An Overview of Energy Consumption in IEEE 802.11 Access Networks

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Abstract. Nowadays users are expecting to have some type of Internet access, independently of the place where they are. This is indeed supported by the fact that wireless access networks are becoming available almost everywhere through different types of service providers. In this context, new applications have emerged with demanding requirements from the network, but also from the end-user device capabilities. Energy is the most prominent limitation of end user satisfaction within the anytime and anywhere connectivity paradigm. Since IEEE 802.11 is one of the most widely used wireless access technologies, this work provides insights on the study of its energy consumption properties, laying the grounds for further improvements towards enhanced battery lifetime. Experimental energy assessment results demonstrate the efficacy of power saving mechanisms and the relevance of wireless devices' state management.

Keywords: Energy · Wireless · IEEE 802.11 · Power saving · Testbed · Methodology

1 Introduction

The deployment of Next Generation Networks (NGN) [1] comprehends a considerable number of wireless devices moving with different speeds, patterns and communicating through various radio interfaces. The NGN heterogeneity together with the fast deployment of all the applications of cloud computing [2] and the usage of many applications as a service, bring many of the common optimization problems (e.g., handover) to the application level, where the network interface energy consumption can be one of the key decision factors. As a result, the energy consumption becomes an important end-user experience parameter, since end-users aim to maximize the device battery life [3].

Concerning the relationship between wireless access networks and energy consumption, although numerous efforts have been done to create low power radio technologies (e.g., IEEE 802.15.4 and ZigBee), IEEE 802.11 [4] stands out within the context of wireless access communications. With the proliferation of

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IEEE 802.11 ready devices, ranging from sensors to mobile phones or laptops, this technology emerges also as a strong candidate to support the upcoming Internet of Things (IoT) [5].

This chapter introduces the key energy saving protocols defined in the IEEE 802.11 standard and discusses the most relevant energy aware optimization solutions found in the literature. Additionally, an empirical and flexible energy consumption methodology [6] to be used within any USB network interface is discussed, and an experimental investigation using the mentioned methodology, in a real wireless testbed, is conducted. The obtained results show that considerable energy savings can be achieved with a proper management of the IEEE 802.11 most deployed power saving algorithm (i.e., the Power Save Mode).

The remainder of this chapter is structured as follows. Section 2 presents the standard power saving mechanisms defined in IEEE 802.11 and the most relevant related work concerning power saving optimization. A methodology to measure energy consumption in real environments is introduced in Sect. 3, followed by an experimental investigation on IEEE 802.11 energy consumption in Sect. 4. Finally, Sect. 5 presents the main conclusions and contributions of the chapter.

2 Related Work on Energy Consumption

This section introduces the standard power saving techniques defined in the IEEE 802.11 standard in Subsect. 2.1, followed by the discussion of the related work on power saving optimization in Subsect. 2.2.

2.1 IEEE 802.11 Power Saving

The IEEE 802.11 standard [4] defines a power management mode that allows the station (STA) to turn off both transmitter and receiver capabilities in order to save energy. The power management operations are distinct in infrastructure and ad-hoc modes. This work will discuss power management operations in the infrastructure mode, since it is the most widely used. The IEEE 802.11 power saving procedure was originally defined by IEEE 802.11-1997 and it is generically named Power Save Mode (PSM) (or Power Save Polling). Later, the IEEE 802.11e [7] introduced, together with many Quality of Service (QoS) related enhancements, two additional power save mechanisms, the unscheduled and the scheduled Automatic Power Save Delivery (APSD). More recently, IEEE 802.11n [8] also announced two contributions to the power save schemes, namely the Spatial Multiplexing (SM) Power Save and the Power Save Multi-Poll (PSMP) techniques. A brief description of these techniques will be performed in the next subsections.

Power Save Mode (PSM). In the Power Save Mode, the STA is able to stay disconnected from the network for a certain period. The STA must inform the AP about the current power management mode by defining the corresponding power management bits in the control frames. When the power saving is enabled for a certain STA, the AP buffers all the packets to that station. If the AP has packets buffered to a certain STA, it will send this information via the traffic indication map (TIM) within the Beacon frames. In PSM, a STA must wake-up regularly to receive the TIM information present in Beacon frames. Listening must be performed every N beacons, where $N \geq 1$. This period is named Listen Interval. By performing this action a STA, which does not have any data buffered on the AP, will be required to awake up recurrently, resulting in unnecessary energy consumption.

To receive the buffered frames in the AP, the STA must send back a Power Save Poll (PS-Poll) frame. When receiving a PS-Poll frame from a STA, the AP can acknowledge it first or send the queued data directly. In the first time, the AP sends only one frame to the STA and sets the "More Data" bit in the frame. When a STA receives a frame with the "More Data" information bit enabled, it must send back a PS-Poll to the AP.

The PSM usage allows the AP to buffer the packets to a certain STA when in sleep mode, however it does not have any mechanism to buffer packets from the STA to the AP. As a result, when an application wants to send a packet to the core network, it will not be queued and the sleep mode will be immediately interrupted.

Automatic Power Save Delivery (APSD). IEEE 802.11e introduces the QoS paradigm in the standard by defining two distinct QoS prioritization schemes, a distributed one defined by the Enhanced Distributed Channel Access (EDCA) channel access mode, and a centralized one defined by the Hybrid Coordination Function Controlled Channel Access (HCCA). Aligned with the QoS prioritization modes, a novel power save mode entitled Automatic Power Save Delivery (APSD) was specified. APSD introduces a concept named Service Period (SP), which is a time reserved for a certain STA to exchange data with the AP. With the employment of the SP concept, the STAs do not need to contend the channel, which results in less energy consumption.

The APSD can work in two distinct modes: scheduled (S-APSD) and unscheduled (U-APSD). The S-APSD is a centralized approach and can use both EDCA and HCCA as access policy, while U-APSD is a distributed method, which uses EDCA. The key point in the U-APSD design is the usage of the STA uplink frames as triggers to deliver the buffered data in the AP while the STA is sleeping. By employing such design, the STA has full control on the awake moment, as this instant does not need to be previously negotiated with the AP. Additionally, the STA does not need to listen regularly for the AP beacons. The U-APSD usage is specially indicated for bidirectional scenarios, but alternative schedule techniques might be used to trigger the AP buffered data. The AP can be triggered by receiving either a QoS Data frame or a QoS null frame (equivalent to the PS-Poll frame in the legacy PSM). For instance, an STA without uplink traffic to be transmitted to the network can use the QoS null frame to enquire the AP about remaining buffered frames.

