Measurement–based Modelling of Power Consumption at Wireless Access Network Gateways☆

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Abstract

Improving the energy efficiency of the ICT sector is becoming an ambitious challenge for industries and research communities alike. Understanding how the energy is consumed in each part of an ICT system becomes fundamental in order to minimize the overall energy consumed by the system itself. In this paper, we propose an experimentally–driven approach to (i) characterize typical wireless access network gateways from an energy consumption standpoint, and (ii) develop simple and accurate power consumption models for such gateways. In this work we focused our attention on the monitoring, measurement and analysis of the energy consumption patterns of WiFi and WiMAX gateways. Our measurements show that the power consumption of such gateways exhibits a linear dependence on the traffic until a saturation point is reached.

Keywords: Green Networking, WiMAX, WiFi, Power consumption, Energy efficiency, Modelling

1. Introduction

In the last decade, "Green Networking" [2, 3, 4, 5, 6] has gained considerable importance for both commercial entities and researchers that aim at understanding and reducing the energy consumption of computing and communication infrastructures [7, 8]. Several studies have shown that the ICT sector accounts for

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2% – 7% of the global energy consumption [9, 10, 3] and it is also responsible for 2% to 3% of total emissions of CO_2 [11, 12, 13]. Moreover, it is important to remark that about 50% of the total energy used in the ICT sector is consumed at the wireless access part [11, 13]. Therefore, network operators and service providers currently compete to optimize the energy efficiency of their access infrastructure in order to reduce both CO_2 emissions and operational costs [14].

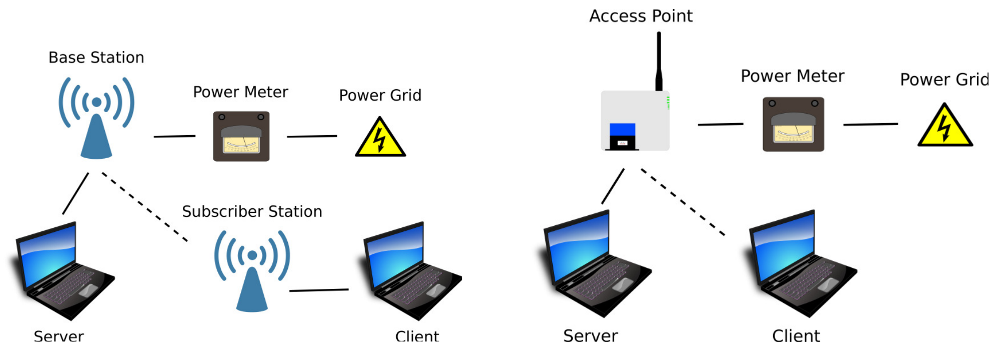
In such scenario, two broadband wireless access technologies, WiFi and WiMAX, are witnessing an increasing usage in both metropolitan and rural deployments. The reason behind their adoption lies in the minimal supporting infrastructure required for their operations, which in time enables a high level of flexibility in network deployments, allowing connectivity to be provided only where *and* when needed. Such fluidity in network deployment and operations is made possible by the architectural choices underpinning the standards. However, while energy efficiency trade–offs have been taken into account for the end–users' terminal, which can be mobile or nomadic, less attention has been devoted to the network gateways which, in either the WiFi and the WiMAX standards, are typically connected to the power grid and, thus, do not pose energy consumption challenges. As a result there is lack of best practices for designing energy efficient network protocols and architectures for broadband wireless access networks.

The main objective of this work is to experimentally measure and analyse the energy consumption patterns of WiFi and WiMAX gateways[1] at both the component and the network level. In particular, our experiments aim at answering the following questions:

- Where and how is the power consumed in WiFi and WiMAX access gateways? How much of the power is wasted?
- What is the relationship between traffic load and power consumption in WiFi and WiMAX access gateways?
- What are the critical aspects of the IEEE 802.11 and the IEEE 802.16 standards with respect to power consumption?

It is the authors' standpoint that the answers to these questions are very important since they would provide us with an increased insight into the network behaviour, paving the way to the development of (i) realistic models for power consumption in wireless networks and (ii) protocols and algorithms for their operations. The main contributions of the paper are the following:

[1]With a slight abuse of terminology we use the term *gateway* to refer to both the WiMAX Base Station (BS) and to the WiFi Access Point (AP).



(a) WiMAX (b) WiFi

Figure 1: Network scenario used for the measurement campaign.

- An empirical approach for understanding the energy consumption behaviour of WiMAX and WiFi gateways. Thereby, we target the characterization of the power consumption of WiFi and WiMAX gateways in terms of (i) the amount of traffic sent/received by the node, (ii) the modulation and coding schemes used, and (iii) the size of the session level data units.

- A simple model for the characterization of the power consumption in WiFi and WiMAX access gateways is presented.

The remainder of this paper is organized as follows. In Sec. 2 we present the experimental settings and methodology used. Experimental results are reported and discussed in Sec. 3. In Sec. 4 we discuss energy efficiency metrics and models. A brief analysis of the related works on measurement driven energy efficiency analysis is presented in Sec. 5. Finally, Sec. 6 is devoted to the final conclusions and pointers to promising research directions.

2. Evaluation methodology

In this section, we will describe the network setups and the methodology used in order to evaluate the power efficiency of the two wireless networking technologies that have been considered in this paper, namely an indoor WiFi network deployed in a typical office environment and an outdoor WiMAX network deployed in a rural area. The network setups exploited in the WiMAX and the WiFi scenarios are sketched respectively in Fig. 1a and in Fig. 1b.

2.1. Network settings

In the WiMAX case, the network is composed of a Base Station deployed on the rooftop of an high building and a single static Subscriber Station (SS) deployed on the rooftop of another building. The testbed is deployed across the

Orange Labs Campus in Lannion, France. The BS and the SS are about 800 meters away from each other and are operating under line of sight conditions. The WiMAX equipment is compliant with the IEEE 802.16–2004 version of the standard and implements the TDD duplexing scheme. The devices operate between 5.47 and 5.725 GHz using omni–directional antennas with a gain of 8dB. With regard to QoS, the devices support the Best Effort (BS), the Real-time Polling Service (rtPS), the Non-real-time Polling Service (nrtPS), and the Unsolicited Grant Service (UGS) traffic classes. The BE class has been used throughout the entire measurements campaign reported in this work.

In the WiFi case, the network is composed of a custom IEEE 802.11g Access Point and a single DELL Latitude D620 notebook acting as static wireless client. The testbed is deployed at CREATE-NET premises in Trento, Italy. The AP 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, while the notebook is equipped with an Intel PRO/Wireless 3945AB wireless adapter. The frequency of operation of the AP is 2.412GHz and the antenna is omni-directional with a gain of 8dB.

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 18dBm ($\sim$63.1 mW) for the WiFi and the WiMAX cases.

2.2. Traffic Generation and Power Consumption Monitoring

Traffic is generated using the Iperf traffic generator [2] and is injected into the network trough either the *Server* or the *Client*. In the former case, we aimed at measuring the power consumed by the BS/AP when it is acting as transmitter, while in the latter case we aimed at measuring the power consumed by the BS/AP when it is acting as receiver. In both cases the power consumption figures reported in this work refer to the BS/AP.

The power consumption is measured using the *Watts Up?*[3] power meter. *Watts Up?* is a "plug load" meter that measures the amount of electricity used by whatever electrical appliance is plugged into it. The meter incorporates digital electronics to perform accurate power consumption measurements. Such measurements are then logged into the device's internal memory with a granularity of 0.1 Watts and a sampling period of 1 second.

The *Watts Up?* meter is interconnected through its USB interface to the *Server* where a custom data logging software is used in order to extract the power consumption samples. It is important to remark that the power consumption is monitored for the whole device. Therefore, the results reported in this

[2] Available at: http://iperf.sourceforge.net/

[3] Available at: http://www.wattsupmeters.com/

paper account for both the power consumed by the processing board for handling the incoming and outgoing traffic (e.g. for segmentation and reassembling, protocol overheads, computing checksums, etc.) as well as for the power consumed to deliver the actual frame over the wireless link (e.g. power amplifiers, modulator/demodulator, etc.).

2.3. Testing Methodology

Synthetic traffic is modeled as single UDP flows. Results reported in this paper are the average of 4 runs. Results are reported in terms of 95% confidence interval. Each run was 500 seconds long for the WiMAX case and 400 seconds long for WiFi cases. The following scenarios have been considered:

- *Constant Traffic Generation Rate, Variable Packet Length.* In this test, the traffic generation rate is kept constant while the datagram size is progressively increased from 32 to 2816 bytes in steps of 256 bytes. Two different settings have been considered for the traffic generation rate resulting in application throughput of 1Mb/s and 10Mb/s for the WiFi case and of 1Mb/s and 5Mb/s for WiMAX case.

