Achilles and the Tortoise: Power Consumption in IEEE 802.11n and IEEE 802.11g Networks

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***Abstract*—Cloud computing is currently emerging as the de facto standard for Internet service provisioning. This uptake is motivated, among other aspects, by the significant reduction in energy consumption that can be achieved by centralizing, consolidating and optimizing large IT infrastructures. At the same time, however, users expect to access cloud services via wireless access networks using smartphones and tablets. Several studies already show that wireless technologies such as WiFi and 4G are becoming the dominant access to cloud services. However, while energy efficiency is accounted for the end-user devices and data-centers, the actual energy consumption of wireless access networks is typically overlooked, even though it is expected to account for about 90% of the entire wireless cloud energy footprint. In this paper, we use real–world measurements to present a complete analysis of the power consumption and performance of IEEE 802.11n. We also compare IEEE 802.11n with its predecessor, the widely deployed IEEE 802.11g standard, and confirm that 802.11n (2x2 MIMO) performs $\sim$ 4.5 times better than 802.11g in terms of maximum network throughput as expected while at the same time reducing the required energy per bit by $\sim$ 50%.**

***Index Terms*—Green networks, Energy efficiency, Measurements, Power meters, Testbed, IEEE 802.11, Energino**

I. Introduction

The modern society is becoming more and more dependent on strong and efficient communication networks, as several daily activities are carried out using Internet-based services and systems. Social networks, such as Facebook and twitter, and the Internet in general are the most attractive and instantaneous medium individuals can tap into in order to express feelings, dispatch news, share pictures/files and access hundreds of applications and services. As smartphones and tablets become the most common access devices, this leads to a consistent trend in the increase of data flowing over wireless. According to recent studies, the amount of traffic in wireless networks is increasing at a compound annual growth rate estimated in the range between 300% and 700% [1]. While the current uptake of cloud computing is allowing large IT providers to significantly reduce their energy consumption by consolidating and optimizing centralized computing resources, the users typically expect to access these new services via wireless access networks. These networks are inherently energy inefficient and according to [2], by 2015 will account for up to the 90% of the entire wireless cloud computing energy footprint.

Wireless local area networks (WLANs) are expected to play a significant role in the wireless cloud computing scenario, as IEEE 802.11 family of standards has become the most popular wireless access technology deployed in cities, universities and enterprises. The recently IEEE 802.11n [3] standard significantly improves the throughput over the previous ones – 802.11a/g – with an increase in the maximum data rate from 54 Mb/s to 600 Mb/s. Future extensions such as IEEE 802.11ac and IEEE 802.11ad will deliver performance beyond 1 Gb/s. Currently, practically all smartphones, tablets and laptops are compliant with the IEEE 802.11n standard, which delivers higher capacity than wide area networks (i.e. 3G, LTE, and WiMAX) enabling a better quality of service (QoS) and consequently, a better quality of experience for users.

Given its widespread use, understanding the energy consumption characteristics of the 802.11n technology represents an imperative step in order to design solutions for reducing the impact to the overall CO_2 footprint of wireless networks [4], [5]. In our previous work [6], we analyzed and experimentally measured the energy consumption of several 802.11g-compliant WiFi Access Points (APs) and WiMAX Base Stations (BS). Here, we use a similar methodology to experimentally measure, analyze and compare the energy consumption patterns of 802.11g and 802.11n devices. In particular, our experiments aim at answering how, where and when the power is consumed in WiFi networks. We investigate whether there is any penalty, in terms of energy consumption, when migrating from old to new technologies and the advantages or disadvantages of such migration. The main contributions of the paper are the following:

- We present an empirical analysis of energy consumption associated to data transmission in 802.11n devices, and perform an experimental comparison 802.11g and 802.11n standards in terms of (i) the amount of traffic sent/received by the AP, (ii) the size of the session level data units, and (iii) the transmission power levels.
- We numerically demonstrate that most of the energy consumed by 802.11 AP – $\sim$ 67%-82% – is hardware dependent and that the IEEE 802.11n standard is more energy efficient than the IEEE 802.11g standard.

The remainder of this paper is organized as follows. A brief analysis of the related work is presented in Section II.

In Section III we present the experimental settings and the methodology used. The results on power consumption of 802.11n APs are reported and discussed in Section IV, while the comparison between the 802.11g and the 802.11n standards in terms of energy consumption and network throughput is presented in Section V. Finally, Section. VI provides some concluding remarks and discusses directions for future work.

