.d. circularly symmetric complex Gaussian noises $\mathcal{CN}(0, N_0)$.

Then the transmission time t_j over link j can be obtained.

$$t_j = D_j / R_j, \forall j, \tag{3}$$

A. Queueing Stability Constraint

During the LI with length l, the STA consistently generates packets with Poisson arrival process. We assume the total traffic D arrived during the LI could be transmitted completely within a SP. This is because if the traffic could not be finished, the remaining traffic will accumulate into next LI. From the long-term view, this may lead to the buffer overflow and queuing unstability for a STA. Hence, given a SP with length T_{SP}, for each link j, the transmission time t_j should be less than or equal to T_{SP}, i.e.,

$$t_j \leq T_{SP}, \forall j, \tag{4}$$

B. Transmission Delay Constraint

For a STA, when a packet is generated, the packet will wait until the next nearby SP to be sent, as shown in Fig.1. The exact waiting time for a specific packet is random. The reasons are two folds. First, the time a packet generated is random. Second, the start time of a SP is also random, which is indicated by the beacon frame it belongs to.

Nevertheless, we could measure the average waiting time for a packet from the long-term view. Since SPs randomly distribute over LIs, for the LI with length T_{LI}, averagely speaking, the interval between two successive SPs is also equal to the length of LI, i.e., T_{LI}. Therefore, for packets arrived within a period of T_{LI}, its average waiting time is $T_{LI}/2$.

Moreover, recall that for a packet with $Mbits$, α_j is the portion divided over link j. Then the transmission time for a packet with portion α_j is $\alpha_j M / R_j$ over link j. In the MLO case, multiple links transmit a packet simultaneously. Then the final transmission time of a packet is the maximum transmission time over all links, i.e., $max\{\alpha_j M / R_j, j = 1, 2, 3\}$.

As a result, the total waiting time for a packet is the summation of $T_{LI}/2$ and $max\{\alpha_j M / R_j, j = 1, 2, 3\}$. For a packet with delay constraint T_{limit}, the total waiting time should not exceed its delay constraint. That is,

$$T_{LI}/2 + max\{\alpha_j M / R_j\} \leq T_{limit}, \forall packet, \tag{5}$$

C. Energy Consumption Minimization

As illustrated in Fig.1. The STA has two states: doze and awake. For simplicity, we assume that the power under doze state is zero. In the awake state, the STA has two behaviors: One is transmitting traffic to AP with total power P_{t_j} over link j. The other is receiving target beacon frames from AP with power P_{r_j} over link j.

The transmission energy over multiple links can be derived as,

$$E_t = \sum_{j=1}^{3} P_{t_j} t_j \tag{6}$$

Also, the receiving energy on target beacons is,

$$E_r = P_{r_j} T_{BF} \tag{7}$$

From this we can see that the energy on receiving beacons is non-negligible, especially when the beacon frame is long, and the number of target beacon frames is large. Besides, to further save energy, in this paper we consider that the beacon frame over one link should contain its own link's SP information as well as other two links' SP information. In this way, there is no need for a STA to listen to 3 links. Only one beacon frame over one link is listened and the energy can be further saved.

As a result, for a long-term period, the total energy consumption of a STA can be calculated in the following way.

$$E_{total} = \lfloor \frac{T}{l} \rfloor (E_t + E_r), \tag{8}$$

where T indicates the long-term scheduling period containing T beacon intervals, and $\lfloor \frac{T}{l} \rfloor$ is the number of LIs within this scheduling period.

D. Overall Problem Formulation

Based on the analysis above, we have the overall problem formulation as follows.

