Blockchain Goes Green?
Part II: Characterizing the Performance and Cost of Blockchains on the Cloud and at the Edge

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ABSTRACT
While state-of-the-art permissioned blockchains can achieve thousands of transactions per second on commodity hardware with x86/64 architecture, their performance when running on different architectures is not clear. The goal of this work is to characterize the performance and cost of permissioned blockchains on different hardware systems, which is important as diverse application domains are adopting them. To this end, we conduct extensive cost and performance evaluation of two permissioned blockchains, namely Hyperledger Fabric and ConsenSys Quorum, on five different types of hardware covering both x86/64 and ARM architecture, as well as, both cloud and edge computing. The hardware nodes include servers with Intel Xeon CPU, servers with ARM-based Amazon Graviton CPU, and edge devices with ARM-based CPU. Our results reveal a diverse profile of the two blockchains across different settings, demonstrating the impact of hardware choices on the overall performance and cost. We find that Graviton servers outperform Xeon servers in many settings, due to their powerful CPU and high memory bandwidth. Edge devices with ARM architecture, on the other hand, exhibit low performance. When comparing the cloud with the edge, we show that the cost of the latter is much smaller in the long run if manpower cost is not considered.

1 INTRODUCTION
Blockchain is increasingly adopted by users and businesses around the globe. While blockchain technology became famous through public, permissionless chains, such as Bitcoin [38] and Ethereum [20] which are used primarily for cryptocurrency transfers, their performance when running on different architectures is not clear. The goal of this work is to characterize the performance and cost of permissioned blockchains on different hardware systems, which is important as diverse application domains are adopting them. To this end, we conduct extensive cost and performance evaluation of two permissioned blockchains, namely Hyperledger Fabric and ConsenSys Quorum, on five different types of hardware covering both x86/64 and ARM architecture, as well as, both cloud and edge computing. The hardware nodes include servers with Intel Xeon CPU, servers with ARM-based Amazon Graviton CPU, and edge devices with ARM-based CPU. Our results reveal a diverse profile of the two blockchains across different settings, demonstrating the impact of hardware choices on the overall performance and cost. We find that Graviton servers outperform Xeon servers in many settings, due to their powerful CPU and high memory bandwidth. Edge devices with ARM architecture, on the other hand, exhibit low performance. When comparing the cloud with the edge, we show that the cost of the latter is much smaller in the long run if manpower cost is not considered.

Fault-tolerance protocols such as Raft [39]. State-of-the-art permissioned blockchains can achieve thousands of transactions per second, by improving consensus, network performance, or by adopting database techniques [22, 29, 55]. However, we note that these systems are designed for traditional enterprise workloads, and are evaluated only on commodity or cluster-grade servers with x86/64 architecture, being at the edge or on the cloud. For example, AHL [22] uses general instances on Google Cloud Platform spanning multiple regions.

As blockchains are maturing, we observe that more and more applications are adopting them. Besides the traditional enterprise data processing applications, such as payment systems, emerging blockchain applications include blockchain cloud services [1, 13], and edge computing [4, 14]. These applications come with different hardware resource demands, that is, they may not run efficiently on x86/64 commodity hardware [33, 47, 48]. Besides x86/64, we have witnessed the proliferation of ARM architecture, which first started with mobile devices. Recently, ARM has been adopted as an alternative architecture in cloud computing [16]. However, the performance and cost of running blockchains on ARM-based hardware are not clear. As a result, users cannot make an informed decision of what system to run their blockchain on.

Our goal is to provide an in-depth analysis of blockchain performance and cost on different CPU architectures, which helps inform the design of emerging blockchain applications. To this end, we select five representative edge and cloud systems, including servers with Intel Xeon CPU, ARM-based Amazon Graviton instances [16], high-end and low-end edge devices with ARM CPU represented by Nvidia Jetson TX2 [26] and Raspberry Pi 4 [2], respectively. We run two representative permissioned blockchains on these hardware nodes, namely, Hyperledger Fabric [9, 19] and ConsenSys Quorum [8]. The former is widely used in the industry and well studied by the database community in the last few years [22, 25, 43, 44, 46]. Fabric adopts an execute-order-validate transaction flow and currently uses Raft as a consensus mechanism for its ordering service. Quorum [8] adopts a more traditional order-execute transaction
We direct the reader to other works [24, 42, 43] for more details on blockchain. A blockchain is a distributed ledger managed by a network of mutually distrusting nodes (or peers). The ledger is stored as a linked list (or chain) of blocks, where each block consists of transactions. The links in the chain are built using cryptographic pointers to ensure that no one can tamper with the chain or with the data inside a block.

Blockchains are most famous for being the underlying technology of cryptocurrencies, but many can support general-purpose applications. This ability is determined by the execution engine and data model. For example, Bitcoin [38] supports only operations related to cryptocurrency (or token) manipulation. On the other hand, Ethereum [20] can run arbitrary computations on its Turing-complete Ethereum Virtual Machine (EVM). At the data model level, there are at least three alternatives used in practice. The Unspent Transaction Output (UTXO) model, used by Bitcoin among others, represents the ledger states as transaction ids and associated unspent amounts that are the input of future transactions. The account/balance model resembles a classic banking ledger. A more generic model used by Hyperledger Fabric consists of key-value states. On top of the data model, developers can write general applications that operate on the blockchain’s states. Such applications are called smart contracts. In this paper, we extend the smart contracts from Blockbench [25] to support Fabric (v2.3.1) and Quorum.

Depending on how nodes can join the network, the blockchain is public (or permissionless) or private (or permissioned). In public networks, anybody can join or leave and, thus, the security risks are high. Most of the cryptocurrency blockchains are public, such as Bitcoin [38] and Ethereum [20]. On the other hand, private blockchains allow only authenticated peers to join the network. Typically, private blockchains, such as Fabric [19] and Quorum [8], are deployed inside or across big organizations.

