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Green Home and Enterprise Networks

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9.1 Home and Enterprise Networks Today

9.1.1 Similarities

In home and small office environments, Internet connectivity is most typically provided with a broadband access, accounting currently for more than 650 million subscribers worldwide [1]. Among different broadband technologies, DSL is the most widespread, with 58% (or about 380 million) share of the market. Other broadband technologies are cable (19%) and fibre, with both fibre to the home (FTTH) and other forms of fibre (FTTx) accounting for 22% of all broadband subscribers.[1] The remaining subscribers are shared among wireless broadband technologies, mainly satellite using K_a band (in Europe and the Americas) and other wireless radio technologies [1]. According to Ref. [1], the current outlook of the market sees the dominant position of the DSL technology firm, despite some customers moving to fibre that is the fastest growing segment of the market, with nearly 10% growth in the first quarter of 2013. Satellite broadband access also experiences a small rise (1.5% quarterly), providing Internet connectivity in the areas where traditional and more cost-effective fixed broadband access technologies are not available.

It is thus safe to state that most of the home environments on the user side consist of a gateway to the broadband access network, called here *home gateway* (H-GW), that is, modem, wireless LAN (WLAN) access point (AP) and router (usually WLAN AP and router are one

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[1] With some regional variations, e.g., about 50% of broadband subscribers in Americas use cable broadband access due to the paid TV subscriptions, whereas Asia has the highest share of the FTTx market accounting for nearly 30% of all subscribers [1].

Green Communications: Principles, Concepts and Practice, First Edition.
Edited by Konstantinos Samdanis, Peter Rost, Andreas Maeder, Michela Meo and Christos Verikoukis.

physical device, whereas modem may be physically separated), and on the ISP side they consist of an ISP modem occupying a port in one of the line cards (e.g., for DSL technology, a typical DSL line card serves 12–72 lines) that are within the control of an access multiplexer, for example, DSL access multiplexer (DSLAM) for the DSL access [2]. Further on the user side, the H-GW is interconnected with the plethora of devices belonging to household inhabitants (in most cases not more than 30 devices in a single home [3]) that can be found useful at home, for example, PCs, laptops, smart TVs, gaming consoles, audio equipment, DVD players, printers, and so on, with more and more new devices capable of being connected to the Internet coming to the market. All these devices are not necessarily connected directly, possibly only via Internet ‘at large’. Very often, due to the coverage problems there is a need to extend the connectivity to the H-GW by means of repeaters, additional APs, and so on. What makes home networking environments extremely interesting is the multitude of available low-cost transmission technologies that are applicable in these scenarios [3]. In case of wired communication, Ethernet (IEEE 802.3) [4] is by far the most commonly used technology. Alternatively, power lines can also be used to transmit the data thanks to the power line communication (PLC) protocol [5]. Nevertheless, wireless communication technologies are gaining the edge, because of the convenience and flexibility they offer. According to a study from 2005 [6], already by then 52% of the US households with a computer network were using wireless technology, with this trend accelerating in the recent years. The most dominant wireless technologies being used in home environments belong to the IEEE 802.11 family (with majority of available products supporting one or multiple of IEEE 802.11a/b/g/n/ac standards) [7]. Another important wireless technology used in home networking is Bluetooth [8], especially in the context of applications that do not require excessively much bandwidth, or simply, as a replacement for cable connections. Recently, body area networks (BANs) are expanding quickly, with many new applications related to monitoring the human body functions and the surrounding environment [9]. Home automation [10] is another field gaining a huge growth of popularity, especially recently in the context of ‘Internet of Things’, and thus requiring a large number of sensor and actuators to communicate in order to fully automate and control home environments. Finally, a recent introduction of broadband femtocells provides good, alternative candidates to be applied as H-GWs [11]. Femtocells are customer-deployed, low-power base stations (BSs) using one or more commercial cellular standards and operating in the licensed part of the spectrum, in contrast to all the above-mentioned wireless standards that operate in the non-licensed industrial scientific medical (ISM) band. In home deployments, small and inexpensive femtocells can typically provide connectivity for up to four users [12]. According to the most recent market outlook presented by Small Cell Forum [12] the number of deployed consumer femtocells overtook the total number of macrocells in February 2013.

Typical home network scenario is summarized in Figure 9.1. Two parts of the network can be clearly distinguished. First, an Ethernet-based backbone that spreads between the ISP access network, H-GW and possible connectivity extensions (APs). The second part of the network, in most cases wireless, interconnects the individual devices with the H-GW, or if available, with APs extending the connectivity. Connection between additional APs and H-GW can be wireless, too.

With the broad adoption of laptops, smartphones and tablets in the recent years, enterprise environments have evolved from the purely Ethernet-based architectures to the networks that offer much more flexibility still being highly secure and reliable. New requirements mean supporting mobile users, flexible hosting of (wireless) guest users, offering the same set of services

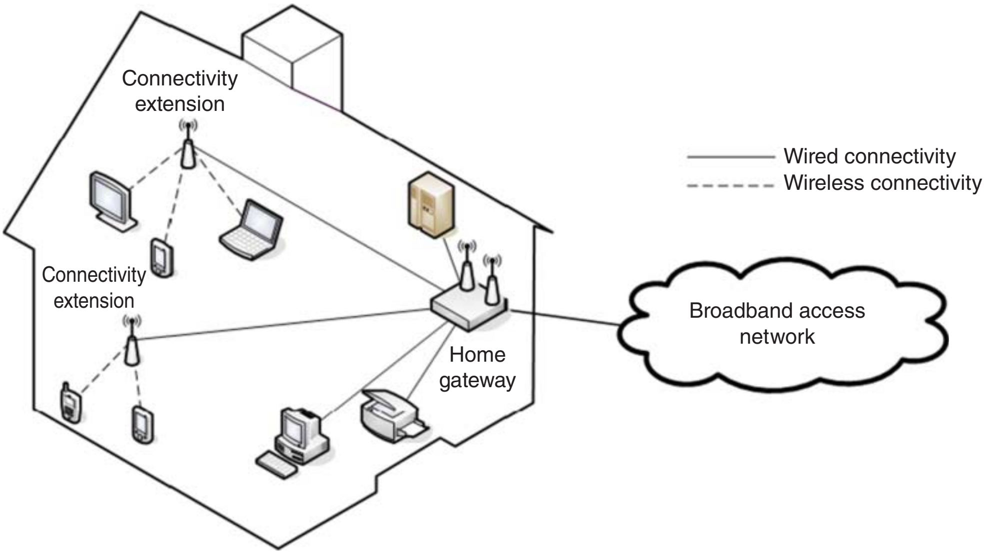

Figure 9.1 A typical home network scenario

at main sites as well as remote offices, just to name a few prominent examples. Nowadays, the structure of enterprise networks ensembles more that of home networks with Ethernet-based backbone and a wireless last hop. Typical deployments feature thousands of APs (e.g., [13] mentions densities up to 4300 WLAN AP per km^2), thus being called *dense WLANs*, in order to provide enough capacity in large buildings usually spanning multiple floors and/or buildings, or even larger complexes. In order to efficiently manage such networks, a centralized management scheme is deployed. The WLAN APs are just providing a simple point of the attachment for the users (so-called *thin APs*), with all (or most of) the management functions being moved to central controller(s) and being powered from switches via IEEE 802.3af power over Ethernet (PoE) ports. Furthermore, due to security policies posed by the companies that limit the scope of the officially allowed access technologies and applications, resulting network architectures are even more complex, including enterprise servers, and so on. Finally, thanks to the recent advances and broad adoption of infrastructures to support cloud computing and software as a service (SaaS), enterprise clouds are also very common in corporate network landscape [14]. The typical structure of an enterprise network is shown in Figure 9.2.