The EDCA channel access method defines four Access Categories (AC), namely AC_VO, AC_VI, AC_BE and AC_BK, which represent voice, video, best effort and background applications, respectively. Each access category can be configured individually regarding buffered data triggering, which enables additional control concerning the STA energy management capabilities.

In the S-APSD centralized scheme the AP schedules the instants when each STA using S-APSD should awake-up to receive data. Both HCCA and EDCA can be used as channel access methods, nonetheless the implementation of the first is not mandatory in the standard. Additional information regarding APSD can be found in the literature [9].

Spatial Multiplexing (SM) Power Save. Spatial Multiplexing (SM) Power Save was introduced in IEEE 802.11n considering the energy demands usually associated with MIMO techniques, as the operation with multiple antennas in multiple channel requires extra power. The SM Power Save allows the STA to disconnect all but one of its radio frequency (RF) chains. The SM Power Save mode can operate into two distinct modes: static and dynamic.

When operating in the static mode, the IEEE 802.11 ready STA must disconnect all but one radio frequency (RF) chain, being comparable to a legacy IEEE 802.11g STA. The AP is notified that the STA will be operating in the static SM power save mode, requiring the AP to send only a single spatial stream to the client, until the client informs about the availability of additional RF chains. With the dynamic mode, the STA also keeps only one active RF chain, but in this mode the STA can promptly activate additionally RF chains when receiving a frame.

Power Save Multi-Poll. IEEE 802.11n also introduced another power save mechanism entitled Power Save Multi-Poll (PSMP). The PSMP aims to solve the issues related with channel contention needed in the ASPD method described above. In the ASDP, the STAs are required to send a PS-Poll frame (i.e., QoS null frame) to the AP in order to collect its buffered packets. The contention generated by these actions might be critical for network performance if many STA are requesting the buffered packets, resulting in lower channel efficiency.

In PSMP, the AP can schedule data transmission according to the application QoS constraints, namely delay and bandwidth. The AP will specify the scheduling for a certain STA downlink and uplink traffic in the beacon frames, allowing the STA to awake up only when it is able to transmit data. Although the PSMP mechanism can reduce contention of the polling mechanism and improve the channel efficiency, it is not as energy efficient as the U-ASPD, since the STA must awake up periodically to receive the schedule information contained in the beacons sent by the AP [10].

2.2 Power Save Mode Optimizations

When analyzing the state of the art concerning energy saving mechanisms for IEEE 802.11, there are several occasions to consider cooperation between energy aware mechanisms at lower (e.g. MAC layer aggregation) and upper layers. As an example, the cooperation between frame aggregation and the native power save mechanisms in the IEEE 802.11 standard, namely Power Save Mode (PSM) or Unscheduled Automatic Power Save Delivery (U-APSD), still is at an early research stage.

Trying to overcome this gap, Camps-Mur et al. [11] have studied the impact of IEEE 802.11 MAC layer aggregation on both PSM and U-APSD schemes. In practice, the main difference between the PSM and the U-APSD is related with the proactivity implemented in the U-APSD scheme. Unlike PSM, where only the Access Point (AP) is able to inform the station about pending packets, in the U-APSD the station can itself ask the AP for new downlink messages pending in the AP's queue. A complete discussion regarding the power saving features introduced in IEEE 802.11e is performed in [12].

Apart from the energy consumption study, Camps-Mur et al. work also focus on the IEEE 802.11 QoS mechanisms, aiming to study the employment of energy consumption optimization techniques while keeping the Quality of Service. As a result, two QoS sensitive applications (voice and video) were used together with two non-QoS sensitive applications (web browsing and FTP). The tested conditions encompass four different scenarios: IEEE 802.11 PSM (without aggregation), IEEE 802.11 PSM + ZFA (Zero Delay Frame Aggregation), U-APSD and U-APSD + ZFA. When analyzing the QoS sensitive applications without using aggregation, it is clear that U-APSD outperforms PSM. The main reason pointed by the authors is the smaller signaling overhead (e.g., polling or RTS/CTS handshake messages) generated by U-APSD. In PSM the polling is only performed by the AP to all the stations. As a result, all the stations aim to access to the medium immediately after receiving the polling information, resulting in a higher collision probability. If aggregation is used, due to decreasing signaling messages, IEEE 802.11 PSM achieves better results than U-APSD. The non-QoS sensitive applications have the same behavior as the QoS sensitive ones. The main reason for this performance, according to the authors' conclusions, is the channel efficiency improvement that is achieved in both cases. Nonetheless, a detailed investigation about the energy efficiency and the network delay introduced in both scenarios was not presented.

Namboodiri and Gao [13] proposed an algorithm, named GreenCall, centered on the U-APSD capabilities, aiming to conserve energy during VoIP calls. The algorithm goal is to minimize the energy consumption, while keeping VoIP quality within a certain acceptable level. In practice, GreenCall tries to increase the time spent by the network interface in the sleep state. Besides an exhaustive theoretical analysis, the proposal was also validated through real testbed assessment and trace-driven simulations. The empirical study encompasses real energy consumption equipment and Linux based end-user devices equipped with IEEE 802.11n interfaces (able to support the U-APSD power save scheme). As highlighted by the authors, a key point resulting from the performed empirical evaluation is that the increasing the delay does not necessarily represent substantial energy savings. However, the GreenCall algorithm achieved energy savings of 80 % for almost all the scenarios, while U-APSD can itself save around 40 % on the device energy consumption. Moreover, taking into account the typical voice call time during a day, a mobile device utilizing the GreeCall proposal can reduce device's overall energy consumption by around 20 %.

Lorchat et Noel [14] have proposed to use frame aggregation to save energy. The main motivation for the work was the possibility to send small packets together, which can bring considerable energy savings, since the Ethernet MTU is 1500 bytes and the IEEE 802.11b/g MTU is 2272 bytes (and up to 7935 bytes in IEEE 802.11n), the employment of aggregation techniques can be useful. The implementation of the proposed aggregation scheme, similar to the A-MSDU approach in the IEEE 802.11n standard, shows energy-efficient benefits when using the proposed frame aggregation technique, but also highlights some costs. The work discusses possible energy costs of extra CPU and memory needed to perform the aggregation. The authors argue that frame aggregation employment must take into account the current bit error rate in the channel, because retransmission might have higher energy cost than transmitting each single frame. However, aggregation can also bring some benefits for error-prone scenarios, since the number of frames being sent is lower and, as a result, the number of medium collisions will tend to be lower.

