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Benchmarking and Review of Raspberry Pi (RPi) 2B vs RPi 3B vs RPi 3B+ vs RPi 4B (8GB)

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ABSTRACT
Raspberry Pi is the name of a series of single-board computers (SBCs) developed in the United Kingdom by the Raspberry Pi Foundation in association with Broadcom, with the main purpose to educate people in computing at low cost. The first Raspberry Pi version launched in 2012 and as the time went by, several iterations and variations introduced into the market since then. This paper presents a performance benchmarking of a variety of Raspberry Pi's focusing on the (RPi) 2 model B, vs RPi 3 model B vs RPi 3 model B+ vs the latest version RPi 4 model B (8GB).

The SW tools used *"SysBench" "hardinfo", "Linpack", "iPerf data transfer", which* stress test the CPU and RAM performance, File I/O and LAN/Wi-Fi networking performance, as well. Following this survey, the performance results, with the technical pros and cons of various RPis gives a comprehensive outlook of benefits to use those tiny and affordable single board computers (SBCs). Eventually, it can be seen that the RPi 4 model B (8GB) introduces a decent performance improvement among the RPi's predecessors and unquestionably RPi 4B (8GB) is more powerful and quicker.

Keywords
Raspberry Pi benchmarking, RPi 2B, RPi 3B, RPi 3B+, RPi 4B (8GB), Linux Benchmark Tools, SysBench, hardinfo, Linpack, iPerf data transfer

1. INTRODUCTION
Dr Eben Cristopher Upton is the founder and inventor of RPi who created a prototype using a Broadcom chip. The operating system for all RPi devices is Linux, an open-source operating system and the programming language is Python. In terms of the name "Raspberry" most likely at the time of RPs inception, it was followed the popular trend for the computer manufacturers to name their products after fruits.

For sure the so called "Pi" refers to the RPi's programming language, which is Python and it's a kind of a nod to the mathematical concept of π (pi). Raspberry Pi (RPi) started with the creation of the first prototype inspired from the British Broadcasting Cooperation Microcomputer System (BBC Micro). The first RPi was born six years later in 2012 where the first official release for the public was the RPi 1 model (B). The astonishing 10 years history and evolution of Raspberry Pi is depicted in "Figure 1".

In this manuscript, a performance benchmarking of a variety of Raspberry Pi's is examined focusing on the (RPi) 2 model B, vs RPi 3 model B vs RPi 3 model B+ vs the latest version RPi 4 model B (8GB) in terms of CPU, Memory, File I/O, LAN/Wi-Fi networking.

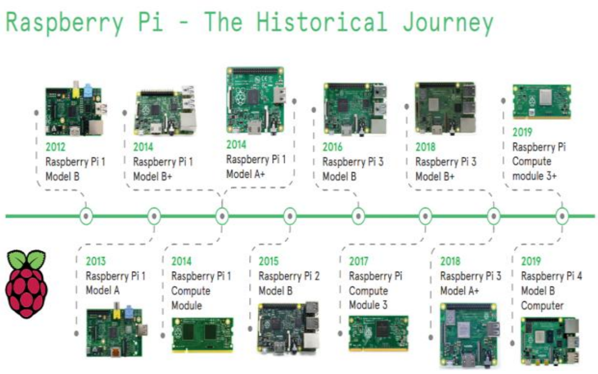


Figure 1: The historical evolution of Raspberry Pi [1].

The general technical specifications of each one is described below:

RPi 2 model (B). – Raspberry Pi (RPi) 2 Model B "Figure 2" is equipped with a CPU 32-bit with 900 MHz quad-core ARM Cortex-A7 (BCM2836) and 1 GB of RAM (LPDDR2-SDRAM). It also has one 100 Base Ethernet, four USB ports, forty GPIO pins, a full HDMI port, a combined 3.5 mm audio jack and composite video, one Camera interface (CSI), a display interface (DSI), a micro-SD card slot and Video Core IV 3D graphics core. Because it has an ARMv7 processor, it can run the full range of ARM GNU/Linux distributions, including Snappy Ubuntu Core, as well as Microsoft Windows 10. The maximum CPU clock of the Cortex-A7 cores in the Raspberry Pi 2 is 900 MHz, while the L2 cache appears to be clocked at only 250 MHz by default and the GPU is clocked at 250 MHz. Moreover, the new Broadcom BCM2836 SoC contains a dedicated 512 KB CPU cache, improving memory performance and performance in general.

Figure 2: Single Board Computer (SBC) - Raspberry Pi 2 Model B [2].

RPi 3 model (B). – Raspberry Pi (RPi) 3 Model B “Figure 3” is equipped with a CPU 64-bit quad-core ARM Cortex-A53 with 1.2 GHz clock frequency, a chipset (SoC) Broadcom BCM2837 and 1 GB memory (LPDDR2-SDRAM). It also has one a Graphic processor Broadcom Dual Core Video Core IV, four USB 2.0 ports, a 40-pin GPIO, an HDMI and RCA video outputs plus one CSI camera connector, an audio output 3.5 mm stereo jack and a MicroSD card.

Moreover, it has a Network Connection of 10/100 Ethernet, and two new connectivity 802.11n Wi-Fi and Bluetooth 4.1 (BLE – Bluetooth Low Energy). Broadly speaking, RPi 3B with the new CPU is about 50% more powerful than the RPi2 pinpointing that the great innovation in this version is undoubtedly the addition of a Wi-Fi chip and a Bluetooth Low energy feature which frees up more USB ports for connecting other devices.

The Raspberry Pi 3 is also compatible with Windows 10 IoT Core, an operating system designed for creating and developing applications destined for home automation, robotics and connected objects. Moreover, Broadcom BCM2837 is a 64-bit CPU where main benefit of the upgrade is that this chip is more efficient and far more powerful than the one in the Raspberry Pi 2 which has a quad-core Cortex-A7 Broadcom BCM2836. The GPU is more powerful, compared to RPi 2, even though they’re of the same Video Core IV family. The reason is that Raspberry Pi 3 has a 400MHz GPU, whereas the RPi 2 a 250MHz one with the RAM to remain at 1GB of DDR2.

Figure 3: Single Board Computer (SBC) - Raspberry Pi 3 Model B [3].

RPi 3 model (B+). – Raspberry Pi (RPi) 3+ Model B “Figure 4” is equipped with a CPU 64-bit quad-core ARM Cortex-A53 with 1.4 GHz clock frequency, a chipset (SoC) Broadcom BCM2837B0 and 1 GB memory (LPDDR2-SDRAM). It also provides dual-band Wi-Fi 2.4 GHz and 5 GHz IEEE 802.11.b/g/n/ac wireless LAN, Bluetooth 4.2, BLE and a Gigabit Ethernet with four USB 2.0 ports, forty GPIO pins, one HDMI output, MIDI DSI display port, MIPI CSI camera port and a micro-SD card slot. The power supply can be done via the GPIO connector or via Power over Ethernet (PoE) where requires a separate PoE HAT. One of the most looking forward expected for RPi 3B+ compared with RPi-3 was the 10/100/1000 Mbps (via USB channel) LAN controller. The HW of RPi 3B+ isn’t that different from its predecessor, there is no extra RAM memory, the GPU remains the same. The biggest difference between this model with RPi 3B is the 200MHz boost in processor speed and moreover there is a new heat spreader helping to reduce throttling and maintain the CPU speed boost.

Figure 4: Single Board Computer (SBC) - Raspberry Pi 3+ Model B [4].

RPi 4 model (B) (8GB ram). – Raspberry Pi (RPi) 4 Model B “Figure 5” is equipped with a CPU processor three times more powerful than the RPi 3B+ model, clocked at 1.5 GHz allowing integration of a Video Core VI graphic chip, capable of managing 2 displays simultaneously in 4K resolution. It comprises dual 4K micro-HDMI display ports, Bluetooth 5.0, a true Gigabit Ethernet port and a dual band Wi-Fi chip.

The SoC upgrade alongside 4GB DDR4 RAM compared to 1GB DDR2 on the 3 B+ makes the Raspberry Pi 4 B a viable desktop computing device. Moreover, provides two USB-2.0 and two USB-3.0 ports. Depending on the model there is an option of having RPi 4B with 2GB, 4GB and 8GB RAM. The connectivity provides a 2.4 GHz/5.0 GHz IEEE 802.11.b/g/n/ac wireless LAN, Bluetooth 5.0, BLE.

The standard 40-pin General Purpose Input/output (GPIO) header remains fully backwards-compatible with previous boards. In addition, there are two micro-HDMI ports (up to 4Kp60 supported), 2-lane MIPI DSI display port, 2-lane MIPI CSI camera port, 4-pole stereo audio and composite video port. In terms of the multimedia, supports H.265 (4Kp60 decode), H.264 (1080p60 decode, 1080p30 encode), OpenGL ES, 3.0 graphics.

The SD compatibility (microSD card slot for loading the operating system and storing data) remains the same. The power is taken by a 5V DC via USB-C connector (minimum 3A), 5V DC via GPIO header (minimum 3A), Power over Ethernet (PoE)-enabled (requires separate PoE HAT). The GPU clock runs by default at 500 MHz.

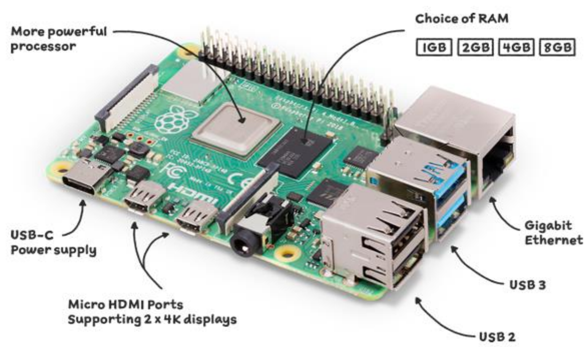


Figure 5: Single Board Computer (SBC) - Raspberry Pi 4 Model B [5].

RPi 4B is unquestionably more powerful and quicker, yet just as economical, the new Raspberry Pi 4 Model B board offers an impressive all-round performance compared to its previous version, bringing us one step closer to computer programming for the masses! "Table 1" depicts a comparison of the technical specifications between RPi 2B, RPi 3B, RPi 3B+ and the latest version RPi 4B.

Table 1. Raspberry Pi's technical specifications

	RPi 2 B Rev 1.2	**RPi 3 B** Rev 1.2	**RPi 3 B+** Rev 1.3	**RPi 4 B** Rev 1.5
CPU Processor	32-bit quad-core ARMv7 Cortex-A7	64-bit quad-core ARMv8 Cortex-A53	64-bit quad-core ARMv8 Cortex-A53	64-bit quad-core ARMv8 Cortex-A72
CPU Broadcom	BCM2836	BCM2837	BCM2837 B0	BCM2711
CPU cores	4	4	4	4
CPU Clock Frequency	900 MHz	1200 MHz	1400 MHz	1500 MHz
RAM	1024 MB LPDDR2 SDRAM	1024 MB LPDDR2 SDRAM	1024 MB LPDDR2 SDRAM	2GB, 4GB, 8GB LPDDR4 SDRAM
GPU	250 MHz Video Core IV	400 MHz Video Core IV	400 MHz Video Core IV	500 MHz Video Core IV
Wi-Fi	No	2.4 GHz 802.11n	2.4 & 5 GHz IEEE 802.11/bg/ n/ac	2.4 & 5 GHz IEEE 802.11/bg/ n/ac
Bluetooth	No	BLE 4.1	BLE 4.2	BLE 5
Storage	MicroSD card	MicroSD card	MicroSD card	MicroSD card
Network Adaptor	100 MBps Ethernet	100 MBps Ethernet	100 MBps Ethernet	Gigabit Ethernet
USB ports	4 USB-2.0	4 USB-2.0	4 USB-2.0	2 USB-2.0 2 USB-3.0
Power Supply	5V 2A	5V 2.5A	5V 2.5A	5V 3A

2. SYSTEM SETUP and DESCRIPTION

2.1 Hardware Equipment

The used Raspberry Pi's for the benchmarking are the RPi-2 model B, RPi-3 model B, RPi-3+ model B and the RPi-4 model B with 8GB RAM memory "Figure 6" connected to a Gigabit switch (TL-SG1024D).