As for the last hop in enterprise networks, WLAN is by far the predominant wireless technology at the moment, with more than 50% of the organizations in the United States deploying WLANs [15]. The market of the enterprise WLAN is also growing very fast, currently experiencing a 32% annual growth rate. Among other wireless access technologies cellular networks are also becoming quite common. Furthermore, femtocells present a high potential and are quickly gaining this sector of the market, with plans to offer small cells as a service (SCaaS) by various operators [12]. Femtocells typically deployed in the corporate scenarios can serve up to 16 users. According to Small Cell Forum [12], in 2013 there were six different deployments for enterprise environments by European operators and another eight for enterprise/consumer sector in the United States and New Zealand.

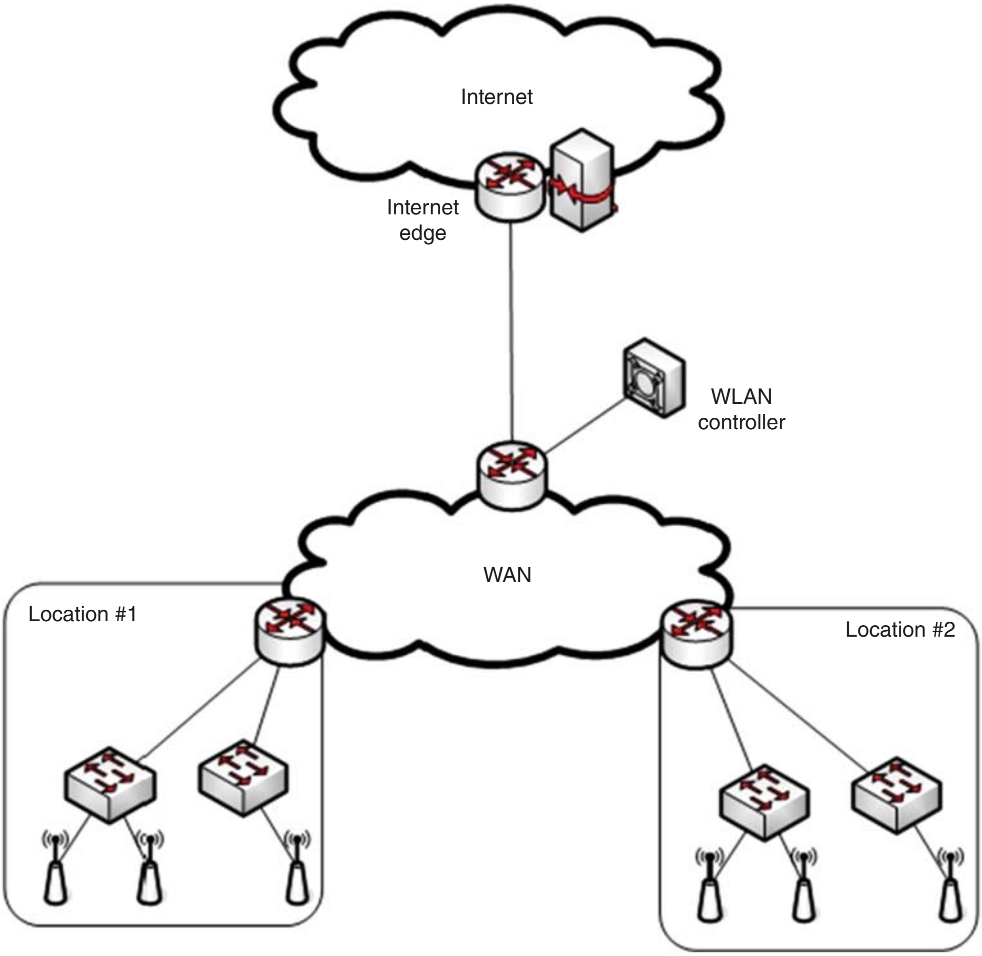

Figure 9.2 Typical enterprise network scenario (simplified version)

9.1.2 *Differences*

Obviously, the two discussed environments exhibit some differences as well. The most important ones will be discussed shortly.

The most evident differences are to be found within the network management approaches. In home networks, network management is split between the ISP and the individual end-user (network owner), with the latter having usually limited training and limited interest in getting deeply involved. This frequently results in poor network management – for example, frequent networking and security-relevant misconfigurations. On the contrary, it also poses strict requirements on the network devices to be easily configurable without requiring too complex setups, so-called *zero configuration*, and self-manageable, that is, being able to detect and adapt to changing network conditions [3]. Moreover, owners (administrators) of different networks have no incentive to co-operate in order to improve network deployment among different apartments, meaning no common interference management scheme is applied at all, leading to a lot of conflicts and inefficiencies.

In contrast to home scenarios and similarly to cellular networks, enterprise networks are now usually deployed under centralized management, with the usage of specialized tools (network design support tools, network management software, and so on for example, [16, 17]). Migration from autonomous to centralized architectures in corporate networks [18] is actually one of the signs reflecting the importance of an energy-efficient operation that is much easier to implement with a centralized scheme, despite the shortcomings that may be potentially introduced, for example, single point of failure, processing latency. Scope of management represented by various possible approaches provided by different vendors may differ significantly, including various proprietary solutions for load and interference management. Typically, two most common approaches to organize network management in enterprise WLANs may be distinguished, either (1) only time-critical functions, for example, exchange of management frames, are executed by the AP, whereas all the control and data traffic is routed to/from a central controller or, more commonly, (2) the central controller does not take complete control over all AP traffic, having, however, precise knowledge about the state of the network (AP notifies the controller using a separate protocol), that is, used channel, number of associated users, and so on. Hence, central controller has a global view of the network and can decide about the actual network configuration according to the traffic handled by the APs.

Another important point is that the corporate networks are designed to meet the performance objective (in terms of throughput and/or delay) and scaled to meet the peak of the user demand. Enterprise networks are thus heavily over-provisioned, with one or more WLAN controller(s), switches forming the Ethernet-based backbone and, more importantly, a dense WLAN with densities ranging up to 4300 APs per km^2 [13] contributing to the total energy bill. To make the things even worse the typical link utilization in the enterprise networks ranges from 1 to 5% [19–21], which is actually even lower than the utilization rates of home environments reported to be about 9% on average [2, 22–24].

Finally, deployment of femtocells has different aims in home and enterprise scenarios. In home environments, the main objective is to avoid leakages in the coverage of a single femtocell into the public space, whereas in enterprise deployments femtocells have to work together to jointly provide the increased capacity in a large building, group of buildings that are typical for enterprise or campus environments [25].

9.1.3 Perspectives

Growing popularity of wireless (mobile) devices heavily contributes to the increasing traffic demand, which in recent years has shown nearly exponential growth [26, 27]. Mobile videos (multimedia streaming) and web browsing are the main applications in both home and enterprise environments that contribute the most to this increase, with the first category foreseen to comprise nearly 70% of all mobile traffic by 2017 [26]. Another important driver is the requirement of ubiquitous connectivity, frequently coupled also with strict requirements regarding the quality of the Internet connection in terms of throughput and/or delay, which is especially important in corporate scenarios, for example, employees accessing the same set of corporate resources (services) from a corporate laptop, smartphone or any other device (virtual desktops). In order to fulfil all the aforementioned requirements there is a need to dramatically expand the existing network infrastructure which in enterprise scenarios would generate huge additional costs not only for installing additional equipment but also for its maintenance. As mentioned in Section 9.1.2, because of the low level of link utilization in both network types (1–5% in enterprise and about 9% in home networks), there would be a drastic increase in the densities of the APs that are required to serve such traffic. This, in turn, will raise severe concerns regarding energy consumption in such networks, which will further be discussed in the next sections of this chapter.

