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On the historical evolution of the performance *versus* cost ratio of Raspberry Pi computers

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Résumé
This article aims to analyze the historical evolution of the cost/performance ratio of the *Raspberry Pi* family of computers, given their representativeness in the field of single-board computers. While comparing the cost/performance ratio of different models of single-board computers is not a new idea, there are no studies focused on evaluating the performance evolution and associated costs of all generations of the *Raspberry Pi B line*. Our analysis considered all generations of *Raspberry Pi B line* available on the market until 2023, and we adjusted computer prices based on the 2012 dollar value, the year of the first *Raspberry Pi*'s launch. The results indicate a clear trend of increasing performance over time, accompanied by a tendency for the price paid for performance to decrease. This reduction becomes even more pronounced when considering the depreciation of the dollar compared to its value in 2012.

Mots-clés : Performance Analysis, Raspberry PI, Cost/Performance Ratio

1. Introduction

The emergence of single-board computers has made it possible to offer a multitude of different applications, ranging from the monitoring of household appliances [6] to the control of improvised mechanical fans for the emergency treatment of severe cases of COVID-19 [1]. Undoubtedly, the main driver of the widespread use of single-board computers has been the advent of the *Raspberry Pi*, whose first version was launched on the market in 2012 and the most recent in 2019 [9]. Moreover, the *Raspberry Pi* is by far the most commercially performant single-board computer, with approximately 30 million units sold in December 2019 [22]. However, the greatest contribution of these devices has probably been the ability to continuously collect data from sensors installed directly in various types of environments (such as forests [11], hospitals [14], and shopping centers [18]), and in a transparent manner from the point of view of the system's users.

Due to the low processing power initially offered by the early models of *Raspberry Pi*, the collected data was sent to be processed in the cloud, which has virtually infinite processing power [5]. However, it was soon realized that this alternative presented the disadvantage of a considerable increase in latency in receiving raw data by the cloud, and in returning processed data to the *Raspberry Pi* [12]. For this reason, the scientific community began to search for alternatives to the "**all-in-the-cloud**" solutions.

This effort led to the emergence of "**edge computing**", which proposes to use resources on the periphery of the network (such as local servers and routers) and to execute tasks [21]. Simultaneously, the evolution of the capabilities of single-board computers (in terms of CPU, memory, and network) has resulted in these devices now having much more power than necessary for the collection and transmission of sensor data. Thus, a legitimate question has arisen as to the possibility of using the excess capacities of such computers installed pervasively in the environment as nearby resources for task execution [7].

However, in order to have a good understanding of the possibilities and limitations offered by these devices, it is necessary to understand their performance and the costs associated with their performance. In parallel, an understanding of their historical evolution can help identify or confirm trends, which is also useful in planning the desired capacity for infrastructures or applications.

Given the representativeness of the *Raspberry Pi* family of computers, any study on the capacity of single-board computers for the execution of a particular type of application should include them. To our knowledge, although the idea of comparing the cost/performance ratio of different models of single-board computers is not necessarily new [8], there are no studies focused on evaluating the historic evolution of the cost/performance ratio of the *Raspberry Pi* family of computers. In this article, we attempt to fill this gap and provide a comparison of the cost/performance ratio of several generations of *Raspberry Pi* computers using inflation-adjusted dollar values.

In continuation, this article is organized as follows : Section 2 presents the state of the art. Section 3 describes the objectives, as well as the methodology used. Section 4 presents the results obtained, while Section 5 concludes this article by presenting the conclusions and indications of future work.

2. State of the Art

Since the release of the first generation of *Raspberry Pi* and subsequent boom of **Single Board Computers (SBC)**, several studies have evaluated the performance of these computers in various domains of applicability. For example, [10] evaluated the maximum processing capacity of a first-generation *Raspberry Pi* cluster in terms of billions of **FLoating-point Operations Per Second (GFLOPS)**, the network bandwidth in **Megabits per second (Mbps)**, and also the I/O performance of the disk system in **megabytes per second (MB/s)**. Additional works, such as [4], performed similar tests on other *SBC*s, but also evaluating the performance of the RAM system during communication between pairs of Message Passing Interface (MPI) application processes.