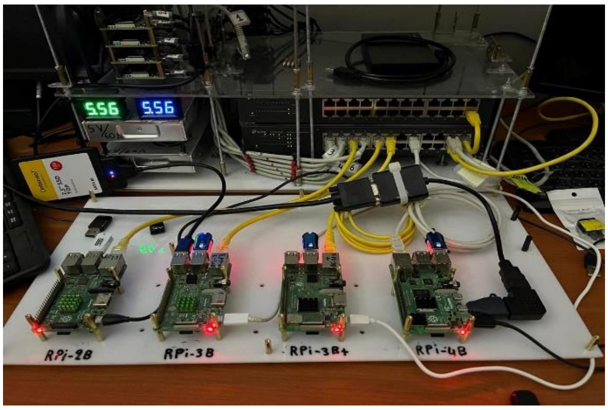


Figure 6: Single Board Computers (SBC) – RPi 2B vs RPi 3B vs RPi 3B+ vs RPi 4B.

In terms of the SD card used for booting and operating purposes, the Kingston Canvas Select Plus microSDCS2 64GBSP was chosen. The Debian version, the Operating release, the kernel version, the hardware version and the RAM memory for all the raspberries can be seen in "Figure 7" and "Figure 8".

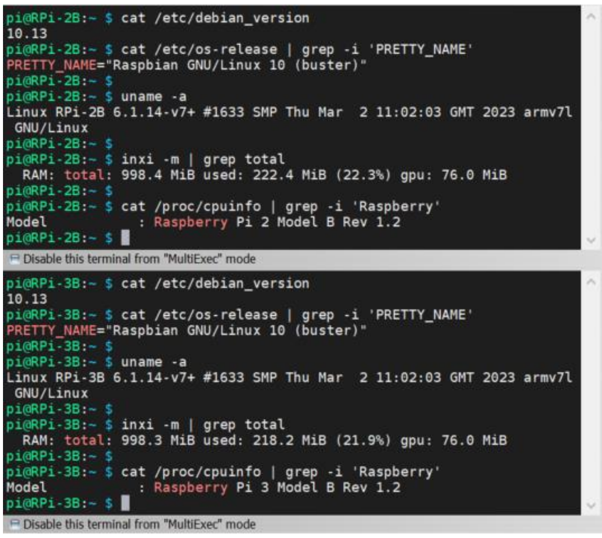


Figure 7: RPi-2B and RPi-3B Debian version, OS release, kernel version, RAM memory and RPi HW version.

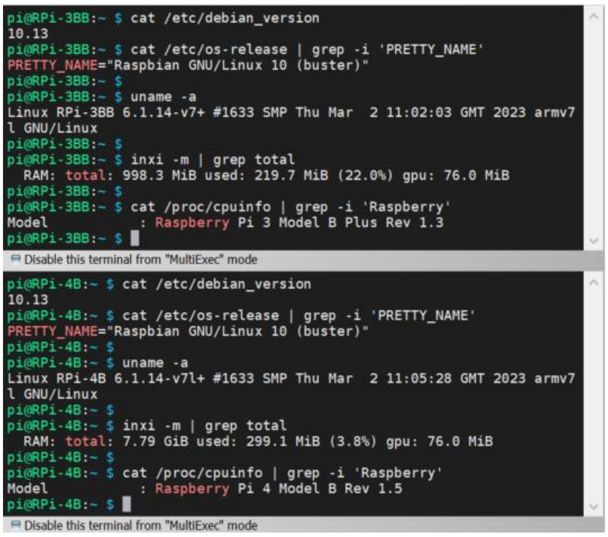


Figure 8: RPi 3B+ and RPi 4B Debian version, OS release, kernel version, RAM memory and RPi HW version.

2.2 Software Tools

The Operating System used to all the raspberries is the same which is "Raspbian GNU/Linux 10 (buster). In terms of the benchmarking tools used per categories (CPU, Memory etc.) are the *"SysBench" "hardinfo", "Linpack", "iPerf data transfer", SW* tools.

3. BENCHMARK and STRESS TESTING

3.1 CPU benchmarking

CPU testing with "SysBench". – The first tool used to stress test the CPU performance is named "SysBench", which is a powerful benchmark suite that allows to quickly get a view of a system performance. The threads, usually small sequences of programmed instructions, allow a CPU to perform multiple processes simultaneously. In simple words the threads are what the CPU is allowed to perform multiple processes or alternatively a thread is a small sequence of programmed instructions. In other words, threads refer to the highest level of code executed by a processor where each CPU core can have two threads. RPi's comprises four cores with two threads per core hence, they can run maximum 8 threads. The "SysBench" is a modular, cross-platform and multi-threaded benchmark tool used to evaluate OS parameters. It runs a specified number of threads and are executed in parallel. The "SysBench" suite is used for CPU stress testing, with (1, 4, 8,) threads.

The commands used for CPU testing are the following:

1 thread: $ sysbench --test=cpu --num-threads=1 run
2 threads: $ sysbench --test=cpu --num-threads=2 run
4 threads: $ sysbench --test=cpu --num-threads=4 run
8 threads: $ sysbench --test=cpu --num-threads=8 run

"Table 2", and "Figure 9" depicts a comparison of the threads execution time in (sec) between RPi 2B vs RPi 3B vs RPi 3B+ and vs the latest version RPi 4B with (8GB) RAM. As can be seen in "Figure 9", there is a decent improvement in the CPU performance regarding the threads execution time among the RPi's predecessors and unquestionably RPi 4B (8GB) is more powerful and quicker. It has also been noticed that all RPi's introduces approximately the same speedup performance regarding the 4&8 threads "Figure 10".

Table 2. Raspberry Pi's *SysBench* (threads) CPU Performance

	RPi 2 B Exec. time **(sec)**	**RPi 3 B** Exec. time **(sec)**	**RPi 3 B+** Exec. time **(sec)**	**RPi 4 B** Exec. time **(sec)**
1 thread	191.5656	143.6209	122.6402	92.8111
2 threads	96.0785	73.319	61.3531	48.3133
4 threads	49.2456	35.9512	30.8056	23.2211
8 threads	48.0927	35.9668	30.8168	23.4060
Speedup (1 thread)	1.000	1.000	1.000	1.000
Speedup (2 threads)	≈ 1.99	≈ 1.95	≈ 1.99	≈ 1.92
Speedup (4 threads)	≈ 3.89	≈ 3.99	≈ 3.98	≈ 3.99
Speedup (8 threads)	≈ 3.98	≈ 3.99	≈ 3.98	≈ 3.96

Regarding CPU performance the RPi-4B introduces approximately a 51% improvement in the CPU performance compared to RPi-2B in 1&4&8 threads and compared with RPi-3B+ introduces approximately 24% in 1&4&8 threads improvement in the CPU performance.

CPU testing with "hardinfo". – The *"Hardinfo"* is a well-known Linux benchmark software which provides HW analysis, system benchmark tests and a number of CPU and FPU performance tests such as [6]:

- CPU Blowfish: Blowfish is a symmetric-key 64-bit block cipher. The Blowfish benchmark measures the encryption speed (in MB/sec) of predefined text block. All operations are performed in memory, and do not involve disk I/O.

- CPU CryptoHash: CryptoHash is a cryptographic hash function that maps data of arbitrary size (often called the "message") to a bit array of a fixed size (called the "hash" or "message digest"). It is a one-way function, that is practically infeasible to invert, and is used in digital signatures, message authentication and hash functions to index data in hash tables.

- CPU Fibonacci: A Fibonacci sequence is a series of numbers in which each number is the sum of the two preceding numbers, such as 1, 1, 2, 3, 5, 8, and so on. This benchmark tests the integer processing ability of a CPU and the program calculates the 46th Fibonacci number in the Fibonacci sequence. The end result is in seconds and lower score is better.

- CPU N Queens: N-Queens finds a way to place a variable number of queens on a chessboard so that no two queens threaten each other by sharing the same row, column or diagonal.

- CPU Zlib: Zlib is a software library used for data compression, which is used by the gzip file compression program. This benchmark is memory intensive, so its results will reflect the speed of the RAM.

- FPU (Floating-Point-Unit) FFT: Fast Fourier Transforms (FFT) converts a signal to frequencies and vice-versa. It is used in audio digital signal processing and image signal processing and is an indication how fast a processor can process video in software if hardware video encoding is not supported.

- FPU raytracing: Ray tracing is a rendering technique for generating an image by tracing the path of light as pixels in an image plane and simulating the effects of its encounters with virtual objects. Like FFT, this benchmark tests how well the processor deals with floating point numbers (i.e., numbers with decimal points).

The results obtained from multiple runs per test with standard deviations less than 5% "Table 3". The standard deviations are not depicted so the values represent a rough estimation of the performance of each RPis. Regarding, Blowfish, Fibonacci, N-Queens, FFT and Raytracing *lower is better* (the results are in seconds) while in terms of the CryptoHash, Zlib, *higher is better.*

Table 3. Raspberry Pi's *Hardinfo* CPU Performance

	RPi 2 B Arm A7 1GB	**RPi 3 B** Arm A53 1GB	**RPi 3 B+** Arm A53 1GB	**RPi 4 B** Arm A72 8 GB
Blowfish (sec) Lower is better	14.21	20.66	9.17	8.73
CryptoHash Higher is better	96.32	67.39	146.58	137.12
Fibonacci (sec) Lower is better	5.35	4.07	3.43	2.39
N-Queens (sec) Lower is better	12.63	18.16	8.02	11.45
Zlib Higher is better	0.1	0.08	0.15	0.11
FPU FFT (sec) Lower is better	15.3	22.25	10.24	7.98
FPU Raytracing (sec) Lower is better	9.36	13.72	6.12	7.09

"Table 3" and "Figure 11" depicts a comparison of the CPU performance in all RPi's predecessors used the testing suite "*Hardinfo*". It is noticed that the RPi 4B (8GB ram) presents a better performance in "*Blowfish*", "*Fibonacci*", "*FPU FFT*" benchmark compared to all RPi's predecessors, but it lags behind at 42% in "*N-Queens*" performance, 15% in "*FPU raytracing*", 7% in "*CryptoHash*" performance, and 36% in "*Zlib*" benchmark performance compared with RPi-3B+.

Indicatively, RPi 4B compared with RPi 3B "Figure 11", introduces better performance at about 57% in "*Blowfish*" benchmark, 41 % in "*Fibonacci*" benchmark, 36% in "N-Queens" benchmark, 64% in "*FPU FFT*" benchmark, 48% in "*FPU raytracing*" benchmark, 50% in "*CryptoHash*" benchmark, 27% in "*Zlib*" benchmark.

