On Energy Consumption of Wi-Fi Access Points

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***Abstract*—With the recent trends towards green communications, several companies introduced low-power Wi-Fi products targeting application domains such as smart grid utilities, home and building automation, healthcare etc. However, Wi-Fi Routers/Access Points (AP) have not been targeted much so far as they are mains-powered and are "always-on" devices. A wireless LAN extension to an existing wired fire alarm system requires the Wi-Fi AP to be powered by the bus where energy might be limited depending on the number of peripherals on the same bus. Moreover, regulations require battery backup power for each device on the bus. In order to better understand the feasibility of such system, we studied the energy consumption of two selected consumer grade APs with different hardware and software architectures. Our study discusses about the contribution of the components on the AP to the overall energy consumption. Furthermore, we investigate the impact of different traffic patterns, data rates, packet sizes, security schemes, number of clients etc., on AP energy usage and analyze the results.**

***Index Terms*—Wi-Fi Access Point, WLAN router, 802.11, energy consumption, green communication, fire alarm system**

I. Introduction

With the growing demand to reduce the environmental impact of technology, strong emphasis is being placed on developing energy-efficient computing devices. This trend is reflected in wireless networks too where traditionally the emphasis is more towards user experience - data throughputs supported, range etc - and so energy consumption was not a major concern. Also, with the prolific rise in the usage of battery-operated devices, energy consumption by WLAN systems has become one of the major areas of work in performance optimization. Several companies have recently developed power-efficient Wi-Fi components targeting wireless sensing applications. This low-power Wi-Fi technology promises multiple years of battery lifetime while maintaining the compatibility with standard Wi-Fi. Authors in [1], [2], and [3] have talked about the feasibility of Wi-Fi Technology for wireless sensor applications on the client side.

As the Wi-Fi routers/APs are always connected to a power supply, reducing the energy consumption of APs, as opposed to stations, is not so aggressively pursued. There are very few works on understanding the APs power consumption and its optimization. However, with the recent trends towards green communication, researchers have started to focus in that area as well. In [4], authors study the power consumption of three different enterprise grade APs by measuring the contribution of base components and radios as well as impact of throughput. In the area of designing low-power APs, Zhang et al. present a design for an IEEE 802.11-based power saving AP intended for use in multihop battery and solar/battery powered applications [5]. Another low-power AP design proposal in [6] suggests using an auxiliary low-power radio to carry out-of-band control information to maintain connectivity and wake up the AP when necessary. In [7] authors propose a "Green Wireless LAN System", which reduces electricity consumption by automatically turning on or off APs in accordance to the presence of stations.

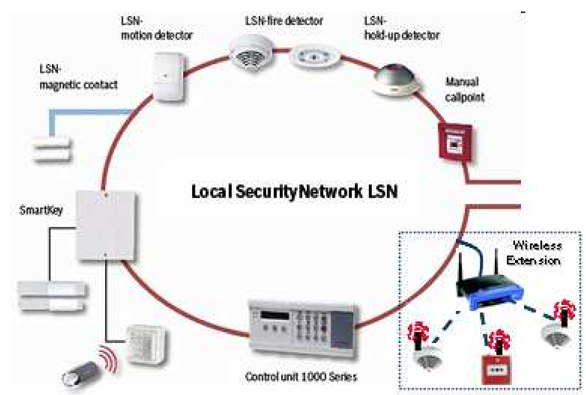

Fig. 1. Wi-Fi Extension to an Existing Wired Fire Alarm System

Our target application - extension of an existing wired fire and intrusion alarm system with wireless LAN (Fig. 1) - requires powering the AP from the bus where the power has to be shared by several peripherals on the bus. Moreover, for each element on the bus, a minimum 72 hour back-up is required by the European regulations ([8], [9]) in case of a power failure. In order to meet this requirement, an AP with an average power consumption of 3W will require a battery pack of 92 AA batteries each with 2.36Wh capacity! Compared to WLAN stations, APs have higher idle state power consumption as the AP should always be on. In addition to the idle state power, the AP draws additional current during transmit and receive in different operating modes. The goal of this work is to understand the power consumption of consumer grade APs and identify the optimization points for a low-power AP design that can meet requirements of our system.

