Greening Wireless Communications: Status and Future Directions

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Abstract

In recent years, concerns on energy consumption and greenhouse pollution due to the operation of wireless devices have triggered a vast amount of research work on the so called *green* wireless technologies, leading to new, energy-aware proposals. Even for the case of battery powered devices, where energy conservation is a key design goal, new approaches have been proposed, based on a better understanding of the cost-performance trade-offs introduced by energy efficient operation, while increasingly focusing on emerging communication technologies, e.g., body sensor networks, MIMO, or LTE. This paper presents a survey of the recent proposals for green wireless communications, with a view to understanding the most relevant sources of inefficient energy consumption and how these are tackled by current solutions. We introduce a classification of the existing mechanisms based on their *operational time-scale*, discuss the most important techniques employed to date from this perspective, analyze the employed evaluation methodologies and undertake a quantitative comparison of their performance gains. Following this analysis, we identify the key challenges yet to be addressed by the research community, as well as several possible future directions towards greener communications.

Keywords: Wireless Networks, Energy Efficiency, Power Consumption

1. Introduction

The number of wireless devices has increased tremendously in the recent years, with applications ranging from the now popular mobile data services to video streaming, surveillance, smart homes and healthcare monitoring. Further, recent forecasts envision the number of mobile-connected devices will exceed the world's population by the end of this year, while the mobile data traffic will increase 18-fold in the next 5 years [1]. Under such predictions, energy expenditure at both infrastructure side and within battery powered wireless nodes is becoming a major concern for telcos, industry and scientific community. As a consequence, increasing effort is devoted to designing solutions that improve the energy efficiency of sensors, portable computers, mobile phones, access points and base stations.

Given the rapid and heterogeneous development of wireless technologies, the mechanisms proposed for reducing energy consumption target different scenarios, from cellular network topologies to personal area networks, while the limitations of the existing architectures have been tackled at different layers of the protocol stacks running on wireless devices. Due to the vast number of research papers on this topic, recent reviews attempt to classify the existing proposals in order to identify their advantages, limitations and potential improvements within specific technologies. Towards this end, Jones *et al.* provided one of the first comprehensive summary of mechanisms that address energy efficiency within different components of the networking stack [2], while more re-

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cently a number of papers surveyed such efforts in cellular, WiFi and sensor networks. For example, Mancuso *et al.* investigated proposals that reduce the energy demand and operational costs in cellular networks [3], a schematic description of green approaches to mobile cellular networking has recently appeared in [4], power saving techniques for wireless local area network topologies are discussed in [5] and [6], while sources of energy consumption and directions towards energy conservation in wireless sensor networks are systematically classified in [7].

However, none of the existing surveys provides a comprehensive vision of the current state-of-the art mechanisms for green wireless communications; indeed, no previous study has tackled a classification of energy-aware schemes from a broad perspective, in order to compare performance across technologies and therefore provide an outlook for future research directions, which shall take into account the increasingly-heterogeneous wireless environment. In contrast, here we provide (among other contributions) a *qualitative* and a *quantitative* comparison of existing green mechanisms, by thoroughly reviewing previous work and identifying, when possible, both the network load under which a mechanism is effective and the savings introduced.[1] We conduct a comprehensive analysis of the proposals for green wireless networking, with the goal of understanding the benefits and shortcomings of existing mechanisms. The scope of our study spans across personal area networks (PANs), wireless local area networks (WLANs), and wireless metropolitan area networks (WMANs). More specifically, for the case of WMANs we restrict ourselves to works that target 3G or WiMAX cellular networks, as well as homogeneous multi-hop 802.11 WiFi deployments; for the case of WLANs we stick to 802.11-based enhancements, while for the case of PANs we select a few representative sensor and body area deployments.

[1]Given the lack of standardized benchmarks and scenario definitions, which prevents the repeatability of previous works, the numerical results from our analysis should be taken with a *grain of salt*.

The paper is structured as follows. We first identify, in Section 2, the key sources of energy consumption at different network entities and at different layers of the nodes' stacks, and discuss how those are tackled in different technologies, with a view to understanding their inherent challenges and benefits. In Section 3, we present a general classification of the existing proposals based on their operational time-scale, to clearly identify similarities and differences between the mechanisms considered. Following this analysis, in Section 4, we perform a three-fold comparison of these mechanisms based on their performance evaluation methodology, energy savings introduced and distribution of research efforts across time-scales. Finally, we discuss several promising research directions in Section 5 and summarize our review in Section 6.

2. Identifying the Causes of Inefficient Energy Consumption

To design solutions that improve energy efficiency in wireless networks, it is essential to first identify the main sources of energy consumption in wireless devices, and understand how wireless protocols and operations affect the energy demand. With this rationale in mind, we proceed with the analysis of power consumption in base stations, mobile devices, and short-range wireless devices, according to the figures reported in the literature (see Table 1). Then, we identify which are the elements and mechanisms responsible for inefficient energy utilization (see Table 2).

This analysis will prove indispensable in assessing the techniques employed by the proposals we review in this survey, which specifically address one or more of the inefficiencies we point out in this section, in order to increase network lifetime, reduce operational costs or improve the ecological footprint of such networks.

Since we consider technologies developed for different network scopes, we start by analyzing the relative impact of the use of the wireless interface for each type of network deployment. More specifically, in Table 1 we summarize the typical energy consumption values for different types of

Table 1: Relative consumption of the wireless interface per device type

Device	Scope	Power Consumption (W)	
		Total	Wireless
Base Station [3, 8]	WMAN	300-3000	20-60 (<20%)
Access Point [9, 10]	WLAN	10	(WiFi) 2.0 (10%)
Mobile Phone (screen on) [11]	WMAN, WLAN	1.5	(WiFi) 1.0 (66%)
Mobile Phone (screen off) [11]	WMAN, WLAN	≈ 1.0	(WiFi) 1.0 (100%)
Fashionable Computer [12]	PAN, WLAN	1.78	(WiFi+Bluetooth) 1.0 (56%)

devices. As the table illustrates, the relative energy consumption of the wireless interface largely varies among the devices composing the network. Differences range from the case of mobile phones, in which the efficient implementation of the stand-by mode[2] results in extremely low power consumption values, to the case of base stations, in which more than half the energy consumption is caused by cooling and power amplifiers drainage. These dissimilarities in the relative power consumed by the wireless interface motivate different approaches to reduce the energy expenditure of different types of devices; still, throughout the survey we will also identify several commonalities among them.

