WiZizz: Energy Efficient Bandwidth Management in IEEE 802.11ac Wireless Networks

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Abstract—In this paper, we propose a new power save operation as well as the corresponding protocol, called WiFi in Zizz (WiZizz), which judiciously exploits the characteristic of the channel bonding defined in IEEE 802.11ac and efficiently handles the channel bandwidth in an on-demand manner to minimize the traumatic energy spent by IEEE 802.11ac devices. Our extensive measurement and simulation show significant performance improvement (up to 73% energy saving) over a wide range of communication scenarios. In addition, the feasibility of easy implementation is demonstrated by a prototype with a commercial 802.11ac device. To the best of our knowledge, WiZizz is the first IEEE 802.11ac-congenial energy efficient bandwidth management while other existing approaches require costly modifications of the IEEE 802.11ac specification.

Index Terms—IEEE 802.11ac, WiFi, channel bonding, energy saving, power consumption modeling.

I. INTRODUCTION

RECENTLY, a largely growing number of portable devices, such as smartphones, tablets, and laptops, are being equipped with WiFi, the hallmark of the IEEE 802.11 wireless LAN (WLAN), in order to meet the ever-increasing traffic demands at low cost. Encouraged by such success, the emerging 802.11 specification, IEEE 802.11ac, mainly focuses on improving physical layer (PHY) rate via enabling multiple antennas, called multiple-input multiple-output (MIMO), and bandwidth widening, known as channel bonding [1]. Nowadays, however, as the battery-powered portable device users place increasingly complex demands on the functionality of their devices, battery life time satisfaction is becoming increasingly important.

It is not easy to run after two hares, i.e., high data rate and energy efficiency, due mainly to the inherent high power consumption of MIMO and channel bonding. Furthermore, channel bonding is considered the dominant factor of WiFi’s power consumption especially for the portable devices, because those devices in practice have a small number (i.e., one or two) of antennas due to the small form factor, while four times wider operating bandwidth, i.e., 80 MHz [1], is mandated. Additionally, the power consumption is amplified by the inefficient design of WiFi, whose radio frequency (RF) chains operate steadily to receive every incoming frame.

Our extensive experiment and simulation have revealed that the power consumption of IEEE 802.11ac network interface card (NIC) is dominated by the receiver’s channel sensing and listening operation (so-called idle state) and the reception of frames destined to others. Furthermore, we confirm that WiFi’s power consumption increases proportionally to the active channel bandwidth. For example, the use of wider bandwidth consumes as high as 1.4x and 2.3x more energy to sense the channel at idle state and to receive the avoidable frames addressed to others, respectively. Theoretically, if WiFi has the prior knowledge of the idle duration and the destination of the frames, it can sleep or filter out the frames at PHY. In reality, the unpredictable behavior of carrier sense multiple access (CSMA) makes the problem difficult to overcome.

Fortunately, thanks to the duplicated format defined in IEEE 802.11ac, control and management frames can be decoded even when the active bandwidth (e.g., 20 MHz) is much narrower than the operating bandwidth (e.g., 160 MHz) [2]. By exploiting the duplicated format based signaling, we propose a bandwidth control technique, called WiZizz, which handles the channel bandwidth on demand to minimize the needlessly spent energy. In summary, the following main contributions are made in this paper:

• We first model the power consumption characteristics of the 802.11ac NIC. It is shown that the proposed model accurately captures the power consumption characteristics with high fidelity, at most 2.3% estimation error for all of 1719 possible parameter combinations.

• To verify the model, we present a synthetic analysis on the power consumption of a state-of-the-art IEEE 802.11ac hardware. From this, we reveal high energy consumption caused by its inherent nature.

• We then propose a practical energy-efficient bandwidth management technique, called WiZizz, which alleviates unnecessary energy cost.

• To evaluate the effectiveness and feasibility of WiZizz, we have implemented it in open source device driver and network simulator.

• Finally, we show that WiZizz reduces energy cost by up to 73% compared with the baseline 802.11ac.

The rest of the paper is organized as follows: We first provide the related work and the background in Sections II and III. Sections IV and V present the proposed power model, the empirical study on WiFi power consumption, and its impact. Then, we describe the details of WiZizz in Section VI. Sections VII and VIII present the implementation details including our prototype and show the performance comparison.

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concludes the paper.

via both measurement and simulation. Finally, Section IX

II. RELATED WORK

There exists a considerable body of research that attempts
to measure and reduce the power consumption of WiFi.

