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# A Comprehensive Study on Enterprise Wi-Fi Access Points Power Consumption

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**ABSTRACT** Wi-Fi networks are becoming more and more ubiquitous and represent a substantial source of energy consumption around the globe, mainly when it comes to Access Points (APs). There has been some work done on the characterization of the power consumption of Wi-Fi APs and network interface cards (NICs), and the power usage of these devices under different configurations and standards but mostly using legacy standards. A detailed AP power consumption analysis, exploring the whole set of degrees of freedom and capabilities of these devices is lacking in the state of the art. In this paper, we present a thorough power consumption analysis, covering the configuration options available in enterprise Wi-Fi APs from the three major vendors on the market. The goal is to understand how the power consumption of an AP varies with the different configurations, and provide insights on the parameters that significantly affect the AP power consumption. The obtained experimental results confirm previous state-of-the-art conclusions but contradict some of the studies and results found in the literature, while updating results and conclusions taken in the past to the most recent standards, configurations, and data rates available today. The analysis provided herein is a valuable source of information for deriving new AP power consumption models and designing energy-efficient Wi-Fi networks.

**INDEX TERMS** Access point, power consumption, energy efficient networks, green WLANs, Wi-Fi.

## I. INTRODUCTION

IEEE 802.11 networks (also known as Wi-Fi networks) continue to grow in traffic and in the number of network devices. Current Wi-Fi networks have an unprecedented number of client devices associated, also known as stations (STAs), as well as a number of network infrastructure devices, named APs. However, these APs are not used 100% of the time, which leads to substantial energy wastage in the network within periods of low user count, such as night-time, weekends, and holidays. In order to devise algorithms and mechanisms that can reduce the current Wi-Fi networks energy bills, especially in medium/large enterprises and in public areas, such as university campuses, airports, and hospitals, a deep understanding of how power is consumed by the APs is needed.

The Information and Communications Technology (ICT) sector shows a foreseeable impact on the energy consumption of the globe due to the current unsustained drivers [1]. Since the number of network devices is growing exponentially, and, especially after the near future impact of the Internet of Things (IoT), Wi-Fi traffic and the corresponding energy consumption will continue to grow. According to [2], 80% of all wireless traffic is generated or terminated indoors, where Wi-Fi is the main access technology. In [3] it is predicted that Wi-Fi will generate almost 50% of all Internet Protocol (IP) traffic in the world by 2021. The increasing traffic and number of devices demand new strategies to reduce the energy consumption of the Wi-Fi infrastructure. In turn, these strategies need a solid analysis of the energy consumption of the devices, namely the APs, in order to provide the necessary understanding of their behavior under the different possible network conditions and configurations.

Existing work on energy consumption of Wi-Fi devices has mainly been focused on Wi-Fi NICs. Wi-Fi NICs are present in laptops, smartphones, and APs. However, APs show very different characteristics than client devices (STAs): they are expected to handle larger amounts of traffic, a large number of STAs, and run 24 hours a day. Thus, analyzing the energy consumption of a single, isolated NIC leads to misleading

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conclusions and results. The power consumption and energy efficiency per bit analysis should be done from a holistic point of view, looking at the device as a whole, and not simply at some of the components present inside the device, such as the NIC alone.

To the best of our knowledge, there is not a comprehensive study on the power consumption of enterprise APs available in the state of the art. On the one hand, some of the works are outdated, not considering the latest Wi-Fi standards (e.g., IEEE 802.11n/ac); on the other hand, most of the work done so far is focused on client devices, such as smartphones and laptop computers, and is performed using lab prototypes instead of real commercial equipment, which makes their conclusions hard to extrapolate to real network infrastructure devices.

The main contribution of this paper is a comprehensive analysis of the power consumption of enterprise Wi-Fi APs, considering the variation of several configuration parameters. The goal is to accurately assess the power consumption of enterprise Wi-Fi APs under several common and possible configurations, allowing the scientific community to: 1) better understand the power consumption of Wi-Fi APs; 2) devise more realistic AP power consumption models, which may even be integrated in existing simulators; 3) design new suitable mechanisms and algorithms for reducing the energy consumption of Wi-Fi APs.

This paper is organized as follows. In Section II we define basic terms and concepts that are necessary to understand the rest of the contents of the paper. In Section III, we review the IEEE 802.11 standard and its amendments, focusing on the main configuration options. Section IV presents the state of the art review. Section V describes the methodology used for gathering power measurements and the Wi-Fi network setup employed. In Section VI, we present the power consumption results obtained for the several configurations tested. In Section VII, we discuss the results obtained and evaluate the validity of the measurements. Finally, in Section VIII we draw the main conclusions and refer the future work.

## II. GLOSSARY

In this section, we define a set of basic terms and concepts that are used throughout the paper.

**Energy efficiency**: a measure of the reduction in power consumption over time.

**Enterprise Wi-Fi AP**: a commercially available AP mostly used in enterprise and public facilities, deployed and configured in standalone mode or through the use of a controller. A Wi-Fi network can contain several of these APs spread out through a building.

**Idle Mode**: the mode in which the device is not transmitting nor receiving any frames. In this mode, one or more radio interfaces may be switched off. If all interfaces are switched off, we call this the Standby state (see definition below).

**Power efficiency**: the measure of the reduction in instantaneous power consumption.

**RX Mode**: the mode in which the device is receiving frames. The IEEE 802.11 standard implies the transmission of an Acknowledgement (ACK) and a certain period of inactivity for medium access. Herein, RX Mode represents the activity on the radio interface of the device while receiving frames and transmitting the corresponding ACK.

**Standby State**: the state in Idle mode in which the device has all its radio interfaces switched off, but the device itself is switched on.

**TX Mode**: the mode in which the device is transmitting frames. The IEEE 802.11 standard implies the reception of an ACK frame and a certain period of inactivity for medium access. Herein, TX Mode represents the activity on the radio interface of the device while transmitting frames and receiving the corresponding ACK.

## III. BACKGROUND ON THE IEEE 802.11 STANDARD

This section presents an overview of the IEEE 802.11 standard and its amendments, along with the main features of interest for the power consumption analysis presented in this paper. A detailed explanation of the physical (PHY) and Medium Access Control (MAC) layers considered by IEEE 802.11 is presented, and the multiple IEEE 802.11 amendments are covered in chronological order.

Wi-Fi is currently the main wireless Internet access technology, using two different frequency bands. The 2.4 GHz frequency band was first released for industrial, scientific, and medical purposes (ISM band). This frequency band covers the spectrum of frequencies between 2.4 GHz and 2.5 GHz. Later, more spectrum was released with the Unlicensed National Information Infrastructure (U-NII)-1, U-NII-2, and U-NII-3 bands, using spectrum in the 5 GHz frequency band.

Over the years, the IEEE 802.11 standard has been evolving through several amendments, improving both PHY and MAC layers. Due to the nature of the unlicensed spectrum used by Wi-Fi communications, the transmission (TX) power is limited by legal regulations. These regulations may vary by country and by the frequency band in use, with the MAC layer always assuming the existence of interference due to the use of unlicensed frequency bands. Other devices may be using the spectrum and multipath fading (a physical phenomenon in which multiple copies of the transmitted signal reach the receiver by multiple paths, with delay [4]) may lead to situations in which frames are not well received or are received with errors. Because of the shared medium, collisions may also occur (i.e., two STAs send frames at the same time, making the information unintelligible to the receiver). To overcome the problem, all effectively received frames must be acknowledged – a failure in the ACK is interpreted as a frame loss. The essence of the IEEE 802.11 MAC layer lays in the Distributed Coordination Function (DCF). DCF is the basis of the standard Carrier Sense Multiple Access/Collision Avoidance

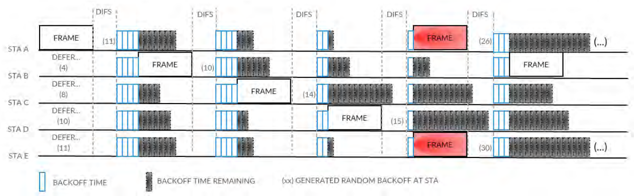


**FIGURE 1.** Illustration of the DCF procedure with frame transmissions and a collision [5].

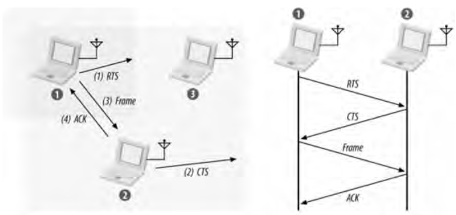


**FIGURE 2.** RTS/CTS procedure. (1) STA1 sends a RTS to STA2 which is not received by STA3 (a hidden node). (2) STA2 sends a CTS which is heard by STA1 and STA3, preventing any eminent transmission of the latter. (3) The frame is transmitted from STA1 to STA2. (4) ACK frame is sent from STA2 to STA1 [7].

(CSMA/CA). This procedure checks whether the medium is clear before any transmission is performed (i.e., listen before talk). In order to avoid collisions with other clients on the network, a random backoff is used. Figure 1 illustrates how DCF works, where each STA chooses a random backoff, and attempts a transmission after waiting the number of backoff slots. A collision occurs when two STAs have the same backoff number.

A random backoff is a number uniformly distributed in the interval $[0, CW[$, in which CW represents the current Contention Window size. After a frame collision, a retransmission is attempted using a CW value twice the value considered in the previous transmission attempt, up to a maximum CW of 1024. After seven attempts, the frame is discarded. Once a transmission is successful, CW is reset.

One important aspect of the MAC layer mechanisms is the presence of hidden nodes. Hidden nodes occur whenever carrier sensing fails between two devices and both can transmit at the same time, triggering a collision at the receiver. One way to avoid the presence of hidden nodes is the use of Request To Send/Clear To Send (RTS/CTS) control frames. Figure 2 shows how collisions can be avoided using RTS/CTS; the cost is air time, damaging aggregate throughput [6].

The PHY layer is the layer responsible for transmitting bits to the air using the antenna. It incorporates a Clear Channel Assessment (CCA) information to indicate the MAC layer the channel is busy when a radio frequency (RF) signal is detected. The PHY layer has immensely evolved over the several IEEE 802.11 amendments and has been the main source of improvement of the technology. Each of those evolution moments is expanded in the next subsections, pointing out the main MAC and PHY improvements that have been taking place throughout the history of IEEE 802.11.

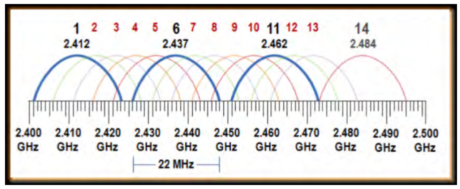


**FIGURE 3.** 2.4 GHz spectrum showing the three non-overlapping channels [8].

**TABLE 1.** IEEE 802.11a data rates.

| Data Rate (Mbps) | Modulation and R | Coded bits per carrier | Data bits per symbol |
|---|---|---|---|
| 6 | BPSK, R=1/2 | 1 | 24 |
| 9 | BPSK, R=3/4 | 1 | 36 |
| 12 | QPSK, R=1/2 | 2 | 48 |
| 18 | QPSK, R=3/4 | 2 | 72 |
| 24 | 16-QAM, R=1/2 | 4 | 96 |
| 36 | 16-QAM, R=3/4 | 4 | 144 |
| 48 | 64-QAM, R=2/3 | 6 | 192 |
| 54 | 64-QAM, R=3/4 | 6 | 216 |

### A. IEEE 802.11-1997 AND IEEE 802.11A/B/G

In 1997, the IEEE 802.11 standard was published and defined three radio technologies for communications: Frequency-Hopping (FH) spread-spectrum, Direct-Sequence (DS) spread-spectrum, and Infrared light (IR) [7]. The three technologies offered very limited data rates, which determined the need for new mechanisms for spectrum efficiency and improved data rates. DS divided the 2.4 GHz spectrum into 14 channels, each of them 5 MHz wide, thus allowing three non-overlapping channels. Figure 3 shows the current layout of non-overlapping channels for the 2.4 GHz frequency band. The modulations used were Differential Binary Phase Shift Keying (DBPSK), with a maximum data rate of 1 Mbps, and Differential Quadrature Phase Shift Keying (DQPSK), with a maximum data rate of 2 Mbps.

In 1999, two new amendments to the standard were proposed, IEEE 802.11a and IEEE 802.11b. While IEEE 802.11b explored the 2.4 GHz frequency band, improving the legacy technologies and allowing faster data rates, IEEE 802.11a was solely focused on a new frequency band (5 GHz), which gradually became available throughout the world [7]. IEEE 802.11a considers a new PHY layer using Orthogonal Frequency Division Multiplexing (OFDM). OFDM divides a channel into subcarriers, and the spacing between subcarriers is said to be orthogonal; at the peak of each subcarrier, the other subcarriers have zero amplitude and do not interfere with each other.

OFDM defines a guard interval (GI) to avoid multipath interference. For IEEE 802.11a it is set to 800 ns. Error correction is also applied in OFDM, using convolution coding, in which the rate R specifies the number of data bits transmitted per code. $R = \frac{1}{2}$ means the transmitter sends one data bit for every two code bits for robustness purposes.

By using OFDM, the 20 MHz channel is divided into 52 subcarriers. Since 4 of those subcarriers are used as pilot carriers, for monitoring path shifts and Inter Channel

Interference (ICI), there are 48 subcarriers available in a 20 MHz channel for actual data transmission. Table 1 shows the PHY data rates, modulations, and coding rates used.

The data rates that are shown in Table 1 are PHY data rates, which means that the MAC level data rate will be the result of the packets successfully received, minus the headers and trailers of the PHY framing, minus the time consumed in resolving collisions, sending ACKs, and performing random backoffs.

IEEE 802.11b continued to improve the 1997 standard in the 2.4 GHz frequency band by using DS, but including Complementary Code Keying (CCK), since further enhancements in phase shifts from DQPSK would require processing even smaller phase shifts, in which multipath becomes a serious hindrance. CCK divides the chip stream into a series of 8-bit code symbols, encoding 4 bits (for a maximum rate of 5.5 Mbps) or 8 bits (for a maximum rate of 11 Mbps), hence the name High Rate DS (HR/DS) [7].

While IEEE 802.11a focused on taking advantage of a new spectrum that became available, with no legacy technologies involved, by 2003 the 2.4 GHz frequency band was already crowded with legacy equipment, namely IEEE 802.11-1997 and IEEE 802.11b. IEEE 802.11g was then published to bring the advantages of IEEE 802.11a and its OFDM PHY layer into the 2.4 GHz frequency band [7]. Therefore, Table 1 is also valid for IEEE 802.11g. However, unlike IEEE 802.11a, IEEE 802.11g had to use protection mechanisms to deal with legacy devices: RTS/CTS and CTS-to-self were two of the strategies proposed, where the control frames are sent using legacy standards to seize the medium. Once the medium is available, the new modulations can be used. However, these protection mechanisms involve transmitting more control frames, which end up cutting the overall throughput by almost 50%.

### B. IEEE 802.11N

IEEE 802.11n was published in 2009. The main goal was to expand the capabilities of Wi-Fi networks by improving the achievable data rates and using both frequency bands available (2.4 GHz and 5 GHz) [9]. Up until this time, MAC layer throughput was half of the PHY data rate in the absence of collisions and all devices were Single Input/Single Output (SISO). This meant that only one frame was sent at a time, and only one frame was received at a time; it was possible to use more than one antenna, but only for robustness and redundancy. IEEE 802.11n introduced Multiple Input/Multiple Output (MIMO), which takes advantage of multipath to send several spatial streams (SS) of bits to the receiver. With MIMO, each antenna can be driven independently, sending different data on each spatial stream, requiring the device to possess multiple radio chains – a radio chain includes the amplifier plus the Fourier transforms applied to the signal. The MIMO capabilities of a device are expressed using the notation **T x R : S**, where T is the number of transmitting radio chains, R is the number of receiving radio chains, and S is the number of streams used. Thus, MIMO $3 \times 3{:}2$ means there are 3 radio chains capable of sending 2 spatial streams, being the third chain a redundancy chain.

