1. Nurulidayu SAINUDDIN[1], 2. Juwita MOHD SULTAN[1], and 3. Mohamed AZUANI[2]

Centre for Telecommunication Research and Innovation (CeTRI),
Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer,
Universiti Teknikal Malaysia Melaka (1)
Balai Bomba dan Penyelamat Melaka Tengah, Melaka, Malaysia (2)

doi:10.15199/48.2023.01.07

Multi-core and Single-core Raspberry Pi Microprocessor's

***Abstract**. A multi-core processor is defined as an integrated chip that consists of two or more processors used for system performance enhancement, speed improvement, and multitasking performances. They collaborate to execute instructions faster than the single-core processor. Hence, this paper provides an overview of the evolution of the processor architecture and analysis of the multi-core processor's performance compared to the single-core processor. It highlights the difference in Central Processing Unit speed, memory bandwidth, power consumption, and the thermal effect on the CPU speed during throttling for single-core ARM11 with Broadcom BCM2835 and a quad-core Cortex-A72 with Broadcom BCM2711B0. Experimental results show that Cortex-A72 has a memory bandwidth of 29 times larger than the ARM11. The CPU speed benchmark indicates that Cortex-A72 is significantly faster and responds to the thermal throttling better than the ARM11 processor. However, as Cortex-A72 has more processing power, it has drawn more power than the ARM11 processor.*

Streszczenie.** Procesor wielordzeniowy jest definiowany jako zintegrowany układ składający się z dwóch lub więcej procesorów służących do zwiększania wydajności systemu, zwiększania szybkości i wydajności pracy wielozadaniowej. Współpracują, aby wykonywać instrukcje szybciej niż procesor jednordzeniowy. Dlatego niniejszy artykuł zawiera przegląd ewolucji architektury procesora i analizę wydajności procesora wielordzeniowego w porównaniu z procesorem jednordzeniowym. Pokazuje różnicę w szybkości jednostki centralnej, przepustowości pamięci, zużyciu energii i wpływie temperatury na szybkość procesora podczas ograniczania przepustowości dla jednordzeniowego ARM11 z Broadcom BCM2835 i czterordzeniowego Cortex-A72 z Broadcom BCM2711B0. Wyniki eksperymentów pokazują, że Cortex-A72 ma przepustowość pamięci 29 razy większą niż ARM11. Test porównawczy szybkości procesora wskazuje, że Cortex-A72 jest znacznie szybszy i lepiej reaguje na dławienie termiczne niż procesor ARM11. Ponieważ jednak Cortex-A72 ma większą moc obliczeniową, pobrał więcej energii niż procesor ARM11. (**Wielordzeniowe i jednordzeniowe mikroprocesory *Raspberry Pi*)

Keywords: Multi-core processor, Single-core processor, Central processing unit speed, Memory bandwidth, Thermal effect
Słowa kluczowe: prosessory wielordzeniowe, Raspberry.

Introduction

Processor design has been a big concern to most designers as processor performance plays an important role in enhancing computer speed. In the last few years, designers had introduced complex feature sets, increasing the CPU clock speeds, and increasing power dissipation. However, users' demand for increasing the processing speed and improving the system performance had fueled the initiative to combine multiple processors (multicore) to execute multiple tasks simultaneously, as studied by [1]. The conventional processor has only a single-core, the dual-core processor consists of two cores, while the quad-core processor has four cores and hexa-core has six cores. As mentioned by [2] a multi-core processor is defined as a parallel computing architecture that includes multiple core units that will read and write all the CPU instructions into a single chip. It has been proved by [3], that the overall performance of the multicore processor is better than the single-core processor as it manages to execute and handle several tasks in parallel.

The usage of a multicore processor can be utilized in several ways, which are homogeneous (symmetric) or heterogeneous depending on the application and user need. For homogeneous architecture, each core combined is identical, and they separate the overall computations and perform parallel processing to execute instructions. This application had shown an improvement in overall processor performance which has been studied by [4, 5]. Next, system performance refers to the time needed to run a specific task and can be measured as in equation (1) [6].

$$performance = instruction\ executed\ perclock\ cycle * frequency \quad (1)$$

Instruction executed per clock cycle and the frequency is an important indicator to evaluate the processor performance and both factors can enhance the processor performance proportionally. However, power consumption will be increased with the rise of the frequency value. The relation of the power and the frequency value can be described as in equation (2) [6]. The modern processor architecture has shown processor designers' effort in balancing the power by adjusting the voltage and the frequency with the instructions executed per cycle (by controlling the speed and the throughput) to achieve better performance and efficient power consumption

$$Power = Voltage * Frequency \quad (2)$$

Single-core Processor

The architecture of the processors has been further developed to offer users a significantly better experience in terms of performance, speed, multi-tasking ability, and efficiency. This section describes the architecture of the single-core processors and multi-core processors, along with their advantages and disadvantages. A single-core processor is a microprocessor that consists of a single core on a chip and can execute and compute a single thread at a time. A system with a single-core processor is expected to take a longer time to execute tasks, compared to the system with a higher number of cores in the processor, as proven in [6]. The evolution of the processor came after the emergence of multicore processors on a single chip that can run several tasks at a time. Fig. 1 shows the architecture of a single-core processor.