- *Variable Traffic Generation Rate, Fixed Packet Length.* In this test, the datagram size is kept constant at 1280 bytes, while the traffic generation rate is progressively increased from 0.1Mb/s up to 54Mb/s for the WiFi case and from 0.1Mb/s up to 30Mb/s for the WiMAX case.

- *Variable Traffic Generation Rate, Mixed Transmission Power.* In this test, the datagram size is kept constant at 1280 bytes while the traffic generation rate is progressively increased. This test has been repeated using two different transmission power levels. In the WiFi case, the first set of measurements has been performed with a transmission power set to *10dBm* ($\sim$10 mW), while in second round of measurements the transmission power has been increased to *18dBm* ($\sim$63.1 mW) for both the AP and the client. Similarly, in the WiMAX the transmission power level have been set to either 10dBm ($\sim$10 mW) or 26dBm ($\sim$398 mW).

- *Variable Traffic Generation Rate, Fixed Modulation Type.* In this test, the datagram size is kept constant at 1280 bytes while the message generation rate is progressively increased. The rate control algorithm is disabled and the transmission rate is set manually using the command line interface. The experiment is repeated for each of the transmission rates supported by the wireless adapter (see Table 1).

It is worth noticing that, the frame length of 1280 bytes used in the scenario 2 through 4 has been chosen in that, according to the outcomes of the first scenario, it is the length at which the power efficiency of both systems is maximized.

Table 1: IEEE 802.11g and IEEE 802.16 OFDM rates and modulation types

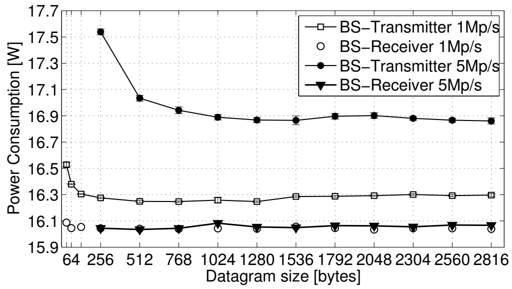
Modulation Type	**Data Rate [Mb/s]**
Binary Phase Shift Keying (BPSK)	6/9
Quadrature Phase Shift Keying (QPSK)	12/18
16-Quadrature Amplitude Modulation (16-QAM)	24/36
64-Quadrature Amplitude Modulation (64-QAM)	48/54

3. Experimental measurements and Analysis

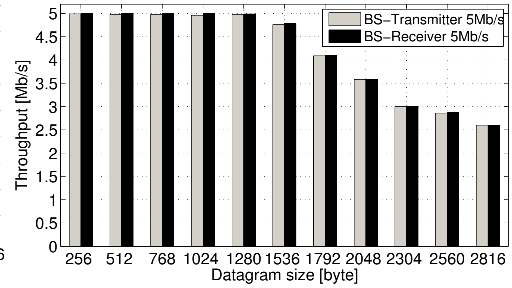
In this section, we present the results from the measurements campaign using WiMAX and WiFi test environments. We use the following notation for the figures throughout the section (a) BS/AP-Receiver is when BS/AP is acting as receiver and (b) BS/AP-Transmitter when BS/AP is acting as transmitter.

In Fig. 2a and 2c, the average power consumption level at the BS and at the AP as a function of the datagram size for a constant throughput is presented. This gives us certain insights in order to understand "how" the datagram size impacts power consumption. Results are plotted when the BS/AP are acting as transmitter and receiver respectively. As it can be seen, the power consumption behaviour for this experiment is similar for both the gateways (BS and AP). The datagram size has a considerable impact on power consumption when the BS/AP are acting as transmitters. However for the WiMAX case, when the BS is acting as receiver, there is no impact on power consumption for any datagram size.

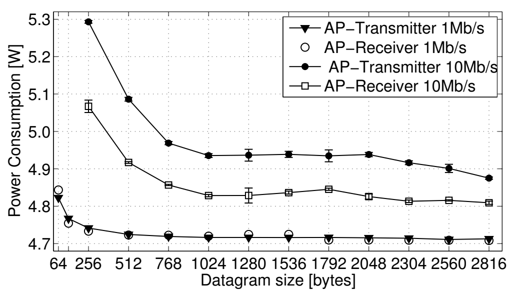
Instead for the WiFi case, when the AP is acting as receiver, the impact on power consumption for any datagram size follows similar behavior of the AP when acting as transmitter but with a lower power consumption. Such differences in power consumption while the BS/AP is in receiving mode can be attributed to the manner in which the MAC receives and processes the packets in the case of the two access technologies. It is also important to note that the amount of traffic, i.e. 1, 5 and 10 Mb/s for the experiment, does not affect the behavior of the power consumption vs. datagram size. However, for low amounts of traffic the difference between power consumption when the AP is acting as receiver or transmitter is lower. Finally, we can observe that (i) for low datagram sizes, the device power is wasted because the BS/AP consumes significantly more power than the large datagram sizes under the same traffic conditions, and (ii) when the datagram size becomes extremely large, fragmentation takes place and consequently, the bandwidth utilization decreases. These effects are shown in Fig. 2b and 2d, the results show the throughput for the experiments performed by 5 Mb/s for WiMAX case and 10 Mb/s for WiFi case. Therefore, the optimal datagram length in terms of power consumption and network performance for a static client is 1280 bytes. The datagram loss for these set of experiments was lower than 1%.



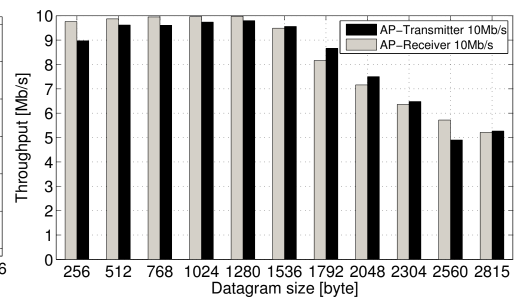
(a) WiMAX case: Power Consumption



(b) WiMAX case: Throughput for the experiment with 5 Mb/s



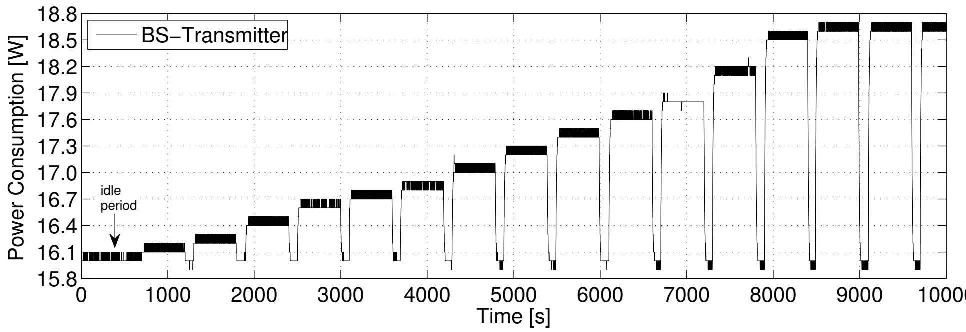
(c) WiFi case: Power Consumption



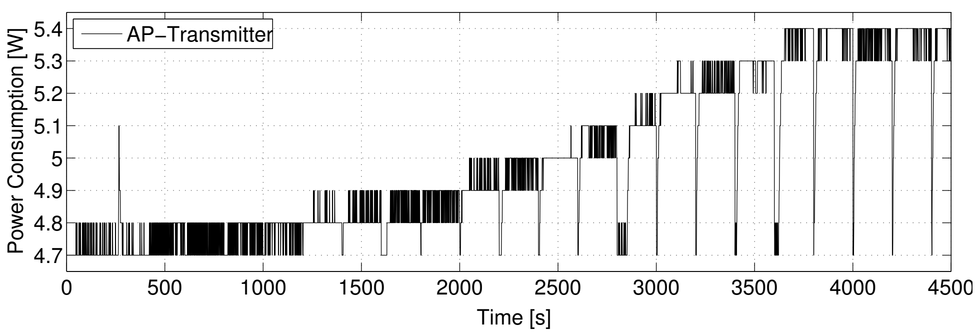
(d) WiFi case: Throughput for the experiment with 10 Mb/s

Figure 2: Average power consumption and throughput at either the BS or the AP as a function of the datagram size for a constant traffic generation rate (1, 5 and 10 Mb/s). Datagram loss was less than 1% during all measurements.

