Deploying Energy Efficient Wi-Fi Networks

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Abstract—The growing number of Wi-Fi networks at homes, buildings and public areas can consume excessive energy and therefore increase CO2 emissions. Hence, the aim of this paper is to investigate the energy consumption of Wi-Fi networks in general. This study is based on real-world observations both usage and energy consumption of Wi-Fi access points. A variety of off-the-shelf Wi-Fi access points were examined to investigate to what degree clients' usage patterns, especially the signal to noise ratio (SNR) affects the energy consumption. The results indicate that low SNR increases the energy consumption up to 136% in various Wi-Fi access points. Therefore, confining clients with a low level of SNR can reduce the energy consumption of Wi-Fi access points while increases network throughput. Hence, findings of this paper can improve the energy efficiency of Wi-Fi networks in particular energy and cost efficiency of public hotspots.

Index Terms—Energy efficiency; Wi-Fi networks; energy monitoring; power consumption; green computing.

I. INTRODUCTION

Wi-Fi is a pervasive technology, and it is going to be the main medium as an access network in homes and buildings or as public hotspots. Wi-Fi has received much attention among wireless technologies in recent years due to high bandwidth capability and economic benefits. It is predicted that by 2023, 658 million households will have Wi-Fi networks, with 364 million households having more than one access point [1]. In addition, 549 million public hot-spots will be deployed [2]. Thus, the total number of Wi-Fi access points will exceed 1.5 billion devices globally by 2023. As a result, it is predicted that Wi-Fi networks can consume 4529 Tera Watt-hour (TWh) energy worldwide by 2030 [3], which compares to approximately 1.17 times of yearly energy consumption in United States [4].

Wi-Fi access points transmit electromagnetic waves in order to transfer data to the stations. Hence, transmit energy considerably affect the energy consumption of access points. Furthermore, maximum transmit energy can cause co-channel and adjacent channel interference in overlapping Wi-Fi networks. However, Wi-Fi access point vendors may not pay attention to the energy consumption of access points because in the majority of deployments, Wi-Fi access points are powered by electricity grids. Even there is no limitation in the energy consumption of grid-powered Wi-Fi networks, excessive use will result in increased energy consumption and thus more CO2 emissions. In the case of public hotspots, the energy consumption of Wi-Fi networks can affect capital

and operational expenditure due to providing equipment for supporting excessive energy requirement and shortened battery life cycle. Various projects have deployed public hotspots such as energy efficient long range Wi-Fi networks [5] and Internet hotspots [6] using solar energy for powering Wi-Fi access points.

Although vendors have improved performance of wireless products, little attention has been paid to energy efficiency of Wi-Fi networks. Therefore, this paper investigates parameters and default configurations affecting the energy consumption of Wi-Fi access points. In particular, effect of signal to noise ratio (SNR) on the energy consumption of Wi-Fi access points are researched in detail. Accordingly, this paper provides suggestions to deploy energy efficient and green Wi-Fi networks in homes and buildings as well as public hotspots. This study built an energy monitoring hardware as a part of a monitoring platform in order to investigate the energy consumption of Wi-Fi access points. The results indicate that a lower level of clients' SNR increased the energy consumption of various Wi-Fi access points up to 136%. Therefore, this paper suggests confining clients with low level of SNR in order to avoid throughput loss and higher latency in Wi-Fi networks. In case of public hotspots powered by renewable energy resources, proposed solution also reduces deployment and operational costs. The rest of the paper is organized as follows:

The description of monitoring platform as well as methods for investigating the energy consumption of Wi-Fi access points appears in Section II. Various Wi-Fi access points examined, and the energy consumption results presented in Section III, while findings were assessed in Section IV. Section V presents related research in wireless energy management followed by the conclusion and future work in Section VI.