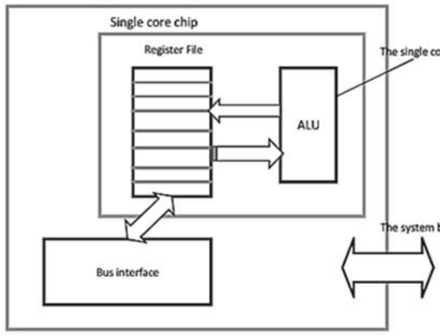

Fig.1. Single-core Processor Architecture [7]

The advantages and disadvantages of a single-core processor are summarized as; i) the power consumption is quite low. Hence, it is recommended to be used in a simple application that requires light processing, where a high-end computing system is not necessary. It also can be implemented in a low power application, such as an energy-harvesting application, and ii) cooler as it requires a smaller number of a van for cooling. Whereas the disadvantages of implementing a single-core processor are i) slow processing time, as a single CPU with a single-core processor takes more time than a multicore processor as it can handle a single thread or execute fewer tasks at a time, ii) lagging, as it cannot run a modern application that requires heavy computing that requires multiple core processing, and iii) the memory is small.

Multicore Processor

The multicore processor consists of multiple cores in one processor that helps in enhancing the overall processing performance and speed. More than one core is integrated into a single integrated circuit, and each core has its pipeline and resources to run various programs seamlessly. For instance, Intel CE 2110 Media consists of an Intel Xscale processor core and Intel Micro Signal Architecture (MSA) DSP core. Each of these cores possesses its specialty. Each core can run multiple threads simultaneously using the same memory, as illustrated in Fig. 2.

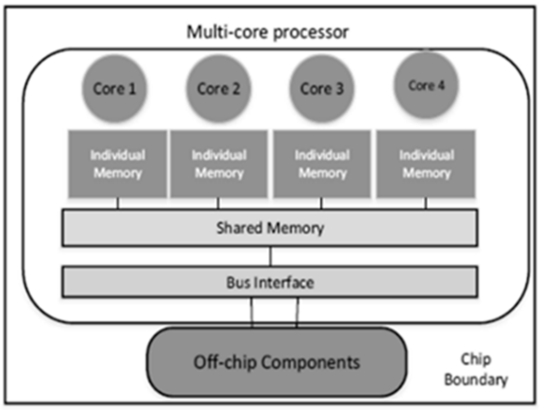

Fig. 2. Multicore processor architecture [8]

In this kind of architecture, multiple threads or programs can be executed simultaneously, which has been implemented by [9]. Hence, the processing speed can be further improved compared to a single-core processor. Advantages of multicore processor architecture are i) speed and performance are significantly better than a single-core processor, ii) allow computers to run multiple processes with greater ease, and enhance the performance by multitasking, and iii) complex computing and applications are preferred to be run in a system that implemented a multicore processor, as proven by [10]. However, there are a few disadvantages of multicore processor architecture, as mentioned by [11], that microprocessor faces power and thermal issues. Implementing multicores on a single chip might dissipate extra heat and consumes more power compared to a single CPU on a chip which can be solved by turning off the unused cores, ii) the interconnection and bus network needs to be improved. Hence, the time required to handle memory requests can be managed which leads to a better processing speed, iii) a parallel processing environment is necessary. In [12], the author had performed multithreading to run a few tasks simultaneously, iv) multithreading issues may arise such as starvation, especially when a program developed is required to be executed in a single thread in a multithread environment. This situation will lead to starvation, in which few threads may be left idle, and v) the process of writing and reading the different cores on the cache memory might cause a cache coherence problem [13, 14].

Quad-core Processor

Fig. 3 shows a quad-core processor as a new version of processor technology in which it contains four cores on a single chip, allowing multithreading to be performed in executing several tasks at once [15]. The quad-core processor had highlighted a greater processing performance, especially in terms of processing speed and execution time.

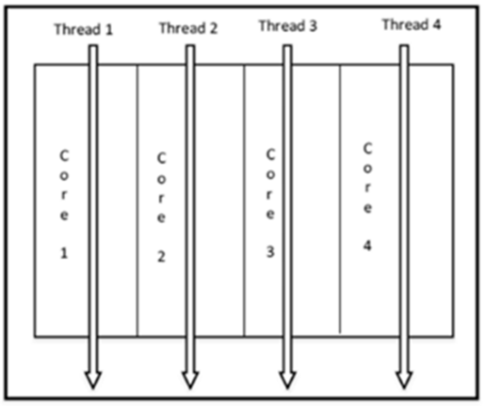

Fig.3. Quad-core processor architecture [8]

Advantages of quad-core processor architecture are i) improvement inability to execute tasks compared to a single-core and dual-core processor, ii) the ability to perform multitasking and multithreading in quad-core is better than dual-core processing performance and, iii) as this version was designed to be small, it dissipates less heat.