Blockchains operate in a network of mutually distrusting peers, where some peers may not be just faulty but malicious. Hence, they assume a Byzantine environment [32], in contrast to the crash-failure model used by the majority of distributed systems. For example, Proof-of-Work (PoW) is a BFT consensus mechanism where participating nodes, called miners, need to solve a difficult cryptographic puzzle. The miner that solves the puzzle first has the right to append transactions to the ledger. Since this mining process is both time and energy inefficient, some alternatives have been proposed, such as Proof-of-Trade (PoS) [12], Proof-of-Authority (PoA), and Proof-of-Elapsed-Time (PoET) [5]. In PoS, the nodes need to set aside some coins (the stake) based on which the validator of each block is chosen. In case a malicious validator is detected, it loses its stake. Through this mechanism, malicious behavior is discouraged. In PoA, some nodes with known identity, called validators, are trusted to validate all the transactions. In case a trusted node acts maliciously, its reputation is affected and it may be removed from the network. In PoET, each node needs to wait for a random period, before being able to propose a new block. The node with the smallest wait period is the one appending the next block.

On the other hand, PBFT [21] consists of exchanging $O(n^2)$ messages among the nodes to reach an agreement on the transactions to be appended to the chain. However, BFT consensus does not scale well and leads to low blockchain throughput [25, 43]. This is one reason why permissioned blockchains started to replace BFT with CFT consensus. For example, both Fabric and Quorum support Raft consensus [39]. Another reason for using CFT consensus in permissioned chains is the higher accountability due to node authentication in such platforms.
2.2 Performance Analysis of Blockchains

There are a number of related works that analyze the performance of blockchains [24], [25], [40], [52], [54], [43]. However, only a few include energy or cost analysis [15], [33], [45], [51], but their analysis is of limited depth.

Sankaran et al. [45] analyze the time and energy performance of an in-house Ethereum network consisting of high-performance mining servers and low-power Raspberry Pi 3 clients. These low-power nodes cannot run Ethereum mining due to their limited memory size, hence, they only take the role of clients. In this paper, we focus on permissioned blockchains and use Quorum as a representative of Ethereum-based blockchains. On the other hand, we use low-power devices with higher performance, such as Jetson TX2 and Raspberry Pi 4.

MobiChain [51] is an approach that allows mining on mobile devices running Android OS, in the context of mobile e-commerce. While it provides an analysis of both time and energy performance, MobiChain has no comparison to other blockchains. In terms of energy analysis, the authors show that it is more energy-efficient to group multiple transactions in a single block since there is less mining work and therefore less time and power wasted in this process. However, larger blocks increase latency and result in a poor user experience.

Jupiter [30] is a blockchain designed for mobile devices. It aims to address the problem of storing a large ledger on mobile devices with limited storage capacity. The testbed in [28] is based on 14 Raspberry Pi 3 nodes running Hyperledger Fabric version 1.0. However, there is no time or energy performance evaluation in both of these works [30], [28].

Ruan et al. [43] compare blockchains with distributed database systems using a taxonomy with four dimensions, namely, replication, concurrency, storage, and sharding. Similar to this paper, they analyze Fabric and Quorum but their analysis is only focusing on the time performance and it is conducted on commodity x86/64 servers. Complementary to our analysis of blockchains on different hardware systems, [43] evaluates the effect of different blockchain and benchmarking parameters, such as record size, block size, replication model, and failure model, among others.

Blockbench [25] is a benchmarking suite comprising both simple (micro) benchmarks and complex (macro) benchmarks. The microbenchmarks, namely CPUHeavy, IOHeavy, and Analytics are stressing different hardware subsystems such as the CPU, memory, and IO. At the same time, the microbenchmarks evaluate the performance of different blockchain layers. For example, CPUHeavy evaluates the performance of the execution engine, while IOHeavy evaluates the performance of the data storage. The macro benchmarks are represented by YCSB, Smallbank, and Donothing. The YCSB macro benchmark implements a key-value storage, while Smallbank represents OLTP and simulates basic banking operations. The Donothing benchmark is used to evaluate the consensus protocol since it does not engage the execution and data storage layers. The performance in terms of throughput and latency is evaluated on traditional high-performance servers with Intel Xeon CPU. We note that Blockbench analyzes the performance of Fabric v0.6 with PBFT. In this paper, we extend Blockbench to support Fabric v2.3.1 and Quorum v20.10.0. Moreover, we do not analyze only the time performance, but also the power and cost of a wider range of node types, including both x86/64 and ARM architectures. To the best of our knowledge, we provide the first extensive time, energy, and cost performance analysis of permissioned blockchains on both x86/64 and ARM architectures, as well as both at the edge and on the cloud.

3 EXPERIMENTAL SETUP

In this section, we describe our experimental setup in terms of blockchains, benchmarks, and hardware nodes.

3.1 Overview

We illustrate our experimental approach in Figure 1. The setup consists of a blockchain network comprising N peers, a set of clients that send transactions to the peers, a controller, and a power meter to collect power and energy measurements. For simplicity, we consider N clients, each client sending transactions to one blockchain peer. In reality, a client can send transactions to multiple peers. The controller node is used to set up the benchmarking environment, start the peers, set up the smart contracts, start the clients, and collect the results, including power and energy.

3.2 Blockchains and Benchmarks

The permissioned blockchain frameworks analyzed in this paper are Hyperledger Fabric (v2.3.1) and ConsenSys Quorum (v20.10.0). Fabric [9] is a crash fault-tolerant (CFT) permissioned blockchain that adopts an execute-order-validate transaction flow. In a Fabric network, there are three types of nodes: peers, orderers, and clients. A client sends a transaction request to a set of peers, depending on an endorsement policy. For example, an AND policy including all the peers means that the client needs to send the transaction and receive endorsements from all the peers. A peer processes the transaction request and creates read and write sets to mark which states
are touched by the transaction. However, the peer does not persist the transaction’s effects on its local database. When the client gets all the endorsements from the peers, it sends the transaction to the orderers such that they will pack it in a block. Once a block is formed, the orderers send it to all the peers. Lastly, each peer validates the transactions in a block and persists the changes to its local database. Fabric v2.3.1 uses Raft [39] as the consensus mechanism among the orderers, and LevelDB [23] as its local database.

