Analysing the Energy Consumption Behaviour of WiFi Networks

Karina Gomez, Roberto Riggio, Tinku Rasheed
Daniele Miorandi and Imrich Chlamtac
CREATE-NET
Via Alla Cascata 56/C, 38123, Trento, Italy
name.surname@create-net.org

Fabrizio Granelli
DISI - University of Trento
Via Sommarive 14, 38100,
Trento, Italy
granelli@disi.unitn.it

***Abstract*—The continuous increase in the energy production cost, together with environmental sustainability issues, is leading research communities, governments and industries to focus their efforts on a reduction of the global CO_2 footprint. Information and communication technologies, which represent the nervous system of the globalized economy and society, account for a significant percentage of the overall global energy consumption. While a number of solutions have been proposed to build new, energy-aware and 'green' communication infrastructures, little attention has been devoted to measuring the actual impact through real-world measurements. In this paper, we focus on wireless access networks, and aim at experimentally investigating the fundamental relationship between traffic and power consumption for a typical wireless LAN based on the IEEE 802.11g standard. The insight obtained through the measurements can be used to develop reliable and realistic energy consumption models, on top of which novel energy aware protocols and algorithms can be designed and developed.**

***Keywords*-Green Networks, Wireless Local Area Networks, Power consumption, Energy efficiency.**

I. Introduction

In the quest for enabling a low-carbon and sustainable economy and society, information and communication technologies (ICT) is playing a twofold role. On the one hand, advanced ICT enables to increase the efficiency in a number of industrial sectors (e.g., smart grids), thereby achieving significant reduction in the associated power consumption. At the same time, ICT itself is a major source of CO_2 emissions. Several studies have shown that the ICT sector is responsible for an estimated 2% - 10% of the global energy consumption [1], [2], [3]. Additionally, ICT sector also produces from 2% to 3% of total emissions of greenhouse gases [4], [5], [6].

Therefore, reducing the energy consumption of ICT systems is becoming a substantial challenge and a major objective for industries [7] and governments [8]. This is meant to (i) decrease the operational costs of the ICT infrastructure, increasing the margins and competitiveness of the ICT industry, and (ii) reduce the global energy consumption and CO_2 emissions associated to ICT infrastructure. Recent studies have revealed that about 50% of the total of energy used in the ICT sector is consumed by wireless access networks [4], [6]. Currently, over 80% of the electrical power in mobile telecommunications accounts to the radio access network (RAN), i.e., the radio base station sites.

In the last years, wireless local area networks (WLANs) have become the most popular wireless access technology. Due to their rapid evolution in terms of sustained data rates, reduced cost of equipment and ease of deployment, WLANs are nowadays extensively used by corporates, universities and municipalities in order to provide Internet connectivity to end users. Trends analysis reveals that the total amount of WLAN devices deployed has been increasing exponentially over the past few years [9]. In this context, optimizing the energy consumption of WLAN devices can significantly impact the overall CO_2 footprint of wireless networks [10].

While this topic has been addressed by various papers in scientific literature, the following questions remain —to a large extent— unanswered:

- Where is the power used in WLANs?
- How is the power consumed in WLANs? How much of the power is wasted?
- What are the critical aspects of IEEE 802.11 standard with respect to power consumption?
- What is the relation between traffic load and power consumption in WLANs?

The answer to these questions are very important since these would provide us the insights to (i) optimize the power consumption of WLANs infrastructure already deployed worldwide, and (ii) focus research on meaningful areas for designing new energy efficient protocols and algorithms for wireless networks.

In this paper, we aim at experimentally investigating the fundamental relationship between traffic and power consumption for a typical wireless LAN based on the IEEE 802.11g standard. Our approach focuses on measuring and analysing the power consumption statistics of WLANs devices in order to understand *where*, *when* and *how* the power is consumed in the network. The main objectives of this work are to quantify the impact of different traffic patterns and network settings on power consumption figures for typical WiFi-based networking devices.

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The main contribution of our work relates to the experimental characterisation of the power consumption of WiFi devices in terms of (i) the traffic sent/received by the node (ii) the modulation and coding schemes used and (iii) the size of the session level data units. We do believe that the insights provided by such measurements can pave the way to the development of realistic models for power consumption of WiFi networks and for the introduction of novel, optimized, protocols for their operations. Finally, we would like to remark that hardware power consumption analysis is not part of this study.

