Diablo-v2: A Benchmark for Blockchain Systems

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Abstract

With the recent advent of blockchains, we have witnessed a plethora of blockchain proposals. These proposals range from using work to using time, storage or stake in order to select blocks to be appended to the chain. As a drawback it makes it difficult for the application developer to choose the right blockchain to support their applications. In particular, the scalability and performance one can obtain from a specific blockchain is typically unknown. The claimed results are often obtained in isolation by the developers of the blockchain themselves. The experimental conditions corresponding to these results are generally missing and the lack of details make these results irreproducible.

In this paper, we propose the most extensive evaluation of blockchain to date. First, we show how the experimental settings impact the performance of 6 state-of-the-art blockchains and argue for more detailed experiments. Second, and to cope with this limitation, we propose a unifying framework to evaluate blockchains on the same ground. The framework includes a suite of 5 realistic Decentralized Applications (DApps), helps deploy the blockchain nodes at different scales and evaluate their performance. Finally, we show that none of the tested blockchains can yet support the load of these realistic DApps.

1 Introduction

With the growing adoption of blockchain technology, the number of readily-available solutions have multiplied dramatically. As of March 2021, approximately five thousand distinct cryptocurrencies have been reported on a single website [2]. Each of these implementations aims at offering improvements through distinctive features, focused on the performance and application to various use-cases. Although a number of these variants could, in theory, be running on multiple instances of the same blockchain, they are often packaged as their own standalone implementation with distinctive features. A recent survey [22] highlights the breadth of the blockchain landscape through a classification of blockchains, listing 8 different protocols to select nodes that are tasked with proposing blocks, 13 different consensus protocols and 9 data structures to store transaction information. This diversity illustrates a probably small subset of all blockchain implementations that exist today.

This plethora of blockchain proposals raises the question of which proposal is the ideal blockchain for a particular application. Unfortunately, most of these proposals are not reported in scientific publications. They are at best presented in the form of white papers that present a 10-000-foot-view of their implementation details. As an example, the Ethereum yellow paper [33] presents the technicalities of the Ethereum Virtual Machine but does not explain how Ethereum participants can reach consensus on a unique block at a given index of the chain. In order to analyse the underlying protocols of such blockchains, researchers typically had to look at the available source code before being able to reason about the correctness of the protocols [13].

Another approach is for researchers to evaluate blockchains as black boxes by generating workloads and measuring their performance. Following this approach, many announcements were made online about the performance of a specific blockchain. As an example, Avalanche was recently claimed to achieve 4500 TPS with a 2 second latency on its official website [1], however the environmental settings are not communicated. This could be confusing, especially given that a technical report or white paper presented a peak throughput at 1300 TPS [24].

There have been some thorough scientific publications about blockchain performance [3, 11, 12, 16, 18, 26]. These provide usually enough details to make the results reproducible. The detailed environmental settings give the reader the ability to get similar performance by re-running the experiments. Most of these evaluations [3, 11, 12, 16, 18, 26], however, evaluate few blockchains on synthetic workloads that are not representative of realistic use-cases. With the growing amount of use-cases and the ability of modern blockchains to run Decentralized Applications (DApps), one

Blockchain	Claimed results			Observed results			Difference	
	throughput	latency	setup	throughput	latency	setup	throughput	latency
Algorand	1K–46K TPS [20]	2.5–4.5 s [20]	?	885 TPS	8.5 s	testnet	0.89×	1.89×
Avalanche	4.5K TPS [23]	2 s [6]	?	323 TPS	49 s	datacenter	0.07×	24.5×
Solana	200K TPS [27]	1 s [35]	150 nodes	8845 TPS	12 s	datacenter	0.04×	12×
Average							0.32×	12.8×

Table 1. Differences between claimed performance and actual performance of different blockchains. The observed results were obtained in a geo-distributed network of 200 machines, as detailed in §6. The testnet and datacenter configurations are detailed in §5.1.

can evaluate blockchain when running real applications, under an existing workload trace. In this paper, we make three main contributions:

1. We propose Diablo-v2 (DIstributed Analytical BLOckchain benchmark framework)[1], written in 10,083 lines of Go code, that allows developers to evaluate their blockchain with real applications. This framework features several DApps including (i) a multiplayer game, (ii) an exchange with the Nasdaq workload, (iii) a web service experiencing the Fifa requests during the soccer worldcup, (iv) a mobility service DApp with a Uber workload, (v) a video sharing service with a YouTube workload.
2. We thoroughly evaluate the performance of 6 state-of-the-art blockchains, including Algorand [14], Avalanche [24], Ethereum [33], Diem [7], Quorum [10] and Solana [35]. We demonstrate that their performance is heavily dependent on the underlying experimental settings in which they are evaluated. In particular, we observe important differences between claimed results and the results we obtain. We thus argue in favor of more detailed blockchain experiments.
3. Our development of DApps in the Solidity, Move and Teal languages revealed that executing generic programs on blockchains can be challenging. First, some of the supported programming languages are too low-level to be written easily without a higher level programming language. Second, the programming languages can have limited support (like for floating point functions). Third, real DApps may not even execute successfully as some of their functions would consume more than the maximum allowed gas per block. On the bright side, the blockchains based on the `geth` virtual machine seem to handle generic programs the best.
4. Finally, our main observation is that, despite being innovative in many regards, the evaluated blockchains are not capable of handling the demand of the selected centralized applications when deployed on modern commodity computers from individuals across the world. We also note that the evaluated Byzantine fault tolerant blockchains are more impacted by constantly high workloads than other blockchains. More research is thus necessary to reduce the overhead of mainstream blockchains before they can fully serve a highly demanding DApp at large scale.

[1]Diablo-v2 is a follow-up of the original Diablo framework [8].

The rest of the paper is organized as follows. We first describe the problem (§2) and then list the 5 decentralized applications we propose (§3). We present our benchmark framework (§4) and our experimental settings (§5) before demonstrating the performance we obtain with 6 state-of-the-art blockchains (§6). Finally, we present the related work (§7) and we conclude by arguing for a more thorough evaluation of upcoming blockchains (§8).

2 Problem Statement

It is common to see new blockchain protocols offering supposedly higher performance results than existing ones, however, these results are usually obtained in isolation and are often non-reproducible, which makes them hard to compare. Table 1 illustrates the magnitude of the differences between the announced results of recent blockchains and our actual measurements.

Solana [35] claims 250,000 TPS and 200,000 TPS on a 50-node and a 150-node testnets, respectively [27]. However, Solana generally recommends GPU and the special AVX2 Intel instructions [28]. It also claims sub-second finality [35] meaning that transactions can supposedly be committed in less than 1 second. However, as Solana can fork it is recommended to wait for additional appended blocks (or "confirmations") to ensure a transaction does not abort [5]. We experimented Solana on machines with up to 36 vCPUs and 72 GiB memory and set the number of confirmations to 30 [19] but could only observe an average throughput of up to 8,845 TPS and an average latency of at least 12 seconds (§6).

