The First Measurement Study of Target Wake Time Mechanism in 802.11ax on COTS Devices

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***Abstract*—Nowadays, the 802.11ax protocol is widely adopted in the local area networks. Compared with the former version of 802.11 standards, 802.11ax brings a new power-saving mechanism named TWT (Target Wake Time). In this paper, we conduct a comprehensive measurement study on how TWT mechanism performs on the commercial-off-the-shelf devices in our daily life. To me more specific, we focus on the impact on power consumption, network performance and stability of TWT mechanism on the smartphones. Counterintuitively, we find that TWT mechanism is not as power-saving as we thought in the experimental setup we built, and it also poses nagative impacts on the network stability. We further perform a root-cause analysis to find the rationale behind the measurement results and we also summarized the implications and suggestions to the stakeholders of 802.11ax.**

***Index Terms*—TWT, 802.11ax, End-to-end Performance, Energy Efficiency, actual devices**

I. Introduction

IEEE 802.11 standards have become the de facto accessing protocol for WLAN (Wireless Local Area Networks) and is widely used in smart phones and laptops. Proposed in 2013, the latest amendment of IEEE 802.11 standards, 802.11ax, introduces a series of enhanced PHY (physical) layer technologies for a more efficient spectrum usage and better user experience. According to the survey from IDC [1], the shipments of 802.11ax-enabled product reach 3.5 billion in 2022 and take up 79% of all IEEE 802.11 shipments.

Among existing network metrics, because of their limited battery capacity, power consumption is one of the most important performance measurement especially for mobile devices [2]–[4]. Hence, IEEE 802.11ax involves the TWT (Target Wake Time) [5] mechanism, which enables the AP (access point) and the STAs (stations) to negotiate a schedule for channel access to obtain a better energy and spectrum efficiency, especially under the congested network scenario.

Existing studies focus on modeling how TWT mechanism saves power [6], [7] or optimizing its scheduling strategies [8]. These studies leverage mathematical models or network simulators (e.g., ns3) to evaluate TWT. Its real-world performance on COTS (commercial-off-the-shelf) devices, however, remains largely under-explored. Therefore, we conduct a comprehensive yet in-depth measurement study on how TWT mechanism affects the performance on COTS mobile devices. Specifically, we build an indoor testbed to measure the performance and select a set of application benchmarks that mimic the the daily usage of one's mobile devices to make our measurement akin to real-world scenario. Moreover, we also build a software tool-set to record the detailed power characteristics of each application on mobile devices during the whole experiment for further offline analysis.

Measurement perspective. Our measurement aims to provide a comprehensive view of TWT mechanism on COTS devices. Hence, we evaluate the TWT mechanism of 802.11ax protocol from three major perspectives:

- *Impact on power consumption.* The first and foremost perspective is how TWT impacts the power characteristic of mobile devices. To understand the power consumption issues with TWT in real-world settings, we select four representative scenarios, i.e., standby, video streaming, gaming and live video chat [9]. We then perform a comprehensive experiment and analyze the results.
- *Impact on network performance.* TWT leverages mandatory and fixed sleep interval to reduce the energy consumption of mobile devices. Hence, besides energy, how TWT affects the network performance, e.g., uplink/downlink bandwidth, jitter and delay, is also an important point of view that need to explore.
- *Impact on network stability.* In this perspective, we mainly use the measurement study to answer the following question: does the TWT mechanism sacrifice the network stability for energy saving? Hence, we conduct experiments on network stability under different network conditions with and without TWT mechanism.

Insights. Our measurement study leads to several major insights, which we summarize as follows:

(1) Our measurement study reveals that TWT does not always saves power on COTS devices. In the four application scenarios we tested, only the live video chat scenario shows TWT reduces the energy consumption. The reason behind this counterintuitive finding is that the negotiated sleep time of TWT on the COTS devices is not adaptive to different network and application, which largely reduces its power saving performance. Furthermore, the usage of TWT leads to additional frame overhead, which consumes more energy.

(2) We find that because the regular negotiation of sleep time TWT mechanism has a negative impact on the performance

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of upload throughput and jitter while does not have obvious effect on download throughput, and delay.

(3) As for the reliability of network, we find that TWT influences the stability especially under poor network.