In order to study the relationship between traffic load and power consumption, we present a set of results that summarizes the behavior of BS and AP respectively in terms of power consumption and network performance. An example of the measurements trace obtained for WiMAX and WiFi cases is reported in Fig. 3a. The power consumption of the BS in idle mode is 16.05 W and when the BS is acting as transmitter, the power consumption is monotonically increasing with the traffic load (in the range of 0.1 - 30 Mb/s), as expected, until it reaches the saturation point. We can observe the same behavior for the power consumption of the AP in Fig. 3b. However, the AP consumes 4.7 W in idle mode and less power in general. The average power consumption of the BS as a function of different traffic generation rates is shown in Fig. 4, for a fixed datagram size of 1280 bytes. The power consumption when the BS is acting as transmitter increases according to the increase in traffic. The power consumption when the BS is acting as receiver remains always unchanged, as expected. We can observe in Fig. 4b



(a) WiMAX case: Power Consumption

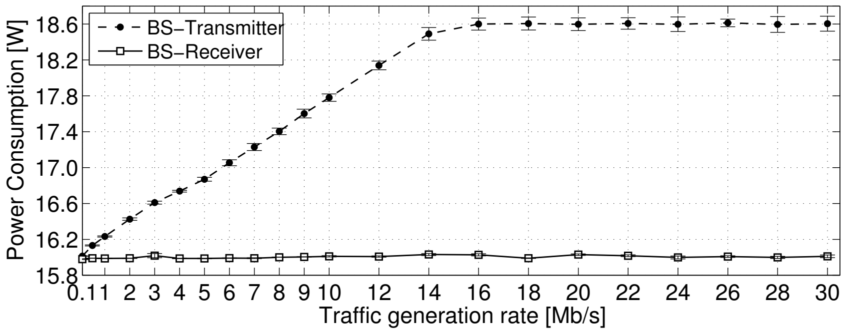


(b) WiFi case: Power Consumption

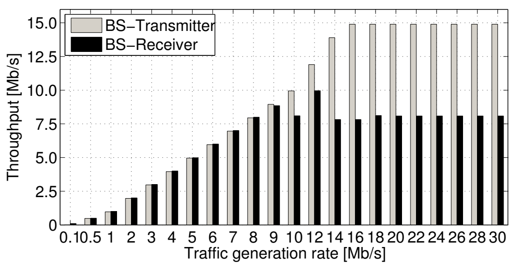
Figure 3: Consumed power at the BS for different traffic rates

that when the BS reaches saturation, the maximum throughput value remains constant. In these set of experiments, the datagram loss starts to increase when the BS reaches saturation for both situations, while it is acting as transmitter and receiver, these results are shown in Fig. 4c.

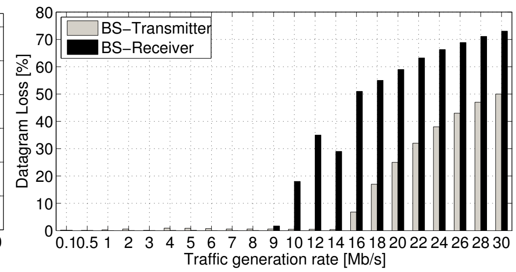
In Fig. 5, we report the average power consumption of the AP as a function of different traffic generation rates, for a fixed datagram size of 1280 bytes. As it can be intuitively corroborated, the relationship between power consumption and traffic for the AP while acting as transmitter follows the same behavior like the BS in WiMAX. In contrast, when the AP is acting as receiver the power consumption increases the same way compared to the AP when acting as transmitter but with lower power consumption. Fig. 5b reports the throughput while Fig. 5c reports the datagram loss for the experiments when AP is acting as transmitter and receiver. We can also observe the effect of saturation in these figures and the increase of datagram loss for large amount of traffic when AP is acting as transmitter. This is due to the fact that, due to the low memory resources of the AP, packets are discarded at the transmission buffer before they get a chance to be transmitted. Instead, when the AP is acting as receiver and the client is acting



(a) WiMAX case: Power Consumption



(b) WiMAX case: Throughput



(c) WiMAX case: Datagram loss

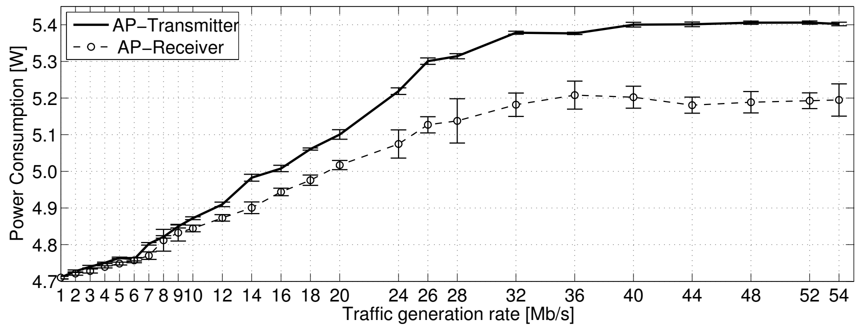
Figure 4: Average power consumption, throughput, and packet loss as a function of different traffic generation rates for a constant datagram size of 1280 bytes.

as transmitter, the larger memory resources that are available at the notebook allow packets to be buffered until a transmission opportunity can be obtained. This explain the fact that when the AP is acting as receiver the packets loss is less that 1% for any amount of traffic.

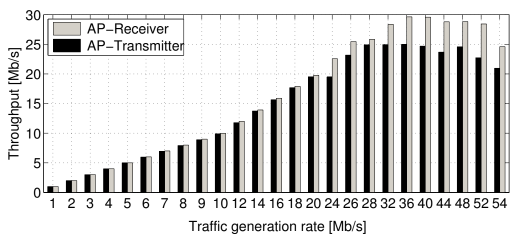
In the next set of measurements, we report only the power consumption statistics relative to the case in which the BS is acting as transmitter. The power consumption when the BS is acting as receiver remains always unchanged as we have explained before. We considered two different transmission power levels for the WiMAX case, i.e., 10 dBm and 26 dBm or 10 mW and ∼398.1 mW, respectively. Results are reported in Fig. 6a. The Fig. 6a shows the average power consumption at the BS as a function of different traffic generation rates for transmission power of 10 dBm and 26 dBm with datagram size equal to 1280 bytes.

Results show that two different transmitter power levels are characterized by the same power consumption in saturation regime. The reason for this behavior is that the contribution of the power amplifier to the overall consumption is below the sensibility of the meter used in our measurements (i.e. lower than 0.1W).

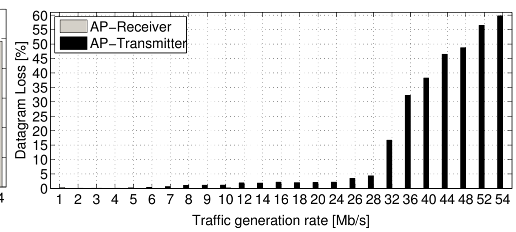
On the other hand what came as a surprise is the fact that the saturation regime when using the high transmission power level (26dBm) is reached for lower