CPU testing with "Linpack". – The Linpack Benchmark is a measure of a computer's floating rate of execution and determines the upper bound of double precision floating point performance on a distributed parallel system. In other words, measures how fast a computer solves a random dense linear system of equations of order (n), $[A \times x = b;\ A \in R^{n \times n};\ x, b \in R^n]$ by first computing the LU factorization [10], with row partial pivoting of $[\, n\ by\ (n+1)\,]$ coefficient matrix $[A\ b] = [[L, U]]$ [7], [8], [9]. The preparation of the CPU testing with *"Linpack"* does not have difficulties since the procedure is well described and being available in the internet [10], [11]. Only the HPL.dat file needs experience since the parameters inside the HPL.dat are sensitive and the whole concept behind choosing the critical parameters such as Number of problems sizes (N), Number of block size (NBs), Number of process grids ($P \times Q$), are well described [7], [11]. A brief explanation is given below:

Number of problems sizes (N). - Parameter (N) specifies the problem size. The aim is to find the largest problem size that fits into the main memory of a specific cluster and for this reason, the main memory capacity for storing double precision (8 Bytes) numbers is calculated. The max problem size is calculated as [13] suggests: $N_{max} = 80\% \sqrt{m \times n}$ where (m) is the free memory in doubles for the machine with the least available free memory and (n) is the number of nodes. The mathematical expression can be seen as such [14]:

$$(1)\quad N_{max} = \sqrt{\left(\frac{\text{Memory in Gbytes} \times 1024^3 \times \text{No of Nodes}}{8}\right)} \times Z$$

As a rule of thumb, it's wise to use the (N) between (80-85) % of available memory in RPI's to avoid cluster crash with errors. For a single RPi, $N_{max} \approx 11585 \times 0.85 = 9847.25$ where a further optimization will follow.

Number of block size (NBs). - The (NB) is the block size in the grid. HPL uses the block size (NB) for the data distribution and for the computational granularity. The principle is that smaller (NB) gives better load balance from a data distribution point of view, but it's preferred not to have very large values of (NB). From computational point of view, a too small value of (NB) will probably limit the computational performance. $N = 128$ is chosen considering 80% memory utilization.

Number of process grids ($P \times Q$). – ($P \times Q$) is the size of the grid where P (the number of process rows) and Q (the number of process columns) should be close to being a "square". According to the developers of the (HPL) in [15], [16] (P) and (Q) should be approximately equal, with Q slightly larger than P which is equal to the number of processors that the cluster has. Based on the equation (1) and regarding the RPi's which have 1GB memory if we consider NB=128, with 1 RPi node, then (N) is calculated as following:

$$N_{max} = \sqrt{\left(\frac{\text{Memory in Gbytes} \times 1024^3 \times \text{No of Nodes}}{8}\right)} \times Z$$

where (Z) is the reduction coefficient, taking values between (80-90) percent, and as a result we have below:

$N = \sqrt{\left(\frac{1GB \times 1024^3 \times 1}{8}\right)} \times 85\% = 11585.23 \times 0.85 = 9847.4455$. A further optimization is done: $\left(\frac{9847}{128} = 76.929\right)$ and next with rounding up $(77 \times 128 = 9856)$.

In the case of RPi 4B which has 8GB RAM memory the $N = \sqrt{\left(\frac{8GB \times 1024^3 \times 1}{8}\right)} \times 75\% = 32768 \times 0.75 = 24576.$ A further optimization is done: $\left(\frac{24576}{128} = 192\right)$ and next with rounding down $(190 \times 128 = 24576)$. A little lower value is chosen ($N = 24300$) since the test crashed in the RPi 4B with memory utilization greater than 75%.

"Figure 12", "Figure 13", "Figure 14" and "Table 4", depicts the results of the CPU Double Precision Linpack test.

Table 4. Raspberry Pi's *Linpack* CPU Performance

HPL.dat	RPi 2 B Arm A7 1GB	RPi 3 B Arm A53 1GB	RPi 3 B+ Arm A53 1GB	RPi 4 B Arm A72 8 GB
N_{max}	9856	9856	9856	24300
NB	128	128	128	128
P	2	2	2	2
Q	2	2	2	2
Memory Utilization	≈ 85%	≈ 85%	≈ 85%	≈ 74%
Results				
Time [sec]	440.56	367.17	390.50	2215.77
GFlops	1.4491	1.7388	1.6349	4.3176

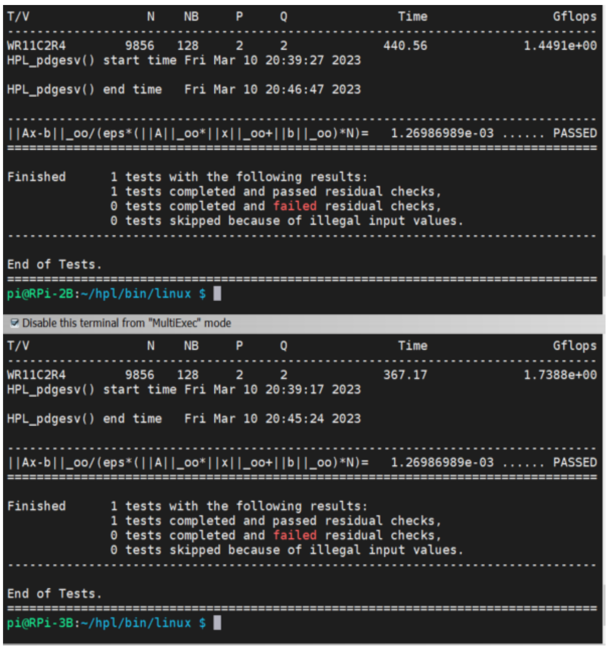


Figure 12: CPU (Double Precision Linpack) testing for RPi 2B and RPi 3B (1GB) RAM.

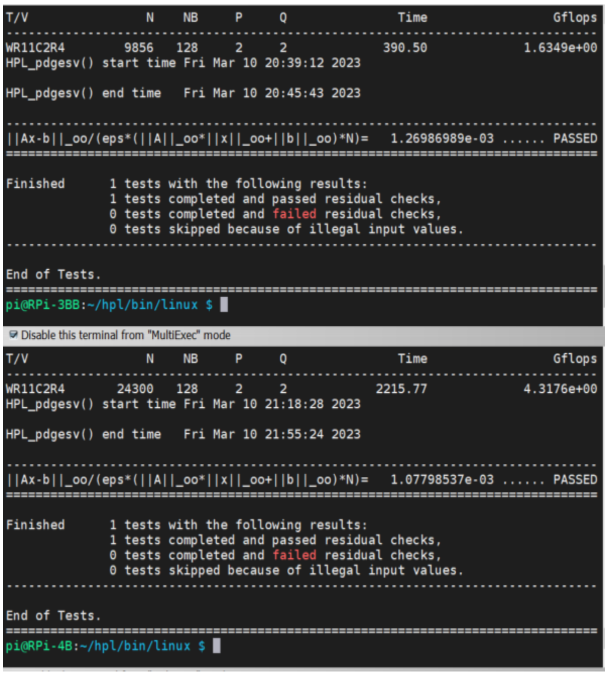


Figure 13: CPU (Double Precision Linpack) testing for RPi 3B+ (1GB) RAM and RPi 4B (8GB) RAM

"Figure 14", introduces the High-Performance Linpack (HPL) benchmark results where the RPi 4B substantially outperforms in the CPU performance compared with the RPi's predecessors. Moreover, it is noticed that the HPL benchmark was crashed in RPi 4B with memory utilization greater than 70% (8GB RAM memory) compared with the rest RPi's predecessors were reached 85% and this is something that it was not expected.

3.2 RAM memory benchmarking

When Synchronous Dynamic Random-Access Memory (SDRAM) introduced in the late of 1990s the data transfer speed was measured in sync with the motherboard clock meaning SDRAM memory 100MHZ indicated (100 x 10^6) data transfers per clock cycle. When Double Data Rate (DDR) introduced from 2000's onwards the number of data transfers per clock cycle was doubled. Following this, a more accurate measurement for the effective data rate (speed) of DDR is used by means of mega transfers (MT/s). One mega transfer is equivalent to one-megabyte and if your RAM indicates a RAM speed of 3,600 MT/s, you can expect it to transfer a maximum of 28.8 Gigabytes of data per second. The memory testing takes place with the "SysBench" which is a command-line tool designed to benchmark database performance but also can be used to run tests and measure the raw performance of CPU, RAM, and storage devices. Keep in mind that RAM performance is not the same as memory performance. Memory performance depends on multiple factors like RAM, pagefile, CPU cache and so on whereas RAM speed measures the raw performance of the RAM dims.

By default, "SysBench" uses a memory block size of 1KB, and this produces inaccurate RAM speed measurements much higher RAM read/write speeds than actual. The reason is that if we use very small block size then it easily goes through the CPU Cache resulting faster operation. As a result, larger block size will be chosen so as to force the system to write more data directly to RAM introducing correct or very close to correct results. Another factor considered is that the "SysBench" must be run with only one *thread* when testing RAM speed. If more than one *thread* is used the reported speed will be higher than the actual one. When testing RAM speed, we must make sure to run *"SysBench"* with 1 thread because if more than 1 thread is used the reported speed will be higher. As an example, the used command is like *"$sysbench --test=memory --memory-block-size=100M --memory-total-size=2G --memory-oper=read --num-threads=1 run*", keeping the *memory-total-size=2G* and increasing the *--memory-block-size=* with values (100M, 200M, 400M, 600M) with --memory-oper=read & write.

Memory performance is usually measured in either transfer rate (MB/s) or operations rate (ops/sec) for read and write operation. As can be seen in "Table 5", "Figure 15", and "Figure 16" there is a decent improvement in the RAM memory performance regarding in terms of "*read*" and "*write*" operation among the RPi's predecessors and unquestionably RPi 4B (8GB) is more powerful and quicker.

Table 5. Raspberry Pi's SysBench (RAM) Memory Performance

	RPi 2 B (ops/sec)	RPi 3 B (ops/sec)	RPi 3 B+ (ops/sec)	RPi 4 B (ops/sec)
100 MB read	29445.95	34939.44	36334.38	45031.14
Total Exec. Time (s)	0.0007s	0.0006s	0.0006s	0.0005s
100 MB write	11.97	16.79	17.44	30.47
Total Exec. Time (s)	1.7540s	1.2510s	1.2042s	0.6891s
200 MB read	13422.43	17999.03	19896.50	24207.80
Total Exec. Time (s)	0.0008s	0.0006s	0.0006s	0.0005s
200 MB write	5.96	8.20	8.68	13.90
Total Exec. Time (s)	1.8472s	1.3418s	1.2672s	0.7914s
400 MB read	8400.86	10525.39	10055.93	12750.63
Total Exec. Time (s)	0.0007s	0.0006s	0.0006s	0.0005s
400 MB write	2.97	4.10	4.45	7.70
Total Exec. Time (s)	2.0168s	1.4641s	1.3491s	0.7790s
600 MB read	6120.55	6608.17	6834.60	8232.49
Total Exec. Time (s)	0.0007s	0.0006s	0.0006s	0.0005s
600 MB write	2.00	2.79	2.95	4.65
Total Exec. Time (s)	2.0021s	1.4333s	1.3544s	0.8595s

