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Research Project II

Improving the Energy Efficiency of SURFwireless

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Abstract

SURFnet offers a service called SURFwireless. This is a distributed Wifi-as-a-Service implementation for SURFnet customers, the higher education and research institutes in The Netherlands. In light of "Greening" the IT footprint SURFnet wanted to investigate methods to improve the energy efficiency of SURFwireless. This research investigates the energy consumption of SURFwireless, and explores methods and proposals to improve energy efficiency of wireless infrastructures. The specific details, opportunities, and the applicability to SURFwireless are evaluated.

A prerequisite to improve the energy efficiency is implementing methods to measure the power consumption of SURFwireless. Due to its distributed nature it is difficult to measure the power consumption and use one specific method at every location. As proof of concept the SURFwireless implementation at SURFnet's offices was measured using features of the PoE switches that power the Access Points. The measurements showed a distinctive day and night pattern, but the used energy does not fluctuate a lot between the minimum and the maximum.

Our study and evaluation of recent research into methods and approaches to improve the efficiency efficiency has resulted in a inventory of advantages and disadvantages. We have concluded that there is no easily applicable method available at this moment.

Acknowledgement

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Contents

1 Introduction

Wireless Local Area Networks (WLANs) provide flexibility in connectivity for mobile devices. It is a ubiquitous solution to provide wireless Internet that satisfies most communication requirements in current environments. A WLAN consists of Access Points and possibly a centralised controller that controls the network. Those WLANs are managed by the network engineers of the network infrastructure. SURFnet offers a service called SURFwireless [1], a distributed solution that provides a managed WLAN for institutes. The WLANs are created by deploying dedicated Access Points (APs) in all areas that require coverage for wireless stations. The Access Points are monitored and managed from a central location by SURFnet, but do not depend on a controller for traffic flow control. The wireless infrastructure of SURFwireless exists of devices such as Access Points and management/monitoring. Currently, it is unknown how much energy the wireless infrastructure utilises spread over many locations. In light of "Greening" the IT footprint, SURFnet wanted to investigate methods to improve the power efficiency of SURFwireless. The research aims to acquire insight into the energy consumption and find capabilities to improve the energy efficiency of the wireless infrastructure. Whilst this research focuses on SURFwireless, the results should also benefit other distributed wireless infrastructures.

1.1 Research Questions

As was mentioned in Section 1, this research focuses on improving the energy efficiency of wireless network infrastructures. Therefore, the research aims to answer the following questions:

How can existing mechanisms be leveraged to maximise the energy efficiency of distributed Access Points in a wireless infrastructure?

In order to guide the enquiry of the research the main research question has been divided into the following sub questions.

- How does one measure accurately the power consumption of each Access Point?
- What solutions are available and applicable to accomplish a lower energy usage of Access Points in SURFwireless?

2 Related Work

A mechanism is introduced by Ohmori et al. [2] that enables energy saving by disabling the power supply of the Access Point. This mechanism is combined using extra devices to authenticate users and Access Points. Every new wireless user is detected by an always-on Access Point and is forwarded to an Access Point that must be booted up or an already booted AP. When the authentication expires, the platform has the knowledge that an Access Point has gone idle and can disable PoE on a port to disable the Access Point.

The method investigated in the paper by Kwan-Wu Chin [3] exploits a scheduler, which dynamically controls Access Point to maintain coverage and performance. This includes modifying the transmission power to fully cover every wireless user. The scheduler finds the minimum number of Access Points to cover and provides the best wireless connectivity for all currently connected wireless devices.

In the research of Chen et al. [4] Software Defined Networking (SDN) is combined with the technique RoD (Radio-On-Demand). SDN includes a central controller and the capability of collecting flow-level traffic statistics. Through the use of the SDN controller the received signal strength indicator (RSSI) and Signal to Noise Ratio (SNR) of each wireless client allows insight into the signal strength received by the wireless devices. Based on this information a system can decide whether to enable the power of APs, and using the flow control feature of SDN switches, to associate the connection flows to a specific AP.

Quentin Bodinier et al. [5] introduced a technique of both switching off APs and adjusting the transmission power of other Access Points to improve the coverage area. The introduced platform finds clusters of wireless stations and adds intelligence to enhance power efficiency such as topology management, relaying, beamforming, offloading and heterogeneous networks deployment. Heterogeneous networks are networks with the interconnection of different protocols, in this sense the paper is introducing mechanisms which are used in Cellular networks.

The method by Ma Lin et al. [6] combines disabling Access Points with a clustering algorithm which provides the knowledge to power on and off a part of the Access Points. A WLAN controller monitors the number of users requesting wireless and decides to power on/off any Access Point.

Hiroyuki Yomo et al. [7] researched a wakeup receiver that works on the 2.4 GHz band just like the 802.11bg standards. When Access Points are in sleep state they can be reactivated by using the intermediate transceiver. Wireless users can send a wake-up signal to an Access Point including an ID that identifies the specific Access Point.

The technique investigated by Yuan Li et al. [8] adjusts transmission power adaptively based on channel estimation. Channel estimation describes how a signal propagates from the transmitter to the receiver and represents the combined effect of, for example, scattering, fading, and power decay with distance. [9] It allows WLAN devices to use a much lower power level in transmit mode and tunes the transmission power adaptively under different channel conditions.

The method by Ma Lin et al. [10] focuses on an algorithm to optimise the deployment of Access Points and the transmission power. It tries to find the minimum number of Access Points to provide full coverage in the area and fine tune the cover area by adjusting the transmission power.

The research accomplished by Toshiyasu Tanaka et al. [11] involves an automatic sleep control strategy that frequently monitors Access Points data traffic conditions and executes the change of APs communication state if traffic conditions changes. A communication state can be a sleep-state, idle-state, busy state, or wake-up state based on network traffic.

The paper written by Zeng Wang et al. [12] deals with controlling the power real-time by extending a power control message type for power control and adding a corresponding control action in the controller and switch. The power control module is connected to the SDN controller through the north API interface. By using the Power control module it is possible to adjust the transmission power of the Access Point. It uses game theory to allocate the transmission power for the best signal to interference plus noise ratio.

The research by Kimin Lee et al. [13] is about optimization on power-operation modes in Access Points (APs), channel selections and user-AP associations for improving energy efficiency and avoiding interference without sacrificing users demands. To do this they use an algorithm in combination with integer programming and implement this in a prototype.

In a research by Robert Riggio et al.[14] consumption monitoring applications are configured on Arduino devices, which are connected to Access Points [15]. The energy consumption of the Access Points is measured by the Arduino. By using an SDN framework the solution allows to move wireless users to different Access Points and allowing the consumption monitoring application to turn off Access Points.

3 Background

In this chapter the background of the research and the technology behind SURFwireless is introduced.