Despite the different energy demands of current wireless devices, we identify a set of key sources that determine inefficient power usage and which are encountered to certain extent in all types of network entities. In what follows, we discuss the underlying factors that cause these inefficiencies for the different network scopes considered. Table 2 summarizes our discussion on inefficient energy utilization, by listing both the source of inefficiency and the wireless technologies affected by such inefficiencies.

First of all, several papers in the literature argue that network infrastructure is often unnecessarily powered on, especially when the number of users and their traffic load are low [13, 14, 15, 16]. This common practice guarantees high degrees of coverage and service availability, but is responsible for a large amount of energy consumption, which could be tackled by intelligent sleep policies. Similar considerations apply at the client side, where cellular phones could go into sleep mode by switching their transceivers off during inactive periods [17]. Likewise, though at different time-scales, sleep mode operation could be enabled for WLAN personal devices engaged in lightweight communications [18], or wireless sensors that will be only requested to propagate information upon certain triggering events [19].

A second important cause of energy consumption is rooted in the hardware design. Indeed, the hardware inefficiencies have been pointed out by many authors, e.g., [20, 3, 8, 21]. This body of work addresses power-hungry processors, poor design of power amplifiers, inefficient heat dissipation demanding intense cooling, etc. Unfortunately, overcoming hardware inefficiency involves completely redesigning the wireless equipment, which is a costly and time consuming endeavor, and thus subject to practical concerns.

Although hardware inefficiencies are difficult to tackle, there exist different degrees of flexibility at various layers of the networking stack of the wireless devices. Existing works indicate most of these components often lack an energy-aware driven design as well. For example, the PHY layer is frequently implementing sub-optimal rate selection and transmission power control algorithms [22, 21]. The MAC operation uses inappropriate contention parameters and yields non-optimal and avoidable collision rates or unsatis-

[2] More specifically, with no screen nor wireless interface activated, and idle CPU.

Table 2: Main sources of inefficiency in energy consumption

Source	Factors	Network scope
inefficient duty cycling	DRX/DTX parameters, sleep protocol; inappropriate MAC behavior	ALL
HW inefficiency	unnecessary power drainage from power amplifiers; too frequently listening in idle mode	ALL
PHY inefficiency	improper rate adaptation (MCS selection); suboptimal TX power selection	WLAN, PAN
MAC inefficiency	energy-agnostic scheduling; suboptimal contention scheme (high collisions rate); interference due to uncoordinated transmissions	ALL
inefficient routing	node density agnostic topology formation and routing	PAN, WLAN
lack of coordination between PHY/MAC/routing	non energy-optimal resource allocation	PAN, WLAN
deficient network planning	increased node density; non energy-proportional operations; unnecessary high capacity provisioning; overlapping networks	ALL
inter-tech interference	lack of harmonization among multiple technologies causing interference and collisions	PAN, WLAN

factory and unfair transmission schedules [23, 24]. Similarly, routing protocols for wireless networks neither use energy as a path metric, nor leverage on node density to minimize energy consumption [25]. Further, coordination between these layers, i.e., PHY, MAC and routing, is missing most of the time [26].

Finally, we observe that, regardless of the network scope, current deployments are not carefully planned, thus suffering from energy wastage due to increased densities, over-provisioning, interference caused by coverage overlapping and occasionally due to the co-existence of different technologies, e.g., 802.11 WLANs and Bluetooth [27, 10, 28, 12].

3. Mechanisms for Improving Energy Efficiency

In this section, we provide an overview of the studied mechanisms for improving energy efficiency in wireless deployments. Recent surveys have focused on a specific network scope, i.e., WLAN [5, 2, 6], PAN [7] or WMAN [4], and have proposed different classifications, based on e.g. the *layer* at which the mechanism operates (PHY, MAC, cross-layer, etc.) or the *device* that runs the respective mechanism (Access Point, Base Station, clients, etc.). In contrast to these taxonomies, and motivated by the identification of the sources of energy consumption described in Table 2, our classification builds on the different *time-scales* of the algorithms considered. More specifically, we will consider the following four time-scales, illustrated in Fig. 1:

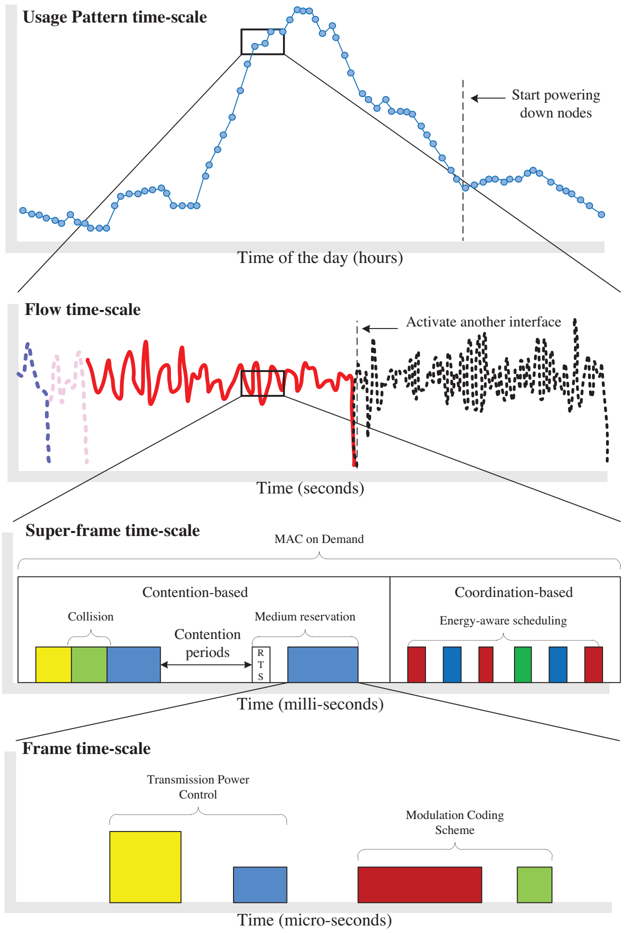

Figure 1: Operational time-scales of the energy-saving algorithms.

