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Towards an energy-efficient Wi-Fi: An experimental study on recent standards power consumption

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Abstract—This paper presents a study of the current consumption of various Medium Access Control (MAC) states for Wi-Fi devices, focusing on the latest IEEE 802.11ax (Wi-Fi 6) and 802.11ac standards. Through detailed experimental measurements, we provide new, precise values for the current drawn in MAC states such as idle, transmission, reception, and sleep. We capture real-time current consumption in different scenarios with various traffic loads, offering an understanding of the power usage across different operational modes. The results reveal significant differences in power consumption patterns compared to earlier Wi-Fi standards (e.g., 802.11n), with notable improvements in energy efficiency in sleep and idle states, but increased current draw in transmission and reception states. These findings provide valuable insights into the energy behavior of recent Wi-Fi devices, offering a solid basis for the simulation of power management optimization strategies in next-generation wireless systems.

I. INTRODUCTION

Energy efficiency in wireless communications has become a key challenge, especially as wireless networks are at the core of modern mobile devices. Wi-Fi has emerged as the principal supporting technology to the cellular technologies used in mobile devices where battery life is a primary concern.

Since the IEEE 802.11a and b releases in 1999, Wi-Fi technologies continued to increase speed, range, efficiency and number of associated devices. IEEE 802.11g, introduced in 2003, has become the norm during that era combining the speed of 802.11a and the range of 802.11b. Taking advantage of using two bands (2.4 GHz and 5 GHz) and multiple antennas (MIMO), IEEE 802.11n extended the range, the speed and reliability with a better interference management. Focusing on the 5 GHz band, the channel bonding and the introduction of MU-MIMO, IEEE 802.11ac dramatically improved the speed. More recently, the introduction of OFDMA (Orthogonal Frequency Division Multiple Access), the 6 GHz band or the Target Wake Time allows IEEE 802.11ax to further increase the speed, reduce the power consumption and effectively manage dense networks. Simultaneously, other standards emerged such as IEEE 802.11ah as alternatives to IoT technologies, operates at 900 MHz and focus on energy efficiency with RAW and TWT mechanisms [1]. Finally, the last Wi-Fi standards such as IEEE 802.11be or IEEE 802.11ay introduce new technologies such as 4096-QAM modulation and 320 MHz channel bandwidth

or 60 GHz channels to accommodate the increasing demand of bandwidth in modern applications [2].

Accurately measuring the power used by Wi-Fi modules remains a challenging task due to the diversity of modern hardware and operating modes. New features such as MIMO (Multiple Input, Multiple Output), channel bonding, and adaptive modulation schemes have added complexity.

Conducting power consumption measurement experiments on Wi-Fi devices represent several challenges due to the complex and dynamic nature of Wi-Fi communications. Multiple factors impact significantly the power usage of the Wi-Fi transmitter such as the strength of the signal, the traffic patterns, the environmental conditions (interference or network congestion). Furthermore, advanced features such as MIMO, power saving mechanisms, adaptive transmission power, or even beam-forming can complicate the measurement by introducing variable consumption patterns. In addition, there is no standardized measurement process to capture the microsecond-level fluctuations of Wi-Fi transmitters. Wi-Fi devices interact with other system components such as CPU and memory leading to inter-dependencies that make measurement difficult to isolate. Moreover, the heterogeneity of Wi-Fi standards and implementations add more complexity, as different devices may behave each in their specific way. Consequently, conducting an accurate and precise power consumption measurement experiment on Wi-Fi devices requires careful control of external factors and the use of specialized tools able to capture detailed power profiles over various states of operation.

In this paper, we conduct an experimental evaluation of the power consumption of a selection of USB Wi-Fi devices, focusing on the latest standards such as IEEE 802.11ax and IEEE 802.11ac. Using USB devices allows to isolate Wi-Fi behavior and to provide accurate measurements in the different MAC states: idle, transmitting, receiving, and sleeping. Such power measurement values remain scarce in the literature [3], although they are required for any simulation-based evaluation as input parameters, for instance in the well-know ns-3 simulator.