**TABLE 2.** IEEE 802.11n data rates (in Mbps) for 20 MHz channel bandwidth and LGI.

| | 1 SS | | 2 SS | | 3 SS | | 4 SS | |
|---|---|---|---|---|---|---|---|---|
| Mod. and R | MCS | Data Rate | MCS | Data Rate | MCS | Data Rate | MCS | Data Rate |
| BPSK, R=1/2 | 0 | 6.5 | 8 | 13 | 16 | 19.5 | 24 | 26 |
| QPSK, R=1/2 | 1 | 13 | 9 | 26 | 17 | 39 | 25 | 52 |
| QPSK, R=3/4 | 2 | 19.5 | 10 | 39 | 18 | 58.5 | 26 | 78 |
| 16-QAM, R=1/2 | 3 | 26 | 11 | 52 | 19 | 78 | 27 | 104 |
| 16-QAM, R=3/4 | 4 | 39 | 12 | 78 | 20 | 117 | 28 | 156 |
| 64-QAM, R=2/3 | 5 | 52 | 13 | 104 | 21 | 156 | 29 | 208 |
| 64-QAM, R=3/4 | 6 | 58.5 | 14 | 117 | 22 | 175.5 | 30 | 234 |
| 64-QAM, R=5/6 | 7 | 65 | 15 | 130 | 23 | 195 | 31 | 260 |

There are a few other PHY layer enhancements introduced by IEEE 802.11n, namely 1) subcarriers were added to the 20 MHz channel to improve spectral efficiency, 2) the use of an OFDM Short Guard Interval (SGI) of 400 ns along with the Long Guard Interval (LGI) of 800 ns already defined in previous standards, and 3) the first channel bonding capabilities, allowing two adjacent 20 MHz channels to be merged into a single 40 MHz channel, duplicating the available bandwidth. Channel bonding is an optional feature for the 2.4 GHz frequency band due to the sparse number of non-overlapping channels available in this frequency band. The main improvement at the MAC layer was the four-fold increase of the IEEE 802.11 frame size and the introduction of frame aggregation. With frame aggregation, a device can spend more time transmitting, avoiding the costly medium access overhead whenever several frames have to be transmitted. Associated with frame aggregation is the new Block ACK, where a window is set for ACK and a receiver can ACK selectively any or all the frames inside the window, which reduces the MAC protocol overhead.

IEEE 802.11n defined the Modulation and Coding Scheme (MCS), an index representing the modulation, coding rate, and the number of spatial streams used in the data transmission. Table 2 shows the PHY level data rates, modulations, and coding rates used by IEEE 802.11n, for LGI. SGI adds 10% efficiency. A channel of 40 MHz doubles the data rate.

### C. IEEE 802.11AC

In 2013, IEEE 802.11ac was published to continue improving data rates and spectrum efficiency in Wi-Fi networks with an increasing number of devices and the need for higher speeds [10]. IEEE 802.11ac uses the 5 GHz frequency band only, which means that IEEE 802.11n is still the

**TABLE 3.** IEEE 802.11ac data rates for LGI and 20, 40, and 80 MHz channel bandwidth (*MCS9 is not allowed for 1, 2, and 4 streams, when using 20 MHz channel bandwidth.).

| BW | MCS | Mod. and R | 1 SS | 2 SS | 3 SS | 4 SS |
|---|---|---|---|---|---|---|
| 20 | 7 | 64-QAM, R=5/6 | 65 | 130 | 195 | 260 |
| | 8 | 256-QAM, R=3/4 | 78 | 156 | 234 | 312 |
| | 9 | 256-QAM, R=5/6 | * | * | 260 | * |
| 40 | 7 | 64-QAM, R=5/6 | 135 | 270 | 405 | 540 |
| | 8 | 256-QAM, R=3/4 | 162 | 324 | 486 | 648 |
| | 9 | 256-QAM, R=5/6 | 180 | 360 | 540 | 720 |
| 80 | 7 | 64-QAM, R=5/6 | 292.5 | 585 | 877.5 | 1170 |
| | 8 | 256-QAM, R=3/4 | 351 | 702 | 1053 | 1404 |
| | 9 | 256-QAM, R=5/6 | 390 | 780 | 1170 | 1560 |

most recent standard for the 2.4 GHz frequency band. IEEE 802.11ac takes channel bonding to a new level by introducing 80 MHz and 160 MHz (optional) channel bandwidths. New PHY layer improvements include: 1) a new modulation type (256-QAM), 2) support for up to 8 spatial streams (in reality, Wave 2 devices have only 3 or 4 spatial streams), 3) beamforming, and 4) multi-user MIMO (MU-MIMO) transmission. MU-MIMO allows more than one client to be served by the AP at the same time, as different data frames are sent to different clients without collisions.

With IEEE 802.11ac, the MCS index is no longer tied to the number of spatial streams, as it was the case with IEEE 802.11n, simplifying the MCS indices. In IEEE 802.11ac, it is possible to get the overall data rate, by combining the MCS index with the number of spatial streams and the channel bandwidth. Table 3 shows the MCSs 7, 8, and 9 of IEEE 802.11ac for LGI, using a 20 MHz channel bandwidth, recalling that MCS 0-7 are equal to the MCS 0-7 already defined in IEEE 802.11n.

As it can be seen from Table 3, MCS 0-7 are equal to the MCS 0-7 defined in IEEE 802.11n, as they are, in fact, the same. IEEE 802.11ac adds 256-QAM modulation and separates the MCS index from the number of spatial streams. This determines that it is no longer possible to impose an MCS on an AP or Wi-Fi NIC client [10]. Up until IEEE 802.11n, it was common practice to choose mandatory data rates or MCSs, which were broadcasted on the network by the AP through the beacon frames. In IEEE 802.11ac, MCS 0-7 are mandatory, MCS 8-9 are optional. A 2-bit field on the beacon frames defines which MCSs are in use, MCS 0-7, MCS 0-8, or MCS 0-9.

It is important to mention that channel bonding and 256-QAM require very good signal conditions, which is not always possible, especially as the number of devices grows in today's Wi-Fi networks. Moreover, the way channel bonding works in IEEE 802.11ac involves an RTS/CTS exchange to seize the medium, where the sender device transmits an RTS frame on each 20 MHz channel and waits for the CTS frames from the receiver device. If some of the 20 MHz channels are being used or show interference, channel bonding will be limited to a smaller channel bandwidth.

*Summary*: This section presented an overview of the IEEE 802.11 standard and its multiple amendments. In fact, due to the nature of the shared spectrum, newer Wi-Fi APs still need to "speak" legacy standards, while incorporating the latest advanced features of the more recent standards. This represents an increasing complexity in these network devices, both in hardware and software, being essential to understand the different configurations and capabilities Wi-Fi networks can have, as this will influence the total power consumption of the APs.

## IV. RELATED WORK

The study of the power consumption of network devices has been a subject with a great amount of work done in recent years. Several works have been proposed to reduce the power consumption of battery-powered devices, e.g., smartphones, tablets, and IoT devices.

However, it is also important to apply these studies to network infrastructure components, namely Wi-Fi APs, since it is becoming common to find enterprise Wi-Fi networks and public hotspots with hundreds or even thousands of APs.

This section is divided into four categories of related work. Firstly, it points out works that look into the power consumption of Wi-Fi APs. Secondly, works that detail the energy consumption of Wi-Fi NICs. Thirdly, it presents related works focused on the power consumption of Wi-Fi on smartphones. Next, works focusing on the relationship between Wi-Fi traffic and power consumption are discussed. The section ends with the main conclusions about the related work, focusing on the major limitations of the power consumption studies available in the literature.

### A. ENERGY CONSUMPTION OF Wi-Fi APS

In [11], the author presents a study on the efficiency, throughput, and energy requirements of enterprise Wi-Fi APs. In this technical report, the main factors with impact on the power consumption of an AP are presented, which include: 1) the **hardware platform and electrical components used**, where the author claims that all the components in the circuit board consume power, or modify the power consumption of the device. An example given is when IEEE 802.11b and IEEE 802.11g traffic are compared, with IEEE 802.11b consuming more power, because the data rates are at a much slower speed, taking more time for the same amount of traffic to be transmitted, when compared with a higher data rate used by IEEE 802.11g; 2) the **hardware interoperability**, which is important to consider in order to select different components to build an AP, since some components may not work together flawlessly, requiring additional resistors or capacitors to properly integrate them; 3) the **software design**, since data structures, protocols, and methods implemented can have a large impact on data processing, increasing the power requirements of an AP. The author points out that commonly the radio front end of an AP is designed using a Class A power amplifier. This type of power amplifier uses a single switching transistor in the standard common emitter circuit configuration to produce minimum distortion and maximum amplitude of the output signal. This requires the AP to have a constant power draw, leading also to power wastage, but preventing fluctuations from occurring. If the Class A circuit is part of a tiered power generation system, other components, such as IEEE 802.11 radios and processors, will help distribute the power load. The author presents a set-up testing three different APs supporting IEEE 802.11a/b/g and discriminates the power consumption of the base components, the 5 GHz NIC, and the 2.4 GHz NIC. The main conclusions of the report are: 1) turning off unused IEEE 802.11 radios can significantly decrease the amount of power needed for an AP; 2) not all APs consume the same amount of power, hence the need for testing several devices from different vendors, in order to reach more general conclusions; 3) one of the APs tested is an example of a circuit that consistently draws the same amount of power regardless of the radio enabled, being invariant to different configurations applied; 4) other APs show a minimum constant power consumption due to its base components and the number of radios enabled increase the overall power consumption drawn.

The work in [12] is claimed to be the first to focus on the power consumption analysis of APs. Two scenarios are considered in the analysis. The first scenario assumed an infrastructure network, where one client communicated via wireless to the AP, sending data to another client connected to the AP using its wired interface. The second scenario considers two clients communicating using Wi-Fi through the AP. Six different APs were tested, but only one of them supported IEEE 802.11n. One of the APs is considered an enterprise AP, the Cisco AIR-AP1131AG. The measurements were conducted at relatively low data rates. The power consumption measurements were performed at the starting state and steady state. By considering the two scenarios described, two sets of measurements were performed, one sending an ICMP echo and the other sending a 2.45 GB file for each IEEE 802.11 standard available at each AP and using the security access control MAC filtering. The main conclusions are that the energy consumption increases in all AP models when MAC filtering is enabled, a file is sent and the communication between clients is done only via the wireless link. Using IEEE 802.11a in the 5 GHz frequency band does not make much difference in energy consumption when compared to the IEEE 802.11 variants operating over the 2.4 GHz frequency band for all the models under test. A comparison between all devices is also performed showing that models with higher capabilities use more power.

In [13], the authors propose an experimental approach to characterize typical wireless access network gateways (Wi-Fi APs and WiMAX base stations) from an energy consumption standpoint. Based on the experimental study they also develop a simple power consumption model. The equipment used for the Wi-Fi case was a custom IEEE 802.11g AP with two wireless interfaces. It is shown that 1) the power consumption of APs exhibits a linear dependence on the traffic until a saturation point is reached; 2) the datagram size has a considerable impact on power consumption in TX mode. For different TX power levels, it is reported that an increase in TX power has no impact on AP power consumption. The conclusion reached about different MCSs is that higher MCSs are more efficient at using the available power and bandwidth than lower MCSs in TX mode. Lower MCSs are more energy efficient than higher MCSs when the AP is in RX mode.

In [14], the authors present a set of measurements of power consumption of IEEE 802.11ac APs. They built a setup consisting of a server connected to the AP through an Ethernet cable and a client connected to the AP through the Wi-Fi interface. Then, they measured the power consumption for different configurations, namely: channel bandwidths of 20, 40, and 80 MHz; UDP packet sizes of 64, 256, 1024, and 1470 byte; TX power of 6, 8, 10, 12, and 14 dBm. With the power consumption measurements obtained, they derived a model for the AP power consumption. The main conclusions of this work are: 1) with increasing channel bandwidths the data rate and power consumption increase; 2) transmitting longer packets at high data rates and shorter packets at low data rates are the more energy efficient configurations among their set-up; 3) for a certain configuration, the data rate and power consumption have low correlation.

### *B. ENERGY CONSUMPTION OF Wi-Fi NETWORK INTERFACE CARDS*

The study of Wi-Fi power consumption has been mainly focused on Wi-Fi NICs connected to laptops and smartphones. In [15], the authors analyze in great detail the energy consumption of the IEEE 802.11n standard. In this work, the authors intend to investigate whether a ''race to sleep'' strategy is indeed efficient, taking into account the premise that power consumption in active modes is orders of magnitude greater than in sleep mode, being always best to transmit at higher data rates in order to spend more time sleeping. Or, whether a radio interface should transmit at the lowest rate possible to be the most power efficient. A detailed analysis of several IEEE 802.11n configuration parameters is done, especially MIMO. The authors reach several conclusions: sleep modes in NIC cards are indeed an effective strategy to save power; increasing the data rate for the same antenna configuration does not turn on extra hardware, therefore, it is not energy expensive to increase data rates; wide channel bandwidths are always more energy-efficient; MIMO shows a large jump in terms of energy consumption from 1 to 2 streams and a small gap between 2 and 3 streams and the number of receiving streams should match the number of transmission streams; TX power control offers little energy gains in practice.

In [16], the authors find out that for low bandwidth and low latency-sensitive traffic (e.g., Voice over Internet Protocol (VoIP)), the inclusion of small sleep opportunities during inter-packet gaps can provide four times energy consumption reduction and for high bandwidth traffic (e.g., High Definition (HD) videos and file transfers) a two-fold reduction is possible using sleep opportunities at the client side when an AP is transmitting to another client, choosing the most energy-efficient antenna configuration. From this, ''snooze'' is a method devised to adapt the client sleep duration and antenna configurations to the traffic on the Wi-Fi network in order to achieve energy savings. This is an AP mechanism, including new control messages sent over the air, which impacts throughput. The studies of energy savings and performance were conducted using two IEEE 802.11n NICs, Intel WiFi Link 5300 and Atheros AR5BXB92. The actual energy consumption measurements were not performed by the authors but were directly imported from [15].

In [17], a new Rate Adaptation (RA) algorithm is designed from an energy-efficiency perspective. Current RA algorithms are designed to achieve high throughput; a high throughput configuration is not energy efficient for a Wi-Fi NIC. Marginal throughput gain is said to be achieved at a high energy cost. RA algorithms dynamically select the PHY configuration based on channel conditions and their traditional goal is to achieve high throughput. The measurements show that an IEEE 802.11n 3 × 3 MIMO receiver consumes about twice the power of IEEE 802.11a during active transmission and 1.5 times more power when in idle mode. In fact, these measurements are performed being both AP and client programmable 802.11n devices, which use Atheros AR9380 2.4/5 GHz 3 × 3 MIMO chipset in infrastructure deployment. Only downlink transmissions from the AP to the client NIC are tested in this work. The measurements and the rest of the work presented are then focused on evaluating how the RA algorithms perform, which is outside the scope of this paper.

In [18], the authors explore the power consumption of IEEE 802.11ad devices, using the 60 GHz band, but they also perform a comparison with IEEE 802.11ac devices power consumption. One of the experimental setups consists of two desktops, each containing a WLE900N5-18 3 × 3 MIMO 802.11ac NIC, featuring a QCA9880 v2 chipset and controlled by the open source ath10k driver, one acting as a client and the other as an AP (configured through hostapd). They plot the throughput, power consumption, and energy per bit as a function of the PHY data rate. For comparison with IEEE 802.11ad, the focus is solely on configurations that can support PHY data rates comparable to those supported by 802.11ad (i.e., at least 385 Mbps), and the results are shown only for those rates. They conclude that in TX mode, the dominant factor is the channel bandwidth, while the impact of the number of streams is negligible. It is also observed a small but non-negligible drop of power use with the MCS. In reception RX mode, both the channel bandwidth and the number of spatial streams affect the power consumption, but MCS has a negligible impact.

In [19], the authors intend to analyze the energy consumption of IEEE 802.11 devices, from the processing at the device to the transmission and reception of bits of data. The study is conducted to assess how much energy is consumed while a frame is delivered across the protocol stack, from the Operating System (OS) to the driver and finally the NIC (being the reverse process applied for the reception of data). This is called the ''cross-factor''. The authors claim this factor cannot be neglected and that it cannot be treated as a constant baseline component since it depends on how a frame is handled by the device.