Nevertheless, several incentives to address this increasing traffic demand, differently from just adding additional infrastructure, can already be observed nowadays. In home networks it is the aggregation of the bandwidth from neighbouring WLAN APs. The idea itself is not new and despite serious security concerns several solutions have already been proposed in the literature, with the most prominent examples being: broadband hitch-hiking (BH^2) [2], coordinated upload bandwidth sharing (CUBS) [24], FastVAP [28], THEMIS [29], PERM [30] and COMBINE [31], to name a few. CUBS addresses increasing the upload bandwidth in order to improve the performance of peer-to-peer applications, whereas COMBINE provides a solution for collaborative downloading. Fast VAP and THEMIS demonstrate the feasibility of bandwidth aggregation with just a single virtualized WLAN card, and PERM discusses how to schedule flows among different available APs. For a more exhaustive survey of WLAN link aggregations see Ref. [2]. BH^2 as being energy-saving oriented solution will be discussed in Section 9.3.1. Nevertheless, practical, large-scale deployments of such wireless solutions remain to be seen. One example of an already deployed wired system is the ‘apartment LAN’ or ‘A-LAN’ deployed in South Korea [1]. A-LAN is defined as using a shared fibre or DSL connection to the apartment block with Ethernet-based distribution within the apartment block.

As stated already, enterprise environments will have to face not only the increasing traffic demand driven by rich multimedia content, for example, teleconferences including voice, high-quality video and data, but also the challenge of ubiquitous, device-agnostic connectivity. This will lead to a change in the concept of enterprise network, as it was previously described in Section 9.1.1. Network boundaries will be pushed beyond corporate firewalls (where they are nowadays) to form a so-called *extended enterprise network* that includes suppliers, vendors, partners, and so on, all working outside of the corporate premises and using any type of available access technology on any possible device (it is forecasted that up to 2020 every human could be associated with 70–100 IP devices), as pointed out in Ref. [32]. In enterprise environments it is network virtualization among many other Internet technology enablers that will play an important role in this paradigm shift. Another issue is the transformation from the network-centric solutions to more flexible architectures that could support ubiquitous connectivity (more human-centric approach) without compromising network security.

Finally, few words must be said about the future outlook of femtocells in the context of home and enterprise environments. According to Ref. [12], the femtocell market is expected to experience a significant growth over the next few years, reaching about 70 million of femtocell access points (FAP) in the market by 2017, growing nearly 40-fold from 2011 to 2016. Several enterprise deployments have already been made. As for 2013, there were 14 different enterprise deployments and more than 30 public customer deployments by different mobile operators worldwide, as reported in Ref. [12].

9.2 Home and Enterprise Networks in the Context of Green Wireless Networking

This section brings the ‘green context’ to the presented picture of home and enterprise networks. To this end, first the important metrics used in the context of green networking in wireless scenarios are introduced, and using these metrics an initial evaluation of the potential energy savings in both scenarios is performed.

9.2.1 Metrics for Green Communication

The forecasted increase in wireless traffic demand, mentioned in Section 9.1.3, has already raised severe concerns regarding energy consumption in both home and enterprise environments. To make this picture even worse, it has to be stated that until very recently, energy efficiency has not been part of the wireless network design considerations [33, 34]. Therefore, to fully understand the problem of energy consumption in wireless networks, it is first necessary to define the most important trade-offs related to the energy-efficient networking. The following discussion extends the framework presented in Ref. [27], addressing particularly home and enterprise environments and helps to define green metrics that are important in this context. From the perspective of system design challenges, there are four trade-offs that need to be discussed:

- Deployment efficiency versus energy efficiency
- Spectrum efficiency versus energy efficiency
- Bandwidth power trade-off
- Delay power trade-off

Deployment efficiency is usually measured in terms of achieved system throughput related to the total cost spent by the network operator on the deployment of the network, that is, both capital (CapEx) and operational (OpEx) expenditures. CapEx typically include infrastructure-related costs, whereas OpEx include operation and maintenance costs, among them energy bills. On the other hand, energy efficiency is defined as the system throughput per unit of energy consumption, or alternatively as energy spent per one user. According to Ref. [27], these two metrics very often lead to the opposite design criteria for network planning, for example, in order to reduce the number of deployed APs one would extend the area covered by one AP, with this in turn leading to a sub-optimal performance of the users placed at the edges of the coverage area of an AP. Typical enterprise networks are designed today to meet the peak of the traffic demand, thus being highly over-provisioned and not energy efficient. Nevertheless, the trade-off between deployment and energy efficiency is now becoming of outmost importance, with multiple reasons behind that. For enterprise networks, all the network deployment costs are paid by the company that is interested in having reliable, secure network capable to support rich multimedia applications. With traffic demand forecasted to further increase, there is a need to look for more sustainable solutions, improving the relation in the deployment and energy efficiency. Examples of such solutions will be further discussed in Section 9.3. The current picture will also change significantly with the wide deployment of femtocells in the enterprise scenarios. Having a heterogeneous network structure with one layer of the cells just providing the coverage, and the other layer providing required capacity would increase both cost efficiency and energy efficiency. In contrast, for home environments energy consumption of a WLAN AP or H-GW constitutes a very small part of the total energy bill that is paid by a residential user, thus giving the user a very little incentive to look for any improvements. Furthermore, to make things even worse, energy efficiency of the devices employed typically in home environments is very low, being two or three orders of magnitude lower than that of core network devices [2].

Spectrum efficiency is usually defined as throughput of the system per unit of the used spectrum, being widely accepted criterion in wireless network optimization [27]. In case of home and enterprise environments the trade-off between spectral and energy efficiency was not considered an issue as long as purely WLAN-based networks were considered. However, with the incorporation of additional wireless access technologies into the corporate scenarios, and especially with the introduction of femtocells to both enterprise and home environments this trade-off becomes a very important one, due to additional inter-cell interferences that are introduced. To this end, various solutions for mitigating inter-cell interferences in femtocell deployments will be discussed in Section 9.3.

Bandwidth and power used for the transmission are the two limited resources in wireless communication. Therefore, the relation between these two factors is important in the context of wireless resource management. Again, examples of such algorithms will be shown in Section 9.3. Whereas bandwidth power trade-off describes mostly solutions that are related to the physical layer, delay (or service latency) power trade-off refers to the application layer performance. In enterprise networks, it is one of the most important design goals to deliver a timely bounded service, often without much concerns about the power consumption. Therefore, in first place, there is not much space in which the delay can be compromised. For home environments, in contrast, there is a certain grade of flexibility in the function of the applications that are most commonly in use, for example, video and web browsing applications permitting some trade-off, whereas online gaming are less elastic.

9.2.2 Green Potential

As pointed out in Section 9.2.1, so far wireless networks have not been designed with the energy efficiency in mind. In order to quantify possible gains that can be achieved in both home and enterprise environments, let us first break down the energy consumption of different parts of each network, stating where lays the biggest potential to save the energy, under assumption of perfect management of each network.

As shown in Figure 9.2 (in Section 9.1), a typical deployment of an enterprise network features one or more WLAN network controller, few switches forming the Ethernet backbone and a huge number of WLAN APs, for example, 125 WLAN APs in a single-building corporate network and up to 5000 WLAN APs in a campus network [15], with a clear trend to further increase these numbers due to the increasing demand for high-quality multimedia traffic. According to the studies that survey power consumption of WLAN network elements, the usual power consumption figures are: up to 466 W for commercially available WLAN controllers (typical WLAN controller being able to manage up to 512 APs and 8192 users) [15], about 350 W for switches (a switch with 24–72 PoE ports) [15], and up to 10 W for a thin WLAN AP [15, 35]. Yet a single WLAN AP does not consume much energy, but due to their abundance, it is safe to state that, similarly to the cellular networks, the radio accessible part of the enterprise network consumes the most energy and thus the APs contribute the most to the total energy bill. For example, a total yearly energy consumption of an enterprise network consisting of 125 APs could be estimated with the data provided above to be about 21 MWh, out of which consumption of WLAN APs would yield nearly 11 MWh.