In the following, we first review the related work and methodologies used in prior research in Section II. Then, we describe our experimental setup and the measurement protocol in Section III. We detail our measurement results in

Section IV, and we propose a comparative evaluation of the ns-3 energy model for Wi-Fi using default parameters and our measurements in Section IV. Finally, we conclude with insights and potential future work directions in Section VI.

II. RELATED WORKS

Various studies have investigated the energy consumption of Wi-Fi networks. Early work focused on 802.11a/b/g standards, which operated on basic hardware configurations. In 2010, Halperin *et al.* [4] conducted an experimental study on the consumption of IEEE 802.11n Intel 5300 transmitter, investigating the power consumption during transmission, reception and idle phases with various antennas scenarios, such as single or multiple antennas. The Wi-Fi energy model of the discrete event simulator software ns-3 is based on the power values they obtained [4]. To this day, the default values used by the Wi-Fi energy model of the ns-3 simulator remains unchanged and are still based on this 2010 chip¹. Furthermore, the idle, CCA_busy and switching current default values of the actual ns-3 energy model have the same value of 273 mA.

Di Piazza *et al.* [5] investigated the impact of transmit power control in IEEE 802.11n Wi-Fi networks. Results of the experimentation are obtained using an USB Wi-Fi card with a 500 MHz oscilloscope measuring the voltage at a resistor in series on the ground wire of the USB cable in order to capture the current drawn during the different frame operations. Their findings indicate that reducing transmission power has a negligible impact on the energy savings.

Underlining the non-trivial aspect of measuring Wi-Fi power consumption, Li Sun *et al.* propose in [6] an experimental study of active energy modeling in smartphones on both IEEE 802.11n and 802.11ac NICs. Both experimental setups rely on a smartphone as a STA and a PC as an AP. Their results show that most of the energy models used in the literature are based on a linear power-throughput model where the accuracy can dramatically drop with high throughput scenarios.

In [7], Andres Garcia-Saavedra *et al.* introduce a cross-factor to represent the non-negligible part of power consumed by a system while using a WLAN device. They provide an energy model to show how the per-frame power consumption is related to different levels of the network protocol stack. However, the experimental setup relies on a IEEE 802.11a/b/g Wi-Fi transmitter and a relatively slow power meter (3 samples per second).

Pablo Serrano *et al.* extended the previous work in [8] by conducting an extensive measurement experimentation on seven devices of different types, including routers, smartphones and embedded devices. They show that the size of the frame has a minimal impact on the energy consumption.

Sebastien Maudet *et al.* present in [9] an experimental measurement of the energy consumption of a IEEE 802.11ah (Wi-Fi HaLow) EVK. The current drawn by the Wi-Fi STA is measured by a high precision current analyzer showing

¹See for the last ns-3 version: https://www.nsnam.org/docs/release/3.43/doxygen/de/d4d/wifi-radio-energy-model_8cc_source.html

TABLE I: Experimentation list of Devices

Device	Reference	Wi-Fi Chipset
TPL3	TP-Link TX20H in USB 3.0 (802.11ax)	RTL8852AU
TPL2	TP-Link TX20H in USB 2.0 (802.11ax)	RTL8852AU
NG	Netgear A8000 in USB 3.0 (802.11ax)	MT7921AU
Asus	Asus USB-AX55-Nano USB 2.0 (802.11ax)	RTL8852AU
DL	D-Link DWA-X1850 (802.11ax)	RTL8852BU
T3U3	TP-Link T3U Plus in USB 3.0 (802.11ac)	RTL8812BU
T3U2	TP-Link T3U Plus in USB 2.0 (802.11ac)	RTL8812BU
T2U	TP-Link T2U Plus in USB 2.0 (802.11ac)	RTL8812AU

highly accurate measurement values. Despite the precision of the results, this work is focused on a protocol that is tailored to minimize energy consumption, and the hardware tested is highly specialized, which could not be applicable to generic energy models.