(a) WiFi case: Power Consumption



(b) WiFi case: Throughput

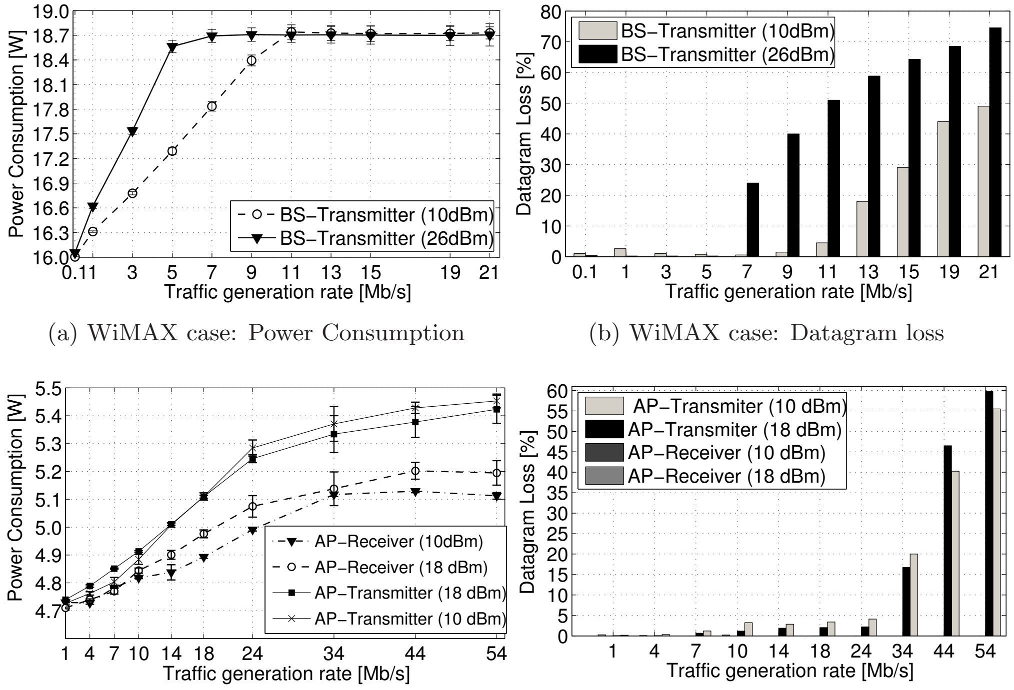


(c) WiFi case: Datagram loss

Figure 5: Average power consumption, throughput, and packet loss as a function of different traffic generation rates for a constant datagram size of 1280 bytes.

data rates than when using the low transmission power level (10dBm). Moreover, increasing the transmitter power results in an increased datagram loss, while one would expected that a better SINR would give better performance in terms of packet loss. In order to investigate this phenomena, we carried out additional measurements by generating a saturated TCP connection from the BS to the SS. The test was repeated using different transmission power levels. The outcomes are reported in Fig 7. As it can be seen, for low transmission power levels, the BS uses high rate modulation and coding schemes (16–QAM 3/4), while when the transmission power level increases the BS switches to less efficient modulation and coding schemes (16–QAM 1/2 and QPSK 3/4). This choice results in less airtime–efficient modulation and coding schemes being used when the transmitter power is set to 26dBm which in time causes the system to reach the saturation point for lower datarates (see Fig. 6a). Likewise, an high datagram loss is experienced by the system when the traffic generation rate increases in that less efficient modulation and coding schemes result is a low bitrate wireless link which in time causes datagrams to be dropped at the wireless interface.

Two different transmission power levels are also considered for the WiFi case, i.e., 10 dBm and 18 dBm or 10 mW and ∼63.1 mW, respectively. The Fig. 6c reports the average power consumption at the AP as a function of different traffic



(a) WiMAX case: Power Consumption

(b) WiMAX case: Datagram loss

(c) WiFi case: Power Consumption

(d) WiFi case: Datagram loss

Figure 6: Average power consumption at the BS and AP and datagram loss as a function of different traffic generation rates for different transmission power levels. Datagram size equal to 1280 bytes.

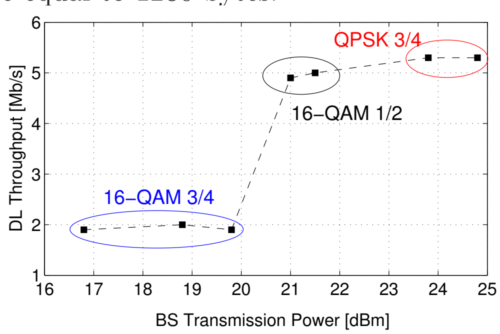


Figure 7: Goodput between BS and SS using different transmission power levels. The results refer to a saturated TCP connection.

generation rates for transmission power of 10 dBm and 18 dBm with datagram size equal to 1280 bytes. The advantage of decreasing the transmission power can be clearly observed only when the AP is acting as receiver. Instead, when the AP is acting as transmitter with 10 dBm and 18 dBm, the results are comparable. The Fig. 6d reports the datagram loss when the AP is acting as transmitter and receiver. The percentage of packet loss when the AP is transmitting with 10 dBm is lower than when the AP is transmitting with 26 dBm, especially with larger amounts of traffic, as explained earlier.

Lastly, we study the impact of modulation and coding schemes on power consumption patterns. We forced the modulation and coding schemes to be used by wireless interfaces and measured the power consumption as a function of the traffic generation rate. The results for the WiMAX case are the following:

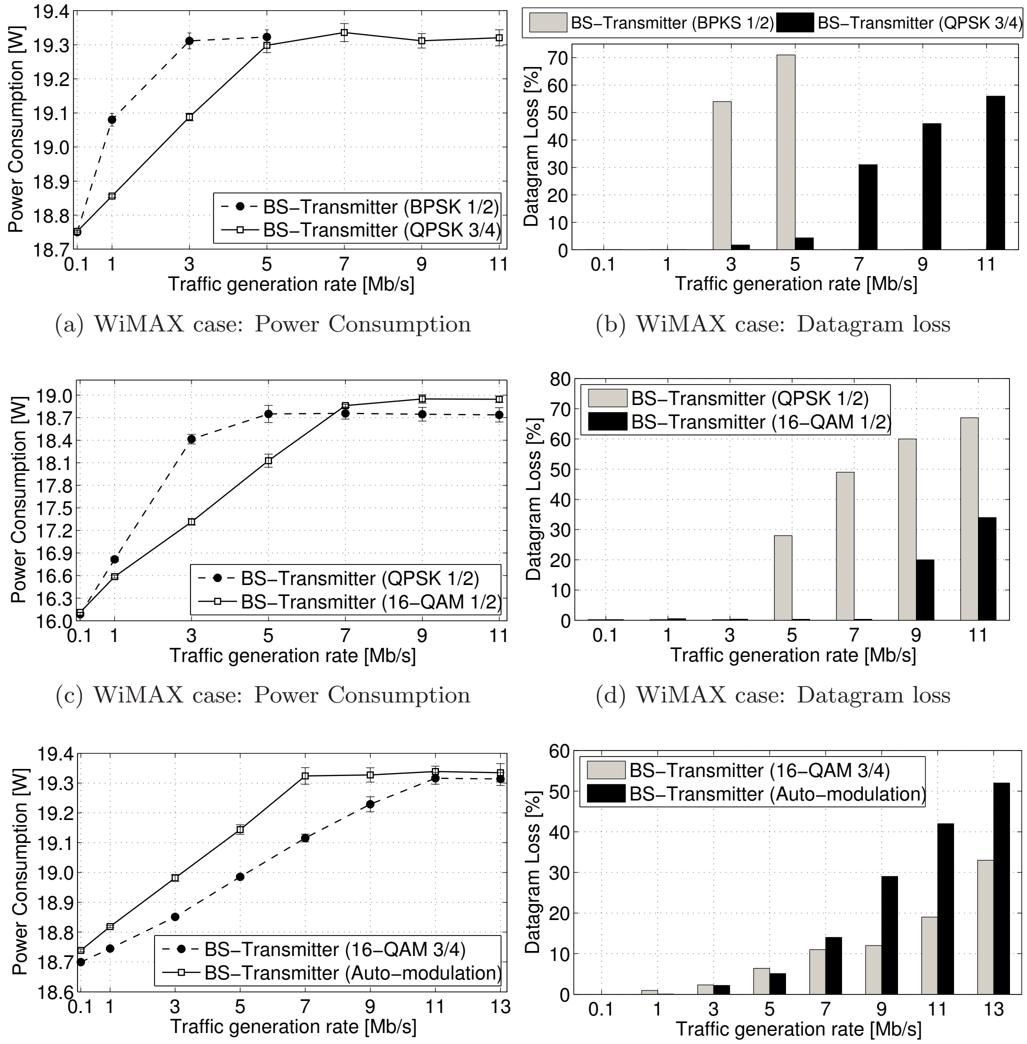
- *BPSK 1/2 and QPSK 3/4 modulations:* Fig. 8a reports the average power consumption at the BS when acting as transmitter, as a function of different traffic generation rates for BPSK 1/2 and QPSK 3/4 modulations. Datagram size equal to 1280 bytes. Fig. 8b reports the datagram loss.

- *QPSK 1/2 and 16-QAM 1/2 modulations:* Fig. 8c reports the average power consumption at the BS when acting as transmitter, as a function of different traffic generation rates for QPSK 1/2 and 16-QAM 1/2 modulations. Datagram size equal to 1280 bytes. Fig. 8d reports the datagram loss.

- *16-QAM 3/4 modulation and Auto–rate:* Fig. 8e reports the average power consumption at the BS when acting as transmitter, as a function of different traffic generation rates for 16-QAM 3/4 modulation and Auto-modulation. Datagram size equal to 1280 bytes. Fig. 8f reports the datagram loss.