Understanding WiFi power consumption: In [3], the authors
measure the power consumption of off-the-shelf IEEE 802.11n
NIC with various operating states. The most recent work in [4]
provides the synthetic view of 802.11ac devices’ performance
including the energy efficiency. These however do not present
an in-depth study of WiFi power consumption and make some
inadequate conclusions as discussed in Section V-B. Our work,
on the other hand, is based on extensive power measurement
of a state-of-the-art 802.11ac device, and presents intensive
analysis and interpretation while taking into account its char-
acteristics.

Power saving of IEEE 802.11: In IEEE 802.11 standard [5],
near power saving schemes have been defined to reduce the
power consumption. Power save mode (PSM) is a basic power
saving protocol that allows WiFi station to suspend all activity
in sleep mode, then wake up periodically to receive beacons
which indicate the existence of pending frames at the access
point (AP). Automatic power save delivery (APSD) is also
defined to allow stations to save power without performance
degradation of delay-sensitive traffic. IEEE 802.11n defines
power save multi-poll (PSMP), which enables AP to schedule
and announce reception and transmission instants of multiple
stations such that stations can avoid receiving others’ ex-
changes. It is known that APSD and PSMP are not commonly
used in practice.

Energy efficient MIMO: After adopting MIMO in WiFi,
energy saving techniques for MIMO have been introduced.
In IEEE 802.11n, spatial multiplexing power save (SMPS) is
defined to make stations save energy by allowing stations to
activate only a single RF-chain in idle period [5]. CMES [6]
finds most energy efficient transmit and receive RF-chain
setting, and furthermore, EERA [7] searches the most energy
efficient PHY rate considering MIMO. Since WiZizz concen-
trates on bandwidth adaptation, it can be easily combined with
these MIMO power saving schemes as demonstrated later.

Downclocking: Downclocking WiFi radio also enables energy
saving. Samplewidth adaptively determines optimal bandwidth
according to the distance between a sender and a receiver [8].
SloMo and Enfold propose downclocked reception to reduce
WiFi power consumption [9, 10], while E-MiLi downlocks
the radio of WiFi in idle period to minimize energy spent
while enabling normal clock to receive/transmit frames [11].

The radio downclocking in wider bandwidth is standard-
incompliant and requires costly modifications. WiZizz, on the
other hand, is amiable to IEEE 802.11ac standard and is
readily implementable as demonstrated later.

III. PREREQUISITES

We now describe the IEEE 802.11ac very high throughput
(VHT) features considered in this paper briefly, and then show
the relation between power consumption and these features.

A. Wider Bandwidth Channel

The widening of channel bandwidth, called channel bond-
ing, is first introduced in IEEE 802.11n. As shown in Fig. 1,
IEEE 802.11ac additionally mandates the operation of 40 MHz
and 80 MHz bandwidth which are yielded by bonding two
and four adjacent 20 MHz channels, respectively. Besides,
160 MHz bandwidth and combining two non-adjacent 80 MHz
channels, namely 80+80 MHz, have been optionally defined.
When enabling channel bonding, the PHY data rate increases
proportionally to the operating bandwidth.

For backward compatibility, IEEE 802.11ac has defined a
transmission format of the PHY that replicates 20 MHz legacy
PLCP protocol data unit (PPDU) transmission over multiple
adjacent 20 MHz channels, referred to as non-VHT duplicate
PPDU. Moreover, the preamble of data frame in the bonded
channel (e.g., 80 MHz or 160 MHz) takes the form of the
replicated 20 MHz preamble structure. By means of this, the
station which operates on 20 MHz channel bandwidth can
detect and receive the preamble of the data in the bonded
channel and the crucial control frames in the form of the
duplicate PPDU, such as request-to-send (RTS), clear-to-send
(CTS), and acknowledgement (ACK), from the 802.11ac AP.

B. MIMO and Higher Order Modulation

IEEE 802.11ac supports MIMO utilizing up to eight an-
tennas. Using MIMO technique, we can achieve much higher
PHY rate, but requires more accurate channel estimation and
compensation to eliminate the spatial interference.

Modulation and coding scheme (MCS) index represents the
pair of modulation type and coding rate. IEEE 802.11ac newly
defines 256-QAM, on top of 64-QAM used by 802.11a/n, thus
enabling encoding four times as dense as 64-QAM.

It is generally known that higher order MCS index provides
faster PHY data rate while lower order MCS index is used for
the more reliable communication.

C. Relation between 802.11ac Features and Power

The 802.11ac VHT features described above provide ever-
increasing PHY rate. However, they have drawbacks.

When channel bonding is used, the sampling rate of analog-
to-digital converter (ADC) and digital-to-analog converter
(DAC) should be increased to handle wider bandwidth signal
correctly based on the Nyquist’s theorem [12]. Accordingly,
the power consumption of ADC/DAC increases proportionally
to the bandwidth. Since DAC power is much smaller than ADC
power, the power consumption of receiver is more sensitive to
the bandwidth [13].
The use of multiple antennas consumes more energy and its growth rate is a linear function of the bandwidth, because the RF-chain of each antenna operates and senses the whole bandwidth separately.