Lin et al. [15] studied the new A-MPDU aggregation mechanism of the IEEE 802.11n standard, aiming at proposing an optimal frame size adaptation algorithm. There is a clear tradeoff between throughput and delay performance when employing aggregation. The attained results show the positive impact in both throughput and delay when using the developed adaptive frame aggregation algorithm compared with fixed and random aggregation sizes. Moreover, the simulation outcomes also underline the strong correlation between the bit error rate and the optimal aggregation size. Other enhanced A-MSDU frame aggregation schemes for IEEE 802.11n was proposed by Saif et al. [16], aiming at reducing the aggregation headers originally proposed in the standard. The new aggregation scheme, called mA-MSDU, uses as main motivation the need to introduce an additional new header for each subframe sent when using the standard A-MSDU. Considering the presented results, the suggested dynamic selection of the aggregation method has some advantages when compared with the single usage of A-MSDU or A-MPDU, even employing dynamic aggregation size.

According to Palit et al. [17] the feasibility of employing packet aggregation is strongly related with the scenario and/or application. In order to understand the typical packet distribution in a smartphone data communication, the authors have analyzed the mobile device traffic. The main observations are that around 50 % of the packets have a size lower than 100 bytes and 40 % have an inter-arrival time of 0.5 ms or less. These conditions enable a good opportunity to do packet aggregation. Using this motivation, the authors have studied the impact of packet aggregation in the smartphones' energy consumption. The proposed aggregation scheme uses a buffering/queue system in the access point (AP) together with the Power Save Mode (PSM) on the client side. By default the last IEEE 802.11 standards (e.g. IEEE 802.11n) already defined a buffer at the access point, where all the packets destined to a mobile station in sleep mode are buffered and sent later. The proposed packet aggregation mechanism was named Low Energy Data-packet Aggregation Scheme (LEDAS). LEDAS receives packets from the different applications through the Logical Link Control (LLC) sub-layer and performs aggregation. For each packet, four additional bytes are used to ensure the correct packet de-aggregation. Although this is a simple aggregation mechanism, it has the advantage of being fully compliant with the IEEE 802.11 standard and with all other TCP/IP compliant transmission protocols (i.e., the solution is not dependent on the access technology). When employing the LEDAS module, the energy savings are between 40 and 60 %, but there is a huge increase in the mean packet delay. Moreover, the study does not take into account the possible bad conditions (e.g., collisions) in the access channel, which can disturb even more the delay.

3 A Flexible Methodology to Measure Energy Consumption in Real Environments

This section describes a flexible methodology to measure energy consumption in real environments. Subsection 3.1 introduces the methodology and explains the underlying designed options, followed by a discussion and comparison with the most relevant work regarding energy assessment in testbeds in Subsect. 3.2.

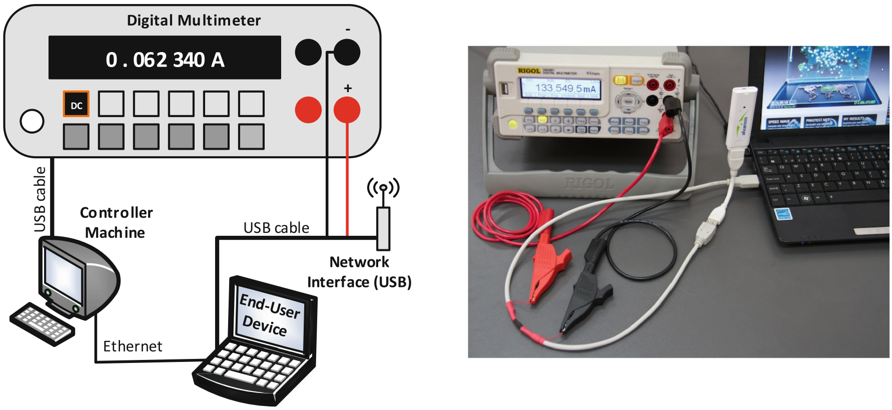
3.1 Methodology

This energy measurement methodology, proposed in [6], was designed to fulfill a set of requirements concerning the assessment of energy consumption in real system equipment, as follows:

- *Testbed measurement:* it is important to perform testbed assessments in order to accurately measure the energy impact in real life systems;
- *High precision measurements:* to guarantee a good accuracy of testbed energy measurements it is vital to use a hardware capable to support multiple samples per second, since energy in small devices (i.e., network interface) tends to have slight variations over time;
- *Independent network interface assessment:* it is essential to limit the measurements solely to the network interface, which allows a proper investigation of the impact of a certain action in the wireless interface energy demands;
- *Technology states evaluation:* it is crucial to enable the possibility to study the different states used in the each network technology, since their correct management might lead to considerable energy savings.

Figure 1 depicts the energy testbed setup, designed to accomplish the defined prerequisites.

Apart from the “End-User Device”, the energy measurement setup encompasses a “Controller Machine” and a high-precision “Digital Multimeter”.



(a) Energy measurement diagram (b) Digital multimeter usage

Fig. 1. Energy measurement setup (Adapted from [6])

The multimeter is a Rigol DM3061, which supports sampling rate of 50.000 samples/second. Since this unit implements the Universal Serial Bus Test and Measurement Class Specification (USBTMC) standard interface and is compliant with the Standard Commands for Programmable Instruments (SCPI) commands (IEEE 488.2 [18]), it is possible to control the multimeter with a standard machine. The "Controller Machine" works as management unit, being responsible to initiate, stop, and collect all the energy related data. This unit can also be connected to the "End-user Device" via Ethernet, enabling a fast and reliable point to control the application level experiments.

The usage of an external USB network interface, ensures the possibility to accurately measure the energy consumed by the network card only, as desired. Moreover, this approach allows the described methodology to be used within any USB network card, namely IEEE 802.11, Bluetooth, or 4G Long Term Evolution (LTE).

As the energy measurements will be done by collecting the current values only, the USB cable was intercepted in the common-collector voltage (VCC) cable (i.e., +5 VDC), as shown in Fig. 1b. Nevertheless, others in literature [19,20] highlight as a main issue concerning the energy measurement in testbeds, the need to provide a stable continuous voltage to the system. In the preliminary tests performed, the USB network interface was directly connected to the "End-User Device" and the impact on the voltage drawn was noticeable. To overcome this limitation, the USB network interface was connected to an external AC powered USB HUB (not illustrated in the figure), able to give continuous stable power to the USB network card. The analysis performed concerning voltage drawn when employing the external USB HUB has shown voltage drops always lower than 1 % of the total employed voltage, which is negligible in the overall system analysis.

