Raspberry Pi Single-Board Computers: Cost/Performance Relationship Over Time

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Abstract— **This study delves into the dynamic landscape of cost versus performance ratio within the Raspberry Pi family of computers, specifically scrutinizing the Raspberry Pi B and Raspberry Pi Zero lines. Based on previous analyses, our comprehensive investigation encompasses all generations of the Raspberry Pi B and Zero lines available until January 2024. Prices are meticulously adjusted to the 2012 dollar value, aligning with the inaugural launch of the Raspberry Pi. The findings illuminate an upward in performance around 229 times over an 11-year period, coupled with a notable decline in the cost per unit of performance. The impact of the dollar's depreciation since 2012 further accentuates these trends.**

I. Introduction

The proliferation of single-board computers (SBC) has ushered in a myriad of applications, ranging from monitoring household appliances [1] to orchestrating makeshift mechanical fans for emergency COVID-19 treatments [2]. A pivotal force driving the widespread adoption of single-board computers is the Raspberry Pi, first introduced in 2012 [3]. The Raspberry Pi stands out as the commercially most performant single-board computer, boasting approximately 30 million units sold by December 2019[1]. The paramount contribution of these devices, however, lies in their capability to seamlessly collect data from sensors embedded in diverse environments, such as forests [4], hospitals [5], and shopping centers [6], all while maintaining transparency for system users.

Owing to the initial limited processing power of early Raspberry Pi models, data collection was predominantly offloaded to the cloud, capitalizing on its huge processing capacity [7]. Yet, this approach incurred a substantial increase in latency for both raw data transmission to the cloud and the subsequent return of processed data to the Raspberry Pi [8]. Consequently, the scientific community sought alternatives to the all-in-the-cloud paradigm.

This pursuit gave rise to the concept of edge computing, advocating the utilization of resources at the network periphery, such as local servers and routers, for specific task execution [9]. Concurrently, the evolution of SBCs capabilities in terms of CPU, memory, and network has rendered them more powerful than strictly required for sensor data collection and transmission. This prompts a question regarding the feasibility of harnessing the excess capacities of these pervasively installed computers as local resources for task execution [10]. However, to truly comprehend the potential and limitations of these devices, we should analyze their performance metrics and the associated costs. Understanding their historical evolution becomes crucial in identifying and validating trends, aiding in the strategic planning of infrastructure capacities.

While the notion of comparing the cost/performance ratio of various SBC models is not novel [11], studies scrutinizing the historical evolution of the cost/performance ratios, specific to the Raspberry Pi family, are conspicuously lacking. This work endeavors to bridge this gap, offering a quantitative analysis of the cost/performance ratios across multiple Raspberry Pi generations using inflation-adjusted dollar values.

II. Related Works

Since the introduction of the inaugural Raspberry Pi generation and the subsequent surge in popularity of SBCs, numerous investigations have scrutinized the efficacy of these computers across diverse application domains [12]. For instance, [13] appraised the peak processing capability of a first-generation Raspberry Pi cluster in terms of billions of Floating-point Operations Per Second (GFLOPS), network bandwidth in terms of Megabits per second (Mbps), and the I/O performance of the disk system in megabytes per second (MB/s). Other studies, like [14], conducted analogous tests on alternative SBCs, extending their evaluation to the RAM system's performance during communication between Message Passing Interface (MPI) application processes.

The authors of [15] juxtaposed the performance of a Raspberry Pi cluster against a power-efficient Next Unit of Computing (NUC) and a Mid-Range Desktop (MRD) across three prominent cryptographic algorithms (AES, Twofish, and Serpent). They assessed the general-purpose performance using the High-Performance Linpack (HPL) benchmark, quantifying the systems' performance in GFLOPS. This study is noteworthy for its comparative analysis of Raspberry Pi with other systems and its examination of a significant and contemporary application. Nevertheless, it concentrates solely on a specific Raspberry Pi version and employs only one performance metric.

Other inquiries, such as [16] and [17], have delved into scrutinizing the performance of Raspberry Pi or analogous computers in big data applications involving extensive disk

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[1]https://www.zdnet.com/article/raspberry-pi-now-weve-sold-30-million/

read and write operations. In our research, we opted not to scrutinize the performance fluctuations in disk read and write operations on Raspberry Pi. However, it is already know that the kind of SD card used can have impact in some applications running on SBCs [18].