In the case of home networks, it is much more difficult to make such a precise balance of the total energy costs, due to the high variability in quantity and type of the devices used. Nevertheless, there are several studies aiming at evaluation of the energy consumption in home environments [36–38]. Spinney et al. [36] analyze the most recent trends of the energy consumption in households, taking into account also social and cultural perspective, stating that there was a huge paradigm shift in our perception of the role of communication in our social relations and habits at home with the introduction and mass deployment of wireless communication and devices such as laptops and smartphones. Interestingly, we tend to spend much more time, than in the era of desktops, using our wireless portable devices to work or for leisure, with emerging practices such as multitasking and always-on-ness. To that end, a very interesting comparison of the energy consumption of a desktop and laptop has been provided. On the basis of participant usage patterns and the energy consumption data available in Ref. [37], it was stated that a two-hour daily on activity incurs about 65% more of the consumed power for laptop (estimated as 1.7 kW per week) than for a desktop computer. The difference is mainly explained by the different usage patterns: desktop computer is completely switched off after completing the on activity, whereas laptop stays in the standby mode for a considerable amount of time, and so are the remaining elements of the network. One more important observation is being made; actually laptops are often not competing with desktops in the home environments, rather being just an additional layer of devices used for communication. Therefore, the total energy consumption in home environments has been recently increasing even more significantly.

Another very important aspect in the context of the green potential of home and enterprise environments is the link utilization. For both networks, the average link utilization has been reported to be very low, in order of 1–5% for the enterprise networks [19–21], and about 9% for home DSL links [2, 22–24]. Yet enterprise networks are highly over-provisioned in order to meet the peak of user demand, which occurs very rarely and may be related to only a small part of a corporate or campus network, for example, Jardosh et al. [39] quantify that around 10–80% of all WLAN APs in a corporate network and 20–65% for the campus deployment are idle during the entire month of the observation time; in addition, they also report more than 70% of all APs being idle for the time span of at least an hour in the corporate scenario and more than 50% in the campus scenario, respectively. To make things even worse, energy consumption of the network devices in both home and enterprise networks is *not proportional to the traffic load*, that is, large fraction of the energy is burned independently of the traffic load, and the lowest level of energy consumption per transmitted bit is achieved at the full load. Several experimental results illustrate how bad the situation actually is. Nguyen and Black [37] report the results of their measurements of home ADSL modems (two ADSL modems and one ADSL/WLAN modem) under different levels of traffic load stating that the difference between the idle state (powered on and not sending any data) and fully loaded state is actually minimal. Hlavacs et al. [38] report the same phenomena for residential (8 port Fast Ethernet switch) and corporate (24 port and 48 port Gigabit Ethernet switch) switches, consuming marginally more power when being loaded than in the idle state. Consumption of WLAN APs has also been analyzed in numerous research studies, for example, Refs. [35, 40], including broad range of possible devices supporting different versions of IEEE 802.11 standard, for example, with multiple input multiple output (MIMO) antennas (IEEE 802.11n), dual-band (2.4 and 5 GHz) operation, and so on, with a common conclusion that at least 70% of the energy was spent just to power the AP (idle state) [40]. Readers may further refer Refs. [35, 40] for more detailed surveys of WLAN AP power consumption of different vendors.

This degree of lack of load proportionality, of course, leads to very high levels of energy consumption per transmitted bit, being two or three orders of magnitude higher than that of core network devices [2]. Therefore, taking into account the huge number of the deployments of dense WLAN environments worldwide, as well as trends indicating further growth in both academia and industry deployments, there is a considerable potential for saving the energy in such networks.

9.3 Possible Savings in the Current Home and Enterprise Network Landscape

This section focuses on the reality of energy savings that are possible to achieve in the current state of home and enterprise networks. To that end, first a short overview of what can be done is given, including possible hardware improvements and network-level solutions. Next, an overview of the most important challenges and limitations preventing the implementation of proposed solutions is provided. And, finally, a detailed survey of the most prominent network-level solutions applicable in dense WLAN scenarios is presented.

9.3.1 Quick Survey of What Can be Done

Lack of load proportionality of network devices currently deployed in home and enterprise scenarios has been one of the main reasons why in the advent of forecasted traffic explosion serious concerns about energy consumption have been raised and spurred a considerable amount of research. All proposed solutions can be divided into two general groups: (1) hardware-level solutions and (2) network-level solutions. In addition, there is a third group of solutions aiming at improving energy efficiency at the user end devices that is important in the context of home networks and will also be discussed shortly.

Hardware-level solutions aim at improving directly the energy efficiency of a network. This means increasing the efficiency of single components, for example, power amplifiers, chipsets, (IEEE 802.11) radios, of network devices in order to decrease power consumed during the transmission or idle mode of operation. A detailed study for WLAN APs [40] has revealed that for the best devices under tests, still at least 70% of the energy was spent on base power consumption (load-independent consumption when the AP is idle). It is therefore reasonable to ask the following question: how much can be actually saved by further improving single components – where are the limits of possible energy savings with hardware-level solutions? In an effort to answer this question, we analyzed collections of power consumption data of WLAN APs made by various manufacturers that are presented in Refs. [35, 40]. The main conclusion that can be drawn is that with the current state-of-the-art devices, the overall power consumption is mainly attributed to the base power consumption, with radio transmission circuits contributing very little, sometimes close to none. Similar conclusions regarding load proportionality are drawn for switches that are currently deployed in enterprise networks, which tend to consume about 90% of the power in the idle mode [14]. Marsan et al. [33]

provide a further theoretical discussion of the above-mentioned question, considering possible energy savings with hypothetical devices, not possible to be constructed with the present state-of-the-art technologies and knowledge that have 90% of load proportionality. Of course, that brings savings when compared to the best devices available today, but even then the amount of energy that is wasted during the periods of low traffic load and in the idle mode is still huge, if we consider the size of a typical enterprise network. Therefore, hardware-level solutions cannot be seen as a viable option in case of dense WLANs, where most of WLAN APs stays idle for most of the time, and there is a need for more efficient low power operation or sleep modes (network-level solutions).

In the context of home networks, an important development is the definition of the low-power Bluetooth profile, within Bluetooth 4.0 specification [8]. However, this and other ongoing improvements to hardware are not able to keep the pace of the rising demand for energy consumption of end-user devices and thus advocate for software-level solutions, including all layers of protocol stack [41].

Network-level solutions, in contrast, try to dynamically adjust the number of active network devices, for example, Ethernet switches, WLAN APs or H-GWs, to the changing traffic load conditions. This means putting unnecessary devices to sleep or even completely switching them off in periods of low traffic load; therefore, network-level solutions are also referred to as resources-on-demand (RoD). To that end, there are several issues that must be addressed, namely, (1) in order to increase the energy efficiency of a network, low-load situations must be correctly recognized and potentially unnecessary devices must be selected, (2) sufficient number of network devices remaining in the operation must be assured in order to provide active users with the requested service, that is, sufficient bandwidth capacity, as well as to avoid coverage holes, that is, sufficient coverage, (3) any increase in the traffic demand must be timely detected and, if required, additional resources must be, also timely, provided. It is therefore quite typical for this type of approaches to define two layers of network devices: these that are absolutely necessary to provide basic operation of the network, that is, *basic coverage*, and additional layer of redundant devices that provide additional network capacity required in situations of heavy traffic load. Decision about switching network devices on and off may be taken either locally, independently of the other devices, or centrally in a coordinated manner, depending on the network architecture.