3.1 SURFwireless

SURFwireless is a service offered by SURFnet to provide wireless connectivity to educational institutes. SURFnet is the National Research and Education Network of The Netherlands, which interconnects all educational institutes. SURFnet develops, implements and maintains services for higher educational institutes. One of the innovative services that SURFnet provides is SURFwireless. SURFwireless is WiFi-as-a-Service where SURFnet builds the network infrastructure at the location of the institute. SURFnet ensures full coverage throughout the building and a stable performing wireless connectivity. The Access Points of SURFwireless are connected to the local area network (LAN) of the institute. Wireless devices that connect to the wireless network, provided by SURFwireless, get appointed to a Virtual LAN configured on the local switches of the institute's LAN. The assignment of IP addresses to wireless devices also occurs, through this VLAN, from the DHCP server of the institute.

The institute pays a monthly fee for the service and receives maintenance, monitoring and management from SURFnet. While SURFnet operates SURFwireless centrally, every customer can still determine their own configuration. SURFnet evaluates the operational requirements of the institute and configures SURFwireless to abide to these requirements. Customers only require to provide a local network infrastructure and other necessary facilities such as Power-of-Ethernet (PoE) for the Access Points. The SURFwireless service of all institutes is managed at a central redundant location. The backbone network infrastructure of SURFwireless is maintained and operated by SURFnet.

SURFwireless makes use of a distributed wireless infrastructure without a controller. The solution that SURFnet adopted for SURFwireless is provided by Aerohive which consists of the Access Points and a Central Manager called the Hive Manager. The controller-less solution poses several advantages for both SURFnet and the customer. There will be no single point of failure where the traffic of every Access Point has to transit through a controller. There is no requirement of supplying a controller at every location. The Access Points can be regulated at one central point. By making use of a distributed solution SURFwireless is able to scale up to ten thousand Access Points [16].

A component of SURFwireless is the monitoring of the performance. Through the use of probes the performance of the wireless network is continuously monitored. The probes send traffic the same way as normal clients to measure the WiFi and network characteristics under normal situations.

3.2 SURFnet Infrastructure

The SURFwireless implementation located at SURF in Utrecht provides wireless connectivity for SURFnet, SURFmarket and SURF. The implementation consists of 33 distributed Aerohive AP230 [17] Access Points which are connected to Juniper EX4300 PoE+ switches [18]. This implementation is SURFnet specific, which means that it can be implemented differently at other customers of SURFwireless. The infrastructure is set up with every Access Point configured differently to provide a sufficient signal strength for every user. If an Access Point is located at the edge of the building the signal is scaled down. The signal strength of Access Points is measured for capacity and coverage. This means that the signal strength must be a minimum of -62 dBm and that there are no more than 50 wireless devices on one Access Points. The bandwidth required for each user is also taken into consideration. By having the aforementioned configuration for the Access Points, wireless devices often detect two or more Access Points. However, a minimum of one Access Point provides a sufficient wireless signal strength.

Every institute with SURFwireless could have a different implementation than the one described above. This includes the backbone network infrastructure to facilitate the network for SURFwireless. The next section will describe methods to measure the energy consumption for a distributed infrastructure.

4 Measure power consumption

A network protocol which is used in monitoring is the Simple Network Management Protocol (SNMP). By using the SNMP agent on the network device it is possible to execute read/write commands to retrieve information and control devices. The read command is the only relevant command for this research. The information can be retrieved by the Network Management System (NMS). When the NMS requests information from the network device the information will be displayed as a list of information which is called the Management Information Base (MIB). By walking through the MIB it is possible to find specific information. Research has concluded that Cisco PoE switches have the possibilities of displaying the energy consumption per port. However, the MIB definitions are different for each hardware device. A server has MIB definitions to monitor for example, the temperature, and the CPU usage, and on a switch it could define the port information and port status. In this situation the MIB definitions of both Cisco and Juniper PoE switches are not similar. When one attempts to acquire the information on the Juniper PoE switches the output is incomprehensible.

The Juniper PoE switches provide a telemetries CLI command that begins collecting the power consumption data of each switch port at a specific time interval [19]. By specifying a duration and a small interval the PoE will report the power consumption at the time the data was gathered. The Juniper switch allows commands to be manually executed to see the current power consumption of every port. The power consumption must be reported multiple times within a short period to detect any changes in the power consumption. Listing 1 displays an example of the output of the telemetry report. During the measuring process the difference of the results between an interval of 2 and 5 minutes seemed to be negligible. However, when an interval of 2 minutes was selected the Juniper did not report the power consumption for 24 hours as the report only sends out 999 records per port. Therefore the default interval of 5 minutes has been selected.

```
ex4300-48PoEplus1> show poe telemetries interface all count all | no-more
Interface  Sl No   Timestamp                Power    Voltage
 ge-0/0/5     1    10-26-2016 15:30:10 UTC  7.1W     55.6V
              2    10-26-2016 15:25:10 UTC  7.1W     55.6V
              3    10-26-2016 15:20:10 UTC  7.3W     55.6V
              4    10-26-2016 15:15:10 UTC  7.1W     55.6V
              5    10-26-2016 15:10:10 UTC  7.3W     55.6V
              6    10-26-2016 15:05:10 UTC  7.3W     55.6V
              7    10-26-2016 15:00:10 UTC  7.1W     55.6V
```

Listing 1: Example of output of Juniper telemetry

As can be seen in Listing 1 the output of the Juniper telemetry function has a specific format. Telemetry is configured to collect the power consumption of all ports of the switch even though only specific ports are needed. By filtering the unnecessary ports the results can be analysed. Following this a Python script is used to calculate the hourly mean energy consumption (see Appendix A).

5 Measurement

This chapter contains the results of the measurements of the power consumption followed by an analysis of the results.

5.1 Results

The measurements of the power consumption are executed multiple days. For a period of 8 days a sample of the watt of each switch port, which has an Access Point connected to it, is created every 5 minutes. To calculate the actual energy consumption one has to take 12 samples and calculate the mean of the samples. By doing this calculation one will get the hourly energy consumption of one Access Point. The total hourly energy consumption of SURFwireless can be calculated by summing up the means of every AP. To acquire an accurate representation of the consumption of each Access Point the mean is calculated of the energy consumption of each Access Point over multiple days. In Figure 5.1 is the daily energy consumption displayed of 28 Access Points. One bar of the histogram represents the sum of the aforementioned means of all measured Access Points. The mean of the hourly energy consumption is 204.27W per hour (or 240.84W per hour for the adapted version as explained later in the section). The figure on the total consumption shows that there is little difference between the hourly consumptions. Therefore, Figure 5.2 shows a graph with a smaller scale for further analysis. Table 5.1 displays some more detailed information on the total daily energy consumption. However, the accuracy of the measurement results can not be determined. There is no information on the accuracy of the measurements in the documentation of Juniper PoE switch.