In a distinct study, [19] assessed the performance of Raspberry Pi 2B and another SBC for Hadoop applications. They employed benchmarks for task execution time, memory/storage utilization, network throughput, and energy consumption. The study's novelty lies in examining the operational cost of SBC-based clusters by correlating energy utilization with the execution time of various benchmarks across workloads of varying sizes. Although this approach offers insights into the cost-performance ratio evolution of SBCs for specific applications, the method fixates on a single use case and exclusively considers one Raspberry Pi model. Our research aims to scrutinize the performance evolution of all major components across all models in the B and Zero segments of Raspberry Pi, targeting individual consumers, while excluding the A family intended for industrial use due to its distinct versatility.

Subsequent studies emerged that not only gauged Raspberry Pi performance, but also assessed the associated costs. For instance, [11] evaluated 17 diverse SBCs, encompassing Raspberry Pi 1B, 2B, and 3B. The assessment considered GFLOPS performance and energy consumption in Watts (W), calculating the Dollar/GFLOPS ratio and the energy cost in W per GFLOPS for each system. Similarly, [20] conducted a parallel study, considering memory and network system performance alongside energy consumption. While insightful, these studies do not emphasize the evolution of Raspberry Pi systems and lack comparisons of equipment costs using a standardized reference year for the dollar. In the case of [20], evaluations are confined to virtualized systems, incurring additional overhead and precluding attainment of the maximum potential performance of the assessed systems.

Nevertheless, none of the aforementioned works encompassed all models from every Raspberry Pi generation in their investigations or factored in the depreciation of the dollar over time in metric calculations. In our research, we account for these aspects, as well as the impact of dissipation systems on performance and the cost-effectiveness of incorporating additional dissipation. The ensuing section delineates the experimental methodology employed in this study.

III. Materials and methods

The main goal 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) Assess the impact of passive and active dissipators on CPU performance in Raspberry Pi computers;
3) Verify if the evolution of the maximum processing capacity of different Raspberry Pi models follows a Moore's Law derivative growth curve;
4) Verify the evolution of available memory capacity, and the cost in dollars per MB;
5) Verify the evolution of communication capacity of the main memory, in terms of bandwidth (in Mbps) and communication latency (in seconds), as well as the cost in dollars of maximum bandwidth; and
6) Verify the evolution of communication capacity in the local network, in terms of bandwidth (in Mbps) and communication latency (in seconds), as well as the cost in dollars of maximum bandwidth.

A. Choice of Raspberry Pi Models

In this study, we evaluated all models of Raspberry Pi computers from lines B and Zero. The first Raspberry Pi released was the model 1B, which features a single-core CPU running at 700 MHz, 512 MB of DDR2 RAM, and a 10/100 Ethernet port. It was launched at the price of $35[2], and was soon replaced by the Raspberry Pi 1B+ model that offered improved power efficiency. The 2B model introduced a significant upgrade with a quad-core CPU clocked at 900 MHz, 1 GB of DDR2 RAM, and also disposed of a 10/100 Ethernet port, providing better performance for various computing tasks. The price of $35[3][4][5] remained the norm until the launch of the 4B model[6].

The Raspberry Pi 3B disposed of a 1.2 GHz quad-core CPU, 1 GB of LPDDR2 RAM, integrated Wi-Fi, and Bluetooth connectivity. This one was also the first to dispose of a 64-bit processor. Its successor, the 3B+, boosts the CPU clock speed to 1.4 GHz, and adds a Gigabit Ethernet port. However, this model was not able to reach a network bandwidth of 1 Gbps due to limitations of the internal communication bus used to communicate with the CPU.

The Raspberry Pi 4B marks a major leap forward with a quad-core CPU running at 1.5 GHz, options for 1 GB, 2 GB, 4 GB, or 8 GB of LPDDR4 RAM, and true Gigabit Ethernet support. The release prices were respectively $35, $45, $55, and $75. Its release saw a higher price point compared to earlier models but justified by its significantly enhanced capabilities. Finally, we have now the Raspberry Pi 5B, with a specially designed quad-core CPU running at 2.5 GHz, options for 4 GB or 8 GB LPDDR4X, and Gigabit Ethernet. The release prices were respectively $60 and $80[7].