II. Related Work

Energy consumption measurements of 802.11n technologies have been performed for mobile phones [7] and Network Interface Cards (NICs) [8]. In [8], power consumption statistics of an 802.11n NIC across a broad set of operating states (channel width, transmit power, rates, antennas, Multiple–Input/Multiple–Output (MIMO) streams, sleep, and active modes) are reported. The testbed used for the power consumption measurements was composed of two nodes placed close to each other. The NIC used in the experiments is available in a mini-PCI Express form factor. To measure the power consumption, the authors placed an extra circuit and used National Instruments 6218 Data Acquisition Module (NIDAM) for logging the voltage and current consumed by the NIC. In order to inject traffic in the experimental testbed, packets of 1500 bytes large are generated. The main conclusions of this work are that (i) for optimizing energy consumption, it is imperative to use the fastest single-stream rate possible, especially for short packets and (ii) the optimal device settings will also depend on channel conditions and workload. The authors also observed that transmit power levels have very little effect on the power consumed by the interface. In contrast to our work, the authors experimental focus is based only on the power consumption of the single 802.11n NIC rather than of the system as a whole, ignoring the energy expenditures related to other functions, such as operations for packet forwarding and reception, fragmentation and reassembling. Additionally, in this work, we also present a comparison between the different 802.11 standards supported by the devices.

In [7], the authors ran a large number of automated tests using Google Android G1, Magic, Hero and Nexus handsets and present results for the average energy consumption of connection and data transmission over 802.11 wireless networks. The phone's power consumption is measured by inserting a high-precision 0.02Ω measurement resistor in series between a battery terminal and its connector on the phone. A National Instruments PCI-MIO-16E-4 sampling board is used in order to measure the voltage across the phone battery and also the voltage drop across the measurement resistor at 250 kHz. Power consumption measurements for cellular phones are also presented in [9]. Here, the authors compare the performance of LTE, 3G and WiFi by local experiments on mobile devices. Specifically for the WiFi measurements, the data network radio interface is turned off and the mobile device is connected to a wireless 802.11g router in channel 2.437 GHz. For cellular measurements, the WiFi interface is turned off and the mobile device is connected to the 4G network. Finally when 4G is disabled, the device connects to the 3G network. The Monsoon power monitor [10] is used as power input for the mobile device measuring power traces at the same time. The main conclusions of this work are that LTE is as much as 23 times less power efficient compared to WiFi, and even less power efficient than 3G, based on the user traces, and the long high power tail is found to be a key contributor to this behaviour. The results reported by the authors in [7], [9] provides us with insights on the power consumption of the client-side rather than of AP-side, which is addressed in this work.

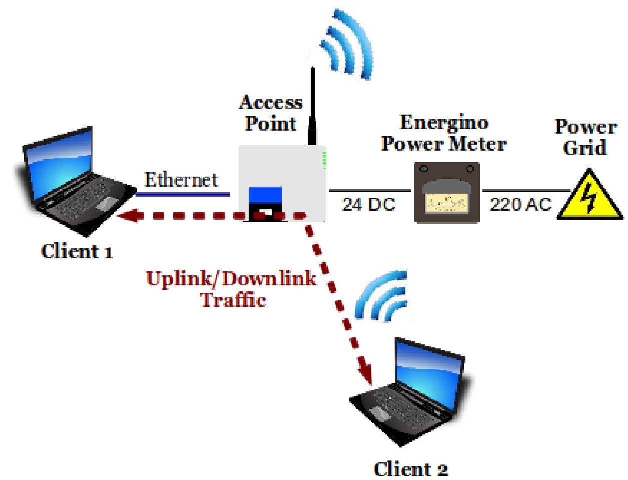


Fig. 1: Network scenario used for the measurement campaign.

III. Evaluation methodology

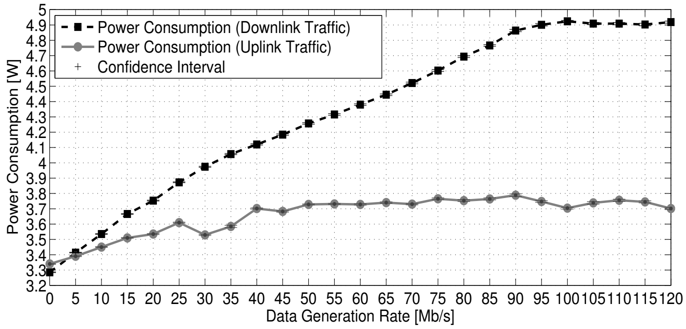
In this section the network set-up and the methodology used to investigate and compare the power consumption of 802.11g and 802.11n APs are described.