There are numerous network-level solutions that have been presented in the literature. In case of enterprise networks, the most prominent solutions for the wired backbone are based on energy-efficient Ethernet (EEE) [42]. EEE adaptively adjust Ethernet link data rate according to the current traffic conditions, and as different rates correspond to different amounts of consumed power more energy-efficient operation is achieved, for example, Refs. [21, 43]. Another example also based on EEE is green virtual LANs (VLANs), solution proposed to optimize energy efficiency of VLANs[2] that are nowadays commonly deployed in the enterprise scenarios [44]. Pointing out the most important deficiencies of the currently deployed VLANs, for example, placement policies, authors suggest an improved VLAN architecture, designed with energy efficiency as one of the optimization criteria. Energy inefficiency of the Ethernet switches is also tackled from the perspective of offloading users (which generate little or no traffic) to the wireless part of the enterprise network while putting remotely such unused switches to sleep, in a solution called smart wireless aggregation (SWA) or energy-efficient

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[2] VLAN groups logically users belonging to the same category (e.g., employees in a division of a company) that are connected to LAN switches or routers despite their different physical location.

wireless (EEW) [45]. EEE and EEW can also be deployed jointly, as proposed in Ref. [21]. Finally, there is a huge group of network-level solutions focusing on the energy-efficient management of the wireless part of the enterprise networks, provided that this is the part of the network that consumes the most energy and has the biggest power saving potential. The most popular WLAN AP management techniques will be surveyed separately in Section 9.3.3. In addition, the most important solutions for future enterprise scenarios that include femtocells will be presented in Section 9.4.

In the context of home networks, the most important network-level solutions focus on the traffic aggregation in the heavily underutilized DSL links, similar to the idea of SWA. Examples such as broadband hitch-hiking (BH^2) [2] (solution already introduced in Section 9.1.3) or energy-efficient protocol for gateway-centric federated residential access [46] propose to reuse the overlapping coverage areas of the neighbouring WLAN APs in order to offload unused WLAN APs. A substantial number of WLAN APs (65–90% according to [2]) can be offloaded and thus switched off, bringing considerable power savings for a federated deployments of WLANs in future home environments. Other solutions for traffic aggregation in the DSL access that were mentioned in Section 9.1.3, do not focus on the energy optimization, however.

In addition, several recent works, for example, [47, 48], proposed approaches to reduce energy consumption in WLANs, having as a main goal increase in the battery lifetime of the end-user devices. These end-user approaches can be easily integrated with network-level energy-aware solutions mentioned here, and may have more importance in home scenarios. Nevertheless, these solutions are out of the scope of the analysis presented in this chapter.

9.3.2 *Challenges and Limitations*

In contrast to cellular networks, both enterprise and home networks have less potential for saving the energy (a single WLAN AP or H-GW is consuming relatively little energy in comparison to a single (macro) BS in cellular networks; see numbers provided in Section 9.2.2) and thus it is more difficult to employ power saving strategies there. Practically, only dense WLAN network in enterprise environments represents a scenario where employing network-level schemes to manage the energy is feasible [33]. In contrast, home networks due to their scattered nature (high level of distribution of the energy cost, with a very small cost per single user) and distribution of management among many different parties are not well suited for the adoption of energy-efficient approaches known from cellular or enterprise environments (with the only exception being federation of WLAN APs; nevertheless, large-scale deployments of federated WLANs are yet to be seen). Of course, one may argue that if the energy saving scheme proposed for distributed deployment is adopted on the mass scale in all households the cumulative energy that may be saved is significant, for example, Ref. [15]; however, such an assumption seems upfront very unrealistic.

But even for dense WLAN environments there are several important limitations that must be taken into account. The main limitations arise from the nature of centralized management scheme that is deployed, especially in the variant where the AP handles all non-time critical functions, namely, creation of a single point of failure, as well as increased processing latency [18] that may not be acceptable for some enterprise deployments. These limitations impose therefore new requirements on manufacturers to provide more flexible and reliable management schemes, facilitating a fast and accurate network re-configuration and being the most important challenges related to dense WLAN deployment nowadays.

Another important limitation is related to traffic aggregation solutions. Whereas traffic aggregation is feasible in enterprise scenarios [21, 43–45], aggregation of traffic in home scenarios may pose severe challenges due to the failure to induce sleep [2]. A DSL line can be put to sleep only if there is no traffic on the line at all, as there are no alternatives for Internet connectivity. Also, it takes about a minute to boot and synchronize the modem with DSLAM, and therefore traffic inactivity must be sufficiently long. However, it is very well-known that due to some periodic traffic updates to keep the network presence of various user applications there is a continuous light traffic flowing almost constantly and thus preventing sleep on idle.

9.3.3 Survey of On/Off Switching Mechanisms for Enterprise (Dense WLANs)

Solutions proposed in the literature to dynamically reduce power consumption of a dense WLAN in periods of very low demand can be divided into two fundamental groups: (1) homogeneous (relying entirely on IEEE802.11 technology) and (2) heterogeneous solutions (assuming support of other, additional network access technology, e.g., IEEE802.15.4, Bluetooth).

Following the general outlines of a design of RoD approaches presented in Section 9.3.1, there are two key aspects that must be addressed for homogeneous solutions, namely, (1) the assessment of the area covered by a given set of WLAN APs and (2) the assessment of the demand. Therefore, there are two issues that heavily influence the design process of such solutions: coverage models and AP placement pattern (also called in the literature the *area coverage problem*). Coverage models will not be discussed here; for a good survey of different approaches refer Ref. [49]. There are two obvious design choices for the area coverage problem: deterministic and random placement of WLAN APs [49]. Random AP placement, although more realistic, leads to a non-homogeneously covered area, which has been proved to be a NP-hard problem. Possible solutions include either tile-based approximation [50] or computationally expensive (and not easily scalable) optimization algorithms to approximate the coverage [51]. Deterministic placement of APs, with all its shortcomings, seems thus a viable alternative, for example, Refs. [52, 53].

One of the first examples of homogeneous solutions has been proposed in Ref. [39].WLAN APs are grouped into clusters on the basis of the Euclidean distance. Within a cluster, only one AP, called *cluster head*, is powered on during the period of low load. The demand is estimated on the basis of the number of associated users, and once the threshold is exceeded, additional APs within the cluster are powered on to provide the capacity. Achieved power saving depends on the APs density, yielding 20–50% power saving for less dense scenarios and 50–80% for dense deployments. However, the criterion for forming the cluster is not very well tailored for wireless environments. Due to fading and interference, even adjacent APs may have significantly different performance, and consequently coverage holes may appear between the clusters. This problem has been addressed in an improved version of this solution, presented in Ref. [15], where detection of neighbouring APs and forming of clusters is based on RSSI criterion. Also, estimation of the user demand has been improved with the number of associated users being substituted with a channel busy fraction metric, that is, the fraction of time the channel is busy due to the transmission and inter-frame spacing, to better reflect the real traffic picture. It is reported that up to 53% and 16% power saving can be achieved for the low and high traffic conditions, respectively (although it is hard to compare these results to that achieved by the previously described solution due to different evaluation scenarios). Another cluster-based strategy, proposed in Ref. [54], is based on the usage patterns, derived from long-term measurements. These usage patterns are fed into two continuous-time Markov chain (CTMC) models of a cluster to calculate the required number of powered-on APs. This approach has been reported to save about 40% of the consumed power. Further, two other approaches use either integer linear programming (ILP) optimization [55] or heuristic (reducing the computational complexity of the former) [56] to adjust the density of the powered-on APs within a cluster. First of the proposed approaches provides a 63% power saving, whereas the latter further increases this gain by 10%.

An alternative approach has been recently presented in Refs. [52, 53]. Authors claim that the density of the WLAN APs can be very drastically reduced, on the basis of the following observation: to detect the user presence (with a given probability) it is actually sufficient that just one out of several Probe Request frames transmitted with the lowest bit rate is received within a desired delay. Once the user presence is discovered, additional APs can be switched on to provide the additional capacity required by the user. One of the main characteristics of the proposed algorithm is that the status of each AP can be determined in a distributed fashion. Initial evaluation demonstrates astonishing power saving: up to 98% of inactive APs can be switched off.