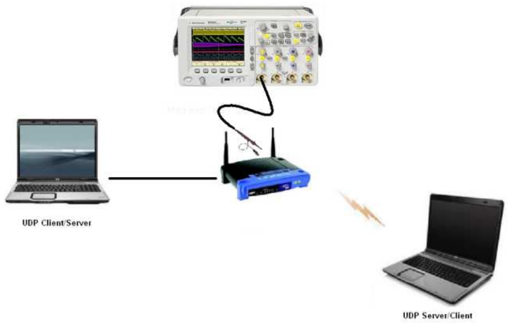

Fig. 2. Experimental Setup used to perform the study on the APs

In this paper, we empirically study the energy consumption performance of two commercially available APs with different architectures and analyze the results. The rest of the paper is organized as follows: In Section II we give an insight into the system model for which this low-power AP is required. Section III talks about the architectures of the chosen APs and the measurement setup. Section IV discusses the empirical studies performed and the obtained results. We conclude in Section V with key findings and future direction.

II. System Overview

Fig. 1 shows a typical wired Local Security Network (LSN)[1] bus for a fire alarm system with proposed wireless LAN extension. LSN combines fire and intrusion alarm systems and is complemented by a vast range of peripheral equipment. LSN allows the network setup to be in loop form, tee offs, or a combination of the two. An LSN loop can support up to 254 LSN improved elements with a maximum line current of 1500 mA or 127 classic LSN elements with a maximum line current of 300 mA. Line length can go up to 3000m depending on configuration and cable type [10].

Extension of an existing wired fire alarm system with wireless components offers many advantages like flexibility, easy installation and reduced cost. In that sense, widely deployed wireless LAN technology emerges as the first candidate with its familiarity, well-accepted security mechanisms and worldwide license free availability features. The envisioned network adds one or more APs to LSN bus and allows extending the network further by adding many new low-power Wi-Fi enabled sensors. The Ethernet interface of regular APs will be required to be replaced by appropriate LSN interface. Wi-Fi enabled sensors will send event-based or periodic data to fire panel like other wired sensors on the LSN bus.

III. Measurement Setup

To measure the current drawn by the AP, an external connector is prepared that has a 1Ω resistance on the ground line and the current is equal to the voltage drop across the resistor. Alternatively, a Digital Multi-meter (DMM) can also be used. The measurement setup consists of an Agilent DSO6034A Oscilloscope, the AP to be evaluated, a wired client connected

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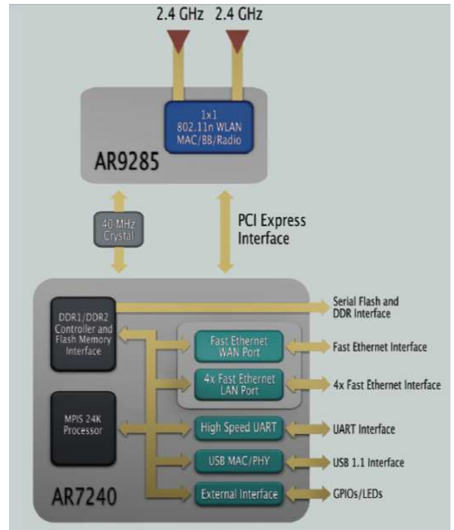

Fig. 3. Reference Design of AP91

on a LAN port and a wireless client associated with the AP - which act as UDP Client and Server respectively during transmit and viceversa during receive. Here, both ‘transmit’ and ‘receive’ are used with respect to the AP. As an AP in a LSN requires only one wired back-end connection and the power consumed does not vary with the number of wireless clients in ”connect” state, this experimental setup accurately reflects the target System Model. The experimental setup is shown in Fig. 2. The following subsection gives an introduction to the APs chosen to conduct the study.