A. Network set-up

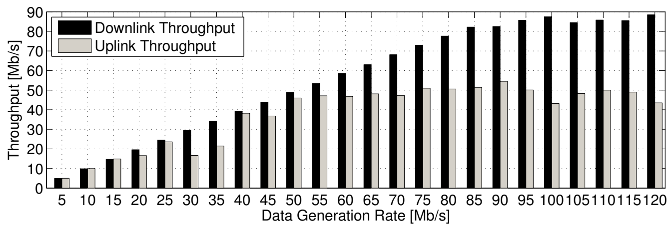
The network set-up used in the indoor scenario is sketched in Fig. 1. The network is composed of a custom 802.11g/n AP and two notebooks. The notebooks, *client 1* and *client 2* in the figure, are regular Fujiitsu SIEMENS and DELL Latitude 6420 respectively, equipped with an Intel PRO/Wireless 3945AB wireless adapter and running Ubuntu 10.04. The first notebook acting as wired *client 1*, which is connected to the AP through Ethernet interface. While the second notebook acting as static wireless *client 2*, which is associated to the AP using the wireless interface (see Fig. 1). The WiFi 802.11g/n AP is part of the Berlin Open Wireless Lab (BOWL) [11] testbed deployed at Telekom Innovation Laboratories in Berlin, Germany. The AP is built around a PCEngines ALIX 3D2 (500MHzx86 CPU, 256MB of RAM) processor board equipped with one 802.11n wireless interface. The AP runs the OpenWRT 10.3.01-rc1 as the operating system. The ath9k [12] Wireless NIC driver has been used during the measurements campaign. The driver is configured to disable RTC/CTS exchange. The AP's operating frequency was set to 2.24 GHz (Channel 11).

B. Power Consumption Monitoring

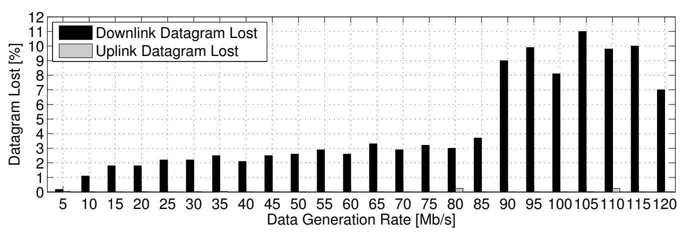
The power consumption statistics are collected at the AP using *Energino* [13] with a granularity of 10 mW and a sampling period of 100 ms. It is important to remark that



(a) Average Power Consumption (AP)

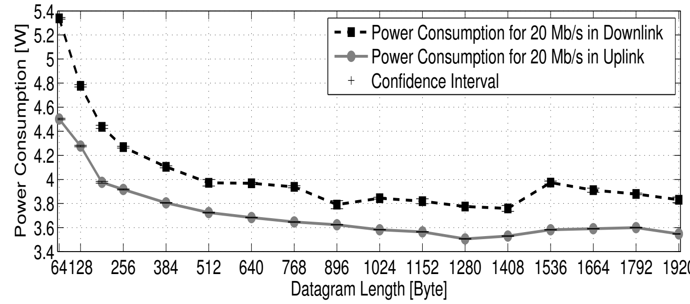


(b) Throughput

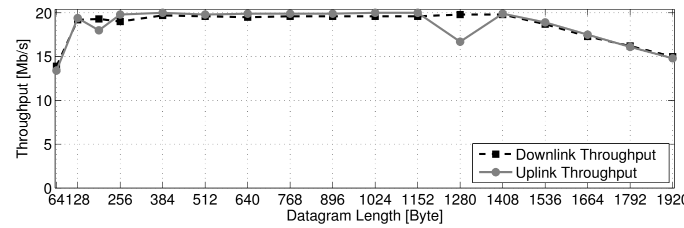


(c) Datagram loss

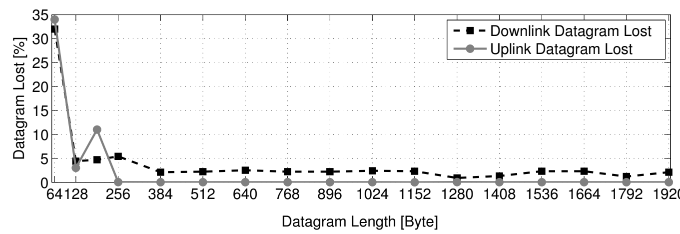
Fig. 2: Average power consumption and network performance at the 802.11n AP as a function of different traffic generation rates for a constant datagram size of 1280 bytes.



(a) Average Power Consumption (AP)



(b) Throughput



(c) Datagram loss

Fig. 3: Average power consumption and network performance at the 802.11n AP as a function of the datagram size for a constant traffic generation rate of 20 Mb/s.

the power consumption is monitored for the whole device. Therefore, the results reported in this paper account for both the power consumed by the processing board for handling the incoming and outgoing traffic (e.g., for segmentation and reassembly, computing checksums, etc.) as well as for the power consumed to deliver the actual frame over the wireless link (e.g., for power amplifiers, modulator/demodulator, etc.).