II. MATERIALS AND METHODS

The current investigation involved building energy measurement equipment, measurement of the energy consumption of wireless access points and collection of wireless parameters of clients. This study has built a low-cost hardware to measure the energy consumption of Wi-Fi access points such that the energy consumption measurements to be stored and visualized in a cloud-based monitoring platform. Hence, the first part will present measurement hardware, while the second part presents a methodology for investigating the energy consumption of wireless networks.

TABLE I
SENSORS AND THEIR SPECIFICATION USED IN THE MEASUREMENT
HARDWARE.

Sensor type	Specification
Voltage	DC voltage sensor, 0-25 Volt
Current	MAX 471, 0-3 Ampere
Temperature	DHT22
Humidity	DHT22
Analog to digital signal converter	ADS1115 , 16-bit converter

A. Measurement Hardware

There are various commercial hardware to measure the energy consumption, though only few can store measurements to an online database. In addition, commercial hardware that are capable of monitoring and storing the energy consumption to online databases are expensive and are often more expensive than the wireless infrastructure. Hence, this project has built an affordable hardware measuring the energy consumption. The hardware is built with a 35\$ Raspberry Pi 3B+ single board computer and a set of sensors including Voltage, current, humidity and temperature. The temperature and humidity sensors were used to make sure environmental condition was similar in all experiments.

On the Raspberry Pi, a Python script was developed in order to collect and send measurements to the monitoring platform for visualization and further analytic, which could collect and send measurements every 40-45 milliseconds. However, measurements are collected and sent to the monitoring platform every second, satisfying the need to demonstrate the trend of the energy consumption. Table I presents the sensors that connected to Raspberry Pi for the energy consumption measurements.

B. Methodology

There are two groups of Wi-Fi access points regarding transmit power control mechanism: the first group leverages dynamic adjustment of transmit powers, while the second group leverages static adjustment of transmit power. Access points with static transmit power control adjust their transmit power to maximum level so that their idle mode energy consumption are considerably higher than those of the first group. Maximizing transmit power extends coverage area and increases the signal to noise ratio (SNR) but increases the co-channel interference. In order to quantify the effects, experiments were conducted to investigate the effect of clients' SNR on the energy consumption of Wi-Fi access points and consequently provide suggestions to improve the energy efficiency of Wi-Fi networks.

In this respect, a series of experiments were performed to record the energy consumption and wireless parameters of various Wi-Fi access points. During experiments, access points of three vendors being Mikrotik, AirTies and Zyxel with details presented in Table II were examined, while a mobile phone and a laptop were used as clients downloading a software image from the Internet. In addition, an open-source platform consisting of Elastic stack [7] was implemented for monitoring

and data analytics. The monitoring platform solution was implemented to be deployed in later stages in a rural area for monitoring and data analytics of public hotspots. Figure 1 presents the setup to collect and send the energy consumption and wireless parameters to the monitoring platform. In this setup, the developed hardware measures and sends the energy consumption value to the monitoring platform, while the Wi-Fi access points send their wireless parameters simultaneously to the monitoring platform.

Fig. 1. Experiments architecture for investigating energy efficiency of Wi-Fi networks.

TABLE II
WI-FI ACCESS POINTS AND THEIR SPECIFICATION.

Model	Specification	Transmit power
Mikrotik RB921GS	802.11a/n/ac, 120 degree antenna, 15dBi	Dynamic
Mikrotik RBwAPG	802.11a/b/g/n/ac, 2dBi	Dynamic
Mikrotik RBD52	802.11a/b/g/n/ac, 2.5dBi	Dynamic
AirTies 4920	802.11a/b/g/n/ac	Static
Zyxel B50B	802.11a/b/g/n/ac wave2	Static

In this study, 4 access points and one Internet gateway examined in order to consider various types of products. Table II presents wireless devices that were examined during this study. The Mikrotik RB921GS is an outdoor access point operating only in 5GHz frequency bands. A client being approximately two meters away from the access point (AP) was connected to the AP, representing a good SNR. The client changed its conditions every three minutes:

- 1) After three minutes, the client started downloading a software image from a server.
- 2) Another three minutes later, while still downloading the image, the client moved away from the AP until the client had poor network coverage.
- 3) Being at the low SNR condition, the client continued for three minutes downloading the image.
- 4) Finally, the client was moved back to the starting position, continuing downloading for three minutes.