In the case of 256-QAM, it is straightforward that the complexity of its modulation/demodulation process is similar to that of lower modulation types, but the resultant high PHY rate (in bits per second) requires high computing power (in joules per second), especially for a decoder, such as Viterbi [14]. Similarly, when 256-QAM is used, the receiver consumes more energy than the corresponding transmitter. We explain the details in the following section.

IV. POWER CONSUMPTION MODELING

This section presents a quantitative model for the power consumption of WiFi in idle, receive (RX), and transmit (TX) state to validate our explanation in Section III-C. Our model takes into account all 802.11ac features presented in Section III.

A. Power Model of 802.11ac Receiver

For the power model of an 802.11ac receiver, we acquire and modify a well-designed 802.11n power model in [7]. The power consumption of a receiver ($P_{rx}$) is given by

$$P_{rx} = N_{rx}P_{t} + P_{fb}$$

where $N_{rx}$ is the number of RX antennas, and $P_{t}$ and $P_{fb}$ are the power consumptions of RF circuitry and baseband processing as shown in Fig. 2, respectively.

$P_{t} = (P_{rc} + P_{rb})$ where $P_{rc}$ and $P_{rb}$ are functions of $N_{tx}$.

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where $P_{rc}$ and $P_{rb}$ are the power consumptions of RF circuitry and baseband processing, respectively.

B. Power Model of 802.11ac Transmitter

Now, we design a novel and accurate power model of an IEEE 802.11ac transmitter. The circuitry and processing paths of the transmitter are reversely similar to those of the receiver except the power amplifier as shown in Fig. 2. Therefore, the TX power is composed of the power consumption of radio circuitry ($P_{rc}$) and the baseband processing ($P_{bb}$), given as

$$P_{tx} = N_{tx}P_{t} + P_{fb},$$

where $N_{tx}$ is the number of TX antennas. The total transmit power ($P_{t}$) is evenly divided into TX antennas. Let $P_{t} = P_{tx}/N_{tx}$ be the transmit power of each antenna, and hence the power consumption of each power amplifier (PA) is given as $P_{amp} = \frac{P_{t}}{\eta(P_{t})}$, where $\eta$ is PA efficiency [16]. Since $\eta$ is a linear-like function of transmit power and $\lim_{P_{t} \to 0} \eta(P_{t}) = 0$ [17], we have

$$P_{amp} \approx \nu_{1}P_{t} + \nu_{2} = \nu_{1}\frac{P_{tx}}{N_{tx}} + \nu_{2},$$

where $\nu_{1}$ is PA power coefficients, and $\nu_{2}$ is PA power when $P_{t} = 0$, caused by the quiescent current of gate voltage. Thus, total PA power is equal to $\nu_{1}P_{tx} + \nu_{2}N_{tx}$. Based on the datasheet in [17], $\nu_{1}$ and $\nu_{2}$ are about 4.9 and 460, respectively. Briefly, the total PA power highly depends on $N_{tx}$, not its output power, $P_{t}$.

Since the DAC power is linearly proportional to $B$, $P_{dc}$ can then be formulated by

$$P_{dc} = \nu_{1}\frac{P_{tx}}{N_{tx}} + \nu_{2} + P_{mixer} + P_{syn} + P_{filter} + P_{DAC}$$

where $\nu_{1}$, $\nu_{2}$, $\nu_{3}$ are the circuitry power coefficients.

The TX baseband processing block is composed of IFFT, modulator, and encoder. As each block has similar power consumption property as the corresponding RX block, the TX power consumption can be modeled as

$$P_{tx} = B(\beta_{1}N_{tx} + \beta_{2}N_{ss} log_{2} B + f_{tx}(N_{ss})) + \beta_{3}N_{tx} + \beta_{4}t + \beta_{5}P_{t} + P_{fb},$$

where $\beta_{1}$, $\beta_{2}$, $\beta_{3}$, $\beta_{4}$, and $f_{tx}$ are the TX power model coefficients.

V. POWER CONSUMPTION MEASUREMENT

To validate our model, we show the measured power consumption of a commercial 802.11ac NIC.
Receive state.

As shown in Fig. 3(a), the measured RX power consumption of QCA9880, where 160 MHz results are from a measurement-driven model.