### C. ENERGY CONSUMPTION OF Wi-Fi ON SMARTPHONES

In [20], a detailed study is performed using four different smartphones, Nexus S, Samsung Galaxy S3, S4 and S5, to determine the behavior of these devices using IEEE 802.11n and IEEE 802.11ac. More specifically, the study aims at understanding what the trade-offs between power consumption and throughput obtained for different configurations are. [21] is considered the first experimental study of 802.11 NICs in RX mode, using a Samsung Galaxy S4 smartphone, and [20] is claimed to be the first detailed experimental study of IEEE 802.11n and IEEE 802.11ac throughput and power consumption in smartphones, with the goal of identifying common trends across different devices. All these studies used LGI, considering that in [22] it was already found that LGI and SGI do not show much difference in terms of throughput and power consumption for smartphones. First, the authors compare the power consumption of the smartphones in non-communicating modes, either Idle (the NIC is waiting for incoming or outgoing traffic) or Power Saving Mode (PSM); in PSM, the device is put in sleep mode and wakes up to listen for beacons periodically sent by the AP, where the AP is responsible for buffering any incoming data. The analysis was performed for different configurations, including the number of streams used (when the device has more than one spatial stream), the standard used (IEEE 802.11n or IEEE 802.11ac), and the channel bandwidth (20 MHz, 40 MHz, or 80 MHz). All the tests were performed under good channel conditions and applications not reaching the data rate limits. The main conclusion is that larger channel bandwidths increase power consumption.

The authors also reach the following conclusions: a smartphone supporting MIMO shows the same power consumption behavior using 1 or 2 spatial streams; TX power consumption is much higher than RX power consumption; recent devices are not necessarily more power-efficient; higher MCS always results in lower per bit energy cost in both TX and RX modes; the ''race to sleep'' strategy is applicable to smartphones, in the case of fixed channel bandwidth and good channel conditions, a conclusion that still holds for IEEE 802.11ac; MIMO is a more energy efficient option than using wider channel bandwidths, but the combination of MIMO and channel bonding is the most energy efficient option for both 802.11n and 802.11ac, a conclusion also reached by the authors of [15]. The overall conclusions are that wider channel bandwidths show a higher energy per bit cost, MIMO has no impact on the power consumption (up to 2 SS), and higher MCSs indices have no impact for low data rates, when the idle power dominates, but are less power efficient for data rates higher than 30 Mbps.

The same authors, in their work presented in [23], go one step forward and try to validate the per-frame energy model proposed in [24], which was performed using legacy equipment, applying the same model to smartphones with IEEE 802.11n/ac interfaces. The goal was to validate whether the model can accurately estimate the power consumption due to Wi-Fi activity and whether it can show the impact of IEEE 802.11n/ac features, such as MIMO and channel bonding on the Wi-Fi power consumption. They demonstrate that the model remains accurate, although its parameters exhibit different trends compared to the ones reported in the original paper. They also found that the idle/base power is the main contributor to the total power consumption except for very high data rates.

In [25], the authors claim to conduct the first extensive measurement study on Wi-Fi active energy consumption based on certain parameters measured by app developers. Since Android drivers do not allow the user to configure any 802.11 TX parameters, the work focuses on RX energy consumption only. As input parameters, the authors propose the use of the constant active power, the transfer size, loss rate, and signal strength to devise an energy consumption model. They first consider a number of parameters used by previous models and show limitations, and then focus on an approach modeling the active energy consumption as a function of the application layer throughput. The conclusions are that, while the proposed linear power-throughput models work well in a number of practical scenarios, its accuracy drops in high throughput settings or when tested on different hardware.

### D. CONNECTION BETWEEN Wi-Fi TRAFFIC AND POWER CONSUMPTION

The authors of [28] focus on experimentally investigating the relationship between traffic and power consumption for the IEEE 802.11g standard. The AP used is built upon PCEngines ALIX 2C2 processor board equipped with two IEEE 802.11a/b/g Wi-Fi NICs Atheros AR5213A chipsets and the AP uses OpenWRT 10.3.01-rc1, a Linux OS targeting embedded devices. As reported, the work considers only traffic generation rates up to 10 Mbps.

The most unexpected result is the power consumption when the Wi-Fi device is used as a receiver, with the AP actually consuming more power than when acting as transmitter.

In [27], the authors propose a Machine Learning (ML) approach to detect the presence of people in a space based on the power consumption of a Wi-Fi AP. The goal is to conduct extensive analysis on the applicability of using the power consumption of a Wi-Fi AP to determine the number of people present inside a room. The power consumption was measured using a custom-built Arduino based smart plug to achieve a higher sampling rate when compared to commercially available smart plugs. The hypothesis proposed in this work is that the power consumption of a Wi-Fi AP should be proportional to the amount of traffic, and the number of devices on the network, using for this the work presented in [28].

The second hypothesis is that the power consumption of the AP should be proportional to the number of devices on the network only. The authors point out that in a previous work of their own [29], they had already determined that multiple active high traffic devices are distinguishable and can be tracked on the network. This included confirming that switching between two networks just switches power consumption between APs and that different AP models do not affect the outcome, as they can be normalized to the same values. In [29], the authors once again base their work on the work done in [28], but tried to test the results by measuring Wi-Fi APs power consumption. Although it seems power consumption grows with increasing data rates, the absolute power consumption of the APs is less than 4 Watt, for traffic generation rates up to 10 Mbps. Based on these two hypotheses, the authors apply an ML algorithm to detect the number of people in a room based on the variation of power consumption of the APs.

### E. CONCLUSIONS

The main limitations of the related work lay in the fact that most power measurements were performed using IEEE 802.11a/b/g equipment and some works were solely focused on client devices, such as smartphones and laptop NICs, rather than APs. The works that have been done on APs still lack detail on the measurements performed. As an example, in the power measurements of the work in [12] using a Cisco AIR-AP1131AG AP, there is a jump of almost 100% from idle to TX and RX modes, without any apparent reason, and no explanation is provided for such unpredictable behavior. Also, the methodology is not always presented, which impedes the scientific community to replicate the same results. There are works where the power consumption is presented as an average value for a given IEEE 802.11 standard, instead of presenting the individual values for each data rate of the standard. Another limitation found is the input parameters chosen in some of the studies considered, namely the variation of TX power. A variation in TX power may disrupt the radio planning of the network. If TX power is too high, the AP may reach the client devices that are further away, but these, in turn, may not be able to reach the AP; if TX power is too low, the opposite may happen, where the client devices can reach the AP, but the AP is not able to reach them, due to the asymmetry of the links.

The way traffic is modeled on a Wi-Fi network is also a limitation in some of the related works. Traffic being generated at the AP is unlikely to be found in most infrastructure networks. In practice, the common scenario is to have the AP relaying upstream (client-to-infrastructure) and downstream (infrastructure-to-client) traffic. The AP power consumption is then the aggregate power consumption due to the traffic passing through both the wired and the wireless NICs; this is in general overlooked by the studies found in the literature.

The main conclusions drawn in the related works presented herein can be summarized as follows:

- General conclusions
  - Legacy standards (IEEE 802.11a/b/g) consume more energy than recent standards (IEEE 802.11n/

ac), due to the longer time they need to transmit the same amount of data.
  - The work in [12] concludes IEEE 802.11a does not make much difference when compared to the standards using the 2.4 GHz frequency band (IEEE 802.11b/g).
  - Energy consumption is dependent on the datagram size.
  - Sleep mode in client NICs is an effective strategy to save energy.
  - MIMO shows a large increase in power consumption when compared to SISO, but MIMO 2 × 2 shows a smaller increase when compared to MIMO 3 × 3. However, [18] refers that for IEEE 802.11ac, in TX mode, the number of spatial streams has a negligible impact on power consumption. Reference [20] also confirms that using 1 or 2 spatial streams leads to the same power consumption.
  - [20], along with most of the other works, confirm that TX mode uses more power than RX mode; however, [28] states that, for offered data rates up to 10 Mbps, RX mode can use more power than TX mode.
  - A "race to sleep" strategy is energy efficient for Wi-Fi NICs.
- Power consumption of Wi-Fi APs
  - Due to the way Wi-Fi APs are built, turning off radio interfaces can save energy.
  - The hardware and software of the Wi-Fi APs can influence power consumption. This means it is important when trying to draw conclusions about the power consumption of Wi-Fi APs that devices from different vendors are compared.
  - Wi-Fi APs with higher capabilities consume more power.
  - TX power does not have a significant impact on the power consumption of a Wi-Fi AP [13] (for an IEEE 802.11g AP).
- Contradictory conclusions
  - [13] affirms higher MCSs are more energy efficient for TX and lower MCSs are more energy efficient for RX; [20] concludes that higher MCSs are more energy efficient for both TX and RX modes. However, [14] refers that data rate and power consumption have low correlation, [18] states that MCS has a negligible impact on power consumption, and [15] refers that it is not energy expensive to increase the data rate for the same spatial stream and channel bandwidth configuration. On the other hand, [17] states that higher MCSs are not energy efficient for a Wi-Fi NIC, and IEEE 802.11n 3 × 3 MIMO uses twice the power of IEEE 802.11a in TX mode and 1.5 times more than in idle. Reference [27] states that power consumption grows with the data rate for offered data rates up to 10 Mbps.
  - [14] and [20] state that increasing channel bandwidth makes power consumption increase, however, [15] states that a wide channel bandwidth is always more power efficient and a 40 MHz channel bandwidth has a negligible impact on the IEEE 802.11n NICs power consumption.

*Summary:* This section reviewed the state of the art works related to the power consumption of Wi-Fi network devices. There are several limitations found in the works published so far, from the setup used to the methodology employed. Several conclusions are contradictory between different works, as different devices may have different behavior under the same configurations. As such, a thorough study is needed to clarify how enterprise Wi-Fi APs consume power. This is the main aim of the study presented herein.

## V. EXPERIMENTAL RESEARCH METHODOLOGY

In this section, we discuss the research methodology used for the study of the power consumption of enterprise Wi-Fi APs. Firstly, the research questions are formulated, filling the gaps found in the state of the art. Ultimately, this paper focuses on determining the behavior of enterprise Wi-Fi APs, which show very different characteristics, features, and compute power than other devices studied in the related work. Therefore, a thorough and detailed study is carried out to fully characterize the power consumption of these devices under the several possible configuration options, including the most recent standards available - i.e., IEEE 802.11n and IEEE 802.11ac. Secondly, the research methodology itself is explained, namely the input parameters and the experiments considered to evaluate the power consumption of enterprise Wi-Fi APs for different settings, the equipment and the laboratory setup defined to run such experiments, and the data gathering procedure. The main goal is to provide the details about the steps followed so that the experiments and the obtained results can be reproduced elsewhere.

### A. RESEARCH QUESTIONS

Our study focused on experimentally determining the power consumption of enterprise Wi-Fi APs considering multiple settings. The following six research questions are formulated:

- What is the power consumption of an AP while booting up?
- What is the power consumption when an AP is in idle, TX, RX, and its radio interfaces are switched off (standby state), for each Wi-Fi standard (IEEE 802.11a/b/g/n/ac)?
- How does the power consumption varies for each Wi-Fi standard, when the MCS, number of spatial streams, and channel bandwidth is changed?
- Is there any power consumption difference in using the 2.4 GHz and the 5 GHz frequency bands?
- What is the impact on an AP power consumption when varying the TX power?

**TABLE 4.** Main features of the three enterprise Wi-Fi APs evaluated.

| Main Features | Aruba 207 | Cisco 1852i | Huawei 8030DN |
|---|---|---|---|
| **Type of AP** | Indoor AP | Indoor AP | Outdoor AP |
| **Wave** | IEEE 802.11ac Wave 1 | IEEE 802.11ac Wave 2 | IEEE 802.11ac Wave 1 |
| **Standards supported** | IEEE 802.11a/b/g/n/ac | IEEE 802.11a/b/g/n/ac | IEEE 802.11a/b/g/n/ac |
| **MIMO** | 2x2:2 | 4x4:4 | 3x3:3 |
| **Maximum data rate** | 867 Mbit/s | 1.73 Gbit/s | 1.3 Gbit/s |
| **Channel bandwidth** | 20, 40, 80 MHz | 20, 40, 80 MHz | 20, 40, 80 MHz |

- What is the energy efficiency per bit for each of the Wi-Fi standards?

### B. EXPERIMENTAL INPUT PARAMETERS

After the analysis of the multiple IEEE 802.11 standards described in Section III, there are a set of parameters that can be configured for most enterprise Wi-Fi APs available. The following list shows the input parameters considered in our experimental study:

- IEEE 802.11 standard used (IEEE 802.11a/b/g/n/ac)
- Frequency band used (2.4 GHz, 5 GHz)
- Channel bandwidth
- TX power
- Data rates (IEEE 802.11a/b/g) or MCS (IEEE 802.11n/ac)
- Number of spatial streams
- Number of antennas connected
- Number of radio interfaces connected

### C. EXPERIMENTAL SETUP AND DATA GATHERING

The experimental setup included three different enterprise Wi-Fi APs from three different vendors: the Aruba 207 [31], the Cisco 1852i [32], and the Huawei 8030DN [33]. The choice of these three vendors resides on the fact that these are the three major vendors of enterprise Wi-Fi APs; according to [30], they currently share around 60% of the global enterprise Wi-Fi AP market. Table 4 summarizes the main features among the three APs.

First and foremost, it is important to notice that the goal of our power consumption study is not to point out which AP is the most energy efficient among the three vendors. The goal is to establish power consumption patterns among the three devices and extrapolate the results to take meaningful conclusions, regardless of the absolute values of power consumption measured for each AP.

The measurements were based on Alternating Current (AC) Voltage and Current obtained using the Keysight 34410A Multimeter [34]. Each measurement value results from the average of 600 power consumption samples recorded over a period of 5 minutes (i.e., 2 samples per second), where

$$P = V_{AC} * I_{AC} \quad (1)$$

is the **power consumption**, in Watt. The energy consumption $E$, in Joule, over a period $t$, in seconds, is defined by Equation 2.

$$E(J) = P(W) * t(s) \quad (2)$$

The **energy efficiency per bit** $E_e$ is the energy used for the transmission of one bit of data at PHY data rate $R$, in Mbps, according to Equation 3, where $E$ is the total energy consumed during the experimental measurement and $B$ is the total PHY bit value over the course of the experimental measurement.

$$E_e(J/Mbit) = \frac{E(J)}{B(Mbit)} = \frac{P(W)}{R(Mbps)} \quad (3)$$

The less amount of energy spent to transmit a bit of data, the more efficient the configuration is.

Figure 4 shows the laboratory setup created to perform the power consumption measurements. The goal of this setup was to replicate an infrastructure Wireless Local Area Network (WLAN). The Keysight Multimeter [34] was placed between the power grid and the Power over Ethernet (PoE) injector to measure the power drawn by the injector and the AP. The ZyXEL PoE12-HP [35] was used, with a maximum power output of 30 W and a maximum bitrate of 1 Gbps. This injector provides the power necessary to operate the AP while connecting the AP to the local Ethernet network prepared for this setup. Most enterprise Wi-Fi networks and public hotspots nowadays take advantage of PoE standards, such as IEEE 802.3af [36] (up to 15.4W), and IEEE 802.3at [37] (up to 25.5W), in order to provide the necessary power to the APs, avoiding the need to deploy electric wires over long distances. With this technology, a single Ethernet cable can supply both data and power to the AP. The PoE injector used is IEEE 802.3at compliant. The Ethernet switch used was a 24 Gbps port TP-LINK T2600G-28TS [38], which interconnects the AP, the Keysight Multimeter, and the desktop computer used as a server, containing the Network Time Protocol (NTP) server, the Dynamic Host Configuration Protocol (DHCP) server, the Domain Name System (DNS) server, the iperf application for traffic generation, and the Keysight logging interface, for collecting the power measurements. The Wi-Fi client is a USB Wi-Fi NIC ASUS AC68 [39], supporting IEEE 802.11a/b/g/n/ac standards, with MIMO $3 \times 4$:3, which was connected to a laptop computer running another iperf service to generate traffic. It was not possible to explore all the configuration options of the Cisco 1852i since the client Wi-Fi NIC does not support MIMO $4 \times 4$. We could have chosen another Wi-Fi NIC with support for MIMO $4 \times 4$, such as the PCE-AC88 [40]. The ASUS USB AC68 was acquired due to its USB3 interface and versatility to be used in a laptop, a representative device of the typical Wi-Fi client.