The rest of the paper is organized as follows. In Sec. II we present the experimental settings and the test instances and methodology used throughout the paper. Experimental results are reported and discussed in Sec. III. Our approach and results are compared with related works in Sec. IV while in Sec. V, we discuss about some metrics in order to calculate and limit the impact of traffic on the power consumption figures. Finally, Sec. VI is devoted to the final conclusions and pointers to promising research directions.

II. Evaluation methodology

A. Testing Environment

The test environment used during our measurements is sketched in Fig. 1. The WLAN is composed of a standard IEEE 802.11g Access Point and a single notebook acting as the client.

WiFi Devices Configuration: Both the Access Point and the Client are built using off-the-shelf hardware components and open source software. In particular, the Access Point is built around a PCEngines ALIX 2C2 (500MHz x86 CPU, 256MB of RAM) processor board equipped with two IEEE 802.11a/b/g wireless interfaces (Atheros AR5213A chipset) with RTC/CTS disabled. The Access Point exploits OpenWRT 10.3.01-rc1 as operating system. The *MadWifi* [11] Wireless NIC driver has been used during the experimentations. The client is a regular DELL D630 notebook equipped with a PCMCIA wireless adapter based on the Atheros AR5212 chipset. The frequency of operation of the BSS was set to 2.412 GHz (channel 1). The rate control policy and the transmission power have been set to, respectively, *auto* and *18dBm* ($\sim$63.1 mW). It is worth noticing that, not all experiments have been carried out using the rate control algorithm embedded in the MadWifi driver (*minstrel*), instead in some experiments, we manually configured the transmission rate in order to assess the energy efficiency of the various modulations supported by the IEEE 802.11g radio.

Traffic generation: Traffic is generated at the Access Point using the Multi–Generator (MGEN), a freely available synthetic traffic generator [12]. MGEN can generate and inject different traffic patterns over TCP and/or UDP sockets. Traffic is then collected at the receiver side (the Client) where suitable tools are available for analysis.

Power Consumption Monitoring: The power consumption is logged using the *Watts Up?* [13], a "plug load" meter that measures the amount of electricity used by whatever electrical appliance is plugged into it. The meter incorporates digital electronics that enable precise and accurate power consumption measurements. Such measurements are logged with a granularity of 0.1 sample per second (which is the minimum sampling period supported by the device). Each sample is the instantaneous power consumption measured by the *Watts Up?* device. Power consumption logs are collected using a proprietary software running on a dedicated machine and interconnected to the *Watts Up?* device through an USB interface. Data is converted in CSV (comma separated value) format and then imported in Matlab for further processing. All devices are synchronized using NTP [14].

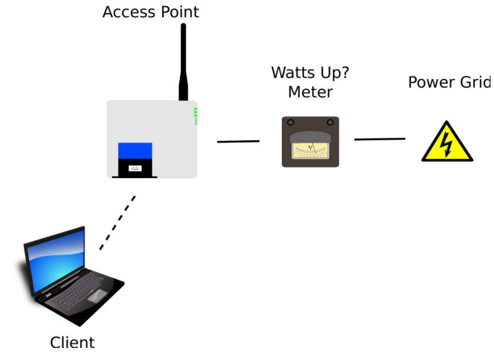


Fig. 1: Network scenario used for the measurement campaign.

TABLE I: 802.11g OFDM Data Rates and Modulation types

Modulation Type	Data Rate [Mb/s]
Binary Phase Shift Keying (BPSK)	6/9
Quadrature Phase Shift Keying (QPSK)	12/18
16-Quadrature Amplitude Modulation (16-QAM)	24/36
64-Quadrature Amplitude Modulation (64-QAM)	48/54

B. Testing Methodology

The measurement campaign on which we report in this paper aimed at assessing the actual power consumed by an IEEE 802.11g Access Point under different workloads. Traffic is injected at either the Access Point or the client and is modeled as a single UDP flow. Power consumption measurements always refer to the Access Point. The power consumption of the Access Point in idle mode, i.e., without any traffic but the standard IEEE 802.11 beacons, has been assessed at 5.3W. The following scenarios have been considered:

- *Constant Bitrate*. In this scenario, the final bitrate is kept constant while the message size is progressively increased from 32 to 2816 bytes in steps of 256 bytes. Two different settings have been considered with throughput equal to, respectively, 1Mb/s and 100Kb/s.
- *Variable Bitrate*. In this scenario, the message size is kept constant at 1280 bytes while the message generation rate is progressively increased from 50 to 1000 message/s in steps of 200 message/s.
- *Variable Bitrate, No automatic transmission rate control*. In this scenario, the message size is kept constant at 1280 bytes while the message generation rate is progressively increased from 10 to 130 message/s in steps of 10 message/s. The rate control algorithm is disabled and the

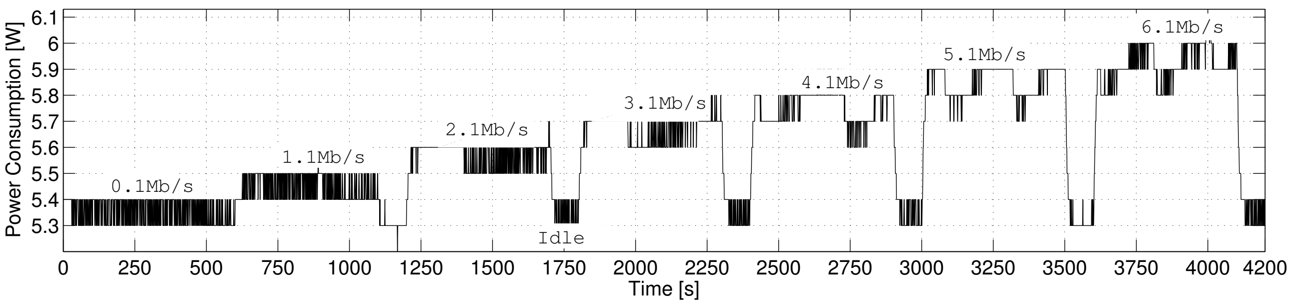


Fig. 2: Consumed power at the Access Point for different traffic rates.

transmission rate, set manually using the command line interface, remains unchanged for the entire duration of the experiment. The experiment is repeated for each of the transmission rates supported by the wireless adapter (see Table I).

- *Variable Bitrate, Mixed Transmission Power*. In this scenario, the message size is kept constant at 1280 bytes while the message generation rate is progressively increased from 10 to 130 message/s in steps of 10 message/s. Two different settings have been considered with the power transmission level of both the Access Point and the client set to, respectively, *10dBm* (∼10 mWatts) and *18dBm* (∼63.1 mWatts).

III. Experimental measurements and Analysis

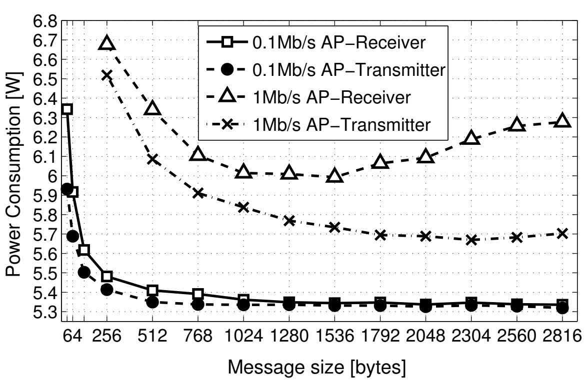
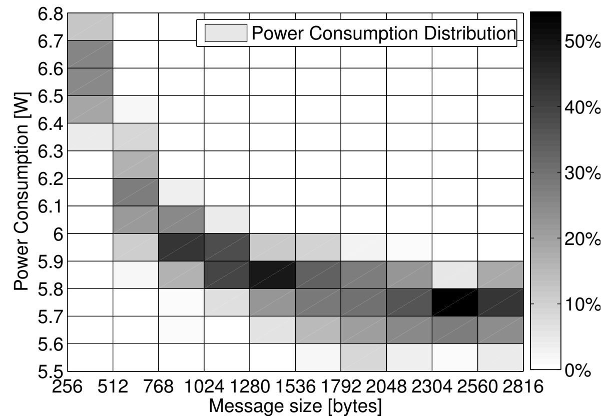
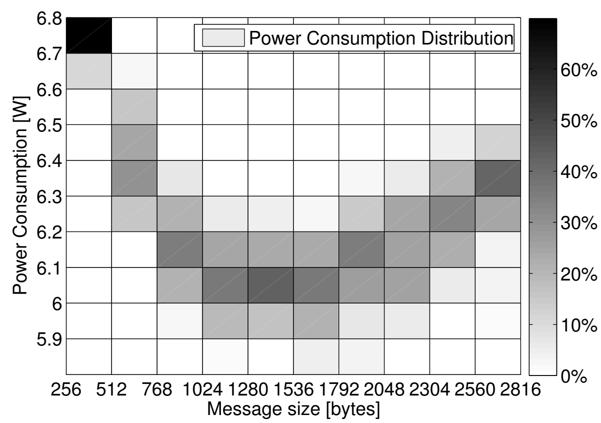