Quorum [8] is a permissioned blockchain that started as a fork of Ethereum. Hence, Quorum supports Solidity smart contracts, but it uses different consensus mechanisms than Ethereum because of its permissioned nature. In this paper, we analyze both a CFT Quorum that uses Raft as the consensus protocol among the peers, as well as a BFT version that uses Istanbul BFT (IBFT) [37] as the consensus protocol. In contrast to Fabric, a Quorum network has only peers and clients, and the transaction flow is order-execute. This means that transactions are first grouped into blocks and then executed by each peer in the network. Similar to Fabric, Quorum uses LevelDB as its local database.

For benchmarking these blockchains, we extend Blockbench2 [25] to support Fabric v2.3.1 and Quorum v2.0.10.0. That is, we implemented Fabric and Quorum smart contracts for the key-value store benchmark and the scripts needed to run the benchmark. We use the YCSB macro-benchmark consisting of 50% read and 50% write operations of single key-value pairs of 1kB in size. One or more client nodes send transactions to the blockchain peers in an asynchronous mode. That is, the request threads of the clients do not wait for the result of a transaction. Instead, a status thread periodically queries the blockchain to get the committed transactions.

In our experiments, the block size of Fabric is set to 500 transactions and the runtime for the benchmark is set to 120s. In Quorum, there is no limit to block size. The runtime is set to at least 240s to account for a slower startup compared to Fabric. We vary the number of blockchain peers from four to ten and we use the client request rate that leads to the best performance. In this paper, we report the best results out of three runs for each experiment. We note that the standard deviation is lower than 10% of the mean for each experiment.

3.3 Hardware Systems
In this paper, we are analyzing the performance of five types of systems (hardware nodes) covering both edge and cloud computing, as well as both x86/64 and ARM architectures. The specifications of these systems are summarized in Table 1. We measure the power and energy of the edge nodes with a Yokogawa power meter connected to the AC lines. We report the AC power values in this paper.

At the edge, we measure the time performance and power of the following three types of nodes. First, we have x86/64 nodes with Intel Xeon E5-1650 v3 CPU clocked at 3.5 GHz, 32 GB DDR3 memory, 2 TB hard-disk (HDD), and 1 Gbps networking interface card (NIC). These nodes, termed Xeon(cloud) in this paper, run Ubuntu 18.04. Second, we use high-end ARM-based devices represented by Nvidia TX2 [26]. A TX2 node has a heterogeneous 6-core 64-bit CPU with two NVIDIA Denver cores and four ARM Cortex-A57 cores clocked at more than 2GHz. Each node has 8 GB LPDDR4, a 32 GB SD card, and 1 Gbps NIC. TX2 is equipped with an integrated low-power GPU. However, we are not using the GPU in our experiments. The TX2 nodes are running Ubuntu 16.04 which is officially supported by Nvidia on these systems. Third, we use low-end ARM-based devices represented by Raspberry Pi 4 model B (RP4) [2]. An RP4 has a 4-core ARM Cortex-A72 CPU of 64-bit ARM architecture, 8 GB of low-power DDR4 memory, a 64 GB SD card that acts as storage, and 1 Gbps NIC. RP4 runs the beta version of the 64-bit Debian-based Raspberry Pi OS [6].

On the cloud, we use two types of instances from Amazon Web Services (AWS) to represent both x86/64 and ARM architectures. AWS was chosen because it is the only widely-known cloud provider that offers ARM-based instances. We use m5n.2xlarge [49] AWS instances to represent the x86/64 architecture. At the time of running the experiments, one such instance costs $0.476 per hour in the US West (Oregon) region. These nodes, termed Xeon(cloud) in this paper, are equipped with Intel Xeon Platinum 8259CL CPUs clocked at 2.5 GHz. Each node has 8 CPU cores, 32 GB RAM, 50 GB SSD storage, and up to 25 Gbps networking. A Xeon(cloud) node runs Ubuntu 18.04 OS. Then, we use large [7] AWS instances to represent the emerging 64-bit ARM server market. These instances, termed Graviton in this paper, are based on Amazon’s Graviton processors that use 64-bit ARM Neoverse architecture [16]. Each node has 8 CPU cores, 32 GB RAM, 50 GB SSD, up to 10 Gbps networking, and runs Ubuntu 18.04. At the time of running the experiments, one such instance costs $0.308 per hour in the US West (Oregon), being 1.55x or 35% cheaper than one Xeon(cloud) m5n.2xlarge instance.

In summary, we note that cloud nodes use CPUs with more cores, higher frequency, bigger cache size, and more levels of cache, as shown in Table 1. Moreover, cloud nodes have bigger RAM sizes and faster networking. We shall see in the next sections how these hardware characteristics impact the performance of blockchain systems.

4 PERFORMANCE ANALYSIS
In this section, we conduct a systematic performance analysis of the selected blockchains and hardware nodes.

4.1 Overview
We first highlight the key findings of our measurement-based evaluation, followed by a systematic in-depth analysis of the hardware systems and blockchain frameworks. These key observations are based on the throughput, latency, and power results presented in Figure 2 for all three blockchains on all five types of nodes.