Avalanche [24] was initially presented in a technical report in 2018 where it could achieve 1300 TPS on 2000 machines with 2 vCPUs and 4 GiB memory each [24]. Avalanche now supports smart contracts and achieves more than 4500 TPS [23] with a 2 second latency [6]. While the settings where these latest results were obtained are not detailed, our

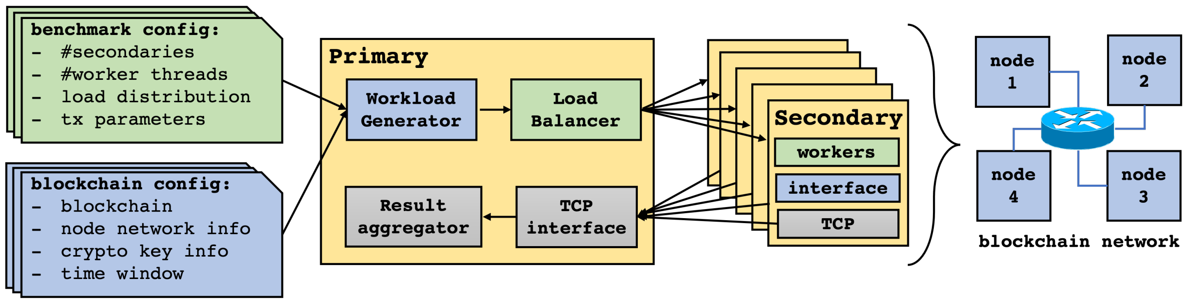


Figure 1. The architecture of Diablo-v2 comprises configuration files in order for the Primary node to send a workload for a dedicated blockchain to a set of Secondaries that then send requests to and collect performance results from blockchain nodes.

experiments showed that Avalanche reaches a peak throughput of 323 TPS and an average latency of 49 seconds. Algorand [14] is known to achieve 1000 TPS with native transactions, but it recently featured Teal smart contracts and was expected to reach 46,000 TPS in 2021 [20]. Unfortunately, it remains unclear whether it can achieve similar performance when deployed in a large network in different countries. In our experiments, we noticed that the highest average throughput across all our experiments is 885 TPS, and after communicating with the development team we got confirmation that only the peak throughput could reach more than 1000 TPS.

Overall, the results observed are suprisingly far from the announced results. For these three blockchains alone, the measured average throughput represents about a third (0.32×) of the announced throughput whereas the measured average latency is about 13× higher than the announced latency. This paper is precisely about offering a benchmark to evaluate blockchains on the same ground when running realistic applications.

3 The Decentralized Applications Suite

In this section, we present the five default Diablo-v2 decentralized applications (DApps) used to measure the performance of blockchains in a realistic setting. As summarized in Table 2, each of these DApps illustrates a distinct behavior and runs a workload trace taken from a real centralized application. For the sake of compatibility with all blockchains, we developed DApps in both the Solidity v0.7.5 (language supported originally by Ethereum but also by Avalanche, Quorum and Solana), the PyTeal v5 (Python language binding for Algorand smart contracts) and the Move v3 (language for Diem smart contracts) programming languages.

Exchange DApp / Nasdaq. We implemented an exchange DApp as a decentralized exchange (DEX) with a workload trace taken from the National Association of Securities Dealers Automated Quotations Stock Market (Nasdaq). The Nasdaq experiences a boom of trades at its opening at 9AM Eastern Time Zone. We extracted the number of trades for Google (GOOGL), Apple (AAPL), Facebook (FB), Amazon (AMZN) and Microsoft (MSFT) from the official website [4]. These workloads proceed in burst by experiencing an initial demand of about 800 TPS for Google, 1300 TPS for Amazon, 3000 TPS for Facebook, 4000 TPS for Microsoft and 10,000 TPS for Apple before dropping to 10–60 TPS. The accumulated workload, denoted GAFAM, runs for 3 minutes and experiences a peak of 19,800 TPS before dropping between 25–140 TPS.

The exchange DApp is implemented as an `ExchangeContractGafam` smart contract with functions `checkStock`, `buyGoogle`, `buyApple`, `buyFacebook`, `buyAmazon`, `buyMicrosoft`. Each order consists of invoking the corresponding `buy*` function that, in turn, checks the availability of the stocks before updating the number of available stocks and emitting a corresponding event. More specifically, the process consists in a fungible token available in limited supply implemented by a single integer counter. Each transaction buys 1 token by decrementing the counter after checking that this counter is greater than 0.

Gaming DApp / Dota 2. We implemented a gaming DApp executing the trace of the most popular game on Steam, which is a Multiplayer Online Battle Arena video games called Dota 2 [32]. The number of Steam users peaked at 26.85 million in March 2021 [29]. Our DApp comprises players who interact with each other and with the environment.

The gaming DApp is implemented as a smart contract `DecentralizedDota` whose `update` function moves the positions of 10 players along the x-axis and y-axis of a 250-by-250 map so that they turn back whenever they reach the limit of the map. The trace lasts for 276 seconds invoking at an almost constant update rate of about 13,000 TPS, which is particularly demanding.

Web service DApp / Fifa. We implemented the web service DApp as the number of requests to the Fifa website during the 1998 soccer world cup. More than 1.35 billion requests to the Fifa website were recorded over the course of the 84 days of the world cup with an average requests length of 3689 bytes. In particular, during the final match

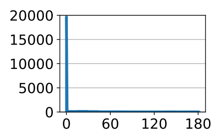
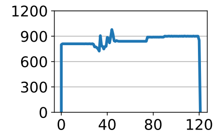
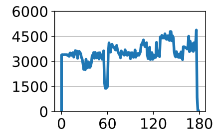
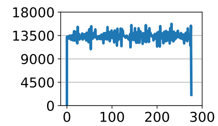
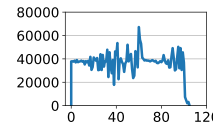
DApp	Exchange	Mobility service	Web service	Gaming	Video sharing
Workload					
Source trace	Nasdaq	Uber	Fifa	Dota 2	YouTube
Characteristics	Burst	Compute intensive	Contended	High sending rate	Very high sending rate

Table 2. Decentralized applications and their associated workload based on realistic traces used as benchmarks in Diablo-v2. Each workload figure shows the number of submitted transaction per second (TPS on the y-axis) for the duration of the run (seconds on the x-axis).

on June 30th, 1998, between 11:30PM and 11:45PM, the total number of requests reached 3,135,993 for an average request per minute of 209,066, a total of 8.5 GB transferred and an average of 580 bytes transferred per minute. During the most demanded minute of this period, 215,241 requests were sent, translating into an average of 3587 TPS.

The web service DApp is implemented as a simple `Counter` smart contract, with an `add` function, that gets incremented at each request, hence its workload is highly contended. The duration of the workload is 176 seconds, sending an overall 3, 500 transactions at a rate varying from 1416 to 5305 requests per second.