Heterogeneous approaches, in contrast, take advantage of multiple radio interfaces that are currently commonly available in the end-user devices. The underlying design assumptions in all solutions of this type are that (1) the alternative network provides the coverage in the entire area in question and (2) the position of the end-user devices is roughly known. Fulfilling these two assumptions guarantees that in the event of an increasing demand WLAN AP(s) can be timely powered on or user connectivity can be provided entirely with the alternative access network. Among several possible technologies to choose from, cellular is the one most often used in this context. One of the first solutions was proposed by Lee et al. [57], who suggested substituting WLAN beacon frames with cellular paging procedure in order to wake up on demand the additional WLAN APs that are in close proximity of the user device. With such an approach, WLAN APs can be very aggressively put to sleep (even all APs can be turned off!), guaranteeing considerable power savings. In the same way Bluetooth technology can be used to provide the basic coverage for low-rate transmissions, with WLAN interface being switched on only on detection of an excessive demand [58]. Using low-power Bluetooth interface traffic from nodes that do not require excessive bandwidth (forming a cluster) is aggregated at one node called *cluster head* that further pushes the traffic to the AP. Once one of the nodes requires more bandwidth, it switches on the more power consuming WLAN interface to communicate with the AP, whereas Bluetooth clusters are reorganized accordingly to reflect the change in the network topology. Finally, one of the most popular approaches presented so far in the literature proposes to additionally equip WLAN APs with IEEE 802.15.4 narrow-band radios that are used as 2.4 GHz band spectrum sensors [59]. Thanks to these sensors WLAN APs are able to detect radio activity (user sending WLAN beacon frames, attempting to connect to an AP) consuming considerably less power than the WLAN radio would (a 91% power saving is claimed). WLAN radios are activated on potential discovery of a user connection; however, the IEEE 802.15.4 sensors are not WLAN-technology-selective and might unnecessarily (a false positive) wake up WLAN APs if any other radiation is present in a channel.

To summarize, solutions that are based purely on IEEE802.11 technology, although sometimes coming close, for example, Refs. [52, 53], cannot reduce the density of the APs as aggressively as the ones based on the heterogeneous technologies. In the latter case, however, usage of multiple radio interfaces is required, which may make the deployment more complicated. Homogeneous strategies have little complexity in terms of deployment, control and management, but their main drawback is that they are not transparent to the users, meaning that the users may experience a slight performance degradation (e.g., delay) during switching on/off phases. A more detailed survey of on/off switching algorithms in the dense WLAN environments can be found in Refs. [53, 60] and interested readers should refer there for further details.

9.4 Possible Savings in Future Home and Enterprise Network

As argued in Section 9.1, the biggest challenge, as well as the biggest opportunity, for home and enterprise environments is related to the deployment of the femtocells on a massive scale (according to a study [61], 30% of corporate and 45% of household users experience poor indoor coverage). Here, we shortly analyze possible implications related to energy consumption, focusing in particular on the problem of interference management in dense deployments of femtocells.

9.4.1 Interference Management Techniques

Perspective of massive deployments of femtocells has increased concerns about their energy consumption. Therefore, quite considerable research efforts have been spent, with most of the work focusing on the interference management problem [62]. Before further discussion, let us first classify the interferences in the environment where femtocells are deployed (femtocells constitute another tier that is coexisting with the traditional access networks, e.g., cellular macro cells). To that end, two main groups can be distinguished [63]:

- *Co-tier interferences*, caused by network elements belonging to the same tier of a network, that is, interferences introduced by femtocells to the other femtocells, usually cells that are deployed in immediate proximity or sufficiently close to each other. Furthermore, there is a need to distinguish between the interferences in uplink direction (introduced by an end-user device) and downlink direction (introduced by a femtocell AP).
- *Cross-tier interferences*, which occur between network elements belonging to different tiers of a network, that is, interferences between femto and macro cells. Also, with further distinction between uplink (end device in a femtocell is a source of interferences to a macrocell, or end device using macrocell to a femtocell) and downlink direction (caused by a femtocell AP to a neighbouring macrocell or from the macrocell BS).

Interference management techniques are strictly tailored to the radio technology being used, for example, CDMA, OFDMA, as well as to the femtocell access mode (open access, closed subscriber group, or hybrid). Efficiency of the interference management schemes is usually highly dependent on the particular femtocell scenario. Whereas less dense femtocells deployments favour very simple schemes, the real challenge remains in enabling the dense femtocell deployments, given the ad hoc nature of the femtocells and high level of cross-tier interferences. The most important schemes for interference management proposed so far in the literature can be divided into three groups: (1) interference cancellation schemes, (2) interference avoidance schemes and (3) distributed interference management schemes [64].

Interference cancellation schemes deal with removing the influence of the interferences from the received signal. As such, they require knowledge of the characteristics of the interfering signal, as well as antenna arrays at the receiver end to cancel these interferences. Therefore, these solutions are targeted to be deployed at the macrocell BSs and femtocell APs, dealing with the uplink interferences.

Interference avoidance schemes include all techniques that may be deployed at the femtocell AP in order to help it self-optimize and self-configure, according to the current network conditions. To that end, a femtocell AP must be able to (i) sense the users in its vicinity, (ii) communicate with neighbouring femtocell APs and (iii) receive feedback from the users about the present conditions [65, 66]. One of the most prominent examples of interference avoidance techniques includes power control aided coverage optimization that deals with finding a compromise between the deployment efficiency and energy efficiency (recall the first of the metrics discussed in Section 9.2.1), taking into account indoor mobility patterns to construct adaptive coverage algorithms, for example, Ref. [66].

Finally, distributed interference management techniques are a subset of interference avoidance schemes, in which a femtocell AP disposes of limited information about the femtocell network, for example, in dense femtocell deployments it may not be feasible to distribute this information via backhaul. The optimization decisions must thus be taken locally, on the basis of the information that is sensed by a femtocell AP in question and its immediate neighbours. Distributor schemes are far more complex than the centralized ones and in order to be efficient may require additional knowledge, for example, about macrocell users that occupy the same spectrum.

Furthermore, more detailed surveys of the most important interference management techniques belonging to each of the three groups mentioned above can be found in Ref. [64, 65].

9.5 Conclusions and Future Outlook

Home and enterprise networks having similar structure and different management systems have different saving potentials. Practically speaking, the only current scenarios in which *significant* energy savings are possible to achieve are dense corporate WLANs. There, the dynamic WLAN AP on/off switching approaches may be applied, resulting in considerable reduction of the energy footprint while keeping the desired level of the QoS. Some further savings are possible in the Ethernet backbone of the corporate networks, where solutions based on EEE can also be deployed. For home scenarios, due to their scattered nature (high level of distribution of the energy cost, with a very small cost per single user) and distribution of management among many different parties, the perspectives for the adoption of energy-efficient approaches on a wide scale are rather low. Federated residential access scenarios (DSL aggregation) have yet to prove to be deployable on wider scale.

In future context, a successful deployment of femtocells in home and corporate scenarios may considerably change the current perspective. The denser deployment of the femtocells forecasted in the near future will require more efficient interference management schemes, especially for femtocells that are applied in a distributed manner. Moreover, more efficient use of (wireless) network resources should also be taken into perspective in the future picture of home and enterprise scenarios, and context-aware networking has the necessary potential to make it reality. Especially in home and enterprise networks, where building smart environments (more and more tailored to the user needs) would soon become reality, this issue is highly relevant and should be discussed in the near future.

References

[1] Point Topic Whitepaper, "World Broadband Statistics Q1 2013", June 2013. Available online: http://point-topic.com/wp-content/uploads/2013/02/Point-Topic-Global-Broadband-Statistics-Q1-2013.pdf. Last accessed: 01.12.2013.