Moving to the Zero line, the Raspberry Pi Zero W combines compact size with wireless connectivity, featuring a single-core CPU running at 1 GHz, 512 MB of DDR2 RAM, and integrated 802.11n Wi-Fi and Bluetooth. Despite its diminutive form factor, it offers ample power for various IoT and embedded projects. Finally, the Raspberry Pi Zero W2 further refines the Zero series with a dual-core CPU running

[2] https://www.raspberrypi.com/news/model-b-now-ships-with-512mb-of-ram/

[3] https://www.raspberrypi.com/news/raspberry-pi-2-on-sale/

[4] https://www.raspberrypi.com/news/raspberry-pi-3-on-sale/

[5] https://www.raspberrypi.com/news/raspberry-pi-3-model-bplus-sale-now-35/

[6] https://www.raspberrypi.com/news/raspberry-pi-4-on-sale-now-from-35/

[7] https://www.raspberrypi.com/news/introducing-raspberry-pi-5/

at 1 GHz, 512 MB of LPDDR2 RAM, and improved wireless connectivity with support for both 2.4 GHz and 5 GHz Wi-Fi bands, offering enhanced performance and flexibility in a compact package. The release prices of these models were respectively \$10[8] and \$15[9].

B. Value of the Dollar

The value of the dollar changed during the period from 2012 to 2024, and it means that the launch value of different Raspberry Pi models has also undergone variations. To allow a fair comparison of the cost-benefit relationship between the different models, we chose to use a unified dollar value. 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 2012, and used this value to establish cost-performance relationships. The dollar values were obtained through the Bureau of Labor Statistics[10], an official agency of the U.S. government.

C. Benchmarks Used and Tests Performed

To measure the computing performance of all Raspberry Pi models used in this study, we adopted the HPL benchmark. HPL measures the amount of GFLOPS performed by a computing system during a linear equation system resolution. We chose HPL because it is the standard method to estimate the computing performance of computer systems [21].

Since we do not know the optimal values for these parameters *a priori*, we performed a single run of the HPL, varying 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. We tested more than 640 parameter combinations and found that the best performance was achieved when using an N size representing an occupation of 85% of the available RAM memory of each Raspberry Pi model, and an NB value of 256. After, we repeated the tests with this configuration 30 times, and the HPL results are presented in the results section.

To measure the bandwidth and the latency 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, UDP, and MPI [13]. 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 device [14]. These tests were also repeated 30 times.

D. Other considerations

All Raspberry Pis 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, all of the Raspberry Pis used non-expensive passive and active cooling systems at some experiments.

IV. Results

The results of our experiments are presented in this section, divided into subsections according to the kind of resource being analyzed.

A. Evolution of CPU Performance and Cost Over Time

In this subsection, we analyze the evolution of computational capacity of Raspberry Pi computers and associated costs based on the data obtained experimentally. The average performance in GFLOPS of all Raspberry Pi models from the B and Zero lines, whether using passive or active heatsinks, is shown in Fig. 1. The first model of Raspberry Pi from the B line exhibits an average performance of 0.107 GFLOPS, while the latest model from the same line demonstrates an average performance of 24.525 GFLOPS (utilizing active heatsinks). This represents a computational power increase of 229 times over an 11-year period.

The most significant performance leap during its evolution occurred between the first and second generations (processing power gain exceeding 7 times), mainly due to an increase in the number of available processing cores, core frequency, and available memory. From the third generation onwards (the first to use 64-bit processors), the performance gain compared to the preceding generation stabilized around 3 times.

The fourth generation of the B line introduced an interesting novelty: models equipped with the same processor but with different options for installed RAM. This allowed expanding the range of Raspberry Pi applications, prompting us to investigate whether adding more RAM in this generation would impact system computational capacity. The results indicate indeed an increase in computational capacity when transitioning from 1GB to 2GB of RAM, and subsequently to 8GB of RAM. However, transitioning from 2GB to 4GB of RAM resulted in a performance reduction, the exact cause of which we couldn't identify. However, there may be some relation to the memory subsystem's performance, as this model exhibited lower interprocess communication bandwidth compared to other models of the same generation 4.

In Fig. 1, it's also observable that the use of heatsinks influences performance only from the third generation of Raspberry Pi onwards. This happens because the early models of the B line lacked a Dynamic Voltage and Frequency Scaling (DVFS) mechanism, which was only introduced starting from the 3B model, and has persisted in all B line models since then, being introduced to the Zero line from the Zero W2 model onwards.