- **Frame**: The mechanisms in this category operate on a per-frame basis, i.e., they update the corresponding variables right before the actual transmission of a frame, based on the observed network conditions. Typical variables include, e.g., transmission power, modulation coding scheme, or frame length.

- **Super-frame**: Here we consider the mechanisms that regulate the protocol behavior between several transmissions. Precisely, here we consider all MAC-related mechanisms, this including both adapting the MAC parameters (e.g., scheduler, contention variables) and configuring the power saving schedule of the wireless interface.

- **Flow**: This category includes the mechanisms that adapt to the *load* in the network, and correspondingly tune the configuration of the resources available to best serve the traffic. This typically involves algorithms that are executed across various hops (e.g., adaptive routing) or the use of inter-technology cooperation (e.g., relay traffic using the WiFi interface).

- **Usage pattern**: Finally, we include in this category those mechanisms whose aim is to dynamically configure the network deployment, taking advantage of the large variations of the user arrival rate with respect to time of day (e.g., office vs. non-office hours). The main feature of these mechanisms is that they provide *infrastructure on demand*, thus saving not only the energy consumed by the wireless interface, but also almost all the energy consumed by the complete device.

Based on these time-scales, the resulting taxonomy for the energy saving proposals is illustrated in Fig. 2. We next provide an analysis of these proposals in an increasing order of their operational time-scales.

3.1. *Frame level time-scale*

As described above, the mechanisms in this category modify the transmission parameters on a per-frame basis, which is also known as *transmission strategy diversity*. The most common parameters that can be tuned are the transmission power [33, 34], the used data rate (i.e., modulation coding scheme) [29, 26], or a combination of those and other metrics such as the frame size [30, 31, 32]. One key challenge when using these schemes is the estimation of the channel conditions. Given that the objective is to maximize the amount of information transmitted per unit of energy consumed, the algorithms need an accurate sampling of, e.g., the noise level to guarantee a successful delivery without incurring energy wastage.

The amount of energy savings introduced by these mechanisms is bounded by the power consumption of the interface, relative to the total

- Frame
  - Transmission strategy diversity [29, 30, 26, 31, 32, 33, 34]
- Super-frame
  - MAC Scheduling
    - Contention-based
      - Reduce Retransmissions [35, 36]
      - Energy-aware contention [24, 23]
    - Coordination-based
      - Energy-aware scheduling [37, 26, 31, 38, 39, 40, 41, 32, 42, 43]
    - Hybrid [44, 45, 46]
  - MAC on Demand
    - Sleeping periods
      - Reduce idle listening [29, 47, 46, 48, 49, 50, 51]
      - Enhancing standard mechanisms [35, 25, 52, 53, 54]
    - Application tailored
      - Application-based power cycle [55, 39, 56, 57, 58, 59, 60]
- Flow
  - Routing
    - Energy-aware routing [29, 61, 62, 63, 64, 65, 27, 66, 67, 68]
    - Enhanced location updates [69, 70, 71]
  - Cooperation
    - Heterogeneous technologies [10, 28, 12, 72, 22, 66]
    - Clustering [28, 12]
- Usage Pattern
  - Infrastructure on demand [9, 16, 73, 74, 75, 76, 17, 77, 78, 15, 79]
  - Adjusting the range of the cell (cell breathing) [80, 81, 82]

Figure 2: Time-scale classification of energy efficient mechanisms.

power consumption of the devices. Thus, based on the values of Table 1, it is clear that the larger the relative consumption of the interface, the higher the motivation to maximize the efficiency when performing wireless-related operations. Furthermore, even if the energy savings are not very high, for devices running on batteries almost any gain is worth the effort of implementing an extension. Therefore, new mechanisms extending the standard functionality are quite common in PANs, and also in WLANs, but are not very frequent in the case of WMANs.

3.2. Super-frame level time-scale

Here we consider the mechanisms operating on a per multiple frames basis, i.e., modifying the parameters that specify how each node's frames gain access to the wireless medium, and when the interface is set to a *doze/sleep* mode. We divide the set of existing mechanisms in two groups: (*ii*) *MAC scheduling* proposals, which configure the parameters of the access protocols, and (*ii*) *MAC on demand* approaches, which adapt the availability of the wireless interface based on the expected arrival time of the next frame.

Proposals in the category of **MAC Scheduling** can be further classified depending on the MAC layer considered, namely: contention-based MACs (e.g., the EDCA channel access in IEEE 802.11 WLANs), coordination-based MACs (e.g., the Guaranteed Time Slot of IEEE 802.15.4), or hybrid protocols that alternate between contention-based and contention-free periods. Contention-based MACs are typically used where no strict QoS guarantees are required, i.e., in PAN and WLAN deployments. The main objective of these solutions is to reduce the overhead caused by contention mechanisms, either by optimally configuring contention parameters such as in [24, 23] or introducing new mechanisms used to reduce the number of transmissions, such as [35, 36].