3.2 Related Work on Energy Consumption Measurement

The research question regarding energy-efficient communication is strongly related to the hardware energy consumption itself, which has a significant impact in the overall results and various studies in the literature addressed the problem by measuring total energy consumption of the end-user device. Although these techniques can be a feasible approach to analyze these systems when compared with the challenge to perform accurate theoretical models for simulation, they do not measure accurately the energy consumed only by the network interface.

Balasubramanian et al. [21] have studied energy consumption in mobile phones with multiple network interfaces, where the main goal was to evaluate the energy-efficiency of 3G, GSM and IEEE 802.11. Their main contribution is the development of a protocol that reduces energy consumption of applications by scheduling the transmission, named TailEnder. Wang and Manner [19] used an Android based phone, and tested energy consumption using Enhanced Data rates for GSM Evolution (EDGE), High Speed Packet Access (HSPA) and IEEE 802.11 wireless technologies. The impact of packet size and packet rate were addressed in the study, but only the total energy consumed by the device was measured, which is a clear drawback when trying to optimize network protocols or applications. Additionally, the study was done using only a specific phone model, which does not exclude the possibility of direct impact of the phone board implementation on the measured energy values.

Rice and Hay [20] proposed a methodology to measure energy consumption of mobile phones IEEE 802.11 interface, by replacing the battery with a personalized plastic battery holder, which allows an accurate measurement within the phone real energy circuit. To avoid the rapid energy consumption changes caused by the high-frequency components of the mobile phones, the measurement system employs a high-precision resistor. While this work is able to measure accurately the mobile phone energy consumption behavior, it is not able to perform an accurate evaluation of the IEEE 802.11 impact on the energy consumed by the mobile phone, since the energy measurements report to the overall mobile phone energy consumption.

The presented methodology enables a flexible energy consumption assessment technique, which can be employed on all USB network interfaces, but also with mobile phones or other devices. As a high-precision equipment was employed, this methodology can also be used to study and improve network or MAC layer level protocols, aiming at saving energy in the IEEE 802.11 interface. Additionally, it can also help to fill the existing gap regarding the testbed experimental evaluation of new wireless access networks, such as the IEEE 802.11ac or 4G Long Term Evolution technology.

4 Investigating Energy Consumption in Wireless Access Networks

This section describes experimental investigations concerning the energy consumption of wireless access networks, using IEEE 802.11 as case study. Nevertheless, as already described in Sect. 3, this methodology can be employed with any USB network card.

The main objective of this assessment is to show how to perform an empirical energy assessment in a real wireless access network. Additionally, by using the presented energy evaluation methodology, a twofold investigation is performed. First, the impact of wireless states management in the network interface energy consumption is discussed, followed by some insights concerning relationship between application design and its energy demands.

4.1 IEEE 802.11 Access Network Testbed and Scenarios

This subsection presents the University of Coimbra IEEE 802.11 testbed. The testbed is composed by a IEEE 802.11n access point, the Cisco Linksys E4200, and by two distinct USB network interfaces: the Cisco Linksys AE1000 dual-band (2.4 GHz and 5 GHz) and the Linksys TP-LINK WN-721n single-band (2.4 GHz). As the energy measurement testbed is fully independent of the employed network interface, it will be possible to use any other USB network interface. The Cisco Linksys E4200 access point is dual-band (2.4 GHz and 5 GHz) and supports Multiple-Input and Multiple-Output (MIMO) 3x3 (6 internal antennas).

Figure 2 depicts the testbed architecture, which encompasses the previously described *Access Network*, and a *Core Network* responsible to manage all the network services and servers.

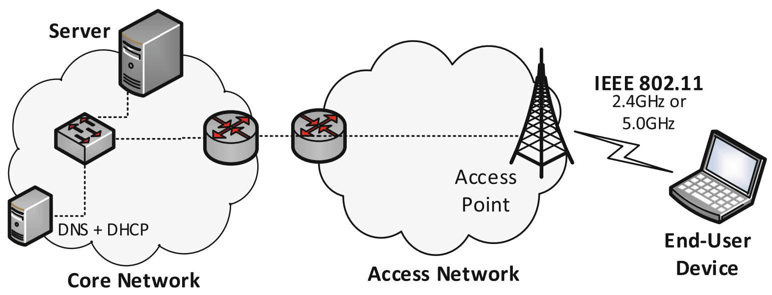


Fig. 2. IEEE 802.11 testbed architecture

The "End-User Device" employed in this setup was an Asus EEE 1001PX-H netbook (CPU: Intel Atom N450 1.66 GHz; RAM: 2 Gb), while the "Server" entity, in the *Core Network*, was running in a HP ProLiant DL320 G5p server (CPU: Intel Xeon X3210 2.16 GHz; RAM: 4 Gb). Both "End-User Device" and "Server" were running Debian 7 with kernel 3.2.0-4, respectively, the 32 and the 64 bits versions. The traffic referred as "receiving" has "Server" as source and "End-User Device" as destination, while the "transmitting" represents the traffic sent from the "End-User Device" to the "Server".

The results presented in the next subsections were obtained using the methodology presented in Sect. 3, and include 20 runs for each test setup with a confidence interval of 95 %. The tests were done in three distinct wireless access scenarios, as depicted in Table 1.

Table 1. Experimental evaluation scenarios

Name	Description
NetworkCard-A 2.4GHz	Tests performed using in the Linksys TP-LINK WN-721n in the 2.4 GHz frequency (the only supported)
NetworkCard-B 2.4GHz	Tests with the Cisco Linksys AE1000 dual-band network card, using the 2.4 GHz frequency
NetworkCard-B 5.0GHz	Tests employing the Cisco Linksys AE1000 dual-band, using the 5.0 GHz frequency

Each test performed has a total duration of 80 s, whereas the first and the last 10 s of the experiment were not considered, in order to avoid the impact of the energy consumed by the User Datagram Protocol (UDP) socket establishment and release procedures. As a result, all the energy results presented only consider the energy consumed during the 60 s.