Therefore, from the 3B model onwards, the use of heatsinks is mandatory to access the full computational power of Raspberry Pi. It's interesting to observe how the use of passive or active heatsinks impacts performance across

[8] https://www.raspberrypi.com/news/raspberry-pi-zero-w-joins-family/
[9] https://www.raspberrypi.com/news/new-raspberry-pi-zero-2-w-2/
[10] https://www.bls.gov/data/inflation_calculator.htm

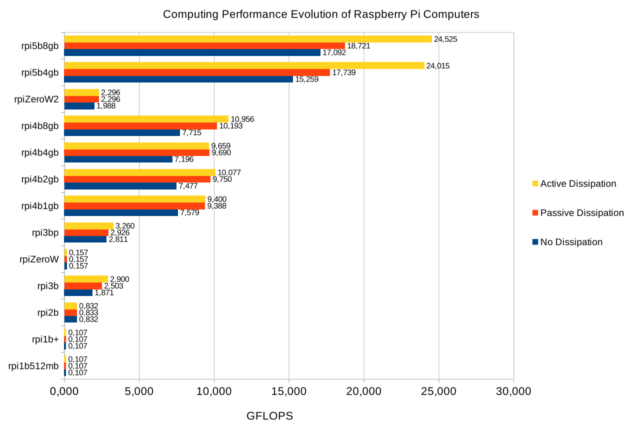

Fig. 1. Computing performance of Raspberry Pi computers over time

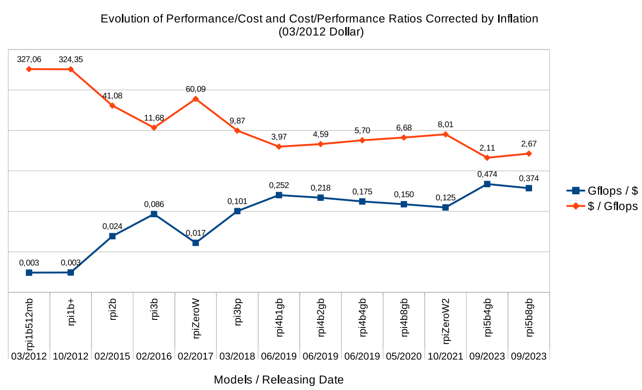

Fig. 2. Evolution of cost/performance ratio of Raspberry Pi computers

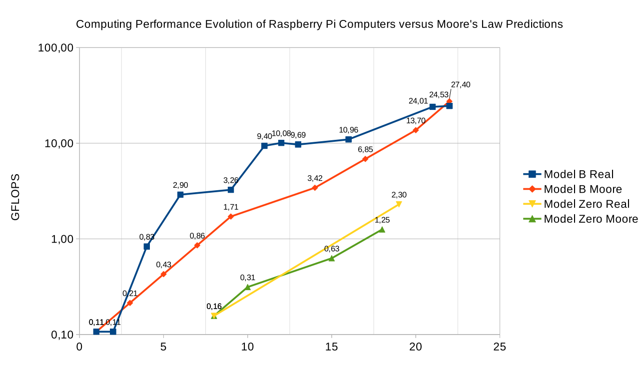

Fig. 3. Performance gain between Raspberry Pi generations versus Moore's Law.

different generations of Raspberry Pi. For example, in third-generation models, the use of active heatsinks can increase performance in 10% compared to passive heatsinks and 15% when compared to no heatsink usage. However, in Raspberry Pi 4 series models, the use of active heatsinks increased system performance by a maximum of 7.5% compared to passive heatsinks. We acknowledge that possible unknown environmental factors may have influenced this result, but note that all tests, with all models, were conducted in the same laboratory and at the same time of the year (European winter of 2023). Finally, the fifth generation of Raspberry Pi absolutely requires active cooling to operate at high performance for extended periods. During our tests, without the use of active heatsinks, we had to interrupt test execution after 5 repetitions for the Raspberry Pi 5B model with 4GB RAM and after only two repetitions for the same model with 8 GB RAM.