The process of moving away from AP and returning back was conducted to identify the effect of the client's signal to noise ratio (SNR) on the energy consumption of access points.

The Mikrotik RB921GS only operates in the 5 GHz frequency band, thus experiments were limited to that band. For all other devices, being the Mikrotik RBwAPG and RBD52, AirTies 4920 and Zyxel B50B, experiments were

Fig. 2. The effect of SNR variation between 60-20 dB on the energy consumption of the Mikrotik RBD52.

Fig. 3. The effect of SNR variation between 60-20 dB on the energy consumption of the Mikrotik RBwAPG.

performed in both 2.4 GHz and 5 GHz frequency bands. During experiments, two clients including a Motorola X4 mobile phone and Microsoft surface pro laptop were used to perform experiments. Each experiment was repeated four times in order to increase confidence and identify possible outliers.

It is notable that all access points were powered by 12V DC power supply to build similar condition for all of the access points. Thus, the only variable in the energy measurement process was the current that wireless devices drew. The energy consumption in Watt (W) is then calculated using the power equation:

$$P = V * I$$

Finally, the monitoring platform provided visualization and data analytic techniques in order to investigate the effect of SNR on the energy consumption of access points and therefore, it was expected that Wi-Fi access points would consume excessive energy while a client with low SNR being connected to a basic service set (BSS). Hence, two scenarios were examined in which a) only one device connected to an access point and b) two devices connected to an access point. In the second scenario, one of the devices placed in the edge of the network in order to investigate whether low SNR will be the only cause of excessive energy consumption or additional clients will cause a significant energy consumption.

III. RESULTS

Based on the set-up described in the previous sections, the energy consumption of wireless access points particularly Wi-Fi access points was investigated with respect to clients' signal to noise ratio (SNR). The energy consumption of five wireless access points were measured, with clients being connected under varying SNR conditions.

According to the recorded temperature and humidity data, experiments were conducted in normal condition, while the temperature was between 20-25 centigrade and humidity was between 20-30 percents. The temperature and humidity did not change substantially so that their effect on wireless transmission were negligible.

Figure 2 presents the energy consumption of the Mikrotik RBD52G in regards to client's SNR variation with an average per 30 seconds. During experiments, a mobile phone was connected to the 5 GHz network and placed near the access point then mobile phone moved away for 3 minutes while downloading an image file. As it can be seen, Mikrotik RBD52G consumed as few as 3.2 Watts when the connected client was not downloading (idle mode). However, when the client started to download, the Mikrotik RBD52G increased the energy consumption by 46%. Furthermore, when the client moved toward the edge in the basic service area (BSA), the SNR decreased consequently to 20 dB, and the Mikrotik RBD52G consumed as much as 5.8 Watts, which is an energy increase of 81% as compared to 60 dB SNR. Furthermore, Mikrotik RBD52 consumed approximately 4.7 Watts to transmit 3 MB/s of data to clients, but when the client's SNR decreased, Mikrotik RBD52G consumed approximately 5.8 Watts to transmit 1.1 MB/s of data to the client. The steep drop of throughput can be due to dependency of rate control algorithm in access point solely to RSSI or SNR.