$$\min_{\{l,\alpha_j\}} \lfloor \frac{T}{l} \rfloor (E_t + E_r) \tag{9}$$

$$\text{s. t. } \alpha_j D/R_j \leq T_{SP}, \forall j, \tag{10}$$

$$T_{LI}/2 + max\{\alpha_j M/R_j\} \leq T_{limit}, \forall packet, \tag{11}$$

$$0 \leq \alpha_j \leq 1, \forall j, \tag{12}$$

$$\sum_{j=1}^{3} \alpha_j = 1, \tag{13}$$

$$l \in \{1, 2, 3, \cdots, T\}, \tag{14}$$

where l and α_j are optimization variables. E_t and E_r are the energy consumption for data transmission and beacon receiving, respectively, and can be obtained through (6) and (7). T is the long-term scheduling period. $D = M \cdot \lambda \cdot lT_{BI}$ is the total traffic generated in the LI. M is the packet size. λ is the traffic arrival rate. T_{BI} and T_{SP} are the time duration of beacon interval and SP, respectively. R_j is the transmission rate over link j, which can be derived through (2). (10) and (11) are queueing stability and delay constraints, respectively.

We can observe from (9)-(14), with the integer variable l, the problem is a mixed integer non-convex optimization problem, which is not easy to solve. In section V, we propose a multi-link optimal algorithm (ML-opt) to transform the original problem (9)-(14) and finally solve it optimally.

V. Multi-link Optimal Algorithm

From the analysis above, the existence of l makes the problem (9)-(14) hard to solve directly. However, since l is an integer and the range of l is $l \in \{1, 2, 3, \cdots, T\}$. Note that T is the number of beacon intervals the scheduling period contained. Hence, the value of l is finite. Inspired by this, we first fix the value of l. For a given $l \in \{1, 2, 3, \cdots, T\}$, the problem (9)-(14) can be transformed into a new optimization problem, which is shown in (15)-(21).

$$\min_{\{\alpha_j\}} \lfloor \frac{T}{l} \rfloor (E_t + E_r) \tag{15}$$

$$\text{s. t. } \alpha_j D/R_j \leq T_{SP}, \forall j, \tag{16}$$

$$T_{LI}/2 + \alpha_1 M/R_1 \leq T_{limit}, \forall packet, \tag{17}$$

$$T_{LI}/2 + \alpha_2 M/R_2 \leq T_{limit}, \forall packet, \tag{18}$$

$$T_{LI}/2 + \alpha_3 M/R_3 \leq T_{limit}, \forall packet, \tag{19}$$

$$0 \leq \alpha_j \leq 1, \forall j, \tag{20}$$

$$\sum_{j=1}^{3} \alpha_j = 1, \tag{21}$$

For each given l, it corresponds to a transformed problem (15)-(21). As a result, the original problem (9)-(14) transform into T sub-problems. For each subproblem in (15)-(21), by fixing l, we can see that the variables are only α_j. Also note that the delay constrain in (11) in original problem is transformed into three sub-constraints in (17)-(19) in sub-problem. The reason behind this is the following. For the maximal value among set $max\{\alpha_j M/R_j\}$, if it can satisfy the constraint (11), then each item in this set could definitely qualify this constraint. Now the sub-problem is linear in terms of α_j, so we could utilize many classical optimization methods to easily solve it. After optimally solving these sub-problems, we could obtain T objective values. Each objective value represents the best energy consumption under a give LI l. Next, we compare these objective values and select the minimal one as the final optimal solution.

In a summary, we describe the main idea of the proposed ML-opt algorithm as follows. First, the mixed integer non-convex original optimization is transformed into T linear optimization sub-problems. Each sub-problem can be optimally and easily solved. Then, a selection is made among T objective values, and the solution with the minimal value is picked up as the optimal solution. Since the sub-problems are linear, and the value of T is finite, the overall complexity of the proposed ML-opt algorithm is acceptable. The detail of ML-opt algorithm is shown in Alg.1

Algorithm 1: ML-opt algorithm

Input: $\lambda, M, T_{BI}, T_{limit}, T_{SP}, T_{BF}, T, I$.
Output: $l_{opt}, \boldsymbol{\alpha}_{opt}$.