In [10], Longhair Zoo *et al.* propose an experimental protocol to measure the power consumption of a smartphone using either Wi-Fi or LTE communication. The monitoring of the power consumption is based on an Arduino board measuring the voltage at a resistor placed in series with the battery of the smartphone. As the purpose of the contribution is to compare the consumption of the two technologies depending on the bit-rate of a video played on the smartphone, the relatively low-cost measurement platform cannot provide highly accurate values of power consumption.

A power monitoring evaluation methodology focused on the AP side is conducted in [11]. Authors show a linear behavior of the consumption on IEEE 802.11n/g until reaching a saturation point. However, this study addresses the consumption on large amounts of data, the monitoring resolution cannot meet the requirements to show the power consumption at the scale of the state of operation of the Wi-Fi transmitter.

Finally, an energy consumption demonstrator is presented in [12], where the power consumption of the Wi-Fi communication of a Wi-Fi lamp, an access point and a smartphone are measured. The protocol to measure the Wi-Fi lamp consumption is similar to previous works by using a shunt resistor in series with the power supply of the communication board based on a Redpine-Signals Wi-Fi chip. The authors focus on the comparison of the energy consumption of the two different operations modes of Wi-Fi (infrastructure and ad-hoc), the power consumption of the different phases of operation is not addressed.

Most of the previously cited work are either quite old measurements on not up-to-date Wi-Fi standards, inaccurate measurements due to low-quality power monitoring devices or not generic measurements done in the context of a particular application or hardware. In the following, we present our set of experimental values obtained on several hardware in each



Fig. 1: 802.11ac/ax Current Measurement setup

MAC state.

III. EXPERIMENTATION PROTOCOL

A. Overview

Our experimentation protocol is designed to measure the energy consumption of Wi-Fi devices across different operating states: transmission (Tx), reception (Rx), idle, sensing when the channel is busy (CCA_busy) and sleep. We utilize specialized hardware and software to capture real-time energy data, ensuring accurate readings. The testbed consists of modern Wi-Fi chipset (802.11ac and 802.11ax), a power measurement tool with 100k sample per second resolution, and a controlled network environment to minimize external interference.

The protocol involves systematic measurement of each device listed in Table I, considering various factors like the target data rate, the transport protocol used (TCP or UDP), and the direction of the traffic (reception or transmission). By repeating each experiment multiple times under controlled conditions, we ensure that the results are reproducible and statistically significant.

B. Experimental Setup

The test bench used is pictured in Figure 1. It consists of an AP, a STA and an Ethernet client. The STA is the only Wi-Fi device associated to the AP. We run the experimentation with six different models of USB Wi-Fi cards, each USB device with their corresponding Wi-Fi chipset is listed in Table I, the AP is a IEEE 802.11ax Tp-Link Archer AX50. The STAs are connected to a Dell Latitude laptop (Intel Core i7 2.80 GHz CPU, 32 GB of RAM) running Windows 10, capable of saturating the 802.11ax/ac link using iperf [13] benchmark. The Ethernet client is connected using an USB-C 1000 Mbps Ethernet adapter on an Apple MacBook Pro (Intel core i9 2.4 GHz, 16 GB of RAM) running iperf application on Mac OS 14.5. A Nordic Semi Power profiler II power meter is interconnected between the STA and the Windows PC on the power supply line of an USB extension cable. For some scenarios, we use both USB3 and USB2 cables. The monitoring of current consumption is managed by the Power Profiler application on the Windows PC. In the experiment, the AP is configured to deliver its maximum transmission power and all the USB Wi-Fi cards are configured to use the IEEE 802.11ac or IEEE 802.11ax when available, maximum transmission power and