Fig. 3: Average power consumption at the Access Point (acting as transmitter or receiver) as a function of the packet size for a constant traffic generation rate (0.1 Mb/s, 1 Mb/s).

In this section, we report on the results from our measurements campaign. Each experiment lasted 900 seconds. Results will be reported only in terms of average values, as 95% confidence intervals were lower than 0.004 W for all cases considered. Experiments have been performed with a maximum traffic load of 10 Mb/s. This comes from the fact that MGEN turned out to show unstable behaviour when generating traffic in excess of such figure. In particular, every attempt to generate traffic with a sustained throughput higher than 10 Mb/s resulted in significant fluctuations (∼ 50%) in the actual transmission bitrate. The power consumption of the Access Point in idle mode was approximately equal to 5.3W.



(a) Transmitter



(b) Receiver

Fig. 4: Distribution of the power consumption at the Access Point (acting as transmitter or receiver) as a function of the packet size for a constant traffic generation rate of 1 Mb/s.

Finally, the power consumption figures reported in this section refer to the whole device, which implies that the power expenditure includes the internal operations for packet generation, fragmentation and reassembling of the packets and the related overhead. An example of the measurements trace obtained is reported in Fig. 2. As it can be seen, variations of the power consumption are observable depending on the offered traffic load. At the same time, a floor is observable, corresponding

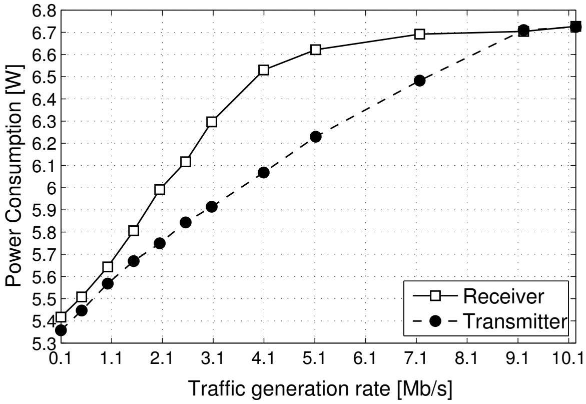
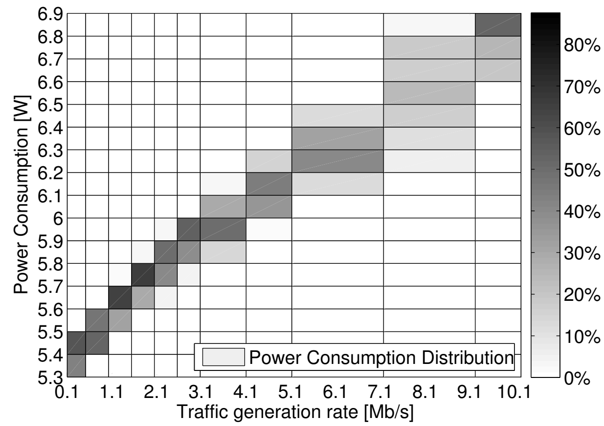


Fig. 5: Average power consumption at the Access Point (acting as transmitter or receiver) as a function of different traffic generation rates for a constant message size of 1280 bytes.

