Power Consumption of the Raspberry Pi: A Comparative Analysis

Girish Bekaroo
Middlesex University (Mauritius Branch Campus)
Bonne Terre, Vacoas, Mauritius.
g.bekaroo@mdx.ac.mu

Aditya Santokhee
Middlesex University (Mauritius Branch Campus)
Bonne Terre, Vacoas, Mauritius.
a.santokhee@mdx.ac.mu

***Abstract*—Over the past few decades, human beings have increasingly adopted different types of personal computers including desktop computers, laptops, tablets and smart phones. More recently, there has been the emergence of the Raspberry Pi and since its release in 2012, this new type of computer has undergone rapid growth in adoption to even become the fastest selling British computer. The Raspberry Pi has often been referred as a computer designed to change the world since it is capable to do most things that a desktop computer can do. The growing concern is that all these computers utilize power in order to operate thereby turning ICT into a power drainer. The diverse functionalities present in modern computers including communication and web browsing, among others, were found to be important components that affect the power consumption of such devices. As such, this paper investigates how power consumption of the Raspberry Pi is affected by the key functionalities that could be performed by end-users on the platform. Moreover, this relationship is compared against other types of common personal computers before recommending on techniques and practices that could reduce the power consumption of this emerging type of computer.**

Keywords— Raspberry Pi Power; Power Consumption Measurement, Power Analysis; RPi Power Reduction;

I. INTRODUCTION

As predicted by Weiser, technology has seamlessly integrated into the everyday life of human beings in the form of computers, smart phones and tablets, among other devices [1, 2]. Recently, the number of mobile devices being used on Earth outnumbered the number of people on this same planet [3]. Considering this statistic, the ratio of all personal computers (e.g. desktop computers, smart phones and tablets) to human beings is undoubtedly higher. The growing concern is that the number of computers is anticipated to grow further in the coming years [3]. Consequently, the power consumption of information and communication technologies (ICT) is expected to increase at the same time as these devices are dependent on power [4]. Hence, it becomes essential to investigate the power consumption of ICT devices, namely personal computers, where the main types in present use include desktop computers, laptops, tablets, smart phones, in addition to the recently developed Raspberry Pi (RPi).

As energy efficiency has emerged as an important design requirement for modern computing systems, various innovations during recent years helped to reduce power consumption of computers [5]. Different types of computers are known to consume different amounts of power to operate where for instance, a desktop computer consumes approximately 65 to 250 watts where as a laptop consumes around 15 to 60 watts [4, 6]. Reduced power consumption of and during the use of personal computers also implies lesser costs, prolonged battery life, in addition to reduced adverse environmental impacts [5]. However, within modern computers, the diverse functionalities present including communication (email, voice, etc), web browsing, gaming, and video playback, among others, were found to be important components that affect their power consumption [7]. In order to analyze the relationship between these diverse functionalities present in modern computers and power consumption, various studies have been conducted.

One such study aimed to analyze the power consumption of desktop computers after simulating 11 common usage features [8]. The study revealed insightful information on power overheads of the various scenarios in addition to how usage patterns impact power consumption of computer systems. Similarly, power consumption profiling of common usage scenario and hardware of laptops revealed useful information about power saving techniques [9, 10]. Likewise, analysis of the relationship between the diverse functionalities present in a smartphone and power consumption helped to develop an energy consumption model for the different usage scenario analyzed [7]. Additionally, after profiling the power consumption of different common functionalities within Android-based tablets, the promise of CPU resource analysis tools for system-wide platform diagnosis was revealed [11]. Although power consumption profiling has been conducted for the diverse features of different types of computers namely, desktops, laptops, tablets and smart phones, work is yet to be undertaken for the emerging Raspberry Pi. This limitation is also a barrier to the comparative power analysis of the diverse functionalities of the RPi against the various other types of computers. To overcome this barrier, it becomes essential to answer the following research questions:

- RQ1: How much power is consumed by the key functionalities performed by end-users on the RPi platform?
- RQ2: How does the data collected in RQ1 compare with power consumption of the other main types of personal computers, namely, desktop computers, laptops, tablets and smart phones?

- RQ3: How to reduce the power consumption of the key functionalities of the RPi during use of the key features identified in RQ1?