The authors of [15] compared the performance of a *Raspberry Pi* cluster to a power-efficient *Next Unit of Computing (NUC)* and a *Mid-Range Desktop (MRD)* on three leading cryptographic algorithms (*AES*, *Twofish*, and *Serpent*) and assessed the general-purpose performance of the three systems using the **High-Performance Linpack (HPL)** benchmark, measuring the performance of these systems in *GFLOPS*. This work is interesting because it compares *Raspberry Pi* to other systems and also tests an important and current application. However, this work is focused on only one version of *Raspberry Pi* and uses only one performance metric.

Other studies, such as [3] and [20], have been concerned with verifying the performance of *Raspberry Pi* or similar computers in big data applications that include a large number of disk read and write operations. In our study, we chose not to evaluate the performance evolution in disk read and write operations in *Raspberry Pi*, as we understand that such variations in performance depend heavily on the *SD* cards used, which are an external item not provided by default with *Raspberry Pi*.

Finally, [19] evaluated the performance of *Raspberry Pi 2* and another *SBC* for Hadoop applications, using performance benchmarks for task execution time, memory/storage utilization, network throughput, and energy consumption. The most interesting part of this study is that they investigated the cost of operating *SBC*-based clusters by correlating energy utilization for the execution time of various benchmarks using workloads of different sizes. This approach is interesting as a method to determine the evolution of the cost performance ratio of *SBC*s for specific applications. However, their method is focused on a single-use case and only considers one model of *Raspberry Pi*. In this work, we aim to examine the performance evolution of all major components of an entire segment of *Raspberry Pi* computers.

Subsequently, studies appeared that evaluated not only the performance of *Raspberry Pi* but also the cost associated with the performance obtained. For example, [8] evaluated the performance of 17 different types of *SBC*s, including *Raspberry Pi 1B*, *2B*, and *3B*. It evaluated the performance of these systems in terms of *GFLOPS* and energy consumption in Watts (W). However, it also calculated the dollar/*GFLOPS* ratio of each of these systems and the energy cost in *W* per *GFLOPS* obtained. [16] did a similar work, also considering the performance of memory and network systems as well as the energy consumption of both. Although interesting, these studies do not highlight the evolution of *Raspberry Pi* systems, nor do they compare the cost in dollars of each equipment using a single reference year for the dollar. In the case of [16], evaluations are made exclusively on virtualized systems, which certainly adds an additional overhead and implies not achieving the maximum possible performance of the evaluated systems.

However, none of the works mentioned in this section used all generations of *Raspberry Pi* in their studies or considered the depreciation of the dollar over time in metric calculations. In this work, we consider all of this. Complementary information about the studies cited in this state-of-the-art are shown in 3 in the Appendix A.

In the next section, we describe the experimental method used in this work.

3. Objectives and Experimental Methodology

The overall objective of this work is to obtain an overview of the historic evolution of *Raspberry Pi*'s capabilities, as well as the relationship between acquisition cost and performance offered. Specifically, we aim to :

1. Verify the evolution of the maximum processing capacity of different *Raspberry Pi* models in terms of *GFLOPS*, and the cost in dollars per *GFLOPS* ;
2. Verify the evolution of available memory capacity, and the cost in dollars per *MB* ;
3. Verify the evolution of communication capacity of the main memory, in terms of bandwidth (in *Mbps*) and communication latency (in *s*), as well as the cost in dollars of maximum bandwidth ; and
4. Verify the evolution of communication capacity in the local network, in terms of bandwidth (in *Mbps*) and communication latency (in *s*), as well as the cost in dollars of maximum bandwidth.