C. *Experiment Methodology*

The measurement campaign accounted in this paper aimed at assessing the power consumed by IEEE 802.11gn APs under different workloads. Client and AP are deployed close to each other ($\approx$ 4 m) in order to have good link quality and thus to exploit the high throughput modulation and coding schemes. Synthetic traffic is generated using the Iperf [14] and injected as a single UDP flow. In order to measured the network performance and power consumption statistics of the AP, downlink traffic is generated in the *client 1* toward the *client 2* while uplink traffic is generated in the *client 2* toward the*client 3* as show in Fig. 1. Results reported in this section are the average of measurements collected during 600 seconds and with 95% confidence interval. We considered the following scenarios:

1) **Variable traffic with fixed datagram length:** In this experiment, the datagram size is kept constant at 1280 bytes, while the traffic generation rate is progressively increased from 5 Mb/s up to (i) 55 Mb/s for 802.11g and (ii) 120 Mb/s for 802.11n in steps of 5 Mb/s for both.
2) **Constant traffic with variable datagram length:** In this experiment, the traffic generation rate is kept constant at 20 Mb/s while the datagram size is progressively increased from 64 to 1920 bytes in steps of 128 bytes.
3) **Variable traffic with variable transmission power level:** In this experiment, the traffic generation rate is progressively increased from 5Mb/s up to 120 Mb/s in steps of 5 Mb/s. The transmission power level is set manually, using the command line interface, to 12 dBm for first experiment and 19 dBm for second experiment.

It is important to note that, unless otherwise specified, the rate adaptation algorithm has been set to auto and the transmission power has been left to its default value equal to 19 dBm for all the experiments.

IV. Measurements and Analysis of the IEEE 802.11n Access Point

In this section, we present the results from the measurements campaign described in the previous section.

A. Variable traffic with fixed datagram length

Fig. 2 summarizes the power consumption and network performance results obtained for the 802.11n AP acting as either a transmitter or a receiver. We observe that:

i) The power consumption behavior is similar for both cases (Fig. 2a). The power consumption is monotonically increasing with the traffic load until it reaches a saturation point. *Saturation* here means that the data generation rate is higher than the physical link data–rate, so the transmitter is constantly backlogged.

ii) The saturation point is different for the two cases (Fig. 2b). Note that the saturation point is determined by the device that is transmitting since it depends on the efficiency of the rate adaptation algorithm. An efficient rate adaptation algorithm should adapt giving priority to higher modulation and coding schemes as much as possible. We observed that, when the AP is acting as a transmitter, the rate adaptation algorithm uses the highest modulation and coding schemes most of the time. Instead, when the *client 2* is acting as a transmitter we observed that it does not use the higher modulation and coding schemes, which consequently means *client 2* saturates earlier than the AP.

iii) When the AP is acting as a transmitter and it reaches the saturation point, the datagram loss increases (Fig. 2c). This is expected since when the transmission buffer is full, new frames are dropped. Instead, when the AP is acting as a receiver the datagram loss is lower than 1%. In this case, the transmitter is the notebook *client 2* and it has enough memory resources for buffering the frames when the wireless interface is saturated.

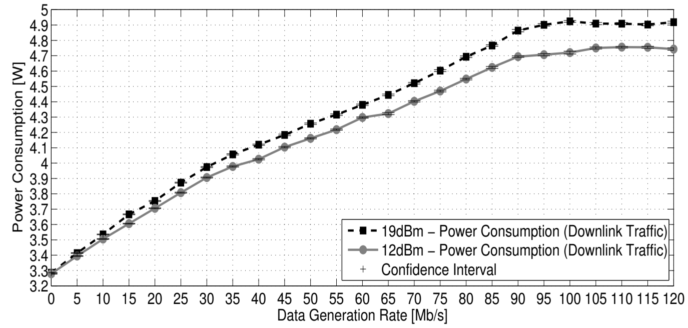
B. Constant traffic with variable datagram length

The Fig. 3 reports the power consumption and network performance of the 802.11n AP as a function of the datagram size for a constant traffic of 20 Mb/s. We observe that:

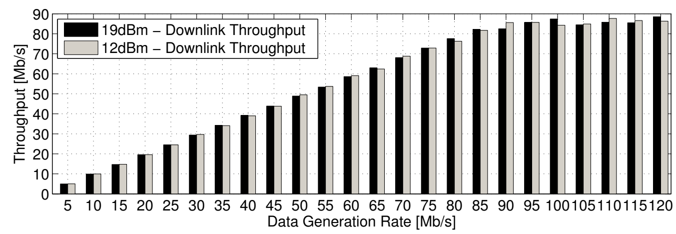
i) When the datagram size becomes extremely small, the AP consumes significantly more power than for large datagram sizes under the same traffic conditions (Fig. 3a). The power expenditure includes (a) the overhead related to the MAC header and (b) the internal operations for generating and buffering the small datagrams.