Contributions. The key contributions of our measurement study can be summarized as follows:

- To the best of our knowledge, this paper is the first one to evaluate the performance implications of TWT mechanism in real-world settings with COTS devices.
- Beyond the our measurement results, we further conduct in-depth code-based and traffic-based root-cause analysis to find the rationale of performance degradation.
- Based on the insights we find in the root-cause analysis, we present the implications of current TWT implementation and our suggestions for stakeholders.
- We have released our dataset, measurement tools and methods to all the research community for facilitating the future study [10].

The rest of the paper is organized as follows. Section 2 introduces the preliminaries on TWT mechanism and OFDMA (orthogonal frequency division multiple access) in 802.11ax. Section 3 describes our measurement setup, scenario and tools. Section 4 presents our detailed measurement results of how TWT mechanism impacts the power consumption, network performance and stability. Section 5 summarizes the implications and our suggestions for stakeholders. Section 6 presents the related works and Section 7 concludes this paper.

II. Preliminaries

A. *TWT (Target Wake Time) mechanism*

TWT is a concept introduced in 802.11ah [11] and applied in 802.11ax. TWT mechanism is a sign that Wi-Fi protocol is open to the IoT (Internet of Things) devices that can save energy when connected to Wi-Fi. This mechanism achieves energy-saving by negotiating the wake-up time between AP and STAs and transferring data only at the wake-up time.

TWT is mainly divided into two types: Individual and Broadcast TWT. Individual TWT can be further divided into explicit and implicit version. When explicit TWT is employed, a STA [7] wakes and performs frame exchange and receives the next TWT information in a response from the TWT responding STA. When implicit TWT is used, the STA calculates the Next TWT by adding a fixed value to the current TWT value. STAs need not be made aware of the TWT values of other STAs. In this paper, we mainly study the implicit mode because only the implicit mode of Individual TWT is currently supported in commercial applications.

For STA to negotiate individual TWT agreements, TWT setup is initiated by the STA, as shown in Fig. 1. After the STA sends the TWT request frame, the AP replies to the STA a TWT response frame to indicate that it agrees with the request of the STA. TWT request frame of STA includes key parameters such as wake interval, target wake time, and wake duration. The TWT message format is shown in Fig. 2. The TWT Wake Interval of the requesting STA is calculated by $T_{int} = T_{mant} * 2^{\epsilon}$, where T_{mant} stands for TWT Wake Interval Mantissa, and ϵ stands for Wake Interval Exponent. Target Wake Time indicates the time point when the TWT session is started. TWT session is equal to nominal Mininum TWT Wake Duration*256µs. TWT Information is utilized to indicate the next wake up time of STA. After negotiation, the STA switches to the doze state until the promised target wake time, as shown in Fig. 1.

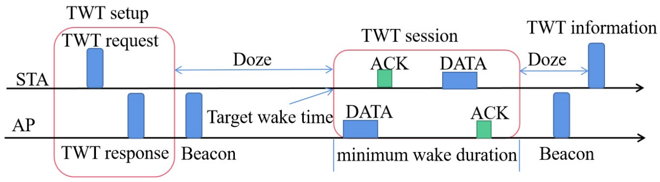


Fig. 1. Implicit TWT flow between STA and AP.

Element ID	Length	Control	Request Type	Target Wake Time	TWT Group Assignment	Nominal Minimul TWT Wake Duration	TWT Wake Interval Mantissa	TWT Channel	NDP Paging
Octets: 1	1	1	2	8 or 0	9 or 3 or 0	1	2	1	0 or 4

Fig. 2. TWT message format.

B. *Transmission mechanism of IEEE 802.11ax*

Because we need to turn off TWT for comparison experiments, the new packet mechanism in 802.11ax is important for us. Trigger frame is a new frame type introduced by 802.11ax. The multi-user transmission of 802.11ax is based on OFDMA technology. When it carries out upload or download transmission, it needs to use Trigger Frames to realize the exchange of scheduling information between multi-user communications, as shown in Fig. 3. When 802.11ax successfully competes, it sends the first trigger frame Trigger #1. The trigger frame type is BSRP (Buffer Status Report Poll), which is used to request the buffer information of the STA. After receiving the BSRP, AP feeds back the BSR (Buffer Status Reports) information, which is used to assist the AP in allocating RU (resource units) resources in UL OFDMA.