Related Work

Previous research and efforts had shown the implementation of a processor in modern applications, ranging from home automation projects as demonstrated in [16, 19]. The processor, or well-known as CPU, plays a major role in supplying the sets of instruction and processing power needed to the computer to complete its task. The recent processor is more updated and offers better performance, in terms of processing speed and power to complete given tasks. Processor designers had improved the processor design and architecture, which then introduced a multicore processor with a few versions; dual-core, quad-core, and Hexa-core processor. By introducing a multicore on a single CPU, the performance of the processor and its ability in computing can be improved.

Numerous research had shown the implementation of single-core and multi-core processors in modern applications, where each of these processors has its pros and cons. The author in [20] had presented an analysis on the single-core and multi-core processors by highlighting the influence of memory systems. In these findings, the size of the cache could certainly improve the processing performance. However, it was found that multicore processors might have a few limiting factors, such as communication overhead and memory latencies. Determining the suitable cache configurations could help in increasing the processor performance by taking the load off from the main memory, and hence reducing the communication and cache coherence latencies. Researcher [21] agreed that a multicore processor offers a better speed and processing performance however, a multicore processor could suffer from core-to-core communication issues and cache coherence. Some researchers had tried to improve the single-core processor performance to match the multicore processor performance by increasing the clock frequency. However, it leads to a rise in the power supply voltage, resulting in severe power and thermal crisis [22]. For heavy computing tasks, multicore processors have often been chosen over the single-core processor for their potential in enabling intensive real-time computation applications [23]. Multiple cores allow a computer to run multiple tasks simultaneously and increase performance by multitasking. In addition, multicore can perform scheduling, multithreading, and parallel programming. Each core on the multi-core processor does not necessarily run as fast as the high performed single-core processors, but the overall performance has been improved with parallelism.

CPU usage pictures how the processor in each machine or system is being utilized. In addition, it indicates the amount of stress that the processor is currently undergoing. CPU utilization is closely related to the speed of a computer or a system. The program or task execution time might be slowing down as the CPU has reached its maximum capacity [24]. The processing speed can be easily estimated by the CPU temperature as more heat will be dissipated during intensive processing activities. The processing speed will be degraded when the CPU is reaching to the threshold specified by the manufacturer as some of the running activities or programs will be disturbed [25]. Therefore, for a smooth processing process and better user experience, it is advised to choose a multicore processor over a single-core processor.

Methodology

This section will discuss the method in analysing the single-core and multi-core CPU's performance, which highlights the difference of these processors as mentioned in the previous section. This research will highlight the differences in these processors' performance in terms of CPU resources allocation and management, CPU speed, memory bandwidth, and thermal condition in response to an increasing workload and power consumption. Recent research has shown various approaches in analysing the single-core and multi-core system. These methods involve the use of compilers or software benchmarking tools such as High–Performance Linpack. In this research, a comparative analysis has been done on a single-core processor Raspberry Pi Zero with a quad-core processor, Raspberry Pi 4. Although many workloads are limited by the CPU speed, some rely on the memory bandwidth. Hence, it is necessary to measure the memory bandwidth to measure the read and write speed, as it is relevant to the speed at which the processor accesses data in RAM.

Raspberry Pi 4 has been redesigned with a 1.5GHz ARM CPU (Broadcom BCM2711B0 quad-core A72 (ARMv8-A)) and a 4GB RAM which offers a remarkable fast speed compared to its predecessors. This brand-new BCM2711B0 System-on-Chip (SoC) had not only boosted the processing speed but immensely enhance the bandwidth of memory and external hardware. In order to measure the CPU speed, the Linpack benchmark has been used. All the experiments had been done by stress-testing both of the processors and running the CPU at full power, in which a series of processes will be executed while monitoring the temperature and the stability of the system. As described in the Raspberry Pi datasheet [26], the optimum working temperature is within -25°C to 80°C before it starts throttling. Therefore, the processor will be run at full speed 1500MHz. Once the temperature reached 80°C, the thermal throttling started and hence, reducing the core clock speed. This mechanism helps to prevent the system from overheating and hardware damage, especially when a heatsink and cooling fan is not provided in the system [27].

The CPU stress-testing tools were used where all the cores were placed under a heavy and continuous load. A repetitive test with a fixed set of CPU instructions is created as the CPU's load. The fixed set of programs in the stress testing could demonstrate the thermal throttling occurrence over time. Even though workloads are restricted by CPU capacity and speed, some workloads are still relying on the memory bandwidth. Next, overall processors performance is also affected by the memory bandwidth. Memory bandwidth refers to the write and reads speed from the Random Access Memory (RAM). Hence, RAM Speed/SMP tool has been used in this research to measure each processor's memory bandwidth.