A. Chosen Access Points

We chose Atheros AP91 and Ralink RT5350 APs for this study. The Atheros AP91, shown in Fig. 3, is an 802.11b/g/n solution with a 1x1 antenna and is an example of current generation of APs where the solution has a Network (NW) Processor (AR7240) - to perform the network layer functionality - which is connected to a WLAN Chipset (AR9285) using a high speed bus. It has 4 LAN ports and 1 WAN port connected to the NW processor through 3 RJ45 transformers, a 128Mbit SDRAM, a 32Mbit serial flash and a Buck Converter to step-down voltage from 12V to 3.3V. The second AP, RT5350, is a smaller footprint solution and reflects the trend in the industry - moving towards single-chip low-power solution. The Ralink RT5350 AP, shown in Fig. 4, is a Router-On-a-Chip (RoC) solution where a single chip handles both NW layer and WLAN capabilities. It also contains 4 LAN ports and 1 WAN port, 3 RJ45 transformers, a 256Mbit SDRAM, a 32Mbit Serial Flash, and a Buck Converter to convert input voltage from 5V to 3.3V.

B. Operating Conditions

We performed the experiments in an office environment where several other Wi-Fi networks were present. To maintain high correlation across experiments, the maximum acceptable packet loss rate at the receiver is set to 0.05% and the retry

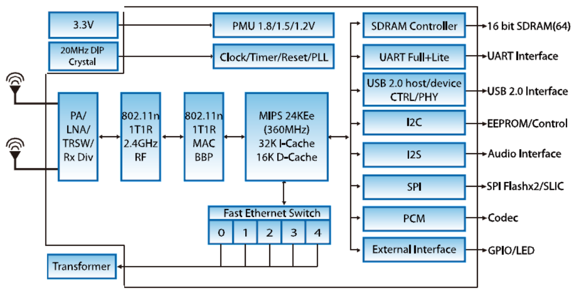

Fig. 4. Reference Design of RT5350

count of the AP is set to a maximum of 4. We used the following AP settings for measurements: 802.11g/n mode, 16dBm transmit power, 20MHz channel width, auto data rate, and channel 6. Each experiment has lasted for 100 seconds.

IV. Performance Evaluation

In IEEE Power Save (PS) mode, the WLAN stations go to sleep mode and wake-up periodically, to enquire about any pending packets at the AP or to transmit any pending packets at their end. But, the WLAN AP's radio should always be turned-on. So, the idle state energy consumption of the AP will be quite significant when compared to 802.11 stations. We define the idle-state of an AP as 'AP being in receive mode and transmitting a beacon for every beacon-interval'. Also, some of the basic parameters/operating modes that have an impact on AP power consumption are - Data Throughput (amount of data transmitted/received), Data rates, Security scheme (Encryption/Decryption of data packets), Number of Clients in the BSS, Transmission(Tx) Power, 802.11 Mode (b/g/n) and Size of packets transmitted. This paper does not include the study of "dependent" factors like distance between wireless client and AP as it effectively translates to packet loss which results in drop of Data Rates. The following subsections talk about the experiments conducted and the results obtained by varying these parameters.

A. Idle-State Power

To efficiently decode packets transmitted from a longer range the APs radio is tuned to higher sensitivity values. This results in AP consuming higher energy in idle-state. In [6], an idea is explored to reduce the energy consumed by radio in idle-state. In this experiment, we try to evaluate the major contributors to the idle-state energy consumption of the AP in addition to the WLAN Radio.

From Fig. 5, it can be seen that the WLAN Radio consumes 19.8% of power in AP91 and 33.3% on RT5350 with absolute power values being 426mW and 320mW respectively - which are significant. Also, on AP91, plugging of each LAN port to a client increased the power consumption by 275mW and on RT5350 it is 160mW. RT5350 provides configurability of the Ethernet ports through an 'ioctl' that also has an option of powering down an ethernet port. So, on powering down each ethernet port, the power reduced by ~80mW. To measure