After BSRP and BSR interact, if there are traditional 802.11 clients in the network, the AP needs to send MU-RTS (Multi-user request to send) frame Trigger #2, which is also a trigger frame and is sent using traditional OFDM (Orthogonal Frequency Division Multiplexing) technology. All STAS can receive it. APs other than 802.11ax set local NAV (Net Asset Value) timers by receiving the Duration/ID fields in MU-RTS frames to ensure that active contention will not be initiated within the remaining UL OFDMA time. The MU-RTS frame also contains RU resource allocation content. We need to note that the AP allocates RU resources in the MU-RTS frame, and the next trigger frame only indicates that the transmission is started. After the AP allocates RU resources, it needs to get feedback from the STA, that is, STA feeds back the CTS (Clear-to-send) frame, informing the AP of its approval and knowing the current resource allocation.

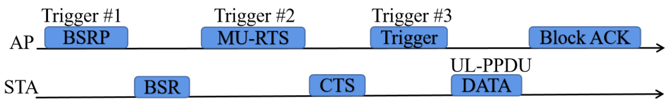


Fig. 3. OFDMA Upload.

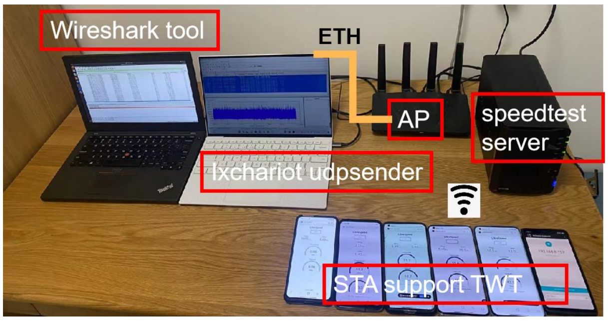


Fig. 4. An overview of the measurement setup.

After the MU-RTS and CTS exchanges are completed, the AP sends the third trigger frame Trigger #3 to notify the STA to perform uplink transmission on the corresponding RU resource. The trigger frame also indicates the time of this uplink transmission. When the uplink UL ODMA transmission is completed, the AP will feed back the Block ACK(Acknowledgement) confirmation to the STAs.

III. Measurement Setting and Tools

Since its commercial launch, the Wi-Fi ecosystem including service deployment, coverage, and devices with Wi-Fi functions have been rapidly expanding and developing [12]–[15].

Wi-Fi AP. In our measurement research, we select two chip solutions of router products, Xiaomi CR6608 of MTK chip and GLiNet AX1800 of QUALCOMM chip. they all support the TWT function. However, we find that the Xiaomi CR6608 is difficult to trigger the TWT mechanism. Therefore, we choose GLiNet AX1800, which supports the open-source OpenWrt system. We enable and disable TWT by modifying the OpenWrt system.

Wi-Fi STA and measurement toolset. We use multiple mobile terminals that claim to support 802.11ax. We obtain TWT frames through the wireless network adapter AX210 and Wireshark. The version of Wireshark is 3.4.8 and the operating system is Ubuntu 18.04. We can get the TWT-relevant fields by Wireshark. In this paper, we use three Xiaomi 10 mobile phone as the STA. The system of Xiaomi 10 is MIUI 12.2.2 which uses the Android 11 kernel. It should be noted that we find Xiaomi 10 only supports TWT in the 2.4G band in the Xiaomi kernel. To reduce the impact of the WAN side on the test results, we build a Speedtest server on the LAN (Local Area Network) side, which is used to evaluate the impact of TWT on Wi-Fi performance.Test environment as shown in Fig. 4.

Power monitoring. We measure power consumption through ADB (Android Debug Bridge). Because the external detector method, such as Monsoon Power Monitor [16], can only detect the overall power consumption. For us, the granularity is not enough. With the help of ADB tools, we can manage the state of the devices. We can also perform many terminal operations and shell commands. ADB is the bridge between Android terminals (such as mobile phones/set-top boxes) and PC terminals. It allows us to comprehensively operate mobile phones on computers and record terminal operation logs. This allows us to develop a logging tool to record the power consumption of mobile phones, so as to evaluate the specific power consumption of mobile phones.