Figure 3 illustrates the energy consumption of Mikrotik RBwAPG versus the client's signal to noise ratio (SNR) variations with an average per 20 seconds. The experiments were conducted as described in the earlier section. Thus, a mobile phone was connected to the 2.4 GHz network and placed near the access point in which mobile phone moved away for 3 minutes while downloading an image file. As it can be seen, the Mikrotik RBwAPG consumed as few as 2.9 Watts when the connected client was not downloading. However, when the client started to download, the energy consumption of the Mikrotik RBwAPG increased by 37%. Furthermore, when the client moved toward the edge in the basic service area (BSA) and consequently SNR decreased to 20 dB, the energy consumption of the Mikrotik RBwAPG increased by 82% as compared to the 60 dB SNR condition. Thus, every consumption is increased by 45% while SNR drops from 60 dB to 20 dB. Furthermore, the Mikrotik RBwAPG consumed approximately 4 Watts to transmit 2.6 MB/s of data to clients nearby, as compared to 5.8 Watts to transmit 0.8 MB/s under

Fig. 4. The effect of SNR variation between 60-20 dB on the energy consumption of the Mikrotik RB921.

low SNR conditions. Mikrotik RBwAPG behaved similarly to RBD52 in the same condition such that it experienced approximately same order of magnitude of energy consumption and drop of throughput.

Figure 4 presents the energy consumption of a Mikrotik RB921 versus the client's signal to noise ratio (SNR) variations with an average per 20 seconds. During experiments, a mobile phone was connected to the 5 GHz network and placed near the access point in which mobile phone moved away for 3 minutes while downloading an image file. As it can be seen, Mikrotik RB921 consumed as few as 2.2 Watts when the connected client was not downloading. However, when the client started to download thus the energy consumption of Mikrotik RB921 increased by 127%. Furthermore, when the client moved toward the edge in the basic service area (BSA), resulting in a decrease of SNR from 60 dB to 25 dB, the energy consumption of the Mikrotik RB921 increased to 8 Watts, which indicates 263% rise in the energy consumption as compared to idle condition. Furthermore, Mikrotik RB921 consumed approximately 5 Watts to transmit 3 MB/s of data to clients, but when the client's SNR decreased, Mikrotik RB921 consumed approximately 8 Watts to transmit 0.6 MB/s of data to the client. Here, RB921 experienced steep drop of throughput even more than RBD52 and RBwAPG. This behavior can be because of RB921 transmits in 5GHz network and 60-25 dB SNR variation had stronger effect on the rate control algorithm.

In other series of experiments, AirTies 4920 Wi-Fi access point was examined such that in the first scenario, only one mobile phone was connected and in the second scenario, one mobile phone in 2.4 GHz frequency band and one laptop in the 5GHz band were connected during the experiments. At the beginning, AirTies 4920 consumed 6.5 Watts when no client was connected, and the access point just sending beacon frames and responds to probes (idle mode). As soon as the mobile phone started downloading a software image, the AirTies 4920 consumed fairly 8 watts, which was equivalent to 20% increase in the energy consumption. However, when the client moved away from the access point with less than 10 dB SNR,

Fig. 5. The effect of SNR variation between 50-5 dB on the energy consumption of the AirTies 4920.

the energy consumption of AirTies 4920 did not significantly increase. In the second scenario, when both interfaces were transferring data thus AirTies consumed at most 11.2 Watts. In this scenario, both interfaces were transmitting data so that the energy consumption increase was expected.

Figure 5 presents the energy consumption of AirTies 4920 access point versus clients' SNR variation with an average per 30 seconds. During this experiment, a laptop was connected to 5 GHz network placed at the edge in the network while mobile phone connected to 2.4 GHz network and placed near the access point in which mobile phone moved away during downloading an image file from the Internet. As can be seen, immediately after the start of the download process, the energy consumption of the AirTies increased as much as 36%. However, when the mobile phone moved toward the edge in the basic service area (BSA), the energy consumption of AirTies did not increase considerably, being as little as 46% as compared to the idle state. Furthermore, transmit throughput of AirTies 4920 has linear relationship with clients' SNR such that transmit throughput of access point toward the client decreased considerably to less than 1 MB/s. The energy consumption growth of AirTies 4920 is less than Mikrotik access points examined here, which can be due to AirTies 4920 already consumes 6.5 Watts for internal processes. This indicates that AirTies 4920 was less affected by low SNR probably because interfaces already transmitted in maximum power so that low SNR could only cause retransmission and throughput drop and consequently could increase processing load of AirTies 4920.