Mobility service DApp / Uber. We implemented a mobility service DApp based on a study of Uber requests in New York City (NYC) from 2018 [9]. The study reports a peak of 16,496 requests per hour between January 2015 and March 2015. As the demand grew since 2015, this peak throughput does no longer reflect the Uber demand. The average Uber demand between 2015 and 2019 grew from 70,348 to 556,387 requests per day with an increase of monthly users of 7.91.[2] We thus approximate the current Uber demand in NYC to $16,496 \times 7,91 = 130,483$ requests per hour, which translates into 36 TPS. To extrapolate this demand to Uber world wide, we observe that in the first quarter of 2019 nearly 1,55 billion Uber trips were booked around the world while 63,48 million Uber trips were booked in NYC alone [31]. As the NYC demand represents 1/24 of the world demand, we derive the Uber demand globally to $24 \times 36 = 864$ TPS.

The mobility service DApp consists of a `ContractUber` smart contract whose function `checkDistance` computes the Euclidean distance between the customer (the requester) and 10,000 drivers in an area (a 2-dimension grid) of $10,000 \times 10,000$ in order to match the closest driver to the customer. As neither the PyTeal nor the Move languages support floating points or define the square root function $\sqrt{}$ to compute Euclidean distances, we implemented the Newton's integer square root function in Solidity, PyTeal and Move languages, and used it to compute the Euclidean distance. As Algorand DApps state is limited to key-value pairs, the PyTeal implementation of `ContractUber` only stores the position of one driver and computes the Euclidean distance to this unique driver 10,000 times. As the function executes a loop with 10,000 iterations computing the distance, the mobility service DApp is computation intensive.

Video sharing DApp / YouTube. We implemented a video sharing DApp based on the number of videos uploaded to YouTube [15]. More precisely, from the YouTube traffic observed during 3 months of 2007, we extracted the day with the peak request rate and the hour within this day with the peak request rate of 1,680,274 transactions per hour. We normalized this result to obtain a request rate of 467 transactions per second. Between 2007 and 2021, the number of videos uploaded to YouTube has been multiplied by 83 [30], hence we approximate the average throughput to $467 \times 83 = 38,761$ TPS, which makes this DApp very demanding. The video sharing DApp corresponds to a smart contract called `DecentralizedYoutube` with an `upload` function that gets some video data as a parameter and assigns the requester's address to the data before emitting a corresponding event.

4 The Benchmark Overview

Diablo-v2, whose architecture is depicted in Figure 1, is a benchmark to evaluate blockchains with real applications. To facilitate distributed workload generation, Diablo-v2 comprises two main components, a single *Primary* and multiple *Secondaries*. For the sake of extensibility, Diablo-v2 offers a blockchain abstraction with 4 functions that a developer can implement to compare their new blockchain protocol to existing blockchains and Diablo-v2 also offers a workload specification language for a developer to add new DApps.

Primary. The purpose of the Primary machine is to coordinate the experiment: it generates the workload and dispatches it between Secondaries, launches the benchmark, aggregates the results and reports them back.

[2] https://toddwschneider.com/dashboards/nyc-taxi-ridehailing-uber-lyft-data/.

Prior to starting the benchmark, its workload generator parses the benchmark and blockchain configuration files. A benchmark configuration file indicates the requests type, whether requests are native transfers or DApp invocations, and their distribution between Secondaries and blockchain nodes over time (§4). For each workload invoking DApps, the Primary also deploys the smart contracts listed in the benchmark configuration file. The blockchain configuration file is necessary to generate the workload appropriately because the transactions distribution depends on the number and locations of the deployed blockchain nodes. Then, the Primary transmits a description of the transactions to the Secondaries, wait for all Secondaries to be ready and informs all Secondaries when to start the benchmark.

Once the benchmark is complete, each Secondary sends its results to the Primary through a TCP interface and a results aggregator collects them to output a JSON file, indicating the start time and end time of each transaction (as recorded by the Secondaries). These timestamps can then be used postmortem to generate time series and analyze the distribution of latencies (e.g., Fig. 6) or more simply to output aggregated values like the average (e.g., Fig. 3).

Secondary. Secondaries are responsible for the presigning of the transactions and the execution of the workload, interacting directly with blockchain nodes for the system under test. The number and specification of the Secondaries are typically chosen to match the resources allocated to the blockchain (cf. Table 3) to be able to stress test the blockchain. Note that each Secondary can send requests to multiple blockchain nodes.

Each Secondary spawns a number of explicit worker threads as told by the Primary and indicated in the benchmark configuration file. (Note that the level of concurrency can be higher due to implicit go routines.) These worker threads mimic individual clients issuing requests concurrently. The Secondary schedules the transactions following the workload distribution instructed by the Primary.

The Secondary interacts with the blockchain through a client interface specific to each blockchain. The current clock is recorded as the submission time right before a transaction is sent. The Secondaries constantly check if the submission time is not too late compared to the time demanded by the Primary and emit a warning otherwise. Each worker thread constantly polls the blockchain nodes to obtain the last block and check whether it contains sent transactions. When a sent transaction is detected within a block, the current clock time is recorded as the decision time for this transaction.

Blockchain abstraction. To make Diablo-v2 compatible with various blockchain implementations, we abstract away the main components of a blockchain. The Diablo-v2 benchmark specification interacts with the resulting blockchain abstraction. Let C be the set of clients. A blockchain is modelled as a tuple $\langle E, R, I \rangle$ where E is the finite set of *endpoints* that act as blockchain nodes, R is a finite set of resources (e.g., account balance, smart contract state) maintained in the blockchain state, and I is a potentially infinite set of interactions types (e.g. asset transfer, smart contract function invocation) between a client and the blockchain. An interaction event is denoted as a tuple $\{(c, i, r, t)\}$ with $c \in C$, $i \in I$, $r \in R$ and $t \in \mathbb{R}$.

The benchmark specification contains a function M mapping the Secondaries to the blockchain endpoints, a set φ^R of resources needed for the test and the interactions $\{(\varphi^c, \varphi^i, \varphi^r, t)\}$ where $\varphi^c \in \varphi^C$, $\varphi^r \in \varphi^R$, $t \in \mathbb{R}$. More precisely, $M : S \times E \Rightarrow \varphi^C$ where S is the set of Secondaries, E is the set of endpoints, both available only at runtime, and φ^C is the set of specified clients, each specified client is implemented by an explicit worker thread. The two types of interactions are `transfer_X` to transfer `X` coins from one account to another one and `invoke_D_Xs` to invoke a Dapp `D` with the parameters `Xs`.

To add a new blockchain, one has to implement at least one of these interaction types as well as 4 functions that convert the benchmark specification to an executable test program: (i) `s.create_client(E)` where $s \in S$, (ii) `create_resource(`φ^r`)` and $\varphi^r \in \varphi^R$, (iii) `encode(`φ^i, r, t`)` where $t \in \mathbb{R}$ and $r \in R$, and (iv) `trigger(`i, r, t`)`. Since these functions are relatively fine grained, the implementations for the blockchains we test are small sized: between 1,000 and 1,200 LOC of Go.