ii) When fragmentation takes place, i.e., when the AP receives a protocol data unit larger than the receiver's maximum transmission unit, the throughput utilization decreases and the power consumption increases. The power expenditure includes (a) the internal operations for packet fragmentation and reassembly, (b) the internal buffering of packets, (c) the overhead related to the additional frame in terms of MAC header and medium access. As it can be seen from Fig. 3a packet fragmentation is more energy consuming than packet reassembly.

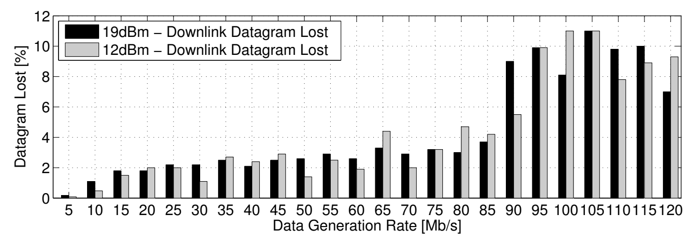
iii) The throughput decreases when (i) large datagrams are transmitted/received due to the fragmentation and (ii) small datagrams are transmitted/received due to the associated protocol overhead which tends to saturate the wireless interface (Fig. 3b).



(a) Average Power Consumption (AP)



(b) Throughput



(c) Datagram loss

Fig. 4: Average power consumption and network performance at the 802.11n AP as a function of different traffic generation rates for different transmission power levels rates for a constant datagram size of 1280 bytes.

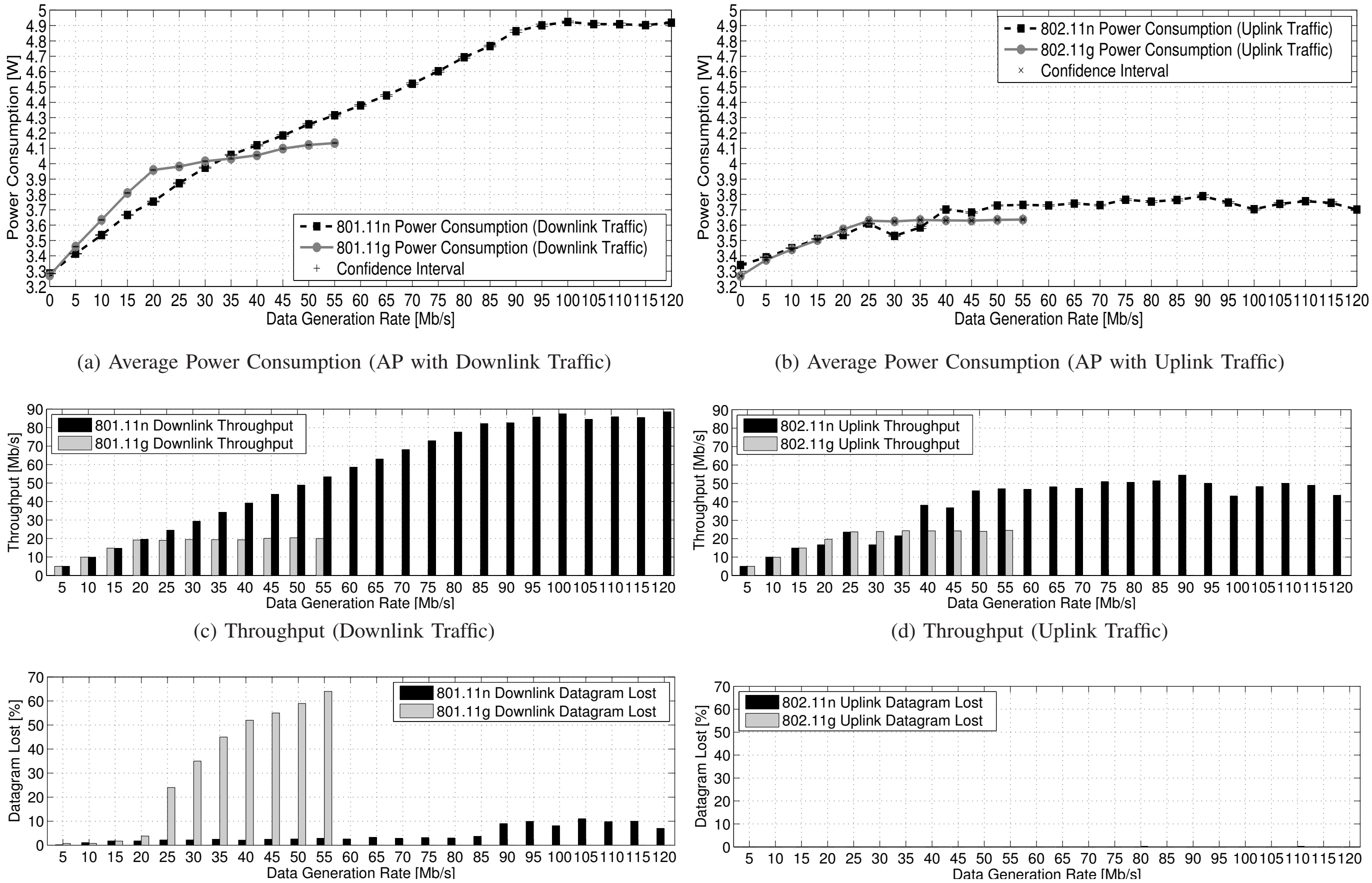
iv) The datagram loss increases when the AP is transmitting small datagrams (see Fig. 3c) since the protocol overhead generated by small datagrams saturates the transmission buffer resulting in a severe datagram loss.