**A. Experimental Setting**

We have conducted extensive experiments using Qualcomm Atheros 9880 chipset (QCA9880), which supports up to $3 \times 3$ MIMO, 80 MHz bandwidth, and 256-QAM. The QCA9880 is installed in a desktop node via a PEX1-MINI-E adapter which converts from mini-PCI express to PCI express [18]. The node is used as a station while running 3.18.0 Linux kernel and open source device driver, ath10k [19, 20]. We also use the node as a programmable AP using hostap [21]. We place the station approximately 0.5 m away from the AP, where the distance is relatively short.

As for the power consumption measurement of the 802.11ac NIC, we use a similar method presented in [3]. We put a 40 mΩ resistor in front of the power pin of the adapter which supplies 3.3 V to the NIC. By using data acquisition tool, i.e., NI USB-6210 [22], we measure and record the voltage drop across the resistor to obtain the current, and thus can compute the power consumption of the NIC. In the case of the transmit/receive power consumption, we send 600 long data frames (i.e., A-MPDU), and average multiple samples over the actual frame transmission/reception duration except idle duration. Otherwise, for the power consumption in idle state, the recorded samples are averaged over a 6 second run in a controlled environment, where no interference is observed.

**B. Power Consumption of IEEE 802.11ac NIC**

We now investigate how much energy is consumed in IEEE 802.11ac NIC according to its state. The 802.11ac features in Section III are considered, and the combination of the features is denoted by $N_{ant} \times B$, where $N_{ant}$ and $B$ are the number of active transmit/receive antennas and the bandwidth, respectively. For example, $3 \times 80$ stands for the setting using 3 active antennas and 80 MHz bandwidth. The state can be classified into three categories: 1) Idle state, 2) receive state, and 3) transmit state.

**Idle state:** Fig. 3(a) shows the measured power consumption in idle state ($P_{idle}$). We observe that the use of wider bandwidth consumes more energy in idle state where the NIC does not receive and/or transmit frames actively. When 1×80, mandated in 802.11ac, is used, $P_{idle}$ increases by 26% and 21% over that of 1×20 and 1×40 setting, respectively. This result presents the opposite conclusion from the result studied in [3]. The authors argue that 802.11 devices simply add subcarriers for channel bonding while keeping the sampling rates the same, but the sampling rate of ADC and fast Fourier transform (FFT) size should be increased to decode the baseband signal correctly as discussed in Section III-C. It is well known that higher sampling rate and larger FFT size consume more power. In short, using channel bonding trades off energy cost for PHY rate.

Furthermore, the use of more antennas intensifies the increase of $P_{idle}$ induced by the widening of bandwidth. As an evidence, $3 \times 80$ consumes 39% more energy than $3 \times 20$. It is due to the fact that each RF-chain listens to the whole bandwidth, and senses the channel with high sampling rate.

**Receive state:** As shown in Fig. 3(b), the measured RX power ($P_{rx}$) shows a similar trend as $P_{idle}$. Especially, in the case of
TABLE I: Measurement-driven power model for QCA9880.

<table>
<thead>
<tr>
<th>( \alpha_1 )</th>
<th>( \alpha_2 )</th>
<th>( \alpha_3 )</th>
<th>( \alpha_4 )</th>
<th>( f_{tx}(N_{ss}) )</th>
<th>( i_1 )</th>
<th>( i_2 )</th>
<th>( P_f )</th>
</tr>
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<tbody>
<tr>
<td>0.035</td>
<td>0.48</td>
<td>82.4</td>
<td>0.47</td>
<td>0.156</td>
<td>4.4</td>
<td>8.6</td>
<td>1.978</td>
</tr>
<tr>
<td>( 8.6 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
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\( \beta_1 \) | \( \beta_2 \) | \( \beta_3 \) | \( \beta_4 \) | \( \beta_5 \) | \( f_{tx}(N_{tx}) \) | \( i_1 \) | \( i_2 \) | \( P_f \) |
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>0.022</td>
<td>0.038</td>
<td>802.2</td>
<td>0.001</td>
<td>4.352</td>
<td>1.623</td>
<td>1.68</td>
<td>1.71</td>
<td></td>
</tr>
</tbody>
</table>

1×20, \( P_{tx} \) is approximately equal to or slightly larger than \( P_{idle} \). This is because that the receive RF circuitry, which is the major energy consumer, shall operate at all times even if there is no frame to transmit and/or receive.

On the other hand, the growth rate of \( P_{tx} \), in accordance with the increase of \( N_{ant} \) and \( B \), is much higher than that of \( P_{idle} \). It is caused by the fact that the energy cost of 802.11ac receiver is increasingly dominated by baseband processing blocks, such as FFT, minimum mean square error (MMSE) detector, and Viterbi decoder, which are not used at idle state.