3.1. Choice of *Raspberry Pi* Models

For this study, we limit ourselves to *Raspberry Pi* models of type *B* that are (or were) sold for a nominal value of $35. These devices were chosen for the following reasons :

1. *B* models are the main line of *Raspberry Pi*, always launched before *A* models or other spin-offs such as *Zero* models ;
2. It is the line that has the most generations of devices. It has 4 generations, compared to 3 generations of the *A line*, and two of the *Zero line* ; and
3. The launch price of *B* models has always been $35, while the launch price of *A* models has been variable.

The only exception to this rule is the *Raspberry Pi B4-2GB* which was initially launched at $45 and quickly saw its price reduced to $35, while the *Raspberry Pi 4-1GB* was quickly withdrawn from the market. Therefore, we consider the *Raspberry Pi B4-2GB* as the entry model for this generation. Complementary information about the evaluated models, as well as their most relevant characteristics, is presented in Table 1 in the Appendix A.

3.2. Value of the Dollar

Although the nominal selling value of *Raspberry Pi B* models remained at $35 at the time of their launch, the actual value of the dollar changed during the period from 2012 to 2019. This means that the launch value of different *Raspberry Pi* models has also undergone variations. In this research, we updated the value of the dollar at the time of the release of each *Raspberry Pi* model to the value of the dollar on March 31, 2023, and used this value to establish cost-performance relationships. The dollar values were obtained through the Bureau of Labor Statistics [1] , an official agency of the U.S. government. The last two lines of the Table 1 in Appendix A below shows the acquisition cost of each of the *Raspberry Pi* models used in this study in 2022 dollars.

3.3. Benchmarks Used and Tests Performed

To measure the computing performance of all *Raspberry Pi* models used in this study, we used the *HPL* benchmark. *HPL* measures the *Flops* performed by a computing system during a linear equation system resolution [23]. We chose *HPL* because it is the default benchmark used by the TOP500 ranking of the most powerful supercomputers in the world, and it is the standard method to estimate the computing performance of computer systems [17].
To run the *HPL* benchmark effectively and achieve the maximum possible performance results, some parameters need to be specified and tested with variations. Some of the main parameters include the linear system order used by *HPL* (*N*), the processor grid topology (*PxQ*), the blocking factor used for the matrix distribution (*NB*), and other configurable parameters. Since the *N* size is crucial for obtaining good performance with *HPL*, we ran *HPL* using 75%, 85%, and 95% of the available memory capacity for each *Raspberry Pi* model. This allowed us to obtain a good indication of the maximum processing performance of each model. The optimal value of *NB* depends on several factors, including the architecture of the processor and the size of the matrix being solved. Complementary information about the values used for the *HPL* mentioned parameters in each *Raspberry Pi* model used are shown in Table 2 in Appendix A.

To measure the bandwidth and the lacency of the memory system as well as the network system of each *Raspberry Pi* model we used the **Network Protocol Independent Performance Evaluator (NetPIPE)** benchmark. NetPIPE monitors network overhead using protocols such as TCP,

1. https ://www.bls.gov/data/inflation_calculator.htm

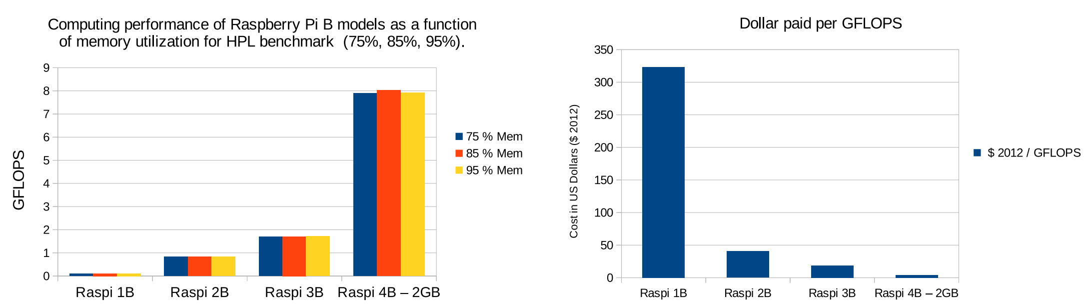
UDP, and MPI [10]. It performs simple ping-pong tests, sending and receiving messages of increasing size between a few processes, whether across an Ethernet-connected cluster or within a single multicore system [4].

