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| Analysing The Raspberry Pi as a COST-EFFECTIVE Solution for SMEs  Cardiff University School of Computer Science and Informatics | Abstract  This project will analyse the Raspberry Pi as a low energy consumption and low-cost solution for SMEs and start-ups. This will look at the Raspberry Pi vs a traditional server set up vs a cloud solution.  Rhys Connor  Supervisor: Martin Caminada Moderator: Crispin Cooper |

# Acknowledgements

I would like to thank my supervisor Martin Caminada and my parents for all the support throughout the project. As well as all the support received from Cisco Systems, Country Connect in helping facilitate physical elements of the project and Dave Smith for providing layer 1 support on the UCS used in the project.

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Table of Acronyms

|  |  |
| --- | --- |
| Domain Name Services | DNS |
| Dynamic Host Configuration Protocol | DHCP |
| Small-Medium Enterprises | SMEs |
| Network Attached Storage | NAS |
| Active Directory | AD |
| Customer Relationship Management | CRM |
| Packet Capture/Packet Analysis | PCAP/PA |
| Operating System | OS |
| Cloud Service Provider | CSP |
| Central Processing Unit | CPU |
| Error Correction Code | ECC |
| Random Access Memory | RAM |
| Double Data Rate 3 | DDR3 |
| Small Computer Systems Interface | SCSI |
| Serial Advanced Technology Attachment | SATA |
| Serial Attached SCSI | SAS |
| Redundant Array of Inexpensive Disks | RAID |
| Raspberry-Pi | RPi |
| Intrusion Prevention System | IPS |
| Intrusion Detection System | IDS |
| Not Suitable for Work | NSFW |
| Power Distribution Unit | PDU |
| Demilitarized Zone | DMZ |
| Infrastructure as Code | IaC |
| Google Cloud Platform | GCP |
| Value Added Tax | VAT |
| Virtual Machine | VM |
| Graphical User Interface | GUI |
| Cisco Integrated Management Console | CIMC |
| Unified Computing System | UCS |
| Managed Service Provider | MSP |
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# 1 Introduction

The objective of this project is to analyse varying models of RPi’s as low energy consumption and low-cost solution for SMEs and start-ups. This will look at the RPi, analyse its performance and cost to performance when compared to a more traditional server set up and compare the cost of these solutions to what a company could also get within a cloud solution. This will also compare the reasons why these companies may want to or not want to use cloud or traditional server setups over a RPi.

This project aims to address the issue of rising energy costs and hardware costs for businesses by either initially hosting or migrating services from a traditional server or cloud infrastructure to a RPi or a cluster of RPi’s. Both the running costs and the initial hardware costs (if applicable) will be under investigation. Some of the services that will be tested on these systems will be AD, DNS, NAS and a company Webserver.

Although some practical uses of the RPi for business have been covered in the past these have been typically in-depth analysis of a single-use case of the RPi for a business, for example:

* Low-Cost network monitoring system (Maulana & Al-Khowarizmi, 2021)
* Low-Cost Real-Time System monitor (Nguye, et al., 2015)
* Intrusion Detection System (de la Cruz, et al., 2016)
* Low-Cost Small Business Brewing (Acácio de Andrade, et al., 2020)

The systems that will be analysed throughout this project are a RPi 4 Model B 2GB, RPi 4 Model B 4GB and a Cisco UCS C220-M3S.

Depending on the time constraints of the project services such as DHCP, Self-Hosted Company CRM, Honeypot and a PCAP/PA server can also be investigated.

To analyse this there will be a compilation of metrics gathered, raw performance metrics, power draw and performance statistics of the services hosted on these devices. Initial assumptions are that the RPi will be significantly lower power draw but also be significantly lower performance. This may however be ideal for services such as AD which are not as resource intensive as PA.

The project can be broken down into the following requirements:

## Requirement 1

What is the raw performance of the RPi vs server?

## Requirement 2

What is the difference in the power draw of the RPi vs server?

## Requirement 3

Using the data pulled from Requirements 1 & 2 we can then find the comparative performance per watt of the RPi vs server.

## Requirement 4

The performance of the RPi vs server when hosting the key requirement services listed below:

* AD
* DNS
* NAS
* Company Webserver

This project is intended to give a detailed insight into the tools and services that SMEs could utilise a RPi for without causing any impact on regular business operation.

## E-Waste

Electronic waste (E-Waste) is the waste produced in both the production and disposal of electronic equipment. Over the past decade technology and electrical equipment have become far more ubiquitous than prior decades (Insert figure of how many devices are in a house now vs 10 years ago). This project hopes to highlight to businesses that firstly any old tech that they have can be utilised for tasks like these and that if they invest in technology like a RPi 4 Model B there are other non-traditional uses for this as they grow from a small into a medium and even large enterprise.

# 2 Background

## Explanation of Services

### Pi-Hole/DNS

Pi-Hole is a free open-source DNS sinkhole (Pi-Hole, 2022), this can also be referred to as a network-wide advertisement blocker and DNS forwarder. This can be utilised by SMEs and Start-ups as a tool to manage the websites that employees can access and filter out any websites that are NSFW. This can be beneficial as it can allow the company to monitor all the devices that are trying to access NSFW sites at work and identify any sites that may need blocking in the future. See the below Pi-Hole dashboard example taken from my home network set up:

Graphical user interface, chart

Description automatically generated

Figure 1 – A Live/Production Pi-Hole dashboard using Pi-Hole’s Dark Theme

*Note: This configuration of Pi-Hole is running on a docker container on a Raspberry-Pi 4 Model B 4GB*

* Does this explain that Pi-Hole isn’t itself a DNS server?
* Should I cover a dedicated DNS server as well or is Pi-Hole sufficient?
* Should I write up why Pi-Hole was used and not something like AdGuard – mention commercial versions
* <https://technitium.com/dns/>
* <https://nextdns.io/>

### NAS

A NAS can be utilised in several ways for the types of businesses studied in this project. This can be utilised as a generally shared network drive for all users, set up as a backup location for user’s documents and folders and even utilised as a shared drive with folders for individual teams that are managed using user groups to allow for the creation of groups for individual teams. This can be done by either setting up a samba (SMB) share for Linux this can be done by installing samba or with Windows this is supported natively the file system must be formatted in a format that is readable by both Windows and Linux for example File Allocation Table (FAT), Extensible File Allocation Table (exFAT)and New Technology File System (NTFS).