Minimum	202.37 Wh	Minimum	238.60 Wh
Maximum	207.33 Wh	Maximum	244.42 Wh
Mean	204.29 Wh	Mean	240.85 Wh

Table 5.1: Left side actual results, right side adapted results

In Chapter 3 was mentioned that there are 33 Access Points in the wireless infrastructure of SURFwireless at SURFnet. However 5 Access Points do not appear in the results or indicate zero watts power consumption. These Access Points are functioning perfectly and do not indicate any issues. After debugging the issue and repeating the measurements the issue persisted. However, to create a hypothesis of the potential total energy consumption consumption the assumption is made that these 5 Access Points have a similar consumption as the mean of the other Access Points. By adding these values the total energy consumption is increased by 17.89%. The Figure 5.3 includes the adapted results.
In Figure 5.4 there are comparisons of the energy consumption of five Access Points between the weekend and weekdays. The weekdays count as from Monday 00:00 until Friday 23:59. The Access Points that are enlisted are specifically selected due to their location. The reason is to possibly correlate the energy consumption with the number of users. The Access Point AP0410, which is located at the Reception, provides a wireless coverage for a smaller number of people than AP0409 which is located in the SURFnet office area. The other locations of the Access Points are of working areas for different type of users. The SURFwireless infrastructure provides coverage on multiple floors; third floor for SURFmarket, fourth floor for SURFnet and fourth floor for SURF offices.