$E_{min} =$ inf, $E = 0$, $\boldsymbol{\alpha} = 0$;
$l_{opt} = 0$, $\boldsymbol{\alpha}_{opt} = 0$;
Compute R_j according to I_j and path loss, for every link j;
for *each l within T* **do**
  Compute D according to λ, M, T_{BI}, l;
  Solve the problem (15)-(21) and obtain $E, \boldsymbol{\alpha}$;
  if $E < E_{opt}$ **then**
    $E_{opt} \leftarrow E$;
    $l_{opt} \leftarrow l$;
    $\boldsymbol{\alpha}_{opt} \leftarrow \boldsymbol{\alpha}$;
  end
end

VI. Numerical Results

In this section, we evaluate the performance of our proposed scheme (ML-opt). We compare it with the following baseline schemes: 1) Multi-Link Random (ML-rand), in which the STA selects LI and the proportion over each link randomly; 2) Single Link Only (SL), in which the STA only transmits data over one link; and 3) Multi-Link Uniform (ML-uni), in which the data transmitted is uniformly distributed across multiple links. The results shown below are the average over 1000 iterations under monte carlo simulation.

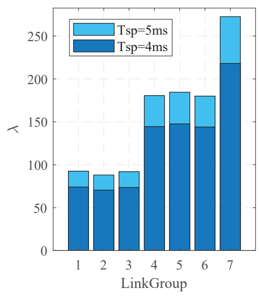

Fig. 2. The maximum λ.

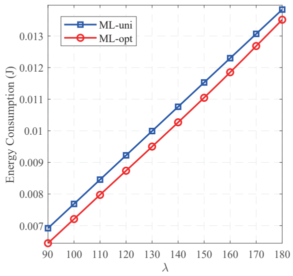

Fig. 3. Performance comparison of ML-opt and ML-uni under λ variation.

A. Simulation Setup

We consider a WLAN where a STA is 10m away from the AP. We assume the T_{BI} of each link is identical, and the beacon transmission time is synchronized on all links. In each iteration, the interference on 2.4GHz, 5GHz, and 6GHz links varies randomly between $[-78, -70]$, $[-83, -75]$, and $[-86, -78]$ in dBm, respectively. For the STA, we set its power P_{r_j} is 31.27dBm when it operates in reception mode, and the power P_{t_j} is 31.37dBm in transmission mode [13]. The other parameters are listed in Table I.

TABLE I
SIMULATION SETUP

Parameter	value
T_{BI}	100 ms
T_{BF}	1.5 ms
T	$120T_{BI}$
M	12000 bits
Bandwidth	2 MHz per link
Path loss	free space model
Noise power density	-174 dBm/Hz
Max TX power	15 dBm

B. Performance Analysis

We first investigate the maximum traffic rate λ the WLAN could support when using different link combinations. By setting T_{SP} =4 ms and 5 ms, respectively, we obtain Fig.2. The No.1, No.2 and No.3 link groups are 2.4GHz, 5GHz, and 6GHz single link, respectively. No.4, No.5 and No.6 are 2.4+5GHz, 5+6GHz, and 2.4+6GHz with two links, respectively. No.7 is the case activating three links together. As shown in the figure, by utilizing more links, the WLAN supports more traffic with higher traffic rate λ. In addition, with the increasing of T_{SP}, the λ increases since more transmission time is allowed.

In Fig.3, we study the effectiveness of the traffic allocation strategy over multiple links. The results show that the ML-opt consumes less energy compared to the ML-uni scheme with the uniform distribution over three links. It indicates that the proposed ML-opt scheme achieve a better energy performance by adaptively allocating the traffic proportions over multiple links.

We then fix $T_{SP} = 5$ms, $T_{limit} = 500$ms in Fig.4. We can see that the proposed ML-opt algorithm has the lowest energy consumption because it reduces the frequency of target beacon reception and save the receiving energy. In contrast, the three SL schemes consume more energy due to insufficient transmission capability and frequently wake up, especially when λ is high. The difference among three SL schemes is due to the different path loss and interference conditions among links.

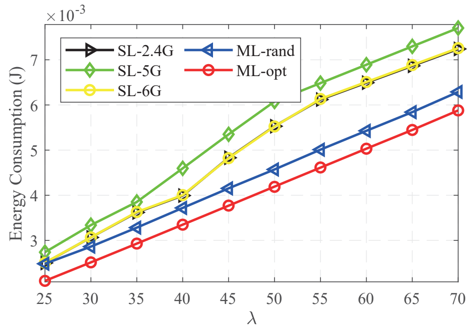

Fig. 4. Energy vs. λ.