4.2 Investigating Energy Consumption of IEEE 802.11 States

This section discusses the impact of each state of the network interface's overall energy consumption. The IEEE 802.11 relevant PHY layer states, which might have impact on the network card energy consumption, are defined as follows:

- ***Disconnected/Init:*** network interface is disconnected from the network, i.e. the radio is switched-off;
- ***Idle:*** network interface is associated with the access point, but no data is being transferred;
- ***Sleep:*** network interface is in a *doze state*. In this state it is not possible to send or receive IP traffic, but the station remains associated with the network. This state was studied by enabling the IEEE 802.11 Power Save Mode, discussed in Sect. 2.1;
- ***Transmitting (TX):*** network interface is sending IP traffic to the network;
- ***Receiving (RX):*** network interface is receiving IP traffic from the network.

The described IEEE 802.11 states transitions diagram is illustrated in Fig. 3.

Figure 4 shows the average power (in milliwatt) used by the three scenarios defined (see Table 1) in *DISCONNECTED*, *IDLE* and *SLEEP* states. As energy consumption of *TX* and *RX* states is affected by the traffic configuration and pattern, these states will be further discussed.

When comparing the network cards tested, it can be observed that the *NetworkCard-A 2.4GHz* average power in the *DISCONNECTED* state is higher

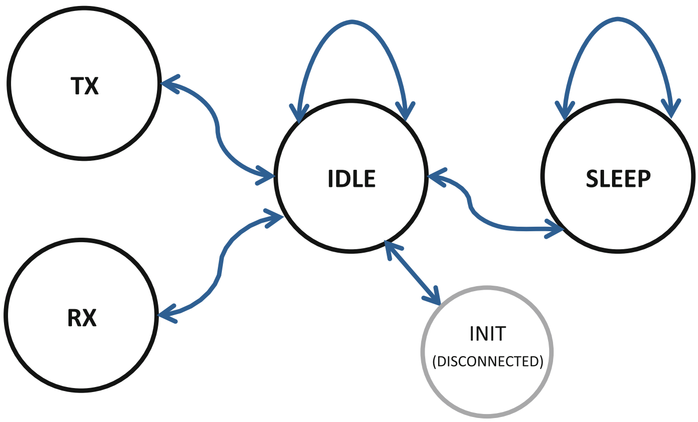


Fig. 3. Simplified IEEE 802.11 states diagram

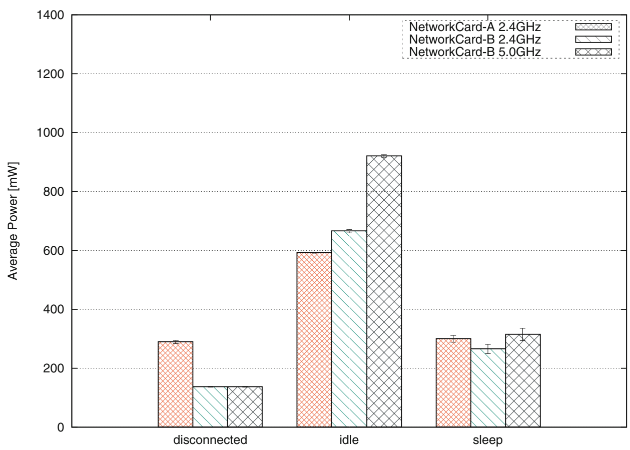


Fig. 4. Average power in disconnected, idle and sleep states

than both *NetworkCard-B 2.4GHz* and *NetworkCard-B 5.0GHz*. The average power in this state is the same for *NetworkCard-B 2.4GHz* and *NetworkCard-B 5.0GHz*, since it is the same USB network card.

In *IDLE* state the behavior is slightly different. The *NetworkCard-B 5.0GHz* needs more energy to support this state, when compared with the other two scenarios. While the *NetworkCard-A 2.4GHz* spends roughly twice more energy in *IDLE* state when compared with *DISCONNECTED* state, the *NetworkCard-B 2.4GHz* and *NetworkCard-A 5.0GHz* need, respectively, about 5 and 7 times more energy.

This behavior is mainly related with the network interface internal design. In this particular case study, it might be related with the supported MIMO type, since *NetworkCard-A* only supports 1x1:1 MIMO (1 internal antenna) and *NetworkCard-B* can benefit from the usage of 2x2:2 MIMO (2 internal antennas). Others in literature have shown the MIMO impact on the energy consumption [22].

Comparing with the *IDLE* state, the *SLEEP* state usage is able to achieve energy savings of around 50 %, 60 % and 65 %, respectively, for *NetworkCard-A 2.4GHz*, *NetworkCard-B 2.4GHz* and *NetworkCard-B 5.0GHz* scenarios.

Although, due to the internal components design, there might be absolute power consumption differences in similar states, one can observe that the power consumption trend among the three depicted states is similar for all the scenarios. This standard energy consumption behavior is extremely relevant, since there are clear energy benefits in keeping the interface as long as possible in the *SLEEP* state, as highlighted during the related work discussion in Sect. 2.

4.3 Investigating the Power Saving Effectiveness

This subsection has two goals. First, it aims at showing the impact of IEEE 802.11 Power Save Mode usage in a real scenario. Second, it explores power consumption during state transition, introduced in the previous subsection, by establishing a set of actions aiming at forcing the most common transitions.

The transition between states depends on the actual network state at IP level. Therefore, a sequence of actions has been defined to study those transitions. Table 2 shows the defined action sequences, including the possible states and the start/end time (in seconds) for each action.

Table 2. Action sequence for testing states transitions

#	Possible states	Action	Time	
			Start	End
1	*DISCONNECTED*	Wait for 4 s	0	0
2	*IDLE, TX, RX*	Connect to the network	4	*
3	*IDLE, SLEEP*	Wait for 10 s	4	14
4	*TX, RX*	Ping “Server” during 10 s	14	24
5	*IDLE, SLEEP*	Wait for 5 s	24	29
6	*IDLE, TX, RX*	Disconnect from the network	29	*
7	*DISCONNECTED*	-	29	35

*Action includes connecting or disconnecting times, which might be slightly variable

Figure 5 depicts the power (in milliwatt) over time (seconds) for the *NetworkCard-A 2.4GHz* scenario, with the IEEE 802.11 Power Save Mode disabled, during the execution of the previous presented sequence. As *NetworkCard-B 2.4GHz* and *NetworkCard-B 5.0GHz* scenarios have similar behavior, only this scenario will be illustrated. To allow enough precision to depict all the small power fluctuations, this study was performed with a rate of 50.000 samples per second. However, due to the very small power fluctuations captured, the usage of a smoothing technique to depict the values was required. As a result, the power values presented in the following figures are using a moving average of 1000 samples.