In another series of experiments, the power consumption of the Zyxel B50B Internet gateway was examined. In a first scenario, only one mobile phone was connected and in the second scenario, one mobile phone and one laptop were connected. At the beginning, the Zyxel B50B consumed 8 Watts when one client was connected to the 5GHz network (idle mode). As soon as the mobile phone started downloading a software image, the Zyxel B50B consumed fairly 10 Watts to transmit data, which was equivalent to 25% the energy consumption increase. However, while the client moved away

Fig. 6. The effect of SNR variation between 50-5 dB on the energy consumption of the Zyxel B50B.

from the access point, no significant change in the energy consumption of Zyxel B50B was observed. In the second scenario, one laptop connected on 5 GHz frequency band at the edge in the network and a mobile phone connected to 2.4 GHz and moved toward the edge of the BSA. Immediately after the clients started downloading, the Zyxel B50B energy consumption increased to 11.5 Watts, which was equivalent to 56% increase of the energy consumption.

Figure 6 illustrates the energy consumption of Zyxel B50B Internet gateway in regard to clients' SNR variation with an average per 20 seconds. The laptop was connected to 5 GHz network placed at the edge of the network while mobile phone connected to 2.4 GHz network and placed near the access point. During download, the mobile phone moved towards the edge of the service area. It is depicted that when both clients' SNR reached minimum level 5 dB thus Zyxel B50B consumed more than 11.5 Watts. The Zyxel B50B consumed approximately 2 Watts for transmitting data to clients at the maximum rate of 2.4 MB/s in the 5 GHz network. Furthermore, Zyxel B50B consumed approximately 10 Watts to transmit 15 MB/s of data to clients in the 2.4 GHz network, but when the client's SNR decreased, Zyxel B50B consumed approximately 11.9 Watts to transmit 5 MB/s of data to the client. The throughput in the 5 GHz band was down to 1.2 MB/s when the SNR dropped to 5 dB.

The results demonstrated that low SNR increased the energy consumption of all access points in this study. Investigation of wireless parameters implied that low SNR could cause drop of transmit rate and excessive retransmission, which consequently increased the energy consumption of access points with static transmit power control. In this respect, the dramatic drop of transmission rate must be because of dependency of transmit rate control algorithm solely to RSSI or SNR. In all experiments using access points with dynamic power control, incrementing transmit power during low SNR must be a cause of significant energy consumption growth. In addition, similar to static power control access points, low SNR could cause drop of transmit rate and excessive retransmission, which consequently increased the energy consumption of Mikrotik

Fig. 7. The effect of SNR variation between 50-5 dB on retransmission and transmit rate on the AirTies 4920.

RB921 up to 263%.

Figure 7 presents the effect of low SNR on transmit rate and retransmitted packets on AirTies 4920. During this experiment, a mobile phone connected to the 2.4 GHz network and placed near the access point in which mobile phone moved away during downloading a file. As can be seen, when SNR decreased, the transmit rate significantly decreased as well. Meanwhile, the packet retransmission rate increased considerably.

IV. DISCUSSION

This study implemented a monitoring platform to monitor the energy consumption of Wi-Fi access points. The results of this study indicate that energy consumption of Wi-Fi access points depends on the signal to noise ratio (SNR) of clients. Given the analysis of 5 different access points, the SNR variation changed energy consumption of access points between 10-136%. Access points with dynamic transmit power control, like the Mikrotik access points, presented considerable energy consumption growth in comparison to access points with static transmit power control. Indeed, access points with dynamic transmit power control were more energy efficient in idle mode and high SNR in comparison to those with static transmit power control. However, access points with dynamic transmit power control were all Mikrotik with RouterOS operating system, which must be a cause for energy efficiency during idle mode. In contrary, examined access point with static transmit power control operates with Linux kernels, which must be a cause for sub-optimal energy management.