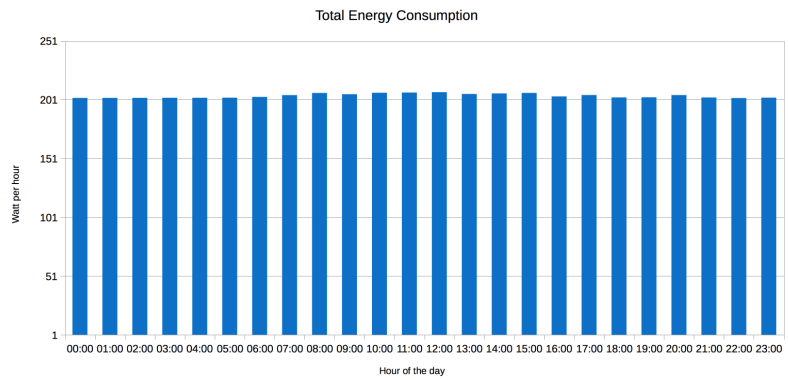

Figure 5.1: Energy consumption of measured Access Points at SURFnet

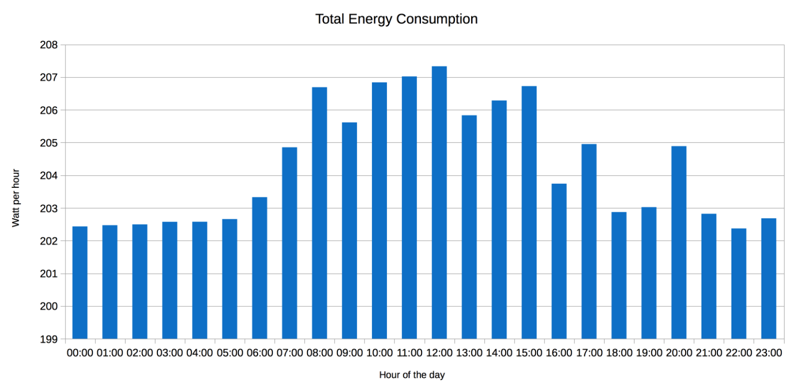

Figure 5.2: Zoomed in results

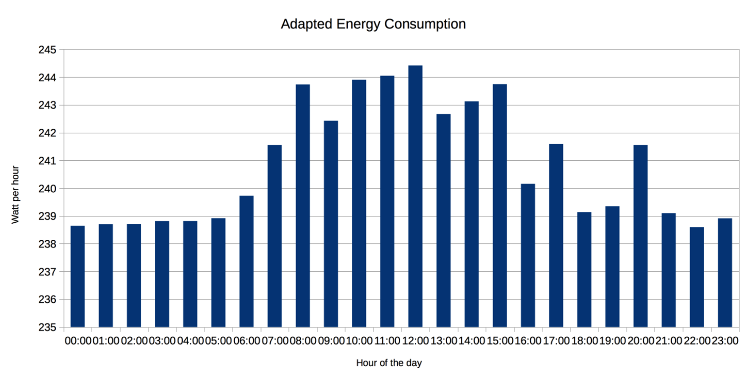

Figure 5.3: Zoomed in adapted results

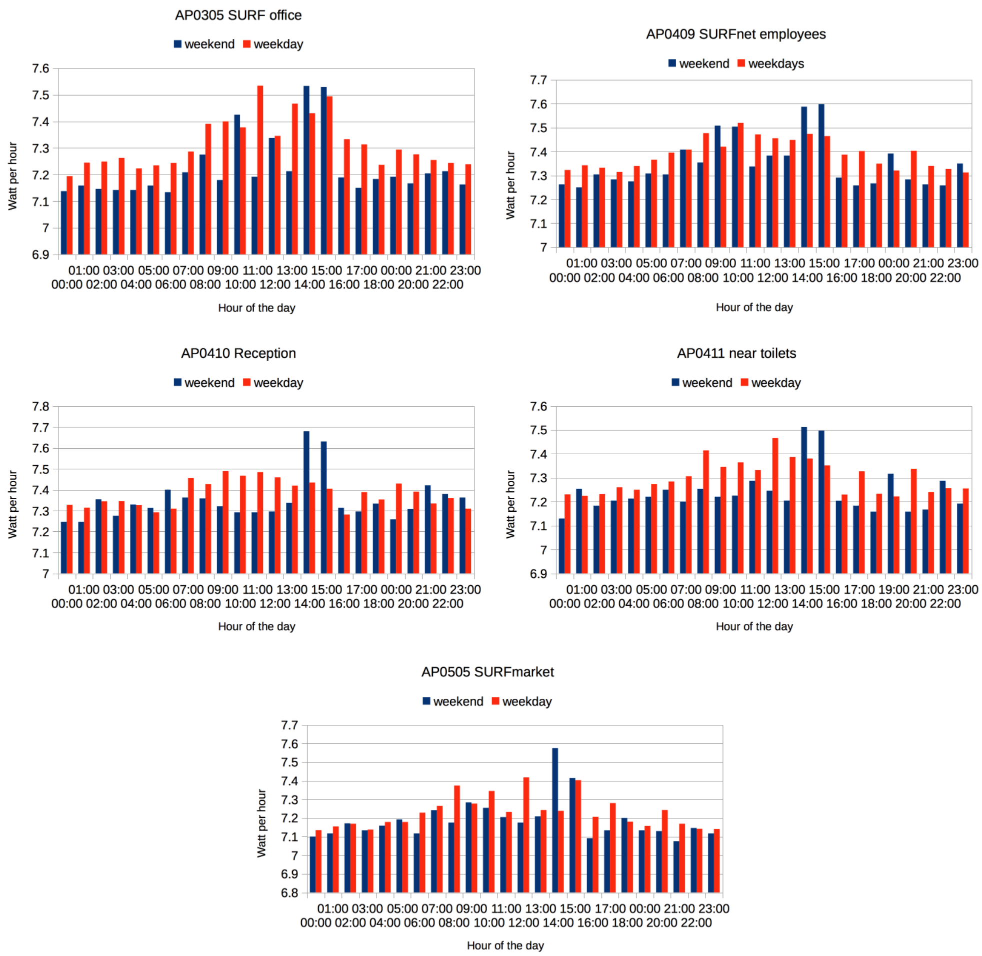

Figure 5.4: Zoomed in comparison Access Points

5.2 Analysis

The graph in Figure 5.1 displays the results of the measurements over multiple days. The results seem to be correlated to the working hours of employees. In the morning the energy consumption of the Access Points is relatively low, until people arrive at work, which is after 6:00 and then the energy consumption increases slowly. The assumption is made that the minimal energy consumption is approximately the idle energy consumption. This minimal energy consumption occurs during night times. There is a possibility that there are devices still active on the wireless network but this number is relatively low compared to office hours. This idle energy consumption seems to be 202.37 watt per hour or 238.60 watt per hour if you include the adapted results. The reasons for the observed peaks at 17:00 and 20:00 could not be determined.

Overall the amount of energy consumption is caused by mostly Access Points being idle while activity on the network does increase the energy consumption, the consumption only increases by a maximum percentage of 2.45%. All results do not take the accuracy of the measurements into consideration.

The graphs of Figure 5.4 display a comparison of the usage of specific Access Points in the weekends and during the week. The Figure 5.4 shows that the energy consumption of the Access Points is higher during the week. The reasons for the peaks at 14:00 and 15:00 could not be determined (see Tables 5.2 and 5.3).

As has been mentioned there are missing results of 5 Access Points. Even after debugging the Juniper Telemetry function and the missing Access Points the reason for missing results is still unknown. All measurements in the research showed the same issue. Therefore further use of the telemetry feature cannot be recommended for reliable measurements of the energy consumption in the future.

Access Point	AP0411	AP0410	AP0409	AP0505	AP0305
Location	Toilets	Reception	SURFnet office	SURFmarket	SURF office
Minimum	7.22 Wh	7.28 Wh	7.31 Wh	7.13 Wh	7.19 Wh
Maximum	7.47 Wh	7.49 Wh	7.52 Wh	7.42 Wh	7.53 Wh
Mean	7.30 Wh	7.38 Wh	7.39 Wh	7.23 Wh	7.31 Wh

Table 5.2: Minimal, Maximum and Mean weekdays

Access Point	AP0411	AP0410	AP0409	AP0505	AP0305
Location	Toilets	Reception	SURFnet office	SURFmarket	SURF office
Minimum	7.13 Wh	7.24 Wh	7.25 Wh	7.08 Wh	7.13 Wh
Maximum	7.51 Wh	7.68 Wh	7.60 Wh	7.58 Wh	7.53 Wh
Mean	7.24 Wh	7.35 Wh	7.35 Wh	7.19 Wh	7.22 Wh

Table 5.3: Minimal, Maximum and Mean weekend

6 Applicability of mechanisms of saving energy

The following chapter describes various techniques to lower the energy usage of wireless networks. Each mechanism is described into detail and the requirements to implement the method into a wireless infrastructure are enlisted. Every method concludes with a discussion on the applicability of the method to SURFwireless.

6.1 Disabling Power Supply

The method by Motoyuki Ohmori et al. [2] is a technique which focuses on detecting new wireless stations into a network infrastructure. The technique involves the concept Resource-On-Demand also called Radio-On-Demand (RoD) which enables Access Points when required. Disabling and enabling Access Points is performed by using a script which executes a command on the Command Line Interface (CLI) to turn off the power supply at the Power Sourcing Equipment (PSE). The method initiates with Access Points disabled and only enables Access Points when new wireless users appear with a high enough signal strength indicator (RSSI) and Signal to Noise Ratio (SNR). This preserves the quality of wireless connections between the available Access Points and wireless users. Before wireless devices can connect they have to authenticate, which is on top of the usual 802.11i standard for authentication. The authentication is set up between the wireless devices and the C3 Central authentication tool, which is used in combination with the Base Quaker (BQ) to detect wireless users. The C3 is also used to detect the disappearance of wireless devices and therefore disabling possible Access Points. The BQ is used as an intermediate AP to relay any connection requests from reappearing wireless devices to another Access Point. The BQ can relay the request to an already running Access Point or send a request to the C3 to wake-up an Access Point.

6.1.1 Discussion

The method assumes that there is more than one Access Point in one area for the detection of new users. While the method requires extra devices, there is no requirement of any modification to the existing hardware. Adding the C3 server and the BQ device increases the energy consumption, these devices are introduced to detect users and to act accordingly. However, when there are absolutely no users to detect the extra devices the C3 server and the BQ device will just stay idle and therefore waste energy. As mentioned in Chapter 5 the energy consumption of the Access Points is relatively low. Even though increasing the number of Access Points will also increase the energy consumption, the energy consumption of the BQ and C3 might exert the energy consumption increase per Access Point. There is only one C3 in the network whilst there can be multiple BQ to detect wireless devices over various locations. Periods which have a low probability of active users such as weekends do not require extra devices to detect users as the wireless usage could be predictable. The method makes sure that each wireless device acquires a good connectivity by allowing the wireless device to prefer an Access Point based on signal information. However, the roaming of users between Access Points is not taken into consideration. To disable the Access Points the paper suggests to execute a Ruby script by a centralised desktop, this script includes a telnet session to execute a command on the PSE. While SSH would be a more secure way to implement this mechanism, executing a script to control a switch port can lead to vulnerable situations. The usefulness of disabling the power supply depends on the boot time of the Access Point. With the Aerohive Access Points it takes about 77 seconds to boot[1] The mechanism relies on an authentication of wireless devices to avoid malicious devices from turning on Access Points. However, this authentication is based on MAC addresses, which can spoofed and therefore add no benefit. The authentication only adds pointless complexity to the wireless infrastructure. The solution is not extensively tested in a testbed, there is only a simulation based on calculations.