The figures shows that for the WiMAX case: (i) QPSK 3/4 modulation is better than BPSK modulation 1/2 and (ii) 16-QAM 1/2 modulation is better than QPSK 1/2 modulation in terms of power consumption and network performance for a static client. Therefore higher modulation rates are more power efficient. This is understood to be due to the fact that higher modulation and coding 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 good. Finally, we can see also that the 16-QAM 3/4 modulation is better than auto–modulation in terms of power consumption and network performance for a static client. This is because the rate control algorithms are based in parameters related with the channel, such as, RSSI and transition successful probabilities. However, the rate control algorithm cannot quickly adapt to the channel variations and it chooses a lower modulation scheme also when the channel conditions allow use a higher modulation scheme.

In the case of WiFi scenario, in Fig. 9a and Fig. 9b, we plot the average power consumption at the AP when acting as transmitter and receiver as a function of



(a) WiMAX case: Power Consumption (b) WiMAX case: Datagram loss

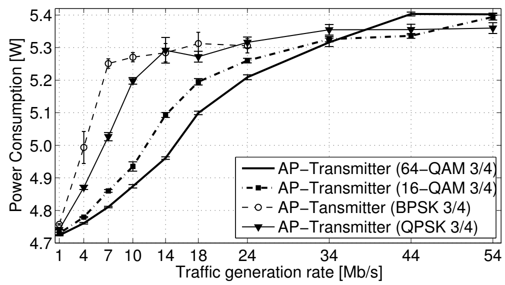
(c) WiMAX case: Power Consumption (d) WiMAX case: Datagram loss

(e) WiMAX case: Power Consumption (f) WiMAX case: Datagram loss

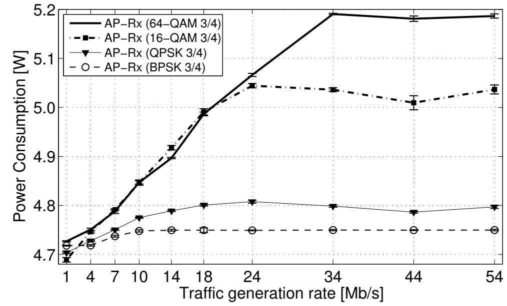
Figure 8: Average of power consumption at the BS (Transmitter) and datagram loss as a function of different traffic generation rate for different modulation types. Datagram size equal to 1280 bytes.

different traffic generation rates for BPSK 3/4, QPSK 3/4, 16-QAM 3/4 and 64-QAM 3/4 modulations. Datagram size is kept at 1280 bytes. Fig. 9e and Fig. 9f reports the datagram loss while the throughput is reported in Fig. 9c and Fig. 9d.

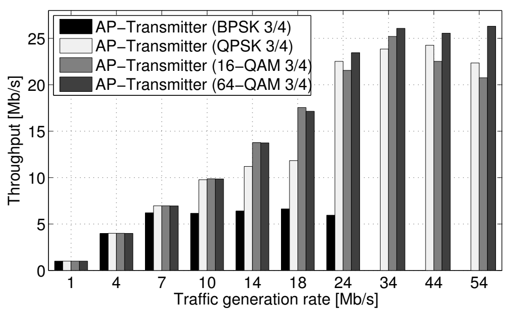
As we can observe from Fig. 9a and Fig. 9c, the higher modulation and coding schemes are more efficient at using the available power and bandwidth than lower modulation and coding schemes when the AP is acting as transmitter.



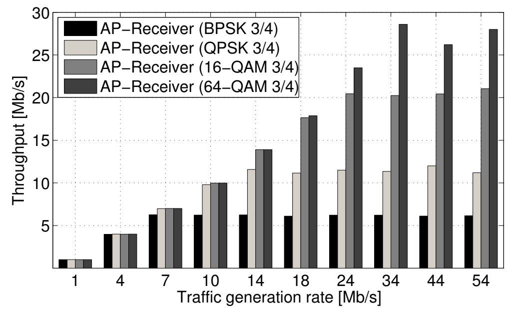
(a) WiFi case: Power Consumption



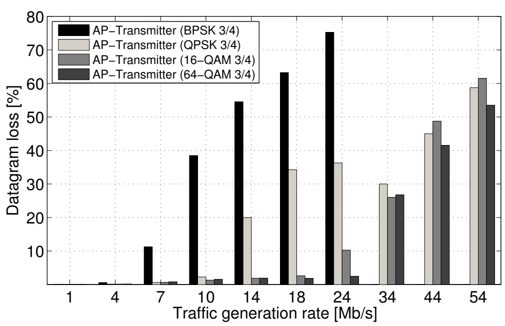
(b) WiFi case: Power Consumption



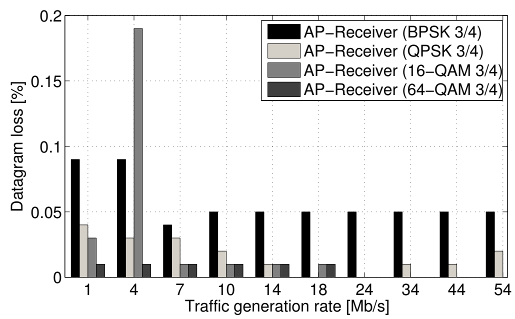
(c) WiFi case: Throughput



(d) WiFi case: Throughput



(e) WiFi case: Datagram loss



(f) WiFi case: Datagram loss

Figure 9: Average of power consumption at the AP and datagram loss and throughput as a function of different traffic generation rate for different modulation types. Datagram size equal to 1280 bytes.

Figure 9e and Fig. 9f shows the datagram loss for each modulation scheme. It is worth noticing that the lower modulation scheme (BPSK 3/4) has been tested using traffic generation datarates up to 24 Mpbs in that higher generation rates resulted in either a packet loss of 100% or in misbehavior in the traffic generator that was not able to maintain the connection. This is due to buffers overflow at the transmitter which in time are caused by the low bitrate link.

In Fig. 9b, we can see that lower modulation and coding schemes are more energy efficient than higher modulation and coding schemes when the AP is acting as receiver. Although, the figure reports the power consumption vs. traffic generation rates at the transmitter side, the traffic received by the AP is lower as shown in Fig. 9d. Thus, it is difficult to evaluate the power consumed by each modulation scheme at the receiver side as it depends on the time that it spends in order to receive all the traffic sent by the transmitter. For this experiment, the datagram loss was lower 0.2% as showed in Fig. 9f.

4. Models

In this section, we aim at introducing a simple, yet accurate model for estimating the power consumption of wireless access network gateways as a function of the traffic rate and of the datagram size. Throughout the section, we use the following notation:

- x is the amount of traffic transmitted or received by the BS/AP (in Mb/s).
- s is the datagram size (expressed in bytes).
- $f_{\cdot}(x)$, where $\cdot = Tx, Rx$ is the power consumption model when BS/AP is acting as transmitter (respectively: receiver).

4.1. Measurements-Based Modelling

We used a curve fitting approach in order to construct a model able to match well the power consumption measurements presented in the previous section. Different types of functions were tested, including polynomials up to the 4^{th} order, mixes of exponential/logarithmic functions and piecewise linear functions. The metric used to assess the goodness of the fit was the standard root-mean-square error (RMSE) [4].

For all cases considered, the best fit was given a simple model in which the power consumption was linear as a function of the traffic rate (respectively: datagram size) until a given threshold was reached. After such a threshold, the power consumption was constant regardless of the traffic rate (respectively: datagram size). The slope of the curve and the threshold value depend on a number of factors, including technology considered (WiFi/WiMAX) and the modulation scheme in use.

[4]The RMSE is a numerical indicator of the differences between values predicted by a model and the values actually observed The RMSE is given by $RMSE = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2$, where y_i is the measured value, $\hat{y}_i$ is the modeled value and N is the total number of samples.

More formally, the model take the following form:

$$\begin{cases} f_{\cdot}(x) = \begin{cases} \alpha(s)\cdot x+\beta & \text{if } 0\le x\le h(s) \ \text{ Mb/s},\\ \gamma & \text{if } x>h(s) \ \text{ Mb/s},\end{cases}\\ f_{\cdot}(s) = \begin{cases} -\delta(x)\cdot s+\epsilon(x) & \text{if } p\le s\le q \ \text{ byte},\\ \eta(x) & \text{if } s>q \ \text{ byte},\end{cases}\end{cases} \tag{1}$$

It is worth remarking that the model for the dependency on x has parameters that in turn depend on s and vice versa.