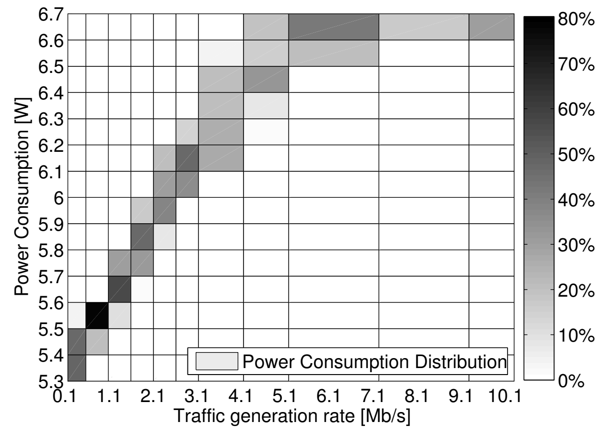
to situations in which no traffic flows through the wireless interface. Yet, in such situations, the device is powered on, thereby resulting in a significant power consumption level (~ 5.3 W).

Figure 3 reports the average power consumption level at the Access Point as a function of the packet size for a constant throughput of 0.1 and 1 Mb/s. Results are plotted for the AP acting as transmitter and, respectively, as receiver. As it can be seen, there is a consistent difference between the power consumed when transmitted at 0.1 and 1 Mb/s. Further, the message size has also a considerable impact. For low values of the message size, the overhead related to the MAC header becomes predominant, leading to an increase in the measured consumed power. When the message becomes extremely large, fragmentation takes place, which leads to a slight increase in the measured power consumption. From the figure, the message length minimising the energy consumption is around 1024 and 1536 bytes for the 0.1 and 1 Mb/s, respectively. We would like also to remark that the packet loss for each experiment was lower than 1%. A colormap representation of the distribution of the power consumption at the Access Point (both as transmitter and receiver) against the message size for a constant throughput of 1 Mb/s is reported in Fig. 4. As we can see from the figure, for a given packet size the measured power consumption varies slightly.

The second set of measurements aims at studying the relationship between traffic load and power consumption at the Access Point. In the Fig. 5, we reported the average power consumption of the Access Point as a function of different traffic generation rates, for a fixed message size of 1280 bytes. As it can be seen, the impact of the traffic load on the power consumption is different when the Access Point is acting as transmitter or receiver. In both cases, the power consumption is monotonically increasing in the traffic load, as expected. When the WiFi device is used as a transmitter, the growth is almost linear. The power consumption at the receiver instead tends to grow very fast at the beginning (i.e., for low-to-medium traffic load) and then to saturate. *It is further worth remarking that for a traffic rate of less than ~ 9 Mb/s, the Access point actually consumes more power when acting as receiver.*



(a) Transmitter

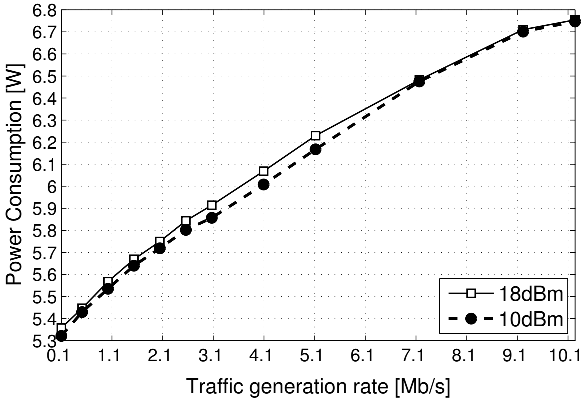


(b) Receiver

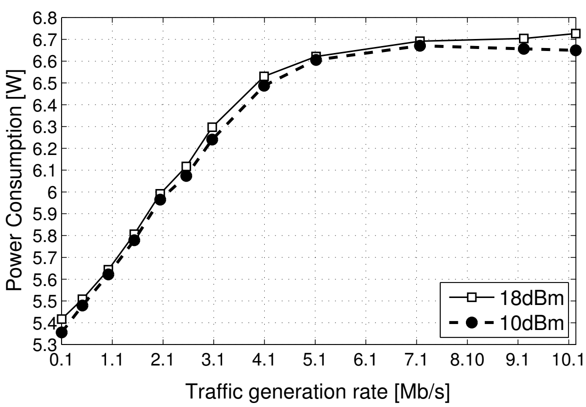
Fig. 6: Distribution of the power consumption at the Access Point (acting as transmitter or receiver) as a function of the traffic generation rate for a constant message size of 1280 bytes.