In addition, we observe that the NIC consumes more power during frame reception with higher order MCS index, because the power consumption of Viterbi decoder, one of power hungry processing blocks, highly depends on PHY rate [14]. Therefore, the RX power increases with the use of higher order MCS, and the amount of the increase becomes higher when the NIC operates with wider bandwidth. For example, when 3×20/40/80 are used, MCS 9 consumes 144, 300, 569 mW more than MCS 0, respectively.

**Transmit state:** Fig. 4(a) shows the TX power consumption \( (P_{tx}) \) with various fixed MCSs when \( P_1 \) is 0 dBm. Unlike \( P_{idle} \) and \( P_{tx} \), the \( P_{tx} \) depends slightly on \( B \) and MCS, but greatly depends on \( N_{ant} \). This is due to the fact that total PA power, which is the majority of \( P_{tx} \), is greatly influenced by \( N_{ant} \) as described in Section IV-B. The transmit components related to \( B \) and MCS, such as DAC, modulator, and encoder, use considerably small or negligible power compared with the corresponding receive blocks of a receiver [14]. Especially, the DAC power is about one forth of the ADC power [13]. Interestingly, due to these aspects, RX power is comparable to TX power when wider bandwidth is used. As an evidence, for 2×80 and 3×80, RX power has come close to TX power.

In Fig. 4(b), we additionally depict TX power consumption with various transmit power \( (P_t) \) from 1 dBm to 17 dBm. \( P_{tx} \) increases as \( P_t \) increases but the amount of the growth is independent of \( N_{tx} \) and \( B \) as explained in Section IV-B. Furthermore, the growth from the varying \( P_t \) is marginal, e.g., 6.3% of the entire power consumption for 3×80.

**C. Power Model Verification**

We now verify our power model through measurement results presented above. As presented in Table I, we calculate the coefficients of idle, RX, and TX power consumption models for QCA9880 using nonlinear regression analysis of IBM SPSS [23]. The average estimation error of the proposed power model is below 2.3% for all PHY parameter combinations, and it leads to better accuracy (as high as 2.4 percent point) compared with the model presented in [7].

As discussed in Section III-C, idle and RX power model is highly related to the bandwidth due to the fact that the relevant coefficients (i.e., \( i_1, \alpha_1, \alpha_2 \), and \( f_{tx} \)) are large enough, but TX power model is not. Moreover, PHY rate coefficient of TX power model \( (\beta_4) \) is negligible while the corresponding coefficient of RX \( (\alpha_4) \) is nonnegligible.

Based on the measurement-driven model, we estimate the power consumption when 160 MHz is used as shown in Figs. 3 and 4.\(^3\) 3×160 consumes 1.9x and 4.1x more energy than 3×20 in idle and RX state, respectively. Furthermore, 3×160 setting consumes even more energy in RX state than in TX state based on our power model. This result is against the common sense that TX is the most energy-hungry state.

**D. Summary**

In a nutshell, our major findings are:

- The wider bandwidth is, the more energy is consumed.
- Particularly, idle/RX state power highly depends on bandwidth, and is comparable to TX state power.

Thus, considering wider bandwidth originated by channel bonding becomes increasingly important to save idle/RX state energy cost for the 802.11ac WiFi which mandates the channel bonding up to 80 MHz. Since most existing researches available in practice attempt to adapt only PHY rate and the number of antennas to save energy as summarized in Section II, we propose a novel sophisticated and practical bandwidth control technique to improve WiFi energy efficiency.

**VI. PROPOSED APPROACH**

**A. WiFi Needs to Zizz**

WiFi is known to be a primary energy consumer in battery-powered portable devices. The root cause is that WiFi preposterously oversamples wireless signal to successfully detect a frame which may or may not exist in near future. In [11], Zhang et al. show that stations spend most of the time in idle state rather than TX/RX and sleep state. For more than 92% of stations, 90% of energy is spent in idle while the fractions of energy spent in TX/RX and sleep are below 20% and 36%, respectively. This confirms that the energy of WiFi is remarkably consumed in idle state even if the PSM is activated.

Moreover, due to the inherent nature of IEEE 802.11, WiFi has to decode and receive the frames destined to other WiFi devices unnecessarily. Our evaluation shows that such needless frame receptions are too costly in a large dense network. The energy cost becomes increasingly dominant along with the usage of wider channel bandwidth.

Fortunately, most crucial frames, such as management and control frames, are transmitted in the format of 20 MHz legacy PPDU (i.e., IEEE 802.11a) over the primary channel or in the duplicated format of legacy PPDU over the entire operating bandwidth as explained in Section III-A. Thus, the receiver can

\(^3\)Throughout the paper, the 160 MHz results are obtained by our power model in Section IV, because 160 MHz-supporting NIC is not available today.
detect and decode such frames easily, even if it only listens to 20 MHz primary channel instead of the whole channel. We called such listening mode zizz mode. By letting WiFi in zizz (WiZizz) on demand, we can save energy surprisingly without sacrificing network capacity.