3.4. Other considerations

All *Raspberry Pi*s used in this study use *Raspbian 5.15* as the operating system. Additionally, all of them have the *Atlas 3.16* linear algebra library and use *OpenMPI 4.0.6* . The first library may influence the performance obtained by *HPL*, while the second may influence the performance of both *HPL* and *NetPIPE*.
Finally, none of the *Raspberry Pi*s use ventilation systems. This measure was adopted to reduce costs, and also because one of the central ideas of these devices is that they are already sold 100% ready to use. Therefore, it is also expected that the results obtained during the benchmark execution represent the maximum performance of these devices under these conditions, and not necessarily the theoretically possible maximum performance.

4. Results

In this section, we present the analysis of the data obtained from the execution of benchmarks on each model of *Raspberry Pi*.



(a) Performance evolution

(b) Cost per GFLOPS evolution

FIGURE 1 – Computing Performance

Initially, let us analyze the evolution of the processing capacity of *Raspberry Pi*. Figure 1(a) below shows the **highest result obtained** after the execution of *HPL* on each model of *Raspberry Pi*, while Figure 1(b) shows the cost in dollars per *GFLOPS* of performance provided by each model of *Raspberry Pi*. From the analysis of both figures, it is possible to conclude that the *Raspberry Pi* shows a progressive increase in processing power, while the cost per such processing decreases steeply. It is interesting to note that the performance gain from the second to the third generation of *Raspberry Pi* is 100%, while the performance gain from the third generation to the fourth is 400%. A possible explanation for this discrepancy would be the change in RAM technology used, as the fourth generation *Raspberry Pi* uses *LPDDR4*, while the *3B* model still uses *LPDDR2* technology.

Figure 2 shows the evolution of the cost in dollars of each *MB* of memory included in each model of *Raspberry Pi*, while figures 3(a) and 3(b) respectively show the evolution of memory bandwidth and latency in communication between pairs of processes that are located on the

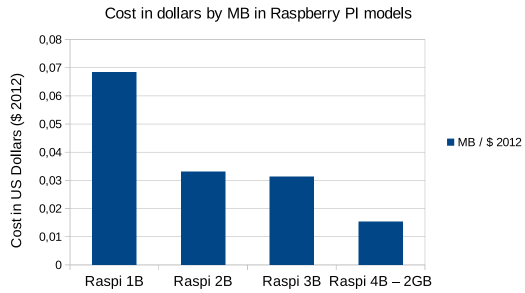
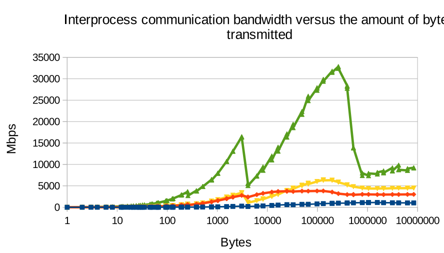
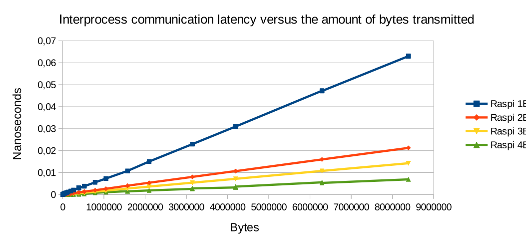