For example, in the case of 50% idle and 50% high SNR in a year, Mikrotik RBD52 will consume 34 KWh while Zyxel B50B and AirTies 4920 will consume 79 KWh and 67 KWh respectively. In case of 50% idle and 50% with a client in low SNR in a year, Mikrotik RBD52 will consume 39 KWh, while Zyxel B50B and AirTies 4920 will consume 90 KWh and 70 KWh respectively. The sample yearly energy consumption indicates that access points with static transmit power control, which by default transmit maximum power will consume twice as access points with dynamic transmit power control. On the other hand, clients in low SNR can

also consume excessive energy because they also use same communication mechanism as access points. When clients are battery powered e.g. IoT devices then excessive energy consumption can increase device operational costs due to requirement for frequent battery replacement. In addition to excessive energy consumption, clients in low SNR will suffer network throughput reduction because of dependency of rate control algorithm to RSSI or SNR.

The present study indicates that energy consumption of access points can result in excessive operational expenditure (OPEX) and CO2 emissions. For example, with global estimated CO2 emission factor of 0.532 Kg/KWh [8], the excessive energy consumption of an access point with clients in low SNR will generate 5.8 Kg more CO2 yearly for house users. With 1.5 billion access points by 2023, they will generate 8.7 billion Kg yearly, which is comparable to CO2 emissions of Luxembourg [9]. In case of battery powered public hotspots, excessive energy consumption directly affects battery life cycle and consequently operational cost (OPEX). For example, Mikrotik RB921 outdoor access points can be powered by 20 Ah battery for 3 days with 50% idle mode and 50% clients in high SNR mode. In contrary, Mikrotik RB921 access points can be powered by 20 Ah battery for 2 days with 50% idle mode and 50% clients in low SNR mode. This implies that clients in low SNR mode reduce battery life cycle by 33%, which results in 33% higher cost of energy requirements.

The findings presented here extend those of Gomez et al. confirming that the energy consumption of Wi-Fi access points depends on different aspects of wireless communication such as type of traffic [10], [11]. In addition, energy monitoring in this study revealed that SNR variation affects the energy consumption of wireless access points. This study indicates that when clients' SNR decreased, the energy consumption of access points increases due to retransmissions and drop of transmission rate. Reduction in clients' SNR implies that pass loss must be increased between clients and access points so that wireless medium condition results in excessive retransmission. However, Figure 7 demonstrates when client's SNR decreased then transmit rate of access point decreased as well while no retransmission happened as an indication of a noisy environment. On the other hand, drop of transmit rate increases the airtime and consequently increases probability of data corruption in the air because transmitted data packets will be exposed more to noise in the environment. This indicates that transmit rate control algorithm depends solely to RSSI or SNR of clients. In case of access points with dynamic transmit power control, access points increased transmit power to improve SNR so that the energy consumption increased as well. Results of this study provide compelling evidence that confining clients with low SNR can result in saving energy, maximizing network throughput and reducing latency. However, confining clients with low SNR or reducing transmit energy can limit coverage area of Wi-Fi networks.

V. RELATED WORK

Numerous research work has investigated the energy efficiency in wireless networks, where some of them have targeted specific wireless communication use cases. Recent research on the energy efficiency of Wi-Fi networks has led to transmit energy management, the energy consumption monitoring and 802.11 standard energy optimization.

Gandarillas et al. investigated the transmit power control in Wi-Fi access points to manage adjacent and co-channel interference in Wi-Fi networks. In this respect, they presented a dynamic transmit energy control method in order to control access points transmit power based on real-time wireless link state conditions [12]. Huang and Parameswaran investigated energy adoption in community Wi-Fi such that access points adapt their energy in order to reduce interference [13]. In this respect, they presented an energy adaption approach for access points of community networks based on maximizing utility in the network in the form of maximum associated clients.