The power consumption of personal computers is important to study since different such devices utilize battery and optimal power consumption can help increase battery life and help towards sustainable computing [7]. This paper attempts to answer RQ1-RQ3 in order to reveal insightful information on power consumption of personal computers. The first research question, RQ1, seeks to determine the amount of power consumed when a user performs different tasks on an RPi (e.g. web surfing, listening to music, etc). RQ2 in turn attempts to compare the same power consumption data collected in RQ1 with common types of personal computers. Finally, RQ3 looks at how to save power when using RPi so as to further reduce consumption during the usage scenario investigated in RQ1. Before delving into the 3 research questions, a background on RPi and power consumption is provided.

II. Raspberry Pi and Power Consumption

Raspberry Pi is a low-cost, credit card sized single-board computer that was developed in 2012 by Raspberry Pi Foundation in UK in order to stimulate teaching of basic computer science in schools [12]. Since its release in 2012, the RPi has become the fastest selling British computer where over 5 million devices were sold in just 3 years [13]. RPi comes in two different models, namely, Model A and B that differ in terms of technical specifications including RAM, USB ports and network connection [14]. It has often been referred to as a computer designed to change the world since it is capable to do most things that a desktop computer would do including web surfing, video streaming, word-processing, computer programming and playing games [15].

The RPi derives the energy it requires for its operations from three different sources. Firstly, the device could be connected using a 5V micro USB mains adaptor with a 1200mA current. Similarly, the Raspberry Pi can be powered using a USB based portable battery compatible with smartphones. Another approach is to use the Mobile Pi Power (MoPi) - a power regulator that offers multiple inputs (e.g. solar cells, car power sockets or standard battery) and offers the facility to swap power supplies without interruption. Likewise, users can power the RPi via a battery box that runs with six or more AA batteries.

Similar to other types of computers, RPi consumes power during its operation. This include power needed to operate the hardware components and to perform tasks or run software on the platform. Recently, a power consumption model of Raspberry Pi, named PowerPi, was proposed after measuring the different power states of the platform [16]. Although the proposed PowerPi models and measures RPi power consumption from various components including the CPU, Ethernet and USB WiFi dongle mainly, the power consumption diverse functionalities present within the platform were not investigated. As such, there is a need to answer RQ 1 – RQ3.

III. Methodology

RQ1 and RQ2 investigate the power consumption of different types of personal computers, namely, RPi, desktop computer, laptop, tablet and smart phone. As such, different devices under test form part of this study. Answering RQ1 and RQ2 also necessitates the compilation of a list of key functionalities commonly performed by end-users on the devices under test. This section describes the methodology of the research for answering the research questions being studied and details the experimental setup and procedures.

A. Devices under Test

5 different types of personal computers were involved in this study and for the experiment, a random device for each category was selected. The selected devices under test were:

1. *Raspberry Pi*

A Raspberry Pi 2 Model B running a software image of Raspbian Wheezy was utilized, having the specifications as in Table I.

TABLE I. RPi Specifications

Component	Specifications
CPU	900MHz quad-core ARM Cortex-A7
RAM	1GB
Wi-Fi	via Wi-Fi dongle
3D Graphics	VideoCore IV 3D graphics core
Other Interfaces	Camera interface (CSI), Display interface (DSI)

2. *Laptop*

An HP ProBook 4530s with 64-bit Windows 7 (Service Pack 1) was utilised. The specifications of this device are given in Table II.

TABLE II. Laptop Specifications

Component	Specifications
CPU	2.30GHz Intel(R) Core(TM) i5-2410M CPU
RAM	8GB
Webcam	Integrated
Network Adapter	Qualcomm Atheros AR9285
3D Graphics	Mobile Intel(R) HD Graphics and Radeon HD6490M

3. *Desktop Computer*

A desktop computer running 64-bit Windows 7 (Service Pack 1) with the specifications as in Table III was utilised.

TABLE III. Desktop Computer Specifications

Component	Specifications
CPU	3.30GHz Intel(R) Core(TM) i3-2120 CPU
RAM	4GB
Network Adapter	Realtek PCIe RTL8111F - 10/100/1000 Controller
3D Graphics	Intel(R) HD Graphics 2000

4. *Smartphone*

A Samsung Galaxy S6 Edge with Android OS (v5.1.1 Lollipop) was utilized and the device had the specifications as in Table IV.