TABLE II: Experimentation Parameters

Parameter	Value
Topology	One AP one STA
Number of different STA	6
Distance AP - STA	1 meter
Environment	Office
Tx Power	Max
Sample per second	100,000
802.11ax specs	1201Mbps, Channel 44 (80MHz wide)
802.11ac specs	866Mbps, Channel 46 (40 MHz wide) (T3U)
802.11ac specs	433Mbps, Channel 46 (40 MHz wide) (T2U)
Frequency	5Ghz
Traffic time	10 sec
Traffic data rate	1 / 10 / 50 / 100 / 200 / 500 / 1000 / 2000 Mbps

USB-3 when available. The AP broadcasts its SSID on channel 5220 MHz and a bandwidth of 80 MHz, MIMO is enabled, the beacon interval is set to 1000 ms, the DTIM interval is configured to its maximum 15 times the beacon interval, the guard interval is left to normal (800 ns).

Each STA device is configured to operate at its maximum speed, with a fixed channel width (40 MHz for IEEE 802.11ac devices and 80 MHz for the IEEE802.11ax devices). We also introduce different levels of network traffic in the iperf benchmark to simulate real-world scenarios.

C. Measurement Methodology

The measurements are carried out by sending and receiving large data packets under different configurations. The power consumption is measured at the STA side of the test bench during various phases: wake-up, data transmission, reception, sleep and idle periods between transmissions. The current consumption data are collected with the Nordic Semi Power profiler Kit II [14] with a sampling period of 10 μ s and a granularity of 100nA. It has to be noted that our current measurement methodology monitors the entire USB device, which includes the Wi-Fi chipset, the RF transceiver and amplifier, the antennas, a LED, the firmware memory and the USB controller. Consequently, the measured current value includes the USB controller which, depending on the components and the data load, could highly vary.

AP and STA are deployed in a indoor environment, with a short distance of 1 meter between each other in order to have a strong link quality and the highest modulation scheme negotiated with the AP to reach the maximum throughput available. As the STA is configured to deliver its maximum transmission power, changing this distance has no influence on the STA power consumption. The transmission scenario is based on an iperf client running on the STA laptop which generates TCP or UDP flows towards an iperf server running on the Ethernet laptop. The reception scenario is the opposite, where the iperf server is located on the STA laptop. Consequently, there is no power measurement on the AP device, our experimentation is focused on the STA device.

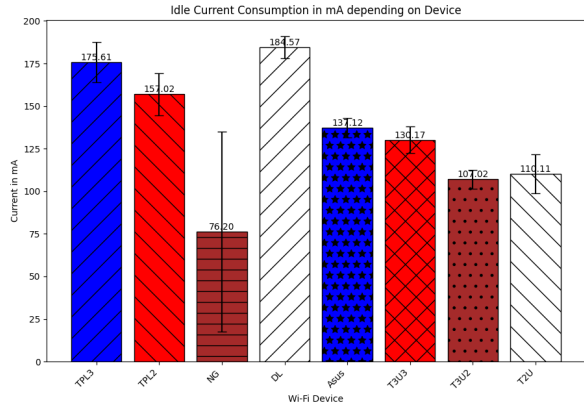


Fig. 2: Idle current consumption depending on STA device

The results reported in this study are as follow: the current transmission or reception value correspond to the maximum value collected during a 10 seconds transmission or reception scenario. The idle current value corresponds to the averaged current value observed between two beacons in a period without any traffic. The CCA_busy current value corresponds to the maximum value observed at the measured STA during a high transmission phase on a second STA associated to the AP. For the variable traffic, we adopt the following parameters: we vary the target data rate from 1 MB/s to 2000 GB/s according to the values displayed in II.

IV. CONSUMPTION MEASUREMENTS ON REAL HARDWARE

In the following, we provide the experimental results obtained for each of the considered MAC states.