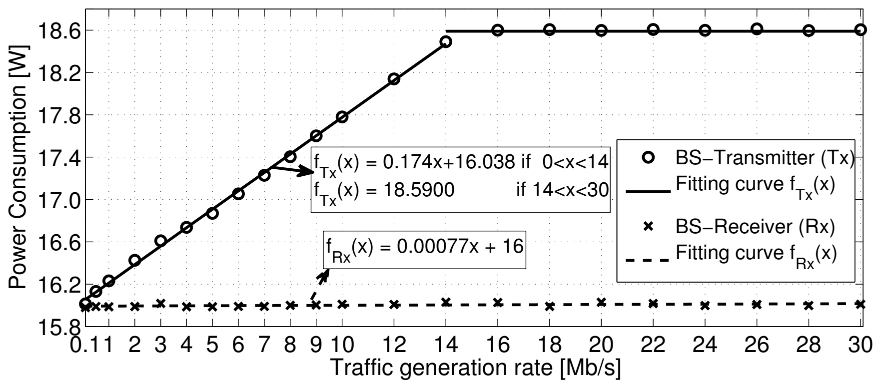
The parameters of the model have the following physical meaning:

- $\alpha(s)$ (expressed in $\mu J/b$) is the amount or energy spent by the wireless device in order to transmit or receive 1 bit of information from the session layer with a datagram size of s bytes;
- β (expressed in W) is the amount of power consumed by the wireless gateway in idle mode;
- γ (expressed in W) is the maximum amount of power consumed by the wireless gateway and represents the saturation power consumption;
- $\delta(x)$ (expressed in $\mu W/bytes$) is the amount of power consumed by wireless gateway in order to transmit or receive 1 byte of information from the session layer at a rate of x Mb/s;
- $\epsilon(x)$ (expressed in W) is the maximum power consumed by the wireless gateway, transmitting at x Mb/s, using extremely small packets.
- $\eta(x)$ (expressed in W) is the minimum power consumed by the wireless gateway to transmit traffic at rate x Mb/s.

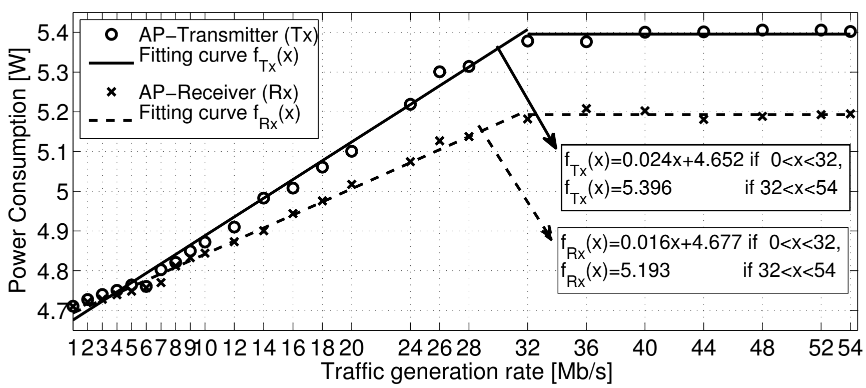
4.2. Model Validation

We first focused on the power consumption model as a function of the traffic generation rate. In Fig. 10 we report the model for the power consumption at the BS and at the AP Vs. different traffic generation rates for a constant datagram size of 1280 bytes. The model parameters have been optimized using Matlab in order to minimize the RMSE. The best fit models obtained are:

$$\text{WiMAX}\begin{cases} f_{Tx}(x) = \begin{cases} 0.174x+16.038 & \text{if } 0\le x\le 14\text{Mb/s},\\ 18.5900 & \text{if } 14<x\le 30\text{Mb/s},\end{cases}\\ f_{Rx}(x) = \begin{cases} 0.00077x+16 & \text{if } 0\le x\le 30\text{Mb/s},\end{cases}\\ \text{with } s=1280\text{bytes},\end{cases} \tag{2}$$



(a) WiMAX case: Transmitter/Receiver



(b) WiFi case: Transmitter/Receiver

Figure 10: Fitted curve of the power consumption at the BS and at the AP with a datagram size equal to 1280 bytes

$$\text{WiFi}\begin{cases} f_{Tx}(x) = \begin{cases} 0.024x + 4.652 & \text{if } 0 \leq x \leq 32\text{Mb/s}, \\ 5.396 & \text{if } 32 < x \leq 54\text{Mb/s}, \end{cases} \\ f_{Rx}(x) = \begin{cases} 0.016x + 4.677 & \text{if } 0 \leq x \leq 32\text{Mb/s}, \\ 5.193 & \text{if } 32 < x \leq 54\text{Mb/s}, \end{cases} \\ \text{with } s = 1280\text{bytes}, \end{cases} \tag{3}$$

The RMSE figures obtained are $9.3968 \cdot 10^{-4}$ (WiMAX, Tx), $1.7139 \cdot 10^{-4}$ (WiMAX, Rx), $5.7165 \cdot 10^{-4}$ (WiFi, Tx), $1.234 \cdot 10^{-4}$ (WiFi, Tx), which confirm the ability of our model to estimate the actual power consumption in a variety of settings.

Similarly, in Fig. 11 we report the model of the power consumption at the BS and at the AP Vs. different datagram sizes for a constant traffic generation rate of 1 Mb/s. The model parameters have been optimized using Matlab in order to minimize the RMSE. The best fit models obtained are:

$$
\text{WiMAX}\begin{cases} f_{Tx}(s) = \begin{cases} -0.0022s + 16.5655 & \text{if } 32 \le s \le 128 \text{ byte,} \\ 16.278 & \text{if } 128 < s \le 2816 \text{ byte,} \end{cases} \\ f_{Rx}(s) = \begin{cases} 16.0469 & \text{if } 32 \le s \le 2816 \text{ byte,} \end{cases} \\ \text{with } x = 1\text{Mb/s,} \end{cases} \tag{4}
$$

$$
\text{WiFi}\begin{cases} f_{Tx}(s) = \begin{cases} -0.0004s + 4.841 & \text{if } 32 \le s \le 256 \text{ byte,} \\ 4.718 & \text{if } 256 < s \le 2816 \text{ byte,} \end{cases} \\ f_{Rx}(s) = \begin{cases} -0.0005s + 4.852 & \text{if } 32 \le s \le 256 \text{ byte,} \\ 4.715 & \text{if } 256 < s \le 2816 \text{ byte,} \end{cases} \\ \text{with } x = 1\text{Mb/s,} \end{cases} \tag{5}
$$

The RMSE figures obtained are $5.9411 \cdot 10^{-4}$ (WiMAX, Tx), $1.5548 \cdot 10^{-4}$ (WiMAX, Rx), $5.6123 \cdot 10^{-5}$ (WiFi, Tx), $1.5638 \cdot 10^{-4}$ (WiFi, Tx), which again confirm the ability of our model to estimate the actual power consumption.

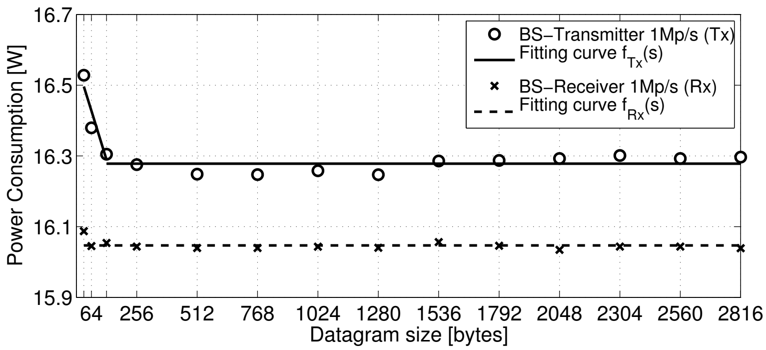
We tested the obtained power consumption model with various modulation schemes. Results are reported in Fig. 12 for a constant datagram size of 1280 bytes. The parameters used in the model (again derived using Matlab) are reported in Tab. 2 and 3 for WiMAX and WiFi access gateways, respectively.

Table 2: Power consumption model parameters for the WiMAX access gateway using a specific modulation/coding schemes ($s = 1280$ bytes).