FIGURE 2 – Cost per MB

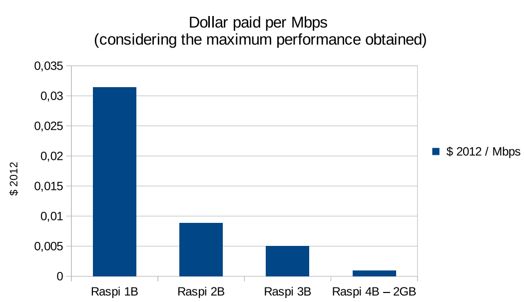
same device and using the *MPI* protocol. Finally, Figure 4 shows the evolution of the cost in dollars paid to obtain the highest possible memory bandwidth (peak value of each data series in Figure 4). Analyzing these figures, it is possible to see that even though there is a constant evolution from one generation to another of *Raspberry Pi*, it is the fourth generation that presents an extraordinary performance leap, with a bandwidth 600% higher than the preceding generation and with latency an order of magnitude lower. Finally, this is also reflected in the cost-benefit ratio.



(a) Bandwidth



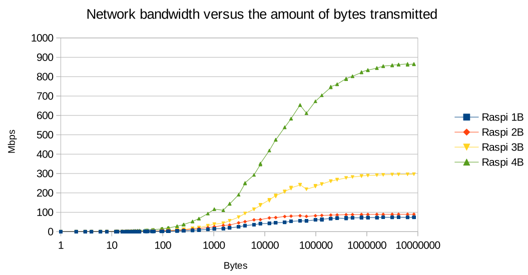
(b) Latency



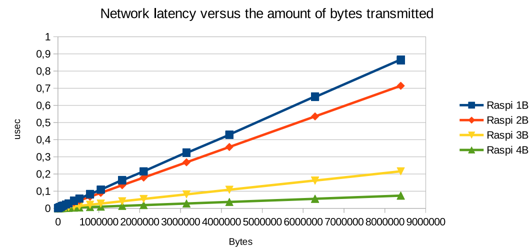
(c) Cost per Mbps

FIGURE 3 – Evolution of IPC communication performance and costs

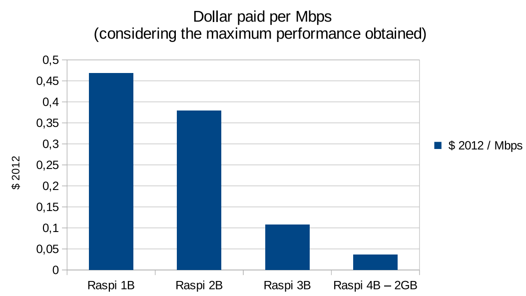
Figures 4(a) and 4(b) show the evolution of bandwidth and latency in communication between pairs of processes located on different devices and using an Ethernet network to communicate using *MPI*. Finally, figure 4(c) shows the evolution of the cost in dollars paid to obtain the highest possible memory bandwidth (peak value of each data series in Figure 4(a). The analysis



(a) Bandwidth



(b) Latency



(c) Cost per Mbps

FIGURE 4 – Evolution of network performance and costs

of this data shows an evolution of performance of the order of 1000% between the first and fourth generations, confirming the trend of a dramatic reduction in the cost paid for the offered performance.

Finally, based on the idea that *Raspberry Pi* represents the general trend of the *SBC* market, it is interesting to note that the evolution of the performance of such systems does not necessarily perfectly follow *Moore*'s Law, unlike what is observed in the PC and Laptop markets. The performance leap from the third to the fourth generation was greater than expected. However, more in-depth studies are needed to confirm or refute this assertion.

5. Conclusion

In this work, we present a comparative analysis of the performance evolution of the *Raspberry Pi* computer family's *B line* and the costs associated with this performance. The analysis considered all generations of *Raspberry Pi* available on the market until the submission date of this article to Compas 2023, and computer prices were adjusted based on a single dollar value : the 2012 dollar, the year of the first *Raspberry Pi*'s launch.