Results and Discussion

Many recent applications have implemented the usage of a multicore processor to perform parallel processing or multitasking to improve the overall system performance and enhance the processing speed. In order to evaluate the performance of the single-core processor and the quad-core processor, the CPU speed, memory bandwidth, CPU resources utilization, thermal effect on the CPU speed, and power is drawn have been taken into consideration. In this study, a stress test has been done on a single-core processor and a quad-core processor to assess the performance. In this testing, the processor is stress-tested by loading each of these processors with the same fixed set of programs, running at full speed. The results show the same trend line of CPU usage for all cores during the stress test in which it will reach a maximum utilization at the end of the stress test as the processor will be running heavier instructions over time. As the instructions executed become more complex and intensive, the CPUs will be required to do more work and the processor speed will be reduced.

Fig. 4 shows the CPU utilization of the first core of the quad-core processors when running 100 sets of instructions for 30 minutes during the stress test. The same usage can be seen in the third and fourth cores as shown in Fig. 5 and Fig. 6 respectively, in which the quad-core processors managed to handle their resources by dividing the workload among each core and succeed to execute all the given instructions smoothly at a full speed without freezing the program. Hence, the CPU can execute the instructions faster by multitasking and by performing load distribution among cores. Theoretically, a single-core processor may take a longer time to execute the same sets of instructions and may reach the maximum usage of CPU faster than the multicore processor. Therefore, a multi-core processor could provide a better performance and a higher processing speed.

This is because the multicore processor can perform parallel processing or multitasking, which results in a shorter execution time. All tasks will be shared among the cores and executed simultaneously. Meanwhile, in a single-core processor, only a single instruction can be executed at a single time, hence, the execution time is expected to be longer than the multicore processor. Therefore, it is advised to use a multi-core processor in the modern application that requires complex and heavy computation, as parallel processing in a multicore processor gives a major benefit in terms of performance and execution time.

The CPU temperature is closely related to the processing speed as the processor will freeze or slow down the running applications to ensure the CPU does not exceed the temperature threshold set by the manufacturer.

Therefore, CPU temperature can be used as the easiest indicator to estimate the processing speed. The normal operating temperature of the Raspberry Pi is between -25°C to +80°C [26].