### Webserver

A webserver is utilised by businesses to host their customer-facing webpage and/or any custom internal tools that they may have built to streamline their internal processes.

### AD

AD is a Microsoft developed service that has alternatives and applications that allow for Linux servers to be the AD for the Windows clients. Microsoft defines AD as “*Active Directory stores information about objects on the network and makes this information easy for administrators and users to find and use. Active Directory uses a structured data store as the basis for a logical, hierarchical organization of directory information.”* (Microsoft, 2022). This is beneficial for all scales of business as it can allow for the creation of users and user groups. It also allows for the management of user permissions which can help a company to secure their network and devices from end-users installing malicious software. This can all be managed through a single AD server, instead of the local user approach where system administrators would have to go through each system when someone leaves to remove their user profile. AD resolves this by being the central management system for the businesses users and their permissions.

### Honeypot

A honeypot in terms of technology is a server that imitates another server that is of high interest to a malicious attacker. This can be beneficial as these can be configured to send notifications to the IT team of the business. With many of these Honeypots’ companies can also implement what is known as a Honeynet, this is a network of Honeypots that mimic a full company network. See the below diagram of an example Honeynet.

Graphical user interface, diagram

Description automatically generated

Figure 2 – An example Honeynet from imperva.com (Imperva, 2022)

### DHCP

DHCP is a protocol used within networking to provide client devices connecting to that network an Internet Protocol (IP) address and all the additional network configuration information required, for example, subnet mask and default gateway. This is under the optional requirements as a lot of business routers and ISP-provided routers will host their DHCP server making this a non-essential requirement, however, it may be beneficial for businesses to host their DHCP server like Linux’s isc-dhcp-server with a glass-isc-dhcp (Miles, 2020) web management portal as this will allow them to potentially have easier control over their DHCP leases and DHCP configuration than they may get with their ISP provided router. See the below example of a glass-isc-dhcp dashboard:

Graphical user interface, application

Description automatically generated

Figure 3 – A demo glass-isc-dhcp dashboard (Miles, 2020)

### CRM

A CRM is a tool used by businesses to manage their customer relationships and even store information about customers who are potential leads. This tool will typically have a Webserver and Database element to it however a lot of CRM companies are now offering their services as a SaaS solution eliminating the need for a business to host this internally on their own servers.

### IPS and IDS

PCAP/PA is often utilised within systems to perform IPS and IDS for the LAN. This is a useful tool used by security analysts to monitor network traffic and can be used to identify any atypical and/or malicious network traffic. This can be helpful to identify if the business’s internal network has been compromised or if suspicious activity is occurring on the network. This has been previously investigated using a RPi 3 Model B, this worked, however, the researchers noticed a limitation with the RAM of the system (peaking at around 90% capacity) (de la Cruz, et al., 2016). This hardware limitation is where the RPi 4 Model B 4GB or 8GB models can further the throughput capacity as this system was tested with 5 clients and peaked around 29Mbps of network traffic.

### Other Services to Note

The below services will most likely not be tested within this project however are noteworthy as they either already have RPi distributions of the services themselves or they have low power requirements that allow them to be run on a RPi.

* Stratodesk – Can be used by MSPs like Country Connect
* Systems monitor (Grafana)
* The use of the RPi as a Desktop – Power consumption difference to SFF PC for web browsing
* Private Cloud using Nextcloud, Own Cloud or similar services
* 3CX VoIP server <https://www.3cx.com/docs/recommended-hardware-specifications-for-3cx/>
* Mail server - <https://mailu.io/1.9/compose/setup.html>
* NTP server

Citrix describes a VDI as “the hosting of desktop environments on a central server.” (Citrix, 2022), VDI Servers are typically used in a variety of use cases as outlined below (VMWare, 2022):

* Remote Work
* Bring Your Own Device
* Task or Shift Work

VDI’s for SMEs can be used by paying an MSP like Country Connect Ltd to host the SMEs hosted desktop infrastructure meaning all the SME has to pay for is the service cost and the cost of electricity for the thin client, whether this is a Dell, HP, or Raspberry Pi. Alternatively, the business could host their own VDI with thin clients or RPi’s.

Stratodesk is a tool that can be utilised by MSP’s to take advantage and manage

## RPi

The RPi is a credit card sized computer that can be used for a wide range of applications from Robotics, Desktop computers, Interactive Museum exhibits and government call centres (Ltd, Raspberry-Pi. 2022). The aim of the Raspberry-Pi computers is to drive “down the cost of general-purpose computing…” (Raspberry Pi Foundation, 2022). The base cost of the RPi ranges from £34 for the 1GB Raspberry-Pi 4 Model B to £73.50 8GB Raspberry-Pi 4 Model B (The Pi Hut, 2022). Mechanical drawing of RPi 4 Model B below (Raspberry Pi Foundation, 2022):

Diagram, schematic

Description automatically generated

Figure 4 Mechanical Drawing of Raspberry-Pi 4 to illustrate the size of the device (Raspberry Pi Foundation, 2022)

## Traditional Server Set-up

Within lots of start-ups and small to medium enterprises they would “traditionally” utilise older refurbished enterprise hardware from companies such as Intelligent Servers (Intelligent Servers, 2022) and Bargain Hardware (Bargain Hardware, 2022). Both companies offer business class refurbished IT hardware such as Servers, Workstations, and Desktop PC’s/Laptops. This hardware can be brought at a wide range of prices starting from £125 (including VAT) for a barebones server up to a £69995 for a pre-configured Dell MD3420 (Bargain Hardware, 2022).