To generate uplink traffic, the iperf on the laptop sent the packets to the AP through the Wi-Fi NIC. Just as in any infrastructure network, the packets are not simply sent to the AP, but they also leave the AP and are sent uplink to the

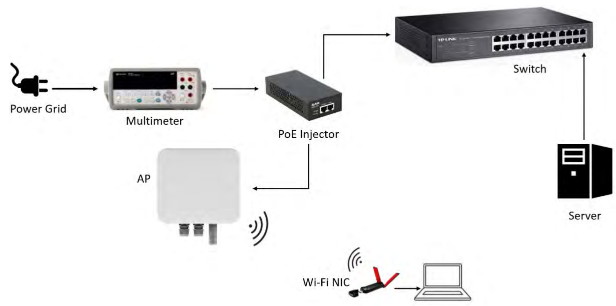


**FIGURE 4.** Laboratory setup used for the power consumption measurements.

wired network, through the AP's Ethernet interface, towards the server computer. The downlink traffic is generated from the server computer to the Wi-Fi client (STA). We only used one client, as this generates the maximum possible data rate on the Wi-Fi network; the more clients associated to the AP, the more time is spent on resolving collisions and doing medium access control.

In the setup, the packet size is the iperf default value, frame aggregation mechanisms are activated for IEEE 802.11n/ac, RTS/CTS and fragmentation thresholds are configured with the default values on all the APs studied. Unless specified otherwise, TX power of the APs is configured as automatic, which in this case is the maximum TX power. The Wi-Fi channels used were chosen to be as much as possible free of interference, at Line of Sight (LOS) range. If none of the Wi-Fi channels in the 2.4 GHz band was free of interference, the channel with the least amount of noise was chosen, using a Wi-Fi spectrum analyzer, and the measurements were performed in periods of low usage of the Wi-Fi network, namely overnight.

As mentioned in Section III, the choice between LGI and SGI is an OFDM parameter that depends on the characteristics of multipath propagation of the Wi-Fi network location, the obstacles around the devices, and the physical propagation of the electromagnetic waves. In our setup, SGI never enabled the achievement of the maximum data rates for each MCS, as it was the case with LGI. As such, the LGI was considered. Table 5 summarizes the experimental setup.

*Summary:* This section presented the research questions to be answered by our experimental study, the methodology used to gather the power consumption measurements, and the enterprise Wi-Fi APs under test. A detailed specification of the setup was given in order to detail the conditions of the tests and the wireless link configurations so that our experiments can be replicated elsewhere.

## VI. POWER CONSUMPTION AND ENERGY EFFICIENCY PER BIT RESULTS

In this section, the power consumption and the energy efficiency per bit results are presented and the main conclusions are pointed out. It is not the goal of this work to point out which AP needs the least amount of power since

**TABLE 5.** Summary of the experimental setup.

| | |
|---|---|
| **Multimeter** | Keysight 34410A |
| **PoE Injector** | ZyXEL PoE12-HP |
| **Ethernet Switch** | TP-LINK T2600G-28TS |
| **Wi-Fi client NIC** | ASUS AC68 |
| **APs tested** | Aruba 207, Cisco 1852i, Huawei 8030DN |
| **Measurement period** | 5 min (each configuration) |
| **Number of samples per measurement** | 600 |

the power consumption levels are highly dependent on the AP features, which are different among the three devices under study. Using the setup illustrated in Figure 4, the power consumption of the PoE injector was subtracted from the power measurements performed as our goal is to characterize the power consumption of the APs themselves; the power consumption of the PoE injector was measured experimentally to be 13.01 +/− 0.08 W. With the exception of the results provided in Subsection VI-A, 95% confidence intervals were considered for all the results presented. Yet, since we have collected 600 samples for each measurement point, the confidence intervals are very small and are not visible in the plots.

The results are organized and presented in the following way:

- results for the non-active modes of the APs (Subsections VI-A and VI-B);
- results for the active modes of the APs (Subsections VI-C, VI-D, and VI-E);
- results for the configuration parameters related to TX power and number of active antennas (Subsections VI-F, and VI-G);

The section ends with a comparison between the major results obtained for the various IEEE 802.11 standards.

Table 6 shows a summary of the major findings of our experimental study and details the general conclusions we are able to draw for all the APs under test. For the detailed findings of this work, please refer to Table 7 in Section VII.

### A. AP BOOT UP TIME AND POWER CONSUMPTION

Enterprise Wi-Fi APs have an OS that is constantly running on the device, which has to be loaded on boot. In order to characterize the energy consumption of the APs when booting up, it is important to determine how much time they take to boot up and how much power they use to do it.

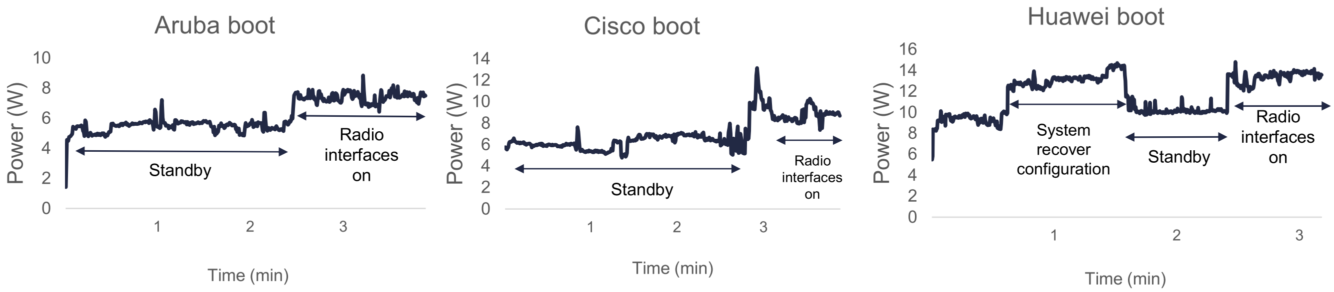


**FIGURE 5.** **The three APs boot up time and power consumption during boot process.**

**TABLE 6.** **Summary of the major experimental findings.**

| Input Parameter | Major finding |
|---|---|
| **IEEE 802.11 standard** | IEEE 802.11n using the 2.4 GHz frequency bandwidth has the highest energy efficiency per bit |
| **Frequency band** | 5 GHz radio interfaces use more power than 2.4 GHz |
| **Channel bandwidth** | Needs further study |
| **TX power** | Low impact on power consumption |
| **Data Rate** | Higher data rates not always consume more power and have better energy efficiency per bit |
| **Number of spatial streams** | Needs further study |
| **Number of radio interfaces connected** | More interfaces on imply more power consumption |
| **Operation Mode** | Standby uses the least amount of power; TX mode uses more power than RX mode |

This is an aspect overlooked in the related works presented in Section IV.

Figure 5 shows how long each AP takes to load the OS and start broadcasting the Wi-Fi Service Set Identifier (SSID). It represents the different power states each AP goes through until the Wi-Fi network is available to exchange traffic with the users.

It is important to notice that **any of the enterprise Wi-Fi APs studied takes more than 3 minutes to be ready to start exchanging traffic with the users**. As depicted in Figure 5, to reach this state of readiness (state "Radio interfaces on"), all APs go through a "Standby" state. The Huawei AP goes first through a "System recover configuration", a state in which there is a high power consumption, between 13 and 16 W, with the power consumption in "Standby" state around 10 W; the next step, observable in the plot, represents the moment in which the radio interfaces are switched on. The Aruba AP has a power consumption in "Standby" state around 6 W, with the step where the radio

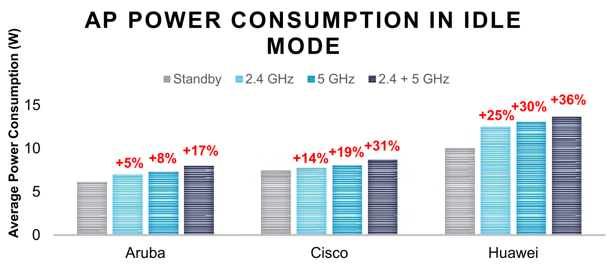


**FIGURE 6.** **Power consumption in idle mode for standby (no radio interfaces on), 2.4 GHz radio interface on, 5 GHz radio interface on, and both 2.4 GHz and 5 GHz radio interfaces on.**

interfaces are switched on being around 8 W. Cisco follows a pattern closely resembling the Aruba boot up process.

## *B. POWER CONSUMPTION IN IDLE MODE*

The power consumption of the devices in idle mode is an important measurement to consider since this is the mode in which the APs spend a great amount of time, especially during nighttime periods or holidays in most enterprise, university campus, and similar facilities.

In this study, the power consumption in idle mode was measured for the three APs considering four different configurations:

1) standby state, in which both radio interfaces are switched off;
2) 2.4 GHz radio interface switched on;
3) 5 GHz radio interface switched on;
4) both 2.4 GHz and 5 GHz radio interfaces switched on.

Figure 6 shows the average power consumption for each AP under study, considering these configurations. The percentage values shown represent a comparison with the standby state. The results show that **the standby state is the state that uses the least amount of energy; the difference in power consumption to the state where both 2.4 and 5 GHz radio interfaces are on can be as high as 36%. As it would be expected, the more interfaces switched on, the more power the APs use**. It is also observable that **the 5 GHz interface uses more power than the 2.4 GHz interface,** with differences of 3%, 4%, and 5%, respectively for the Aruba, the Cisco, and the Huawei AP.

The second set of measurements was made for evaluating power consumption when channel bonding is used.

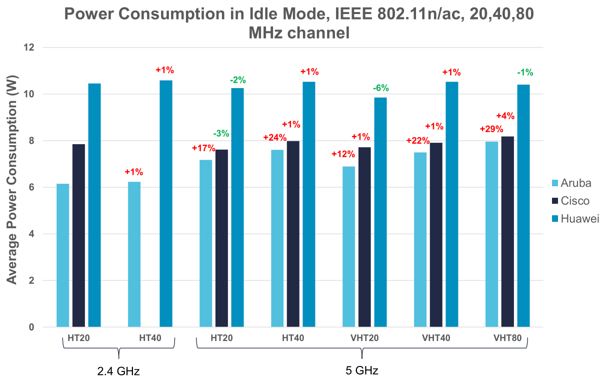


**FIGURE 7.** **Power consumption in idle mode for different channel bonding options using IEEE 802.11n/ac.**

Figure 7 presents the results obtained for different channel bonding options supported by the APs. For the 2.4 GHz frequency band, using IEEE 802.11n High Throughput (HT) PHY, there are two options available: 20 MHz and 40 MHz. For the 5 GHz frequency band, using IEEE 802.11n, there are the same options available, while using IEEE 802.11ac Very High Throughput (VHT) PHY there are three options available: 20 MHz, 40 MHz, and 80 MHz in the APs under study. The Cisco AP used in our tests does not support 40 MHz channel bandwidth using the 2.4 GHz frequency band; this is an optional feature of the standard.

The percentages that are shown in Figure 7 were obtained in comparison with the HT20 values for the 2.4 GHz frequency band and 20 MHz channel bandwidth. The Cisco AP and the Huawei AP are never really affected by the different configurations and the power consumption in idle mode remains approximately the same. The Aruba AP does show some differences in power consumption, with a constant rise in the 5 GHz band for the different channel bonding configuration options. We can conclude that **channel bonding does not affect the power consumption for the 2.4 GHz frequency band. Depending on the vendor and the configuration applied, channel bonding may influence the power consumption of the AP in the 5 GHz frequency spectrum and this should be considered by solutions whose goal is to design energy-efficient Wi-Fi networks**.

### *C. POWER CONSUMPTION IN TX AND RX MODES USING LEGACY STANDARDS (IEEE 802.11A/B/G)*

IEEE 802.11a/b/g are legacy standards still available on current enterprise Wi-Fi APs due to the mandatory backwards compatibility imposed on every new IEEE 802.11 standard released. Figures 8, 9, and 10 show the power consumption and energy efficiency per bit for both TX and RX modes for the three APs under study for legacy standards. For the sake of better visualization, the following plots are represented as continuous lines, even though the data rate is a discrete variable.

It is important to analyze in detail the results shown in Figures 8, 9, and 10. Firstly, it is possible to conclude that **the curves for the three APs are very similar**. Also, the power consumption behavior is very similar, for both TX and RX modes. The first conclusion is that **higher data rates do not mean higher power consumption in TX mode** for enterprise APs; in fact, the power consumption can be similar or even slightly lower for higher data rates. As an example, the Aruba AP and the Cisco AP use less power for 54 Mbps than for 6 Mbps in TX mode for IEEE 802.11a; the Huawei AP uses less power for 48 Mbps than for 6 Mbps. This may be explained by the higher number of packets that are transmitted, per second, using higher data rates, when compared to lower data rates. Lower data rates imply a longer time in TX mode for each packet, which results in a smaller number of medium access procedures per second. Higher data rates can end up spending less time in TX mode, per second, as the higher number of packets to transmit imply a higher number of medium access procedures. The time spent on medium access is the same, regardless of the data rate used, hence, the results obtained.

Secondly, the **TX mode always uses more power than RX**, which is explained by the power amplification step in TX mode and confirms the results found in the state of the art (cf. Section IV). The difference between TX and RX power consumption is significant for IEEE 802.11a when using lower data rates. Equation 4 can be used to calculate the difference (in percentage) between TX and RX power consumption.

$$\frac{P_{TX} - P_{RX}}{P_{RX}} \times 100\% \tag{4}$$

It is 87% for the Aruba AP, 70% for the Cisco AP, and 77% for the Huawei AP. This difference diminishes for the three APs as the data rate increases; for 54 Mbps, it is only 30% for the Aruba AP, 40% for the Cisco AP, and 34% for the Huawei AP. The **RX power consumption tends to increase with increasing data rates**, which can be explained by the increasing amount of bits needed to process and the longer periods, per second, the AP is in medium access, due to the higher number of frames to be transmitted using higher data rates. For IEEE 802.11b, the difference in power consumption between TX and RX modes can be up to 40%, and the same is valid for IEEE 802.11g; it is interesting to notice, though, that some data rates show a small difference between RX and TX, such as 36 Mbps for Aruba and 24 Mbps for Cisco. This is explained by the less power consumption the 2.4 GHz interface shows in all the three devices in TX mode, which decreases the differences in percentage between TX and RX modes.