Workload specification. The benchmark configuration file specifies the function M, the set φ^R and the interactions $\{(\varphi^c, \varphi^i, \varphi^r, t)\}$ described above. For example, the gaming DApp configuration file below defines 4 variables: `acc` (line 4) is a set of 2,000 user accounts, `dapp` (line 5) is a set containing one instance of the `dota` DApp. Those 2 variables form the φ^R set. The variable `loc` (line 2) is the set of Secondaries tagged with the string `us-east-2` (an AWS availability zone) and `end` (line 3) is the set of all endpoints. These two variables are used in the definition of the M function (lines 7-10) which defines 3 clients invoking the DApp `dapp` from accounts in `acc` with the parameters parsed from `update(1, 1)` at the rate specified in the `load` section (lines 16-19): each client sends 4,432 TPS for the first 50 seconds then 4,438 TPS for the next 70 seconds which is the end of the test.

```
1  let:
2    - &loc { sample: !location [ "us-east-2" ] }
3    - &end { sample: !endpoint [ ".*" ] }
4    - &acc { sample: !account { number: 2000 } }
5    - &dapp { sample: !contract { name: "dota" } }
6  workloads:
7    - number: 3
8      client:
9        location: *loc
10       view: *end
11       behavior:
12         - interaction: !invoke
```

```
          from: *acc
          contract: *dapp
          function: "update(1, 1)"
        load:
          0: 4432
          50: 4438
          120: 0
```

5 Experimental Settings

In this section, we detail the experimental settings to evaluate six different blockchains when deployed in five configurations, called `datacenter`, `testnet`, `devnet`, `community` and `consortium`, on up to 200 machines distributed in 10 countries around the world.

5.1 Deployment configurations

We deployed Diablo-v2 and the blockchains in different configurations with up to 200 virtual machines ranging from c5.xlarge (2 vCPUs and 4 GiB memory) to c5.9xlarge (36 vCPUs and 72 GiB memory) and spread equally among different geo-distributed regions in five continents: Cape Town, Tokyo, Mumbai, Sydney, Stockholm, Milan, Bahrain, São Paulo, Ohio, Oregon. Table 3 lists these different configurations.

Datacenter. The `datacenter` configuration aims at showcasing the blockchain peak performance in an idealized setting. Such a configuration features powerful c5.9xlarge machines located in the closed network of a single datacenter, the Ohio AWS availability zone. These machines are not commodity hardware as each machine features 36 vCPUs and 72 GiB memory, the bandwidth and latency between machines are 10 Gbps and 1 ms[3], respectively, which is not representative of an open network. Instead, this configuration allows to evaluate blockchains when a lot of resources are available.

Testnet. The `testnet` configuration features small c5.xlarge machines located in a single datacenter, the Ohio AWS availability zone. This typically corresponds to a testnet setting were blockchain developers typically run their blockchains in order to assess performance and stability during development phases. As the machines are cheaper to rent than c5.9xlarge, they allow the testnet to run for long period of time, allowing for continuous deployment.

Devnet. The `devnet` configuration geo-distributes the machines in an open network to assess the performance in a setting involving the network latencies over long distance communications. This intends to mimic the performance one could expect from a blockchain devnet, where external beta testers or preliminary validators from different regions could participate in the evaluation of the blockchain before a release of a mainnet available to internet users.

[3] https://aws.amazon.com/ec2/instance-types/c5/.

Community. The `community` configuration increases the number of machines to about the number of countries around the world. This configuration aims at mimicking the performance of the blockchain if it was used in a geo-distributed environment involving as many blockchain participants as there are jurisdictions (there are currently 195 universally recognized self-sovereign states in the world). Such highly distributed setting is often considered to be particularly censorship resistant, by not being strongly affected by political decisions in only one of the jurisdictions where it operates.

Consortium. The `consortium` configuration geo-distributes 200 blockchain nodes similarly to the `community` configuration, however, it features more powerful c5.2xlarge machines that better represent modern computers featuring 8 vCPUs and 16 GiB of memory. This aims at mimicking a consortium of individuals or institutions, like the R3 consortium [21], who have resources to devote modern machines without specialized hardware to participate in the blockchain service.

5.2 Blockchains

In this section we describe the six blockchains with smart contract support that we compare using Diablo-v2. They are listed in Table 4.

Algorand. Algorand [14] is a proof-of-stake blockchain that elects a subset of nodes, through sortition, that can append the next block. It does not fork with high probability, so the transaction is final as soon as it is included in a block.[4] Algorand features a blocking API that waits for the transaction to be committed before returning to the client. Although it makes it natural to use this blocking call to detect the commit of each transaction, Diablo-v2 was too demanding, hence we made Diablo-v2 polls every appended block to detect transaction commits, which improved significantly Algorand's performance.

We experimented the Algorand version with commit `116c06e` dated from Nov. 23^{rd} 2021 and available at https://github.com/algorand. We wrote a version of each DApp of §3 in PyTeal because Algorand only supports the Transaction Execution Approval Language (Teal), which is bytecode and requires a conversion from the PyTeal higher level language.

Avalanche. Avalanche [24] is a blockchain also offering instant finality with high probability. There are now three blockchain protocols in Avalanche: one featuring the Ethereum Virtual Machine (C-Chain), one supporting only native transfers (X-Chain), and another one for metadata management. To evaluate the DApps of §3, we used C-Chain, which exposes a web socket streaming API (shared by Ethereum and Quorum) to access the current blockchain head or the latest block.

[4] https://algorand.foundation/algorand-protocol/core-blockchain-innovation.

Configuration	Blockchain nodes number	#vCPUs	memory	Regions
`datacenter`	10	36	72 GiB	Ohio
`testnet`	10	4	8 GiB	Ohio
`devnet`	10	4	8 GiB	all
`community`	200	4	8 GiB	all
`consortium`	200	8	16 GiB	all

	Cape Town	Tokyo	Mumbai	Sydney	Stockholm	Milan	Bahrain	Sao Paulo	Ohio	Oregon
Cape Town		26.1	36.0	20.8	59.8	67.1	33.6	27.1	43.6	35.9
Tokyo	354.0		89.3	112.1	42.1	48.1	66.8	39.3	85.8	108.8
Mumbai	272.0	127.2		75.9	81.3	103.2	336.3	30.8	53.3	48.5
Sydney	410.4	102.3	146.8		32.0	42.4	59.6	31.2	57.0	80.8
Stockholm	179.7	241.2	138.9	295.7		404.6	81.8	48.2	94.7	67.6
Milan	162.4	214.8	110.8	238.8	30.2		105.7	49.4	104.9	70.1
Bahrain	287.0	164.3	36.4	179.2	137.9	108.2		29.9	49.4	38.7
Sao Paulo	340.5	256.6	305.6	310.5	214.9	211.9	320.0		92.3	60.5
Ohio	237.0	131.8	197.3	187.9	120.0	109.2	212.7	121.9		105.0
Oregon	276.6	96.7	215.8	139.7	162.0	157.8	251.4	178.3	55.2	

Bandwidth (Mbps)

Round trip time (ms)

Table 3. The experimental settings range from a `datacenter` scenario with extensive resources to a `testnet` of collocated machines, to a geo-distributed `devnet`, to a large scale `community` of machines, to a large-scale `consortium` of modern machines. The left side indicates the number of blockchain node deployed, the hardware they use and on how many regions they are spread. The right side indicates the bandwidth (top right corner) and round trip time (bottom left corner) between each region measured with `iperf3` on machines from the devnet configuration.