## Cloud

Over the past decade the utilisation of Cloud infrastructures has become more and more prevalent within large enterprise. The subscription-based offering provided by the cloud and its ease of scalability was beneficial to large companies as their hardware costs are higher than SMEs where they can also get exclusive contracts with cloud providers. These can then however be costly through the subscription, for example see the below pricing for Microsoft Azure’s mid-range Virtual Machine (VM) offering (Microsoft Azure, 2022):

Graphical user interface

Description automatically generated

Figure 5 A pricing table for Microsoft Azure (Microsoft Azure, 2022)

## Hardware Costs of Each System

### Raspberry Pi

Currently when in stock the RPi 4 Model B can be found for the below prices:

* 1GB model £34
* 2GB model £43.50
* 4GB model £54
* 8GB model £73.50

The above prices all include VAT and reflect the price of the RPi 4 Model B as of February 2022 on the reseller sit [The Pi Hut](https://thepihut.com) (The Pi Hut, 2022). Although the RPi 3 is no longer commercially available the starter kits to these can be typically found for £40-60 on resale sites such as eBay, Facebook Marketplace, and Gumtree.

### Cisco UCS C220-M3

A similar model of Cisco UCS C220-M3S as the one used for this project can be seen as refurbished units for sale on sites like [IT in Stock](https://www.itinstock.com/cisco-ucs-c220-m3-ucsc-c220-m3s-2x-quad-core-e5-2643-330ghz-600gb-24gb-server-48623-p.asp) for £760 Ex VAT or £912 including VAT (IT in Stock, 2022).

### GCP

Although there are no initial hardware costs associated with the GCP the substantial subscription cost associated with this negates the hardware cost in a lot of instances.

# 3 Approach

This section will outline the justification of choices for Hardware, Software and Platforms used in the project.

## Hardware Decisions

The RPi 4 B was the first edition of RPi to offer varying RAM sizes with the RPi. The RPi 4 was also the first iteration of the RPi to include separate lanes to the CPU for network and USB. Prior to the RPi 4 the USB and network shared one CPU lane.

The RPi 4 has the following hardware outlined on their RPi 4 datasheet (Raspberry Pi LTD, 2019):

* Quad core 64-bit ARM-Cortex A72 @ 1.5GHz
* 1, 2 and 4 Gigabyte LPDDR4 RAM options
* H.265 (HEVC) hardware decode (up to 4Kp60)
* H.264 hardware decode (up to 1080p60)
* Supports dual HDMI display output up to 4Kp60
* IEEE 802.11 b/g/n/ac Wireless LAN
* Gigabit Ethernet port (supports PoE with add-on PoE HAT)

Comparatively the RPi 3 has the following hardware outlined on their RPi 4 datasheet (Raspberry Pi LTD, n.d.):

* Quadcore Broadcom Cortex-A53 @ 1.4GHz
* 1GB LPDDR2 SDRAM
* IEEE 802.11.b/g/n/ac wireless LAN
* Gigabit Ethernet over USB 2.0 (maximum throughput 300Mbps)
* H.264, MPEG-4 decode (1080p30)
* H.264 encode (1080p30)

The main differences between these systems are the RAM, CPU and network. The CPU processing power according to [Pass Mark](https://www.cpubenchmark.net/) almost doubles from the RPi 3 to the RPi 4. The score of the RPi 3’s Cortex A53 gets a CPU score of 357 compared to the Cortex A72 of the RPi 4’s CPU score of 666 (PassMark Software, 2022). These scores are calculated from other user’s submissions after running the Pass Mark benchmarking software.

Although it is already known that the RPi will be less powerful than the traditional server however it is also known that Linux has lower hardware requirements than a Windows server instance (see the below table).

|  |  |  |
| --- | --- | --- |
| Hardware Requirements | Debian 11 Server | Windows Server |
| CPU | 1GHz | 1.4GHz |
| RAM | 512MB | 512MB (2GB with Desktop Experience installed) |
| HDD | 10GB | 32GB |

Figure 6 - Hardware Requirements for Server OS Installations

The above table must also be considered alongside the hardware requirements of the services you wish to run on the server, see the below example hardware requirements for Bitwarden a password manager that can be hosted on a local server:

|  |  |  |
| --- | --- | --- |
|  | Minimum | Recommended |
| Processor | x64, 1.4GHz | x64, 2GHz dual core |
| Memory | 2GB RAM | 4GB RAM |
| Storage | 10GB | 25GB |
| Docker Version | Engine 19+ and Compose 1.24+ | Engine 19+ and Compose 1.24+ |

Figure 7 - Table Showing Hardware Requirements of Bitwarden (Bitwarden, Inc, 2022)

For this project the “Traditional” server instance will be demonstrated using a Cisco UCS C220-M3S This is a 1U rackmount server with 2x X79 CPU sockets, up to 512GB DDR3 ECC RAM, up to four 3.5” or up to eight 2.5” SAS/SATA drives, 2 PCIe Gen 3 slots and 2 1GE LAN interfaces on the motherboard (Cisco Systems Inc, 2017). The 2 LAN interfaces will typically be connected with one allowing access to the servers CIMC platform, that can allow for remote configuration and management of the server. The second LAN port will then typically be utilised by the OS/Hypervisor installed on the system. For the instance of this project the hypervisor used will be ESXi installed onto the UCS C220-M3S. The hardware configuration of the UCS C220-M3S in this project is as follows:

* 2x Intel Xeon E5-2643 8 Core 16 thread CPUs @ 3.3GHz
* 16x 8GB 1600MHz DDR3 ECC RAM
* 1x LSI 9271-8i MegaRAID SAS Host Bus Adapter
* 4x 280GB 7200RPM 6Gb/s Toshiba HDD
* 4x 280GB 7200RPM 6Gb/s Seagate HDD

Text

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Figure 8 – Cisco UCS M3 Boot Screen

The Cisco UCS C220-M3S, outlined above, was used in the place of the traditional server as it was available for me to have one racked in the Cisco Systems, Green Park, Reading Lab DMZ. This allows me to remotely access this UCS. With this available to me, the use of Panduit G5 IP managed PDUs gives greater insight into the power drawn by the server at the wall. Using the Cisco labs DMZ, I was able to access my UCS without access to Cisco’s internal corporate network. My former colleagues were also available to provide me with layer 1 support should I experience any issues.