IV. TWT Performance: Results and Analysis

In this section, we present our measurement results on TWT in terms of power consumption, network performance, and stability. Based on the experimental results, we further leverage code-based and traffic-based root-cause analysis to find out the rationale behind real-world performances. Our measurement starts with the impact of power consumption of STAs, followed by the impact of performance and stability.

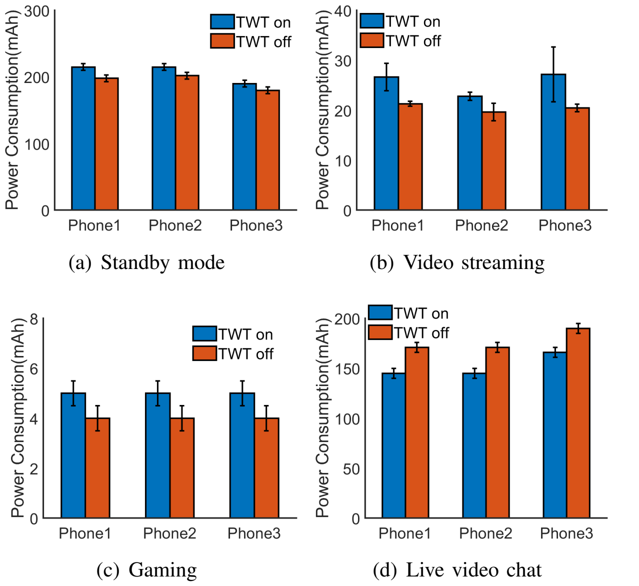
A. Impact of power consumption

Methodology. In this perspective, we leverage four representative scenarios according to [9], [17] to test if TWT could save power. For standby scenario, we set the mobile phone as standby mode with the screen on (to keep the network connection alive). For the video streaming, gaming and live video chat scenario, we use Tencent video, Honor of Kings and WeChat video call as the representative application, respectively We run the application on STA for a certain length of time and use our measurement script to record the power characteristic. At the same time, we create a congested network condition in order to trigger TWT.

Measurement results. Following the above methodology, we conduct thorough measurements on the impact of the power consumption of TWT mechanism. The evaluation results are summarized as follows.

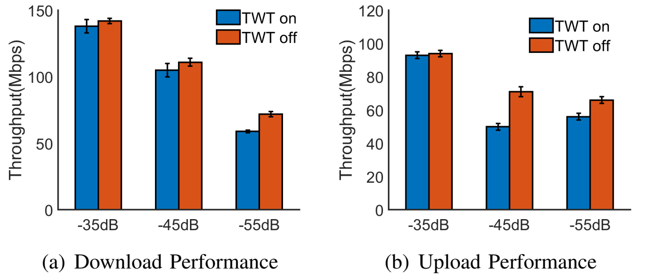
Standby mode. First, we test the power consumption in standby mode. The detailed test method is to turn on and turn off the screen display, and then create a congestion condition by sending UDP traffic to the companion device Xiaomi 8SE. When the TWT of router is turned on and turned off, we evaluate the power consumption of the Xiaomi 10. We find that the Xiaomi 10 consumes more power when the TWT is turned on. as shown in Fig. 5(a), when the TWT is turned on, 6.5% more power is consumed on average than the TWT is turned off. Furthermore, we use Wireshark to capture the TWT interactive frame. Even if the mobile phone has no service, as long as the mobile is in the condition of congestion, it will trigger the TWT mechanism to send the frame of TWT. This causes Wi-Fi to send redundant messages, thus consuming more power. However, the TWT trigger condition is not considered in the current simulation work.