The results indicate a clear trend of increasing performance over time, accompanied by a tendency for the price paid for performance to decrease. This reduction becomes even more pronounced when considering the depreciation of the dollar compared to its value in 2012.

As future work, we plan to extend the experiments to all *Raspberry Pi* models that have been released. Additionally, we also intend to redo the tests and observe the energy consumption of each *Raspberry Pi* model during the execution of each test to observe the relationship between energy consumption and performance obtained.

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A. Appendix I - Tables

TABLE 1 – *Raspberry Pi* main hardware evolution and prices

Model	**1B**	**2B**	**3B**	**4B (2 GB)**
Release Year	2012	2014	2018	2019
SoC	BCM2835	BCM2836	BCM2837	BCM2711
Processor	ARM1176JZF-S	Cortex-A7	Cortex-A53	Cortex-A72
Arch.	Arm-v6 / 32 bit	Arm-v7 / 32 bit	Arm-v8 / 64 bit	Arm-v8 / 64 bit
Number of Cores	1	4	4	4
Core Freq. (MHz)	700	900	1400	1800
Mem. (GB)	0,5	1	1	2
Mem. Type	DDR 2	LPDDR 2	LPDDR 2	LPDDR 4
Ethernet	Fast / 100 Mbps	Fast / 100 Mbps	Gigabit / 300 Mbps	Gigabit / 1000 Mbps
Wifi	-	-	802.11b/g/n	802.11ac
Release Price	35	35	35	45 (35)
Release Prize Adjusted to 2022	35	33.92	32.01	31.52

TABLE 2 – Values used for the main *HPL* parameters

	1B	**2B**	**3B**	**4B 2 GB**
N	5396 5745 6073	8852 9424 9963	8500 9049 9566	12812 13640 14220
NB	64 128 192 256	64 128 192 256	64 128 192 256	64 128 192 256
PxQ	1x1	1x4 4x1 2x2	1x4 4x1 2x2	1x4 4x1 2x2

TABLE 3 – State of the art

Parameters x works	**This work**	[10]	[4]	[3]	[13]	[16]	[8]	[15]	[2]}	[19]
Single CPU performance (GFLOPS)	-	-	x	-	-	-	-	-	-	-
Max CPU performance (GFLOPS)	x	x	x	-	-	x	x	x	x	-
Cost/CPU performance (dollars/GFLOPS)	x	-	-	-	-		x	-	x	-
Adjust costs considering inflation	x	-	-	-	-		-	-	-	-
Cost/Memory size (dollars/GB)	x	-	-	-	-		-	-	-	-
Memory bandwidth (Mbps)	x	-	x	-	-	x	x	-	-	-
Cost/max memory bandwidth (dollars/Mbps)	x	-	-	-	-		-	-	-	-
Memory latency (µs)	x	-	x	-	x	-	-	-	-	-
Network bandwidth (Mbps)	x	x	x	-	x	x	-	-	-	x
Cost/max network bandwidth (dollars/Mbps)	x	-	-	-	-	-	-	-	-	-
Network latency (µs)	x	-	x	-	x		-	-	-	x
Resource sharing effects	-	-	x	x	-		-	-	-	-
Energy-efficiency (GFLOPS/Watt)	-	-	-	-	-	x	x	-	x	x
Energy-consumptiom cost in dollars (dollars/Watt)	-	-	-	-	-	-	x	-	x	-
Other metrics (domain-specific)	-	-	-	-	-	x		x	x	x
Disk I/O performance (MB/s)	-	x	-	-	x	-	-	-	-	x
Raspberry Pi 1	x	x	-	-	-	-	x	-	x	-
Raspberry Pi 2	x	-	-	-	-	x	x	-	x	x
Raspberry Pi 3	x	-	-	-	x	x	x	x	x	-
Raspberry Pi 4	x	-	-	-	x	-	-	-	-	-
Other SBCs	-	-	x	x	x	x	x	x	x	x