## OS/Platform

This section will explain the platforms/OS used and why these platforms were chosen.

* Debian
* Raspian
* Proxmox/ESXi
* GCP

I will be using a hypervisor such as Proxmox/ESXi as this accurately represents both what I have seen being utilised in business and what I have read is best practice for servers. A hypervisor, also referred to as a Virtual Machine Monitor, is a piece of software that is used to create, manage, and run VMs (VMWare, 2022). Hypervisors can either be run on top of the host OS, these are classified as Type 2 hypervisors, the other one often behaves like a lightweight OS, and these are Type 1 hypervisors. For this project we Using a hypervisor has become common practice as it allows for the server’s resources to be split up into VMs that are easier to increase the CPU cores, RAM, and HDD space than on a barebones installation. This allows for Systems Administrators and IT team to increase the power of a server with the click of a few buttons as opposed to a barebones installation where the server could be down for hours whilst old CPUs, RAM modules and SSD/HDDs are removed, and new models added. The VM approach on the other hand can take a Systems Administrators and IT team 10-20 Minutes of downtime for the service which is a lot less impactful to everyday business use than the hours that may be needed for a barebones upgrade (Jackson, et al., 2020).

Following the advent of VMs and subsequentially DevOps another approach to hosting applications became more widespread. This technology is Containerization and was popularised by Docker. Docker became widely used and popular to remove the argument between Developers and Operations where applications wouldn’t work on the client machines/servers but would work on the developer’s machine. Docker provided a platform for Developers to build applications and run within a Docker container knowing that this will be platform independent so thus remove the former issue where applications would run on the Developers machine and not run in the production environment. Docker Compose was then developed as a tool to enable multi container applications, for example a developer could write one docker compose file and deploy a Linux-Apache-MySQL-PHP stack for a web application. See the below example of the Docker Compose file used to deploy Pi-Hole in the project:

version: "3"

# More info at https://github.com/pi-hole/docker-pi-hole/ and https://docs.pi-hole.net/

services:

  pihole:

    container\_name: pihole

    image: pihole/pihole:latest

    ports:

      - "53:53/tcp"

      - "53:53/udp"

      - "67:67/udp"

      - "80:80/tcp"

      - "443:443/tcp"

    environment:

      TZ: 'Europe/London'

      WEBPASSWORD: 'INSERT-PASSWORD'

    networks:

      your-network:

        ipv4\_address: 192.168.1.3

# Volumes store your data between container upgrades

    volumes:

      - './etc-pihole/:/etc/pihole/'

      - './etc-dnsmasq.d/:/etc/dnsmasq.d/'

    # Recommended but not required (DHCP needs NET\_ADMIN)

    #   https://github.com/pi-hole/docker-pi-hole#note-on-capabilities

    cap\_add:

      - NET\_ADMIN

    restart: unless-stopped

networks:

  your-network:

    external:

      name: name-of-your-docker-network

Figure 9 - docker-compose.yml file to Create a Pi-Hole Container

### RPi OS

For this project it has been decided that the OS to be used for the RPi will be RPi OS Lite (64-bit) for the RPi 4 and used for the RPi 3 to test the raw performance of this system. This is the chosen OS as this is developed and maintained by the RPi Foundation, the version used for the testing is as follows (Raspberry Pi Foundation, 2022):

* Release date: January 28th, 2022
* System: 64-bit
* Kernel version: 5.10
* Debian version: 11 (bullseye)
* Size: 435MB
* SHA256 file integrity hash: d694d2838018cf0d152fe81031dba83182cee79f785c033844b520d222ac12f5

It was decided that for this testing the Lite version would be used as this share’s similarities to the Server releases of other Linux Distributions like Debian Server, Ubuntu Server etc.

### Debian

For the traditional server the operating system of choice is Debian 11 because this distro of Linux is what the RPi OS is built upon and derived from. As shown above in the RPi OS outline. With the RPi OS also being Debian 64bit and Debian based means that the commands run on a Debian machine will also be the same as the commands run on a RPi OS machine. With the exception of the leading sudo as this is not installed by default with a barebones Debian 11 Server install. Details of the version used is listed below (Debian Org, 2021):

* Release Date: December 18th, 2021
* Kernel Version: 5.10
* Size: 378MB
* SHA512 file integrity hash: c685b85cf9f248633ba3cd2b9f9e781fa03225587e0c332aef2063f6877a1f0622f56d44cf0690087b0ca36883147ecb5593e3da6f965968402cdbdf12f6dd74

### Proxmox vs ESXi

* Why did I choose to use a Hypervisor?
  + Most industry use them
  + Allow for better resource scaling to services and VMs on these
  + Cite (Jackson, et al., 2020) for Bare Metal vs Hypervisor installations
* Why ESXi and not Proxmox or Hyper-V?
  + Industry experience setting up and configuring ESXi
* Should I use Proxmox as it is free and open source? Especially as this is a cost-based report and analysis

### GCP

GCP is one of the big 3 cloud providers, these outlined below:

* Amazon Web Services
* Microsoft Azure
* Google Cloud Platform

Comparing the offerings of these three providers in the table below (Figure 10) , It can be seen that GCP has a cheaper but similar offering to AWS at the entry level and offers higher CPU counts but less RAM in the high end at similar costs to both AWS and Azure.