Video streaming. When testing the Tencent video application, we play the video on all the test STAs at the same time. In order to maintain the same test conditions as much as possible, we fully charge and restore the factory settings of the mobile phones during each test. The test cycle is 30 minutes. We find that when Tencent videos are played, the TWT on state



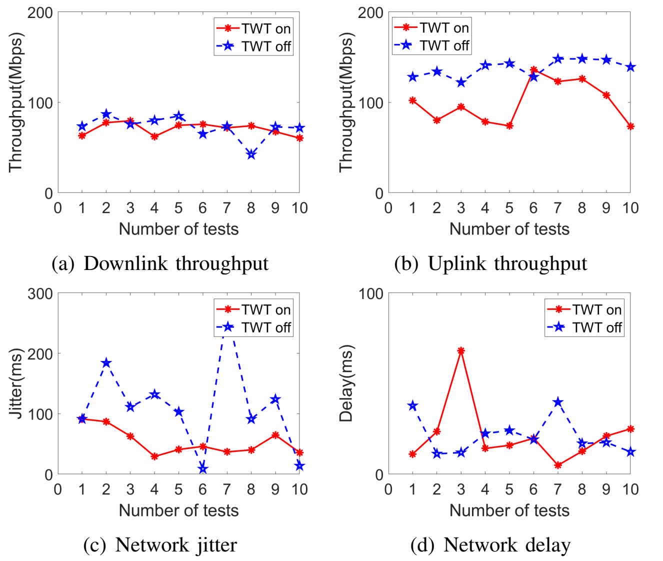
(a) Standby mode
(b) Video streaming
(c) Gaming
(d) Live video chat

Fig. 5. Four traffic types Wi-Fi power consumption.



(a) Download Performance
(b) Upload Performance

Fig. 6. Three STAs in each group performance by send or receive UDP traffic.



(a) Downlink throughput
(b) Uplink throughput
(c) Network jitter
(d) Network delay

Fig. 7. Measurement results of the impact of network performance of TWT.

consumes more power than the TWT off state. As shown in Fig. 5(b), When the TWT is turned on, 19% more power is consumed on average than the TWT is turned off.

Gaming. When testing the game, we choose to test Honor of Kings. We created congestion conditions by sending UDP traffic to Xiaomi 8SE, which is a companion testing device. The test cycle was 10 minutes. We find that in the game business, the TWT on status consumes more power than the TWT off status. as shown in Fig. 5(c), when the TWT is turned on, 20% more power is consumed on average than the TWT is turned off.

Live video chat. Similarly, we test the WeChat video chat function. To ensure the consistency of test conditions, we enable the WeChat video function and play the same video content in front of the camera of the phone to be tested, so that the content of the WeChat video chat is consistent every time. The test cycle is 30 minutes. as shown in Fig. 5(d), different from other applications that consume more power when the TWT function is turned on. We find that 14% more power will be saved on average when the TWT is turned on than the TWT is turned off.

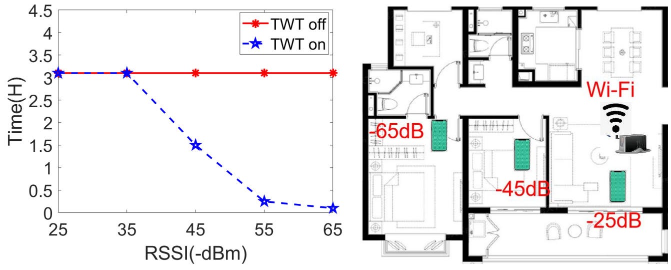
According to the in-depth analysis of the source code, we find that TWT does not control energy conservation, which means that TWT only relieves congestion and has no connection to the power drive. We further perform root-cause analysis in Section IV-C.

B. Impact of performance and stability

Methodology. We evaluate the impact of TWT by the strategies are follows: (*i*) Place devices Xiaomi 10 at different RSSI (Received Signal Strength Indicator) locations. (*ii*) Test the extreme performance of mobile terminals by sending UDP traffic with the `ixchariot` tool. (*iii*) A laptop connect to the LAN side of the router as the client, and five mobile phones connect to the Wi-Fi side of the router as a server. (*iv*) Three Xiaomi 10 mobile phones are the main tested devices, and the two companion mobile phones (Xiaomi 8SE and Red Devil 5s) are used to produce congestion. (*v*) In order to reduce the uncertain impact of the WAN (Wide Area Network) side, we built a local Speedtest server and connect the server to the router with a network cable. Then we run the Speedtest server client on mobile phones, as shown in Fig. 4.