TABLE IV. Smartphone Specifications

Component	Specifications
CPU	Quad-core 1.5 GHz Cortex-A53
RAM	3 GB RAM
Display	Super AMOLED capacitive touchscreen

5. Tablet

A Samsung Galaxy Note 10.1 (2014 Edition) with Android OS (v4.4.2) was utilized and the device had the specifications as in Table V.

TABLE V. TABLET SPECIFICATIONS

Component	Specifications
CPU	Exynos® 5 Octa (1.9GHz Quadcore + 1.3 GHz Quadcore)
RAM	3GB
Display	Super clear LCD capacitive touchscreen

All devices under test were restored to factory settings and then updated in order to ensure that the number of installed applications were minimal. Also, pre-installed power-saving features within the different devices were disabled in order to obtain more accurate power estimates. Furthermore, the number of processes during runtime was kept minimal so as to minimise fluctuations in CPU utilisation and power as far as possible.

B. Features under Investigation

Since RQ1 and RQ2 investigate the power consumed by key functionalities performed under the various platforms, a list of such common operations had to be prepared. For this, the common usage scenario identified in previous studies [8, 10] were compiled and extended so as to cover more such tasks. During the compilation process, only common tasks that could be performed on all platforms were considered. As such, tasks including sending an SMS or making phone calls were not considered due to their specificity to smart phone. The compiled features under investigation are given in Table VI.

TABLE VI. OPERATIONS PERFORMED DURING EXPERIMENT

No.	Operation	Description
O1.	Device Start-up	Switching on the device under test until the welcome screen is shown.
O2.	Idle Mode	During idle mode of the device under test.
O3.	File-Management Operation I	Involved copying a file of approx. 2 GB from one location to another on the same disk used by the device under test.
O4.	File-Management Operation II	Involved copying the same large file in O3 from the device under test to an external source via USB.
O5.	Surfing the web	Involved actively surfing the IEEE Xplore website to browse research papers using the default browser in device under test.
O6.	Playing a browser game	Involved playing the online Cut the Rope [18] game using the default browser in the device under test.
O7.	Downloading a file	Involved downloading a file of approximately 1GB using the default browser in the device under test.
O8.	Playing an installed game	Involved playing an installed computer game. For this, the classic Pacman was chosen due to its availability on all platforms.
O9.	Listening to Music	Involved listening to music (an MP3 file) by using the default music player in the device under test while volume set as 50%.
O10.	Watching a video	Involved watching a movie using the default movie player in the device under test.
O11.	Watching a video online	Involved watching a video on YouTube using the default browser in the device under test.
O12.	Using Image Gallery	Involved going through a set of images within the device under test under full-screen mode.
O13.	Word-processing	Involved using the Word package to actively write a document in the device under test.
O14.	PowerPoint Presentation	Viewing a PowerPoint presentation in the device under test.
O15.	Calling using a Messenger	Involved talking (with video disabled) with another contact using Skype installed in the device under test.
O16.	Calling using a Messenger II	Involved talking (with video enabled) with another contact using Skype installed in the device under test.
O17.	Reading a PDF	Involved reading a PDF manual using the default pdf reader in the device under test.
O18.	Installing an Application	Involved installing a new application on the device under test.
O19.	Sleep Mode	Switching the device under test to sleep mode.
O20.	System shut down	Involved switching off the device under test from the idle state.

Different operations listed in Table VI needed use of the appropriate software. For this, the version compatible with the device under test and operating system was used. Furthermore, a few operations needed the use of particular files (e.g. .mp3 file for O9, movie for O10, and images for O12, among others), and for this, the same files were used for all platforms wherever possible.

C. Measurement Methodology

Due to unavailability of a standard power measurement tool compatible with all platforms under test, different hardware and software were used to measure power consumption of operations listed in Table VI. For devices that could be operated by using electric current sourcing directly from the power outlet, the Eco-Worthy electronic wattmeter was used. The hardware approach was preferred for measuring power as compared to the use of software due to better accuracy of results [10]. Use of the power-meter involved plugging the device into the power socket and then connecting the device under test to the power meter. It should be noted that even though powering the meter needs electricity, the power meter 0.0W when no device is plugged to it.