Gomez et al. analyzed traffic and the energy consumption of Wi-Fi access points. Their research used the Watts Up energy consumption meter and one 802.11g access point (PCEngines ALIX 3D2 with 500MHz x86 CPU, 256MB of RAM) with OpenWRT operating system in which RTS/CTS frames are disabled. They presented that different type of traffic has distinct impact on the energy consumption of access points, in which smaller packets consume more energy because of MAC layer overhead [10]. They also presented an affordable energy monitoring solution for Wi-Fi access points. In this solution, they used the Arduino platform using 10-bit analog to digital convertor to convert analog sensor measurements. The result showed that the energy consumption of transmission and receive was similar and the energy consumption increased while traffic increased until it reached a saturation point. Thus, they presented that lower modulation and coding schemes were more energy efficient [11]. Riggio et al. presented an energy monitoring and control approach for Wi-Fi networks. In their approach, they provided an Arduino based energy monitoring hardware and Odin software defined master-slave networking in order to monitor the energy consumption of access points in a network and consequently master access point turned on or off the slave access points in order to increase network capacity or save energy [14], [15]. Riggio et al. also presented an approach to leverage parameters of Wi-Fi access points including bytes/packets transmitted and received, transmission energy and average CPU load in order to model the energy consumption of access points. In this approach, parameters obtained from standard SNMP management interface [16].

Furthermore, various efforts have been done on optimizing the energy efficiency of 802.11 implementations, including optimizing packet decoding so that clients do not process unintended packets [17] or reducing packet collision in 802.11 networks in order to improve energy efficiency [18].

VI. CONCLUSION

The number of Wi-Fi access points will grow to 1.5 billion by 2023 thus Wi-Fi networks is going to be the main access

network at homes and buildings as well as providing low-cost public access to the Internet. The increasing number of Wi-Fi networks can consume 4529 Tera Watt-hour (TWh) energy worldwide by 2030. However, the default configuration of Wi-Fi access points and non-optimized deployment strategies can result in excessive energy consumption, poor network throughput, high latency and co-channel interference.

This paper implemented an energy monitoring platform to investigate energy efficiency of Wi-Fi access points. The low-cost monitoring system consists of developed measurement hardware and open-source cloud-based visualization and data analytic. The results demonstrated that virtually in all cases, clients with poor signal to noise ratio (SNR) increased the energy consumption of access points up to 263%. The excessive energy consumption were dramatic for access points with dynamic transmit power control mechanism. Furthermore, results indicate that poor SNR can reduce network throughput and increase the delay in Wi-Fi networks. Therefore, this paper suggests confining clients with poor SNR in the network in order to minimize the energy consumption of Wi-Fi networks and latency as well as maximizing throughput. The study shows that access points can save at least 3 KWh energy in a year when low SNR devices are omitted. However, energy saving for whole network would be higher. In effect, reducing the energy consumption of Wi-Fi networks will result in reducing 8.7 billion Kg CO₂ emissions globally. In addition, findings of this paper suggest deploying hot-spots with adaptable power profiles, allowing at least 30% reduction of energy, and thus improve cost efficiency of public hotspots. Furthermore, applying the results in solar-powered rural areas will lead to better power management, reduced operational expenditure and consequently improve Internet penetration in rural areas.

The energy efficiency approach of this paper may result in reduction of Wi-Fi coverage so that some of the stations can not connect to the network. Therefore, a future work will develop a transmit power control and client management mechanisms in order to maximize the energy efficiency of Wi-Fi networks based on wireless communication parameters such as retransmission rate, access point transmit rate, and noise level.