A colormap representation of the distribution of the power consumption at the Access Point (both as transmitter and receiver) against the traffic load for a constant message size of 1280 bytes is reported in Fig. 6. As it can be seen from the figure, for lower values of the traffic, more than 60% of the power consumption samples are concentrated around the same value, while for higher values of the traffic the power consumption samples are spread on larger intervals. This effect can be noted both when the Access Point is transmitting and receiving traffic. In this set of experiments the packet loss rate was always smaller than 1.5%.

The third set of measurements aimed at investigating the impact of rate adaptation and transmission power on the power consumption figures. First, we considered two different transmission power level, i.e., 10 and 18dBm, corresponding to 10 mW and ~ 63.1 mW, respectively. We varied the traffic generated as in the previous set of experiments (with constant message size of 1280 bytes) and measured the power consumption. Results are reported in Fig. 7 with the Access



(a) Transmitter

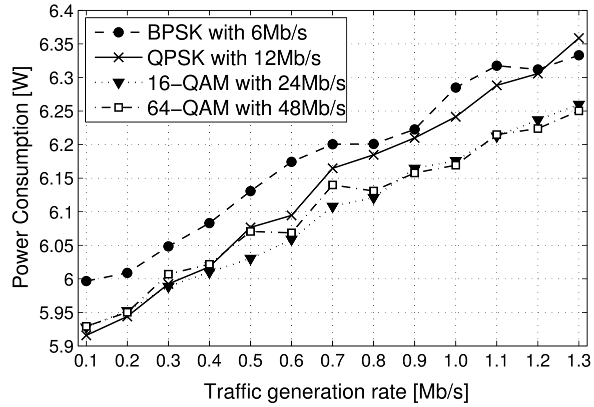


(b) Receiver

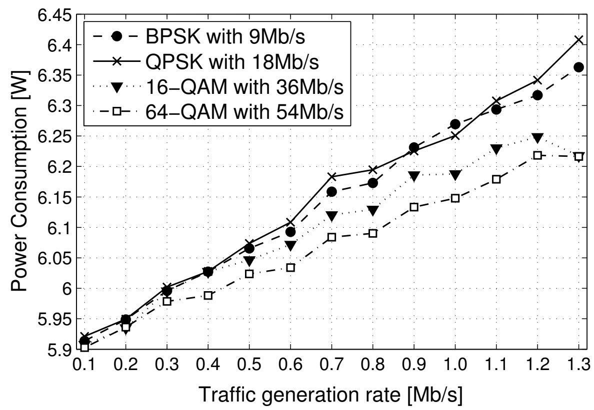
Fig. 7: Average power consumption at the Access Point as a function of different traffic generation rates for different transmission power levels (10 and 18 dBm), constant message size of 1280 bytes.

Point acting as transmitter (a) and receiver (b). As we can see little advantage can be gained by reducing the power consumption at the transmitter side. This means that, for the settings considered, mechanisms aimed at dynamically tuning the transmission power level provide little enhancement in terms of system-level power consumption.

Second, we forced the modulation and coding schemes to be used by the IEEE 802.11g interface and measured the power consumption as a function of the traffic generation rate. The results, in terms of average power consumption, are reported in Fig. 8. In this case results for the transmitter side only are reported, as the power consumption figures when operating as receiver turned out not be affected by the coding/modulation scheme employed at the transmitter. The figure shows that higher modulation rates are (slightly) more power efficient. This is understood to be due to the fact that higher modulation schemes keep the transmitter RF interface in the 'on' state for a shorter amount of time. Of course this holds in a situation in which the channel condition is very good, as the case in our experimental settings. The packet loss in this set of experiments was about 4% at 6 Mb/s and less than 2% for all the others coding/modulation rate.



(a) FEC Rate 1/2



(b) FEC Rate 3/4

Fig. 8: Average of power consumption at the Access Point (Transmitter) as a function of different traffic generation rate for different modulation types.

IV. Related Work

In this section, we present an overview of the related work on power consumption measurements and methodologies for WLANs and a short literature review on the energy efficiency improvements proposed for WLANs.