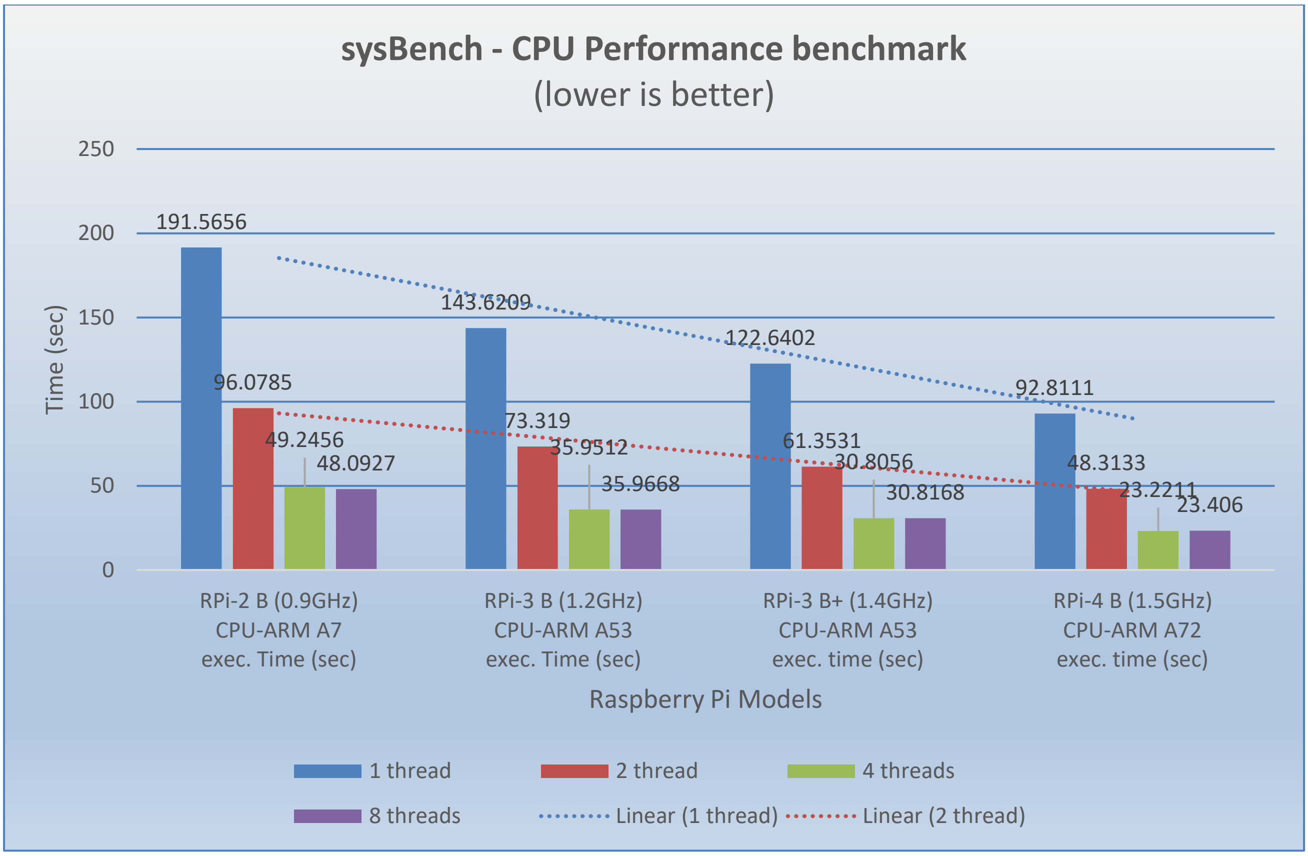


Figure 9: RPi's CPU Performance using SysBench SW tool.

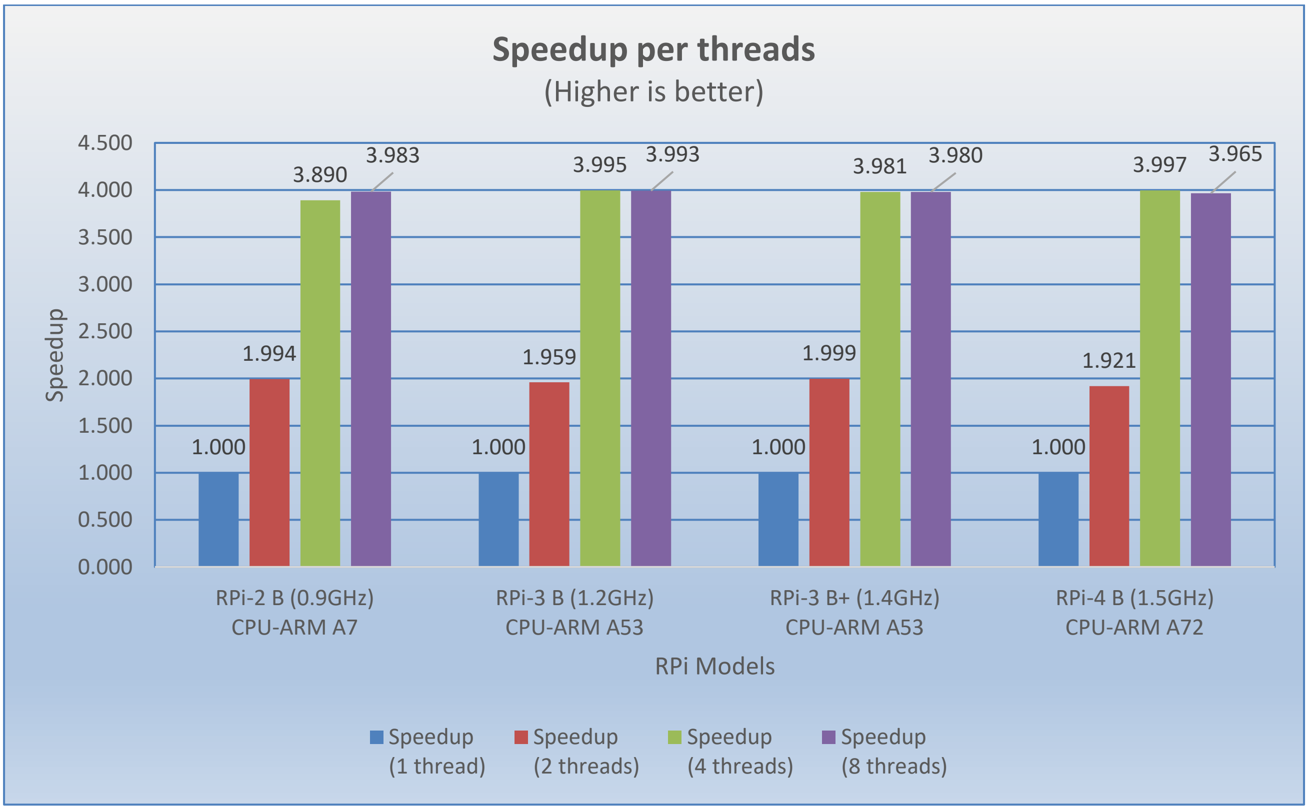


Figure 10: RPi's Speedup/threads CPU Performance using SysBench SW tool.

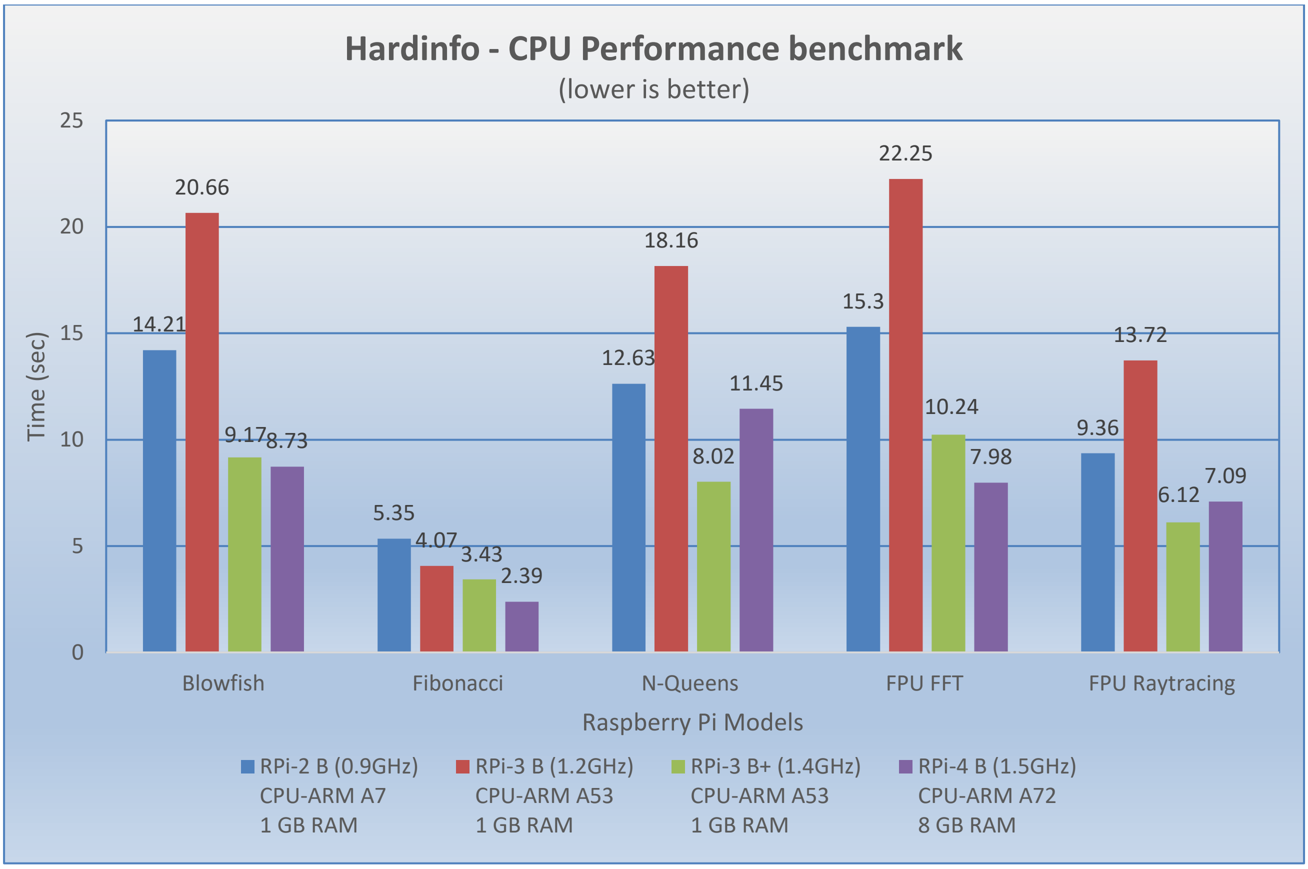


Figure 11: RPi's CPU Performance using Hardinfo SW suite.