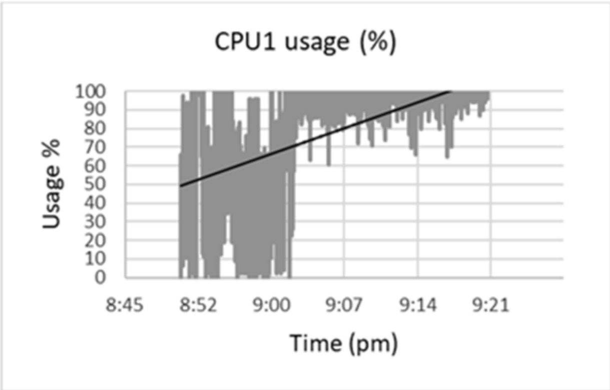

Fig. 4. Percentage of CPU1 usage to execute 100 sets of instruction

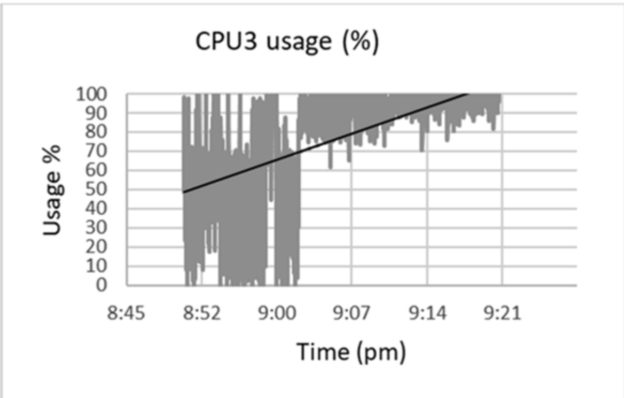

Fig. 5. Percentage of CPU3 usage to execute 100 sets of instruction

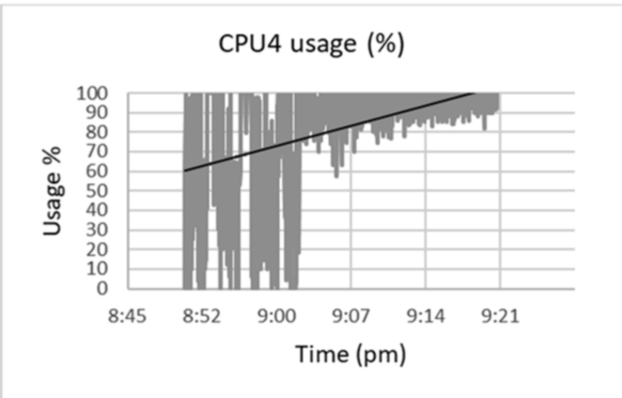

Fig. 6. Percentage of CPU4 usage to execute 100 sets of instruction

Besides, as the CPU temperature is reaching around 80°C to 85°C, the thermal throttling effect will take place as pictured in Fig. 8. As thermal throttling occurs, the CPU clock speed is reduced to minimize the generation of heat and prevent components damage. However, Raspberry Pi 4 managed to stay longer than the other processor before the heavy workload causes thermal throttle. During the heavy workload, the CPU speed is reduced which shows that the speed performance becomes slower as the SoC is getting hot. As the SoC temperature is reduced gradually, the processors perform at a better rate, resulting in an average speed up considerably.

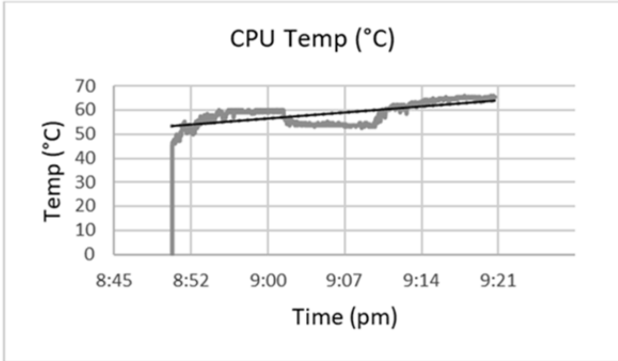

Fig. 7. CPU temperature during the stress test

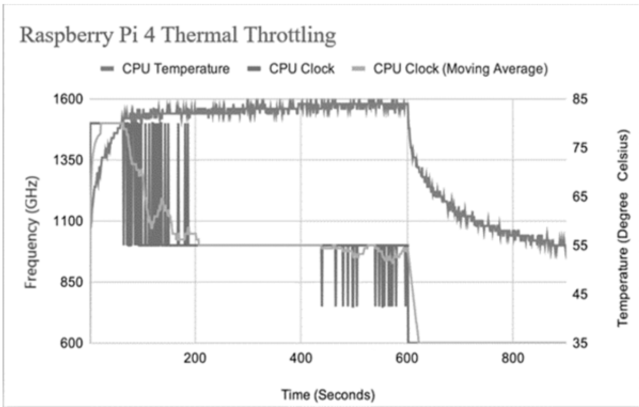

Fig. 8. Raspberry Pi 4 thermal throttling

Fig. 9 illustrates the Raspberry Pi Zero CPU speed and temperature changes during a heavy workload running on the system. The CPU reached a soft-throttles mark of 60°C faster than the Raspberry Pi 4 to avoid the SoC from reaching the maximum hard-throttle value, which is 80°C. Therefore, the remains are throttled and work at an average of 1.0 GHz during the stress test.

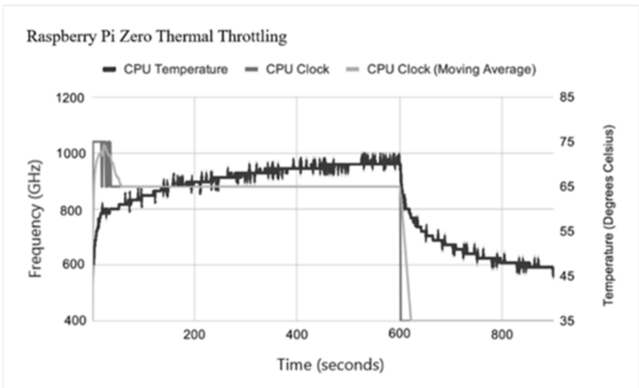

Fig.9. Raspberry Pi Zero thermal throttling

Next, it has been studied that the random-access memory (RAM) will allow the CPU to access files faster. In addition, it will help the processor to execute more programs simultaneously. A multicore processor often comes with a larger RAM or memory size compared to a single-core processor. The larger size of RAM will provide faster RAM cycles in MHz; therefore, more processes can be run. Fig. 10 depicted the memory usage of the Raspberry Pi 4 during the stress test. It shows that the processor has not used the overall memory spaces to execute the 100 sets of tasks, leaving more spaces for the processor to run other sets of instructions.