Blockchain	Prop.	Consensus	VM	DApp lang.
Algorand [14]	prob.	BA⋆ [14]	AVM	PyTeal
Avalanche [24]	prob.	Avalanche [24]	`geth`	Solidity
Diem [7]	det.	HotStuff [36]	MoveVM	Move
Quorum [10]	det.	IBFT [25]	`geth`	Solidity
Ethereum [33]	◇	Clique [17]	`geth`	Solidity
Solana [35]	◇	TowerBFT [34]	eBPF	Solidity

Table 4. Blockchains evaluated in Diablo-v2 where their properties are either probabilistic (prob.), deterministic (det.) or eventual (◇).

For the experiments, we used the `master` branch with commit number `7840200`. We initially tried to setup the Avalanche experiments using the RSA4096 cryptographic signature scheme as recommended by Avalanche. However, this signing process was taking too long due to the scale of our experiments. As we could not make Avalanche work after replacing RSA4096 by ED25519, we opted for using ECDSA instead. Avalanche supports the London release improvement of Ethereum (improvement #1559 of August 5th, 2021) with the new gas fee structure with tips, which means the gas fee is computed dynamically (differently from Ethereum's original method). Avalanche limits the gas per block to 8M gas and lower bound the period between blocks to 1.9 seconds[5].

Diem. Diem, formerly known as the Libra blockchain [7], was initiated by Facebook. It features a variant of the HotStuff protocol that solves the consensus problem deterministically (hence avoiding forks) while reducing the communication of traditional consensus protocols in good executions. Like Ethereum, Diem requires that each transaction contains a sequence number, i.e., a monotonically incremented integer. The difference with Ethereum is that Diem nodes only accept a maximum of 100 transactions from the same signer in their memory pool, limiting the rate at which a unique signer can submit transactions. To bypass this limitation, we made workloads submit from 2,000 different accounts in most deployment configurations, however, we noticed that the provided setup tools would fail systematically after creating 130 accounts. This is why we restricted the number of accounts to 130 in the `community` and `consortium` configurations. We explicitly indicate when this caused issues in §6.

We experimented the testnet branch from Aug. 21^{st} 2021 with commit number `4b3bd1e` of the Diem repository https://github.com/diem/diem. Diem testnet branch is dated Aug. 20 of 2021, while the main branch was updated at the time of writing (Feb. 27, 2022). Even though the testnet branch seems outdated, the official Diem tutorial still recommends using the testnet branch for development purpose: https://developers.diem.com/docs/tutorials/tutorial-my-first-transaction/.

Ethereum. Ethereum [33] is the second largest blockchain in market capitalization. As the default version of Ethereum uses the proof-of-work cryptopuzzle resolution which inherently limits its throughput, we exclusively used the Ethereum proof-of-authority consensus protocol, called Clique, as available in `geth`. This version still limits the block period to 15 seconds by default. Just like Avalanche, the Ethereum API exposes a web socket streaming API to access the current blockchain head or the latest block.

We evaluated the `geth` version from the `master` branch with commit hash `72c2c0a` from Dec. 12 of 2021 available at https://github.com/ethereum/go-ethereum. In August 2021, the "London" update to the gas calculation introduced the notion of tips. With this new version, the gas fee changes at

[5] https://snowtrace.io/chart/blocktime.

every block, which can impact the execution of transactions: when the fee increases then the transaction risks to be underpriced. This is why, we tried to adjust the fee dynamically during the execution of the benchmark—this implied signing transactions online.

Quorum. Quorum [10] is a blockchain initiated by J.P. Morgan and currently maintained by Consensys. It features different consensus algorithms: Raft, which only tolerates crash failures and IBFT and QBFT, which both tolerate Byzantine failures and partial synchrony. As Quorum features the `geth` Ethereum Virtual Machine, with the latest changes from the Berlin upgrade (April 15th, 2021), it also features the Clique proof-of-authority consensus algorithm, however, it does not feature the more recent London gas fee computation used by Ethereum and Avalanche.

We experimented the `master` branch with commit hash `919800f` of Quorum from 2 Nov. of 2021 available at https://github.com/ConsenSys/quorum. Given that Clique is vulnerable to message delays [13] and Raft is vulnerable to arbitrary failures, we exclusively run Quorum with IBFT in our experiments. Similar to Ethereum and Avalanche, Quorum exposes a web socket streaming API to access the current blockchain head or the latest block.

Solana. Solana is a recent blockchain that is highly optimized for special hardware features (GPU and Intel instructions). Similar to Ethereum, Solana may fork and needs to wait for 30 confirmations (additional appended blocks) before a stored transaction can be considered final [19]. Its algorithm builds upon proof-of-history and "depends on messages eventually arriving to all participating nodes within a certain timeout" [35]. To append a block every 400 milliseconds, Solana replaces the Merkle Patricia Trie of Ethereum with a simplified data structure and replaces the ECDSA signature scheme with EdDSA (ED25519).

We experimented the commit number `0d36961` of the `master` branch of Solana from March 12 of 2022, as available at https://github.com/solana-labs/solana. Solana uses its own API, also based on a web socket, that allows the client to specify a commitment level. The clients listen for new blocks with the desired commitment level by subscribing to a web socket interface. Interestingly, Solana fetches the block hash before issuing transactions because the last block hash needs to be signed as part of the issued transaction. Previous tests ran by the Solana team all consisted of requesting the last block hash before issuing concurrently transactions withdrawing from different accounts. We could not use this technique while evaluating realistic DApps because Solana requires the hash to be created less than 120 seconds before the transaction request is received while DApps can run for longer. To cope with this limitation, the Solana-Diablo-v2 interface periodically fetches the last block hash.

5.3 Diablo-v2 configuration

To measure the impact of geo-distribution on the blockchain performance we deployed both the blockchains and Secondaries in the deployment configurations of §5.1 as depicted in Table 3. In all cases we applied the same geo-distribution strategy to the blockchain nodes and to the Secondaries: each Secondary submits its requests to its collocated blockchain node so as to mimic requests being routed from a client towards its closest blockchain node. In all these configurations, a single Primary was used for setting up the experiment and gathering the performance results. As the Primary is not involved during the performance monitoring phase, its location does not impact the experimental results.

```
diablo primary -vvv --port=5000 \
   --env="accounts=accounts.yaml" \
   --env="contracts=dapps-directory" \
   --output=results.json --compress --stat \
   10 setup.yaml workload.yaml
```

To run the Primary, we specify the verbosity level, port number for the secondaries to connect to, path to the accounts file, DApps source codes, output file path, compress output (with gzip), printing statistics to standard output, number of Secondaries (10 in the example), blockchain setup file, and workload specification file.

```
diablo secondary -v --tag="us-east-2" \
    --port=5000 127.0.0.1
```

To run the Secondary, we again specify the verbosity level, port and address of the Primary to connect to and a tag to indicate the Secondary location for collocation with blockchain nodes.

6 Evaluation Results

In this section, we stress test the blockchains described in §5.2 under the realistic DApps of §3. Due to their decentralized nature that offers enhanced security, we observe that, on modern commodity hardware, blockchains cannot yet handle the workload experienced by centralized applications. We then run a combination of synthetic workload and real but less demanding workload traces to compare the scalability, robustness, universality and availability of these blockchains.