C. Variable traffic with variable transmission power level

Fig. 4 summarizes the results when the 802.11n AP is acting as either transmitter or receiver using different transmission power levels. We considered two different power levels: 12 dBm and 19 dBm (19 dBm is the maximum transmission power supported by the AP). We observe that:

i) Different transmitter power levels present different power consumption in the saturation regime. The advantage of decreasing the transmission power can be clearly observed in the Fig. 4a.

ii) The network performance does not change much due to the particular set-up used in our deployment, in which the AP and the client are just 4 meters apart. The results for throughput and datagram loss are shown in Fig. 4b and Fig. 4c respectively.



(a) Average Power Consumption (AP with Downlink Traffic)

(b) Average Power Consumption (AP with Uplink Traffic)

(c) Throughput (Downlink Traffic)

(d) Throughput (Uplink Traffic)

(e) Datagram loss (Downlink Traffic)

(f) Datagram loss (Uplink Traffic)

Fig. 5: Comparison of the average power consumption and network performance for the 802.11g AP and 802.11n AP as a function of different traffic generation rates for a constant datagram size of 1280 bytes. AP acting as a transmitter or receiver.

iii) These observations also hold when the AP is acting as a receiver (for more details, see [15]).

V. Power Consumption Comparison between IEEE 802.11g and 802.11n

Fig. 5 compares the power consumption of 802.11g and 802.11n APs. We observe that:

i) The average power consumption of an idle AP is 3.3 W and it is the same for both technologies (see Fig. 5a and Fig. 5b). The power consumption behavior is similar, however, the power consumption at the saturation point is different.

ii) The power consumption for the AP acting as a transmitter at the saturation point is around 4.9 W for 802.11n and 4 W for 802.11g. The power consumption for the AP acting as a receiver is around 3.75 W for 802.11n and 3.63 W for 802.11g.

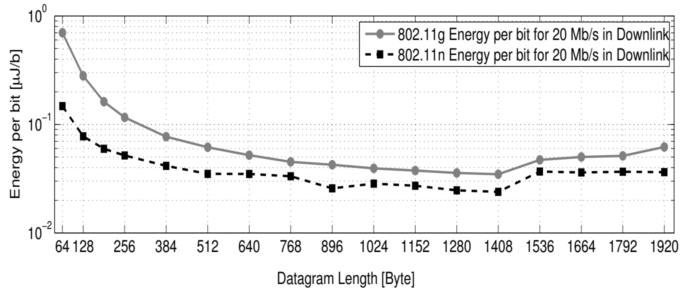
iii) The energy spent for transmitting or receiving one bit is quantified as $\approx 0.01487\ \mu J/b$ and $\approx 0.009217\ \mu J/b$ respectively in 802.11n case, and $\approx 0.03447\ \mu J/b$ and $\approx 0.01403\ \mu J/b$, respectively in 802.11g case. Therefore, the 802.11n AP is more energy efficient than the 802.11g AP. Note that the energy per bit is computed excluding the measurements of the saturation region.

iv) When the AP reaches the saturation point, the maximum throughput and the power consumption remains constant. The throughput results are shown in Fig. 5c and Fig. 5d. The saturation point for the AP acting as a transmitter is around 90 Mb/s for 802.11n and 20 Mb/s for 802.11g, while for the AP acting as a receiver, it is around 45 Mb/s for 802.11n and 23 Mb/s for 802.11g.