When it comes to energy efficiency per bit, defined by Equation 3, the three APs show very similar behavior. **For IEEE 802.11a/b/g, it is more energy efficient to transmit/receive data using higher data rates**, a technique known in the state of the art as "race to sleep", where devices use higher data rates to transmit their data faster and spend more time in sleep modes. This strategy is supported by our

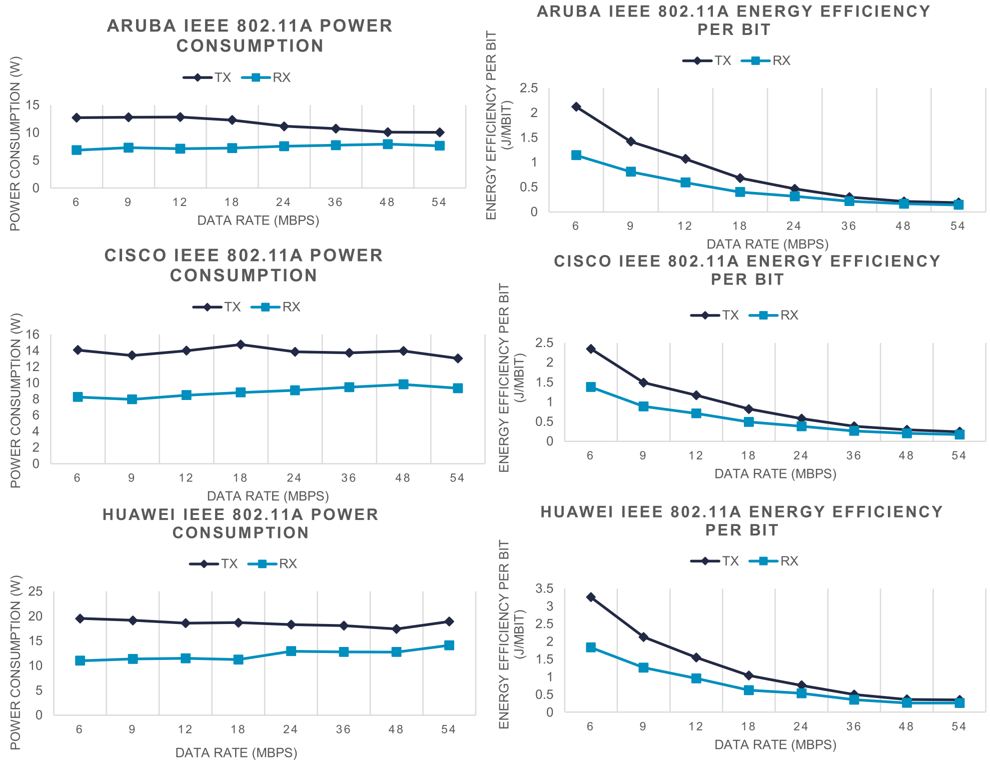


**FIGURE 8.** IEEE 802.11a power consumption and energy efficiency per bit for the three APs analyzed.

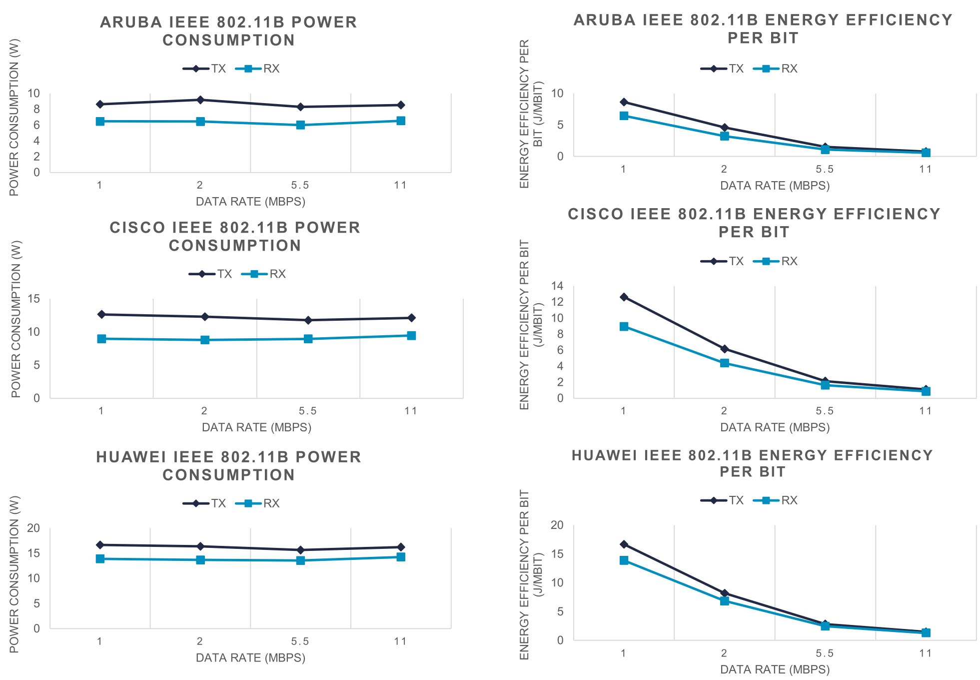


**FIGURE 9.** IEEE 802.11b power consumption and energy efficiency per bit for the three APs.

measurements for both TX and RX modes, though in this case, we can refer to it as a ''race to idle'' strategy. The reason for this behavior is explained by 1) the baseline power consumption of the device, which is the dominant factor in the total power consumption, and 2) the relatively small variations that may occur in power consumption for higher data rates, which do not significantly reduce their energy efficiency.

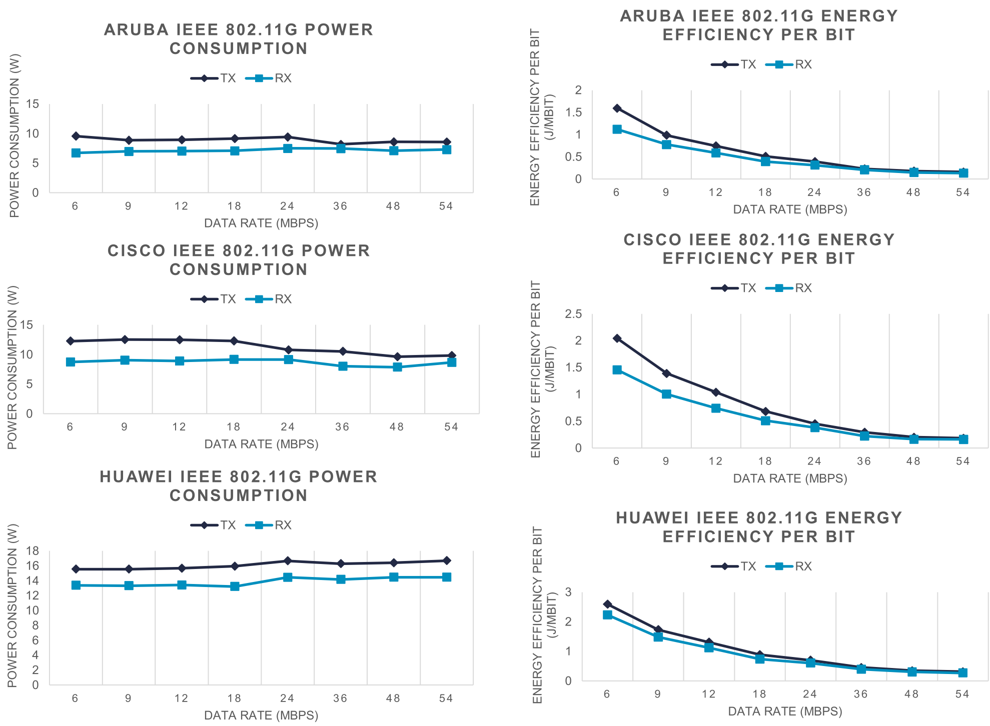


**FIGURE 10.** IEEE 802.11g power consumption and energy efficiency per bit for the three APs.

### D. POWER CONSUMPTION IN TX AND RX MODES USING IEEE 802.11N

IEEE 802.11n is a standard that can operate on both 2.4 GHz and 5 GHz frequency bands. The amount of possible configurations with this standard is higher than in previous standards and the analysis presented herein is made for both frequency bands. Using either one or the two bands, the APs allow the configuration of a single 20 MHz channel bandwidth and channel bonding to form a 40 MHz channel bandwidth (except for the Cisco AP in the 2.4 GHz). Depending on the number of radio chains, there is a variable number of MCSs available. For the Aruba AP, with MIMO $2 \times 2$, there are 16 different MCS indices, 0-15. In the case of the Huawei AP, it supports MIMO $3 \times 3$ with 24 MCSs, 0-23. The Cisco AP is a MIMO $4 \times 4$ device with 32 MCSs, 0-31. There were three issues that could not be solved during the experiments with this standard. Firstly, the client NIC used is a MIMO $3 \times 4$:3 device, which was not able to fully use all the MCSs of the Cisco AP; for that purpose, we would need a MIMO $4 \times 4$ client device. Secondly, the client device could not achieve the data rates for all the MCSs available for 3 SS using the Cisco AP (MCSs 20 to 23) in RX mode. During the tests, the Cisco AP entered in a kernel panic behavior and rebooted. We believe this may be a problem with the kernel version of the Cisco 1852i used, as other related issues were found in the support forums for the OS version used (8.4.100.0). Finally, for the Huawei AP, it was not possible to choose MCSs when using the IEEE 802.11n standard. Both Aruba and Cisco APs permit the user to choose a single supported MCS index in IEEE 802.11n, which is then broadcasted on the beacon frames. The only possible way to isolate an MCS using the Huawei AP was to transmit at maximum rate, with the best possible Signal to Noise ratio (SNR), which allowed us to determine the MCS being used as MCS 7, MCS 15, and MCS 23, when using, respectively 1, 2, and 3 spatial streams. In the following Figures 11 to 16, the x-axis represents the MCS index for 1 SS and the numbers in parenthesis are the MCS indices for more than 1 SS.

#### 1) IEEE 802.11N USING 2.4 GHZ FREQUENCY BAND

Figure 11 shows the power consumption and energy efficiency per bit for both TX and RX modes for the Aruba and Cisco APs, when a 20 MHz channel bandwidth is used.

From the plots shown in Figure 11, and focusing on the Aruba AP, we can see that **using 1 or 2 spatial streams have a negligible impact on power consumption for TX mode. For RX mode, from MCS 10-15, 2 spatial streams use more power than 1 spatial stream**. This conclusion is aligned with the previous results obtained in Subsection VI-C, as RX mode power consumption shows a dependency on the data rate for the Aruba AP. In terms of energy efficiency per bit, **the best configurations to use are the higher MCSs using 2 spatial streams for both TX and RX**. Looking at the results obtained for the Cisco AP, **the higher the number of spatial streams used the higher the power consumption**. Using 2 SS draws a relatively higher amount of power when compared to 1 SS, but using 3 SS does not show a significant increase in power consumption. This

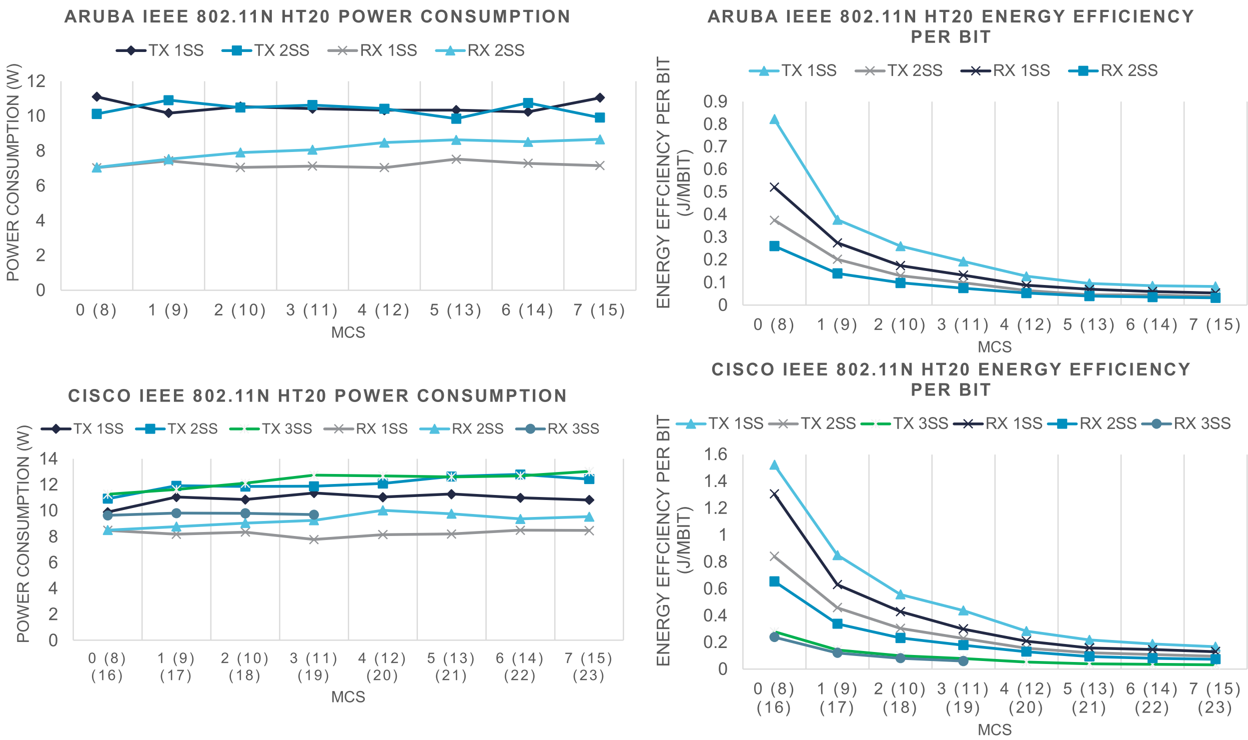


**FIGURE 11.** **IEEE 802.11n power consumption and energy efficiency per bit for the Aruba and Cisco APs using a 20 MHz channel bandwidth in the 2.4 GHz frequency band.**

behavior is aligned with other conclusions drawn in the state of the art, as seen previously in Section IV. For RX mode, we see the same behavior as for TX mode, where the higher the number of spatial streams the higher the power consumption, even though we could not assess the power consumption for all the MCSs using 3 SS, with MCSs 20 to 23. However, in terms of efficiency, **the best configurations to use are MCSs using 3 spatial streams**.

Figure 12 shows the power consumption and energy efficiency per bit for both TX and RX modes for the Aruba AP, using a 40 MHz channel bandwidth. The Cisco AP does not allow channel bonding on the 2.4 GHz frequency band and the Huawei AP does not allow the selection of the MCS index neither the number of spatial streams used, being the configuration and rate optimization fully automatic. The only values that were easy to isolate were the highest MCS 23 data rates, using 3 spatial streams, for both TX and RX, respectively, 17.82 and 14.88 W. The increase in power consumption for channel bonding, using the Huawei AP is only 8% for TX and 6% for RX. Therefore, we only present the results for the Aruba AP.

Taking into account the measurements performed for the Aruba AP, some conclusions can be drawn. **Using 1 or 2 spatial streams does not have a significant impact on power consumption for TX and RX modes**. In terms of energy efficiency per bit, just as with a 20 MHz channel bandwidth, **the best configurations to use are the higher MCSs using 2 spatial streams for both TX and RX**.

Figure 13 shows a comparison between the results for both 20 MHz and 40 MHz channel bandwidths. A few more conclusions can be drawn. For the Aruba AP, **channel bonding has more impact on power consumption than MIMO**. In fact, the configurations that need more power are the ones using channel bonding, to the point where a 40 MHz channel bandwidth has a similar power consumption in RX mode than a 20 MHz channel bandwidth in TX mode. If the comparison is made between a 40 MHz channel bandwidth using a single spatial stream and a 20 MHz channel bandwidth with 2 spatial streams, the data rates offered are practically the same with differences in power consumption of up to 16% between the two configurations. Yet, due to the absence of results for the other APs, these conclusions shall be confirmed in the future.

### 2) IEEE 802.11N USING 5 GHZ FREQUENCY BAND

Figure 14 shows the power consumption and energy efficiency per bit for both TX and RX modes for the three APs, when using IEEE 802.11n on the 5 GHz frequency band and a 20 MHz channel bandwidth. Again, the **TX mode uses more power than RX mode for the three APs**, as it has been verified for the previous standards. Analyzing the results obtained for the Huawei AP, the conclusion drawn for the 2.4 GHz frequency band holds: **using more spatial streams does not imply higher power consumption**. With the Aruba AP, we continue to observe that **using 1 or 2 spatial streams do not introduce a significant difference in the power consumption of the AP**. However, it is interesting to look at the results obtained for the Cisco AP power

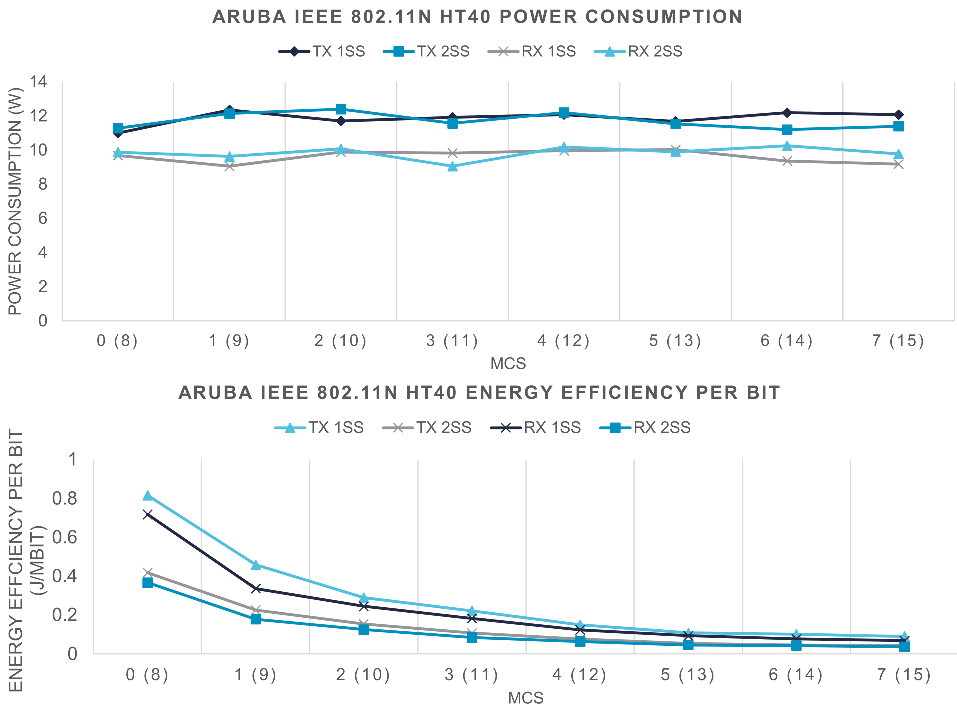


**FIGURE 12.** IEEE 802.11n power consumption and energy efficiency per bit for the Aruba AP using a 40 MHz channel bandwidth in the 2.4 GHz frequency band.