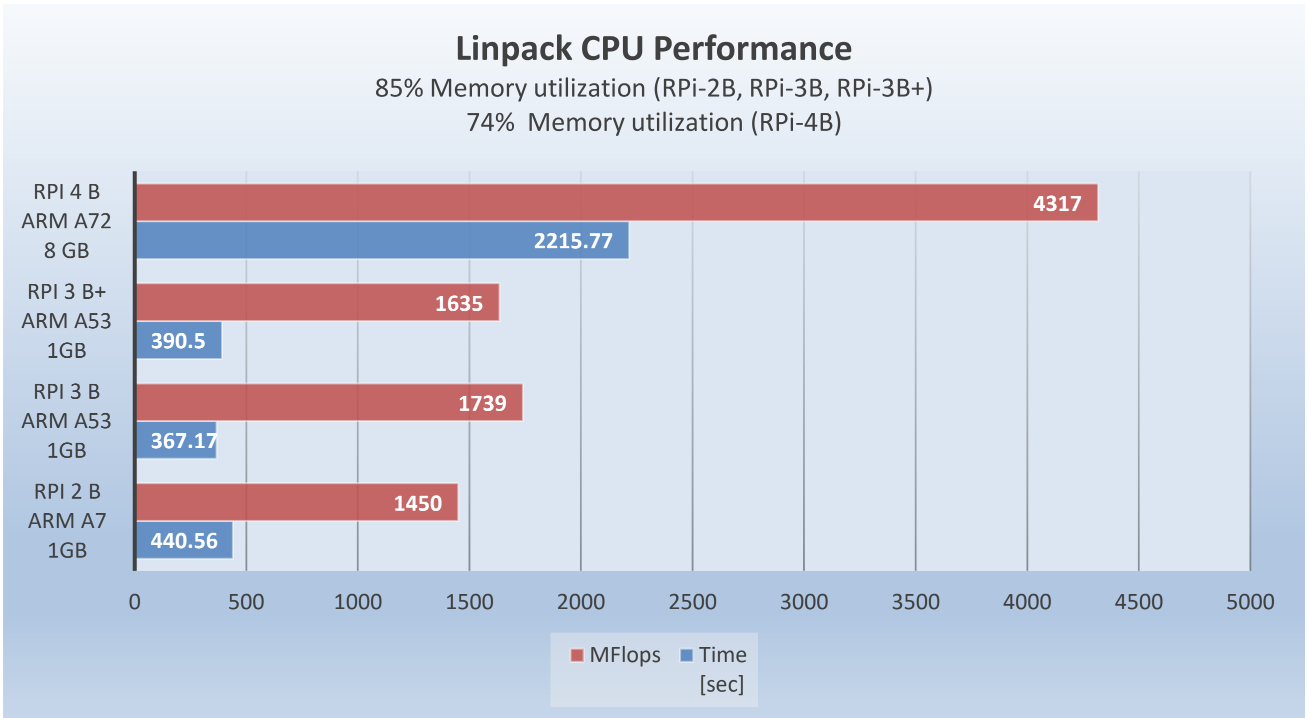


Figure 14: High-Performance Linpack (HPL)- CPU performance results in MFlops (4 threads per node)

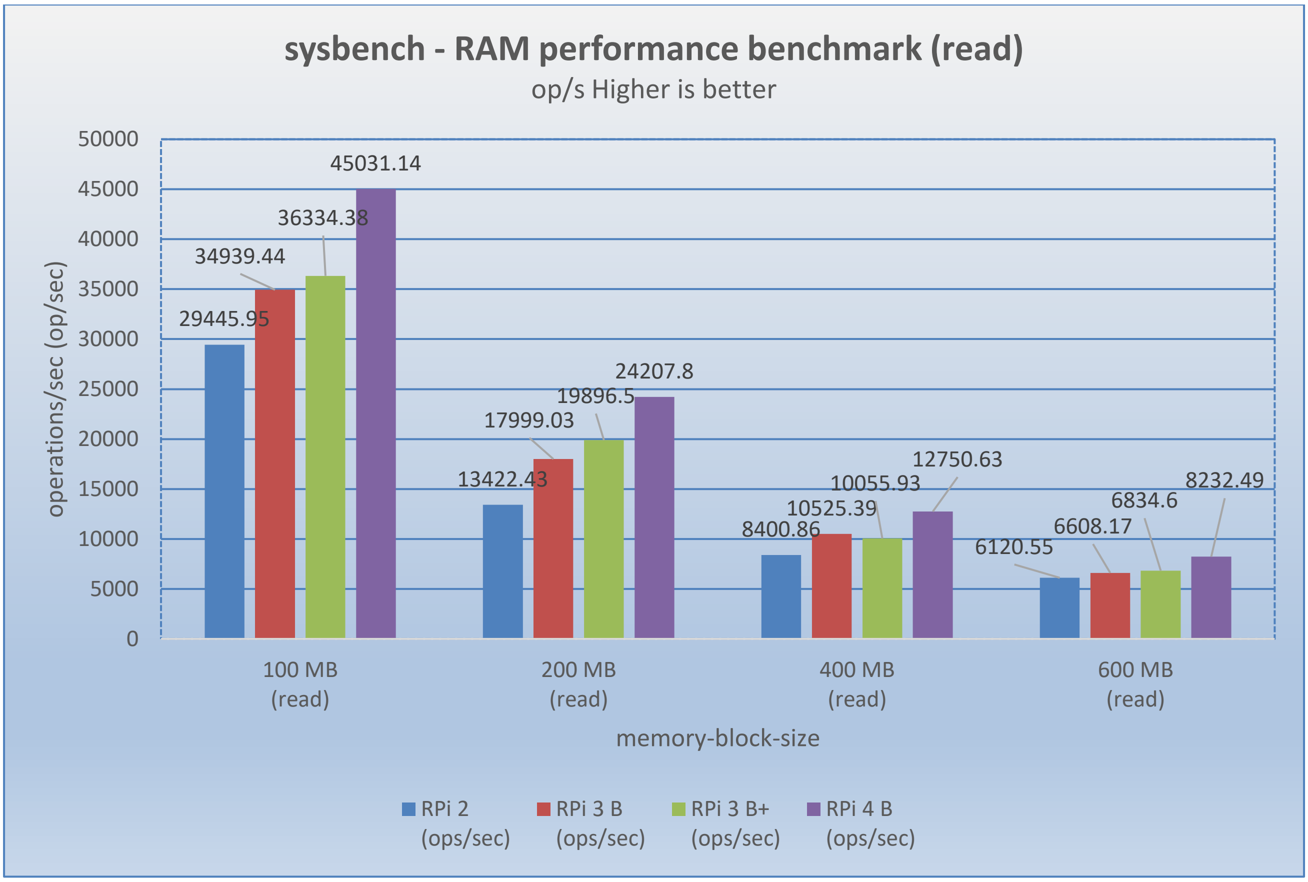


Figure 15: RPi's RAM Performance using SysBench SW (read operation)

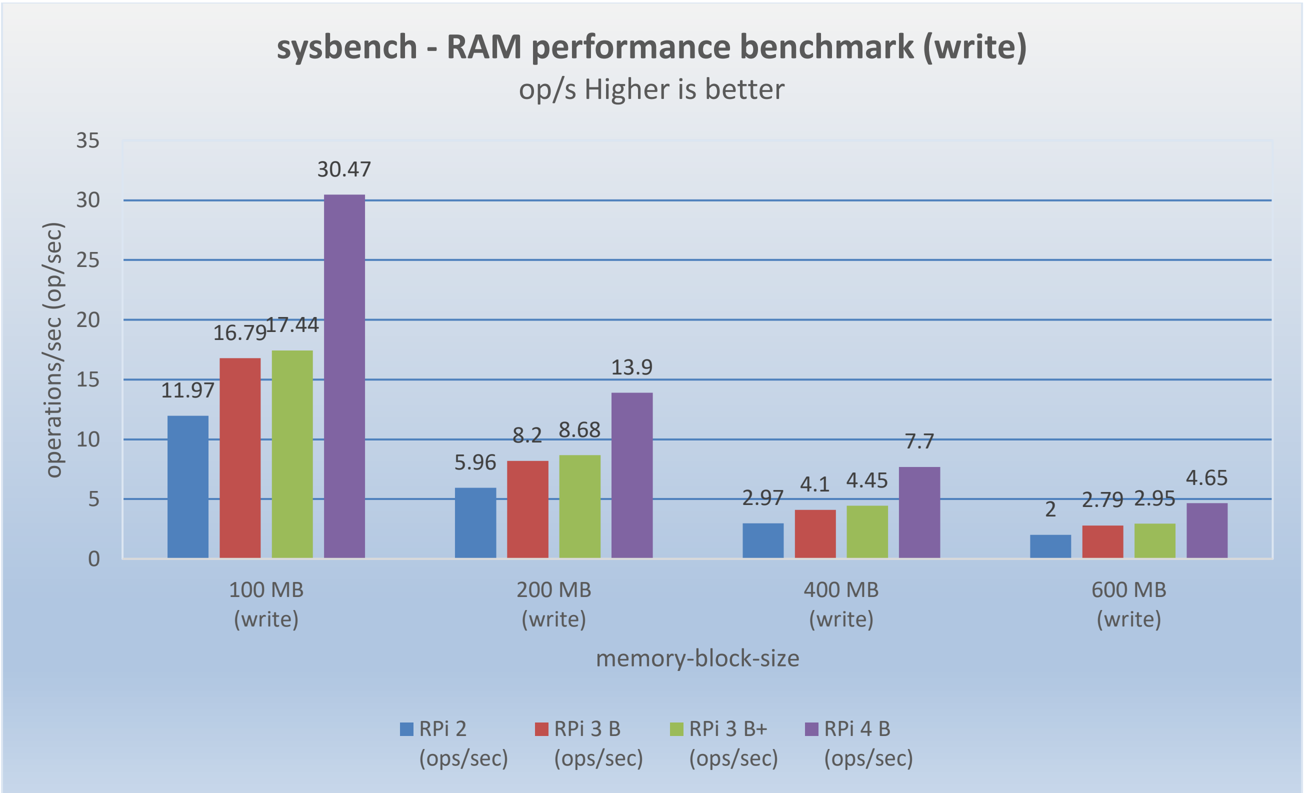


Figure 16: RPi's RAM Performance using SysBench SW (write operation)

3.3 File I/O benchmark

The used HDs for the testing are referred below:

- microSD mounted: the used microSD is the Kingston SDCS2 64GB micro SDXC 100R A1 C10 with maximum 100MB/sec read (UHS-I Speed class 1 (U1). The microSD is connected to USB 2.0 in every RPi with a USB 2.0 card reader and regarding RPi 4B (8GB) in USB 3.0 slot, with a USB 3.0 card reader.
- SSD HD mounted: the used SSD (Solid State) is INTENSO 3812430 top performance 128GB 2.5'' SATA3 with maximum (520 MB/sec read and 500 MB/sec write). The SSD HD is connected to each RPi in USB 2.0 and in USB 3.0 (RPi 4B) with a USB 3.0 to SATA Rp-sma adaptor.

File I/O testing with "SysBench". – The "SysBench" benchmarking test for I/O testing requires some preparation steps such as mount the SD card and SSD disk, creation of a test file, and then to run the testing. When using "*fileio*", it is needed to create a set of test files to work on and it is recommended that the size is larger than the available memory to ensure that file caching does not influence the workload too much as it was chosen "10GB". By using the "SysBench" benchmark there is an option to run sequential reads, writes or random reads, writes, or a combination.

- Random I/O performance: Random reads and writes are probably the more common types of storage loads. Due to different requests from varying tasks, consecutive accesses to storage rarely fall in neighboring addresses, hence the access pattern is called random.

Prepare file on disk: "*sysbench --test=fileio --file-total-size=10G prepare*"
Test with SysBench: "*sysbench --test=fileio --file-total-size=10G --file-test-mode=rndrw --max-time=300 --max-requests=0 run*".
Cleanup after finishing the testing: "*sysbench --test=fileio --file-total-size=10G cleanup*".
seqwr # sequential write
seqrd # sequential read
rndwr # random write
rndrd # random read
"Table 6", "Table 7" depicts the results of the SysBench File I/O benchmark regarding the random write on SSD disk and random write on microSD. "Figure 17" depicts the comparison of "*write operation*" performance of all RPi's where RPi 4B presents a decent performance improvement compared with the RPi's predecessors.