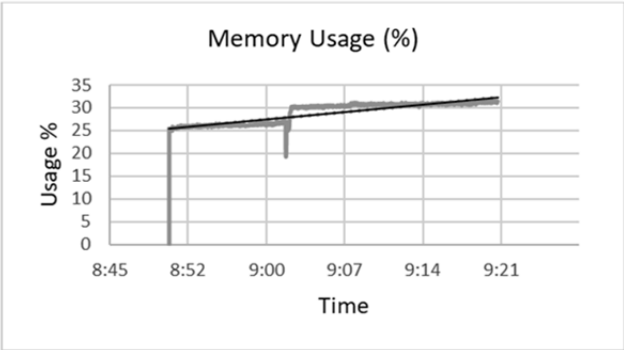

Fig.10. Memory usage of the quad-core processor

As a benchmark for the CPU speed during the stress testing, the Linpack benchmark has been used to compare the CPU speed of both processors. The Linpack benchmark is a test problem used to rate the performance of a computer on solving a simple linear algebra problem and can be used as a measurement of a system's floating-point computing power that measures the speed of a computer. As the number and type of instructions used in the benchmarks are known, performance results can be easily converted to Millions of Instructions per Second (MIPS) or Millions of Floating-Point Operations per Second (MFLOPS). The floating-point number can be represented in two ways; Single Precision (SP) and Double Precision (DP). Single Precision is a format proposed by IEEE for the representation of the floating-point number that occupies 32 bits in the computer memory while Double Precision is a representation of the floating-point number that occupies 64 bits in computer memory. The Linpack Single Precision and Linpack Double Precision benchmark are the standard measures of floating-point performance, which can measure Millions of Floating-Point Instructions per Second (MFLOPS). Next, Arm Neon technology is an advanced Single Instruction Multiple Data (SIMD) architecture extension for the Arm Cortex-A and Cortex-R series processors. Neon registers are considered as vectors of elements of the same data type in which Neon instructions operate on multiple elements simultaneously. Multiple data types are supported by the technology, including floating-point and integer operations as featured in Raspberry Pi 4.

The benchmark testing was done on the Raspberry Pi Zero running at 1GHz and the Raspberry Pi 4 running at 1.5GHz. As illustrated in Fig. 11, the Raspberry Pi 4 shows a great difference in CPU speed compared to Raspberry Pi Zero. Raspberry Pi Zero rated at 64.47 MIPS and 40.38 MIPS for single precision and double precision respectively. Whereas Raspberry Pi 4 rated at 925.47 MIPS, 748.73 MIPS, and 2037.33 MIPS for single precision, double precision, and Neon single precision respectively. Therefore, Raspberry Pi 4 could give a better processing speed and could handle a higher workload compared to the other processor.

However, heavy computing and bigger processing power might be drawing a lot more power. The implementation of a multicore processor may lead to a rise in power consumption compared to the system that is using a single core processing unit. Hence, it is preferable to use a single-core processor in a system that works on low power and requires a simple processing task. In this analysis, it has been found that idle power drawn from the Raspberry Pi 4 is 3.4 Watts while the load power drawn is 4.4 Watts. As shown in Fig.12, Raspberry Pi Zero withdraws a lower idle power and load power than Raspberry Pi 4, which are 0.8 Watts and 1.5 Watts simultaneously.

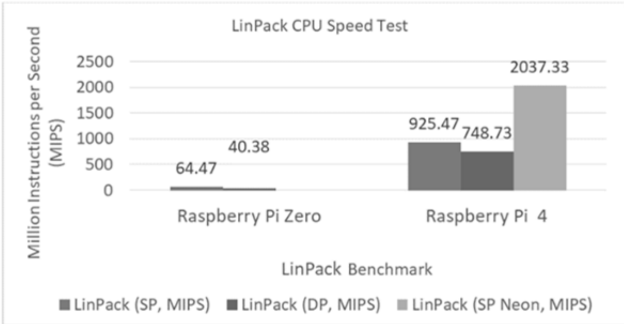

Fig.11. LinPack CPU test

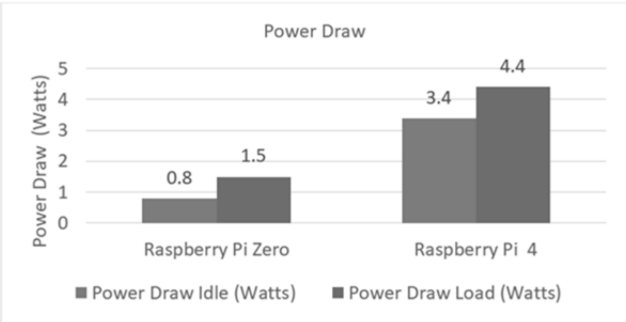

Fig.12. Power Drawn by Raspberry Pi Zero and Raspberry Pi 4

Besides, to benchmark the memory bandwidth of both processors, the RAM Speed utility has been used. As pictured in Fig.13, Raspberry Pi 4 with a quad-core processor can read and write to the RAM faster than the Raspberry Pi Zero. In another word, the Raspberry Pi 4 could transfer the data at a higher speed. Raspberry Pi 4 could read at 4129.83 Mbps and write to the RAM at 4427.18Mbps. However, Raspberry Pi Zero could only read and write at 142.17 Mbps and 253.78 Mbps rates simultaneously.