|  |  |  |  |
| --- | --- | --- | --- |
| Machine Type | AWS | Azure | GCP |
| Smallest Instance | An instance with 2 virtual CPUs and 8 GB RAM will cost you around USD69/month. | An instance with 2 virtual CPUs and 8 GB RAM will cost you around USD70/month. | Instance with 2 virtual CPUs and 8 GB RAM will cost you around USD52/month. |
| Largest Instance | Largest instance that includes 3.84 TB RAM and 128 vCPUs will cost you around USD 3.97/hour. | Largest instance that includes 3.89 TB RAM and 128 vCPUs will cost you around USD 6.79/hour. | Largest instance that includes 3.75 TB RAM and 160 vCPUs will cost you around USD 5.32/hour. |

Figure 10 – Table from Veritis comparing CSPs (Veritis, n.d.)

These differences mean that GCP is good to use for the comparisons in this project. As the small businesses will likely use the systems on the lower end of the scale where GCP is more cost effective.

## Raw Performance

This section will outline how the raw performance benchmarks for each system will be achieved.

### CPU/Memory

To stress-test the CPU and memory in the system the following tools can be used to test these:

* GeekBench
* Sysbench
* Hard Info
* Phoronix Test Suite

The test suite that will be used for this project will be Sysbench/GeekBench. Testing will also be performed using Phoronix Test Suite to compile Firefox and timing how long this takes to compile. Compiling an application such as Firefox or the Linux Kernel is a good raw performance test of a system as this process puts a lot of strain on both CPU and Memory in the system, this is also very close to the real-world use of a software build server that is utilised in a development environment. Compiling software such as the Linux Kernel, Google Chrome and Firefox is often also used when technology reviewers like LinusTechTips, Level1Techs and Gamers Nexus.

The below commands were used to install and run the raw performance benchmarks:

* sudo apt-get install sysbench
* sysbench –test=cpu run
* sysbench –test=memory run
* sysbench –test=fileio –file-test-mode=seqwr run
* wget http://phoronix-test-suite.com/releases/repo/pts.debian/files/phoronix-test-suite\_7.8.0\_all.deb
* sudo apt install gdebi-core
* sudo gdebi phoronix-test-suite\_7.8.0\_all.deb
* phoronix-test-suite --version
* phoronix-test-suite benchmark build-linux-kernel

Initially start with the sysbench benchmarks as these are the least time consuming and can give an immediate insight into the raw performance of individual components of each system. Then move onto the Linux Kernel compile as it is a real-world use and stresses the whole system. As highlighted by Passmark Software’s online comparison we can expect that the RPi 4 will perform about 1/10th of the performance of the UCS C220-M3S in CPU heavy workloads (Passmark Software, 2022), The below link gives a more detailed comparison of the RPi 4 CPU vs the CPU in the UCS used:

* <https://www.cpubenchmark.net/compare/ARM-Cortex-A72-4-Core-1800-MHz-vs-Intel-Xeon-E5-2643/4078vs1217>

The timed Linux kernel build provides 2 options of how to run the test:

* Defconfig
* Allmodconfig

The defconfig option builds the config file with the default settings based on the systems architecture, where the allmodconfig builds a config file that makes as many parts of the Linux kernel as possible a module. The below graphs pulled from Open Benchmarking show the spread of data from all uploaded results of this Linux kernel build.

Chart, scatter chart

Description automatically generated

Figure 11 - Average Deviation of Linux Kernel Compile Runs (Open Benchmarking Org, 2022)

Chart

Description automatically generated

Figure 12 - Time to Complete Linux Kernel Compile (Open Benchmarking Org, 2022)

### Network

To test the network performance of the devices the below physical network was used:

Diagram, timeline

Description automatically generated

Figure 13 - Physical Network Example of How iperf Test Was Performed

To test the NIC on the devices the following commands were run:

Host A

Host B

In all instances the hardware of each device w

* Jeff Gerling RPi router video covers this <https://www.youtube.com/watch?v=w7teLVwi408&t=2s>

## How to Benchmark Performance of Different Services

This section will outline how each individual service is intended to be benchmarked.

### DNS

* How will DNS be benchmarked?
* <https://www.grc.com/dns/benchmark.htm>
* Time to Resolve?

### AD

* How do you even benchmark such a service?
* This is lightweight and typically a thousand requests can be handled per CPU core
* Can this be handled by the RPi? Could I set up a server and get hundreds of machines running joined to the AD?

### Webserver

* <https://geekflare.com/web-performance-benchmark/>

### DHCP

Time to receive DHCP Lease?

<https://manpages.ubuntu.com/manpages/xenial/man8/perfdhcp.8.html>

Perfdhcp achieves this

## IaC

This section outlines the IaC scripts and processes used for each of these.

### Docker Compose

* .yml files which utilise a Declarative IaC approach
  + Do I explain Declarative IaC?

### Portainer

* Typically run in its own docker container this can be used to manage multiple docker hosts and the containers running on them
* You can store docker compose templates which allow for an easy rebuild of the container

### Bash

* In terms of an IaC approach Bash scripts would be considered an Imperative approach
  + Do I explain Imperative IaC?

# 4 Implementation

## Network Infrastructure

### Home

Diagram

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Figure 14 - Network Diagram of Home Configuration

The network configuration used for the RPi’s included network segregation with the home devices, IoT devices and Servers all sitting on 3 separate VLANs outlined below:

* VLAN 1 – 192.168.1.x/24
* VLAN 2 – 192.168.2.x/24
* VLAN 3 – 192.168.3.x/24

The RPi’s will operate on VLAN 3, with Docker configured with a MAC VLAN to allow for separate services to operate on different IP addresses.