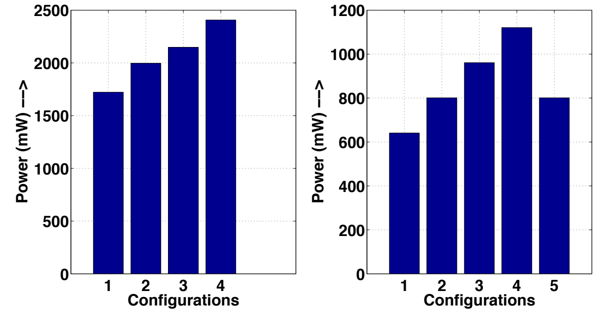

Fig. 5. Idle-State power consumption of AP91 and RT5350. The configurations are 1. No Ethernet Connected & Radio Off 2. Ethernet Connected & Radio Off 3. No Ethernet Connected & Radio On 4. Ethernet Connected & Radio On 5. Power-down of the rest 4 LAN/WAN ports

the power consumed by the digital logic on the RoC, all the LAN/WAN ports are powered-down and the WLAN Radio is switched-off, then the resultant power is 230mW. The efficiency of the Buck-Converter for the idle-state current of RT5350 is 85% and the SDRAM and Flash memories consume around 20-40mW and if we assume that the current drawn by the rest of the components like LEDs is negligible, the power consumed by the digital logic blocks on the RoC is 18%. Since our application requires only one wired back-end network connectivity, for subsequent experiments on RT5350, configuration 5 shown in Fig. 5 is used.

B. Data Throughputs and Encryption

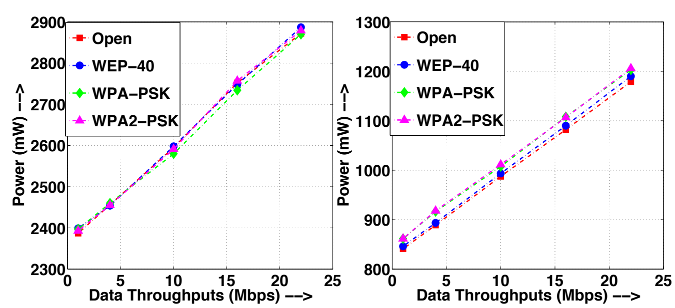

Fig. 6. Effect of data throughputs, encryption on power of AP91 & RT5350

Fig. 6 shows the impact of data traffic as the transmit data throughput is varied from 1Mbps to 22Mbps. Since the radio draws higher power during transmit than receive, the impact of transmission is higher on AP's energy consumption. In fact, when measured for receive the increase in power is mainly due to transmission of ACKs by the AP. During transmission, AP91 has 23mW increase per 1Mbps of data transmitted and it is 18.6mW for RT5350. For Receive, the increase is 8mW and 4.6mW for AP91 and RT5350 respectively. As the Fig. 6 shows, encryption does not have much impact on AP91 but an average increase of 25mW for WPA2 on RT5350. One of the possible reasons for encryption not having an effect on AP91 is because the gate count of the core security algorithm used in the encryption standards will be of the order of 12k - 15k. This is quite less when compared to the total gate count of the NW Processor and WLAN Chipset put together. So, if the power save techniques, like Clock-Gating, are not implemented for the security modules then the power consumed will not be much different between Open and Security modes.

C. Data Rates

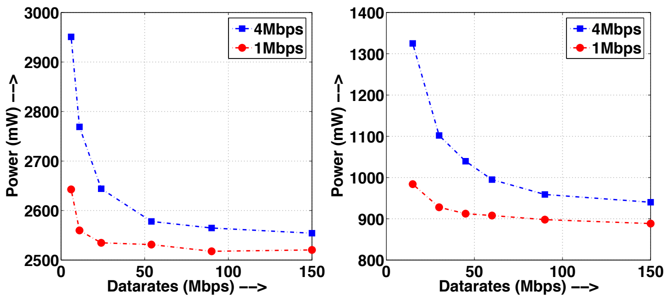

Fig. 7. Impact of datarates on power consumption of AP91 and RT5350

The term "Data Rate" indicates the amount of time for which each bit of the packet is transmitted on-air. This is different from "Data throughput" which is the amount of data sent per second. The relation between 802.11 data rates and energy consumption is shown in Fig. 7. Though there is huge difference in power values between 6Mbps and 150Mbps, in real-world, the data rates do not often fall below 24Mbps unless there is huge data traffic or communication range problems due to distance between AP and the clients. Also, on AP91, the transmission periods at different data rates - measured at the WLAN PHY layer by probing the power line during 4Mbps of data traffic - has the following relation with the power values which shows that the impact of Data Rates is only on the power consumption of PHY layer.

$$\frac{P_{D1} - P_{D2}}{T_{D1} - T_{D2}} \approx const. \qquad (1)$$

where P_{D1}, P_{D2} are Power Values at Data rates D1, D2 T_{D1}, T_{D2} are transmission times at Data rates D1, D2. Here the transmission time is sum of the actual on-air transmission time and the time taken for the antenna to switch from receive to transmit mode and back.