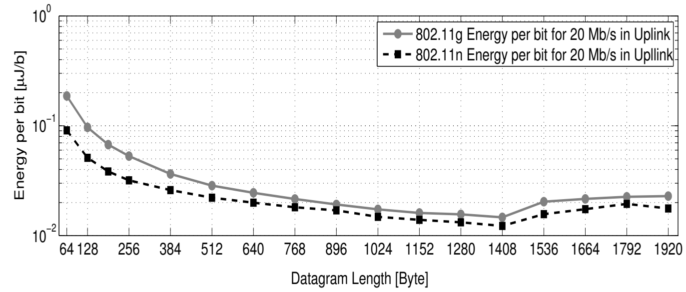
v) The datagram loss performance is shown in Fig. 5e and Fig. 5f. We observe a significant difference in terms of datagram loss between the two technologies, especially when the AP is acting as a transmitter. The reason can be traced back to the higher capacity of 802.11n, which prevents frames from being dropped due to buffer overflows.

Fig. 6 depicts the average energy per bit and network performance at the 802.11g and 802.11n AP as a function of the datagram size for a constant traffic generation rate of 20 Mb/s. We observe that:

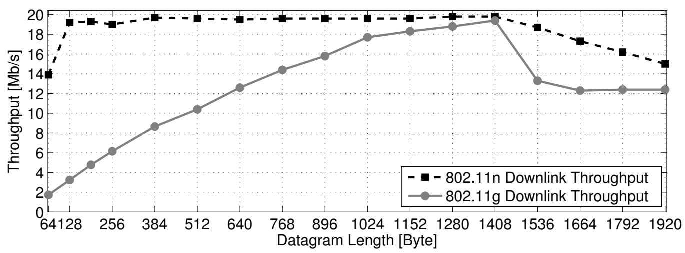
i) When the datagram size is extremely small, 802.11n is significantly more energy efficient than 802.11g (see the Fig. 6a and Fig. 6b). The difference in energy efficiency decreases as the datagram size increases.



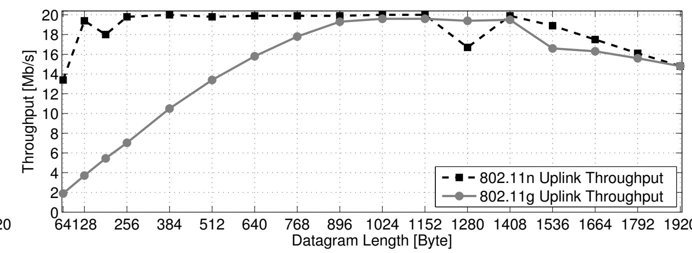
(a) Average energy per bit (AP with Downlink Traffic)



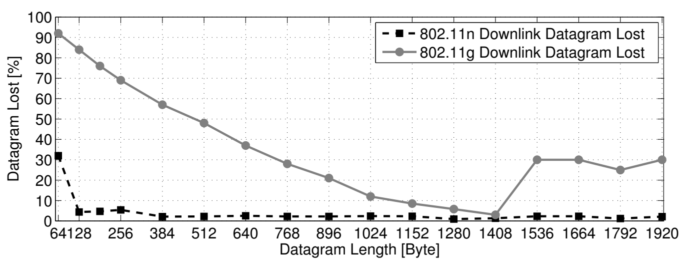
(b) Average energy per bit (AP with Uplink Traffic)



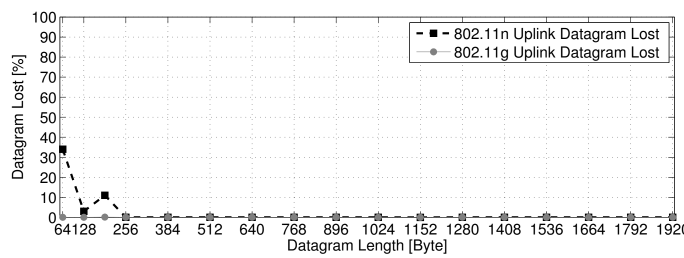
(c) Throughput (Downlink Traffic)



(d) Throughput (Uplink Traffic)



(e) Datagram loss (Downlink Traffic)



(f) Datagram loss (Uplink Traffic)

Fig. 6: Comparison of the average power consumption and network performance at the 802.11g AP and 802.11n AP as a function of the datagram size for a constant traffic generation rate of 20 Mb/s. AP acting as a transmitter or receiver.

ii) The throughput decreases for small datagram sizes for both technologies. However, this is more evident in 802.11g, which is affected for datagram sizes 64-1204 bytes, while for 802.11n, the negative effect is observed 64-128 bytes (see the Fig. 6c and Fig. 6d).

iii) When the AP is acting as a transmitter, the results show that the datagram loss increases for the large datagrams only with 802.11g (see the Fig. 6e), while the datagram loss increases for small datagrams using both technologies. Again, while this occurs for 64-1024 bytes in 802.11g, in 802.11n only 64-128 bytes datagrams incur loss.

iv) When the AP is acting as a receiver, the results show that the datagram loss increases for small datagrams only for 802.11n (see the Fig. 6f). This behavior is related to the memory resources of the device as explained previously.