B. Overview of WiZizz Design

We now describe the details of our approach, called WiZizz, which manages the active bandwidth to minimize the power consumption of a station which enables the channel bonding in 802.11ac standard. WiZizz allows the station to operate with only 20 MHz bandwidth of primary channel (i.e., zizz mode) for a significant portion of time while avoiding needless frame reception. To support WiZizz, 1) AP should be able to let a receiver know when its bandwidth must be changed, and 2) the receiver then should switch the active bandwidth quickly. It is well known that the receiver is unable to decode the frame transmitted with wider bandwidth than its active bandwidth. However, we can simply solve the issue by exploiting the duplicate format for the purpose of WiZizz signaling.

C. Dynamic WiZizz

We first introduce dynamic mode of WiZizz which controls active bandwidth per frame basis. Fig. 5 illustrates an example of the WiZizz operation. When there is no ongoing transmission for a dynamic WiZizz station (i.e., STA1), the station continuously listens to the 20 MHz bandwidth of primary channel. Shortly, it is put to zizz mode.

When the station receives the preceding sequence of a data frame exchange (e.g., RTS/CTS sequence) addressed to it, the station immediately switches from zizz mode to awake mode, where the station enables the full operating bandwidth, within short inter frame space (i.e., SIFS, 16 µs). Note that the AP can decide whether or not to send the preceding sequence using the following condition:

$$T_{\text{Data}}(r_{20}) + T_{\text{ACK}} + SIFS_{\text{zizz}} > T_{\text{RTS}} + T_{\text{CTS}} + T_{\text{Data}}(r_{80}) + T_{\text{ACK}} + 3\text{SIFS},$$

where $r_{20}$ and $r_{80}$ is the PHY rate in 20 MHz and 80 MHz bandwidth, respectively. $T$ is a frame duration. Briefly, if the exchange sequence duration of WiZizz (i.e., RTS/CTS/Data/ACK exchange duration) is longer than the data frame duration with 20 MHz bandwidth, the station remains in zizz mode and the AP send data with 20 MHz PPDU. This is because, when the size of data is small enough, the unacceptable overhead of WiZizz may decrease overall network capacity and the energy efficiency of the receiver. After finishing the data exchange sequence, the receiver switches back to the narrowest bandwidth, and “zizz” again.

However, if the switching delay of a NIC is longer than SIFS, the dynamic WiZizz is inapplicable for the NIC, because it cannot receive the following data frame at right time.

D. Pseudo-Dynamic WiZizz

As presented in Section VII-B, QCA9880 chipset is unable to adopt dynamic WiZizz due to the relatively long bandwidth switching delay. To address this challenge in practice, we design pseudo-dynamic mode which controls the active bandwidth in a long-term strategic manner.

Unlike dynamic mode, when a WiZizz station receives the WiZizz action frame whose bandwidth field set to the full operating bandwidth, its active bandwidth becomes wider to prepare the data frame reception, as STA2 does in Fig. 5. Note that the action frame is transmitted in the duplicate format of legacy PPDU. The network allocation vector (NAV) of the action frame is determined by considering the switching delay, $D_{\text{up}}$, which is delivered to the AP at the association stage. The upward-switching follows a similar rule presented in Eq. (8), and it is given by:

$$T_{\text{Data}}(r_{20}) + T_{\text{ACK}} + SIFS_{\text{zizz}} > T_{\text{RTS}} + T_{\text{CTS}} + T_{\text{Data}}(r_{80}) + 2T_{\text{ACK}} + 2\text{SIFS}.$$  

$$= D_{\text{up}} + D_{\text{down}} + T_{\text{Action}} + T_{\text{Data}}(r_{80}) + 2T_{\text{ACK}} + 2\text{SIFS}.$$  

Shortly, Action/ACK/Data/ACK exchange duration and its switching delay should be shorter than the data frame exchange duration with 20 MHz bandwidth.

On the other hand, the station decides to switch back to zizz mode through any of the following conditions:

Cond. 1: It receives the WiZizz action frame addressed to it, and its bandwidth field set to 20 MHz.

Cond. 2: It receives a frame addressed to another station, and its duration specified in the frame control field is...
longer than the switching delay ($D_{\text{up}} + D_{\text{down}}$). Afterwards, the station switches back to the full operating bandwidth at the end of the frame as shown in Fig. 5.