Observation 1. Surprisingly, Graviton exhibits up to 8% higher performance compared to Xeon(cloud) when running Fabric, as shown in Figure 2a. On the other hand, Graviton exhibits 20% and 26% lower throughput when running Quorum(Raft) and Quorum(IBFT), respectively, compared to Xeon(cloud), as shown in Figure 2c and Figure 2e, respectively. In the context of 35% lower cost of Graviton compared to Xeon(cloud), the ARM-based server is more cost-efficient.
Figure 2: Throughput, latency, and power with increasing number of peers.
Table 1: Hardware systems characterization.

| Characteristic     | Xeon(edge) | Xeon(cloud) | System | TX2     | RP4      |
|-------------------|------------|-------------|--------|---------|----------|
| ISA               | x86-64     | x86-64      | AARCH64| AARCH64 | AARCH64/ARMv7|
| Cores             | 6 (12)     | 8           | 8      | 6       | 4        |
| Frequency         | 1.2-3.5 GHz| 2.5 GHz     | 2.5 GHz| 0.346-2.04 GHz| 0.6-1.5 GHz|
| L1 Data Cache     | 32 kB      | 32 kB       | 64 kB  | 32-128 kB| 32 kB    |
| L2 Cache          | 256 kB (core) | 1 MB (core) | 1 MB (core) | 2 MB | 1 MB |
| L3 Cache          | 12 MB      | 35.8 MB     | 32 MB  | N/A     | N/A      |
| Memory            | 32 GB DDR3 | 32 GB DDR4  | 32 GB  | 8 GB LPDDR4| 8 GB LPDDR4|
| Storage           | 1 TB SSD   | 50 GB SSD   | 50 GB SSD| 64 GB SD card| 64 GB SD card|
| Networking        | Gbit up to 25 Gbit| Gbit up to 10 Gbit | Gbit | Gbit |
| CPU               | CoreMark (one core) [IPS] | 25,201.6 | 24,061.6 | 20,266.2 | 9,936.1 | 8,555.1 |
|                   | System power [W] | 70.6 | - | - | 4.2 | 3.6 |
|                   | CoreMark (all cores) [IPS] | 170,864.7 | 137,126.8 | 162,054.4 | 68,092.3 | 34,253.1 |
|                   | System power [W] | 115.5 | - | - | 10.4 | 5.7 |
|                   | Idle system power [W] | 50.8 | - | - | 2.4 | 1.7 |
| Storage           | Write throughput [MB/s] | 160 | 132 | 58.3 | 16.3 | 19.0 |
|                   | Read throughput [MB/s] | 172 | 134 | 141 | 89 | 46 |
|                   | Buffered read throughput [GB/s] | 8.1 | 6.5 | 6.9 | 2.7 | 1.3 |
|                   | Write latency [ms] | 9.3 | 0.51 | 0.49 | 17.1 | 1.33 |
|                   | Read latency [ms] | 2.5 | 0.22 | 0.22 | 2.8 | 0.72 |
| Network           | TCP bandwidth [Mbits/s] | 941 | 9530 | 9680 | 943 | 943 |
|                   | UDP bandwidth [Mbits/s] | 810 | 4540 | 3800 | 546 | 957 |
|                   | Ping latency [ms] | 0.14 | 0.1 | 0.09 | 0.3 | 0.15 |

**Observation 2.** As shown in Figure 2, Xeon(cloud) exhibits up to 50% higher throughput compared to Xeon(edge) when running Fabric, while Xeon(edge) exhibits up to 26% higher throughput compared to Xeon(cloud) when running Quorum.

**Observation 3.** Surprisingly, the performance gap between Graviton and TX2 (or RP4) is big when running Fabric. As shown in Figure 2a, TX2 exhibits a throughput that is 6 – 9× lower compared to Graviton. On the other hand, the throughput of TX2 running Quorum is only 2 – 3× lower compared to Graviton.

**Observation 4.** While we expected TX2 to exhibit higher performance than RP4, it is interesting to observe that TX2 is also more power-efficient. This is because TX2 offers more performance per unit of energy compared to RP4, even if the latter uses less power.

**Observation 5.** The cost of hosting blockchain nodes at the edge is much lower compared to the cloud, in the long run, when manpower cost associated with operating and maintaining the edge nodes is disregarded. Conversely, adding the manpower cost leads to almost double cost at the edge compared to the cloud.

These observations give rise to a series of questions for which we seek answers in the following sections. Here, we outline some of these questions.

**Question 1.** Why does Graviton achieve higher performance than Xeon(cloud) when running Fabric, while Xeon(cloud) has higher performance when running Quorum?

**Question 2.** Why does Xeon(cloud) achieve higher performance than Xeon(edge) when running Fabric, while Xeon(edge) has higher performance when running Quorum?

**Question 3.** Why is there such a big performance gap between TX2 and Graviton when running Fabric?

**Question 4.** Why is the power efficiency of RP4 lower compared to TX2?

**Question 5.** Where and under what performance-cost circumstances should blockchain nodes be hosted: at the edge or on the cloud?

4.2 Systems Characterization

Before answering the above questions related to the blockchain frameworks, we characterize the hardware systems using a series of benchmarks that stress key sub-systems, such as CPU, memory, storage, and networking.

To assess the performance of the CPU of each type of node, we first use CoreMark [17], a modern benchmark from Embedded Microprocessor Benchmark Consortium (EEBMC) designed to characterize CPU cores of both x86/64 and ARM architectures. CoreMark estimates the CPU performance in terms of iterations per second (IPS). In Figure 3a and Figure 3b, we show the performance and average power usage of the five systems running CoreMark on a single core and all cores, respectively. For multi-core analysis, we enable all available cores, including virtual cores in systems that support Hyper-threading. The exception is Xeon(edge) which has 12 virtual cores, but we benchmark only 8 of them for a fair comparison with Xeon(cloud) and Graviton.

At the single-core level, Xeon(edge) achieves the highest performance, followed by Xeon(cloud), Graviton, TX2, and RP4, which are 1.05, 1.2, 2.5, and 2.9 times slower, respectively. Even if Xeon(edge) has a newer Xeon CPU, it exhibits lower performance compared to...
Xeon(edge) due to lower clock frequency. That is, the Intel Xeon E5-1650 of Xeon(edge) runs at 3.5 GHz, while the Intel Xeon Platinum 8259CL of Xeon(cloud) runs at 2.5 GHz. Nevertheless, the newer Intel Xeon Platinum 8259CL is more efficient since it yields higher performance per GHz. On the other hand, Graviton achieves impressive performance for an ARM-based CPU [35]. Even if its clock frequency is not officially stated, our measurements suggest that Graviton CPU runs at 2.5 GHz. Lastly, the performance of TX2 and RP4 is lower compared to the other systems, but their power consumption is also much lower. For example, TX2 and RP4 use $17 \times$ and $20 \times$, respectively, less power compared to Xeon(edge).