Coordination-based MAC schemes rely on a central node in charge of scheduling the transmissions for all the nodes in the network, hence avoiding contention and collisions, and are equally available for the three considered network scopes. For instance, GTS has been proposed for IEEE 802.15.4 [47], and HCCA for IEEE 802.11 [83]. Many schemes have been suggested for scheduling in IEEE 802.16, since the standard does not provide details on scheduling and reservation procedures. In fact, IEEE 802.16 only defines bandwidth allocation and QoS mechanisms, including scheduling classes, but it does not define a precise scheduler. Due to scalability and complexity issues, schedulers implemented in operational IEEE 802.16 base stations use rather simple scheduling schemes, e.g., the Weighted Round Robin or Stratified Round Robin [84] schedulers have been widely adopted. The use of coordination-based MAC, furthermore, eases the use of sleeping mechanisms, as transmission times can be determined in advance and therefore nodes are not required to spend much time in the idling or listening states. We also include in this category the works that, even if they use a distributed MAC layer such as EDCA for IEEE 802.11e, obtain energy savings from the coordination performed by a central point, responsible for e.g. configuring global optimal Power Saving Periods [42] or contention parameters [32]. Among the solutions using a true Coordinated MAC, we encounter mechanisms that enhance the standard TDMA operation, such as [26, 31, 37, 41], and solutions proposing completely new coordination mechanisms based on a diversity of ideas, such as fuzzy logic [38], reduction of duty cycle based on strict coordination [40], use of external triggers for synchronization [39] or application aware schedulers [43].

Some coordination-based mechanisms introduce a period of time during which stations willing to access the medium contend to for subsequent schedules. We denote these MAC schemes, based on alternating contention-based and contention-free operations, as *hybrid* approaches [44, 45, 46]. With these, the main mechanisms to achieve energy efficiency consist of reducing the overhead of the contention-free part, minimizing the collision probability on the contention interval, and tuning the beacon frequency to reduce the length of idle periods.

For the case of **MAC on Demand** proposals, the main objective is to take advantage of idle periods to configure the wireless interface in a low energy consumption state (i.e., the so-called *sleep* or *doze* state). Existing protocols enable this sort of energy savings through the use of a centralized device; for the case of 802.11 WLANs this is the Power Saving Mode (PSM [18, 85]), for cellular communications in WMANs some notable examples are the Discontinuous Transmission (DTX) and Discontinuous Reception (DRX) patterns standardized by 3GPP [86], while in IEEE 802.16 deployments a control channel is used for traffic advertisement [87]. In particular, IEEE 802.16 defines three types of sleep-window-based Power Saving Classes [88], to adapt to different traffic profiles with different procedures of activation/deactivation, policies for adapting the sleep-window duration, and policies for mobile station availability for data transmission. Namely, Power Saving Classes of Type I are meant for best effort and non-real-time traffic, Power saving Classes of Type II are for real-time traffic, and Power Saving Classes of Type III are for *other* traffic (e.g., multicast and management traffic). A similar mechanism is also available for PANs, where, e.g., traffic can be advertised through beacons in 802.15.4 deployments [89].

There are two different set of approaches building on this sort of mechanisms, depending on whether they have been designed as general-purpose or rather they have been tailored to a specific application.

On one hand, there are *application-agnostic* proposals that aim at maximizing performance under general traffic conditions. Given that, even in the absence of traffic, stations have to periodically poll the centralized device for packets, there is some energy wastage related to this operation. Based on this observation, some approaches focus on reducing the time spent in idle listening [29, 46, 47, 51], which constitutes one of the major sources of energy consumption. Some other approaches focus on reducing the energy consumption of idle listening, not the time spent performing this task. These approaches use novel sampling techniques to detect whether a frame is being transmitted, such as [48, 50]. Finally some other proposals try to reuse the sleep/wake up concepts in other contention periods [49].

On the other hand, there are *application-*

tailored proposals, which are specifically designed to reduce the power consumption when a given application is being considered [39, 55, 56, 57, 58, 59]. Typical examples include the cases of periodic patterns, e.g., sensing or GPS localization applications [60]. For the case of healthcare applications, some cross-layer approaches use the heartbeat of a patient to synchronize the activities of the various body sensors [39].

3.3. Flow level time-scale

Next, we discuss the mechanisms that operate at a macroscopic scale, adapting the operation of the network to the number of flows and their demand. Existing approaches can be classified into two different categories: (*i*) those that adapt the routing protocol to maximize network lifetime, and (*ii*) those that enable additional wireless interfaces to accommodate incoming traffic demands.[3]

Energy-aware routing has been widely studied in PAN environments, as devices operate under batteries and the network lifetime is determined by the node with the least capacity remaining. The key challenge in these deployments is to properly share the relaying functionality, i.e., deciding which nodes are required to perform forwarding in addition to the sensing operations [61, 62, 63, 64]. A similar problem arises for the case of ad-hoc and mesh WLANs [65, 27], and even for the case of WMAN when they are extended with relay nodes [66, 67, 68]. Other solutions reduce the amount of energy spent on location updates and idle mode updates, by introducing new mechanisms for paging [69, 70, 71].

Another set of proposals build on the availability of various interfaces at the same node, running the same or multiple technologies. Some works propose to use a *primary* wireless interface for heavy data exchange, and a *secondary* interface for basic control operations, like paging or localization. In this way, the main wireless interface is used *on demand*, while the other energy efficient interface is devoted to periodic, low-traffic operations [10, 22]. This use of heterogeneous interfaces can also be applied to inter-technology operations, where it is typical to perform data clustering over the low power interface and then use the other interface as a gateway to the Internet. These sort of heterogeneous schemes have been proposed for WiFi+Bluetooth [12], WiFi+802.15.4 [10], and WiFi+3G [28, 72, 66].

3.4. Usage pattern time-scale

We classify in this section those mechanisms that aim at re-configuring the network deployment, which requires non-negligible time (e.g., multiple seconds for the case of a 3G base station [15]) and therefore has to be performed on large time-scales, based on variations of user arrival rates. Therefore, these mechanisms are not practical for sensor or personal area networks, as these operate at smaller time-scales and the number of users involved is rather limited.