6.1 Motivating blockchain improvements

To provide an overview of blockchains performance executing realistic DApps, we deploy each DApp of §3 in the `consortium` deployment configuration (200 8 vCPUs–16 GiB machines spread over 10 countries in 5 continents) and generate the workload associated with each of these DApps. For each run, we make sure that Diablo-v2 uses enough Secondaries to not be the bottleneck.

Figure 2 shows the average throughput, average latency and the proportion of committed transactions for each blockchain-DApp pair. We observe that for the Exchange

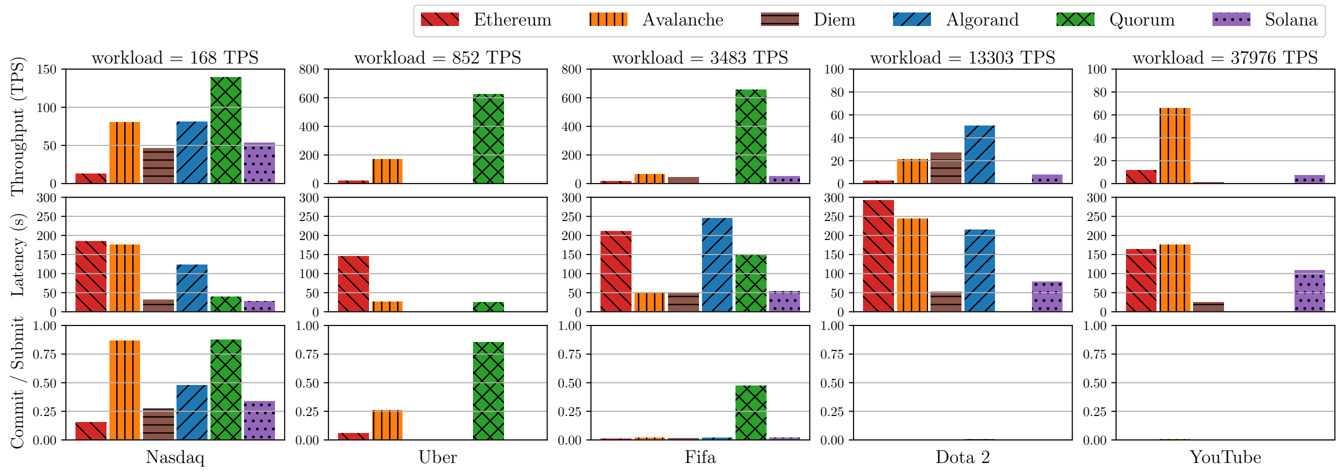


Figure 2. Evaluation of blockchain performance when executing realistic DApps. For each DApp (column), shows the average workload effectively submitted by Diablo-v2 (top of each column), average throughput (first row), average latency (second row) and proportion of committed transaction (third row) for each blockchain. Each blockchain is deployed on 200 c5.2xlarge AWS instances spread among 10 datacenters.

DApp, which has the lowest average workload, Nasdaq, of 168 TPS only, Avalanche and Quorum commit more than 86% of the transactions, all the other blockchains commit 47% or less of the transactions. For the most demanding workload, the YouTube workload, the proportion of commits is lower than 1% for all evaluated blockchains. In addition, when the average workload is of 852 TPS (like the Uber workload), or 3,483 TPS (like the Fifa workload), only Quorum maintains a throughput higher than 622 TPS while the other blockchains have a throughput lower than 170 TPS. For higher workloads (like Dota 2), no blockchain maintains a throughput higher than 66 TPS. Finally, among all DApps, no blockchains commit with a latency lower than 27 seconds. These results contrast with the claimed performance that we describe in Table 1. We indicate below what are the causes of this performance gap and how a blockchain developer can use Diablo-v2 to find these causes on their own blockchain.

6.2 Scalability and deployment

Using Diablo-v2, we quantify *scalability* as the ability to allow a large number of unprivileged users to participate to the blockchain execution. To this end, we deploy the blockchains on networks of different sizes composed of machines ranging from enterprise grade hardware with high computational power (`datacenter`) to commodity hardware with modest computational power (`community`). We then measure their performance when stressed with a synthetic workload.

More precisely, we deploy each blockchain on four deployment configurations: `datacenter`, `testnet`, `devnet` and `community`. For each configuration we use Diablo-v2 to emulate clients sending native transactions to the blockchain during 120 seconds at a constant rate of 1,000 TPS which is the same order of magnitude as the average load of the Visa

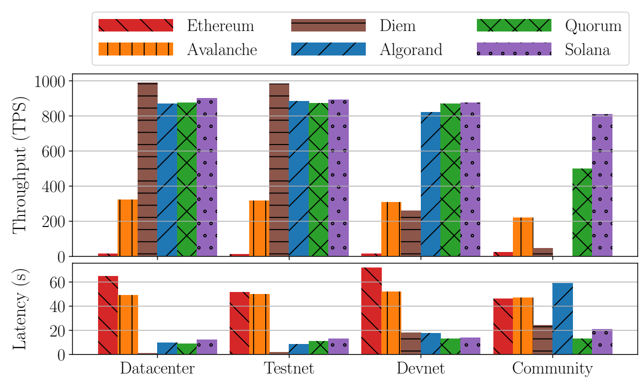


Figure 3. Average throughput and average latency of each blockchain when stressed with a constant workload of 1,000 TPS on different configurations, from the less challenging (`datacenter`) to the most challenging (`community`).

system[6]. We measure the average throughput and average latency for each blockchain. If the measured throughput is close to the workload of 1,000 TPS then we conclude that the blockchain handles the simple payment use case for the configuration.

Figure 3 shows the average throughput and average latency for each blockchain on the four configurations. We observe that only Solana handles a 1,000 TPS constant workload for all configurations while maintaining a throughput higher than 800 TPS with a latency below 21 seconds. Solana uses an eventually consistent consensus based on a verifiable delay function which puts away all communication steps but a broadcast. By using a verifiable delay function, Solana makes the block generation delay independent from

[6]Visa claims 150 million transactions per day = 1,736 TPS on average (https://usa.visa.com/run-your-business/small-business-tools/retail.html)

the number of cores the participant uses. By removing most of the communication steps, Solana also performs better on more challenging network settings. Quorum also stands out in the community setup with a throughput of 499 TPS for a latency of 13 seconds. Quorum uses a well known deterministic consensus algorithm which does not introduce artificial delays and provide immediate finality. In addition, Quorum benefits from many blockchain specific optimizations by using `geth` as a base code. For all blockchains there is no significant difference between the datacenter and the testnet configurations. Over all the configurations, Diem achieves the best throughput (more than 982 TPS) and the best latency (2 seconds or less) but only on configurations with a local setup. We conjecture that Diem is designed to provide very low latency and is optimized to run on network setups with a low round-trip time (RTT). Over the remaining blockchains, only Algorand achieves a throughput higher than 820 TPS when deployed on the `devnet` configuration, which is a geodistributed network. In particular, the best average throughput that Algorand reaches in 885 TPS on the `tesnet`. We conjecture that the other blockchains, namely Avalanche and Ethereum are designed to run at a relatively low throughput regardless of the available computational power or network bandwidth.