Based on the performance results and a historical survey of Raspberry Pi launch values, we were able to analyze the evolution of cost in dollars paid per each GFLOP obtained, as well as how many GFLOPS one could purchase with a dollar, as shown in Fig. 2. We observed a reduction of 122,3 times between the first and last generations of Raspberry Pi model B in the dollar value paid per each GFLOP obtained. If this evolution curve continues in this manner, models from the next generation may present a Dollar/GFLOP ratio lower than 1, which would be a significant qualitative advancement.

Finally, we compared the evolution of Raspberry Pi performance with what should be observed if performance evolution follows Moore's law, which broadly states that the processing capability of computational systems tends to double every 18 months, as shown in Fig. 3. To our surprise, the evolution of performance gains of the B line of Raspberry Pi computers does not follow Moore's law, having shown much greater performance gains than predicted between the first and fourth generations, and reaching growth values close to expected only from the fifth generation, 12 years after the first.

We believe this occurred because, initially, the developers of Raspberry Pi did not have the necessary investment capacity to make large-scale purchases, and thus used low-end components. With increasing sales and popularity of the devices, producers could afford to use existing technologies with greater computational capacity. Secondly, during the fifth-generation B line models are being equipped for the first time with a processor specially designed for Raspberry Pi, which may explain why this generation is slightly below what is expected by Moore's law. However, this is one of the inherent risks of technological evolution, and we can cite a similar example in Apple's break with Intel and the launch of the M1. Finally, a similar pattern seems to repeat with the Zero line models, albeit to a lesser extent.

B. *Evolution of Memory Performance and Cost Over Time*

Fig. 4 shows the evolution of the cost in dollars of each MB of memory included in each model of Raspberry Pi. The amount of dollar paid for each MB decreases from one

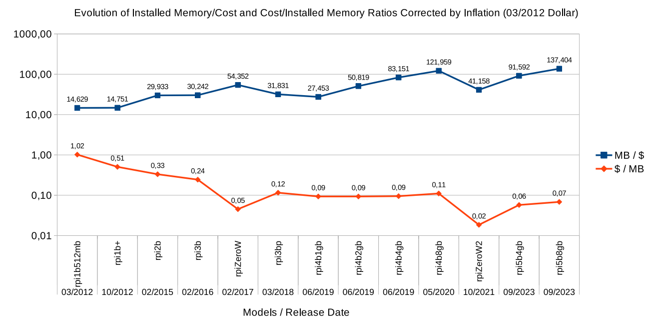

Fig. 4. Installed memory and its associated costs on Raspberry Pi computers.

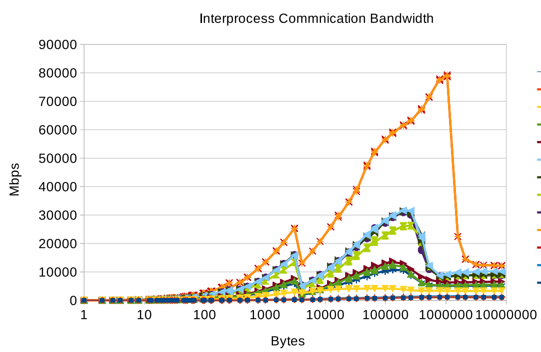

Fig. 5. Memory bandwidth on Raspberry Pi computers over time.

generation to another. Also, at the same generation models offering more memory presents a better Dollar/MB ratio. A similar pattern is observed in Zero Line.

From Figs. 5 and 6, we can deduce 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 300% higher than the preceding generation and with latency an order of magnitude lower. A similar performance leap is observed in the fifth generation, presenting a bandwidth 293% higher than the preceding generation, and this is also reflected in the cost-benefit ratio. Finally, Fig. 7 shows the evolution of the cost in dollars paid to obtain the highest possible memory bandwidth (peak value of each data series in Fig. 5).

C. Evolution of Network Performance and Cost Over Time

Fig. 8 and 9 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, Fig. 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 Fig. 10. The analysis 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. However, in the fifth generation the cost/performance ratio is bigger than in the previous

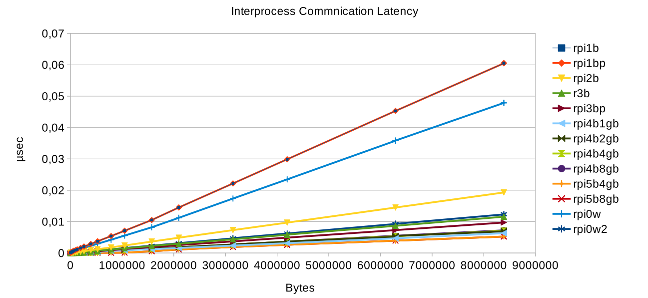

Fig. 6. Memory latency on Raspberry Pi computers over time.