[2] E. Goma, M. Canini, A. Lopez Toledo, N. Laoutaris, D. Kostić, P. Rodriguez, R. Stanojević and P. Yagüe Valentin, "Insomnia in the access: or how to curb access network related energy consumption", SIGCOMM Comput. Commun. Rev., vol. 41, no. 4, pp. 338–349, 2011.

[3] H. El Abdellaouy, D. Bernard, A. Pelov and L. Toutain, "Green home network requirements", In Proc. of 2012 IEEE International Energy Conference and Exhibition (ENERGYCON), pp. 896–902, 2012.

[4] D. Boggs and R. Metcalfe, "Ethernet: distributed packet switching for local computer networks", ACM Commun., vol. 19, no.7, pp. 395–404, 1976.

[5] A. Majumder and J. Caffery Jr., "Power line communications", IEEE Potentials, vol. 23, no. 4, pp. 4–8, 2004.

[6] D. Becker, "Wi-Fi takes over homes", January 2005. Available online: http://news.cnet.com/Wi-Fi-takes-over-in-homes/2100-1010_3-5544025.html. Last accessed: 01.12.2013.

[7] IEEE 802.11-2012, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE standards, 2012.

[8] Bluetooth Special Interest Group, "Bluetooth Core Specification version 4.0", 2010, Available on line: https://www.bluetooth.org/en-us/specification/adopted-specifications. Last accessed: 02.12.2013.

[9] S. Ullah, H. Higgins, B. Braem, B. Latre, C. Blondia, I. Moerman, S. Saleem, Z. Rahman and K. Kwak, "A comprehensive survey of wireless body area networks: on PHY, MAC, and network layers solutions", J. Med. Syst., vol. 36, no. 3, pp. 1065–1094, 2012.

[10] J. Gerhart, Home Automation and Wiring, McGraw-Hill Professional, 1999. ISBN 0070246742.

[11] J. Andrews, H. Claussen, M. Dohler, S. Rangan and M. Reed, "Femtocells: past, present, and future", IEEE J. Sel. Areas Commun., vol. 30, no. 3, pp. 497–508, 2012.

[12] Informa Telecoms & Media, "Femtocell Market Status", Femtoforum whitepaper, February 2013. Available online: http://www.smallcellforum.org/smallcellforum_resources/pdfsend01.php?file=050-SCF_2013Q1-market-status%20report.pdf. Last accessed: 01.12.2013.

[13] J. Cox, "Designing 'iPad WLANs' poses new, renewed challenges", Network World, March 2012. Available online: http://www.networkworld.com/news/2012/032612-ipad-wlans-257585.html. Last accessed: 01.12.2013.

[14] P. Mahadevan, S. Banerjee, P. Sharma, A. Shah, and P. Ranganathan, "On energy efficiency for enterprise and data center networks", IEEE Commun. Mag., vol.49, no. 8, pp. 94–100, 2011.

[15] A. P. Jardosh, K. Papagiannaki, E. M. Belding, K. C. Almeroth, G. Iannaccone, and B. Vinnakota, "Green WLANs: on-demand WLAN infrastructures", Mob. Netw. Appl., vol. 14, no. 6, pp. 798–814, 2009.

[16] Cisco Validated Design, "Campus Wireless LAN, Technology Design Guide", August 2013, Available online: http://www.cisco.com/en/US/docs/solutions/CVD/Aug2013/CVD-CampusWirelessLANDesignGuide-AUG13.pdf. Last accessed: 01.12.2013.

[17] Cisco Whitepaper, "Save Energy in the campus or distributed office", 2013. Available online: http://www.cisco.com/en/US/prod/collateral/switches/ps10904/ps10195/ps13408/white-paper-c11-729777_ps10195_Products_White_Paper.html. Last accessed: 01.12.2013.

[18] T. Sridhar, "Wireless LAN switches - functions and deployment", Internet Protocol J., vol. 9, no. 3, pp. 2–15, 2006.

[19] K. Christensen, C. Gunaratne and B. Nordman, "The next frontier for communications networks: power management," Comput. Commun., vol.27, no. 18, pp. 1758–1770, 2004.

[20] A. Odlyzko, "Data networks are lightly utilized, and will stay that way", Rev. Netw. Econ., vol. 2, no. 3, pp. 210–237, 2003.

[21] P. L. Nguyen, T. Morohashi, H. Imaizumi and H. Morikawa, "A performance evaluation of energy efficient schemes for green office networks", In Proc. of IEEE Green Technologies Conference 2010, 2010.

[22] M. Dischinger, A. Haeberlen, K. Gummadi and S. Saroiu, “Characterizing residential broadband networks”, In Proc. of 7th ACM SIGCOMM Conference on Internet Measurement (IMC’07), pp. 43–56, 2007.

[23] G. Maier, A. Feldmann, V. Paxson and M. Allman, “On dominant characteristics of residential broadband internet traffic”, In Proc. of 9th ACM SIGCOMM Conference on Internet Measurement Conference (IMC’09), pp. 90–102, 2009.

[24] E. Tan, L. Guo, S. Chen and X. Zhang, “CUBS: coordinated upload bandwidth sharing in residential networks”, In Proc. of 17th IEEE International Conference on Network Protocols (ICNP 2009), pp. 193–202, 2009.

[25] F. Mhiri, K. Sethom, R. Bouallegue and G. Pujolle, “AdaC: adaptive coverage coordination scheme in femtocell networks”, in Proc. of 4th Joint IFIP Wireless and Mobile Networking Conference (WMNC), 2011, October 2011.

[26] Cisco Report, “Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update 2012-17”, February 2013. Available online: http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html. Last accessed: 01.12.2013.

[27] C. Yan, Z. Shunqing; X. Shugong and G. Li, “Fundamental trade-offs on green wireless networks”, IEEE Commun. Mag., vol. 49, no. 6, pp. 30–37, 2011.

[28] S. Kandula, K. C.-J. Lin, T. Badirkhanli, and D. Katabi, “FatVAP: aggregating AP backhaul capacity to maximize throughput”, 5th USENIX Symposium on Networked Systems Design and Implementation (NSDI ’08), pp. 89–104, 2008.

[29] D. Giustiniano, E. Goma, A. Lopez Toledo, I. Dangerfield, J. Morillo, and P. Rodriguez “Fair WLAN backhaul aggregation”, in Proc. of 16th Annual International Conference on Mobile Computing and Networking (MobiCom’10), pp. 269–280, 2010.

[30] N. Thompson, G. He, and H. Luo, “Flow scheduling for end-host multihoming”, in Proc. of 25th IEEE International Conference on Computer Communications (INFOCOM’06), 2006.

[31] G. Ananthanarayanan, V. Padmanabhan, L. Ravindranath, and C. Thekkath, “COMBINE: leveraging the power of wireless peers through collaborative downloading”, In Proc. of 5th International Conference on Mobile Systems, Applications and Services (MobiSys’07), pp. 286–298, 2007.

[32] P. Nedeltchev, “The new opportunities of enterprise networking”, Cisco IT Trends in IT Article, Extended Enterprise Network, 2012. Available online: http://www.cisco.com/en/US/solutions/collateral/ns340/ns1176/borderless-networks/extended_enterprise_network.html. Last accessed: 01.12.2013.

[33] M. Ajmone Marsan and M. Meo, “Green wireless networking: three questions”, In Proc. of 10th IFIP Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net), pp. 41–44, 2011.

[34] T. Chen, Y. Yang. H. Zhang, H. Kim and K. Horneman, “Network energy saving technologies for green wireless access networks”, IEEE Wireless Commun., vol. 18, no. 5, pp. 30–38, 2011.