Table 6. Raspberry Pi's SysBench File I/O testing (Random write on SSD disk)

	RPi 2 B USB 2.0 SSD-HD	RPi 3 B USB 2.0 SSD-HD	RPi 3 B+ USB 2.0 SSD-HD	RPi 4 B USB 2.0 SSD-HD	RPi 4 B USB 3.0 SSD-HD
Random Write (GB)	1.1948	1.3281	1.416	1.5182	1.5182
Total transfer (GB)	1.1948	1.3281	1.416	1.5182	1.5182
Total transfer (MB/sec)	4.0781	4.5332	4.8333	5.1823	5.8854
Request/sec	261	290.13	309.33	331.67	376.67

Table 7. Raspberry Pi's SysBench File I/O testing (Random write on microSD)

	RPi 2 B USB 2.0 microSD	RPi 3 B USB 2.0 microSD	RPi 3 B+ USB 2.0 microSD	RPi 4 B USB 2.0 microSD	RPi 4 B USB 3.0 microSD
Random Write (GB)	0.65312	673.44	659.38	704.69	765.62
Total transfer (GB)	0.65312	673.44	659.38	704.69	765.62
Total transfer (MB/sec)	2.177	2.2447	2.1979	2.3489	2.5521
Request/sec	139.33	143.66	140.66	150.33	163.33

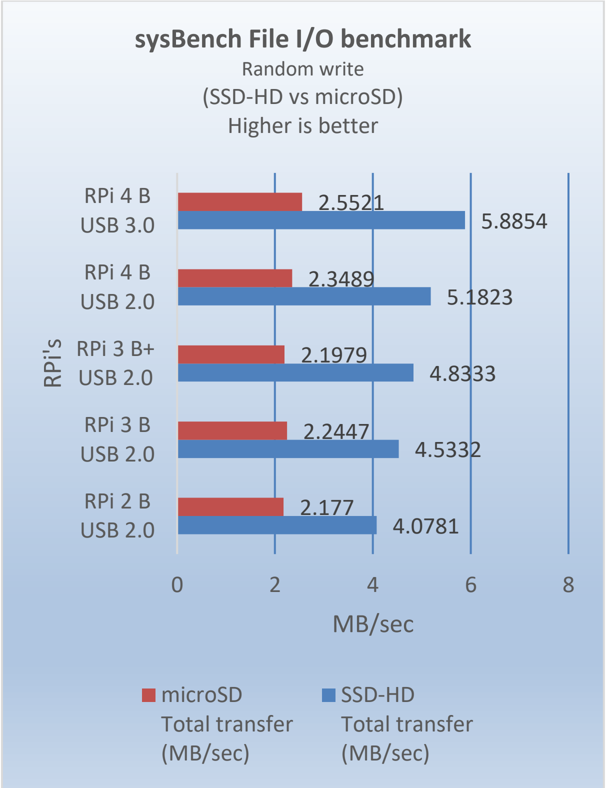


Figure 17: SysBench File I/O benchmark (random write operation (microSD vs SSD-HD)

Moreover, "Table 8", "Table 9" presents the results of the SysBench File I/O benchmark regarding the random read on SSD disk and random read on microSD. "Figure 18" depicts the comparison of "*read operation*" performance of all RPi's where RPi 4B presents a decent performance improvement compared with the RPi's predecessors.

In overall, there is a decent performance improvement in "random read-write" operation compared with the RPi's predecessors.

Table 8. Raspberry Pi's SysBench File I/O testing (Random read on SSD disk)

	RPi 2 B USB 2.0 SSD-HD	**RPi 3 B** USB 2.0 SSD-HD	**RPi 3 B+** USB 2.0 SSD-HD	**RPi 4 B** USB 2.0 SSD-HD	**RPi 4 B** USB 3.0 SSD-HD
Random Write (MB)	5.3799	5.5365	5.492	14.429	21.656
Total transfer (MB)	5.3799	5.5365	5.492	14.429	21.656
Total transfer (MB/sec)	18.363	18.898	18.746	49.251	73.92
Request/ sec	1175.25	1209.47	1199.74	3152.05	4730.9

Table 9. Raspberry Pi's SysBench File I/O testing (Random read in microSD)

	RPi 2 B USB 2.0 microSD	**RPi 3 B** USB 2.0 microSD	**RPi 3 B+** USB 2.0 microSD	**RPi 4 B** USB 2.0 microSD	**RPi 4 B** USB 3.0 microSD
Random Read (GB)	2.8683	3.2552	3.2455	5.8377	7.5269
Total transfer (MB)	2.8683	3.2552	3.2455	5.8377	7.5269
Total transfer (MB/sec)	9.7904	11.111	11.078	19.926	25.692
Request/ sec	626.58	711.12	708.99	1275.26	1644.28

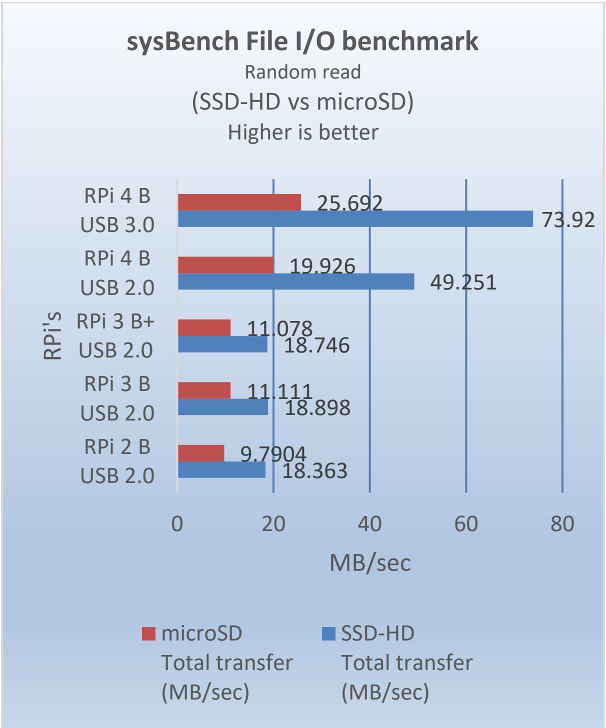


Figure 18: SysBench File I/O benchmark (random read operation (microSD vs SSD-HD)

- Sequential I/O Performance: Sequential access to storage is common with large file sizes such as audio and video. When a system is reading or writing in sequential order, the storage device wastes less time in related operations and due to faster access, the sequential operation provide better throughput and benchmark scores.

Furthermore, "Table 10", "Table 11" presents the results of the SysBench File I/O benchmark concerning the sequential write on SSD disk and sequential write on microSD. "Figure 17" depicts the comparison of "*write operation*" performance of all RPi's where RPi 4B presents a decent performance improvement compared with the RPi's predecessors.

Table 10. Raspberry Pi's SysBench File I/O testing (Sequential write in SSD disk)

	RPi 2 B USB 2.0 SSD-HD	**RPi 3 B** USB 2.0 SSD-HD	**RPi 3 B+** USB 2.0 SSD-HD	**RPi 4 B** USB 2.0 SSD-HD	**RPi 4 B** USB 3.0 SSD-HD
Seque-ntial write (GB)	10	10	10	10	10
Total transfer (MB)	10	10	10	10	10
Total transfer (MB/sec)	12.545	13.486	13.708	14.048	23.146
Request/ sec	3211.63	3452.3	3509.19	3596.4	5925.5

Table 11. Raspberry Pi's SysBench File I/O testing (Sequential write in microSD disk)

	RPi 2 B USB 2.0 microSD	**RPi 3 B** USB 2.0 microSD	**RPi 3 B+** USB 2.0 microSD	**RPi 4 B** USB 2.0 microSD	**RPi 4 B** USB 3.0 microSD
Seque-ntial write (GB)	10	10	10	10	10
Total transfer (MB)	10	10	10	10	10
Total transfer (MB/sec)	8.2343	8.7248	8.0692	10.247	15.339
Request/ sec	2107.97	2233.56	2065.71	2623.29	3926.75

In overall, there is a significant performance improvement in "sequential write" operation compared with the RPi's predecessors "Figure 19" as well as in "sequential read" operation as can be seen in "Figure 20".

Indicatively, USB 3.0 provides a better performance compared with USB 2.0 in RPi 4B, approximately 12% in random write (on SSD disk), 8% in random write (on microSD), 33% in random read (on SSD disk), and 22% in random read (on microSD).

In sequential test USB 3.0 provides a better performance compared with USB 2.0 in RPi 4B approximately 39% in sequential write (on SSD disk), 33% in sequential write (on microSD disk), 74% improvement in sequential read (on SSD disk), and 72% in sequential read (on microSD).

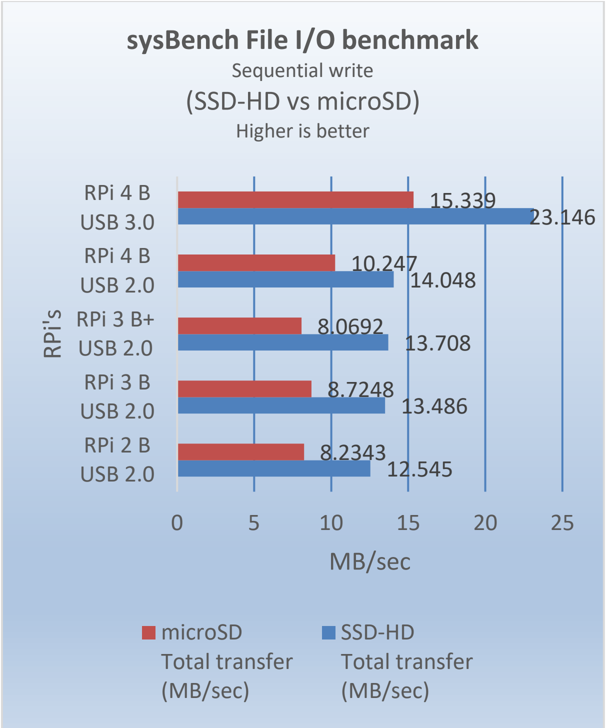


Figure 19: SysBench File I/O benchmark (sequential write operation (SSD-HD vs microSD)

Table 11. Raspberry Pi's SysBench File I/O testing (Sequential read in SSD disk)

	RPi 2 B USB 2.0 SSD-HD	**RPi 3 B** USB 2.0 SSD-HD	**RPi 3 B+** USB 2.0 SSD-HD	**RPi 4 B** USB 2.0 SSD-HD	**RPi 4 B** USB 3.0 SSD-HD
Seque-ntial read (GB)	10	10	10	10	10
Total transfer (MB)	10	10	10	10	10
Total transfer (MB/sec)	30.736	32.035	31.413	34.772	134.99
Request/ sec	7868.31	8200.86	8041.8	8901.74	34556.4 9

Table 12. Raspberry Pi's SysBench File I/O testing (Sequential read in microSD disk)

	RPi 2 B USB 2.0 microSD	**RPi 3 B** USB 2.0 microSD	**RPi 3 B+** USB 2.0 microSD	**RPi 4 B** USB 2.0 microSD	**RPi 4 B** USB 3.0 microSD
Seque-ntial read (GB)	10	10	10	10	10
Total transfer (MB)	10	10	10	10	10
Total transfer (MB/sec)	17.818	19.928	19.762	20.117	71.972
Request/ sec	4561.31	5101.46	5059.13	5150.02	18424.8

A striking notice from the File I/O benchmarking is that the USB 3.0 in RPi 4B gives an unquestionable advantage compared with the RPi's predecessors where they have only USB 2.0. The transfer rate increases remarkably when it comes to SSD disk connected to USB 3.0.