These *infrastructure on demand* mechanisms introduce the largest energy savings, as their aim is to power down almost completely the wireless device; as described in Section 2, this is of particular interest for the case of WMAN deployments, given that most of the energy consumption of the infrastructure is due to non-wireless hardware [74, 75, 76, 17, 77, 79]. The main challenge posed by these proposals lies in deciding when to switch off a base station, given the impact on the service experienced by users – in particular, the potential reduction in coverage. Similar considerations can be made for the case of very dense WiFi deployments in office environments [9, 16]. For the case of residential environments, a smart management of Access Points / DSL routers can enable further savings on the operator's infrastructure [73].

Given the amount of time required to switch the state of a base station, some authors have addressed the design of more efficient mechanisms towards this end [78]. Instead of performing these switches, other works propose to dynamically tune the coverage areas (i.e., *breathing* or *zooming*), to adapt to the user density [80, 81, 82].

[3]Note that when a given node is not using any of its wireless interfaces, it could be completely powered down. However, given the time required to power on/off a device, we classify these mechanisms in the next section.

4. Comparing the Mechanisms for Green Wireless Communications

In this section, we undertake a comparison of the mechanisms analyzed above, with a view to the employed evaluation methodologies, reported performance gains and the distribution of current research efforts. Thus, our aim is three-fold: first, we seek to investigate whether the three evaluation strategies available, namely analysis, simulation and experimentation, are equally spread among the different scenarios, or rather some scenarios are typically tackled with a particular methodology; second, we want to quantitatively compare the energy savings across technologies, to understand if there are common trends among them; finally, we compare the volume of research works within each group of the proposed operation time-scale based classification of the mechanisms, to understand the focus of previous efforts.

4.1. Performance evaluation methodologies

We first discuss the type of performance evaluation carried out when proposing a new energy efficient mechanism. To this end, we consider the three usual categories:

- **Experimental evaluation**: We classify in this category those proposals that carry out various forms of prototype-based evaluation in a real testbed, at least as a "proof of concept". Note that, for the cases where proposals perform a *mixed* evaluation, i.e., presenting prototype results jointly with those from simulations (e.g., [73]), we include those in this category.

- **Simulation assessment**: We group in this category the mechanisms whose performance is assessed only via simulations and do not present any experimental results. Even though there exist some works that use measurements obtained experimentally and/or vendor data sheets as input parameters for the conducted simulations (e.g. [49]), in case no experimental report on the validity of the proposal is explicitly provided, they are classified in this category.

- **Analytical studies**: Finally, we classify in this category those works aiming at an analytical understanding of the energy consumption of wireless devices, including both analytical models of power consumption, like e.g. [85], and numerical analysis of the maximum bounds achievable, like e.g. [13].

The resulting classification following the above guidelines is presented in Table 3. We first note that the total amount of reviewed work per network scope is relatively well balanced, as PAN, WLAN and WMAN have a similar number of references (around 20). In contrast, the distribution of work per methodology is not equally distributed across scopes, with analytical studies accounting for approximately one tenth of the total number of references, while simulation and experimentation studies account each one for approximately one half of the remaining references.

An immediate observation from the table is that, as compared to PAN and WLAN, for the case of WMAN there has been relatively very little experimental work. This can be easily explained considering the difficulties of running experiments in large-scale testbeds: not only the required number of users is large and tests should last for long periods of time (given the typical usage patterns), but also the hardware required is expensive and not available as commercial off-the-shelf (COTS) devices. Because of these difficulties, some alternatives build on collaborations between network operators and academic institutions, but these are typically limited to the exchange of network traces for their analysis (e.g., [75]). In contrast to this scarcity of experimental work, for the case of WMAN there are significantly more analytical studies than for the cases of PAN and WLAN.

For the case of PAN and WLAN, the situation is somehow the opposite to the one described above. For these network scopes, there are relatively fewer analytical studies, with work based on simulation or experimentation accounting for most of the references reviewed. We also note that the split between these two methodologies is well balanced, although there is some slight bias

Table 3: Type of performance evaluation.

Scope	PAN	WLAN	WMAN
Analysis	[24] [27]	[23] [85] [16] [70] [71]	[54] [13] [76] [17] [15] [79]
Simulation	[29] [44] [30] [37] [26] [45] [31] [38] [39]	[41] [25] [36] [18] [49] [32] [33]	[74] [43] [65] [75] [81] [82] [51] [77] [78]
Experimentation	[35] [47] [55] [40] [56] [46] [48] [19] [21]	[9] [10] [57] [28] [12] [52] [58] [59] [42] [53] [69] [50] [90]	[73] [60] [72]

towards experimentation for the case of WLAN, which can be easily explained given the huge success of the 802.11 technology and the corresponding availability of COTS devices, many integrated with current laptops, mobile phones, PDAs, etc.

The above qualitative analysis of the methodology used for the performance evaluation shows that there are some significant differences among network scopes, a result that can be explained based on the required size of the network deployment and the availability of COTS devices for each considered technology. We next provide a quantitative comparison of the savings introduced by the different proposals.

4.2. Quantitative comparison

Our next aim is to quantitatively analyze the gains derived from the use of the mechanisms considered in our survey. More specifically, we want to compare the *energy savings* introduced by each proposal, regardless of the methodology used for the performance evaluation or the network scope considered. We identify two key challenges when performing a fair comparison of the existing mechanisms, namely: (*i*) specifying a common performance metric, as the considered figures significantly differ (e.g., reduction in Watts vs. bits per Joule); and (*ii*) characterizing the network operating conditions, as the considered load also shows significant variance (e.g., paging schemes with little, if any, traffic vs. duty cycles approaching 90%). We next describe how we have addressed these challenges.