A. Power consumption measurements

Real power measurements of the WLAN devices are not usually performed as it require very accurate devices in order to obtain the power consumption statistics. In [15], the authors present several measurements for an IEEE 802.11 wireless network interface operating in the Idle, sleep, receive and transmit modes. In order to obtain these measurements, the authors use two wireless devices operating in an ad hoc networking environment which are monitored using an oscilloscope. Similar work in terms of methodology is presented in [16]. The paper presents several results for power consumption of an IEEE 802.11g wireless network interface. The scenario used in this paper was built using two laptops with WLAN interfaces and an oscilloscope in order to monitor power consumption on the wireless interface. These experiments are similar to the test setup adopted for our measurements. Both papers report several measurements and power consumption models for WLAN interfaces. Nevertheless, the results provided insights of power consumption only at the wireless interface level. Since the interface is part of an whole device, the additional operations for energy expenditures such as the internal operations for packet generation and reception, fragmentation and reassembling of the packets were ignored. The total energy expenditure should be taken into account as it is relevant in order to (i) model the real power consumption behaviour for WLAN devices and (ii) determine $where$ and how the energy output of the WLAN devices are wasted.

B. Energy efficiency improvements

One of the most significant works in reducing network energy consumption is studied in [17] where several techniques are investigated within the wired network scenarios. Nevertheless, the approach can be applied to wireless networks as well taking into account the inherent limitations of wireless communications. The paper [17] investigates two forms of power management schemes for energy savings. The first scheme explores the possibility of putting components to sleep mode and the second scheme explores the possibility of adapting the rate of "network operation" to the workload in order to reduce the energy consumed in the absence of packets and when actively processing packets. The authors also determine the best conditions to select sleep mechanisms and rate adaptation mechanisms respectively. Both sleep and rate adaptation are performed showing improvements in energy consumption with a small increase in latency and packet loss.

The sleep mechanisms are also used in [6] and [9] for wireless networks. These works affirm that most of the energy consumed in a wireless network is wasted because of the large period of idle states in the absence of traffic. In [9], SEAR, an on–demand strategy for power on/off of resources in high–density WLANs is proposed, where the WLAN access points are dynamically powered on/off according to the user demand. A similar approach is used in [6], focusing mainly on the wireless access. The proposed technique analyses traffic in different hours, days and weeks in order to optimize the management of on/off state (idle or sleep) and transmission power of access stations. More approaches and techniques for optimizing energy consumption in WLAN technologies are presented in [10] [18]. In [10], different approaches are explored in order to reduce the energy consumption and increase the energy efficiency in wireless mesh infrastructures. The authors mainly address techniques at the MAC layer, physical layer and network level. Instead in [18], the authors focus on energy efficient network operation at the Application level (VoIP, for example), where an adaptive algorithm is proposed to save energy during VoIP calls.

V. Towards Energy Efficiency Metrics

In this section, we outline some steps towards the definition of energy efficiency metrics for designing energy-aware wireless network. The purpose of this section is to estimate (i) the optimal message size to be used by the access point, in terms of power consumption, in order to save energy, (ii) the average amount of energy spent by the access point in order to transmit one bit and (iii) the relationship between traffic and power consumption for the acces point.

We use the following notation throughout the section:

- N a set of experimental runs
- $\cdot_i$ is a variable referenced to the i–th experiment.
- T_i is the traffic generation rate (expressed in b/s)
- L_i is the message size (expressed in bits) .
- P_i is the power measured during the i–th experimental run.
- ε_i is the probability that a message is not correctly received by the intended destination during the i–th experimental run.

We remark that the message loss probability depends on a number of factors, including channel conditions, which may change over time.

The optimal message size: Assuming that the pattern of message errors follows a Bernoulli process (i.e., errors are independent and identically distributed), the average *energy efficiency* of the i–th experimental run (expressed in J/b) can be written as:

$$\eta_i = \frac{P_i}{T_i \cdot (1 - \varepsilon_i)}. \tag{1}$$

This metric can be used to study the impact of various parameters on the overall 'energy awareness' figure of the system. As an example, we could consider running a set of measurements keeping a constant traffic generation rate and varying the message size, as presented in Sec. III. In this way, we could experimentally identify, for a given traffic load, the optimal message size. This could be, in turn, used to define optimal message fragmentation strategies at Layer 3.

Using the notation above, for $T_i = \hat{T} \quad \forall i$, we define the optimal message size as:

$$L^* = \arg\min_i \eta_i|_{T_i=\hat{T}}. \tag{2}$$

From the experimental measurements reported in Fig. 3, it turns out that in our experimental settings, considering $T_i = \hat{T} = 1$ Mb/s, the optimal message size is $L^* = 1280$ bytes, which resulted in an energy efficiency value $\eta^* = 3\mu J/bit$.