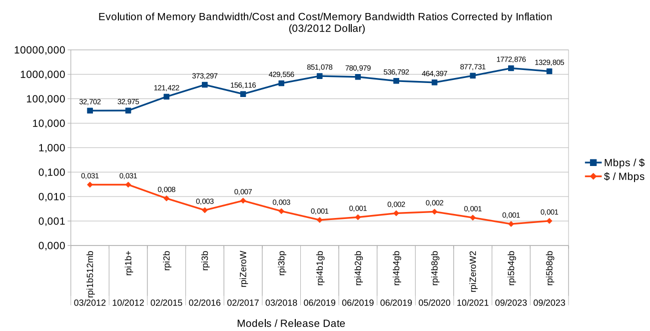

Fig. 7. Evolution of Memory Bandwidth/Cost ratio on Raspberry Pi computers

generation. To change that, the next Raspberry Pi generation should include a 2,5 Gbps network interface at the same selling price.

V. Conclusions

In this study, we present a comparative analysis of the performance evolution within the Raspberry Pi computer family, focusing on the *B* and *Zero* lines, along with associated costs. The analysis encompasses all generations of Raspberry Pi available on the market up to the submission date of this article to IEEE SMC 2024. Computer prices were adjusted using a single reference point: the 2012 dollar, corresponding to the inaugural launch year of the first Raspberry Pi.

The findings reveal a discernible trend of performance enhancement over time, coupled with a tendency for the

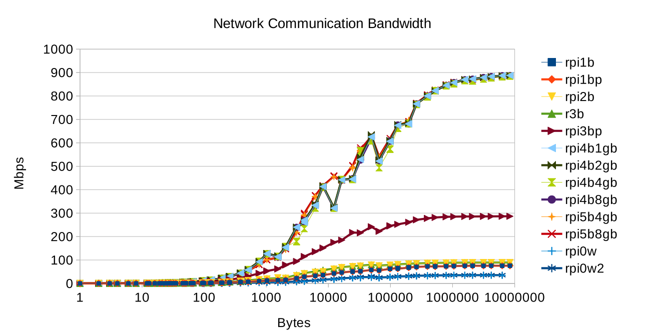

Fig. 8. Network bandwidth on Raspberry Pi computers over time.

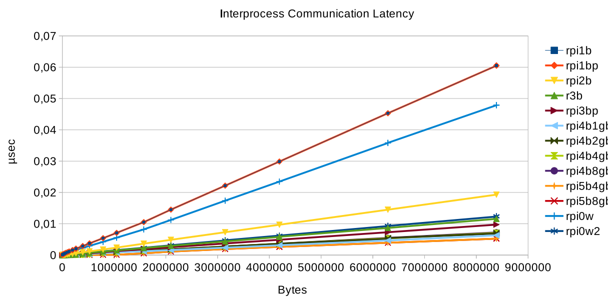

Fig. 9. Network latency on Raspberry Pi computers over time.

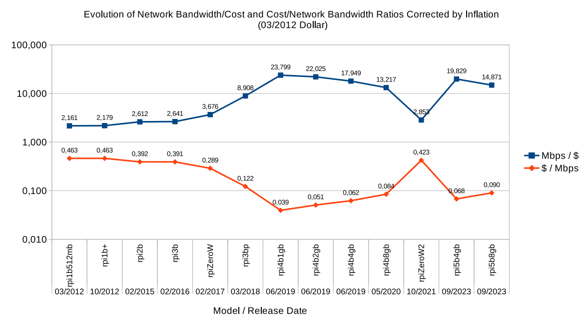

Fig. 10. Evolution of Net Bandwidth/Cost ratio on Raspberry Pi computers.

price-to-performance ratio to decrease. This decrease is particularly notable when factoring in the depreciation of the dollar relative to its 2012 value. Notably, similar trends are observed within both the B and Zero lines.

As part of our future endeavors, we aim to broaden the scope of our experiments to encompass all Raspberry Pi models. Additionally, we intend to monitor the energy consumption of each Raspberry Pi model during test executions to explore the correlation between energy consumption and performance.

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