[35] S. Chiaravalloti, F. Idzikowski, and Ł. Budzisz, “Power consumption of WLAN network elements,” TKN Group, TU Berlin, Tech. Rep. TKN-11-002, 2011.

[36] J. Spinney, N. Green, K. Burningham, G. Cooper, and D. Uzzell, “Are we sitting comfortably? Domestic imaginaries, laptop practices, and energy use”, Environ. Plann. A, vol. 44, no.11, pp. 2629–2645, 2012.

[37] T. Nguyen and A. Black. Preliminary study on power consumption of typical home network devices. Technical Report 07011A, Centre for Advanced Internet Architectures (CAIA), 2007. Available online: http://caia.swin.edu.au/reports/071011A/CAIA-TR-071011A.pdf. Last accessed: 01.12.2013.

[38] H. Hlavacs, G. Da Costa and J. Pierson, “Energy consumption of residential and professional switches”, In Proc. of International Conference on Computational Science and Engineering (CSE ’09), vol. 1, pp. 240–246, 2009.

[39] A. P. Jardosh, G. Iannaccone, K. Papagiannaki, and B. Vinnakota, “Towards an energy-star WLAN infrastructure”, In Proc. of 8th IEEE Workshop on Mobile Computing Systems and Applications (HotMobile ’07), pp. 85–90, 2007.

[40] A. Murabito, “A comparison of efficiency, throughput, and energy requirements of wireless access points,” University of New Hampshire, InterOperability Laboratory, 2009.

[41] H. El Abdellaouy, D. Bernard, A. Pelov and L. Toutain, “Green home network requirements”, In Proc. of IEEE International Energy Conference and Exhibition (ENERGYCON 2012), pp. 896–902, 2012.

[42] IEEE 802.3az-2010, “IEEE P802.3az Task Force: Energy Efficient Ethernet”, 2010. Available online: http://ieee802.org/3/az/public/index.html. Last accessed: 01.12.2013.

[43] C. Gunaratne, K. Christensen, B. Nordman and S. Suen, “Reducing the energy consumption of Ethernet with adaptive link rate (ALR)”, IEEE Trans. Comput., vol. 57, no. 4, pp. 448–461, 2008.

[44] K. He, Y. Wang, X. Wang, W. Meng and B. Liu, “GreenVLAN: An energy-efficient approach for VLAN design”, In Proc. of International Conference on Computing, Networking and Communications (ICNC 2012), pp. 522–526, 2012.

[45] P. Morales, J. Ok, M. Minami and H. Morikawa, “Smart wireless aggregation for access network infrastructure power saving in the office environment,” IEICE Technical Report, IN2008-209, 2009.

[46] C. Rossi, C. Casetti and C.-F. Chiasserini, “An energy efficient protocol for gateway-centric federated residential access networks”, 2011. Available online: http://arxiv.org/abs/1105.3023. Last accessed: 01.12.2013.

[47] Y. Agarwal, R. Chandra, A. Wolman, P. Bahl, K. Chin, and R. Gupta, “Wireless wakeups revisited: energy management for VoIP over Wi-Fi smartphones”, In Proc. of 5th International Conference on Mobile Systems, Applications and Services (MobiSys’07), pp. 179–191, 2007.

[48] W. Ye, J. Heidemann, and D. Estrin, “Medium access control with coordinated adaptive sleeping for wireless sensor networks,” IEEE/ACM Trans. Netw., vol. 12, no. 3, pp. 493–506, 2004.

[49] B. Wang, “Coverage problems in sensor networks: a survey,” ACM Comput. Surveys, vol. 43, no. 4, pp. 32:1–32:53, 2011.

[50] M. Panjwani, A. Abbott, and T. Rappaport, “Interactive computation of coverage regions for wireless comm. In multi floored indoor environments,” IEEE J. Sel. Areas Commun., vol. 14, no. 3, pp. 420–430,1996.

[51] R. Whitaker, L. Raisanen, and S. Hurley, “A model for conflict resolution between coverage and cost in cellular wireless networks”, In Proc. of 37th Hawaii Intl. Conf. on System Sciences (HICSS’04), 2004.

[52] F. Ganji, Ł. Budzisz, and A. Wolisz, “Assessment of the power saving potential in dense enterprise WLANs”, TKN Group, TU Berlin, Tech. Rep. TKN-13-003, 2013. Available online: http://www.tkn.tu-berlin.de /fileadmin/fg112/Papers/papers_all/TR-final-20130426.pdf. Last accessed: 01.12.2013.

[53] F. Ganji, Ł. Budzisz, and A. Wolisz, “Assessment of the power saving potential in dense enterprise WLAN”, In Proc. of IEEE 24th International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC ’13), pp. 2850–2855, 2013.

[54] M. Ajmone Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, “A simple analytical model for the energy-efficient activation of access points in dense WLANs”, In Proc. of 1st International Conference on Energy-Efficient Computing and Networking, pp. 159–168, 2010.

[55] J. Lorincz, A. Capone, and M. Bogarelli, “Energy savings in wireless access networks through optimized network management”, In Proc. of 5th International Symposium on Wireless Pervasive Computing (ISWPC ’10), pp. 449–454, 2010.

[56] J. Lorincz, M. Bogarelli, A. Capone, and D. Begusic, “Heuristic approach for optimized energy savings in wireless access networks”, In Proc. of International Conference on Software, Telecommunications and Computer Networks (SoftCOM ’10), pp. 60–65, 2010.

[57] S. Lee, S. Seo, and N. Golmie, “An efficient power-saving mechanism for integration of WLAN and cellular networks”, IEEE Commun. Lett., vol. 9, no. 12, pp. 1052–1054, 2005.

[58] J.-W. Yoo and K. H. Park, “A cooperative clustering protocol for energy saving of mobile devices with WLAN and Bluetooth interfaces”, IEEE Trans. Mobile Comput., vol. 10, no. 5, pp. 491–504, 2011.

[59] N. Mishra, K. Chebrolu, B. Raman, and A. Pathak, “Wake-on-WLAN”, In Proc. of 15th international conference on World Wide Web (WWW ’06), pp. 761–769, 2006.

[60] Ł. Budzisz, F. Ganji, G. Rizzo, M. Ajmone Marsan, M.Meo, Y. Zhang, G. Koutitas, L. Tassiulas, S. Lambert, B. Lannoo, M. Pickavet, A. Conte, I. Haratcherev and A. Wolisz, “Dynamic resource provisioning for energy efficiency in wireless access networks: a survey and outlook,” IEEE Commun. Surveys Tutorials, vol. 16, no. 4, pp. 2259–2285, 2014.

[61] J. Cullen, “Radioframe presentation”, Femtocell Europe, 2008.

[62] X. Wang, A. Vasilakos, M. Chen, Y. Liu, T. Kwon, “A survey of green mobile networks: opportunities and challenges,” Mobile Netw. Appl. vol. 17, no. 1, pp. 4–20, 2012.

[63] M. Yavuz, F. Meshkati, S. Nanda, A. Pokhariyal, N. Johnson, B. Roghothaman and A. Richardson, “Interference management and performance analysis of UMTS/HSPA+ femtocells”, IEEE Commun. Mag., vol. 47, no. 9, pp. 102–109, 2009.

[64] T. Zahir, K. Arshad, A. Nakata and K. Moessner, “Interference management in femtocells”, IEEE Commun. Surveys Tutorials, vol. 15, no. 1, pp. 293–311, 2013.

[65] F. Mhiri, K. Sethom and R. Bouallegue, “A survey on interference management techniques in femtocell self-organizing networks”, J. Netw. Comput. Appl., vol. 36, no. 1, pp. 58–65, 2013.

[66] H. Claussen, L. Ho and L. Samuel, “Self-optimization of coverage for femtocell deployments”, In Proc. of Wireless Telecommunications Symposium (WTS 2008), pp. 278–285, 2008.