D. Number of Clients

The energy consumed by the clients increases with the number of clients in the BSS because of retransmissions. In case of AP, to analyze the power consumption, the study is categorized into three parts. If the AP is only transmitting then the power consumed by the AP depends on the amount of data transmitted but not upon the number of clients between which it is divided. Also, the number of clients does not have an impact when the AP is receiving because the power increases if there are any retransmission of ACKs and this does not occur - unless there is a hidden node - as the ACK is transmitted after Short Interframe Space (SIFS). This is shown empirically

TABLE I
IMPACT OF INCREASE IN NO. OF CLIENTS TRANSMITTING DATA - 8MBPS - ON AP91 AND RT5350

Number of Clients	AP91	RT5350
1 Client	2580mW	990mW
2 Clients	2584mW	993mW
4 Clients	2582mW	997mW
8 Clients	2586mW	994mW

TABLE II
IMPACT OF INCREASE IN NO. OF CLIENTS TRANSMITTING AND RECEIVING DATA - 8MBPS TX & 8MBPS RX - ON AP91 AND RT5350

Number of Clients	AP91	RT5350
1Tx & 1Rx Client	2658mW	1041mW
2Tx & 2Rx Clients	2668mW	1048mW
4Tx & 4Rx Clients	2713mW	1080mW

with the results in Table I. Here the amount of data transmitted is 8Mbps which is divided, equally, among the clients as their number increases. When the AP has both transmit and receive data streams, then the power consumption increases due to retransmissions and drop in data rates. The effect of this on power consumption is tabulated in Table II. Here the amount of data transmitted is 8Mbps Tx and 8Mbps Rx which is divided among the clients.

E. 802.11n features

The impact of 802.11n features - Channel Bonding (HT40 mode) and Aggregation - is evaluated using a 11n client, and the results are shown in Fig. 8 and 9. With Channel Bonding enabled, the AP tunes its radio to 40MHz which increases the idle-state power consumption of the AP. The advantage of channel bonding is the capability of transferring messages at higher data rates which implies lower transmission period compared to HT20 mode. The higher data rates result in lower slope of the curve for HT40 mode. The idle-state power of AP91 increased by 176mW on switching to HT40 mode but it is only 40mW for RT5350.

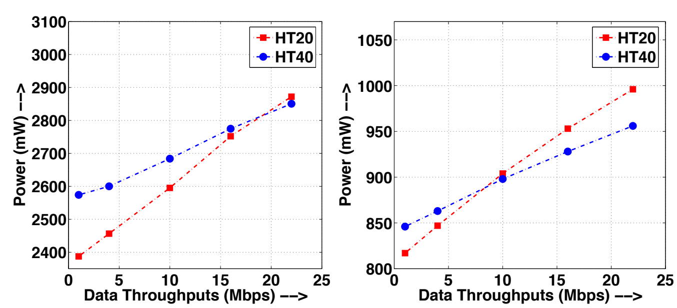

Fig. 8. Impact of channel bonding on power of AP91 and RT5350

Since the data is transferred to a single application, the aggregation taking place is MSDU aggregation. The AP aggregates all the packets that arrive in a certain interval and this happens more at higher data throughputs and so, there is not much difference in energy consumed at lower throughputs.