Furthermore, only the CPU power was considered during the experiment in order to get better comparative values for RQ2. For the RPi and desktop computer, the CPU power could be directly measured by using the power meter. However, for the laptop, power used by the screen component had to be subtracted from the measurements of power meter. For measuring the screen power consumption, Microsoft Joulemeter was calibrated and utilized. Also, the battery of the laptop was removed so as to ensure that the device under test is powered directly from the socket, to which the power meter is connected.

For the smartphone and tablet, the power meter could not be utilized since these devices do not operate without battery while being plugged directly to the power outlet. As an alternative, PowerTutor was used to measure power consumption of both devices. This tool has been used in different studies related to power measurement of components within Android based devices [17, 18].

D. Experimention Procedures

To begin the experiment, the power measurement tool for the selected device under test was activated by the research team. For the RPi, desktop computer and laptop, the initially switched-off device under test was connected to the power meter while ensuring that the meter was reading 0.0W. For the smartphone and tablet, PowerTutor was opened and profiling was started within the application. Once the power measurement mechanism was activated, the first operation described in Table VI was performed. If the operation being investigated needed internet connectivity, network access was granted. Else, Wi-Fi connectivity was turned off so as to prevent any background processes from using the network, thus increasing power consumption of the device. As the operation was being performed, values from the power measurement tool was recorded at every 2 seconds interval for a maximum of 2 minutes so as to ensure enough values were obtained for reliability. As an example, for measuring the power consumption of O1, once the power button of the device under test was pressed, values from the power meter was recorded at every 2 seconds until the welcome screen was displayed. The recorded values were then averaged. The same operation was conducted three times so as to ensure the reliability of results obtained. The overall average for the three different instances was then calculated. The same process was repeated for all the operations given in Table VI and with the different devices under test. At the end of the experiment, the collected data were analyzed by using a statistical package, namely, SPSS.

IV. Results and Discussions

The average power measurements from the 3 instances of the experiment with each device under test are as in Table VII.

TABLE VII. Results – Average Power Consumptions

No.	Average Power Consumption (W)				
	Desktop	**Laptop**	**Smartphone**	**Tablet**	**RPi**
O1.	47.50	31.40	__	__	2.80
O2.	33.80	10.20	0.12	0.16	2.20
O3.	37.10	13.10	0.14	0.21	2.60
O4.	37.80	14.20	0.14	0.25	3.20
O5.	42.30	20.70	0.60	0.36	3.40
O6.	49.30	29.00	0.67	0.66	3.80
O7.	39.70	14.40	0.81	0.42	3.50
O8.	44.60	26.30	0.52	0.49	2.30
O9.	36.50	12.30	0.48	0.40	2.40
O10.	38.80	14.40	0.51	0.42	2.80
O11.	46.50	22.90	0.80	0.54	4.00
O12.	36.50	15.70	0.15	0.22	2.60
O13.	34.20	11.90	0.14	0.19	2.40
O14.	35.60	12.40	0.15	0.19	2.50
O15.	40.40	17.80	0.86	0.28	__
O16.	46.80	22.70	0.91	0.37	__
O17.	38.10	15.80	0.17	0.23	2.60
O18.	44.20	19.90	0.29	0.19	2.90
O19.	29.20	1.20	__	__	__
O20.	40.20	27.20	__	__	2.30

During the experiment, it could be observed that both the electronic wattmeter and PowerTutor were reading power consumption at every 1 second interval. Also, as per Table VII, a few operations could not be completed due to limitations discussed in the next sections during while attempting to answer RQ1 and RQ2.

A. RPi Power Consumption Analysis (RQ1)

During the experiment involving the RPi, 3 operations could not be measured. O15 and O16 could not be performed since at the time of the experiment, no Skype version compatible with the RPi was available for installation. Although Skype could be installed via a virtual machine such as ExaGear Desktop, this would introduce an inconsistent experimentation environment and new parameters to be measured, e.g. power consumption of the virtual machine. Furthermore, O19 could not be measured as no sleep mode is available in the RPi Model B.