We also vary the T_{SP} in Fig.5 by setting $\lambda = 29$ and $T_{limit} = 500$ms. Compared with other schemes, ML-opt can achieve the best performance in terms of energy consumption. As T_{SP} increases, the energy consumption for all schemes decreases. The longer T_{SP} leads to a larger LI, which prolongs the sleep time and reduces the number of receiving beacons. Due to the multiple data transmission capability, the ML-opt can have a larger l under the same T_{SP}. So its energy consumption is lower. For $T_{BI} = 100$ms, the energy consumption of SL schemes decreases in an approximately stepwise trend.

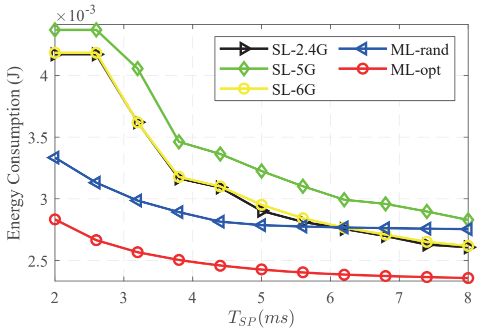

Fig. 5. Energy vs. T_{SP}.

Similarly, we change T_{limit} to investigate the impact of traffic delay constraints, with $\lambda = 18$ and $T_{SP} = 5$ms in Fig.6. When T_{limit} is small, the main factor limiting the selection of LI is T_{limit}. Due to the delay limitation, ML-opt can not select a larger LI, so the energy consumption is close to SL. When T_{limit} becomes large, T_{SP} limits the LI selection. Therefore, as T_{limit} increases, the energy consumption of SL schemes remain the same, but ML-opt can still sleep longer to save more energy.

Finally, in Fig.7, we investigate the relationship between the transmission time of beacon frame T_{BF} and the energy con-

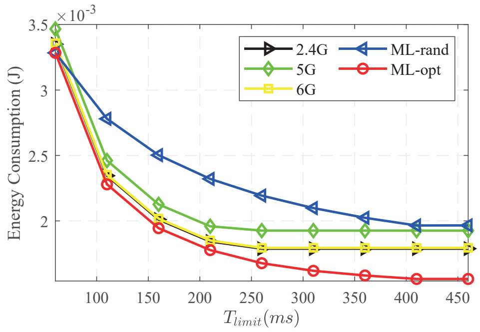

Fig. 6. Energy vs. T_{limit}.

sumption, by setting $\lambda = 50$, T_{SP} =5ms and $T_{limit} = 500$ms. As we can see from the figure, the energy consumption of each scheme increases as the T_{BF} increase. Because the STA needs to receive the beacon frame for SP information, the overhead increases accordingly. ML-opt can achieve good performance, especially when the size of beacon frame becomes large.

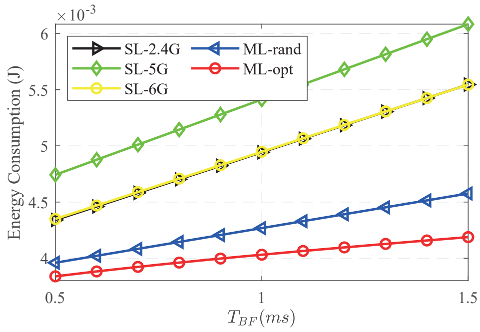

Fig. 7. Energy vs. T_{BF}.

VII. Conclusion

We have studied the energy optimization problem for a STA in WLANs, by jointly considering the broadcast TWT and MLO. We adjust the LI parameter and MLO together, and formulate the optimization problem with the goal of energy consumption minimization. The tradeoff among energy consumption, transmission delay, queueing stability, and multi-link scheduling is investigated and balanced jointly. The energy minimization problem is formulated as a mixed-integer non-convex problem. The ML-opt algorithm is proposed to optimally and easily solve the problem. Finally, simulation results show the advantages of the proposed scheme. In the future, we will investigate multi-user LI and MLO optimization problem for dense scenario that more constraints are included.

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