### DMZ

Diagram

Description automatically generated

Figure 15 - Network Diagram of DMZ Infrastructure for UCS

## Docker Infrastructure

For the services tested these will be run using docker compose and Portainer to manage the containers running.

* Outline of the containers that will be run

## VM Infrastructure

* Outline the VM
  + The CPU cores (going to match the Pi)
  + Memory
  + Storage

## IaC Examples

### Portainer

### Pi Hole

# 5 Results

## Raw Performance Results

This section will analyse the results acquired by the raw performance tests below:

* Sysbench
* Timed Linux Kernel Compile

### Sysbench

#### RPi 4 – 2Gb

Sysbench CPU

Text

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Figure 16 - CPU Benchmark of RPi 4 2Gb using Sysbench

Sysbench Memory

Text

Description automatically generated

Figure 17 - Memory Benchmark of RPi 4 2Gb using Sysbench

I/O

Text

Description automatically generated

Figure 18 - I/O Benchmark on RPi 4 2Gb Using Sysbench

Iperf Network Test

Text

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Figure 19 - Result of Iperf Test on RPi 4

#### RPi 4 – 4Gb

Sysbench CPU

cmake cmake-data perl perl-base perl-modules libsdl-perl libperl-dev yasm

Text

Description automatically generated

Sysbench Memory

Text

Description automatically generated

Sysbench I/O

Text

Description automatically generated

#### RPi 3

Sysbench CPU – Single Thread

Text

Description automatically generated

Sysbench CPU – Multi Thread

Text

Description automatically generated

Sysbench Memory

Text

Description automatically generated

Sysbench I/O

Text

Description automatically generated

#### UCS C220-M3S

Sysbench CPU – Single Thread

Text

Description automatically generated

Figure 20 - CPU Benchmark of UCS using Sysbench

Sysbench CPU – Multi Thread

Text

Description automatically generated

Sysbench Memory

Text

Description automatically generated

Figure 21 - Memory Benchmark of UCS using Sysbench

Sysbench I/O

Text

Description automatically generated

Figure 22 - I/O Benchmark of UCS using Sysbench

### Timed Linux Kernel Compile

#### RPi 3

Text

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<https://openbenchmarking.org/result/2203196-FO-RPI3RUN1804>

Text

Description automatically generated

<https://openbenchmarking.org/result/2203205-FO-RPI3RUN2568>

Text

Description automatically generated

<https://openbenchmarking.org/result/2203201-FO-RPI3RUN3300>

#### RPi4 – 2Gb

Text

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Figure 23 - Linux Kernel Compile Failed Attempt on RPi 4

<https://openbenchmarking.org/result/2203072-FO-FIRSTRUNR33>

Text

Description automatically generated

Figure 24 - First Run of defconfig Linux Kernel Compile on RPi 4

<https://openbenchmarking.org/result/2203070-FO-SECONDRUN71>

Text

Description automatically generated

Figure 25 - Second Run of defconfig Linux Kernel Compile on RPi 4

Text

Description automatically generated

Figure 26 - Third Run of defconfig Linux Kernel Compile on RPi 4

#### RPi4 – 4Gb

Text

Description automatically generated

<https://openbenchmarking.org/result/2203152-FO-RPI44GBRU67>

Graphical user interface, text

Description automatically generated

<https://openbenchmarking.org/result/2203150-FO-RPI44GBRU48>

Text

Description automatically generated

<https://openbenchmarking.org/result/2203168-FO-RPI44GBRU89>

Text

Description automatically generated

<https://openbenchmarking.org/result/2203168-FO-RPI44GBRU88>

<https://openbenchmarking.org/result/2203173-FO-FIRSTRUNR50>

#### UCS C220-M3S

Text

Description automatically generated

Figure 27 - A Failed attempt to benchmark compiling the Linux Kernel on the UCS

Text

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Figure 28 - First Run of defconfig Linux Kernel Compile on UCS

Text

Description automatically generated

Figure 29 - Second Run of defconfig Linux Kernel Compile on UCS





Text

Description automatically generated

Figure 30 - Third Run of defconfig Linux Kernel Compile on UCS

Text

Description automatically generated

#### RPi4 vs UCS C220-M3S

Compare the TTC of the Linux kernel compile

### Power Draw of Systems

#### RPi 4

Output of top command whilst running Linux kernel compile.

Text

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Figure 31 - Output of top Command from RPi 4 2GB

A picture containing graphical user interface

Description automatically generated

Figure 32 - Output of HTOP Command from RPi 4 4GB

The USB-C to USB-C Multimeter only highlights the volts and amps used by the RPi 4 at the time of measurement. This however means that Ohms Law must be applied to calculate the watts. To do this the average voltage and current was taken to perform the calculations.

|  |  |  |  |
| --- | --- | --- | --- |
| Workload | V | A | W |
| Idle | 5.25 | 0.3 | 1.575 |
| Linux Compile 1 | 5.25 | 0.8 | 4.2 |
| Linux Compile 2 | 5.25 | 0.9 | 4.725 |
| Linux Compile 3 | 5.25 | 0.7 | 3.675 |

Figure 33 - Table of Power Draw Readings Gathered from USB-C to USB-C Multimeter

When this data was initially collected it was believed that the figures for power usage from the below Multimeter were wrong. Following this a different variety of Multimeter was ordered. This new Multimeter sits between the power brick and outlet on the wall. This confirmed that there was a slight variation to these figures however not as large a deviation as was initially suspected.

A picture containing USB-C to USB-C multi meter readings

Description automatically generated

Figure 34 - Image of USB-C to USB-C Multimeter Reading Idle power draw of RPi 4

The above image shows the original Multimeter used that sits between the power brick and power cable for the RPi 4. This was then changed in favour of the below configuration that better matched the server setup and how power draw was measured for this.