6.2 Covering wireless devices through scheduler

The scheduler developed by Kwan-Wu Chin [3] is a method that supposedly focuses on Quality of Service (QoS) and guarantees appropriate coverage whilst disabling unnecessary Access Points. The terminology used as QoS defines the signal quality to acquire specific bandwidth rather than applying traffic priority and resource reservation control mechanisms. When one disables an AP and lowers the RSSI of wireless stations, the wireless throughput will decrease simultaneously. To avoid this issue the method is using a solution, which is similar to the set covering problem which essentially finds the minimum number of elements, in this case Access Points, to cover the set of wireless stations. By balancing the energy consumption of Access Points and QoS requirements the right Access Points will be switched off dynamically. To detect all wireless stations the method requires the 802.11k standard which allows both wireless device and Access Point to interchange connectivity information, this includes the negotiation of transmission power. Both wireless device and the Access Point must support the 802.11k standard and the 802.11v amendment that supports roaming to other Access Points. The 802.11k standard is used by both Access Point to send out reports of neighbouring Access Points. The standard allows Access Points to request wireless devices to send information on the wireless channel utilisation and interference information. The reports also include performance data such as packet loss, signal quality and throughput. Lastly 802.11k instructs Access Points on hidden terminals and allows both Access Points and wireless device to negotiate and modify their transmission power [20].
The proposed mechanism utilises a central node which controls Access Points to broadcast measurement frames on every power level. Wireless devices respond to this frame and report back the observed signal strength. Through this method the green scheduler can determine which wireless user is reachable with a specific transmission power of the Access Point and the achievable data rate.

6.2.1 Discussion

The mechanism implies a high-density wireless network infrastructure. High-density wireless networks are topologies where the number of wireless devices and required wireless throughput exceeds the capacity of the network design and the Access Point. With this issue a high RSSI and/or a good Signal-to-Noise Ratio (SNR) is insufficient to provide a good performing wireless connectivity for wireless devices. A used solution for this is implementing more Access Points and avoid interference by using techniques such as different channels for the wireless signals. SURFwireless does not have a wireless infrastructure with a high density set up. The method attempts to find the set of Access Points that will provide the Quality of Service for the wireless devices. It is based on information acquired by the 802.11k standard which can provide reports on nearby Access Points and information on their accessibility. The network will experience more

[1] The boot time has been determined by starting up the AP and testing the reachability of the AP from the local wired network.

overhead due the 802.11k packets. The method assumes that both wireless devices and the Access Points support the 802.11k standard, the Aerohive APs supports this standard. The SURFwireless Access Points are already making use of 802.11k capabilities. While the scheduler is dynamic and therefore adjusting to the situation of wireless devices and Access Points, the method does not completely demonstrate this. The scheduler has not been proven to be functional as the paper only contains simulation results. There is no test-bed available currently, however, this is part of the future work for the developer of the mechanism.

6.3 Energy Saving with QoS Guarantee for WLAN using SDN

The method in the research by Yu-Jia Chen et al. [4] suggests to use Software Defined Networking (SDN) on wireless networks. Through the use of an SDN controller in SDN networks it is possible to collect flow-level statistics of the traffic. The bandwidth requirements can be derived from these statistics. The method suggests to adjust the number of Access Points based on the bandwidth and the RSSI requirement of the wireless devices. The Access Points are connected to an OpenFlow switches.

An extra device called the Energy Saving Policy Server (ESPS) uses the SDN flow-level statistics provided by the SDN controller to estimate the bandwidth requirements. Following this is the RSSI measurement of the mobile devices to the other Access Points nearby to indicate handoff possibilities and assess the maximum capacity provided by the AP. Every mobile device sends its RSSI of nearby APs to the ESPS and the handover latency limitation for a potential handover.

The optimisation of the resources per Access Point is solved by using Integer Programming which ensures that wireless devices acquires sufficient bandwidth. This paper does not go further into details of Integer Programming. Based on all information the ESPS can decide whether another AP can be turned on or turned off. By using the possibilities of SDN it is possible to hand off wireless users to other Access Points by using the forwarding table of an Openflow switch. Before handing off a wireless device the ESPS ensures all data to be multicasted by the OpenFlow switch to multiple Access Points. By completing this handoff no data is lost and the formed Access Point can be turned off.

6.3.1 Discussion

This method is interesting in theory, however, there seems to be no implementation of Software Defined Wireless Networking (SWDN) available. There is no modification required in the wireless devices, the evaluation of the power efficiency is done centrally. Part of the method is to use SDN in combination with an extra device to measure the bandwidth requirements. Aerohive Access Points and/or Aerohive Manager are already able to view statistics such as the CPU usage/bandwidth of each wireless device. Handing off clients to other Access Points can be possible by using SDN capabilities. The technique assumes that the network has a high-density infrastructure. Therefore, a handoff to another AP in a non-dense infrastructure would mean that the device will have a lower RSSI and thus possibly decreasing the signal quality of wireless. Currently, there are no OpenFlow switches integrated in the infrastructure of SURFwireless. Implementing this method into SURFwireless means that the current PoE switches must be replaced with OpenFlow switches with PoE support. The method does not include a description of the mechanism to turn off the Access Points which is an essential part of a method that relies on disabling Access Points. Integrating an ESPS device into a network infrastructure means an extra device that uses energy and therefore decreasing the energy efficiency.

6.4 WiFi-Based Platform

The methods in the research by Quentin Bodinier et al. [5] are topology management based energy efficiency schemes. The platform includes a method to remotely control Access Points by a server through a switch. By using the wireless devices to report information about the neighbouring Access Points such as RSSI, the wireless infrastructure can be optimised. Through creating clusters of mobile devices it is possible to optimise the WLAN signal by using enhancements such as beam forming, relaying, offloading and heterogeneous network deployment.

Beamforming

Beamforming provides the possibility to have a signal with a longer distance by combining multiple antennas. Usually antennas are radiating their signals with a circular shape to the wireless devices. By using beamforming one can send send the signals to a specific region. when using beamforming there is a lower transmission power per antenna required and thus it lowers the total energy consumption per Access Point.

Relaying

A relay is a node that serves as an intermediate node between the source and the destination device. When using relay nodes the signal only has to be transmitted to one direction. A single target transmission will impact the transmission power and therefore the required power consumption.

Offloading

Wireless offloading is making use of other networking technologies to transmit data destined for cellular networks. By introducing offloading the amount of data being transmitted over the cellular networks is reduced. It has a positive effect to the signal reception when too many wireless devices are trying to receive a signal.

Heterogeneous Network Deployment

Heterogenous network deployment consists of a method that is supposedly to improve the capacity of dense data usage areas. Through the deployment of small cells, which act like extenders, with low transmit powers the actual coverage can be extended. Therefore you require less Base-stations to achieve the same capacity and distance.