At the multi-core level, the surprise is Graviton which achieves higher performance than Xeon(cloud) on 8 cores, as shown in Figure 3b. Even if the Intel Xeon Platinum 8259CL CPU has 24 physical cores, our measurements suggest that a m5n.2xlarge instance uses only 4 physical cores, while the other 4 are Hyper-threading cores. In contrast, a m6g.2xlarge instance uses 8 physical Graviton cores. This leads to a higher performance of Graviton with 8 cores compared to Xeon(cloud). On the other hand, RP4 suffers from having only 4 cores, being $5\times$ and $20\times$ slower than Xeon(edge) and TX2, respectively.

A significant aspect of blockchain is the usage of cryptography operations which are, in general, compute-intensive. Both Fabric and Quorum use elliptic curve, namely ECDSA with secp256r1 and with secp256k1 respectively. Our second CPU benchmarking assesses the performance of such cryptography operations. Our profiling of Fabric shows that a significant proportion of the CPU time is spent in the secp256k1_fe_sqr_inner and secp256k1_fe_mul_inner calls (see Listing 1) which are part of the crypto/secp256k1 package. Secp256k1 is a way to compute the elliptic curve which is also employed in Bitcoin [3]. Hence, we benchmark the sign operation which uses this function and we show the results in Figure 4b. Interestingly, this cryptographic algorithm is around 22% slower on Xeon(cloud) compared to Xeon(edge). We attribute this difference to the higher clock frequency of Xeon(edge) and the fact that secp256k1 is very compute-intensive and highly optimized. This can be observed from the high IPC yielded on all the systems. On Xeon and Graviton, more than three instructions are executed in one cycle, while on TX2 and RP4 there are more than two instructions per cycle. For such an application, the CPU clock frequency matters more, hence, Xeon(edge) is the fastest system.

Next, we assess the performance of the memory sub-system in terms of read-write bandwidth measured with lmbench [50]. The results in Figure 5 represent the read-write bandwidth measured with lmbench [50]. At level one cache (L1), Xeon systems exhibit high bandwidth for both reads and writes, the ARM-based systems exhibit low bandwidth. The storage IO sub-system plays a key role in blockchain since the ledger and the state database need to be written to persistent storage. Hence, we measure the performance of the memory sub-system using dd and ioping Linux commands, respectively. The results expose a complex landscape. While the Xeon systems exhibit high bandwidth for both reads and writes, the ARM-based systems exhibit low bandwidth.
systems expose asymmetric performance where the write operations are a few times slower than the read operations. This is expected since TX2 and RP4 are equipped with SD cards and Graviton is equipped with NVMe-based SSD. On the other hand, the latency of both reads and writes is higher on Xeon(edge) compared to Xeon(cloud) and we attribute this to mechanical hard-disk (HDD) versus solid-state disk (SSD).

At the networking level, we measure the bandwidth and latency using `iperf` and `ping` Linux commands, respectively, and summarize the results in Table 1. As per their specifications, the cloud-based systems have higher bandwidth which is close to 10 Gbps. In contrast, edge-based systems have bandwidths close to 1 Gbps. The slightly higher `ping` latency of TX2 and RP4 can be attributed to the lower clock frequency of these wimpy nodes. To validate this hypothesis, we measured the networking latency while disabling the DVFS by fixing the clock frequency. TX2 supports twelve frequency steps in the range 346 MHz-2.04 GHz. RP4 supports ten frequency steps in the range 600 MHz-1.5 GHz. We obtained Pearson correlation coefficients of -0.93 and -0.84 for TX2 and RP4, respectively, between the frequency and networking latency. These coefficients suggest strong inverse proportionality and expose the impact of CPU processing on the networking stack.

Lastly, we discuss the difference in using the experimental 64-bit OS on RP4 compared to the official 32-bit OS. A 64-bit OS better matches the 64-bit ARM CPU of RP4, and this is well highlighted by the benchmarking results. For example, there is a 10% improvement in CoreMark performance when using the 64-bit OS, while consuming the same power. For ECDSA the difference is much more significant. Both the signing and verification are 8× faster on the 64-bit OS. This is due to the very inefficient implementation of the algorithms on the 32-bit Instruction Set Architecture (ISA). On 32-bit, there are 8× more instructions executed compared to the 64-bit ISA. At memory and networking levels we did not observe any significant difference between the two types of OS. However, we observed a slight improvement in storage performance. There is a 2× improvement in both direct write and buffered read bandwidths. This is due to more efficient drivers for the direct write, and double access size for the buffered read which uses the main memory. In summary, we recommend the use of the 64-bit OS on RP4 for improved performance.

### 4.3 Performance Analysis

In this section, we aim to answer the questions related to the performance of the blockchain frameworks. We start by answering the first part of **Question 1**, that is, why does Graviton achieve higher performance than Xeon(cloud) when running Fabric? Based on our benchmarking in Section 4.2, the advantage of Graviton may stem from its higher performance when using all the cores or from its higher memory bandwidth compared to Xeon(cloud). To further investigate this, we profile Fabric with `perf` Linux tool. We observe that the average number of CPU cores used at runtime is below 1.3, meaning that Fabric mostly uses a single core. Hence, Graviton could not take advantage of its higher multi-core performance. On the other hand, memory references have a higher impact on the performance of Fabric. Our analysis shows between 5 and 6.5 billion last-level cache (LLC) references in 120 seconds, out of which 10% are misses. Let us suppose that all LLC references are hits, each reference takes 60 cycles [10], the references are not overlapped, and the clock frequency is 3.5 GHz. This results in 90-110s...
out of the 120s spent in accessing the LLC. Although this is a simplified analysis, it shows that Fabric’s execution is cache/memory-intensive. As such, Graviton achieves higher performance due to its higher LLC and main memory bandwidth.