A picture containing text, wall, kitchen, indoor

Description automatically generated

Figure 35 - Mulitmeter Configuration to Check Accuracy of USB-C to USB-C Multimeter

The table below shows the readings gathered from the outlet Multimeter. The average from the USB-C to USB-C Multimeter is 4.2W vs the average from the outlet Multimeter of 5.2W. This shows a 1W difference, this could be due to inefficiencies with the power brick.

|  |  |
| --- | --- |
| Test | Average Power Draw in Watts |
| Idle | 2.1 |
| Linux Kernel Compile 1 | 5.2 |
| Linux Kernel Compile 2 | 5.3 |
| Linux Kernel Compile 3 | 5.1 |

Figure 36 - Table of Power Draw Readings Gathered from Outlet Multimeter

#### UCS C220-M3S

|  |  |
| --- | --- |
| Test | Average Power Draw in Watts |
| Idle | 115 |
| Linux Kernel Compile 1 | 300 |
| Linux Kernel Compile 2 | 298 |
| Linux Kernel Compile 3 | 299 |

Figure 37 - Table of Power Draw Readings Gathered from Panduit G5 Web GUI

Background pattern

Description automatically generated with low confidence

Figure 38 - Power Draw as Measured from Panduit Web GUI

Table

Description automatically generated

Figure 39 - Power Draw as Measured from CIMC

## Comparison of RPi 4 vs UCS C220-M3S Power Draw

Using Figure 29 and Figure 30 tables and the data gathered from both the Multimeter and Panduit G5 PDU, a full comparison of the energy cost to complete a Linux kernel compile, the cost of the idle systems outside business hours and consequently the average cost to run each system over business hours.

The graph below (Figure 37) illustrates the power draw of each system in 3 given scenarios bullet pointed below:

* Power draw of the system in an idle state - this is the average power drawn in watts from the outlet.
* Power draw running Linux kernel compile – this is the average power drawn in watts from the outlet.
* Max power draw seen – This is the upper power draw seen from each system during stress tests and benchmarking.

Figure 40 - Graph Illustrating the Power Draw of Systems

# 6 Evaluation

## Raw Performance

### Sysbench

### Timed Linux Kernel Compile

The below calculations were used to work out the Standard deviation for these runs:

Diagram, schematic

Description automatically generated

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| σ2 = | |  | | --- | | Σ(xi - μ)2 | |  | | N | |

σ = Standard Deviation

#### RPi 4

|  |  |
| --- | --- |
| Run | Time To Compile (Rounded to nearest second) |
| 1 | 2665 |
| 2 | 2684 |
| 3 | 2681 |
| 4 | 2665 |
| 5 | 2682 |
| 6 | 2684 |
| 7 | 2626 |
| 8 | 2651 |
| 9 | 2651 |
| Average | 2665 |
| Standard Deviation | 17.8 |

#### RPi 3

|  |  |
| --- | --- |
| Run | Time To Compile |
| 1 |  |
| 2 |  |
| 3 |  |
| 4 |  |
| 5 |  |
| 6 |  |
| 7 |  |
| 8 |  |
| 9 |  |

#### UCS C220-M3S

|  |  |
| --- | --- |
| Run | Time To Compile |
| 1 |  |
| 2 |  |
| 3 |  |
| 4 |  |
| 5 |  |
| 6 |  |
| 7 |  |
| 8 |  |
| 9 |  |

## Energy Usage of Systems

### Energy Cost of Linux Kernel Compile

The below calculation is used to determine the total power draw for full duration of the test. This calculation can be used for both the RPi 4 and for the UCS C220-M3S.

|  |  |  |  |
| --- | --- | --- | --- |
| System | Time To Compile | Average Power Draw | Total Power Used (kWh) |
| RPi 4 |  |  |  |
| UCS C220-M3S |  |  |  |

### Energy Cost of Idle Time Between Business Hours

The below calculation is used to determine the total power draw for the Idle hours between standard business operating hours. This calculation can be used for both the RPi 4 and for the UCS C220-M3S.

### Energy Cost to Run Systems

The below calculation is used to determine the total power draw for full duration of business hours assuming a lower bound of 50% utilisation and 90% upper bound. This calculation can be used for both the RPi 4 and for the UCS C220-M3S. As this project only covers SME’s MNE’s will not be considered for this calculation as their power utilisation would be covered on a 24/5 or 24/7 basis dependant on the company.

# 7 Future Work

Testing of more tools

Deeper Analysis into the stability

Business use cases of home assistant is this a valid argument?

# 8 Conclusions

# 9 Reflection on Learning

# References

Abu Sharkh, M., Jammal, M., Shami, A. & Ouda, A., 2013. *Resource allocation in a network-based cloud computing environment: design challenges,* s.l.: IEEE.

Acácio de Andrade, A., Batista Dietrich, Á., Francisco Blumetti Facó, J. & Reolon Jorge, R., 2020. *Low Cost Solution for Home Brewing and Small Brewing Business Using Raspberry Pi,* s.l.: Springer Nature.

Bargain Hardware, 2022. *Refurbished Servers, PCs, Workstations & Parts | Bargain.* [Online]   
Available at: https://www.bargainhardware.co.uk  
[Accessed 6 February 2022].

Bitwarden, Inc, 2022. *Install and Deploy - Linux | Bitwarden.* [Online]   
Available at: https://bitwarden.com/help/install-on-premise-linux/  
[Accessed 18 March 2022].

Cisco Systems Inc, 2017. *Cisco UCS C220 M3 Rack Server Data Sheet.* [Online]   
Available at: https://www.cisco.com/c/en/us/products/collateral/servers-unified-computing/ucs-c220-m3-rack-server/data\_sheet\_c78-700626.html  
[Accessed 11 February 2022].