6.4.1 Discussion

The method requires a server to control the Access Points through a so-called WLAN switch which the author does not explain. The method requires wireless devices to send information about neighbouring Access Points to the server, however it does not describe the approach of sending information. The method also proposes to use other existing technologies such as Beamforming, relaying, offloading, and heterogeneous network deployment. While the first two are useful for clustering, the latter two suggest to make use of cellular or other network technologies to offload the energy consumption of the WLAN network. The technique does not seem to have any other modification requirements. Unlike other mechanisms there is no high-density network infrastructure precondition, the clustering of wireless devices can be done according to the working environment. However, the usage of other networking technologies introduces complexity to a WiFi service. The paper does not include information and results of a testbed which could prove the capability of the method.

6.5 Waking up AP through its Extended Service Set Identifier

The method created by Hiroyuki Yomo et al. [7] is another form of RoD and focuses on waking up Access Points by a 'unique' ID. This ID is based on the Extended Service Set Identification (ESSID) which is not unique. Every Access Point in a wireless network has a Basic Service Set Identifier (BSSID) and the total collection of all BSSIDs is called the ESSID. Only Access Points that do not share an interconnection have multiple ESSIDs. By attaching a wireless receiver to the Access Point a client is able to send a Wake-Up signal to the Access Point.
When there are multiple APs with the same ESSID and a wireless device sends a wake-up signal there is a possibility that multiple APs will be turned on. This can be fixed by introducing a small timeout in which the Access Point that did not receive an association will turn back into sleep mode. However, when a new device wants to connect to an Access Point it will first scan through all channels to find a candidate AP to connect to. This initial scanning process takes a long time and therefore a new Wake-up protocol is proposed. This protocol uses two new messages; the Wake-up Notification (WN) and Wake-up Reply (WR). After receiving the wake-up signal from a new wireless device, the APs send WN messages which include information that the wireless device requires to associate. To associate with an AP the wireless device sends a WR message only to the target Access Point. Afterwards the other Access Points will wait a specific time until they go back to sleep mode. The protocol must be supported by both Access Point and user device.

6.5.1 Discussion

The method is created for any type of network without a high-density requirement. However, by allowing the wireless devices to send wake-up signals Access Points require an extra wake-up receiver. The Aerohive Access Points only have Ethernet ports for connectivity with switches. Connecting an external receiver through Ethernet might be an option, however it is questionable whether the Access Point would support this. This solution would also require an extra receiver for every single Access Point and wireless devices need support for special wake-up signals. The Hive manager API can be used to sent a wake-up signal [21]. However, it is not an appropriate solution to allow API access on every wireless device. Both wireless device and Access Point require support to the proposed wake-up protocol which adds complexity. The method ensures quality of service for every wireless device and through the Access Point specific solution the wireless devices are able to roam around the network and send wake-up signals to every Access Point. There is no testbed available which could indicate whether it is a valuable technique.

6.6 Optimisation deployment and transmitting power of AP

The method suggested by Ma Lin et al.[6] combines clustering of Access Points with adjusting the transmitting power. High-density infrastructure includes a lot of redundant Access Points and therefore have a lot of idle APs. The method implies that interference exists within the network. Therefore, by using the

Fuzzy K-mean algorithm the number of Access Points in an area is decreased to cover the same area. By reducing the number of APs for the same coverage and finely adjusting the transmitting power the overlap of radio signals is minimised.

6.6.1 Discussion

This method is only interesting for high-density network infrastructures which is not the case with SURFwireless. A network such as SURFwireless is already optimised for the minimum required coverage and does not include more Access Points than needed.

6.7 Modifying transmission power based on wireless channel condition

The Adaptive Transmission Power Control Mechanism (A-TPCM) proposed by Yuan-Li et al.[8] is attempting to minimise the transmission power. The mechanism can be deployed at either Access Point and wireless devices. By using an algorithm that focuses on three parameters the transmission power is reduced. The algorithm involves around three criteria; the statistics of how many Blocks of frames have been ACKed to identify the packet loss, generating the adjusting decision based on channel estimation and applying decisions before each transmission of packets. The channel estimation describes how a signal propagates from the transmitter to the receiver and represents the combined effect of, for example, scattering, fading, and power loss caused by distance. The mechanism describes that the transmission must be as low as possible and still satisfy the condition of successful transmission at the same time. The mechanism procedures is as follows:

When a Block ACK times out a success counter is cleared to indicate that the channel condition might be bad. When the Block ACK is received, the subframe error rate (SFER) is calculated. This SFER indicates the measurement of the transmission condition of aggregated frames. Block ACKs are basically aggregated subframes. The SFER will be compared with the lower limit and upper limit which identify a good and bad channel condition. The result of the comparison will lead to an increase of the fail or success counter. The fail counter is increased by a bad channel condition outcome and the success counter will be increased by a good channel condition. If the success counter is continuously increased ten times the sender will conclude that the channel condition is good. However, if the fail counter reaches two, the sender will conclude that there is a bad channel condition. Based on these results, the sender generates a power adjusting decision and leads to an increase or decrease of transmission power.

6.7.1 Discussion

The method tries to finely adjust the transmission power based on the performance of the wireless connectivity. It relies on an algorithm without any hardware and/or hardware modification requirement. The proposed algorithm suggests a relation between one wireless device and one Access Point. Therefore, a large scale of the method might lead to several issues, which are not mentioned. However, the algorithm has not been implemented or tested in a testbed and thus these concerns cannot be cleared. The algorithm ensures a sufficient quality of service. Adaptive Transmission Power Control Mechanism can be applied to any sort of wireless network infrastructure. Currently, Access Points in SURFwireless are configured to provide a wireless signal according to their location. This means that the transmission power is reduced to cover every part of the area. The confusion around multiple wireless devices simultaneously using the technique needs to be cleared before an actual implementation of the mechanism can be recommended.

6.8 Access Point in sleep mode

The method by Toshiyasu Tanaka et al.[11] is a continuation on RoD Wireless Network where Access Points are in sleep mode with only low energy use components powered on. Custom-made Access Points use an internal wireless receiver to receive wake-up signals when demand is required. By monitoring the network traffic of the Access Point it is possible to determine whether an Access Point is required. When the Access Point is not active it will transit to sleep-mode and will shut down everything except for the wireless receiver. The Access Point will wake-up by receiving a wake-up signal from a wireless device. However, this process will restrict the association process of an Access Point with a wireless device. Usually when a wireless device wants to associate to an Access Point there is a scanning process. This scanning can be passive or active. Passive scanning means that beacon frames are sent from Access Points. Wireless devices listen on each wireless channel periodically for these beacon frames. Following this, a wireless device decides to send association request frames to a selected Access Point and the Access Point responds to these request frames. Active Scanning requires initiation by the host without beacon frames being sent by the Access Points. Hosts start with broadcasting Probe Request frames and an Access Point responds to this probe. With the solution of an Access Point that is always in sleep mode the passive scanning process is impossible. The Access Point requires a wake-up signal to be sent by the host including an identifier of the Access Point. The recurring transit to sleep-mode when there is no traffic may reduce the energy consumption. The paper proposes an automatic sleep control based on the history of data traffic. Through this history it can predict the future traffic load and controls the trade-of between QoS and power-saving effects when disabling Access Points.
The RoD Access Point that is used for the mechanism has four states:

- Idle-state: The Access Point is powered on and is waiting for network traffic. The Access Point will go into this state after finalising a data flow;
- Busy-state: The Access Point is powered on, detected the arrival of network traffic, and transmits/receives network traffic;
- Sleep-state: The Access Point is switched off and only the wireless receiver is turned on to receive wake-up signals from wireless devices;
- Wakeup-state: The Access Point is transitioning from sleep to busy-state. The Access Point is unable to receive or transmit any data traffic.