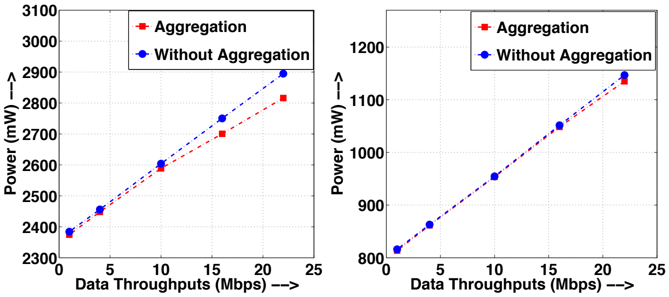

Fig. 9. Impact of Aggregation on power consumption of AP91 and RT5350

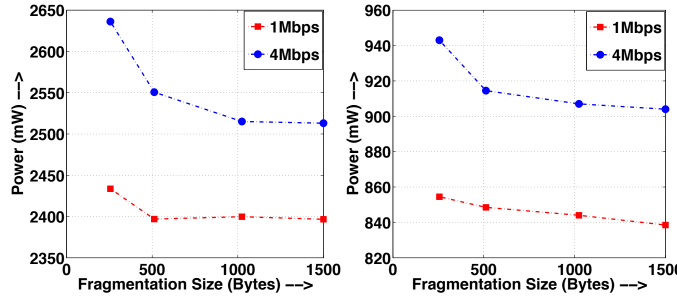

Fig. 11. Impact of fragmentation on power consumption of AP91 and RT5350

Although, at 22Mbps, the difference in power on AP91 is 79mW and 12mW on RT5350, these values are not significant when compared to their corresponding idle-state power.

F. Packet Sizes and Fragmentation

The results of the effect of the these parameters are shown in Fig. 10 and 11. As expected application layer packet sizes has significant impact on the power consumption due to the direct relation with number of packets to be sent/received. For 4Mbps of data traffic, AP91 consumes 157mW (6.4%) higher power at 256B than 1500B and RT5350 consumes 10% more at 4Mbps from 1500B to 128B packets.

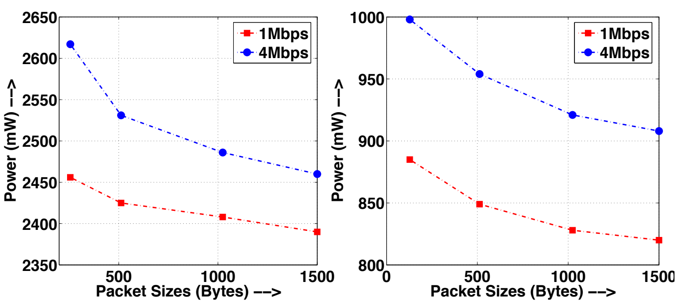

Fig. 10. Impact of packet sizes on power consumption of AP91 and RT5350

Fragmentation is another form of adjusting packet sizes at MAC layer. So the results are quite similar. The increase in power from no fragmentation to 256B fragmentation threshold is 123mW (4.9%) at 4Mbps for AP91 and 39mW (4.3%) for RT5350.

V. CONCLUSION

The factors that have substantial impact on energy consumption are listed in Table III. AP mainly consumes its energy in idle state where the primary contributors are Ethernet and WLAN radio. Components like memories have little effect on the total power consumption. So, in designing an AP for LSN networks which requires only one ethernet connection to the back-end network, powering down all the other LAN/WAN ports reduces the power consumption by 28.5% on RT5350. Also, since the AP is idle most of the time for these applications, power-save techniques for digital logic like changing to lower operating frequency when idle, gating the clock for unused digital blocks etc, will be explored. From the study, digital-logic consumes 18% of the total power on RT5350 and so, on implementing these two techniques, the estimated power consumption of AP with one active wired connection is around 640mW. With this, an AP in a LSN network has a reduced back-up battery pack size of 20 AA batteries (each 2.36Wh) from 35 batteries. To reduce this further, we will concentrate on ways to reduce Wi-Fi radios power consumption and more specifically, in reducing its listen mode power.

TABLE III
MAJOR FACTORS AFFECTING POWER CONSUMPTION ON AP91 & RT5350

Parameter	AP91	RT5350
idle-state	2407mW	921mW
Data Throughputs	23mW↑ per 1Mbps	18.6mW↑ per 1Mbps
Data rates (@4Mbps)	400mW↑(150-6 Mbps)	385mW↑(150-15 Mbps)
Packet Sizes(@4Mbps)	157mW↑(1500B-256B)	90mW↑(1500B-128B)

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