Results in Table VII show that every usage scenario consumes more power than when the device is in idle mode (O2). This implies that the use of software and connected hardware have an impact on overall power consumption of the Raspberry Pi. Moreover, an increased number of devices connected to the RPi also showed a rise in the power consumed by the RPi. For instance, without any attached external hardware, the power consumption of RPi was 2.10W and when connecting a mouse and keyboard, its power consumption increased to 2.20W.

Moreover, the power consumption of every operation was unique, where no two operations showed to consume the same average power. This is because of the various factors that affect the power consumption of the CPU during the operations including workload and processing speed, among others [15]. Overall, the average power consumption of the various operations investigated was 2.84W and this was only 0.60W above the idle mode power. This relatively small value highlights a reasonably low overall power consumption during common operations using the RPi. Among the various operations investigated, watching an online video and playing an online game were the highest power consumers of the experiment involving the RPi.

From the collected results, it was observed that operations needing internet connectivity consumed relatively more power than those working offline. For instance, watching an online video consumed 4.00W as compared to 2.80W for watching the same video via the default video player on the device under test. This is due to the significant energy cost imposed by wireless communication on computational devices [19]. Overall, operations needing internet connectivity averaged to 3.68W as compared to 2.58W for those not needing internet connectivity. These statistics are better depicted in the boxplot given in Fig. I.

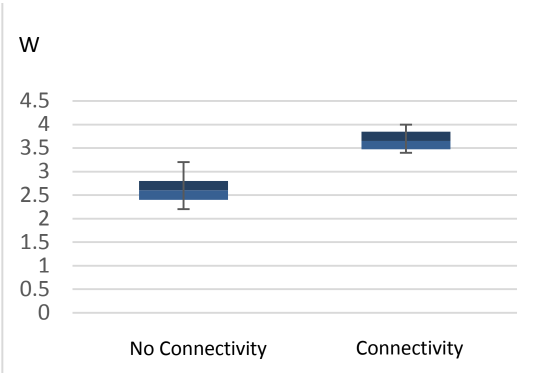

Fig. I. Boxplot Comparing Connectivity Power.

B. Comparison of RPi Power against Other Platforms (RQ2)

As compared to the laptop and desktop computer, a few operations with the smartphone and tablet could not be measured, namely O1 - device start-up, O19 - sleep mode and O20 - system shut down. This is because PowerTutor could not operate under these modes, namely when switching on or off the device and when in sleep mode. Similar to the RPi, all other platforms under test consumed the least power when the devices were in idle mode (O2). Likewise, operations needing internet connectivity consumed more power than those working offline. The line graph comparing the power consumptions of the various devices under test is given in Fig II.

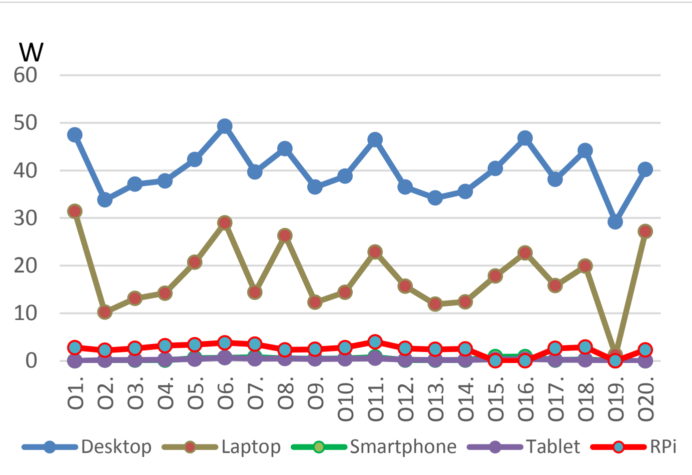

Fig. II. Power Consumption Comparison

As depicted in Fig. II, the different platforms under test showed similar power consumption pattern for most operations investigated. However, a major deviation was observed for O8 – playing an installed game where the laptop showed an increase of 157% in terms of average power consumption as compared to 32% rise for the desktop computer and 5% increase for the RPi with reference to idle power. Although the same game was used for both the laptop and desktop computer, the variance could be due to the differing specifications of the computers under test.