The idle, busy, and wakeup-state are included in the active-mode and the sleep-state is in the sleep-mode. The Access Point will transition to this state after all communication has been finished. Before an Access Point transitions to sleep-state the amount of saved power must be determined to avoid losing QoS and unnecessary enabling the Access Point after an amount of time. The amount of saved power must be high enough to allow the transition to initiate, this is to avoid the QoS from being affected. Therefore there is a threshold that must be surpassed for an Access Point to transition to sleep state. This means that the amount of saved energy, when being in sleep state, must be more than the amount of power that is required to power up the Access Point.

The paper also proposes a cooperative sleep control method in RoD, which basically transits specific Access Points to sleep-mode based on their location. This method is basically correlating the placement of the wireless device and the data traffic. As the method is similar to the one mentioned in Section 6.6 it will not be repeated here.

6.8.1 Discussion

A sleep mode depicts an ideal resolution to an energy utilisation problem. The Access Point does not completely turn off when there is no activity but only transits into sleep mode. As mentioned before booting the Aerohive AP230 Access Point requires a relatively long time. Other Access Points might be able to boot faster. However, there is a hardware or hardware modification requirement to implement this in SURFwireless. The current Aerohive implementation does not support a sleep mode. Through the analysis of traffic patterns the quality of service is retained. The method does not have a specific network requirement such as a high-density infrastructure. The sleep control method has not been proven to be functional as the paper only contains simulation results. There is no test-bed available at the moment of writing this report.

7 Off the shelf solutions

This chapter consists of the results of the investigation to possible Commercial Of the Shelf solutions provided by network device supplies.

7.1 Cisco Systems, Inc

Cisco Systems, Inc. is an American multinational that develops, manufactures, and sells networking hardware. Cisco is a company that strives for Green IT and with its *Cisco Energy Efficient Data Center* solutions it wants to improve the energy efficiency in data centers [22]. Cisco also supplies multiple solutions for wireless connectivity. These solution are controller and controller-less. The enlisted Access Points do not provide explicit features on power saving mechanisms in the specifications or in the data-sheet. If one examines the Cisco website there is also no information on energy saving features [23].

7.2 Aruba Networks

Aruba Networks, a Hewlett Packard Enterprise company, is a networking vendor selling enterprise wireless LAN and edge access networking equipment. Aruba was first to market with purpose-built 802.11ac AP and has the second largest market share of 802.11ac APs [24]. Just like Cisco Aruba provides Controller and Controller-less products. The newer AP300, AP310 and AP330 series provide 802.11ac Wave 2 wireless connectivity and also a feature called Intelligent Power Monitoring (IPM) [25]. IPM provides the AP with the capability to continuously monitor and report its power consumption and possibly lower this consumption with disabling certain capabilities. It is also possible to disable certain facilities by using the software capabilities of the Aruba Network APs.

7.3 Ruckus

Ruckus Wireless, Inc. is a Brocade Communications Systems Inc company since April 2016. Ruckus offers indoor and outdoor "Smart Wi-Fi" products to mobile carriers, broadband service providers, and corporate enterprises. Both controller and controller-less solutions do not provide explicit features around power saving mechanisms. Ruckus does provide a patented feature called Beamflex+, which enables the antennas to have a directional signal sent to each client. The website of Ruckus does not mention anything specifically about energy saving methods [26][27].

7.4 Aerohive

Aerohive Networks Inc. provides cloud-based products using enterprise cloud networking, WiFi connectivity, and application and insights technology. The implementation of SURFwireless makes use of the controller-less solution developed by Aerohive and managed by Aerohive's product Hive Manager. Aerohive's website does not mention anything explicitly about energy saving methods. Since SURFwireless is using Aerohive's implementation a set of questions was formulated to request for information about developments on energy efficiency. Aerohive indicated that there is a software implementation of Access

Point scheduling. This scheduling of Access Points can turn off radio's based on parameters e.g. no radio signals during the night. There is no further explanation of the devices supporting this feature and whether other Aerohive products would be able to receive this feature in the future. The Hive Manager includes an Application Programming Interface (API), which allows the user to monitor the infrastructure, but it also has control options such as turning off Access Points. Aerohive has plans for the future to further improve the API to allow for more Access Point control such as lowering the transmission power.

8 Discussion

The methods mentioned in Chapter 6 are shown as comparison in the table in Appendix B. The table enlists only the most important characteristics. When analysing the comparison of the methods one can notice that they show a lot of similarities. One of the similarities is that 5 out of 8 mechanisms either has a hardware requirement or hardware must be modified. Another similarity is that 6 out of 8 mechanism introduce energy efficiency by disabling the Access Points. The latter is an obvious suggestion because turning a device off completely eliminates the power usage. In Chapter 5 the assumption has been made that the minimum energy consumption, which also occurs during night times, is equal to the idle consumption. The results show that this idle consumption of the Access Points seems to be the main factor of the total energy consumption. Any activity of wireless devices only increases the value of the energy consumption slightly. Based on the comparison of the advantages and disadvantages one can conclude that there is not one, easily applicable method among them. The general idea of some techniques can be recommended, however, the mechanism behind the idea makes it unusable. If one could combine specifics into one technique then there would be a different conclusion. For example putting Access Points into sleep mode and waking them up by sending a wake-up signal over the normal 802.11 standard channels. Also disabling Access Points can work at times when the Access Points are only idle, which seems to be between 00:00 o'clock and 6:00 o'clock (see Chapter 5). However, this is impossible with the current hardware, and the methods mentioned in Chapter 6 do not offer a solution.

9 Conclusion

We have researched in this paper methods to measure the power consumption, and increasing the energy efficiency of SURFwireless. We came to the following conclusions from the research.

- The process of measuring the power consumption of SURFwireless is complex due to its distributed aspect, which voids central monitoring;
- The energy consumption of SURFwireless is mostly determined by the idle energy consumption of the Access Points and only increases slightly with network load;
- The researched energy efficiency mechanisms cannot be simply adapted to SURFwireless to lower the energy consumption;
- The overall effort of network companies to improve the energy efficiency of wireless network infrastructures is minimalistic.