**Cond. 3:** It receives a frame, addressed to it, with the more data bit in the frame control field set to 0.4

An example of WiZizz operation is described in Fig. 5. STA1 (dynamic mode) changes its bandwidth for every frame exchange while STA2 (pseudo-dynamic mode) basically switches its bandwidth when WiZizz action frame is received. Moreover, STA2 starts to zizz when it receives a frame whose duration is long enough to meet **Cond. 2** (i.e., RTS) or whose more data bit is 0 (i.e., meet **Cond. 3**).

**E. PHY-level Filtering of WiZizz**

A station, which enables WiZizz, is able to achieve an additional energy save effect for the avoidable frame reception. For a frame destined to other stations and transmitted with wider bandwidth, i.e., 40 MHz, 80 MHz, and 160 MHz, than the active bandwidth in zizz mode, i.e., 20 MHz, the station in zizz discards the frame right after decoding the bandwidth information of the preamble. Thanks to the duplicate structure of the preamble, the station can decode the bandwidth information successfully even in zizz mode. This is a kind of PHY-level filtering.

To prove this, we measure and record the QCA9880’s power consumptions in both awake and zizz modes, when there are incoming frames addressed to another station with 20 MHz or 80 MHz bandwidth. As shown in Fig. 7, a station in zizz consumes constant power when a frame with 80 MHz bandwidth is detected (green line with cross), which means that the station discards the frame and senses the channel consistently. The station in awake mode, in contrast, consumes more than 2.3x energy for the needless frame reception (blue line with triangle). Additionally, WiZizz station can detect and receive a frame with 20 MHz PPDU as described above (red line with circle), and the reception further requires only marginal energy.

**VII. Testbed Experiments**

**A. Implementation and Testbed Setting**

To verify the feasibility of the proposed approach, we have implemented WiZizz using QCA9880 and ath10k of the nodes in Section V-A. Due to the long switching delay of QCA9880 as shown in Section VII-B, pseudo-dynamic 4If the station in PSM, it can be put to sleep instead of zizz.

WiZizz is implemented in both the AP and station nodes. The details of experimentation setting are described in Section V-A. Additionally, we have placed the stations 1 m away from the AP, and use the fixed MCS 0 and 3/80 setting for all experiments. Throughout the paper, all results are measured at the station side.

**B. Bandwidth Switching Delay**

We first examine how long the commercial 802.11ac NIC, QCA9880, takes to switch bandwidth. To estimate the delay, we have measured and recorded the power consumption of QCA9880 over time by varying its operating bandwidth and the number of active antennas, as shown in Fig. 6. We measure 15 runs for each setting.

We observe that the upward-switching delay is much longer than the downward-switching delay for all the cases. The delay does not depend on the number of antennas, but on the operating channel bandwidth. For example, switching between 20 MHz and 40 MHz takes less than that between 20 MHz and 80 MHz, while the delays of both the cases with single antenna and three antennas are almost the same. In average, $D_{\text{up}}$ and $D_{\text{down}}$ between 20 and 80 MHz is 73.6 and 48.5 $\mu$s, but those between 20 and 40 MHz takes 40.5 and 22.7 $\mu$s, respectively.

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4Due to the limited modifiability of ath10k, we only consider **Cond. 1** in this paper. So, the AP transmits the action frame at the end of every frame exchange sequence to let the station zizz.
Switching between 20 MHz and 80 MHz is done in two stages as shown in Figs. 6(a) to 6(d). Presumably, the receiver first converts its bandwidth to an intermediate bandwidth (i.e., 40 MHz), and then the final bandwidth switching is performed. If the bandwidth switching is available without an intermediate bandwidth, the delay may decrease.

C. Performance Evaluation

We now evaluate the effectiveness and feasibility of WiZizz. Fig. 8(a) plots the the power consumption comparison of the receiving station in one-to-one scenario, where the source rate of Iperf is varied from 20 kb/s to 20 Mb/s to make different traffic loads [24]. From the result, we can argue that WiZizz saves energy in idle state because, when the source rate is low (e.g., 20 kb/s), the baseline 802.11ac consumes 34% more power than WiZizz. However, the energy-saving gain decreases as the source rate increases due to the fact that the fraction of time spent in idle is gradually diminished.

We then investigate the impact of the number of stations \(N_{\text{sta}}\) under saturated traffic loads as shown in Fig. 8(b). There is a WiZizz station, and the others disable WiZizz. As \(N_{\text{sta}}\) increases, the power consumption of the WiZizz station \(P_{\text{WiZizz}}\) decreases while that of the baseline 802.11ac station \(P_{\text{baseline}}\) remains the same regardless of \(N_{\text{sta}}\). The gain is induced by PHY-level filtering, discussed in Section VI-E. Consequently, the maximum 55% energy-saving gain can be achieved by adopting WiZizz.