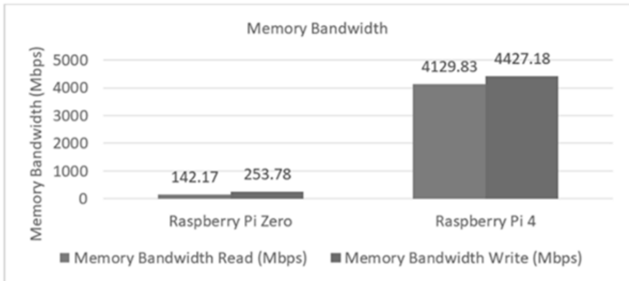

Fig.13. Comparison of memory bandwidth between Raspberry Pi Zero with Raspberry Pi 4

Summation

Processor designers have improved the conventional processor architecture by introducing a new generation of a central processing unit. Each generation as its performance and processing speed improved. Few actors may affect the CPU performance, such as the number of cores, cache memory, clock speed, address bus width, and data bus width. Other parameters that may influence the efficiency and performance of the multi-core system are RAM size, parallelism issues, power, and thermal issues. This paper provides an overview of the evolution of the cores of the processors and an analysis of the multi-core processor's performance. Results show that increasing the number of cores in a single chip or circuitry may not necessarily give an improvement in terms of performance and speed, depending on the application. Since more applications and programs have implemented the usage of a multicore processor for its benefits, the users may face a few challenges in terms of designing and balancing the performance quality.

Acknowledgements

The authors would like to acknowledge the support of this work by the Universiti Teknikal Malaysia Melaka and the Fire and Rescue Department of Malaysia under the research grant of PJP/2020/FKEKK/HI21/S01719 and the facility support provided by the Broadband and Networking (BBNET) Research Group, UTeM.

Authors: *Dr Juwita Mohd Sultan, Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer, Universiti Teknikal Malaysia Melaka.Email: juwita@utem.edu.my.*
Nurulisayu Sainuddin. Email: dayudyaz@gmail.com. Mohamed Azuani. Email: black.kubu@gmail.com.

REFERENCES

[1] Wang, L., Tao, J., von Laszewski, G. and Marten, H, Multicores in Cloud Computing: *Research Challenges for Applications. JCP*, vol. 5, no. 6, pp. 958-964, 2010.

[2] Valerievich, Bakulev Aleksandr, Pyurova Tatiana Anatolievna, Bakuleva Marina Alekseevna, Skvortsov Sergei Vladimirovich, Kozlov Maksim Aleksandrovich, and Hrukin Vladimir Ivanovich, "Modern Approaches to the Development Parallel Programs for Modern Multicore Processors," in *6th Mediterranean conference on embedded computing (MECO)* on IEEE, 2017, pp. 1-4.

[3] Manumachu, R.R. and Lastovetsky, A, "Bi-Objective Optimization of Data-Parallel Applications on Homogeneous Multicore Clusters for Performance and Energy," *IEEE Transactions on Computers*, 2017, vol. 67, no. 2, pp. 160-177.

[4] Liu, L. and Qi, D, "An Independent Task Scheduling Algorithm In Heterogeneous Multi-Core Processor Environment," *IEEE 3rd Advanced Information Technology, Electronic and Automation Control Conference*, pp. 142-146, 2018.

[5] Rupanetti, D. and Salamy, H. "Task Allocation, Migration and Scheduling for Energy-Efficient Real-Time Multiprocessor Architectures," *Journal of Systems Architecture*, vol. 98, pp. 17-26, 2019.

[6] Rinku, Dhruva R., and M. Asha Rani, "Analysis of Multi-Threading Time Metric on Single and Multi-Core Cpus with Matrix Multiplication," in *Third International Conference on Advances in Electrical, Electronics, Information, Communication, and Bio-Informatics*, pp. 152-155, 2017.

[7] Rakhee Chhibber and R.B.Garg, "Multicore Processor, Parallelism and Their Performance Analysis," *International Journal of Advanced Research in Computer Science & Technology*, pp.112-121,2009.

[8] De Pestel, S., Van den Steen, S., Akram, S. and Eeckhout, L, "RPPM: Rapid Performance Prediction of Multithreaded Applications on Multicore Hardware," *IEEE Computer Architecture Letters*, vol. 17, no. 2, pp. 183-186, 2018.

[9] Liao, S.L., Liu, B.X., Cheng, C.T., Li, Z.F. and Wu, X.Y," Long-Term Generation Scheduling of Hydropower System using Multi-Core Parallelization of Particle Swarm Optimization," *Water Resources Management*, vol. 31, no. 9, pp. 2791-2807, 2017.

[10] Tyagi, S.K.S., Jain, D.K., Fernandes, S.L. and Muhuri, P.K, "Thermal-Aware Power-Efficient Deadline Based Task Allocation in Multi-Core Processor," *Journal of Computational Science*, vol. 19, pp. 112-120.