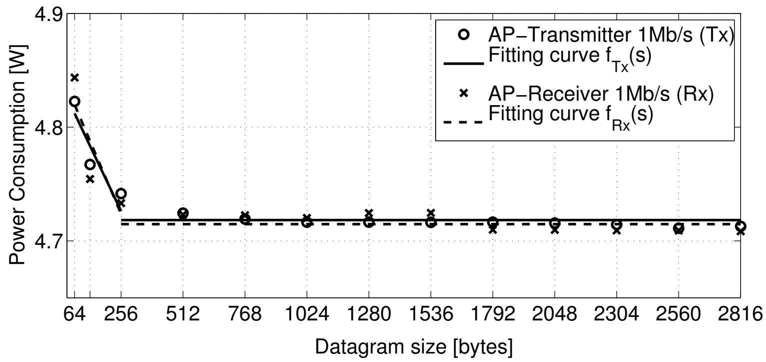
Modulation/Coding	α $[\mu Ji/b]$	β $[W]$	γ $[W]$	**h** $[Mb/s]$	**RMSE** $[W]$
Tx: QPSK 1/2	0.761	16.036	18.748	3	0.002
Tx: 16QAM 1/2	0.394	16.132	18.918	7	0.0017
Rx	0	16	16	11	$1.7139 \cdot 10^{-4}$

Finally, in order to validate our power consumption model in the presence of the bi–directional traffic we have loaded the WiFi AP with the traffic showed in Fig. 13a and measured the power consumption of the AP. Figure 13a shows the amount of traffic that AP is transmitting and receiving vs. time. It is important to notice that in order to use the power consumption model described in (1) when the WiFi or the WiMax access gateway is acting as transmitter and receiver at the same time, β must be considered only once. In other words, the total power consumption f_{Tx+Rx} is given by $f_{Tx+Rx} = f_{Tx} + f_{Rx} - \beta$, where f_{Tx} and f_{Rx} are given by (1).

The model output vs. the AP power consumption is reported in Fig. 13b for a datagram size equal to 1280 bytes. As it can be seen, our model is capable of qualitatively following the actual power consumption of the AP in the presence of



(a) WiMAX case

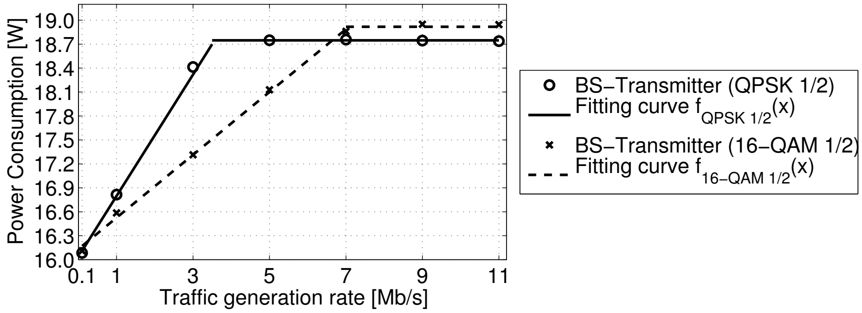


(b) WiFi case

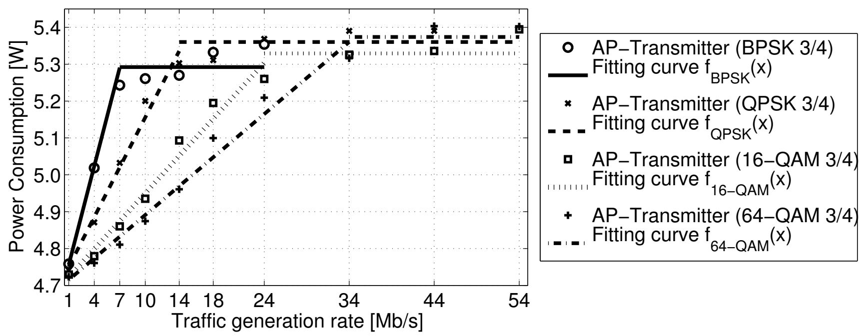
Figure 11: Fitted curve of the power consumption at the BS and at the AP for a constant traffic rate of 1 Mb/s

Table 3: Power consumption model parameters for the WiFi access gateway using a specific modulation schemes ($s = 1280$ bytes).

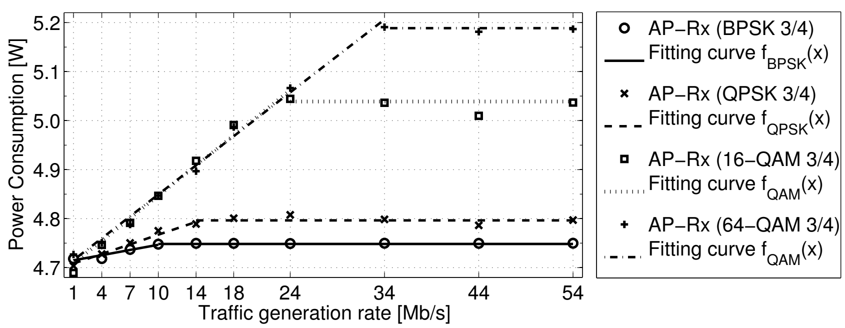
Modulation/Coding	α $[\mu J/b]$	β $[W]$	γ $[W]$	**h** $[Mb/s]$	**RMSE** $[W]$
Tx: BPSK 3/4	0.089	4.667	5.292	7	0.0012
Tx: QPSK 3/4	0.045	4.705	5.360	14	0.0011
Tx: 16−QAM 3/4	0.025	4.697	5.329	24	0.0014
Tx64−QAM 3/4	0.019	4.695	5.374	34	0.0012
Rx: BPSK 3/4	0.0035	4.711	4.748	10	$5.009{\cdot}10^{-6}$
Rx: QPSK 3/4	0.0065	4.702	4.796	14	$4.538{\cdot}10^{-5}$
Rx: 16−QAM 3/4	0.0154	4.6933	5.0389	24	$9.7329 \cdot 10^{-5}$
Rx: 64−QAM 3/4	0.015	4.700	5.1886	34	$1.2910{\cdot}10^{-4}$



(a) WiMAX: Transmitter



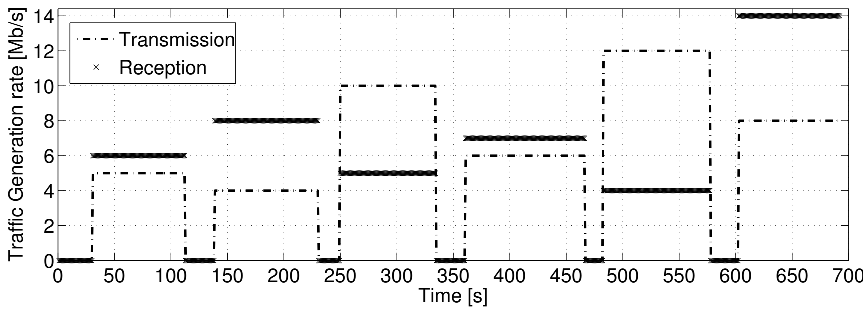
(b) WiFi: Transmitter



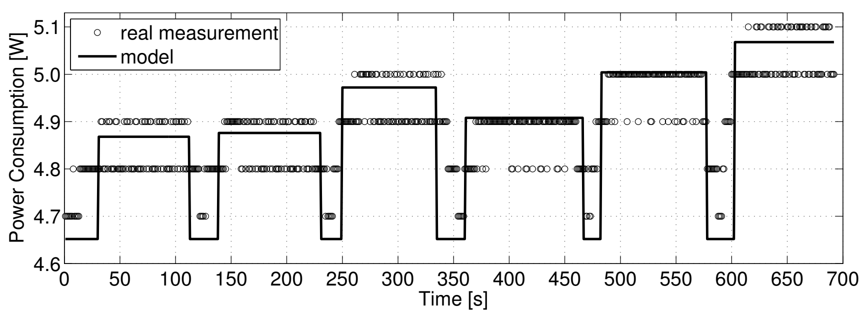
(c) WiFi: Receiver

Figure 12: Fitted curve of the power consumption at the AP for different modulation/coding schemes. Datagram size equal to 1280 bytes.

bi–directional traffic. However, due to the power meter's low resolution (0.1W) it was not possible to perform a better validation of our model in this scenario, that, we recall, aims at assessing the capability of our model to predict the *instantaneous* power consumption of a wireless gateway.



(a) Traffic



(b) Power Consumption

Figure 13: Comparison between real and modeled values of the power consumption at the AP vs. time in the presence of the bi–directional traffic. Datagram size equal to 1280 bytes

5. Related Work

Real–world energy consumption measurements of wireless networking devices have not been often performed in the past. This, in turn, led to unrealistic and/or over–simplified models being used in simulations.