A. Idle power consumption analysis

We define the idle state as the state when the STA, being associated with the AP, neither sends nor receives traffic. As the STA is the only device associated with the AP, only signaling is to be reported on the link. The idle current phase is then observed between two peaks of current corresponding to the beacons received from the AP. Figure 2 shows the mean value of the current consumption measured across multiple tests for each device. The whiskers illustrate the standard deviation of the measurements, showing a low variability of the idle current consumption, except for the D-Link DWA-X1850 device having a lower average idle current consumption with a high variability leading to a difficult interpretation of the different states of this particular device. Apart from the D-link device, all other STA are roughly within the same order of magnitude, the main difference can be observed between USB3 and USB2 links, the latter being less energy-intensive. The TP-Link TX20H and the Asus AX55-Nano sharing the same Wi-Fi chipset, but having a different USB interface, they show a reduction of 20% of the idle current consumption.

B. CCA Busy power consumption analysis

In order to capture the current drawn by the STA when sensing an occupied channel, we associate a second STA to

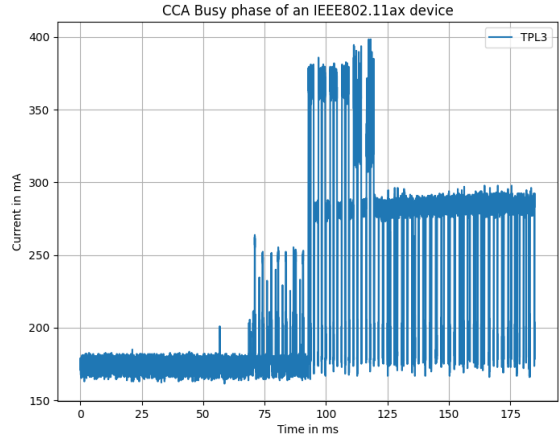


Fig. 3: Current measurement of the CCA Busy state

TABLE III: Instantaneous transmission and reception current values

Device	Tx Current	Rx Current
TPL3	630 mA	289.27 mA
TPL2	610 mA	240.59 mA
NG	550 mA	106.85 mA
DL	720 mA	289.07 mA
Asus	485.42 mA	179.76 mA
T3U3	436.22 mA	258.45 mA
T3U2	418.85 mA	246.16 mA
T2U	630 mA	117.21 mA

the AP, on the same channel, with the same parameters. We measure the current on an STA device when the new associated STA is receiving traffic from the Ethernet laptop, saturating the link. Results of this scenario are shown on Figure 3. This scenario is conducted using the Tp-Link TX20H connected in USB3, showing an average current consumption of 280 mA.

C. Transmission power consumption analysis

To characterize the transmission phase of the STA device, we conduct two different analyses. We first measure the maximum instantaneous value of current drawn by the device during a transmission phase for each STA device, at the scale of a packet. Secondly, we measure the power consumption of each STA device during a transmission phase of 10 seconds depending on the target bandwidth at the client side.

The results of the first experiment are shown in Table III. It has to be noted that the precision of the Nordic Semi Power Profiler Kit depends on the range of current measured. Above 500 mA, the precision of the power meter is decreased to 10 mA.

The results of the second experiment are shown in Figure 4. Both Figure 4a and Figure 4c show that increasing the target bandwidth has a low impact on the current consumption of the Asus device. This may be explained by the conception of the device itself, where the chipset used (RTL8852AU IEEE 802.11ax) is coupled to a USB2 interface which is not fast