Average amount of energy per bit: Given a set of experiments Ψ characterized by a set of traffic generation rates and message sizes $\{T_i, L_i\}_{i=1,\ldots,N}$, we can define the average device energy efficiency as:

$$\eta^{\Psi} = \sum_{i=1}^{N} \frac{\eta_i}{N}. \tag{3}$$

Such a value can be used as a benchmark to assess the energy efficiency of wireless networks devices, given a well defined test suite Ψ, i.e., a set of representative experiments. As an example, setting $L_i = 1280$ bytes and $T_i = \{0.1, 1.1, 2.1, 3.1, 4.1, 5.1, 6.1, 7.1, 8.1, 9.1, 10.1\}$ Mb/s, the average energy efficiency of the device used in our measurements campaign resulted in $0.1637\mu J/bit$ (see Fig. 5).

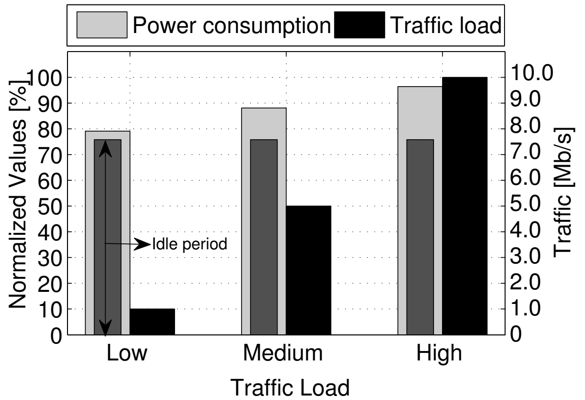


Fig. 9: Normalized energy consumption and traffic for different loads in the wireless device considered.

As a final remark, we would like to stress the fact that the power consumption of the devices we considered turned out to be only slightly sensitive to changes in the traffic load. In Fig. 9 we depicted, for providing an intuitive visualization of the results obtained, the normalized values of the energy consumption (peak value) and traffic load for three traffic generation rates ($1.1, 5.1, 10.1$ Mb/s). It is interesting to note that though solutions aimed at optimizing the traffic flowing on wireless channel (by employing e.g., message/header compression or similar mechanisms) showed limited impact on the overall power consumption in our measurements, on a longer term, such solutions could prove vital in improving the overall energy efficiency of the network.

VI. Conclusions and Future Work

Even though, at present, the impact of wireless networks on the global energy footprint is relatively small, as more and more data traffic moves onto the wireless network, the energy resources are set to increase rapidly in the near future. The ironical fact is that the energy and operational efficiency of mobile networks is rapidly increasing, driving down the energy necessary to send a bit of traffic. Hitherto, the problem is with the number of bits transmitted which is exploding – the improvement in network efficiency is far slower than the rate of overall traffic growth. In this paper, we conducted an experimental investigation to understand the fundamental relationship between data traffic and power consumption in wireless networks, considering a typical WiFi LAN network. Such an experimental campaign permitted us to ascertain the impact of traffic on the energy efficiency of wireless devices.

We can conclude from the results that there is a significant impact for traffic on the power consumption pattern of wireless devices, both at the interface level, with respect to the power expenditure for transmission and reception, and at the device level, with respect to the energy spent for processing of the traffic. As the types of wireless applications and services are diverse, we can observe distinct impacts on power consumption for different traffic sizes and data rates. As the wireless devices get fully loaded, such impacts can drive the power consumption of the device to very high levels, essentially creating energy wastage, which when measured over a longer period of time, could lead to critical energy wastage in wireless networks. It is imperative that optimizations at network level and application level are introduced to drive down the impact of the ever increasing traffic on wireless and mobile networks.

We are currently analysing the effects of traffic on power consumption in multi-hop wireless networks with multiple clients considering different application scenarios and traffic classes. We are also modeling the effect of traffic on energy consumption at different device loads and traffic levels, which will permit us to develop accurate energy efficiency metrics and to design energy efficient mechanisms that allow wireless networks to operate efficiently with respect to increasing levels of traffic. Finally, we are planning to extend our work to other technologies (e.g. UMTS, WiMAX) in order to compare the power consumption trends and behaviors of each technology.

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