VIII. Simulation Results

We now evaluate WiZizz’s energy efficiency through network-level simulation to provide in-depth performance analysis in more general environments.

A. Simulation Methodology

We have developed ns-3, where IEEE 802.11ac PHY/MAC layer protocol stacks are additionally implemented [25]. Furthermore, in order to reflect reality well, when a station receives frames transmitted with wider bandwidth than its active bandwidth, the station drops the frame and just senses channel. We use the Rayleigh fading channel model with the assumption of the antenna correlation matrix is the identity matrix. In addition, for the comparison purpose, we have implemented SMPS and the power measurement module based on our proposed model described in Section IV.

B. Constant Traffic Source with Fixed MCS

We first consider the constant traffic source with the fixed MCS 0 with varying traffic loads and \(N_{\text{sta}}\). Stations with 3 active antennas are evenly spaced on a circle around the AP with the radius of 5 m. There are negligible channel errors.

Fig. 9(a) shows the power consumption in each idle and RX state with varying traffic loads in one-to-one scenario. As discussed in Section VII-C, WiZizz reduces energy cost in idle state. Especially, when 160 MHz bandwidth is used, the maximum 53% energy-saving gain can be achieved.

As shown in Fig. 9(b), the baseline 802.11ac station consumes more traumatic energy with the increase in the number of stations, which receive saturated traffic, because the station should decode and receive all the frames including avoidable ones. Thanks to PHY-level filtering, \(P_{\text{WiZizz}}\) in RX gradually decreases due to the fact that the fraction of RX time decreases while time and energy cost fraction in idle state increases. As a result, WiZizz remarkably reduces the total power consumption (as high as 73%) compared with the baseline.
Fig. 9(c) plots the energy efficiency of the baseline 802.11ac and WiZizz. The baseline 802.11ac shows almost same energy efficiency irrespective of the operating bandwidth and $N_{sta}$. However, when WiZizz is used, the efficiency increases with the increase of the bandwidth and $N_{sta}$, because our approach not only saves the energy cost significantly but also its overhead can be neglected thanks to our judicious decision using Eqs. (8) and (9) and efficient MAC of 802.11ac. Note that frame aggregation features of 802.11ac amortizes the overhead over multiple aggregated frames. In particular, the maximum 3.9x energy efficiency can be achieved when the station operates on 160 MHz bandwidth while contending with 20 stations.

Fig. 9(d) shows the impact of $N_{ant}$, where $N_{sta}$ is 20. The energy-saving ratio of WiZizz over the baseline (i.e., $P_{baseline}/P_{WiZizz}$) increases as $N_{ant}$ and bandwidth increase. Shortly, when more $N_{ant}$ and/or wider bandwidth are used, WiZizz can save more energy.

C. Comprehensive Traffic Patterns

In order to evaluate the effectiveness of WiZizz in a more general environments, we have implemented various types of traffic, such as voice over IP (VoIP), web browsing, and file transfer protocol (FTP) in $ns$-3 [26–28]. Stations are randomly scattered on a disk around the AP with radius of 50 m, and use ideal rate adaptation which selects the optimal MCS maximizing throughput. We consider both small and large scale networks, where $N_{sta}$ is 20 and 50, respectively.

Regardless of the traffic pattern and network size, WiZizz consistently outperforms the baseline 802.11ac as shown in Fig. 9(e). Specifically, WiZizz reduce about 55% and 60% power consumption compared with the baseline 802.11ac in small and large network, respectively. This is due to the fact that $P_{baseline}$ increases as network size increases while WiZizz stations consume the same power regardless of network size thanks to the PHY-level filtering.

D. Collaboration with SMPS

Last, we additionally evaluate the performance of WiZizz inter-playing with dynamic SMPS (WiZizz+SMPS), which minimizes idle power from MIMO features. The collaboration allows a station to operate with only one antenna and the narrowest bandwidth for a significant portion of time. As shown in Fig. 9(e), WiZizz+SMPS shows the least power consumption over all comparative schemes for all tested environments. To conclude, our approach works independently of other power saving schemes, such as SMPS and PSM, and hence the joint use of them is helpful to further minimize WiFi energy cost.

IX. CONCLUSION

In this paper, motivated by our accurate modeling and extensive measurements of the commercial 802.11ac hardware, we have proposed WiZizz, a practical, standard-congenial bandwidth management that achieves remarkable energy saving. The primary contribution of WiZizz is to minimize the avoidable power consumption in idle and RX state by utilizing the duplicate frame format defined in 802.11ac standard. We demonstrate its benefits and feasibility via open source device driver prototype implementation and network simulation. We envision WiZizz to be a strong and practical battery saver for future WiFi systems.

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