Citrix, 2022. *What is VDI? Virtual Desktop Infrastructure.* [Online]   
Available at: https://www.citrix.com/en-gb/solutions/vdi-and-daas/what-is-vdi-virtual-desktop-infrastructure.html  
[Accessed 11 March 2022].

de la Cruz, J. E. C., Goyzueta, C. A. R. & Cahuana, C. D., 2016. *Intrusion Detection and Prevention System for Production Supervision in Small Businesses Based on Raspberry Pi and Snort,* s.l.: IEEE.

Debian Org, 2021. *Debian -- News -- Updated Debian 11: 11.2 released.* [Online]   
Available at: https://www.debian.org/News/2021/20211218  
[Accessed 15 March 2022].

Imperva, 2022. *What is a Honeypot | Honeynets, Spam Traps & more | Imperva.* [Online]   
Available at: https://www.imperva.com/learn/application-security/honeypot-honeynet/  
[Accessed 6 February 2022].

Intelligent Servers, 2022. *Intelligent Servers.* [Online]   
Available at: https://intelligentservers.co.uk  
[Accessed 1 February 2022].

IT in Stock, 2022. *Cisco UCS C220 M3 UCSC-C220-M3S 2x Quad Core E5-2643 3.30GHz.* [Online]   
Available at: https://www.itinstock.com/cisco-ucs-c220-m3-ucsc-c220-m3s-2x-quad-core-e5-2643-330ghz-600gb-24gb-server-48623-p.asp  
[Accessed 21 February 2022].

Jackson, C., Gooley, J., Iliesiu, A. & Malegaonkar, A., 2020. *Cisco Certified DevNet Associate DEVASC 200-901 Official Cert Guide.* s.l.:Cisco Press.

Maulana, H. & Al-Khowarizmi, 2021. *Analyze and Designing Low-Cost Network Monitoring System,* Medan, Indonesia: IOP.

Microsoft Azure, 2022. *Cloud Computing Services | Microsoft Azure.* [Online]   
Available at: https://azure.microsoft.com/en-us/  
[Accessed 2 February 2022].

Microsoft, 2022. *Active Directory Domain Services Overview.* [Online]   
Available at: https://docs.microsoft.com/en-us/windows-server/identity/ad-ds/get-started/virtual-dc/active-directory-domain-services-overview  
[Accessed 3 February 2022].

Miles, C., 2020. *GitHub - Akkadius/glass-isc-dhcp: Glass - ISC DHCP Server Interface.* [Online]   
Available at: https://github.com/Akkadius/glass-isc-dhcp  
[Accessed 4 February 2022].

Nguye, H.-Q., Loan, T. T. K., Mao, B. D. & Huh, E.-N., 2015. *Low Cost Real-Time System Monitoring,* s.l.: IEEE.

Open Benchmarking Org, 2022. *Timed Linux Kernel Compilation Benchmark - OpenBenchmarking.org.* [Online]   
Available at: https://openbenchmarking.org/test/pts/build-linux-kernel-1.13.0  
[Accessed 08 March 2022].

PassMark Software, 2022. *ARM Cortex A53 4 Core 1400 MHz vs ARM Cortex A72 4 Core 1500 MHz.* [Online]   
Available at: https://www.cpubenchmark.net/compare/ARM-Cortex-A53-4-Core-1400-MHz-vs-ARM-Cortex-A72-4-Core-1500-MHz/4143vs3917  
[Accessed 2 March 2022].

Passmark Software, 2022. *ARM Cortex-A72 4 Core 1800 MHz vs Intel Xeon E5-2643 @ 3.30GHz [cpubenchmark.net] by PassMark Software.* [Online]   
Available at: ARM Cortex-A72 4 Core 1800 MHz vs Intel Xeon E5-2643 @ 3.30GHz [cpubenchmark.net] by PassMark Software  
[Accessed 12 March 2022].

Pi-Hole, 2022. *Overview of Pi-hole - Pi-hole documentation.* [Online]   
Available at: https://docs.pi-hole.net/  
[Accessed 2 February 2022].

Raspberry Pi Foundation, 2022. *Operating system images - Raspberry Pi.* [Online]   
Available at: https://www.raspberrypi.com/software/operating-systems/  
[Accessed 15 March 2022].

Raspberry Pi Foundation, 2022. *Raspberry Pi.* [Online]   
Available at: https://www.raspberrypi.com  
[Accessed 1 February 2022].

Raspberry Pi Foundation, 2022. *Raspberry Pi 4 Datasheet.* [Online]   
Available at: https://datasheets.raspberrypi.com/rpi4/raspberry-pi-4-mechanical-drawing.pdf  
[Accessed 3 February 2022].

Raspberry Pi LTD, 2019. *raspberry-pi-4-datasheet.pdf.* [Online]   
Available at: https://datasheets.raspberrypi.com/rpi4/raspberry-pi-4-datasheet.pdf  
[Accessed 1 March 2022].

Raspberry Pi LTD, n.d. *raspberry-pi-3-b-plus-product-brief.* [Online]   
Available at: https://datasheets.raspberrypi.com/rpi3/raspberry-pi-3-b-plus-product-brief.pdf  
[Accessed 1 March 2022].

The Pi Hut, 2022. *The Ultimate Raspberry Pi & Maker Store.* [Online]   
Available at: https://www.thepihut.com  
[Accessed 1 February 2022].

Veritis, n.d. *AWS Vs Azure Vs GCP – The Cloud Platform of Your Choice?.* [Online]   
Available at: https://www.veritis.com/blog/aws-vs-azure-vs-gcp-the-cloud-platform-of-your-choice/  
[Accessed 13 February 2022].

VMWare, 2022. *What is a hypervisor?.* [Online]   
Available at: https://www.vmware.com/topics/glossary/content/hypervisor.html  
[Accessed 21 February 2022].

VMWare, 2022. *What is VDI? | Virtual Desktop Infrastructure | VMware Glossary.* [Online]   
Available at: https://www.vmware.com/topics/glossary/content/virtual-desktop-infrastructure-vdi.html  
[Accessed 11 March 2022].