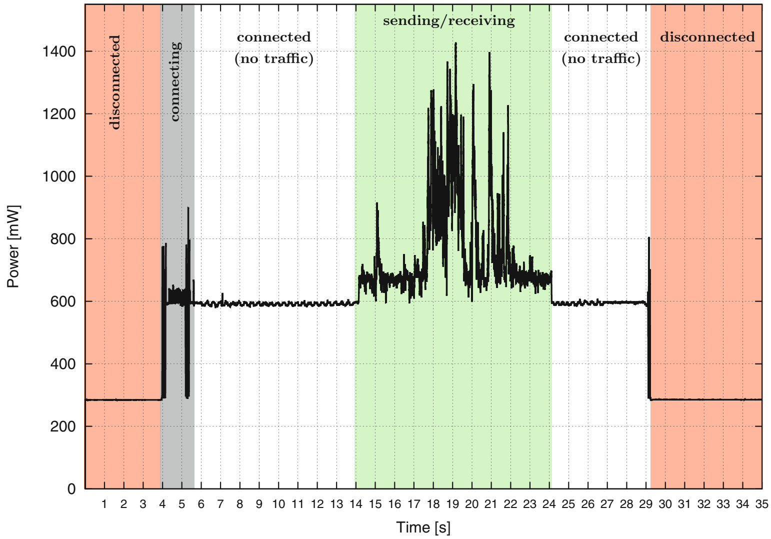


Fig. 5. *NetworkCard-A 2.4GHz* states transition with power saving disabled

The relationship between the network card interface state and the power consumption is clearly visible. When connecting to the network ($time = 4$ s, from now on $t = time$) the power consumption has some fluctuations, mainly because there is information being sent and received from the network. The power consumption becomes stable since no traffic has to be sent or received ($t \geq 5.5$ s and $t \leq 14$ s). During this period, the network card is in the *IDLE* state. Since power saving mode is disabled in this scenario, it not possible to change to the *SLEEP* state.

The power cost of sending and receiving IP traffic ($t \geq 14$ s and $t \leq 24$ s) is evidently outlined. Here, the power fluctuations are bigger since the usage of the Internet Control Message Protocol (ICMP) (using the *ping* tool) enables bidirectional traffic in the channel, and several state transitions turn up in short time intervals.

When the traffic transmission ends ($t = 24$ s) the network card backs into *IDLE* state, until it disconnects again from the network after 5 s ($t = 29$ s).

Figure 6 also shows the power (in milliwatt) over time (seconds) for the same sequence and scenario (*NetworkCard-A 2.4GHz*), but with the IEEE 802.11 Power Save Mode enabled.

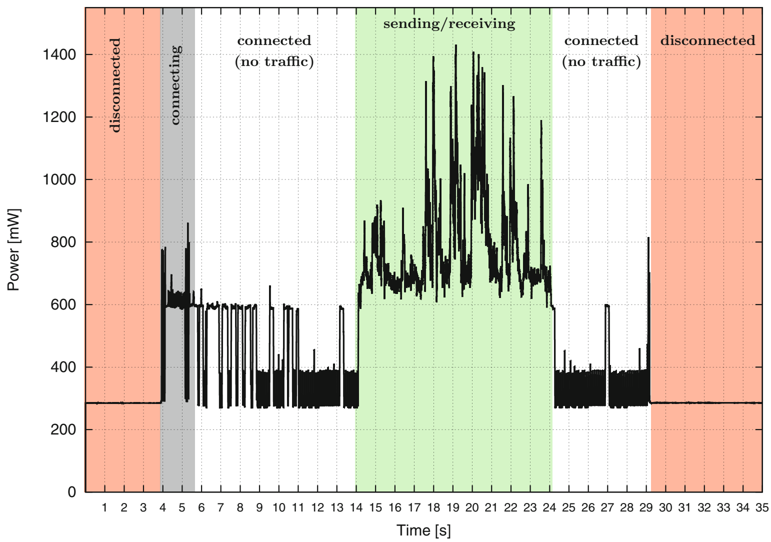


Fig. 6. *NetworkCard-A 2.4GHz* states transition with power saving enabled

The power consumption behavior is very similar to the one showed in the case where power saving mode is disabled, unless when there is no IP traffic to be sent or received. In this case, the system implementation of IEEE 802.11 Power Save Mode allows the network interface to change the state from *IDLE* to *SLEEP*. Such state changes have a direct impact in power consumption, as depicted in the lower power consumed in both ($t \geq 5.5$ s and $t \leq 14$ s) and ($t \geq 24$ s and $t \leq 29$ s) intervals.

Even though this representation gives a good overview of the power consumption behavior over time, it is not able to show the fast power fluctuations captured by the used high precision measurement technique. Therefore, it is important to look in the available data with more detail.

Figure 7 zooms four key actions of the data depicted in Fig. 6, namely the network connection, the starting of data transmission/reception, the ending of transmission/reception, and the disconnection from the network.

Figure 7a depicts the connecting phase, starting in ($t = 4$ s). The higher power needed by the network interface to enter and setup the wireless network can be observed. The power consumption increasing of almost 2 times when changing from *SLEEP* to *RX* and/or *TX* state is illustrated in Fig. 7b. Figure 7c shows the end of transmission/reception and illustrates power consumption reduction when IP transmission is finished ($t = 24$ s).

Unlike in the *DISCONNECTED* state, when a network interface is in the *SLEEP* state, power fluctuations occur regularly. The regular power fluctuations in *SLEEP* state are caused by the IEEE 802.11 Power Save Mode (PSM) protocol design (see Sect. 2.1). When operating in PSM, the device needs to regularly wake up for receiving the *Beacon Frames*, which allow the device to be informed of