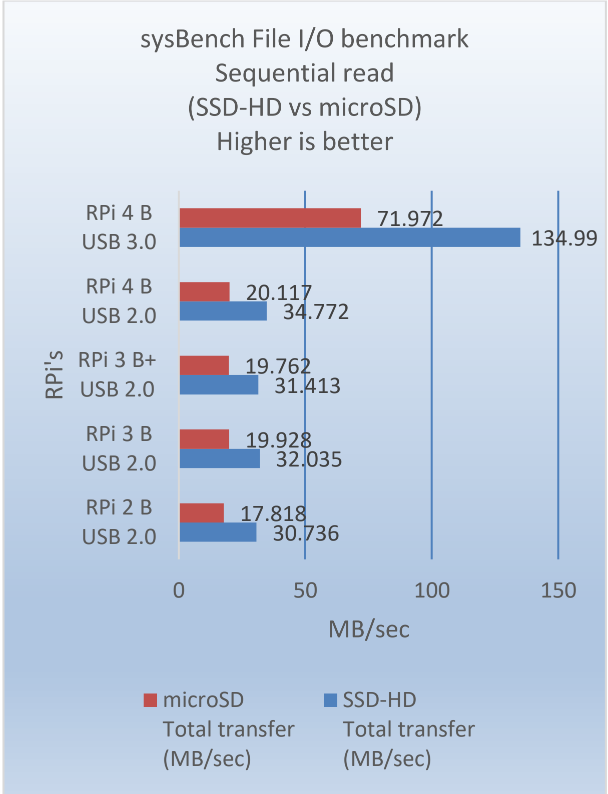


Figure 20: SysBench File I/O benchmark (sequential read operation (microSD vs SSD-HD)

3.4 Ethernet and Wi-fi throughput benchmarking

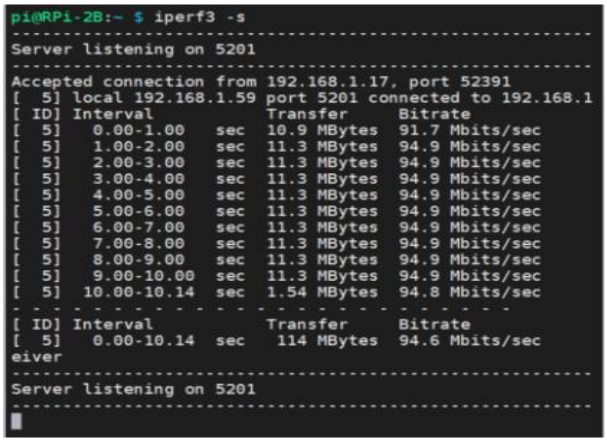
Ethernet throughput testing with "iperf3. – "*Throughput*" gives information about how much data are transferred from a given source at any time to destination within a given timeframe and "*bandwidth*" informs about how much data could be transferred from a source at any given time. In other words, "*throughput*" measures how many packets arrive at their destinations successfully. "B*andwidth*" in other words, is defined as the maximum transfer throughput capacity of a network and is measured in bits, megabits or gigabits per second. Something very important to bear in mind is that bandwidth doesn't actually increase the speed of a network. For instance, when a network bandwidth is increased then the amount of data is increased that can be sent at one time, without increasing the transmission speed of said data. Bandwidth doesn't change the speed at which packets are traveling and moreover to remember, high bandwidth does not necessarily equal high network performance.

"iperf3" is a very powerful tool for measuring network throughput over protocols such as TCP, UDP, and SCTP a powerful tool for measuring network throughput over protocols such as TCP, UDP, and SCTP. It is a very useful tool for testing and monitoring the maximum achievable bandwidth on IP networks and in addition supports both IPv4 and IPv6 as well. The biggest benefit of using "iPerf3" is that there is a control over both ends of the connection. What is really needed is two devices points where the measurements take place. For instance, one point is the RPi and the second an Apple Mac or a Windows PC or a Linux PC where one is acting as a "*server*" and the second one as the "*client*" sender/receiver with a prerequisite one point to support 1GBps Ethernet port.

Ethernet throughput testing with "iperf3. – The condition of the testing has preconditions all the RPi's and my HP Laptop *(EliteBook 840 G5)* to be connected with the Gigabit switch (TL-SG1024D). "Table 13", presents the LAN, Wi-Fi 2.4GHz and 5GHz throughput performance of all the RPi's.

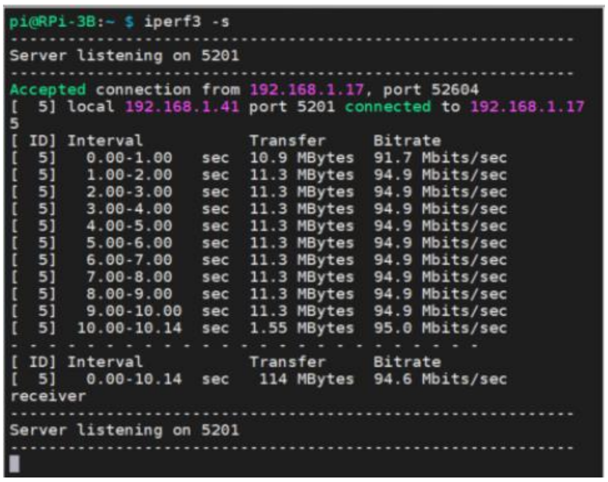
Table 13. iperf3 – Ethernet, Wi-Fi 2.4GHz and 5GHz throughput performance (Mbits/sec)

	RPi 2 B	RPi 3 B	RPi 3 B+	RPi 4 B
Ethernet (Mbits/sec)	94.6	94.6	94.6	935
Wi-Fi 2.4GHz Mbits/sec)	N/A	20.2	23.9	23.7
Wi-Fi 5 GHz Mbits/sec)	N/A	N/A	74.4	89.9



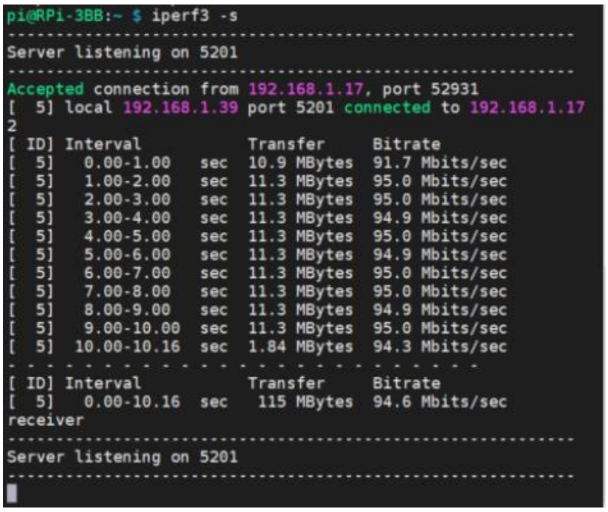
```
pi@RPi-2B:~ $ iperf3 -s
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 192.168.1.17, port 52391
[  5] local 192.168.1.59 port 5201 connected to 192.168.1
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-1.00   sec  10.9 MBytes  91.7 Mbits/sec
[  5]   1.00-2.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   2.00-3.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   3.00-4.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   4.00-5.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   5.00-6.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   6.00-7.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   7.00-8.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   8.00-9.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   9.00-10.00  sec  11.3 MBytes  94.9 Mbits/sec
[  5]  10.00-10.14  sec  1.54 MBytes  94.8 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-10.14  sec   114 MBytes  94.6 Mbits/sec
eiver
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
```

Figure 21: iperf3 – (RPi 2 B) Ethernet throughput performance (Mbits/sec)



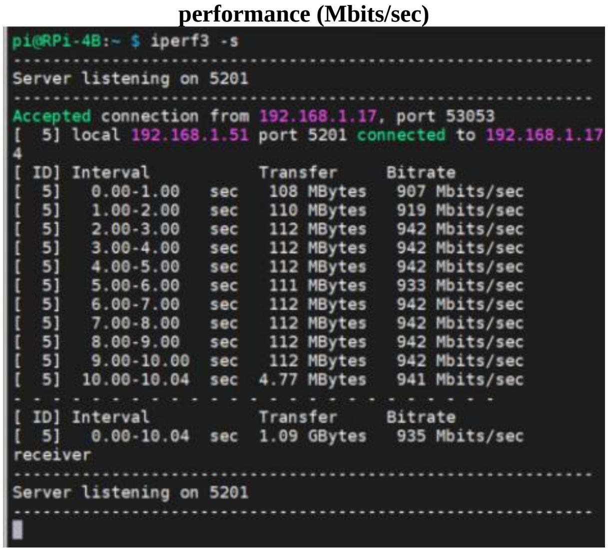
```
pi@RPi-3B:~ $ iperf3 -s
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 192.168.1.17, port 52604
[  5] local 192.168.1.41 port 5201 connected to 192.168.1.17
5
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-1.00   sec  10.9 MBytes  91.7 Mbits/sec
[  5]   1.00-2.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   2.00-3.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   3.00-4.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   4.00-5.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   5.00-6.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   6.00-7.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   7.00-8.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   8.00-9.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   9.00-10.00  sec  11.3 MBytes  94.9 Mbits/sec
[  5]  10.00-10.14  sec  1.55 MBytes  95.0 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-10.14  sec   114 MBytes  94.6 Mbits/sec
receiver
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
```

Figure 22: iperf3 – (RPi 3 B) Ethernet throughput performance (Mbits/sec)



```
pi@RPi-3BB:~ $ iperf3 -s
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 192.168.1.17, port 52931
[  5] local 192.168.1.39 port 5201 connected to 192.168.1.17
2
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-1.00   sec  10.9 MBytes  91.7 Mbits/sec
[  5]   1.00-2.00   sec  11.3 MBytes  95.0 Mbits/sec
[  5]   2.00-3.00   sec  11.3 MBytes  95.0 Mbits/sec
[  5]   3.00-4.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   4.00-5.00   sec  11.3 MBytes  95.0 Mbits/sec
[  5]   5.00-6.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   6.00-7.00   sec  11.3 MBytes  95.0 Mbits/sec
[  5]   7.00-8.00   sec  11.3 MBytes  95.0 Mbits/sec
[  5]   8.00-9.00   sec  11.3 MBytes  94.9 Mbits/sec
[  5]   9.00-10.00  sec  11.3 MBytes  95.0 Mbits/sec
[  5]  10.00-10.16  sec  1.84 MBytes  94.3 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-10.16  sec   115 MBytes  94.6 Mbits/sec
receiver
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
```

Figure 23: iperf3 – (RPi 3 B+) Ethernet throughput performance (Mbits/sec)



```
pi@RPi-4B:~ $ iperf3 -s
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 192.168.1.17, port 53053
[  5] local 192.168.1.51 port 5201 connected to 192.168.1.17
4
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-1.00   sec   108 MBytes   907 Mbits/sec
[  5]   1.00-2.00   sec   110 MBytes   919 Mbits/sec
[  5]   2.00-3.00   sec   112 MBytes   942 Mbits/sec
[  5]   3.00-4.00   sec   112 MBytes   942 Mbits/sec
[  5]   4.00-5.00   sec   112 MBytes   942 Mbits/sec
[  5]   5.00-6.00   sec   111 MBytes   933 Mbits/sec
[  5]   6.00-7.00   sec   112 MBytes   942 Mbits/sec
[  5]   7.00-8.00   sec   112 MBytes   942 Mbits/sec
[  5]   8.00-9.00   sec   112 MBytes   942 Mbits/sec
[  5]   9.00-10.00  sec   112 MBytes   942 Mbits/sec
[  5]  10.00-10.04  sec  4.77 MBytes   941 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-10.04  sec  1.09 GBytes   935 Mbits/sec
receiver
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
```

Figure 24: iperf3 – (RPi 4 B) Ethernet throughput performance (Mbits/sec)

"Figure 21", "Figure 22", "Figure 23", "Figure 24" presents the "*iperf3*" Ethernet throughput performance regarding the RPi 2B, RPi 3B, RPi 3B+ and RPi 4B respectively. It is noticed that the RPi 4B Gigabit ethernet port reaches 935 Mbits/sec -as expected- which is very close to the specification.

Wi-Fi (2.4 GHz) and (5 GHz) throughput testing with "iperf3.