6.3 Robustness and denial-of-service attacks

To better understand whether blockchain are *robust* to high demand, we used Diablo-v2 to inject high workloads and test whether the blockchain collapses or continue treating requests further. Intuitively, a blockchain is more robust, if a higher workload is needed to penalize its latency and throughput. This property is desirable to measure how hard it is for an adversarial user to perform a denial-of-service attack on the blockchain by submitting transactions at a high rate. The test consists of deploying the blockchain in a deployment configuration where it performs well under moderate workload and observing whether a higher workload leads to performance degradations.

To compare the blockchain robustness, we deploy each blockchain on its most suited deployment configuration (see §6.2) and observe its performance when stressed with a high workload. To this end we configured Diablo-v2 to send native transactions to the blockchain during 120 seconds at a constant rate of 10,000 TPS which is 10× higher than the sending rate in the deployment challenge. Although Diablo-v2 can send transactions at higher rates, we found this workload to be sufficient to show some interesting behaviors of the tested blockchains.

Figure 4 compares the throughput and latency of each blockchain when stressed with workloads of 1,000 TPS and 10,000 TPS. Diem and Quorum are the most negatively affected by the higher workload: Diem throughput is divided by 10 while Quorum throughput drops to 0. Interestingly, Diem and Quorum are the only blockchains we evaluated

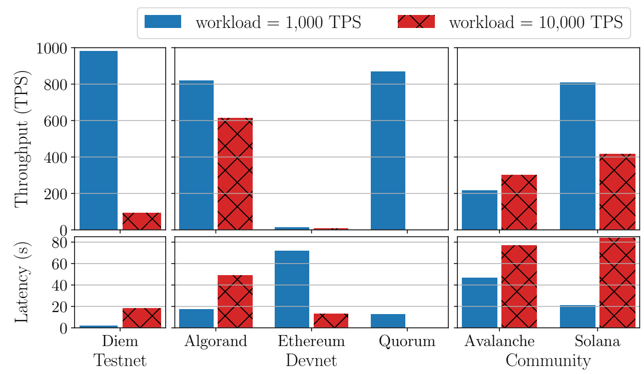


Figure 4. Throughput and latency of each blockchain when stressed with a constant workload of 1,000 TPS (left bar) or 10,000 TPS (right bar). Each blockchain is deployed on the most challenging configuration where it runs with a throughput higher than 800 TPS under a workload of 1,000 TPS, with the exception of Ethereum.

that use a deterministic Byzantine fault tolerant (BFT) consensus. These algorithms were originally designed to commit as many client requests as possible, a behavior that easily leads to saturate memory pools or network queues when exposed to high workloads. When applied to blockchains, this effectively results in a vulnerability to DoS attacks[7].

Algorand and Solana are more robust as their throughputs are divided by 1.45 and 1.94, respectively, while the latencies of Algorand and Solana are multiplied by 2.43 and 4, respectively. These results show that despite being affected by a high workload, these two blockchains do not completely collapse and the performance decrease likely results from the inability of the underlying hardware to handle too many requests. Interestingly, Avalanche throughput is not negatively affected by the higher workload, as its throughput is multiplied by 1.38 which makes it comparable to Solana throughput for the same workload. This confirms the conjecture of §6.2 that Avalanche throttles its throughput. It is hard to say something about Ethereum results since this blockchain only commits 0.09% of the transactions when the workload is 10,000 TPS.

6.4 Universality and DApp executions

To understand whether a blockchain is *universal* in that it can handle requests that are made arbitrarily complex, we test whether the blockchains can handle a large variety of DApps with a potentially complex execution logic. To this end, we first deploy the smart contracts of the DApps of §3 on the blockchains and then execute the real workload that invokes the functions of these contracts.

To test if a blockchain can execute arbitrary programs, we use the Mobility service DApp (§3), which is CPU intensive and generates a 810–900 TPS workload during 120 seconds.

[7] Generating 10,000 TPS with Diablo-v2 costs less then 8 USD/hour on AWS.

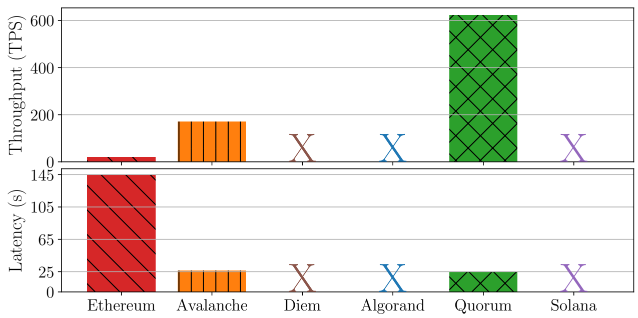


Figure 5. Throughput and latency of each blockchain when stressed with a workload between 810 TPS and 900 TPS where each transaction invokes a computationally intensive smart contract function. Each blockchain is deployed on 200 c5.2xlarge AWS instance spread among 10 datacenters.

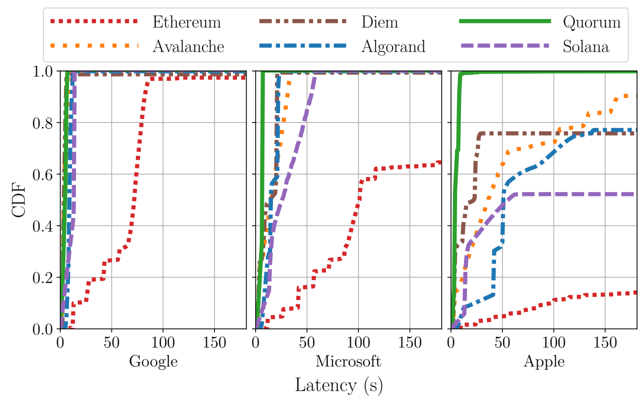


Figure 6. CDF of the transactions latency for each blockchain when stressed with a peak load of 800 tx (Google), 4,000 tx (Microsoft) or 10,000 tx (Apple) followed by a low workload.

We test whether the blockchains can provide the service delivered by Uber by measuring the throughput and latency and verify that it matches the demand. As one can expect this workload to be more demanding than with the native transferred generated above, we deploy the blockchains in the `consortium` configuration (see Table 3), which has the same number of machines and the same network as the `community` configuration but with more powerful machines.

Figure 5 shows the throughput and latency for each blockchain running the Mobility service DApp on the `consortium` configuration. When the blockchain is unable to execute the smart contract, Figure 5 shows an **X** letter instead. Algorand, Diem and Solana are unable to execute the DApp because the client reports an error of type `"budget exceeded"` indicating that the execution ran out of gas or timed out. This execution limit is hard-coded and cannot be lifted by paying a higher gas fee in the transaction. We conjecture this limit is hard-coded to prevent a rich adversary to slow down or completely stop the blockchain by executing compute intensive tasks in smart contracts. Interestingly, the three blockchains able to execute the DApp use the `geth` implementation of the Ethereum Virtual Machine (EVM), which comes with no hard limit on gas budget of a transaction. Over these three blockchains, Quorum has the highest throughput of 622 TPS which is close to the average workload while the two other blockchains, Avalanche and Ethereum, have a throughput lower than 169 TPS.