In [15], the authors present several measurements for an IEEE 802.11a–based wireless network interface operating in idle, sleep, receive and transmit modes. Such measurements are obtained using an oscilloscope. In the work, the per–packet energy consumption E is approximated using a linear model $E = mS + b$, where S is the length of the packet and the values of the linear coefficients m and b must be determined experimentally for various operation modes. The authors conclude that the energy consumption of an IEEE 802.11a wireless interface has a complex range of behaviours according to several factors such as relative proportions of broadcast and point-to-point traffic, packet size and reliance on promiscuous mode operations. The behaviour of power consumption as a function of packet size is shown to follow a linear behaviour. However, the model does not consider the case of link–layer fragmentation and the impact of the different amount of traffic on power consumption figures.

Similar work in terms of methodology is presented in [16]. The paper presents several results for power consumption of an IEEE 802.11b wireless network interface. The scenario was built using two laptops with WLAN interfaces and an oscilloscope in order to monitor power consumption on the wireless interface. The authors do not provide a power consumption model but they derive a novel metric from their measurements. The metric is the energy per bit goodput $E_{bitgood}$ given by $E_{bitgood}[J/Bit] = Average_{CP}[W]/Goodput[Bit/s]$. In order to determine $E_{bitgood}$, the (MAC) goodput must be recorded simultaneously with the power consumption measurements ($Average_{CP}$). The $E_{bitgood}$ indicates the amount of energy expenditures in order to transmit one bit of payload data successfully. The authors also conclude that large packets use energy more efficiently than small ones as well as high modulation schemes are more energy efficient. In contrast to our work, the author's experimental focus is based only on varying the packet size in order to investigate the power consumption behaviour while the impact of traffic on power consumption figures is not considered.

In [17], the authors focus their analysis on the novel IEEE 802.11n standard using a wide range of experiments. Each experiment aimed at assessing the impact that a certain feature (e.g. channel width, transmission power, modulation and coding scheme, etc.) has on the global energy consumption figures. The testbed used for the power consumption measurements was composed of two nodes placed close to each other in order to have good link quality, which in time allowed the authors to effectively exploit all the IEEE 802.11n modulation and coding schemes. To measure the power consumption, the authors placed a resistor (40Ω) on the 3.3V power supply to the wireless interface. A National Instruments 6218 Data Acquisition Module (NIDAM) was used in order to measure and record the voltage drop across the resistor. Thus, the power consumed by the wireless interface was calculated using the data recorded with NIDAM. 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 shorter 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 [18], the authors present a power consumption model for IEEE 802.11g WLANs exploiting the power saving mode. The authors also show the power consumption model accuracy w.r.t. physical data measured from three popular mobile platforms, namely Maemo, Android and Symbian. The model aims at estimating the energy usage based on the flow characteristics which are easily available on all the platforms without modifications to low–level software components or hardware. The authors conclude that energy is wasted by the idle status between packet intervals, in line with our results.

A theoretical energy consumption model is also presented in [19]. In their work, the authors aims at assessing the amount of energy spent by an IEEE 802.11 station in order to transmit 1 MB of data. In contrast to our work, the scenario considered is based on an IEEE 802.11 network with N stations rather than 1 station. The authors assume that the power consumption depends of five physical radio states which are transmit, receive, listen, sleep, and off. The resulting model estimates the total energy (in Joules) consumed by a station in order to transmit/receive 1 MB of data based on (i) the energy consumed by the station in a specific state and (ii) the energy consumed by the station for transmitting/receiving 1 MB. Based on calculations, the author concludes that energy usage for the station grows approximately linearly with N and as N increases, the energy wastage also increases. Such behaviour is mainly due to passive overhearing of packets intended for another station. The power consumption is analysed only for a fixed amount of traffic.

The results reported by the authors in [15, 18, 16, 17, 19] provides us with insights on the power consumption of the single wireless interface 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 etc. On the other hand, in this work, we focus our attention on the overall energy expenditure in that it is useful to (i) model the real power consumption behaviour for WWAN and WLAN gateways and (ii) determine *where* and *how* the energy is wasted in wireless access network gateways.

In [20], the authors focus on the energy consumption of a wireless network as a whole. The authors present a joint experimental evaluation of energy consumption and performance in a IEEE 802.11–based WLAN using both 802.11a and 802.11n operating modes. The testbed consisted of an AP communicating with a single station. The power consumption measurements are taken using a suitable power meter and traffic is injected using the iperf traffic generator. The authors have exploited an application–level approach, varying the packet size and transmission rate and evaluating the energy consumption across a wide transmission rates. They also perform a comparison of the energy consumed by popular Internet applications such as YouTube and Skype. A metric for energy usage namely Effective Application–specific energy–usage (E_A) was defined, as follows: E_A =(mean power used during transmission of flow)$[J]$/(mean throughput of flow)$[Mb]$. The authors also observed that both the application's transmission rate and the packet size have an impact on power consumption when the device is acting as transmitter. In contrast to our work, the case when the device is acting as receiver in not considered, and no power consumption model is provided.

In [21], the authors present a power consumption model for wireless access networks and, in particular, for mobile WiMAX, HSPA and LTE networks. The scenario is a suburban area and a physical bit rate of 10 Mb/s is used. The authors compare wireless technologies for one SISO system and three MIMO systems considering a ranking of the wireless technologies as a function of their power consumption, range and energy efficiency. To compare the different technologies, the authors define models in order to calculate the total power consumption per user and the power consumption of the base station. In contrast to our work, the model provided by the authors is based in the amount of power consumed by each part of the system separately rather than the power consumption of the system as a whole. The authors also present relevant analysis to (i) determine which technology is the best solution for the specified area, and (ii) compare the power consumption of the wireless access networks with the power consumption of the wired access networks. The most relevant conclusion of the paper is that with a pre–defined bit rate of 10 Mbps, the mobile WiMAX is the most energy–efficient solution compared with HSPA and LTE. However, the investigation is limited to a fixed amount of traffic consequently the scenarios of low traffic load and very high traffic load are not considered leaving the question "how the traffic affects the power consumption of the WiMAX, HSPA and LTE devices" unanswered.

6. Conclusions and Future Work

In this work, we proposed a measurement–based methodology for characterizing the energy consumption behaviour of networked wireless devices. In particular, we focused our attention on WiFi and WiMAX access gateways and we derived their energy consumption figures as a function of (i) the traffic load, (ii) the modulation and coding schemes and (iii) the size of the datagrams used.

It is the authors' standpoint that a simple and accurate power consumption model, that can be easily plugged into typical network simulations tools such as ns3 or Omnet++, is essential to drive the design and development of energy aware network protocols and algorithms. Such an approach will pave the way to an *energy proportional networking* paradigm where wireless networks are designed in order to provide coverage and capacity but only when and where needed. Consequently, it is imperative to reformulate wireless communication system design in terms of energy efficiency by taking into consideration that "always available" does not mean "always on".

The main observations of this work are:

- The energy consumption of the wireless access network gateways depends on several factors, such as the amount of traffic, packet size, transmission power level, modulations and coding schemes and channel conditions.
- Large packets use energy more efficiently than small ones as well as high modulation and coding schemes are more energy efficient. Additionally, the

transmit power levels have very little effect on the power consumed by the wireless gateways.

- The power consumption follows a linear behaviour until the gateway reaches a saturation point.
- The energy consumed when the gateways are in idle mode is approximately the 80% of the maximum power consumption in saturation regime, in both the WiFi and WiMAX cases.

As it can be seen from the results, the challenges in wireless networking in terms of energy efficiency are (i) improving the energy efficiency of the wireless access network gateway when it is transmitting data as well as when it is in idle mode and (ii) introduce novel indicator of energy efficiency as part of the standard of each wireless technologies.

We are currently analysing the effects of traffic on power consumption in multi–hop wireless networks with multiple clients considering real application scenarios and traffic classes. We are also working toward a generalized model capable of taking into account traffic load *and* datagram size. Such model shall be able to provide a more precise prediction of the power consumed by a wireless gateway in realistic settings where multiple clients are transmitting and receiving different types of traffic.

Finally, we are currently developing a custom hardware and software solution for power consumption monitoring capable of addressing the limitations of the approach used in this work, namely low sampling rate (1 sample per second) and low resolution (0.1W). The new solution is expected to deliver increased insights into the behavior in saturation regime (higher resolution) and in the transition between linear and saturation regimes (higher sampling rate).

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