To obtain a **common metric**, which we will refer to as *savings*, we have to define a unified figure of merit on every paper. While in many cases authors provide explicit figures on reduction in energy consumption, in some cases we had to perform the corresponding computation to translate, e.g., improved network lifetime, into energy savings. Furthermore, it should be noted that these savings may refer to the energy consumption of different elements: while reductions in terms of energy consumption typically consider only the wireless interface, battery lifetime improvements are associated with the energy consumption of the whole device. Whenever it was possible, we obtained the figure related to the wireless interface, but in some situations this was not feasible, therefore, some bias was unavoidably introduced when comparing against the works considering the overall consumption of a device.[4]

The second challenge is to understand the **operating conditions** of the scenario when carrying out the performance evaluation. This is also required because it would be unfair to compare, e.g., resource on demand mechanisms, which introduce the largest gains when there is little traffic in the network, with rate adaptation mechanisms, whose improvements are only noticeable when the wireless interface is sending traffic. We note that this is a much more difficult challenge that the

[4]It is worth remarking that, even for the case of analytical studies, there are non-negligible differences among works, in terms of, e.g., the number of energy consumption states that an interface undergoes, or the presence/absence of transient conditions when switching between states.

previous one, not only because there is no common definition of network load across technologies (e.g., traffic rate in packets/second, duty cycle), but also because the type of the arrival process has dramatic consequences on performance (e.g., constant vs. Poissonian). Given these difficulties, we decided to use the following coarse categories to estimate the network conditions:

- **Light load**: In these cases, the network is carrying little, if any, traffic. Typical examples include sensor networks tailored to health monitoring, or paging-like mechanisms.

- **Medium load**: Here we consider proposals tackling *average* duty cycles ($\approx 50\%$), as well as those works using traces gathered from realistic environments, which typically work at this network load.

- **Heavy load**: In this category we classify those papers approaching *saturation conditions*, i.e., when nodes always have traffic ready to be sent.

Based on these guidelines, we determine for every mechanism the largest savings and the network load under which they were typically achieved, i.e., the tuple

$$\{savings, network\ load\}.^5$$

It should be noted, though, that following the above guidelines to obtain the tuples is very challenging, given the lack of standardized network conditions and the heterogeneity of metrics, not only across technologies but also within the same technology.[6] Sill, even if our methodology should be taken with some caution, the obtained results are very illustrative, as we discuss next.

[5]Note that, for some mechanisms, we took different tuples, in case authors analyzed performance under a large variety of scenarios.

[6]As we will discuss in Section 5, this lack of standardized benchmarks constitutes one of the major research gaps in green wireless communications.

Following the analysis of each solution, we depict in Fig. 3 the different tuples obtained for the considered references,[7] marking with a different point style each network scope (PAN, WLAN, WMAN). Based on the results from the figure, we derive the following observations:

- The range of savings obtained is very wide (from 10% to almost 95%), and relatively well sampled as well. Although most of the contributions are located in the [50%,95%] range, there are references providing savings as low as 10%. We believe that the 10% value could be regarded as a performance gain threshold, indicating whether a mechanism would be worth deploying or not.

- The range of network load considered in the literature is very wide as well, with most of the contributions focused towards the light load regime, but with several contributions in the medium to heavy range. As compared to the previous dimension, though, it is clear that the density of mechanisms proposed for heavy load conditions is relatively small.

- All three network scopes (PAN, WLAN, WMAN) are well spread across the figure, as no cluster of points from the same technology can be easily identified. Furthermore, all network scopes are represented in the three network load regions. Remarkably, even the PAN technology, which is typically used for periodic data polling, is represented in the heavy load region.

Another key conclusion we draw from the figure is that the network load has a significant impact on the savings that can be achieved. Indeed, while for heavy load regimes the savings range between 10% to 40%, for the case of light loads they span in the 50% to 95% range. This is easily explained based on the type of mechanism considered for

[7]We left out those references in which it was not possible to identify one of these two variables.

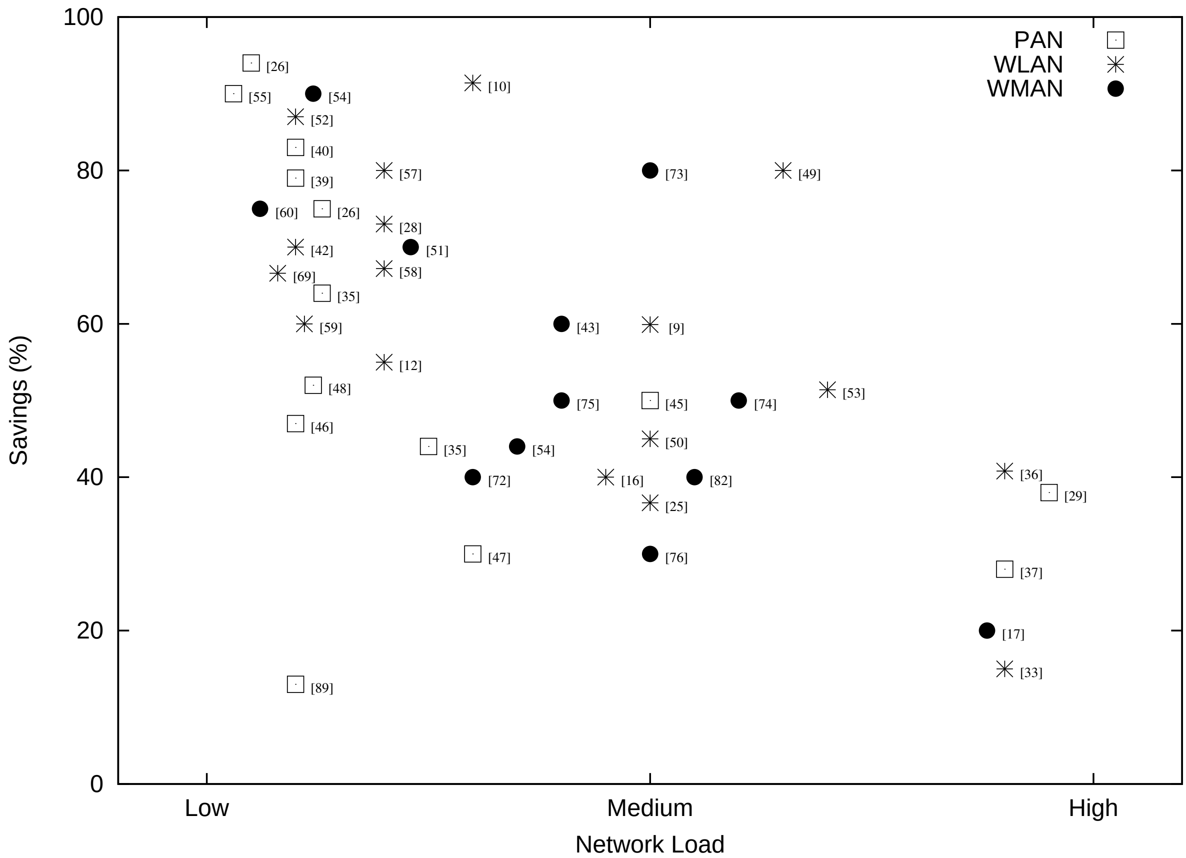

Figure 3: Typical savings achieved depending on the network load.