In contrast, the execution of Quorum exhibits around 4.5 and 7.6 billion LLC references in 360s on follower peers and the leader peer, respectively. With the same assumptions as above, the time spent in accessing the LLC is around 80s, or 131s for the leader, out of the 360s of runtime. Hence, Quorum is less cache/memory-intensive compared to Fabric. Even at CPU core utilization, Quorum is less intensive compared to Fabric since it uses only 0.6 and 0.8 cores, on average, with Raft and IBFT, respectively. Hence, Quorum exhibits higher performance on the Xeon-based systems compared to Graviton, but this is because of poor utilization of the hardware resources.

Next, we answer Question 2, namely, why does Xeon(cloud) achieve higher performance than Xeon(edge) when running Fabric, while Xeon(edge) has higher performance when running Quorum? We show in Section 4.2 that Xeon(edge) has better CPU performance but lower storage access latency and networking bandwidth compared to Xeon(cloud). Hence, we investigate the effect of slower storage and different networking bandwidth on Fabric. To investigate the effect of slower storage, we introduce artificial delays during the read and write operations in the YCSB smart contract. However, we do not observe any difference in Fabric’s throughput.

To investigate the effect of slower networking, we use tc Linux tool to limit the bandwidth of the networking interface on each Xeon(cloud) peer of the Fabric network. As shown in Figure 6 for six Fabric peers and one orderer, networking bandwidth has a significant impact on the performance of Fabric. When limiting the bandwidth of Xeon(cloud) to 1 Gbps or 500 Mbps, Fabric’s throughput is similar to the one on Xeon(edge). If the bandwidth is further limited to 200 and 100 Mbps, the throughput drastically decreases to around 350 and 170 tps, respectively. This can be explained by the interplay between transaction size, request rate, and networking bandwidth. In our experiments, each transaction operates on a record (key-value) of around 1 kB. The endorsement policy is AND, meaning that each of the six peers needs to endorse the transaction and send the read-write sets back to the client. When the client submits the transaction to the ordering service, the overhead is 

$$(N + 1) \times$$

due to the read-write states endorsed by the $N$ peers plus the original transaction. Let us take the example of the 3,000 tps request rate. This leads to at least 21 MB/s sent to the ordering service, without considering the overheads of meta-data. This is close to the 25 MB/s bandwidth on a 200 Mbps link.

At a closer look, we observe that Fabric’s ordering service is a bottleneck because all the transactions and their endorsements are sent to this service. But in our default setup, we use a single orderer. Hence, we increase the number of orders, selecting setups with 4, 6, and 8 orders. We then run experiments in both the 10 Gbps and 200 Mbps networks. As shown in Figure 7, increasing the number of orderers to a certain value may help in a low-bandwidth network. For example, having four orderers instead of one leads to a change in throughput from 350 tps to 550 tps in a 200 Mbps network. But increasing the number of orders further leads to a drop in throughput. For example, using 8 orderers in a 200 Mbps network results in 175 tps. This is because of Raft overhead which grows with the number of nodes that need to follow the leader. This overhead impacts the performance of Fabric even in high-bandwidth networks, as shown in Figure 7 for the 10 Gbps link.

Similarly, we can explain the drop in throughput shown by 10 Xeon(edge) peers in Figure 2a. When we limit the bandwidth of Xeon(cloud) to 1 Gbps, we obtain a throughput of 607 tps on 10 peers, similar to 588 tps on Xeon(edge). This, together with the results presented above, highlight the trade-off between networking bandwidth and the number of orders in Fabric. In particular, it is not always possible to have high bandwidth networking in the real world, especially in cross-continent setups. For example, our measurements on AWS cloud expose bandwidths of around 10 Mbps across continents. Hence, running Fabric in a cross-continent setup is challenging.

In contrast to Fabric, networking has a negligible impact on the performance of Quorum, as shown in Figure 8. Similar to the analysis of Fabric, we use Xeon(cloud) and the tc Linux tool to limit the bandwidth of the networking interface on each Xeon(cloud) peer of the Quorum network. When using Raft consensus, we observe a small (5%) drop in throughput only in a 100 Mbps networking link. When using IBFT, the best performance is achieved in a 500 Mbps link, while in a 10 Gbps network, the throughput of Quorum(IBFT)
Figure 8: Effect of networking bandwidth on Quorum.

is 7% lower compared to the 500 Mbps network. However, these values are within the standard deviation of the measurements, thus, we do not attribute the throughput drop to networking bandwidth.

Next, we answer the second part of Question 2, namely, why does Xeon(edge) have a higher performance than Xeon(cloud) when running Quorum? Concretely, Xeon(edge) exhibits up to 15% and 26% improvement over Xeon(cloud) when running Quorum(Raft) and Quorum(IBFT), respectively. We attribute this difference to the higher CPU performance of Xeon(edge) compared to Xeon(cloud). Recall that, in Section 4.2, we show that Xeon(edge) is 22% faster than Xeon(cloud) in ECSDA operations. Since the signing operations take the most time in Quorum’s execution compared to other functions, as shown in Listing 1, Xeon(edge) has an advantage over the other systems.

Fabric uses a different curve for its ECSDA operations, namely secp256r1 as opposed to the secp256k1 in Quorum. Our measurements in Section 4.2 show that it is less optimized. In particular, Figure 4 shows that the IPC of secp256k1 is higher compared to secp256r1. Nonetheless, the ECSDA operations take the most time in Fabric’s execution compared to other functions, as shown in Listing 2.