Overall, results showed that the desktop computer was the highest power consumer with an average of 39.96W, which is also above 10 times higher than the average power consumption of the RPi to perform the same set of operations. An important observation with the desktop computer was that under sleep mode, the device was still consuming 29.20W as compared to only 1.20W for the laptop. On the other hand, although the laptop consumed lesser average power than the desktop computer with 17.68W, it consumed over 4 times more power than the RPi. The least power consumers of the experiment were the smartphone and tablet with an average of 0.44W and 0.33W respectively. This result also highlights the significant work done in order to optimize power consumption of battery operated devices.

The study was also marked by a few challenges. The major challenge was that power measurements of various operations had fluctuating values and this was due to the software and hardware components within the device under test including memory and network interface, among others [9]. The operations with highest fluctuations in power readings across the various devices under test were surfing the web (O5), playing a browser game (O6) and calling using a messenger (both O15 and O16). All these operations needed internet connectivity and fluctuations were possibly due to the input or events triggered by the user in the form of voice and video input, mouse clicks, etc. Periodic recording of power measurements in addition to multiple repetitions of the same experiment ensured reliability of the results obtained. Another challenge was to perform the operations within the experiment in a standard way, e.g. typing behavior for O13 and interval to change slide for O14. To ensure reliability of power readings collected, a standard behavior pattern was established for such operations where actions involved consistent typing for O13 and changing slides every 5 seconds for O14.

In terms of limitations, the inability to use a standard power measurement mechanism for all devices under test was the major one. The experiment involved use of three different mechanisms, namely, electronic wattmeter, PowerTutor and Microsoft Joulemeter and inaccuracies of the software approach to measure power could affect the recorded power measurements [10]. The use of different tools also had different precisions where PowerTutor measured in mW and the electronic wattmeter gave measurements in W (with 1 decimal place).

Overall, results of the experiment showed that RPi can be considered as a low power device as compared to desktop computers and laptops. Being a low cost and low power device, the RPi has the potential to save both money and energy if successfully integrated within households. However, a few best practices can also be applied to further reduce costs when using the RPi.

V. Further Reducing RPi Power Consumption

In order to further reduce the power consumption of RPi and to answer RQ3, a few techniques and best practices could be applied during its operation. These techniques are:

1. *Disconnect Peripherals that are not in use*

During the experiment, it was observed connecting more peripherals to the RPi affected the power consumption of the device. One of the easiest ways to save power with RPi is to disable or disconnect devices that are not in use. For instance, if a connected printer or webcam is not being used with the RPi, it could be disconnected.

2. *Work offline whenever possible*

Results showed that network related tasks consumed more power than those working offline. By disconnecting from the network whenever possible, power consumptions could decrease by approximately 30% as per calculations.

3. *Switch-off device when not in use*

In the absence of the sleep mode within the RPi, a way to save power is to switch off the device completely when not in use.

4. *Using the RPi in headless mode*

The HDMI could be switched off when using the RPi in headless mode. This could lead to less power consumption.

5. *Using daemons wisely*

Experiments suggest that running several daemons on the RPi results in the processor consuming more energy. It is also advisable to run power efficient applications which do not require a large stack of software.

Even though there are a few other power saving techniques in addition to the ones described above, further evaluation is needed so as to assess their effectiveness.

VI. CONCLUSIONS

This paper investigated how power consumption of the Raspberry Pi is affected by the key functionalities that could be performed by end-users on the platform. In this process, the power consumptions of 20 distinct operations were investigated within lab experiments. Results showed that the average power consumed by each operation is affected by various factors internal to the CPU. Moreover, it was observed that operations needing internet connectivity consumed relatively more power than those working offline due to the significant energy cost imposed by wireless communication. Furthermore, the power consumptions of the same 20 operations were compared against other types of personal computers including desktop computers, laptops, tablets and smartphones. Results showed that the RPi consumed relatively lower average power as compared to the desktop computer and laptop and has the potential to save both money and energy due to its low cost and relatively low power consumption.

As future work, a standard technique to measure power consumption of all the devices under test could be further investigated so as to eliminate any inaccuracies involved by the use of the software approach to measure power consumption. Delving into a standard power measurement mechanism might also help to complete power consumption measurement of operations that could not be measured. Moreover, the savings in terms of money and power of the various best practices could be further investigated.

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