[11] Sethi, A. and Kushwah, "Multicore Processor Technology-Advantages and Challenges," *International Journal of Research in Engineering and Technology*, vol. 4, no. pp. 87-89, 2015.

[12] Juyal, C., Kulkarni, S., Kumari, S., Peri, S. and Somani, A, "Achieving Starvation-Freedom with Greater Concurrency in Multi-Version Object-based Transactional Memory Systems," *In International Symposium on Stabilizing, Safety, and Security of Distributed Systems*. Springer, pp. 209-227. 2019.

[13] Hassan, M., Kaushik, A.M. and Patel, "Predictable Cache Coherence for Multi-Core Real-Time Systems," in *IEEE Real-Time and Embedded Technology and Applications Symposium*, pp. 235-246, 2017.

[14] Gonzalez, C., Floyd, M., Fluhr, E., Restle, P., Dreps, D., Sperling, M., Rao, R., Hogenmiller, D., Vezyrtis, C., Chuang, P. and Lewis, D., "The 24-Core POWER9 Processor with Adaptive Clocking, 25-Gb/S Accelerator Links and 16-Gb/S Pcie Gen4," *IEEE Journal of Solid-State Circuits*, vol. 53, no. 1, pp. 91-101, 2017.

[15] Zeebaree, S.R., Haji, L.M., Rashid, I., Zebari, R.R., Ahmed, O.M., Jacksi, K. and Shukur, H.M., "Multicomputer Multicore System Influence on Maximum Multi-Processes Execution Time," *TEST Engineering & Management*, vol. 83, no. 3, pp. 14921-14931, 2020.

[16] Manda, V.B., Kushal, V. and Ramasubramanian, N, "An Elegant Home Automation System Using GSM and ARM-Based Architecture," *IEEE Potentials*, vol. 37 no. 5, pp. 43-48, 2018.

[17] Chen, C., Xiang, X., Liu, C., Shang, Y., Guo, R., Liu, D., Lu, Y., Hao, Z., Luo, J., Chen, Z. and Li, C, "A Commercial Multi-Core 12-Stage Pipeline Out-Of-Order 64-Bit High Performance Risc-V Processor with Vector Extension: Industrial Product," in 2020 *ACM/IEEE 47th Annual International Symposium on Computer Architecture*, pp. 52-64'

[18] Bartók, R. and Vásárhelyi, J. "Parallelization of FIVE Method on Multicore Embedded System," in 2018 19th *International Carpathian Control Conference on IEEE*, pp. 400-403, 2018.

[19] Bui, J., Xu, C. and Gurumurthi, S. "Understanding Performance Issues on Both Single Core and Multi-Core Architecture," *Computer Organization*, pp. 1-8, 2007.

[20] Mohanty, R.P., Turuk, A.K. and Sahoo, B. "Analyzing the Performance of Multi-Core Architecture", *1st Int. Conf. On Computing, Communication and Sensor Network*, CCSN-2012.

[21] Tyagi, S.K.S., Jain, D.K., Fernandes, S.L. and Muhuri, P.K. 2017. Thermal-Aware Power-Efficient Deadline Based Task Allocation in Multi-Core Processor," *Journal of Computational Science*, vol. 19, pp. 112-120, 2012.

[22] Xiao, J., Altmeyer, S. and Pimentel, A, "Schedulability Analysis of Non-Preemptive Real-Time Scheduling for Multicore Processors with Shared Caches," in *2017 IEEE Real-Time Systems Symposium*, pp.199-208, 2017.

[23] Valery, O., Liu, P. and Wu, J.J, "A Collaborative CPU–GPU Approach for Principal Component Analysis on Mobile Heterogeneous Platforms," *Journal of Parallel and Distributed Computing*, vol. 120, pp. 44-61, 2018.

[24] Benoit-Cattin, T., Velasco-Montero, D. and Fernández-Berni, J., "Impact of Thermal Throttling on Long-Term Visual Inference in a CPU-Based Edge Device," *Electronics*, vol. 9, no. 12, pp. 2106, 2020.

[25] N.Sainudin, J.M Sultan, F.Idris and M.Azuani, "Data Collision and Interference Minimization in Wireless Sensor Network using Node Data Addressing with Random Access Time", *Jurnal Kejuruteraan*, Vol 33(4), pp.1105-1112, 2021.

[26] Raspberry Pi Compute Module 3+ Lite, 9 Raspberry Pi (Trading) Ltd, viewed 16 Mei 2021, URL:https://www.raspberrypi.org/

[27] Z.Hamadouche, M.Khiat, A. Chaker, "Nonlinear Controllers Design for Plug-in Hybrid Electric Vehicle", Prezeglad Elektrotechniczny, vol. 6 ,p. 149, 2022.