To answer Question 3, we take a closer look at the performance of Fabric on TX2. As shown in Figure 2a, TX2 exhibits a throughput that is 6 – 9x lower compared to Graviton. In contrast, TX2 exhibits a throughput that is only around 2x smaller compared to Graviton when running Quorum. For Quorum, the reason is clear: TX2’s CPU core is around 2x slower compared to Graviton’s CPU core. But for Fabric, there is an interplay among all the system’s components. As shown previously, Fabric’s execution is memory-intensive and the memory of TX2 has almost 5x lower bandwidth compared to the memory of Graviton. Hence, when using 4 and 6 peers, the lower performance of the CPU and memory of TX2 lead to lower Fabric throughput. On 8 and 10 nodes, besides the CPU and memory, there is the 1 Gbps networking link of TX2 that hinders the throughput. This is similar to our analysis on networking bandwidth for Xeon(edge) versus Xeon(cloud). We also note that a similar analysis applies to RP4, just that this edge device has even lower performance compared to TX2.

Lastly, we evaluate the impact of the endorsement policy on the performance of Fabric. As mentioned before, we use an AND policy by default in our experiments. This means that all the peers in the network need to execute and endorse a transaction. At the other extreme, there is the OR policy which means that only one peer needs to endorse a transaction. As such, it is expected that OR policy should yield higher throughput due to higher transaction execution parallelism. Indeed, the throughput of Fabric on 4, 6, 8, and 10 Xeon(edge) peers, respectively, is 1.4, 1.5, 1.5, and 2.3 times higher when using OR compared to AND policy, as shown in Figure 9a. In addition, with more peers in the network, the throughput continues to grow as opposed to dropping in the case of AND policy. This can be explained by both the increasing parallelism in the execution phase and the smaller message size in the ordering phase which leads to lower networking overhead. Note that only one endorsement needs to be forwarded to the ordering service when using OR policy.

On the other hand, the improvement in throughput on TX2 when using OR endorsement policy is between 1.5x higher on 4 peers and 2.3x higher on 10 peers. This gap is because (i) the throughput of Fabric with OR policy slowly increases due to higher parallelism, and (ii) the throughput of Fabric with AND policy decreases due to networking overhead. Hence, the gap becomes bigger.

4.4 Power Analysis

In this section, we analyze the power usage of the edge-based systems, namely Xeon(edge), TX2, and RP4, when running Fabric and Quorum. First, we observe that Fabric is more power-hungry than Quorum. For example, Xeon(edge) uses around 1.4x and 1.5x more power to run Fabric compared to Quorum(Raft) and Quorum(IBFT), respectively. TX2 uses up to 1.6x and 1.8x more power to run Fabric compared to Quorum(Raft) and Quorum(IBFT), respectively. Finally, RP4 uses up to 1.2x more power to run Fabric compared

| Question 2 | Example of perf report output for Quorum(IBFT) on Xeon(edge). |
|------------|---------------------------------------------------------------|
| 5.88% | 256k1_fe_sqr_inner |
| 4.87% | runtime.scancobject |
| 3.99% | runtime.findObject |
| 3.95% | 256k1_fe_mul_inner |
| 3.98% | github.com/ethereum/go-ethereum/vendor/golang.org/x/crypto/sha3/secp256k1_fe_sqr_inner |
| 2.52% | runtime.greypobject |
| 1.63% | github.com/ethereum/go-ethereum/rp.encodedString |
| 1.55% | 256k1_ge_set_xo_var |

| Question 3 | Example of perf report output for Fabric on Xeon(edge). |
|------------|---------------------------------------------------------------|
| 15.06% | p256MulInternal |
| 8.82% | p256SqrInternal |
| 5.01% | runtime.mallocgc |
| 2.62% | runtime.scancobject |
| 2.19% | p256SqrInternal |
| 2.56% | github.com/golang/protobuf/proto_unmarshalUint64Value |
| 2.49% | crypto/elliptic.p256Select |
| 2.38% | runtime.adjustframe |
| 2.25% | runtime.enterersyscall |
| 2.10% | crypto/elliptic.p256PointAddAffineAsm |
to both Quorum(Raft) and Quorum(IBFT). This is because Fabric is more CPU- and memory-intensive compared to Quorum. Recall that Fabric uses 1.3 CPU cores, on average, compared to 0.6 and 0.8 CPU cores used by Quorum(Raft) and Quorum (IBFT), respectively. Moreover, it is well-known that the CPU power accounts for the most significant part of a system’s power [18, 35].

Second, Quorum(Raft) uses more power than Quorum(IBFT), as shown in Figure 2h. In particular, Quorum(Raft) uses up to 13%, 13%, and 1% more power that Quorum(IBFT) on Xeon(edge), TX2, and RP4, respectively. This is intriguing since Quorum(IBFT) has a slightly higher CPU utilization compared to Quorum(Raft). But at a closer look using Linux perf tool, we observe that the IPC of Quorum(Raft) is higher compared to Quorum(IBFT). This suggests that some of the cycles of Quorum(IBFT)’s execution are spent on waiting for cache/memory operations and these cycles usually incur less power compared to the execution of other instructions [41, 53]. Indeed, Quorum(IBFT) exhibits up to 30% more cache references compared to Quorum(Raft), out of which 21% are cache misses.

For Fabric, there is a slight increase in power when AND endorsement policy is used compared to OR policy, as shown in Figure 9b. Specifically, there is up to 13% and 14% increase in power when using AND policy on Xeon(edge) and TX2, respectively. But this is expected because AND policy uses all the peers during the endorsement phase, thus, incurring more power compared to OR.

Third, we compare the power efficiency across the three edge systems under test. Power efficiency is reflected by the performance-to-power ratio (PPR), computed as

\[
PPR = \frac{\text{Throughput}}{\text{Power}} \quad \text{Transactions per Joule (ppj)}
\]

and expressed in transactions per Joule (ppj). For this, we select the number of peers that yield the best performance and present the results in Table 2. We observe that TX2 exhibits the best PPR across all systems and when running all three blockchains. Compared to Xeon(edge), TX2 exhibits better PPR because it uses much lower power, as shown in Figure 2g and Figure 2h. Compared to RP4, TX2 exhibits better PPR because it yields higher performance using just a bit more power. For example, TX2 exhibits 35% higher throughput while using just 7% more power when running Fabric on 4 peers compared to RP4.