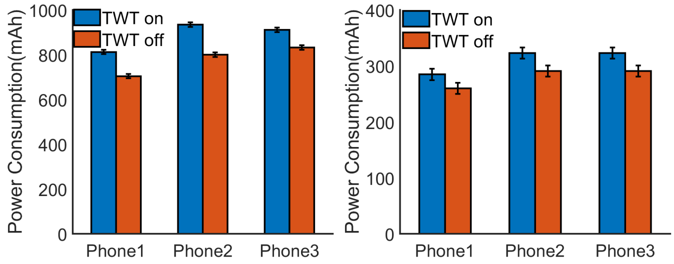
Measurement results. The measurement results of network performance and stability are shown as below.

Network performance. At different RSSI, we test the upload and download performance of the mobile phone. We find that the performance of -35dBm, -45dBm, and -55dBm are the same. When the router turns on the TWT, the upload performance of the mobile phone is higher than the TWT is turned off. In terms of download performance, the performance of mobile phones with TWT on is lower than that with TWT off, as shown in Fig 6. At the same time, we test its performance and stability indicators through the famous Speedtest server. Connect mobile phones to the router's Wi-Fi at the same time. The result is shown in Fig. 7. The jitter and download do not have too much difference in Fig. 7(a)(d), turn on and turn off the TWT of the router, the average delay is 21.6ms and 21.29ms, the average download is 70.65 Mb/s and



(a) stability Performance (b) The house' RSSI map

Fig. 8. Performance of stability under different RSSI.



(a) Power consumption under -25dBm (b) Power consumption under -45dBm

Fig. 9. Power consumption of UDP traffic during three hours of operation.

```
▾ Request Type: 0x2863
  . . . .  . . . .  . . . .  . . . 1  =  Requester: This STA is a TWT Requesting STA
  . . . .  . . . .  . . . .  0 0 1 .  =  Setup Command: Suggest TWT (1)
  . . . .  . . . .  . . . 0.  . . . .  =  Trigger: TWT SP does not include trigger frames
  . . . .  . . . .  . . 1 .  . . . .  =  Implicit: TWT is implicit
  . . . .  . . . .  . 1 . .  . . . .  =  Flow type: TWT is unannounced,
                                          the TWT  responding STA can send frams at any time
  . . . .  . . 0 0 0 . . .  . . . .  =  Flow ID: 0
  . 0 1 0 1 0 . .  . . . .  . . . .  =  Wake Interval Exponent: 10
  0 . . .  . . . .  . . . .  . . . .  =  Protection: False
  Target wake Time: 455091616
  Nominal Minimum TWT Wake Duration: 40
  TWT Wake Interval Mantissa: 100
  TWT Channel: 10
```

Fig. 10. Structure of TWT frame.

TABLE I
PACKET STATISTICS OF UDP AND LIVE VIDEO CHAT.

Frame Type	UDP		Live video chat	
	TWT ON	TWT OFF	TWT ON	TWT OFF
Beacon	63	65	14	18
Probe response	3	4	0	0
Action	6	1	4	1
Probe request	10	10	0	0
Acknowledgement	17	12	4	0
Trigger basic	8	10	8	27
Trigger buffer status report poll	31	21	101	27
Clear-to-send	116	84	109	155
Block ACK	2956	2863	189	263
Request-to-send	586	550	12	15
Total packages	**3796**	**3620**	**441**	**506**

72.59 Mb/s. As shown in Fig. 7(b)(c), turning on and turning off the TWT of the router have an obvious effect on the upload and jitter, the average jitter is 53.44ms and 112.854ms, the average upload is 99.61 Mb/s and 137.8 Mb/s.

Stability. At different locations that leverages different RSSI, as shown in Fig. 8(b), the tool ixchariot continuously sends UDP traffic to evaluate the impact on stability and performance. As shown in Fig. 8(a), when TWT is enabled, the mobile phone can be connected stably at the near point -25dBm. When the mobile phone is at -45dBm, the traffic can only be maintained for 90 minutes. When the mobile phone is at -55dBm, the traffic can only be maintained for 15 minutes. When the mobile phone is at a lower signal strength of -65dBm, the traffic will be cut off within 3 minutes.