6.5 Availability despite load peaks

We measure the *availability* of a blockchain as its ability to commit submitted transactions in a timely manner even when stressed with load peaks. A blockchain is more available when it handles more intense bursts of transactions with low latency and without dropping any transaction. This property is desirable for a blockchain to handle realistic workloads where users are likely to send many transactions to the blockchain at the same time and expect to receive a confirmation from the blockchain within a reasonable delay. To measure the availability of the blockchains, we first deployed each blockchain in the `consortium` configuration (see Table 3) and then generates short bursts of transactions of varying intensities, extracted from the Exchange DApp / Nasdaq workload (see §3). In particular, we use Diablo-v2 to send buy transactions at the same rate as the trade rate during the Nasdaq opening for 3 companies: Google, Microsoft and Apple. Finally, we measure the proportion of dropped transactions and the latencies of committed transactions.

Figure 6 shows the cumulative distribution function (CDF) of the transaction latencies for all blockchains under three workloads. Over the tree workloads, only Quorum commits all the transactions. Specifically, when stressed with the Apple workload which consists in an initial load peak of 10,000 transactions during the first second, Quorum commits all transactions, among which 91% of the transactions are committed with a latency of 8 seconds or less. Interestingly, Quorum commits its transactions with similar latencies of 7 seconds or less when stressed with lower load peaks. Quorum uses IBFT, a deterministic BFT consensus which was historically designed to never drop a client request. We conjecture that this design choice is still present in the Quorum blockchain as we already mentioned in §6.3.

The other blockchain based on a deterministic BFT consensus, Diem, only commits 75% of the transactions, all of them in less than 30 seconds. Diem drops transactions during the load peak because of the limited size of the mempool on each blockchain node. While this dropping mechanism prevents Diem from committing all transactions during high load peaks, it also makes it less prone to completely collapse during constant loads, as opposed to Quorum (see §6.3). Algorand and Solana also drop transactions, as shown by their CDF plateauing at 77% and 52% of committed transactions, respectively, whereas Avalanche and Ethereum keep committing transactions until the end of the experiment. While it takes up to 162 seconds for Avalanche to commit some of the transactions, this blockchain manages to commit 90% of the submitted transactions. Despite its low throughput, Avalanche is the second blockchain to commit the most transactions.

As opposed to the Apple workload, the Google workload presents an initial load peak of 800 transactions during the first second. As a result, all the blockchains commit more than 97% of the Google workload transactions. In addition, all the blockchains but Ethereum commit all the Google workload transactions in less than 14 seconds while Ethereum does it in 118 seconds. The Microsoft workload has a moderate load peak of 4,000 transactions during the first second. On this workload, while all blockchains but Ethereum commit all transactions, they take more time to do so with the exception of Quorum, which commits all of its transaction with a latency of 7 seconds. Specifically, Solana has its maximum latency rising from 1 second for the Google workload to 59 seconds while Algorand, Avalanche and Diem have their maximum latency going from 10-14 seconds to 22-37 seconds. On the Microsoft workload, Ethereum commits only 64% of the transactions.

6.6 Discussion

In this section, we summarize the key results of the evaluation (§6). While the realistic DApp evaluation (§6.1) reveals that current blockchains are not yet ready to deliver the same performance as centralized infrastructures to provide common services, the in depth analysis of blockchains performance shows that some blockchains fullfill some of their promises and identifies key factors of performance.

In §6.2, it appears that a blockchain using eventual consistency, like Solana, scales more easily to networks with many nodes. A decent throughput is also achieved by Quorum, a blockchain based on long studied consensus protocols but which also benefits from modern engineering techniques. More importantly, two blockchains, Diem and Avalanche, fail at using more challenging configurations most likely because they simply do not consider these configurations as a use case: high RTT networks for Diem and large hardware resources for Avalanche.

In §6.3, the two blockchains using BFT consensus protocols, namely Quorum and Diem, are the most impacted by constantly high workloads. The Algorand, Avalanche and Solana blockchains, which use either probabilistic or deterministic consensus protocols, maintain a non negligible throughput when stressed with high constant workloads.

In §6.5, Quorum and Diem, the least robust blockchains in the face of peak loads are also the blockchains committing the largest portion of transactions under reasonable delay. This seems to indicate that there is a tradeoff between robustness and availability.

In §6.4, only the three blockchains using the `geth` implementation of the EVM, Avalanche, Ethereum and Quorum, execute smart contracts with a complex and computationally demanding logic. The other blockchains having a virtual machine with a hard limit on the computational cost of a transaction are unable to provide complex services.

7 Related Work

Hyperledger Caliper [3] is a blockchain benchmark framework enabling users to evaluate the performance of blockchains developed within the Hyperledger project, such as Fabric, Sawtooth, Iroha, Burrow and Besu. It also supports Ethereum and has plans to extend to other blockchains in future. Caliper provides pre-defined workloads, specifying the calling contract, functions and the rate of transaction sending over time. Unfortunately, all these workloads are synthetic and we are not aware of any pre-defined DApps with realistic workloads that can be used with Caliper.

Blockbench [12] is one of the most notable benchmarking frameworks for blockchains, as it supports a number of micro and macro benchmarks. The most significant aspect of Blockbench is that it ports over the notable YCSB workload from the database systems community. Aimed at private blockchains, Blockbench benchmarks the different layers of the blockchain, such as consensus or data storage, with tailored workloads, allowing fine-grained testing and measurement of the effectiveness of each of these layers. The evaluation metrics available show throughput and latency, but also the tolerance of faults through injected delays, crashes and message corruption. Blockbench's complexity introduces difficulty when extending to other blockchains or introducing new workloads.

The variety of Ethereum adapted blockchains motivated the development of Chainhammer [18], a benchmark tool focused on the performance of Ethereum-based blockchains under extremely high loads. Chainhammer, unlike others, does not follow a workload curve but provides continuous high load generation, aiming to measure the throughput in extreme situations. The design is specialised, meaning that there is little flexibility in modifications to support other workloads. Conversely, as Chainhammer is exclusively for Ethereum, it can perform post-benchmark analysis and obtain metrics on information critical to the Ethereum infrastructure, such as transaction cost analysis and the structure of blocks.

Most evaluations that were made on blockchains are ad hoc and do not aim at comparing very different blockchain designs on the same ground. Previous works have, for example, focused on permissioned blockchains as one can find in the context of Internet of Things [16], others have evaluated exclusively Byzantine fault tolerant blockchains [26].

8 Conclusion

We proposed a new benchmark called Diablo-v2 and presented the most extensive evaluation of blockchain performance to date. The results indicate that none of the tested blockchains can treat all requests from any of the realistic DApps we proposed: gaming, web service, exchange, mobility service, video sharing. We believe that our framework will be instrumental in evaluating blockchains in a more transparent manner.

Acknowledgments

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