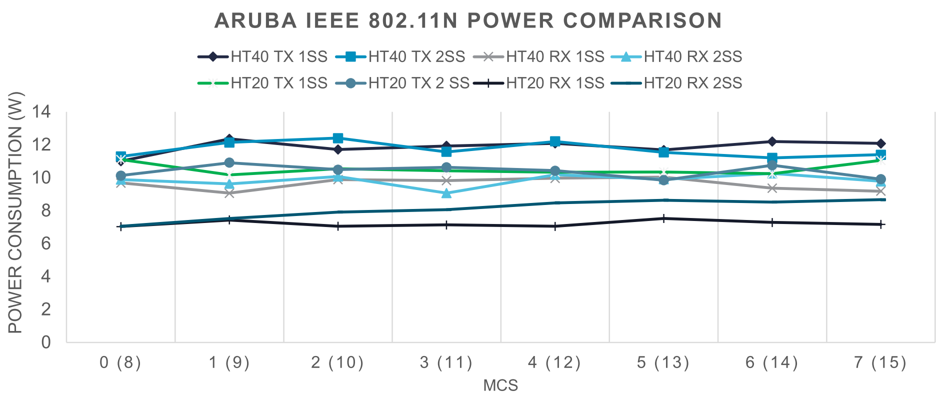


**FIGURE 13.** IEEE 802.11n power consumption comparison between 20 MHz and 40 MHz channel bandwidths for the Aruba AP using the 2.4 GHz frequency band.

consumption, because in the 5 GHz frequency band the number of spatial streams has different behavior. **Using three spatial streams is no longer the configuration with higher power consumption for both TX and RX modes**. Since we do not have all the power consumption values for 3 SS in RX mode, it is hard to draw conclusions. However, in TX mode, the difference is notorious and we believe it may be the effect of the use of Space-Time Block Code (STBC) in the 2 spatial streams configuration, in which three or even four antennas are being used to send the two streams of bits over the air, for the sake of robustness.

Figure 15 shows the power consumption and energy efficiency per bit, using now a 40 MHz channel bandwidth. We continue to observe that the **TX mode consumes more power than the RX mode**. With the Huawei AP, the behavior is very similar to the one shown with the 20 MHz channel bandwidth, recalling that using 2 spatial streams uses less power in TX mode. For the Aruba AP, **using 1 or 2 spatial streams does not have a significant impact on power consumption for both TX and RX modes**. With the Cisco AP, in most configurations, **the use of 1, 2, or 3 spatial streams leads to similar results in terms of power consumption**. This way, **the use of a different number of spatial streams does not have an impact in power consumption**. Concerning energy efficiency per bit for the three APs, and for both TX and RX, **the best configurations to use are the higher MCSs using a higher number of spatial streams**.

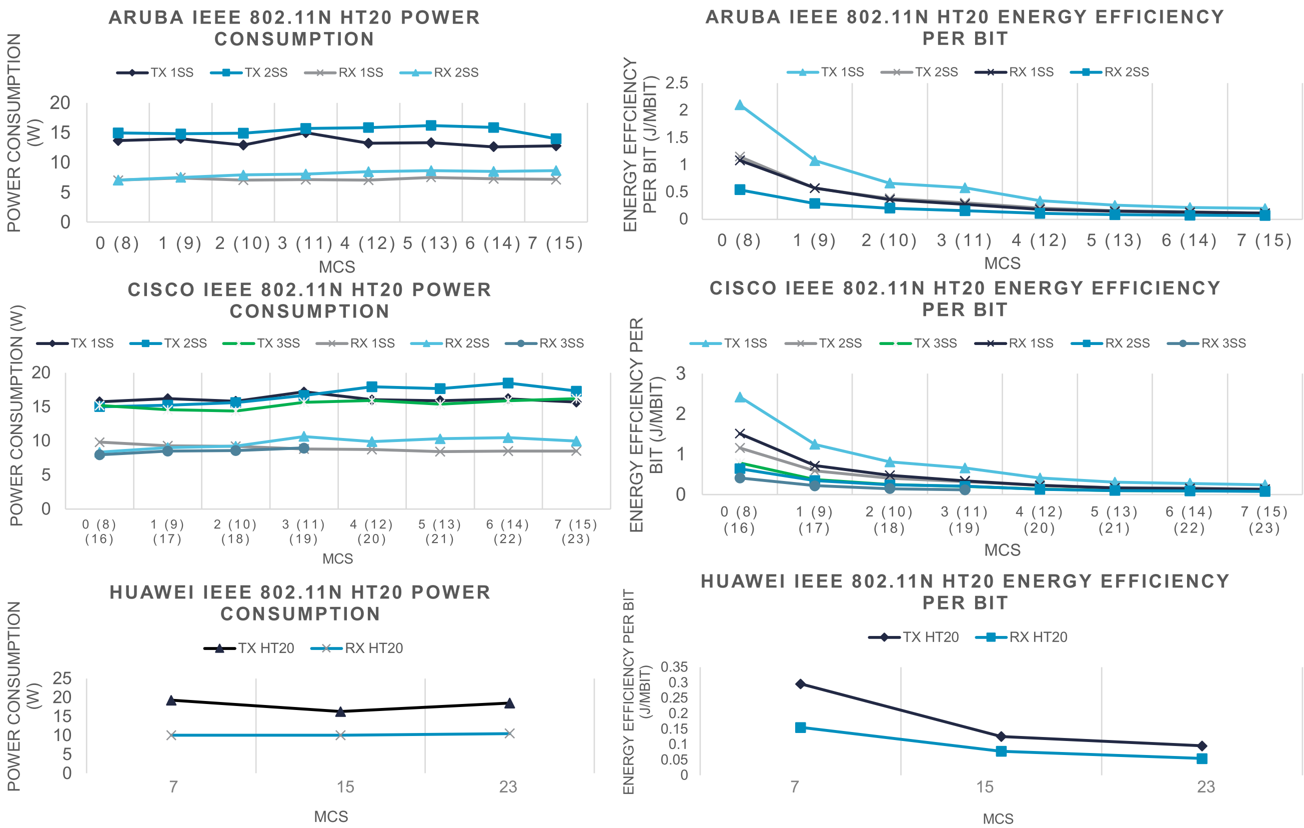


**FIGURE 14.** **IEEE 802.11n power consumption and energy efficiency per bit for the three APs using a 20 MHz channel bandwidth, in the 5 GHz frequency band.**

The plots of Figure 16 show a comparison between the 20 MHz and the 40 MHz channel bandwidth configurations. **The Huawei AP does not show any notable difference between using a 20 MHz channel and a 40 MHz channel bandwidth. With 2 spatial streams, less power is used in TX mode**. In the case of the Aruba AP, using a channel bandwidth of 20 MHz and 2 spatial streams is the configuration that has the highest power consumption. It is interesting to notice that for some MCSs – MCS 1 and MCS 2 –, **2 spatial streams for a 40 MHz channel bandwidth use less power than 1 spatial stream for the same channel bandwidth**. Another interesting fact is that **in RX mode the power consumption for 1 or 2 spatial streams is similar**. For the Cisco AP, in RX mode, a 40 MHz channel bandwidth with 3 spatial streams is the configuration that uses more power. However, if using a 20 MHz channel bandwidth, for the same 3 spatial streams, it is the configuration showing the lowest power consumption, in RX mode. It is important to notice that, for the TX mode, the configurations with a 40 MHz channel bandwidth are not the most expensive in terms of power consumption, but rather the configuration with 2 spatial streams using a 20 MHz channel bandwidth, noticeably from MCS 10 to 15. A final conclusion that can be drawn is that for IEEE 802.11n **the RX mode uses approximately half the amount of power than the TX mode for all devices and MCS indices analyzed**. So, **channel bonding does not increase power consumption and has higher energy efficiency per bit**.

### *E. POWER CONSUMPTION IN TX AND RX MODES USING IEEE 802.11AC*

IEEE 802.11ac is the most recent standard, only running on the 5 GHz frequency band. This standard allows channel bonding up to 160 MHz; the APs under study only allow up to 80 MHz. When compared to IEEE 802.11n, IEEE 802.11ac adds the 256-QAM modulation, with MCSs 8 and 9. As such, the additional measurements done were for MCS 8 and 9 for VHT 20 and VHT 40. For VHT 80, as IEEE 802.11ac does not allow the selection of individual MCS indices, the measurements were done only for MCS 7-9. Moreover, some configurations are simply not allowed in IEEE 802.11ac, namely, MCS 9 is not allowed to be used on a 20 MHz channel bandwidth with 1, 2, or 4 spatial streams (c.f. Subsection III-C). Also, the NIC used as client device in our tests did not support some of the configurations using 80 MHz channel bandwidth. This is why the results for such configurations could not be obtained. In the following plots, instead of the MCS index, we present the physical data rate, in Mbps, for the configuration applied. The numbers in the x-axis represent the data rates for 20 MHz, 40 MHz, and 80 MHz channel bandwidths, respectively.

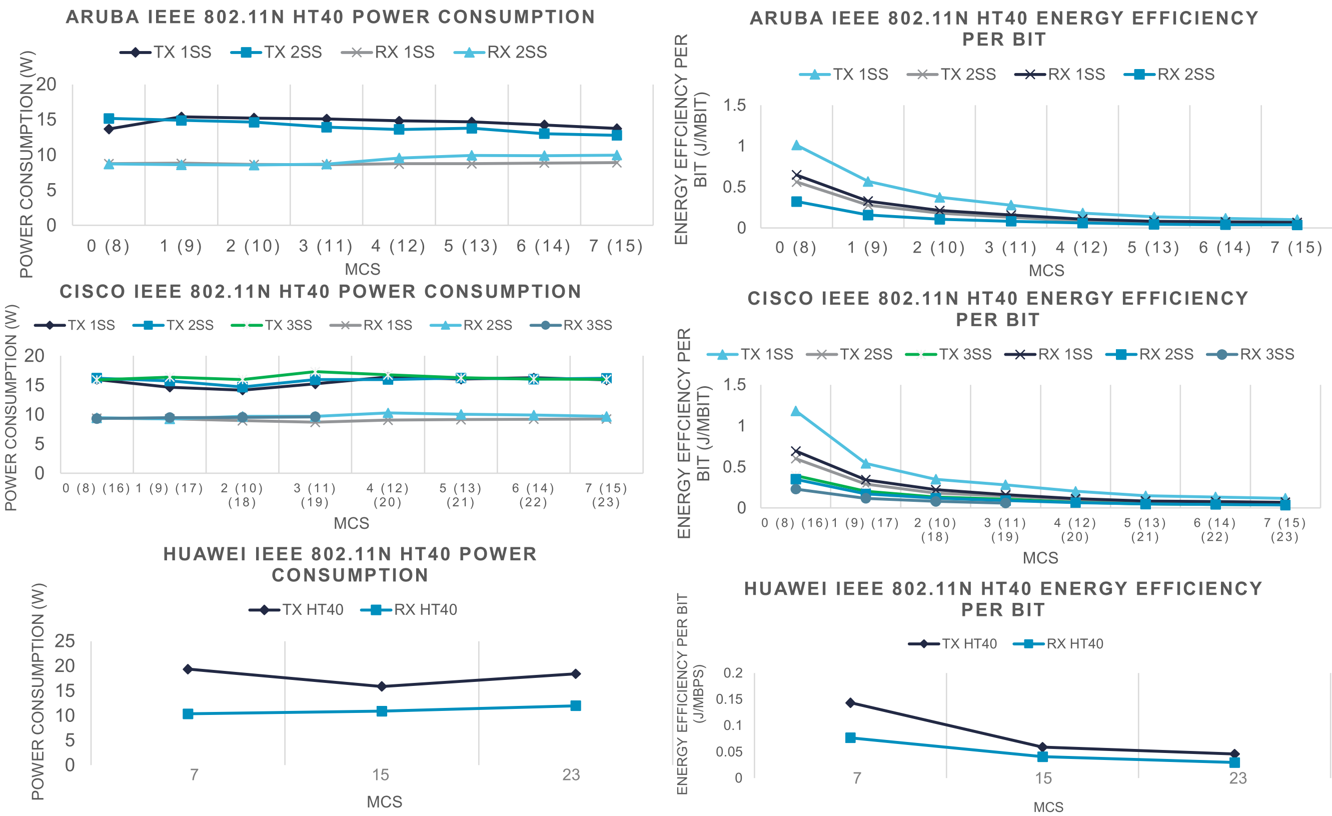


**FIGURE 15.** IEEE 802.11n power consumption and energy efficiency per bit for the three APs using a 40 MHz channel bandwidth, in the 5 GHz frequency band.

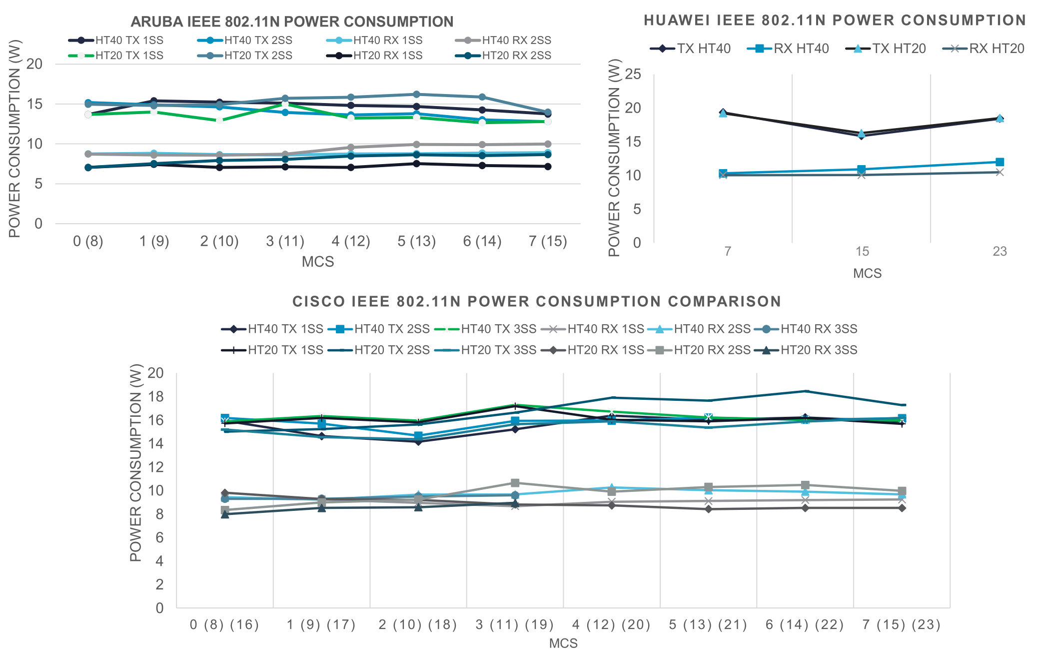


**FIGURE 16.** IEEE 802.11n power consumption for the three APs using 20 MHz and 40 MHz channel bandwidths in the 5 GHz frequency band.