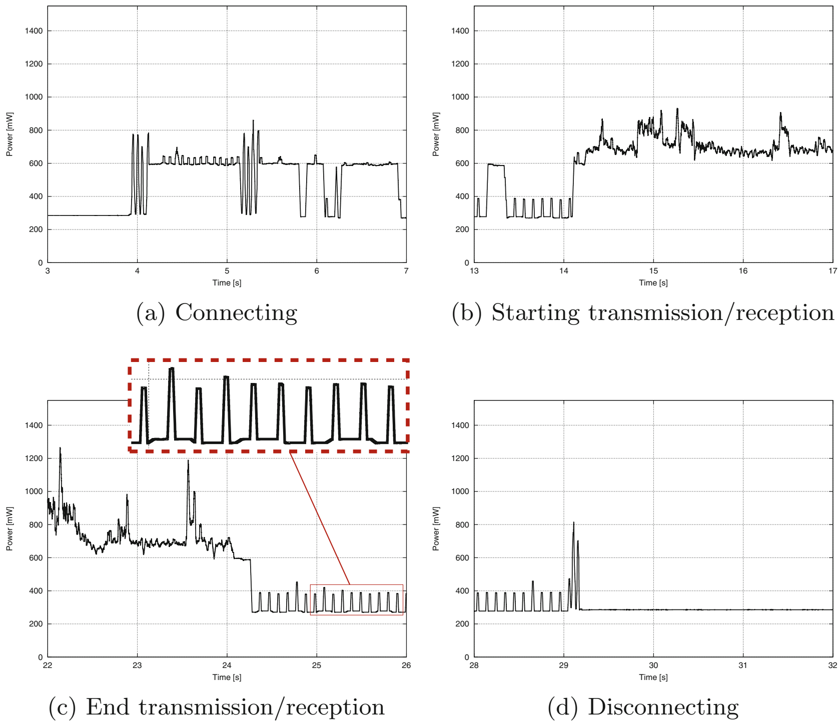


Fig. 7. Detailed state transitions when employing *NetworkCard-A 2.4GHz* with power saving enabled

pending data at the Access Point. Such fact produces the power consumption behavior depicted in Fig. 7c zoom box (red dashed). This zoom box in the subfigure represents 1 s of duration, and 10 power peaks related with *Beacon Frames* reception can be observed. As the beacon interval in the used Access Point is configured to 100 ms, there will be 10 beacons to be received each second, as depicted.

Figure 7d illustrates the network disconnecting phase, starting in ($t = 29$ s). The higher power consumption requested upon disconnecting is mainly related with the extra power needed to change to such state, but also to send disconnecting information to the network (e.g., releasing IP address). Again, in the ($t \geq 26$ s and $t \leq 27$ s) interval, the *Beacon Frames* reception impact on power consumption in the *SLEEP* state can be perceived.

The possibility to investigate the states' energy consumption with this detail creates a good asset to employ this methodology in the validation of novel energy-aware protocols or applications.

4.4 Investigating the Packet Size Impact

This subsection investigates the packet size impact on the energy consumption. The tests were done employing Constant Bit Rate (CBR) with a fixed sending of 100 packets per second. As explained before, each test has a total duration of 80 s, but the first and the last 10 s of each experiment were not considered aiming to avoid the impact of upper layer protocol establishment and release procedures in the energy consumption.

Figure 8 shows the energy consumption in Joule (y-axis) needed to transfer 6000 packets (i.e., 100 packet per seconds during 60 s). The studied packet sizes range from 64 byte to 1400 byte (value near the Maximum Transmission Unit (MTU) for Ethernet), as depicted on the x-axis. Additionally, each scenario was also tested independently in *RX* and *TX* states.

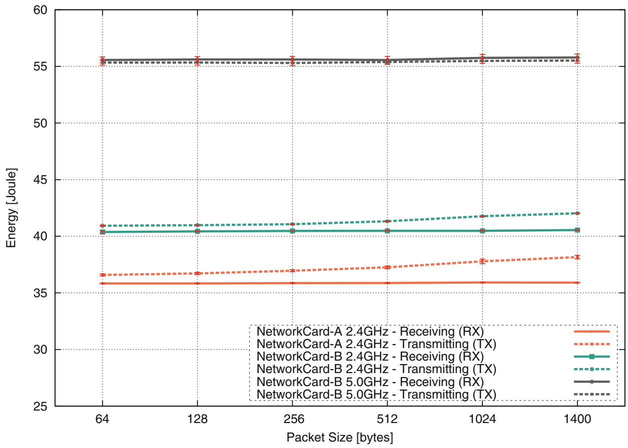


Fig. 8. Energy consumption with distinct packet sizes

The obtained results for *NetworkCard-A 2.4GHz* and *NetworkCard-B 2.4GHz* scenarios show a non negligible energy consumption difference between the energy needed to transfer the same amount of information in the *TX* and the *RX* states. Nonetheless, the same relationship can not be verified for the *NetworkCard-B 5.0GHz* case. In this later scenario, the energy consumption to send and receive the total 6000 packets is similar in the *TX* and *RX* states. Yet, by analyzing the error bars in this scenario, it is possible to notice a higher uncertainly in the *NetworkCard-B 5.0GHz* scenario when compared with the others.

Apart from the performance comparison between the distinct network cards, it is also important to assess the impact of packet size in the energy consumption. Such study is commonly performed by analyzing the energy cost per bit transmitted [23].

Figure 9 depicts average energy cost per bit transmitted/received in milliJoule (y-axis) for the tested packet sizes using the *NetworkCard-A 2.4GHz* scenario. Again, as the other scenarios have similar related behavior only this one will be depicted.

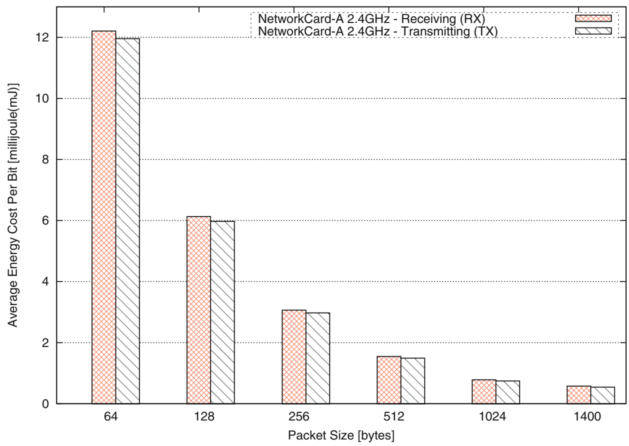


Fig. 9. Average energy cost per bit with distinct packet sizes

The cost of transmitting a byte using small packets (e.g. 64 byte packet size) is clearly higher than transmitting packets near the Maximum Transmission Unit (MTU) size. For instance, in the depicted *NetworkCard-A 2.4GHz* scenario, each bit received when using 64 byte packet size has a cost of 12.19 mJ, while using a 128 byte packet size the cost is roughly a half (i.e., 6.12 mJ). Moreover, using packets with 1400 byte, the cost of each byte received is only 0.58 mJ. As expected, according to the values presented in Fig. 8, the energy consumption per bit when transmitting (TX) and receiving (RX) the data is very low (around 0.04 mJ).