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REFERENCES

- [1] Rethink Research. (2018, June) The multi-ap wifi revolution: How wifi jumps 10x and takes over the world. [Online]. Available: <https://rethinkresearch.biz/report/the-multi-ap-wifi-revolution/>
- [2] Cisco. (2017, Dec) Cisco visual networking index: Global mobile data traffic forecast update, 20162021 white paper. [Online]. Available: <http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html>
- [3] A. Andrae and T. Edler, "On global electricity usage of communication technology: trends to 2030," *Challenges*, vol. 6, no. 1, pp. 117–157, 2015.
- [4] World Data. (2019, June) Energy consumption in the united states. [Online]. Available: <https://www.worlddata.info/america/usa/energy-consumption.php>
- [5] K. Ab-Hamid, C. E. Tan, and S. P. Lau, "Self-sustainable energy efficient long range wifi network for rural communities," in *2011 IEEE GLOBECOM Workshops (GC Wkshps)*. IEEE, 2011, pp. 1050–1055.
- [6] J. Noll, S. Dixit, D. Radovanovic, M. Morshedi, C. Holst, and A. S. Winkler, "5g network slicing for digital inclusion," in *2018 10th International Conference on Communication Systems & Networks (COM-SNETS)*. IEEE, 2018, pp. 191–197.
- [7] Elastic. (2019, June) Elastic stack. [Online]. Available: <https://www.elastic.co>
- [8] Norwegian water resources and energy directorate. (2019, June) Electricity disclosure 2017. [Online]. Available: <https://www.nve.no/energy-market-and-regulation/retail-market/electricity-disclosure-2017/>
- [9] World Bank. (2019, June) Co2 emissions. [Online]. Available: <https://data.worldbank.org/indicator/EN.ATM.CO2E.KT>
- [10] K. Gomez, R. Riggio, T. Rasheed, and F. Granelli, "Analysing the energy consumption behaviour of wifi networks," in *2011 IEEE Online Conference on Green Communications*. IEEE, 2011, pp. 98–104.
- [11] K. Gomez, R. Riggio, T. Rasheed, D. Miorandi, and F. Granelli, "Energino: A hardware and software solution for energy consumption monitoring," in *2012 10th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*. IEEE, 2012, pp. 311–317.
- [12] C. Gandarillas, C. Mart'ı n-Engeños, H. L. Pombo, and A. G. Marques, "Dynamic transmit-power control for wifi access points based on wireless link occupancy," in *2014 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2014, pp. 1093–1098.
- [13] C.-Y. Huang and P. Ramanathan, "Joint association and power adaption in wifi community networks," in *2011 45th Annual Conference on Information Sciences and Systems*. IEEE, 2011, pp. 1–6.
- [14] R. Riggio, C. Sengul, L. Suresh, J. Schulz-Zander, and A. Feldmann, "Thor: Energy programmable wifi networks," in *2013 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. IEEE, 2013, pp. 21–22.
- [15] R. Riggio, C. Sengul, K. Mabell Gomez, and T. Rasheed, "Energino: Energy saving tips for your wireless network," in *Proceedings of the ACM SIGCOMM 2012 conference on Applications, technologies, architectures, and protocols for computer communication*. Citeseer, 2012, pp. 273–274.
- [16] R. Riggio and T. Rasheed, "Toward enterprise virtual power consumption monitoring with joule," in *2014 IEEE Network Operations and Management Symposium (NOMS)*. IEEE, 2014, pp. 1–6.
- [17] B. Feng, C. Zhang, H. Ding, and Y. Fang, "Exploiting wireless broadcast advantage for energy efficient packet overhearing in wifi," *IEEE Transactions on Vehicular Technology*, 2019.
- [18] B. Abhimanyu and N. Jyoti, "Improve qos performance with energy efficiency for ieee 802.11 wlan by the algorithm named contention window adaptation," in *2017 International Conference on Computing, Communication, Control and Automation (ICCUBE)*. IEEE, 2017, pp. 1–5.