each load: for the case of heavy loads, the mechanisms aim at optimizing the behavior of wireless technologies, which are already efficiently designed, hence there is relatively little room for improvement; in contrast, for the case of light loads, most of the approaches can be classified as *MAC on demand*, and therefore instead of optimizing, e.g., the MAC scheduling, they rather completely switch off the interface, thus leading to large reductions in energy consumption.

Finally, it is worth noting that there are a few *outliers* in the figure that do not follow the observed behavior of savings vs. load, namely [90], [73] and [49]. In [90], authors consider the overall consumption of the device, and not the wireless interface itself, therefore savings are relatively moderate; in the case of [73], the proposed WLAN mechanism supports powering down also part of the wired DSL infrastructure, thus leading to larger gains; finally, the large savings introduced by [49] are obtained by non-standard mechanisms, namely, replacing channel sensing and backoff by a sleep mode, which introduces some fairness considerations with respect to standard stations.

4.3. Distribution of research efforts

We complete our analysis of the studied state-of-the art proposals for green wireless communications by giving a view on the volume of research targeting each network scope, with respect to the operational time-scale classification introduced. Specifically, our goal is to identify the main research trends in the recent years, accounting for the particularities of each family of technologies, and potentially pinpoint the areas where more work is required. To this end, in Fig. 4 we depict the distribution of the solutions reviewed, considering the two aforementioned aspects.

The trend observable in the figure is inline with our discussion on the main sources of energy consumption presented in Section 2. Since the main sources of energy consumption for the PAN family of protocols resides at the radio, research has been focused on the short and medium time-scale. Conversely, the primary source of expenditure on WMAN technologies is related to the power consumption of the base stations, hence, the research in this area has been mainly focused on techniques to reduce the number of active base stations (long term optimizations). In contrast, the approaches designed for WLAN are spread over all time-scales, since significant energy savings can be achieved both by improving the transmission and MAC procedures (short time-scale) and by minimizing the number of active APs when the network load is reduced (long time-scale).

5. Open Challenges and Future Directions

In light of the work analyzed so far, which covers the most important directions in the field of green wireless networking research, we are now ready to identify open challenges and future research directions. Specifically, as detailed in the following paragraphs, we are envisioning an increasing interest in: (*i*) *standardizing benchmarks* to provide an homogeneous performance evaluation framework; (*ii*) studying ways to gain the most out of the *combination* of different green networking proposals; (*iii*) employing novel *agile radios* to efficiently use the spectrum; (*iv*) providing low-cost platforms to enable the diffusion of academic *experimentation* in the WMAN field; and, finally (*v*) designing low consumption networks and protocols, which permit the utilization of off-the-grid *renewable sources* of energy.

Standardizing benchmarks. The concern on the energy consumption of IT equipment has triggered a lot of attention from the research community. Given the variety of methodologies, devices and network scopes, this has resulted in a notable heterogeneity of power consumption models and performance evaluation figures (we have hinted at part of this issue in Section 4.2). Therefore, one key challenge to address is the lack of a common vision with respect to these two main variables, namely, the power consumption of the equipment and the improvements introduced by the proposed mechanisms. To this end, some recent approaches have proposed a common benchmark for the energy consumption of network devices [91], and a framework for the analysis of energy efficiency in communication networks [92], but whether these will be adopted as *de facto* standards by the research community is unknown. We envision more effort in this area, which would help to compare existing approaches and to understand which mechanisms are better suited for a given scenario.

Combining different approaches. Another challenge, related to the lack of a standard framework, is analyzing whether combining existing proposals could provide any benefit. Indeed, given the lack of a common specification, it is hard to evaluate the possible gains of, e.g., using a resource-on-demand protocol with a per-frame optimization of the modulation and coding scheme. Given the proliferation of heterogeneous devices and the availability of new, more flexible mechanisms like, e.g, Wi-Fi Direct [93], we believe that the problem of how to combine different energy saving proposals (this including proposals aimed at different network scopes) will receive further attention.

Emergence of agile radios. Recent advances in software defined radio technologies have opened new avenues towards improved spectrum utilization, new medium access paradigms (e.g. SDMA), more robust communications, as well as advanced dynamic power control techniques and faster channel/interface switching times. From the energy expenditure perspective, among the immediate benefits of employing such agile hardware we identify improved interference mitigation, lower channel access times, resilience to channel errors, etc. Consequently, increasing research efforts are likely to be focused on developing energy efficient solutions that exploit the advantages of cognitive networking, smart antenna systems and cooperative techniques, such as, e.g., the work currently carried out within the ICT C2POWER[8] and ICT SACRA[9] research projects.