By analyzing these results, the importance of the packet size on the energy consumption becomes clear. For instance, the typical small packet size applications like Voice Over IP (VoIP) are potential energy demanding applications, whereas the bulk data transfer applications should be more energy efficient, since typically larger packets are used. Concerning the importance of the aggregation others in literature, e.g., [14], have studied the benefits of employing aggregation techniques.

5 Conclusions

Energy efficiency in wireless access networks plays an important role in the end-user quality expectations. The mostly deployed wireless access network standard, IEEE 802.11, has introduced several power saving optimization mechanisms aiming to maximize the end-users devices' battery lifetime. Furthermore, others in literature have proposed optimizations to the standard mechanisms, ranging from generic MAC layer optimizations to the ones fully dependent on the application. This chapter has introduced both the standard mechanisms and the most relevant related work concerning power saving mode optimization in IEEE 802.11 networks.

Additionally, a technology independent and flexible empirical methodology to assess energy consumption in all USB network cards has been presented. The experimental investigation conducted using the mentioned methodology in a real IEEE 802.11 testbed highlighted the energy benefits of using power saving modes correctly. By observing the attained results, it was possible to conclude that the correct management of the wireless states might lead to energy savings up to 65 %. The gathered data also depicted the application level designed impact on the energy consumption, namely by adjusting the packet size or using aggregation techniques.

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References

1. Lee, C., Knight, D.: Realization of the next-generation network. IEEE Commun. Mag. **43**(10), 34–41 (2005)
2. Jamshidi, P., Ahmad, A., Pahl, C.: Cloud migration research: a systematic review. IEEE Trans. Cloud Comput. **1**(2), 142–157 (2013)
3. Chen, Y., Zhang, S., Xu, S., Li, G.: Fundamental trade-offs on green wireless networks. IEEE Commun. Mag. **49**(6), 30–37 (2011)
4. IEEE: Ieee std 802.11-2012 (revision of ieee std 802.11-2007). IEEE, pp. 1–2793 (2012)
5. Tozlu, S., Senel, M., Mao, W., Keshavarzian, A.: Wi-fi enabled sensors for internet of things: a practical approach. IEEE Commun. Mag. **50**(6), 134–143 (2012)
6. Bernardo, V., Curado, M., Staub, T., Braun, T.: Towards energy consumption measurement in a cloud computing wireless testbed. In: 2011 1st International Symposium on Network Cloud Computing and Applications (NCCA), pp. 91–98 (2011)
7. IEEE: Ieee std 802.11e-2005 (amendment to ieee std 802.11, 1999 edition (reaff 2003). IEEE, 0_1-189 (2005)
8. IEEE: Ieee std 802.11n-2009 (amendment to ieee std 802.11-2007 as amended by ieee std 802.11k-2008, ieee std 802.11r-2008, ieee std 802.11y-2008, and ieee std 802.11w-2009). IEEE, pp. 1–565, October 2009
9. Prez-Costa, X., Camps-Mur, D., Vidal, A.: On distributed power saving mechanisms of wireless lans 802.11e u-apsd vs 802.11 power save mode. Comput. Netw. **51**(9), 2326–2344 (2007)
10. CISCO: 802.11n: The next generation of wirelessperformance. White paper, CISCO (2011)

11. Camps-Mur, D., Gomony, M.D., PéRez-Costa, X., Sallent-Ribes, S.: Leveraging 802.11n frame aggregation to enhance qos and power consumption in wi-fi networks. Comput. Netw. **56**(12), 2896–2911 (2012)
12. Perez-Costa, X., Camps-Mur, D.: Ieee 802.11e qos and power saving features overview and analysis of combined performance [accepted from open call]. IEEE Wirel. Commun. **17**(4), 88–96 (2010)
13. Namboodiri, V., Gao, L.: Energy-efficient voip over wireless lans. IEEE Trans. Mob. Comput. **9**(4), 566–581 (2010)
14. Lorchat, J., Noel, T.: Energy saving in ieee 802.11 communications using frame aggregation. In: 2003 GLOBECOM '03 Global Telecommunications Conference, IEEE. vol. 3, pp. 1296–1300, December 2003
15. Lin, Y., Wong, V.: Wsn01-1: frame aggregation and optimal frame size adaptation for ieee 802.11n wlans. In: 2006 GLOBECOM '06 Global Telecommunications Conference, IEEE, pp. 1–6 November 2006
16. Saif, A., Othman, M., Subramaniam, S., Hamid, N.: An enhanced a-msdu frame aggregation scheme for 802.11n wireless networks. Wirel. Pers. Commun. **66**(4), 683–706 (2012)
17. Palit, R., Naik, K., Singh, A.: Impact of packet aggregation on energy consumption in smartphones. In: 2011 7th International Conference on Wireless Communications and Mobile Computing (IWCMC), pp. 589–594, July 2011
18. IEEE: Standard digital interface for programmable instrumentation - part 2: codes, formats, protocols and common commands (adoption of (ieee std 488.2-1992). IEC 60488–2 First edition 2004–05; IEEE 488.2, pp. 1–261 (2004)
19. Wang, L., Manner, J.: Energy consumption analysis of wlan, 2g and 3g interfaces. In: 2010 IEEE/ACM International Conference on Green Computing and Communications (GreenCom), Cyber, Physical and Social Computing (CPSCom), pp. 300–307, December 2010
20. Rice, A., Hay, S.: Measuring mobile phone energy consumption for 802.11 wireless networking. Pervasive Mob. Comput. **6**, 593–606 (2010)
21. Balasubramanian, N., Balasubramanian, A., Venkataramani, A.: Energy consumption in mobile phones: a measurement study and implications for network applications. In: Proceedings of the 9th ACM SIGCOMM Conference on Internet Measurement, IMC '09, New York, NY, USA, ACM, pp. 280–293 (2009)
22. Li, G., Xu, Z., Xiong, C., Yang, C., Zhang, S., Chen, Y., Xu, S.: Energy-efficient wireless communications: tutorial, survey, and open issues. IEEE Wirel. Commun. **18**(6), 28–35 (2011)
23. INFSO-ICT-247733 EARTH (Editors: Jose Alonso-Rubio, Pter Fazekas, Per Skillermark, Wieslawa Wajda): Most Suitable Efficiency Metrics And Utility Functions. INFSO-ICT-247733 EARTH - Delivery D2.4, pp. 1–55 (2012)