The Aruba AP did not allow selecting the number of spatial streams when using IEEE 802.11ac; in this way, only the data rates using 2 spatial streams are represented in Figure 17. With the Aruba AP, **an 80 MHz channel bandwidth shows the highest power consumption of the AP**. With the Cisco AP, **the differences between TX and RX modes are**

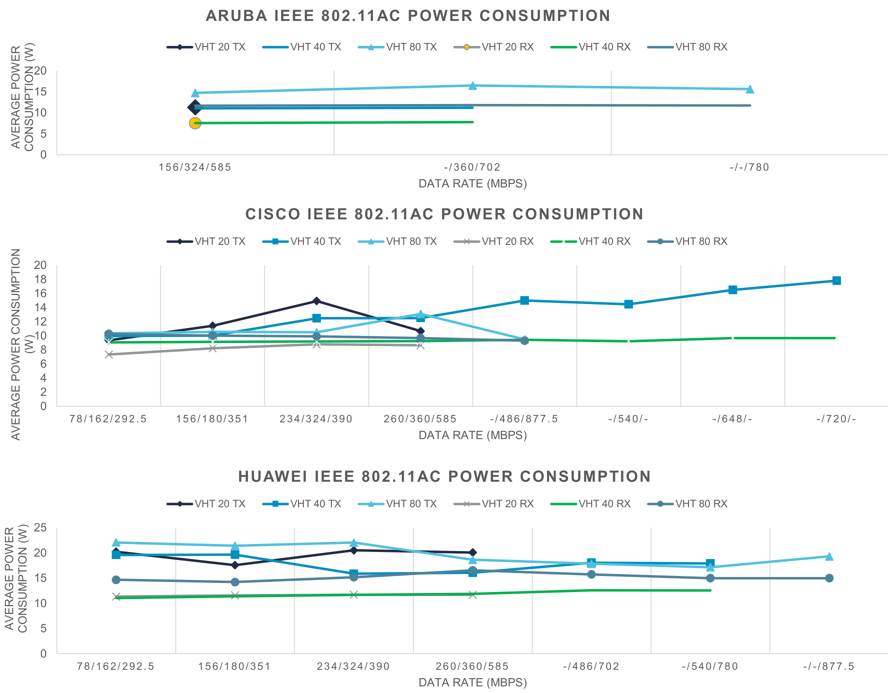


**FIGURE 17.** IEEE 802.11ac power consumption for the three APs using channel bandwidths of 20, 40, and 80 MHz.

**minimal for lower data rates, but as the data rates increase, the gap between the two operation modes is substantial**, and in TX mode, with a channel bandwidth of 40 MHz, it reaches a difference of 84%. The effect of the very high data rates become notorious for the three APs analysed, with the devices consuming the highest power values of all configurations tested. In the case of the Huawei AP, **the configurations with wider channel bandwidths have higher power consumption for TX mode**. Still, it is interesting to notice that **for RX, the 20 MHz and 40 MHz channel bandwidths have a very similar behavior**. Therefore, **higher data rates using higher channel bandwidths have higher power consumption**.

Figure 18 shows that for the three APs, **the higher the channel bandwidth and the number of spatial streams, the more energy efficient per bit the configuration is**. The same behavior is shared among the three APs analyzed. However, with IEEE 802.11ac, **for the higher data rates, the energy efficiency per bit remains constant as the PHY data rate increases**. This happens with the three APs, and the reason lays in the rise in power consumption that the higher data rates show. This represents a constant energy efficiency per bit, as the increase in the PHY data rate introduces a higher power consumption. In this way, **very high data rates should only be used when the network shows a substantial demand for high throughput applications**.

### F. POWER CONSUMPTION WHEN TX POWER IS VARIED

Another configuration commonly suggested as a means of reducing the power consumption of Wi-Fi devices is the fine-tuning of the transmission power. In order to determine the impact of this configuration, the TX power value was varied for the three APs, from the maximum to the minimum allowed. Figure 19 shows the power measurement results for the three APs, considering both the 2.4 GHz and 5 GHz frequency bands. The percentages on the plot show the amount of power saved by reducing the TX power to the minimum. In order to collect these values, a configuration was defined for the 5 GHz frequency band, IEEE 802.11a, using 6 Mbps data rate. The configuration used for the 2.4 GHz was IEEE 802.11g, using the same 6 Mbps data rate. As we want to assess the power consumption differences by varying the TX power, a simpler configuration and data rate can be used.

From the plot of Figure 19, **the variation of TX power has low impact on power consumption of enterprise APs** (up to 13%). For instance, the total power consumption of the Aruba AP does not suffer any changes for the 5 GHz frequency band; for the Cisco AP when using the 2.4 GHz frequency band, the power consumption varies by 1%. The major impact is for the Cisco AP when using the 5 GHz frequency band (13% difference), and for the Aruba AP using the 2.4 GHz frequency band (9% difference). As such, **TX power variation should only be considered as a radio planning tool and not as a means of reducing the power consumption of the APs**.

### G. NUMBER OF ACTIVE ANTENNAS

During the analysis of the different configuration parameters, one interesting configuration, only available for the Cisco AP, was the ability to switch off antennas. In this way, each one of

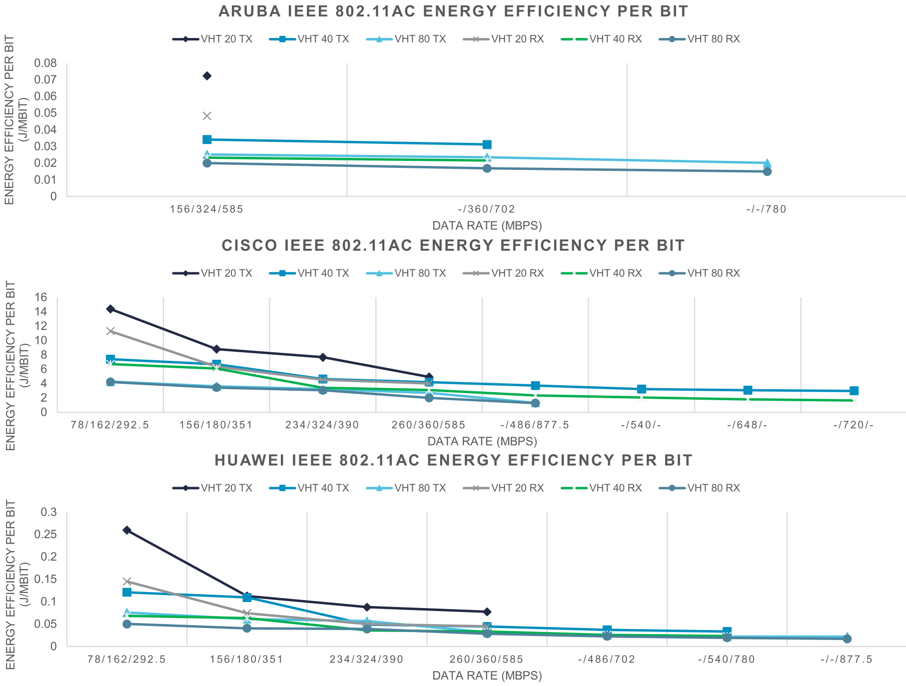


**FIGURE 18.** IEEE 802.11ac energy efficiency per bit for the three APs using channel bandwidths of 20, 40, and 80 MHz.

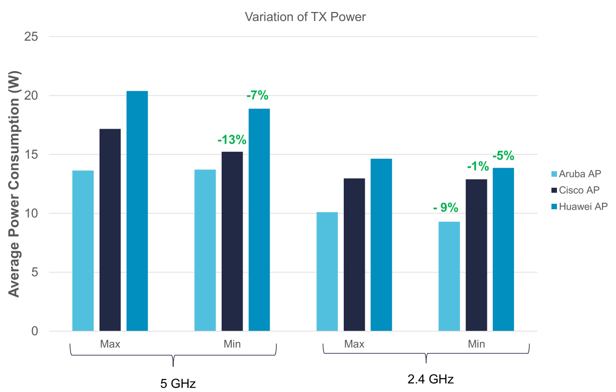


**FIGURE 19.** Power consumption of the three APs when the TX power was varied from the maximum to the minimum value allowed by the vendor.

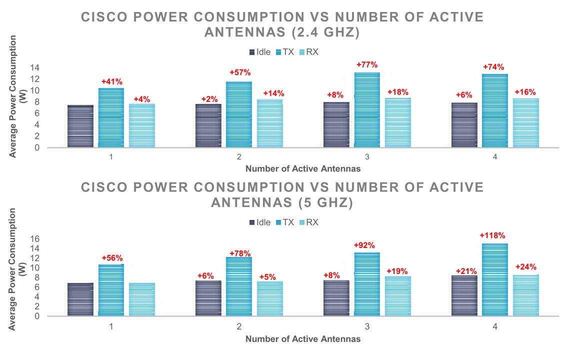


**FIGURE 20.** Power consumption of the Cisco APs for idle, TX, and RX modes, when changing the number of active antennas.

the 4 antennas present in the Cisco AP, for both 2.4 GHz and 5 GHz, can be switched off regardless of the other parameters of the device. Figure 20 shows the power consumption results for idle, TX, and RX modes.

The percentages in Figure 20 refer to the comparison with the power consumption obtained in Idle mode for 1 antenna, for both the 2.4 GHz and 5 GHz frequency bands. It is visible that the greatest differences are not for the power consumption in idle mode, where 4 active antennas use 6% more power for 2.4 GHz and 21% more power for 5 GHz. RX mode shows an increase up to 24% in power consumption, which can be regarded as a considerable difference. **The major differences in power consumption are in TX mode**, with an increase of up to 74% for the 2.4 GHz frequency band and 118% for the 5 GHz frequency band. This difference is explained by the RF chain each antenna has attached to it, including the power amplifier used in the TX mode. **Despite being a feature only found in the Cisco AP, the number of active antennas can be a configuration used to save energy on enterprise APs since it would be limiting the maximum power used by the AP**.

### *H. COMPARISON BETWEEN IEEE 802.11 STANDARDS*

In this section, the results on power consumption and energy efficiency per bit are compared for the three enterprise APs studied, considering different IEEE 802.11 standards. The analysis takes into account standards and configurations that can be compared in terms of data rates. For that purpose, for each AP the results for IEEE 802.11a/g/n are condensed in a single plot in order to evaluate how each standard performs in comparison with other standards.

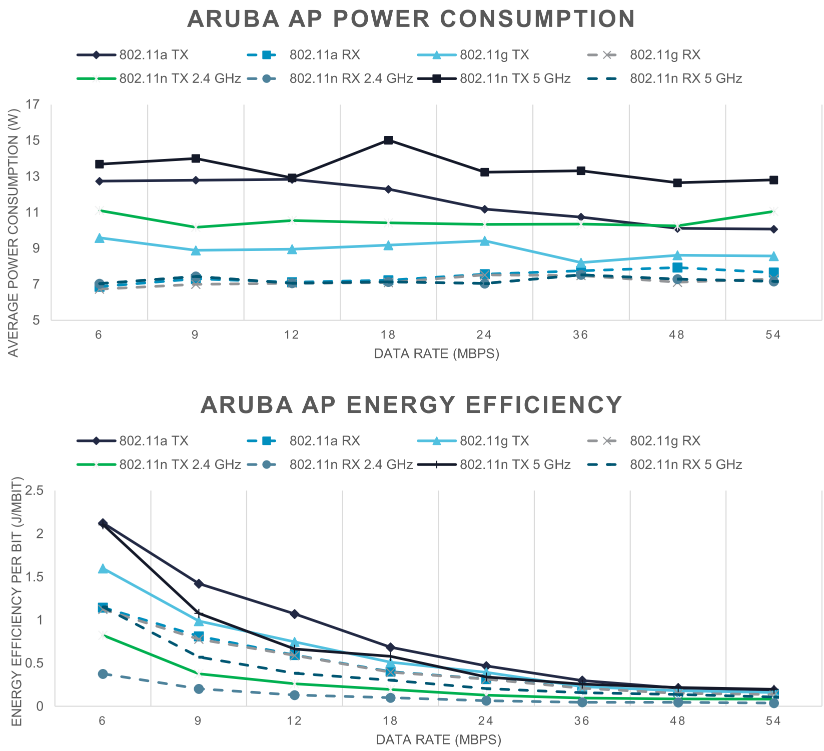


**FIGURE 21.** Power consumption and energy efficiency per bit of the Aruba AP.

The plot of Figure 21 shows the results obtained for the Aruba AP using the 20 MHz channel bandwidth. The most efficient standard is IEEE 802.11n when running on the 2.4 GHz frequency band, as it is the standard with the least amount of power consumed for the same data rates. The configurations with the highest energy efficiency per bit are the ones using the highest data rates or MCS indices, as the power consumption, as seen previously, does not vary significantly with the data rates. IEEE 802.11g can also be a good option for TX mode, as it uses the least amount of power for this AP. However, IEEE 802.11n is more efficient as there is a slight increase in the data rates achieved by this standard when compared to the legacy IEEE 802.11g, due to the use of a few more subcarriers for the same channel bandwidth, and the option of SGI. The lowest energy efficient standard is IEEE 802.11a for both TX and RX modes.

The results obtained for the Cisco AP are shown in the plot of Figure 22. For the same data rates, the most efficient standard is IEEE 802.11n running on the 2.4 GHz frequency band. This conclusion is the same as for the Aruba AP because the 2.4 GHz uses less power than the 5 GHz frequency band, and the data rates achieved are the same in the two frequency bands, for the same channel bandwidth. The configurations with the highest energy efficiency per bit are those using the highest data rates or MCS indices, for both the 2.4 GHz and the 5 GHz frequency bands. For higher data rates, IEEE 802.11g can be a valid option for TX mode, as the power consumption is the lowest of all configurations analyzed. The worst energy efficient standard is IEEE 802.11a for TX and IEEE 802.11g for RX. IEEE 802.11a consumes more power, using the 5 GHz frequency band, and IEEE 802.11g is the standard that uses more power in RX mode, up to 24 Mbps of data rate.

Figure 23 shows the results obtained for the Huawei AP. For the same data rates, the most efficient standard is IEEE 802.11n using the 2.4 GHz or the 5 GHz frequency bands, even though only measurements for MCS 7 are available. The most efficient configurations are the ones using the highest data rates or MCS indices. For lower data rates, IEEE 802.11g can also be a good option in TX mode. The worst energy efficient standard is IEEE 802.11a for TX and IEEE 802.11g for RX. IEEE 802.11a in RX shows good energy efficiency per bit as well.

Thus, for maximum energy efficiency per bit, IEEE 802.11n using the 2.4 GHz frequency band should be the standard used.

*Summary:* In this section we presented the power consumption and energy efficiency per bit results for all the configurations tested. We can see definitive patterns for both power consumption and energy efficiency per bit concerning the three APs under study in most of the configurations tested. Some results, however, are device specific and the absolute values of both power and energy efficiency per bit are device dependent. We discuss this further in Section VII.