These statements lead to the conclusion that there is no easily applicable method, neither for measuring the power consumption accurately nor improving the energy efficiency, available for SURFwireless at the time this research was conducted.

Complex measuring

We have shown the difficulty to measure the energy consumption of SURFwireless. It is a distributed network infrastructure, therefore, a central solution to determine the consumption is difficult. The current implementation of SURFwireless does not support a mechanism to monitor the power consumption. The wireless service is implemented at multiple locations, where there are differences in existing hardware and implemented technologies. No current best practice known defines a method or protocol to measure the energy consumption. Chapters 4 and 5 illustrate that the accuracy cannot be clearly defined because the Access Points are not directly measured and the method is using software to determine the power consumption rate. There is not one single approach that can be used to determine in real-time the energy consumption of the complete wireless network infrastructure.

High idle energy consumption

The results of the measurements indicate that the energy consumptions of Access Point is not proportional to the load. Even when there is network traffic over the WLAN the energy consumption only increases by a few percentage. A self-evident method to improve the energy efficiency is to decrease the idle energy consumption, which requires no extra complexity. The graph in Chapter 4 shows a difference between the energy consumption in the afternoon and at night. However, the minimal value of the energy consumption and the maximum do not have a substantial fluctuation. The graphs and the tables in Chapter 5 indicate unexpected peaks, which have an unknown reason. There are too many variables to actually establish a conclusion of the power consumption.

No Simple applicable method

The research of energy efficiency methods have shown that it is difficult to find techniques in literature. Most of the mechanisms, that are enlisted in Chapters 2 and 6, refer to each other and extend on or improve the method. The mechanisms have operative similarities and often are still in the beginning phase of development. There are no test-beds available, which in some papers of methods is part of the future work for the development of the technique. Techniques are generally created to introduce energy efficiency for a specific network infrastructure, which makes it problematic to form a comparison. All those network infrastructures do not completely resemble SURFwireless.

Minimal effort by network companies

As a final step we investigated commercial of the shelf solutions provided by renowned network companies. None of them mention anything power efficient related on their websites with the exception of Aruba Networks. Aruba Networks provides a monitoring and power efficiency feature. Nevertheless, that information is hidden in a data sheet instead of emphasizing it as an important feature. After contacting Aerohive on their ongoing developments, they indicated that there is a software feature, which allows Access Points to be enabled according to a scheduling scheme. However, there is no further information about this feature and the current implementation of SURFwireless does not support this feature.

10 Future Work

In this report the power consumption of SURFwireless at SURFnet, SURF and SURFmarket is measured. However, the service SURFwireless is available at multiple locations and therefore the total energy consumption is not determined. In the future it could be interesting to see the consumption of different type of institutes and compare those with the SURFnet implementation. As mentioned the other institutes might have different network devices and could make the measuring process different. Making use of the SNMP MIBs of Cisco PoE switches is part of this process. The investigation of existing solutions provided by renowned networking companies resulted in interesting results. Aruba Networks includes IPM to ensure power monitoring and power efficiency, and Aerohive provides a software feature to schedule access points. For future research it would be interesting to assess the possibilities of both options and use other Access Points than the Aerohive AP230. In addition to this, the other networking companies might have ongoing researches or existing techniques that are not mentioned on their website. Contacting the companies can lead to interesting information. The papers researched included creating a testbed in their future work. At the time of writing these testbeds were not available, future work could include contacting the authors to ask whether a testbed or implementation is still planned for the future.

A Mean energy consumption Script

```
grep -v -E
↪ [0-9]{1,3}.*-*.-2016\s\d{2}:\d{2}:\d{2}\sUTC\s.(0.*|1.*|2.*|3.*|4.*|5.*)W\s.*
↪ type.script
```

```
#! /usr/bin/python3
import sys

if len(sys.argv) < 2:
    print("Usage: hour-avg.py <filename>")
    sys.exit("Too few arguments")

file = open(sys.argv[1],'r')

index = 0
watt_avg = 0
last_line = file.readline()         # make the first read
interface = last_line.split()[0]    # read the first interface
file.seek(0)                        # reset back to the first line in the file
last_line = last_line[last_line.split()[0].__len__()+1:]    # format the line the way
↪ the first print would  expect it
date = last_line.split()[1]

for line in file:
    if "ge" in line.split()[0]:
        print(interface,date,last_line.split()[2:4], watt_avg/(index-1))
        interface = line.split()[0]
        index = 0
        watt_avg = 0
        line = line[line.split()[0].__len__()+1:]
    watt_avg += float(line.split()[4][0:-1])
    if index == 12:
        print(interface,line.split()[1],line.split()[2:4], watt_avg/12)
        index = 0
        watt_avg = 0
    index += 1
    last_line = line
    date = line.split()[1]
```

B Comparison of methods

Method	Advantages	Disadvantages
Disabling Power Supply (see Section 6.1)	– Possibility of implementation in SURFwireless – Ensures sufficient RSSI and/or SNR – No modification hardware – Testbed and/or Implementation	– Extra Devices – Central decisions which APs should be booted – AP has to be booted up every time – Long boot times – Added complexity through extra authentication scheme – One backup AP always turned on
Covering wireless devices through scheduler (see Section 6.2)	– Makes use of Aerohive supported standard – Ensures that all wireless devices are covered by APs	– Seems to be infeasible to implement in SURFwireless – Only aiming to shutdown unnecessary APs – The method seems to be incomplete – Scheduler does not take moving users into consideration – High-Density topology req. – No Testbed and/or Implementation
Optimisation deployment and transmitting power of AP (see Section 6.6)	– None suitably	– Cannot be implemented in SURFwireless – High-Density topology requirement

Method	Advantages	Disadvantages
WiFi-Based Platform (see Section 6.4)	– Ensures sufficient RSSI and/or SNR – Beamforming is supported by Aerohive devices	– Incomplete paper/method – requires introduction of other protocols than 802.11 – Seems to be infeasible to implement in SURFwireless – No Testbed and/or Implementation
Waking up AP through its Extended Service Set Identifier (see Section 6.5)	– Custom wireless receiver works on 2.4 Ghz	– modification hardware requirement – A new protocol needs to be implemented in both wireless device and AP – No Testbed and/or Implementation – Long boot times
Modifying transmission power based on wireless channel condition (see Section 6.7)	– No modification hardware – Ensures sufficient RSSI and/or SNR	– Method only describes the relation between one AP and one wireless device, unclear when there are multiple devices – No Testbed and/or Implementation
Access Point in sleep mode (see Section 6.8)	– Access Points are not completely turned off therefore no boot times – No waste of network traffic for sending AP beacons	– Modification hardware requirement – No Testbed and/or Implementation

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