Regarding the Wi–Fi 2.4 GHz and Wi–Fi 5 GHz for the RPi -2B is not applicable and in terms of RPi 3B the Wi–Fi 5 GHz is not applicable as well. The condition of the testing has preconditions all the RPi's (except RPi 2B) and my HP Laptop *(EliteBook 840 G5)* to have a Wi-Fi connectivity unplugging the LAN cable from the LAN slot. In terms of the Wi–Fi 5 GHz testing, the Internet router transmits only on Wi–Fi 5 GHz (the 2.4 GHz Wi-Fi is disabled) so that to force RPi's to be connected accordingly.

```
pi@RPi-3B:~ $ iperf3 -s
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 192.168.1.54, port 58088
[  5] local 192.168.1.42 port 5201 connected to 192.168.1.
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-1.00   sec  1.56 MBytes  13.1 Mbits/sec
[  5]   1.00-2.00   sec  1.81 MBytes  15.2 Mbits/sec
[  5]   2.00-3.00   sec  1.71 MBytes  14.3 Mbits/sec
[  5]   3.00-4.00   sec  2.49 MBytes  20.9 Mbits/sec
[  5]   4.00-5.00   sec  2.78 MBytes  23.3 Mbits/sec
[  5]   5.00-6.00   sec  2.83 MBytes  23.7 Mbits/sec
[  5]   6.00-7.00   sec  2.50 MBytes  21.0 Mbits/sec
[  5]   7.00-8.00   sec  2.59 MBytes  21.7 Mbits/sec
[  5]   8.00-9.00   sec  2.83 MBytes  23.8 Mbits/sec
[  5]   9.00-10.00  sec  2.84 MBytes  23.9 Mbits/sec
[  5]  10.00-10.43  sec  1.24 MBytes  24.2 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-10.43  sec  25.2 MBytes  20.2 Mbits/sec
ceiver
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
```

Figure 25: iperf3 – (RPi 3 B) Wi-Fi 2.4 GHz throughput performance (Mbits/sec)

```
pi@RPi-3BB:~ $ iperf3 -s
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 192.168.1.54, port 58146
[  5] local 192.168.1.40 port 5201 connected to 192.168.1.
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-1.00   sec  2.28 MBytes  19.2 Mbits/sec
[  5]   1.00-2.00   sec  2.69 MBytes  22.6 Mbits/sec
[  5]   2.00-3.00   sec  2.64 MBytes  22.1 Mbits/sec
[  5]   3.00-4.00   sec  2.69 MBytes  22.5 Mbits/sec
[  5]   4.00-5.00   sec  2.44 MBytes  20.5 Mbits/sec
[  5]   5.00-6.00   sec  3.06 MBytes  25.7 Mbits/sec
[  5]   6.00-7.00   sec  3.11 MBytes  26.1 Mbits/sec
[  5]   7.00-8.00   sec  3.22 MBytes  27.0 Mbits/sec
[  5]   8.00-9.00   sec  3.15 MBytes  26.4 Mbits/sec
[  5]   9.00-10.00  sec  3.21 MBytes  26.9 Mbits/sec
[  5]  10.00-10.41  sec  1.21 MBytes  24.8 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-10.41  sec  29.7 MBytes  23.9 Mbits/sec
ceiver
-----------------------------------------------------------
Server listening on 5201
```

Figure 26: iperf3 – (RPi 3 B+) Wi-Fi 2.4 GHz throughput performance (Mbits/sec)

```
pi@RPi-4B:~ $ iperf3 -s
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 192.168.1.54, port 58468
[  5] local 192.168.1.52 port 5201 connected to 192.168.1.
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-1.00   sec  2.43 MBytes  20.4 Mbits/sec
[  5]   1.00-2.00   sec  2.86 MBytes  24.0 Mbits/sec
[  5]   2.00-3.00   sec  2.81 MBytes  23.6 Mbits/sec
[  5]   3.00-4.00   sec  2.88 MBytes  24.2 Mbits/sec
[  5]   4.00-5.00   sec  2.98 MBytes  25.0 Mbits/sec
[  5]   5.00-6.00   sec  2.69 MBytes  22.6 Mbits/sec
[  5]   6.00-7.00   sec  2.98 MBytes  25.0 Mbits/sec
[  5]   7.00-8.00   sec  2.85 MBytes  23.9 Mbits/sec
[  5]   8.00-9.00   sec  2.80 MBytes  23.5 Mbits/sec
[  5]   9.00-10.00  sec  3.05 MBytes  25.6 Mbits/sec
[  5]  10.00-10.24  sec   669 KBytes  22.7 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-10.24  sec  29.0 MBytes  23.7 Mbits/sec
ceiver
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
```

Figure 27: iperf3 – (RPi 4 B) Wi-Fi 2.4 GHz throughput performance (Mbits/sec)

```
pi@RPi-3BB:~ $ iperf3 -s
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 192.168.1.54, port 59412
[  5] local 192.168.1.40 port 5201 connected to 192.168.1
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-1.00   sec  10.9 MBytes  91.6 Mbits/sec
[  5]   1.00-2.00   sec  12.2 MBytes   102 Mbits/sec
[  5]   2.00-3.00   sec  11.4 MBytes  95.7 Mbits/sec
[  5]   3.00-4.00   sec  12.3 MBytes   104 Mbits/sec
[  5]   4.00-5.00   sec  11.7 MBytes  98.0 Mbits/sec
[  5]   5.00-6.00   sec  7.98 MBytes  66.9 Mbits/sec
[  5]   6.00-7.00   sec  7.71 MBytes  64.6 Mbits/sec
[  5]   7.00-8.00   sec  7.35 MBytes  61.7 Mbits/sec
[  5]   8.00-9.00   sec  5.49 MBytes  46.0 Mbits/sec
[  5]   9.00-10.00  sec  2.88 MBytes  24.1 Mbits/sec
[  5]  10.00-10.14  sec  0.00 Bytes  0.00 bits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-10.14  sec  90.0 MBytes  74.4 Mbits/sec
eceiver
-----------------------------------------------------------
Server listening on 5201
```

Figure 28: iperf3 – (RPi 3 B+) Wi-Fi 5 GHz throughput performance (Mbits/sec)

```
pi@RPi-4B:~ $ iperf3 -s
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 192.168.1.54, port 59448
[  5] local 192.168.1.52 port 5201 connected to 192.168.1.
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-1.00   sec  9.80 MBytes  82.2 Mbits/sec
[  5]   1.00-2.00   sec  11.0 MBytes  92.0 Mbits/sec
[  5]   2.00-3.00   sec  10.7 MBytes  89.5 Mbits/sec
[  5]   3.00-4.00   sec  9.07 MBytes  76.1 Mbits/sec
[  5]   4.00-5.00   sec  11.0 MBytes  92.0 Mbits/sec
[  5]   5.00-6.00   sec  10.4 MBytes  87.4 Mbits/sec
[  5]   6.00-7.00   sec  10.5 MBytes  88.5 Mbits/sec
[  5]   7.00-8.00   sec  10.5 MBytes  88.0 Mbits/sec
[  5]   8.00-9.00   sec  10.6 MBytes  88.6 Mbits/sec
[  5]   9.00-10.00  sec  10.4 MBytes  87.0 Mbits/sec
[  5]  10.00-10.11  sec  1.35 MBytes   100 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-10.11  sec   105 MBytes  87.3 Mbits/sec
eceiver
-----------------------------------------------------------
Server listening on 5201
```

Figure 29: iperf3 – (RPi 4 B) Wi-Fi 5 GHz throughput performance (Mbits/sec)

It is observed that RPi 3B, RPi 3B+ and RPi 4B introduced low Wi-Fi speed rate regarding 2.4 GHz most likely because of the Internet Service Provider (ISP) abilities and the type of the router which is a logical interpretation of the results. Contrary to Wi-Fi 2.4 GHz, the Wi-Fi 5GHz introduces significantly higher Wi-Fi speed rate at about 67% at RPi 3B+ and 73% at RPi 4B "Figure 30".

In summation, RPi 4B introduces remarkable better Ethernet throughput performance and decently better Wi-Fi 5GHz throughput performance in comparison with the other RPi's predecessors.

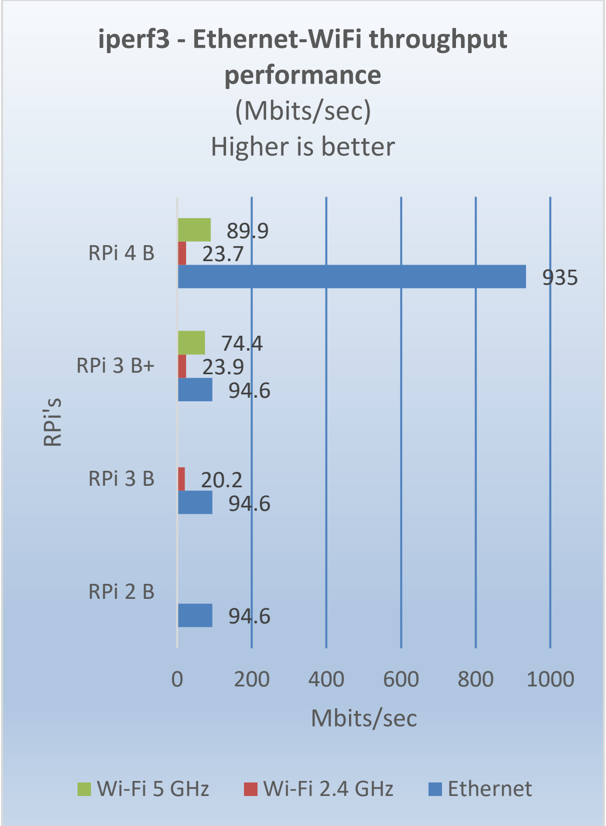


Figure 30: iperf3 – LAN and Wi-Fi 2.4 and 5 GHz throughput performance (Mbits/sec)

4. CONCLUSION

In this project, a benchmarking and review accomplished regarding the RPi 2B with (1GB ram) , RPi 3B with (1GB ram), RPi 3B+ with (1GB ram) and RPi 4B with (8GB) ram.

Regarding the CPU performance the RPi-4B introduces approximately a 51% improvement in the CPU performance compared to RPi-2B in 1&4&8 threads and compared with RPi-3B+ introduces approximately 24% in 1&4&8 threads improvement in the CPU performance. In particular with the HPL Linpack benchmarking "Figure 14", the RPi 4B introduces a remarkable performance in terms of GFlops and time execution but it was noticed that greater than 70% memory utilization lead the HPL test to crush compared with the other RPi's which reached 85% of system memory utilization.

Concerning the RAM memory testing, RPi 4B introduces better performance but not as expected considering that RPi 2B, RPi 3B, RPi 3B+ holds a DDR2 memory and RPi 4B holds a DDR4. On the other side, DDR4 memory is not compatible with any earlier type of random-access memory (RAM) due to different signaling voltages, physical interface, and other factors.

In terms of File, I/O benchmark, in overall, RPi 4B introduces a decent performance improvement in "random read-write" operation compared with the RPi's predecessors especially with USB 3.0 ports.

Last but not least, regarding the Ethernet and Wi-Fi throughput testing RPi 4B introduced low Wi-Fi speed rate regarding 2.4 GHz most likely because of the Internet Service Provider (ISP) abilities and the type of the router. Contrary to Wi-Fi 2.4 GHz, the Wi-Fi 5GHz introduces significantly higher Wi-Fi speed rate at about 67% at RPi 3B+ and 73% at RPi 4B "Figure 30". In addition, RPi 4B introduces remarkable better Ethernet throughput performance and decently better Wi-Fi 5GHz throughput performance in comparison with the other RPi's predecessors

5. FUTURE WORK

The RPi 4B (8GB) ram introduced in overall very good performance results and it is intended by the authors to be used in different cluster such as Beowulf, Hadoop, Spark and Kubernetes to see the cluster performance. Moreover, data mining algorithms are going to be tested in such a clusters architecture to evaluate the performance.

6. ACKNOWLEDGMENTS

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