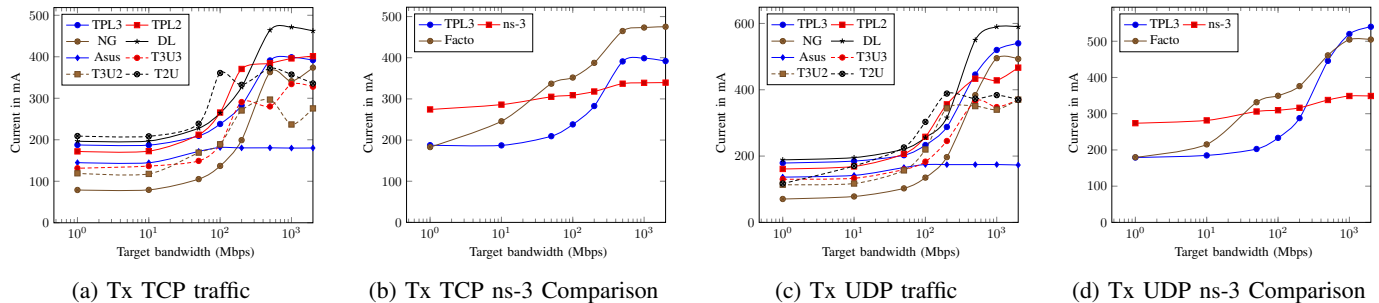


Fig. 4: Transmission scenario experiment results

enough to saturate the maximum data-rate reachable with this Wi-Fi chipset. Except the Asus device, all the other tested devices show a similar behavior when increasing the target bandwidth. Unsurprisingly, the current consumption is lower for an UDP traffic when the traffic is slow but reaching the highest data rates, having a faster throughput, the current drawn at high speed is higher compared to a TCP traffic.

D. Reception power consumption analysis

To characterize the reception phase of the STA device, we conduct the same analysis described in the transmission section but the iperf server is located on the STA laptop and the client sending data is located on the Ethernet laptop. We first measure the maximum instantaneous value of current drawn by the device during a reception phase for each STA device, at the scale of a packet. Secondly, we measure the power consumption of each STA device during a reception phase of 10 seconds depending on the target bandwidth at the client side. The results of the first reception experiment are shown in Table III. The results of the second experiment are shown in Figure 5. Both Figure 5a and Figure 5c show that each measured STA has a similar behavior, only differentiated by the idle current consumption as an offset. We can observe a slightly higher increase of current consumption when using TCP compared to UDP on each STA.

E. Impact of the USB connection and USB interface consumption

Most of today Wi-Fi USB sticks can operate on USB3.0 which is capable of delivering a higher current than USB2.0. To evaluate the difference inducted by this connection, we compare the current consumption of a USB3 device connected on a USB2 port to the regular consumption with a USB3.0 connection. We can observe both on the IEEE 802.11ax and 802.11ac devices compared in USB3 and USB2 that connecting an USB3 Wi-Fi STA in an USB2 port result in a slight decrease of the overall current consumption of the STA. However, our findings confirm that most of USB3.0 devices take an overall profit of the higher capabilities of the USB3.0 connection, drawing more current, especially during transmission operations. Furthermore, USB3 modern controllers are more efficient than previous USB2 controllers, but it has to be mentioned that a non negligible part of the consumption

measured in each STA in this experiment is attributable to the USB controller itself.

V. USING THE OBTAINED EXPERIMENTAL VALUES WITHIN SIMULATION TOOLS

Simulator frameworks, such as ns-3, can take advantage of the current values obtained in the previous section.

A. ns-3 Energy Model

The popular discrete event network simulator ns-3 propose a Wi-Fi energy model that provide a detailed framework to estimate the power consumption of Wi-Fi devices by capturing their behavior across different operational states, such as transmission (Tx), reception (Rx), idle, sleep and CCA_busy. Each state can have a specific power consumption profile, and the model calculates the total energy usage of the device by logging the time spent in each state and multiplying these times by the corresponding power value. This energy model is integrated in the simulator Wi-Fi protocol stack, which includes the support of various IEEE 802.11 standards from 802.11a to 802.11ax and allows to take into account the factors of influence of each standards specificity on the power consumption. It also accounts for power-saving mechanisms such as PSM and TWT. Apart from the energy model, an energy source is also defined and simulated, such as a battery, which allows to analyze how communications affects the depletion of device energy over time. For instance, by simulating battery consumption, the model offers insights on device operational lifetime under different network conditions or implementations. The energy model allows users to define custom power consumption values for each state to accommodate new standards or devices. Despite its versatility, the accuracy of the ns-3 Wi-Fi energy model highly depends on precise calibration with real-world power measurements. Furthermore, the evolution of Wi-Fi technologies require updates to the energy values in order to account for the specificity of each standard.