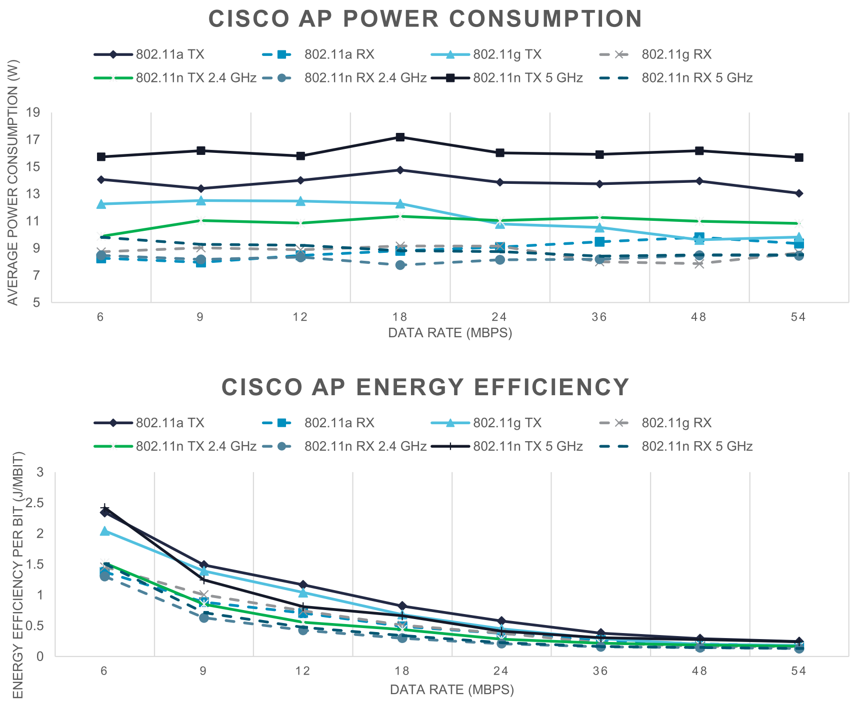


**FIGURE 22.** Power consumption and energy efficiency per bit of Cisco AP.

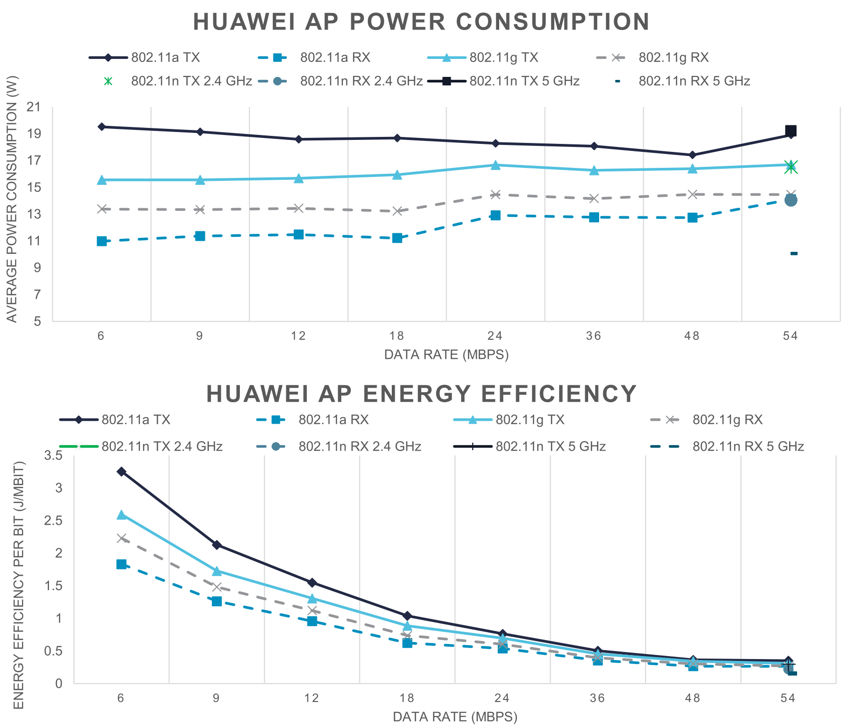


**FIGURE 23.** Power consumption and energy efficiency per bit of the Huawei AP.

## VII. DISCUSSION

In this section, a discussion of the experimental results obtained is presented, in order to assess the validity of our findings and how they complement and go beyond the conclusions drawn in the related works presented in Section IV. Table 7 summarizes the major findings obtained in our study.

Some of the obtained results and corresponding conclusions are device specific and not shared by all the enterprise Wi-Fi APs analysed – one of the factors that

**TABLE 7. Major findings of our experimental study on enterprise Wi-Fi APs power consumption and energy efficiency. Emphasized text represents findings that are common to the three APs.**

| Major findings | Aruba 207 | Cisco 1852i | Huawei 8030DN |
|---|---|---|---|
| **Idle Mode** | | | |
| Standby state uses the least amount of power | *YES* | *YES* | *YES* |
| 5 GHz uses more power than 2.4 GHz | *YES* | *YES* | *YES* |
| More interfaces switched on imply more power used | *YES* | *YES* | *YES* |
| Channel bonding affects power consumption | YES (up to 30%) | NO | NO |
| **IEEE 802.11a** | | | |
| TX mode uses more power than RX mode | *YES* (up to 87%) | *YES* (up to 70%) | *YES* (up to 77%) |
| Higher data rates imply higher power consumption | *TX: NO RX: YES* | *TX: NO RX: YES* | *TX: NO RX: YES* |
| Higher data rates are more energy efficient | *YES* | *YES* | *YES* |
| **IEEE 802.11b/g** | | | |
| TX mode uses more power than RX mode | *YES* (up to 40%) | *YES* (up to 40%) | *YES* (up to 20%) |
| Higher data rates imply higher power consumption | *NO* | *NO* | *NO* |
| Higher data rates are more energy efficient | *YES* | *YES* | *YES* |
| **IEEE 802.11n 2.4 GHz** | | | |
| TX mode uses more power than RX mode | *YES* | *YES* | *YES* |
| More SS use more power | TX: NO RX: YES 40 MHz channel bandwidth: NO | Not always | Not enough data |
| Higher data rates imply higher power consumption | TX: NO RX: YES 40 MHz channel bandwidth: NO | Not always | Not enough data |
| Higher data rates are more energy efficient | YES | YES | Not enough data |
| Channel bonding impacts power consumption | YES | Not enough data | Not enough data |
| **IEEE 802.11n 5 GHz** | | | |
| TX mode uses more power than RX mode | *YES* | *YES* | *YES* |
| More SS use more power | NO | YES (2SS) NO (3 SS) | NO |
| Higher data rates imply higher power consumption | *NO* | *NO* | *NO* |
| Higher data rates are more energy efficient | *YES* | *YES* | *YES* |
| Channel bonding impacts power consumption | *NO* | *NO* | *NO* |
| **IEEE 802.11ac** | | | |
| TX mode uses more power than RX mode | *YES* | *YES* (up to 84%) | *YES* |
| More SS use more power | *Not always* | *Not always* | *Not always* |
| Higher data rates imply higher power consumption | *NO* | *NO* | *NO* |
| Higher data rates are more energy efficient | *YES, up to a threshold* | *YES, up to a threshold* | *YES, up to a threshold* |
| Channel bonding impacts power consumption | *YES* | *YES* | *YES* |
| **TX Power** | | | |
| Impact on power consumption | *LOW* (up to 9%) | *LOW* (up to 13%) | *LOW* (up to 5%) |
| **Number of active antennas** | | | |
| Impact on power consumption | No data available | YES 2.4 GHz: up to 77% savings; 5 GHz: up to 118% savings | No data available |

contribute to these differences is that not all configurations were possible to apply to the three APs used in our study.

Looking back at the conclusions collected from the state of the art review (cf. Section IV), it was confirmed that legacy standards consume more power than recent standards (cf. Subsection VI-H); it was confirmed that IEEE 802.11a does not make much difference in power consumption when compared to the standards using the 2.4 GHz frequency band, even though we found the 5 GHz radio interface to consume more power than the 2.4 GHz radio interface, the difference in power consumption was only 5% more in TX mode. We also saw that Idle mode and Standby state effectively save energy (cf. Subsection VI-B). On the other hand, the results did not back up the idea that MIMO shows a large increase in power consumption when compared to SISO (cf. Subsections VI-D and VI-E); even though there is an impact using some configurations, that impact cannot be considered significant. The reason for this lays in the fact that the use of more than one spatial stream implies the use and powering of extra hardware, as each spatial stream carries different bits, and those bits have to be processed by their own individual components. Multiple spatial streams have higher power requirements, due to the individual Fourier transforms and signal amplifying. This would suggest that a higher number of spatial streams used would imply higher power consumption. However, there is another feature in IEEE 802.11n/ac called STBC that requires two radio chains to transmit a single spatial stream [9]. By spreading a spatial stream across two radio chains and two paths, it is possible to increase the redundancy in transmission to offset path loss, though at the cost of overall transmission speed. Therefore, using one spatial stream in IEEE 802.11n/ac may imply the use of more than one radio chain. In fact, disabling STBC is possible at the AP, but multipath fading may affect the overall throughput of the experiment. In this way, in a multiple spatial stream AP, we can see that one spatial stream configuration can use 2 radio chains, and a 2 spatial stream configuration can use 3 radio chains. This explains the obtained results, as there is not always a one-to-one relationship between the number of spatial streams and the radio chains used. This is why a configuration with more spatial streams does not always lead to the usage of more power. The results show that there are changes in power consumption, but they are not significant when compared the total power consumption of the AP.

Channel bonding was another configuration that did not always show impact on the power consumption of the AP. This can be explained as channel bonding increases the size of the Fast Fourier Transform (FFT) but follows all the processes that a 20 MHz channel bandwidth follows. The only difference is the size of the FFT and the sampling and clock rate increase to maintain the standard IEEE 802.11 symbol period. Therefore, with channel bonding the de-multiplexer and demodulator must be run at twice the speed (for a 40 MHz channel bandwidth) or at fourfold speed (for an 80 MHz channel bandwidth) [41]. There is no extra hardware switched on for channel bonding, only an increase in processing speed by the NIC. This explains why, for some configurations, the results show that increasing the channel bandwidth does not significantly increase the total power consumption of the AP.

TX power was another configuration that showed negligible impact on power consumption. Looking at TX power results, the variation is not high (up to 13% for Cisco AP when using the 5 GHz frequency band) because the increase in power consumption, which may be significant if only the power consumption of the NIC is considered, is small when we take into account the power consumption of the device as a whole. Even though varying TX power can increase the power consumption of an NIC, as some state of the art suggests, when we consider an AP with multiple NICs the TX power only represents a small increase in the total power consumption of the device. This explains the obtained results concerning the sensitivity of the total power consumption to the change of the TX power.

The "race to sleep" strategy was confirmed to be an effective solution since higher data rates show higher energy efficiency per bit. Also, it was confirmed that the TX power variation does not have a significant impact on the power consumption of the device. Regarding the contradictory conclusions pointed out in the state of the art, we did not find lower MCSs to be more energy efficient for RX; rather, we found that higher MCSs are more energy efficient. Furthermore, the selected MCS has a negligible impact on power consumption, when using the same IEEE 802.11 standard, the same number of spatial streams, and the same channel bandwidth configuration.

After the detailed analysis provided in Section VI, it is important to discuss the power consumption, the energy efficiency per bit, and the performance trade-offs. The configuration of the APs in the 2.4 GHz frequency band results in less power consumption but this frequency band is crowded. This was the main reason why IEEE 802.11ac focused solely on the 5 GHz spectrum; the 5 GHz radio interfaces consume more power but the 5 GHz frequency band has more channels available. More recently, this is leading to Wi-Fi radio planning based on 5 GHz channels rather than the typical 3-channel 2.4 GHz radio planning. In addition, with IEEE 802.11ac, with channel bonding and multiple spatial streams, the 5 GHz frequency band allows much higher data rates. If MU-MIMO is added, more users can be served, which will greatly increase the energy efficiency per bit. On the other hand, the power consumption will be inherently higher with these configurations when compared, for instance, to a single stream configuration with a 20 MHz channel bandwidth in the 2.4 GHz frequency band.

Despite the theoretical high energy efficiency per bit observed for channel bonding, in practice, it can be difficult to achieve very high data rates, namely in dense Wi-Fi networks. Firstly, as discussed in Subsection III-C, larger channel bandwidths can be harder to obtain in crowded areas. This is even more critical in the 2.4 GHz due to the sparse radio spectrum available; also, as seen in Section VI, some APs may not even support channel bonding in this frequency band. With channel bonding, the noise floor is inherently higher, which demands the user to be closer to the AP to get good enough SNR. Narrower channel bandwidths allow the receiver to filter out more noise, thus improving the SNR. This means that the most energy efficient configurations, found to be those using higher data rates and wider channel bandwidths, will demand good coverage so that the users can take advantage of those settings, which in real scenarios may be hard to achieve. In order to overcome the problem, a dynamic configuration may be applied to APs to increase the number of configuration options available in a real scenario, allowing the AP to use larger channel bandwidths when possible, increasing the performance of the Wi-Fi network, but allowing the fallback to narrower channel bandwidths whenever the channel quality is degraded.

Therefore, it is important to adapt the Wi-Fi network to the traffic demand observed, in light of the findings of our experimental work. In periods where the Wi-Fi network has a higher traffic demand from the users, the APs should be configured with higher energy efficient configurations per bit. This allows the higher traffic volume to be sent in potentially higher speeds, keeping a low energy cost per bit transmitted. In periods when the Wi-Fi network shows a low traffic demand, the APs should be configured to save the maximum amount of energy, using configurations with the lowest possible power consumption.

The main limitations of the results presented herein have to do with the lack of a client NIC with MIMO $4 \times 4$ to test the full capabilities of the Cisco AP, along with two NICs with MU-MIMO capabilities to test this feature. Moreover, some configurations were not fully tested, due to problems faced with the NIC drivers and kernel panics at the AP. The fact that some APs did not allow the selection of individual MCSs could have been solved using extra hardware to confirm the modulation used on the frames sent over the Wi-Fi network. Nevertheless, this would increase the long time needed to run the full set of tests.

These are some of the trade-offs and limitations involved in the conclusions that can be drawn from the results we obtained in our experimental study. It is now clear what are the power consumption and energy efficiency per bit patterns that could be identified in the three APs under test and how these results can impact current and future Wi-Fi networks.

## VIII. CONCLUSIONS

Enterprise Wi-Fi APs use a significant amount of power in today's ubiquitous Wi-Fi networks. As such, it is essential to understand how these devices consume power and which configurations are the most efficient. There are some studies available in the state of the art which analyse APs and Wi-Fi NICs in terms of power consumption under different configurations. Still, most of these works are outdated, not considering the recent IEEE 802.11 standards; also, the methodology applied is not applicable to today's Wi-Fi network deployments. This paper provided a comprehensive analysis of the power consumption and energy efficiency per bit of enterprise

Wi-Fi APs, considering three APs from the major vendors on the market.

As general conclusions, it was determined that the Standby state shows the least amount of power usage and TX mode uses more power than RX mode, the same way as single-band uses less power than dual-band devices, with the 5 GHz radio interface using more power than the 2.4 GHz radio interface. Some of the state of the art assumptions and conclusion were not confirmed by our study. For instance, in contrast to the conclusion reported in related works, we found TX power has little impact on the enterprise Wi-Fi AP power consumption. Also, the rationale that higher data rates always use more power was not verified; according to our study, in some configurations, higher data rates for some IEEE 802.11 standards use in fact the same power level or even less power than lower data rates. Due to this, higher data rates are always more energy efficient configurations.

Given the nature of the implementation of enterprise Wi-Fi APs firmware, the set of conclusions related to IEEE 802.11n/ac could not be fully detailed, as not all configurations could be isolated and measured. However, it was confirmed that a ''race to idle'' strategy is efficient for all the configurations tested; APs use the least amount of power when in idle mode and it was verified that higher MCSs do not mean higher power consumption in the APs. In TX and RX modes, for the same frequency band, the factors that impact power consumption the most are the number of spatial streams and the channel bandwidth; the MCS selected does not have a great impact for the majority of the tests performed.

As future work, the measurements taken can be used to derive a general power consumption model for enterprise Wi-Fi APs. In fact, we studied the possibility of developing a model that would allow the scientific community to use our results in an easy way. For that purpose, we created a dataset containing all our measurements and we used multivariate linear regression to provide a preliminary model. However, when analyzing the dataset, we found that the power consumption of the APs is very dependent on the AP vendor and model. In this way, our model would only be suitable for the three APs under study (explaining roughly 70% of the variance of our data), but it would fail when attempting to predict the power consumption of other devices, as we tried to do using another Cisco AP (the 1042N model). Therefore, we left for future work the detailed study of a power consumption model. This model could be implemented in network simulators, to achieve more realistic and reliable power consumption estimations. The model can also be used to produce better energy efficient mechanisms in today's and future Wi-Fi networks to save energy at the APs. Another future update that can be done is the test of an IEEE 802.11ax (Wi-Fi 6) compliant enterprise Wi-Fi AP. This standard introduces new features such as uplink MU-MIMO and Orthogonal Frequency Divison Multiple Access (OFDMA) for multiple uplink clients to communicate with the AP at the same time, if spatially distanced. In our testbed, only AP Cisco 1852i already had MU-MIMO support (and only in the downlink), which made the comparison among the three APs under test impossible, but MU-MIMO (uplink) and OFDMA are technologies that will become gradually available with IEEE 802.11ax as enterprise APs and Wi-Fi NICs become available. This work may also be extended to other network infrastructure devices, namely, switches and routers.

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