[8] "Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Network" project—`http://www.ict-c2power.eu`

[9] "Spectrum and Energy efficiency through multi-band Cognitive Radio" project—`http://www.ict-sacra.eu`

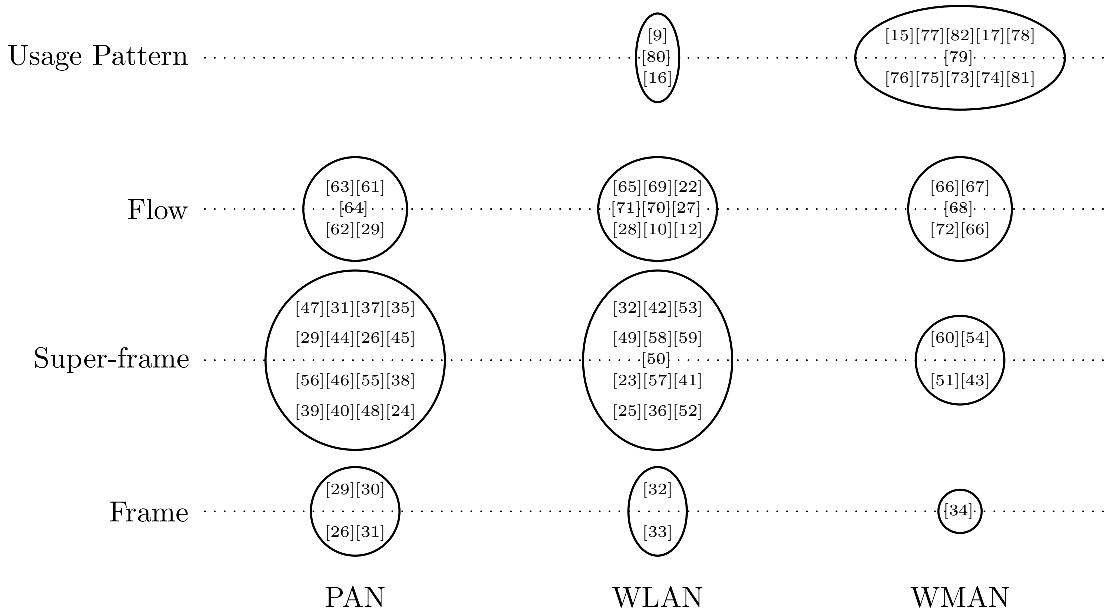

Figure 4: State-of-the-art distribution wrt. operational time-scale and technology family

Experimentation in WMAN. Due to their prohibitive installation costs, WMAN systems have been scarcely investigated from an experimental point of view. A few works report on prototype experimentation (e.g., [72]), other works report on measurements in operational networks (e.g., [74]), or on smartly extending 802.11 access over metropolitan areas (e.g., [73]). In particular, deploying base stations for testing has been so far impracticable, and only network operators have conducted experiments with a few mobile base stations. However, base stations are evolving towards low form factors and low power consumption [3], which paves the way to the deployment of fully operational and experimental WMAN topologies without the need for connecting to the electrical grid or for transporting huge pieces of equipment. As a consequence, power-efficient wireless protocols and devices will soon allow for on-site WMAN experimentation at the cost of few thousands Euros for a lightweight testbed, instead of the several tens of thousand Euros needed to deploy traditional base stations on street lampposts or towers. Another challenging issue, which prevents today's wide diffusion of WMAN testbeds, is the lack of general-purpose devices that can be operated without the support of vendors and network providers. In fact, all base stations available on the market are closed systems that cannot be easily configured and cannot be easily re-programmed to modify protocols and resource management mechanisms. A few European projects exist in the Seventh Frame Programme, which are currently addressing this issue with the aim of providing flexible and programmable platforms for schedule based MAC, e.g., ICT FLAVIA,[10] and ICT ACROPOLIS.[11]

Solutions based on renewable sources. Power efficiency is particular appealing not only because it allows to save energy and money, but also because it enables the development of green

[10] "Flexible Architecture for Virtualizable future wireless Internet Access" project—`http://www.ict-flavia.eu`

[11] "Advanced coexistence technologies for radio optimization in licensed and unlicensed spectrum" Network of Excellence—`http://www.ict-acropolis.eu`

devices, generating a sustainable CO_2 footprint. In turn, installing power-efficient devices makes it possible to operate wideband wireless systems by means of renewable energy generators, which are scarcely reliable in terms of guaranteed power generation, and necessitate massive deployments for generating large amount of power. As pointed out in [3], wind or solar based power generators, or a combination of the two, are now suitable to supply base station systems with limited capital expenditures. Indeed, it is possible to run a tri-sectorial 3G base station covering several square kilometers, by placing solar panels on a small surface (a few square meters). Note that, the enhancements in both the efficiency of renewable power generators and in the power utilization at the wireless devices, promise to make realistic the wireless data coverage of entire cities at zero CO_2 impact.

6. Summary

Today's wireless technologies play a primary role in the networking market and they are currently facing a re-design process, aiming at greening their impact on operational costs and pollution. So far the research has focused, on one hand, on battery powered devices that require low-power MAC technologies to maintain a reasonable lifetime for day by day operation. On the other hand, since the overall energy consumption constitutes a large portion of operators' OPEX, the research has also focused on energy-efficient deployments of broadband wireless networks such as WLANs and WMANs.

In this work, after classifying the relevant literature on green wireless networking according to its PAN, WLAN or WMAN nature, we undertook a power consumption analysis for different types of devices, identifying the key sources of poor energy efficiency in currently deployed wireless networks. In particular, we have found inefficiencies at various architectural levels, including hardware, PHY and MAC layers, and wireless routing schemes.

An accurate analysis of the existing body of work has revealed that green enhancement proposals would affect the network operation at various time-scales, i.e., from a frame level time-scale to a usage pattern time-scale, which covers network reconfiguration and re-deployment. He have discussed to which extent analysis, simulations or experimental methodologies can be employed in attempting to ameliorate the efficiency and have compared quantitatively the reported performance gains. We have also identified interesting relations between networks' operational properties, i.e., coverage and operational load, and characteristics of the proposed greening mechanisms, i.e., achievable savings and operational time-scales of the proposed enhancements.

The classification of existing proposals according to operational time-scales also shows that the problem of energy efficiency cannot be solved at just one level, but require complementary approaches that handle the inefficiency of the network at all layers, including PHY, MAC, routing operation and network planning. In particular, we have identified the main challenges and the most promising research directions towards a greener and more sustainable wireless networking.

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