C. Root-cause analysis

We leverage a quantitative approach to find the root-cause of TWT performance degradation. To be more specific, we use the STAs to send UDP traffic and analyze the detailed beacon number during a three-hour experiment. The results are shown in Fig. 9. The power consumption is still higher when the TWT is turned on than the TWT is turned off. For the detailed packet content and message count, we use Wireshark to capture TWT packets. Through analyzing the wireless packets obtained, we find that the implementation of TWT on mobile phones is based on a *fixed* Target Wake Interval, which is mentioned in Section 2. As shown in Fig. 10, which is capture by the Wireshark, the TWT Wake Interval mantissa is 100, and the Wake Interval Exponent is 10 on our test STAs. Therefore, the target wake interval is equal to $100*2^{10}$. The result is 102400µs which is exactly a beacon cycle.

More quantitatively, we send UDP traffic for 5 seconds continuously and make statistics on the wireless messages obtained, as shown in Table I. We find that the number of sleep reported by Xiaomi 10 do not change, which was 6 times, but the management message sent more TWT messages. Further analysis shows that the TWT is always suspended once every time the next wake-up time is reserved. For live video chat, We find that the total number of packets sent when the TWT is on is 332, and the total number of packets is 487 when the router TWT function is turned off, the result is as shown in TABLE I. Therefore, proper scheduling can enhanced spectrum utilization and improved energy efficiency of the network.

V. IMPLICATIONS AND SUGGESTIONS

According to our measurement results and root-cause analysis in Section IV, we find that the TWT wake interval is fixed on the COTS wireless routers and mobile phones. This fixed TWT wake interval does not consider the actual application requirements for transmission latency and further leads to more energy consumption. The latency requirement of non-real-time applications (e.g., file download/upload, web browsing) are mostly larger than 80ms, while requirements of real-time applications is much shorter, such as 50ms for Zoom audio call and 25ms for Discord Video Call.

Hence, if the stakeholders leverages an adaptive TWT sleep interval and set larger for non-real-time applications, we can foresee the energy saving of mobile devices. In the future version of OSes on mobile phones, stakeholders could consider to provide an interface for applications to claim the network latency requirement under each usage situations. Then, the OSes or phone manufacturers could jointly consider the application demands to calculate TWT wake interval proposals and negotiate with the wireless routers. It is generally believed that routers are plugged in and do not need to save power. However, our analysis perspective is different. We believe that there are many routers and a few single ones that can be saved. Each household has one, which is a large volume.

VI. Related Work

The empirical research on TWT is limited, since it is the latest 802.11ax standard. And they are all based on simulation. Yang et al. [7] conduct a simulation study on TWT using NS3. Due to it being based on simulation, they make some assumptions, such as do not take into account frame errors, scheduling only a single user in a single TWT SP to avoid collaboration and interaction they assume that the STA transmits the BSR for every uplink frame. In addition to the simulation of energy consumption, the other is the study of performance. Maddalena et al. [18] proposed new disruptive uses of TWT to improve the operation of next-generation WLANs by explicitly reaching a collision-free operation. They show that significant performance gains in throughput can be achieved when combined with the MU capabilities of IEEE 802.11ax by simulation. Chen et al. [19] proposed a TWT scheduling scheme (TSS) to avoid TWT is not properly scheduled, deteriorated throughput, and high power consumption occurring because of collisions.

Our work is different from existing research on spectrum efficiency or energy consumption studies [19]–[21]. We focus on the measurement study of TWT mechanism with commercial devices in practical scenarios. In contrast, our measurement activity is the first time to measure and analyze the real-world power consumption of TWT. And we test different types of applications and the impact of TWT, which has not been discussed before. Our measurement research complements these works through a comprehensive analysis of commercial TWT in the real-world environment.

VII. Conclusion

In this paper, we show the performance of TWT in real-world business applications for the first time, and we show the real-world interaction process and message content of TWT for the first time and give a detailed explanation. Our research gives proof that the TWT in specific business applications is not ideal, and do not bring obvious benefit to mobile phone. We consider the classification of different applications and measure the real-world power consumption of TWT in mobile devices. We provide another way to study TWT and describe the specific experimental steps, which are not limited to simulation. We have sent emails to the stakeholders of 802.11ax, they also test by some Simulation methods. Our work also provides a new testing idea for the industry.

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