These PPR results give rise to Question 4, namely, why is the power efficiency of RP4 lower compared to TX2? The answer to this question is indicated in our system analysis in Section 4.2. For example, one CPU core of RP4 has between 16% and 30% lower performance compared to one TX2 CPU core, depending on the benchmark considered. For example, one TX2 core exhibits 16% higher performance while using 17% more energy compared to RP4 when running CoreMark. When running cryptography operations, TX2 has even higher performance while using slightly higher power. Hence, its PPR is higher compared to RP4. Part of the lower performance can be attributed to the 26% lower clock frequency of RP4. Another source of inefficiency is the memory hierarchy. For example, the memory bandwidth of TX2 is 3× higher compared to RP4.

### 4.5 Cost Analysis

In this section, we answer Question 5 by conducting a cost analysis across both edge and cloud systems. This analysis is useful for permissioned blockchain users that want to host their own nodes. It helps the users in determining whether to host these nodes at the edge or on the cloud, and on what type of system. On the cloud, the utilization of an instance is usually billed every second, based on a price that may vary according to the datacenter location. At the edge, we use a cost model to estimate the total cost of ownership (TCO) which considers the fixed hardware cost, the continuing energy cost, and the manpower cost for system administration. To this end, we adopt the cost model used in our previous works [34, 36].
Table 3: Cost model parameters.

| Notation | Description | Values |
|----------|-------------|--------|
| $T$      | cluster lifetime | 3 years (26,280 hours) |
| $N$      | number of cluster nodes | 10 (6) |
| $C_{ph}$ | cost of electricity per hour [USD] | 0.10 |
| $C_{mh}$ | cost of manpower per hour [USD] | 6.85 (5,000 per month) |
| $C_a$    | cost of acquisition per node [USD] | 5,000 | 800 | 100 |
| $P_o$    | average power per node [W] | Fabric: 101.6 | 5.1 | 4.2 |
|          |             | Quorum(Raft): 73.4 | 4.1 | 2.4 |
|          |             | Quorum(IBFT): 65 | 3.2 | 3.7 |

Figure 10: Comparison of cost across all systems.

The edge TCO model adopted in this paper consists of the equipment cost over a period of time, which is usually three years [36], and the cost of electricity,

$$C = N \cdot C_s + N \cdot T \cdot P_o \cdot C_{ph} + T \cdot C_{mh}$$  \hspace{1cm} (2)

where $N$ is the number of nodes, $C_s$ is the cost of buying one node, $T$ is the lifespan of the cluster in hours, $P_o$ is the average power of one node in kilo-Watts (kW), $C_{ph}$ is the electricity cost per kilo-Watt-hour (kWh), $C_{mh}$ is the cost of manpower per hour. The assumption is that node utilization, hence, the average power is constant throughout the lifespan of the cluster. In reality, the power depends on the request rate, but here we suppose we have a high enough request rate to keep the blockchain busy. To compare edge nodes with cloud nodes, we divide the TCO by the number of nodes and the lifespan in hours to get the average price per hour for a single edge node.

The model parameters are summarized in Table 3. For a fair comparison with the cloud costs used in this paper, which represent the AWS region hosted in Oregon, we use the price of electricity in Oregon, which is $0.09 USD for commercial entities [11]. For manpower cost, we use $5,000 per month, which is in the lower range of the salary of an Amazon datacenter technician [27]. The acquisition price of the nodes is based on our own records. The number of nodes and the corresponding average power per node depend on the blockchain framework. We select the number of nodes that yield the best performance, which is 10 for Fabric and Quorum(Raft), and 6 for Quorum (IBFT).

When computing the TCO, we consider two scenarios. First, we assume that there needs to be a technician in charge of setting up and providing maintenance for the hardware nodes. Second, we assume that both the edge and the cloud need a system administrator to set up and operate the nodes, hence, we do not include this manpower cost in the TCO. Here, we assume that the cloud is used as Infrastructure-as-a-service (IaaS). The price per hour per node for Fabric is shown in Figure 10 for both these scenarios. Our key observation is that the edge is much cheaper than the cloud when manpower cost is disregarded. For example, Xeon(edge), TX2, and RP4 are respectively 1.5X, 10X, and 75X cheaper than Graviton.

On the other hand, adding manpower cost results in almost 2X higher cost of the edge nodes compared to the cloud nodes. For example, Xeon(edge) costs $0.884 per hour, while Xeon(cloud) costs $0.476 per hour. These results show that the cost of continuous operation due to energy has little impact in the long run. Instead, the hardware and manpower costs have a high impact, and this may lead the users to choose cloud computing over on-premise setups.

5 CONCLUSIONS

In this paper, we conducted an in-depth performance evaluation of two widely-used permissioned blockchains on a diverse range of hardware systems. The two selected blockchains, Hyperledger Fabric and ConsenSys Quorum represent execute-order-validate and order-execute transaction flows, respectively. In addition, we analyze the performance of both Quorum with Raft and Quorum with IBFT to represent both CFT and BFT application scenarios. The hardware systems represent both the cloud and the edge, as well as, both x86/64 and ARM architectures. For example, we use cloud instances with Intel Xeon and ARM-based Graviton CPUs, edge servers with Intel Xeon CPU, and edge devices such as Jetson TX2 and Raspberry Pi 4.

Among the key observations, we show that ARM-based Graviton cloud instances achieve higher performance than Xeon-based instances due to impressive CPU and memory performance. Moreover, these instances are around 35% cheaper than their Xeon counterparts. On the other hand, edge devices based on ARM CPUs exhibit much lower performance but higher power efficiency compared to Xeon-based servers. Depending on the application scenario, if high throughput is not required, then low-power edge nodes can be used to run the blockchain. In the long run, hosting blockchain nodes at the edge (on-premise) may lead to substantial savings in cost, if the manpower cost is not included in the total cost of ownership.

ACKNOWLEDGMENTS

This research is supported by the National Research Foundation, Singapore under its Emerging Areas Research Projects (EARP) Funding Initiative. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not reflect the views of National Research Foundation, Singapore.

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