A. How, where and when the power is consumed in WiFi 802.11g/n AP?

The power consumption of an AP can be divided into two parts for both technologies. The first part is fixed and is related to the power consumption of the circuit plus the basic operation of the AP. The second part is variable and it is related to whether the AP is 802.11n or 802.11g, as well as the operating conditions, including the transmission power level, the datagram size, the modulation and coding schemes and in particular, the traffic load. We also observe that i) large packets use energy more efficiently than small ones, ii) highest modulation and coding schemes are more energy efficient, and ii) the transmit power levels have very little effect on the power consumed by the APs. Additionally, our results indicate that a significant fraction of the energy consumed by AP is not traffic or software dependent in both the 802.11g and 802.11n cases. More specifically, we found that the energy consumed when there are no users in the network, i.e., the energy consumed by hardware and regular signalling, constituted $\sim 67\%$ of the total energy necessary to support highest throughput in the 802.11n case. This percentage is $\sim 82\%$ in the 802.11g case.

B. What is the penalty to pay, in terms of energy, to migrate from old to new technologies?

Based on the results, we can observe that the key innovations of 802.11n standard positively impacts its performance [3]. Such innovations refer to:

- Support of MIMO techniques for increasing the maximum data rate and the transmission range (the 802.11n allows up to 4 x 4 MIMO configuration).
- Inclusion of pre-coding and post-coding techniques for improving the received signal quality.
- Addition of coding rate (5/6) for increasing the data rates achieved by each modulation.
- Doubling of the bandwidth per channel from 20 MHz to 40 MHz (doubling the data rate).
- Support of frame aggregation for packing multiple MAC protocol data units together (reducing the overheads).

Due to these additional features, 802.11n transmits and receives faster than 802.11g. Thus 802.11n offers greater performance than 802.11g in terms of both energy efficiency as well as key network performance metrics (i.e. throughput and datagram loss). We can conclude that 802.11n APs provide higher network throughput than 802.11g APs *without* penalty in terms of energy consumed. Rather, this migration is expected to improve energy efficiency. More specifically, we observe that using 802.11n devices the energy cost for transmitting and receiving one bit from/to session layer is reduced to $\sim$ 50% and $\sim$ 30% with respect to 802.11g, respectively. Our measurements also confirm that 802.11n (2x2 MIMO) performs $\sim$ 4.5 times better than 802.11g in terms of maximum network throughput. Therefore, the migration from old to new technology and the reduction of hardware-dependent energy consumed by the new devices enable more sustainable wireless access.

C. What are the advantages and disadvantages of that migration?

There are several advantages in the migration from old to new technologies from both (i) the improvement of the network throughput and (ii) the reduction of the energy cost related to data transmission. In the case of IEEE 802.11 standard, the migration from old to new standard implies software and (minor) hardware updates. However, this is not the case for several 3G technologies, in which the migration implicates high costs and efforts. On the other hand, when the migration requires a complete replacement of the hardware, the cost to decommission the old equipment must be carefully taken into account. Therefore, the energy efficiency of the devices should be improved in the total life-cycle:

i) During the production of the device, through cleaner manufacturing and use of less materials and energy.
ii) During operation by using less energy and extending lifetime (energy efficiency protocols and algorithms).
iii) In end-of-use by recycling materials and refurbishing for reuse.

VI. Conclusions and Future Work

In this paper, we investigated and compared the power consumption behaviour of 802.11n and 802.11g APs. We observed a similar power consumption pattern for both technologies, namely a linear behavior until the AP reaches a saturation point. However, there are relevant differences in the amount of (i) the power consumed for transmitting and receiving data and (ii) the traffic rate at which the AP saturates. The measurements presented in this paper can be used as input for technology designers and vendors for understanding and improving the energy efficiency of their network devices, paving the way to more efficient hardware and software solutions. More specifically we envision the use of energy efficiency assessment methodology similar to the ones presented in this work across an entire product lifecycle. We also argue in favor of policies and standards accounting for energy efficiency rating for wireless networking equipments.

In terms of future research directions, we plan to investigate deeply how the different MIMO configurations and modulation/coding schemes affect the power consumption behaviour of 802.11n APs. Additionally we are also planning to investigate the trade-off, in terms of network performance and energy consumption, when the link quality between AP and client varies over time.

Acknowledgments

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