Despite the large adoption of the ns-3 Wi-Fi model, and furthermore, its energy model, few studies have considered updating the default values and behavior to modern Wi-Fi devices, particularly those implementing 802.11ac and 802.11ax. Our work tries to provide new values and recommendation to improve the accuracy and the realism of future simulations of Wi-Fi architectures.

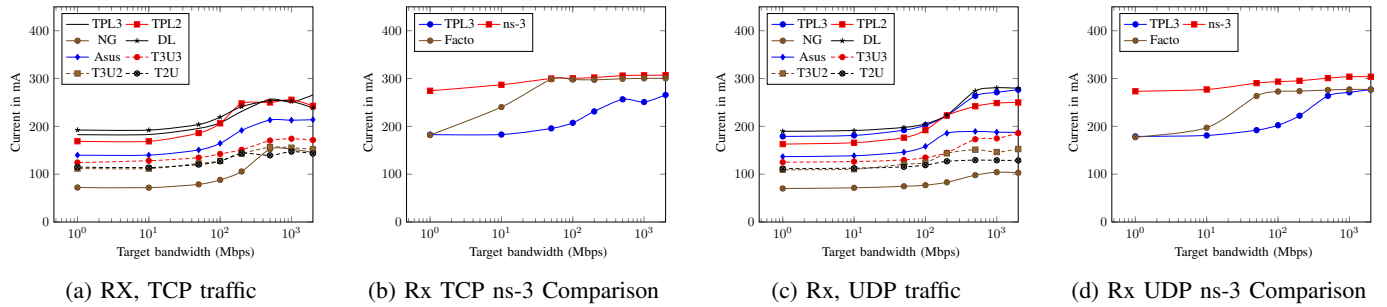


Fig. 5: Reception scenario experiment results

B. Comparing ns-3 current instantiation with our own

We compare results obtained with the default ns-3 values against results obtained with the ns-3 models instantiated with the consumption values measured in Section IV.

We select the values measured on the most stable STA device (having the smallest standard deviation on all measured current values), the Tp-Link TX20H. We create a simple Wi-Fi scenario consisting in a unique STA associated to an AP, with the same parameters as described in our test-bed.

Figure 4b, Figure 4d, Figure 5b and Figure 5d show a comparison of the measured current values for the second experiment for the Tp-Link TX-20H connected in USB3 (*TPL3*), with the default current values of the ns-3 Wi-Fi energy model (*ns-3*) and the ns-3 energy model updated with our current values (*Facto*). Focusing on the transmission, no matter the transport protocol used, we show that the default ns-3 model can be close to the measured values only for medium data rates, but the model updated with our values offer a similar behavior despite having a slight offset. Results on the reception show a better accuracy of the ns-3 model with higher data-rates. The ns-3 model updated with our current values shows a slightly more comparable behavior with our measurements, but shows differences with medium data rates.

VI. CONCLUSION

This paper introduces a comprehensive experimentation protocol for measuring the energy consumption of modern Wi-Fi devices. Our results demonstrate the complexity of energy usage in Wi-Fi networks, especially when considering devices with advanced features like MIMO, channel bonding, and adaptive modulation.

The findings suggest that a careful selection of current values in ns-3 energy model, especially the idle and transmission values, can significantly precise the power consumption and increase the accuracy of energy efficiency improvement studies.

Future work will focus on extending these experiments to more complex network environments and newer Wi-Fi standards, such as 802.11be. We also plan to explore the impact of dynamic network conditions, such as interference and mobility, on energy consumption, as well as a detailed analysis on the current consumption during the wake-up phase of an STA device.

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