Simulating BFT Protocol Implementations at Scale

Christian Berger
christian.berger@sec.uni-passau.de
University of Passau
Passau, Germany

Sadok Ben Toumia
sadok.ben-toumia@unisg.ch
University of Passau
Passau, Germany

Hans P. Reiser
hansp.reiser@ru.is
Reykjavík University
Reykjavík, Iceland

Abstract
The novel blockchain generation of Byzantine fault-tolerant (BFT) state machine replication (SMR) protocols focuses on scalability and performance to meet requirements of distributed ledger technology (DLT), e.g., decentralization and geographic dispersion. Validating scalability and performance of BFT protocol implementations requires careful evaluation. While experiments with real protocol deployments usually offer the best realism, they are costly and time-consuming. In this paper, we explore simulation of unmodified BFT protocol implementations as a method for cheap and rapid protocol evaluation: We can accurately forecast the performance of a BFT protocol while experimentally scaling its environment, i.e., by varying the number of nodes or geographic dispersion. Our approach is resource-friendly and preserves application-realism, since existing BFT frameworks can be simply plugged into the simulation engine without requiring code modifications or re-implementation.

CCS Concepts: • General and reference → Performance: Evaluation; Experimentation; • Computing methodologies → Distributed algorithms.

Keywords: simulation, emulation, Byzantine fault tolerance, state machine replication, consensus, Shadow, Phantom

1 Introduction
The current transition towards Web3 presents many challenges in terms of scalability and performance of distributed ledger technology (DLT). Proof-of-Work [23] is still widely used today, even if it is not environmentally sustainable and can often not meet performance requirements of applications [7]. Consequently, coordination-based Byzantine fault-tolerant (BFT) state machine replication (SMR) algorithms experienced renewed research interest [3, 32] – resulting in many novel BFT protocols with focus on improving scalability [9, 11, 24, 31, 36], or boosting performance under geographic dispersion [5, 8, 20, 30].

It is a challenging endeavour to reason about the performance and run-time behavior of these novel BFT protocols. In fact, analyzing BFT protocols requires thorough evaluation, which is why the research papers describing these protocols contain evaluations with large-scale deployments that are conducted on cloud platforms like AWS, where experiments deploy up to several hundred nodes (e.g., like in [9, 11, 20, 24, 36] and many more) to demonstrate a protocol’s performance and scalability. Evaluations using real protocol deployments usually offer the best realism, but are costly and time-consuming. Thus, a reasonable alternative for cheap and rapid validation of BFT protocol implementations (that are possibly still in development stage) can be to rely on either emulation or simulation.

Emulation vs. Simulation. Emulation tries to duplicate the exact behavior of what is being emulated. A clear advantage of emulation is how it preserves realism: BFT protocols still operate in real time and use real kernel and network protocols. As examples serve Mininet [15, 19], which creates a realistic virtual network running real kernel, switch and application code on a single machine, or Kollaps [14], a decentralized and dynamic topology emulator.

In contrast to emulation, simulation decouples simulated time from real time and employs abstractions that help accelerate executions: Aspects of interest are captured through a model, which means the simulation only mimics the protocol’s environment or its behavior. This has the advantage of easier experimental control, excellent reproducibility (i.e., deterministic protocol runs) and increased scalability when compared to emulation. As potential drawback remains the question of application-realism since the model may not fairly enough reflect reality. Examples of simulators include ns-3 [26] or Shadow [16], which are both discrete-event network simulators for internet applications.

Evaluating BFT Protocols. BFTSim [29] is the first simulator that was developed for an eye-to-eye comparison of BFT protocols but it lacks the necessary scalability to be useful for the newer “blockchain generation” of BFT protocols (and apparently only up to n = 32 PBFT [10] replicas can be successfully simulated [34]). A more recent tool [34] allows for scalable simulation of BFT protocols but it unfortunately requires a complete re-implementation of the BFT protocol in JavaScript. It also can not make predictions on system throughput. Kollaps [14] was used to reproduce AWS-deployed experiments with BFT-SMaRt [6] and WHEAT [30] but it is not sufficiently resource-friendly as it executes the real application code in real-time, thus requiring many physical machines to conduct large-scale experiments.

Research Questions & Contributions. We explore simulation as a method to evaluate BFT protocol implementations, which leads us to the following two research questions:

R1 What are properties of an ideal performance evaluation tool for the “blockchain generation” of BFT protocols?
The simulator does not mimic real network protocols, instead it tries to capture network characteristics in a high-level model where messages can be delayed by some variable sampled from a (to be defined) Gaussian or Poisson distribution. Like BFTSim, it does not provide application layer realism and demands the re-implementation of a BFT protocol in JavaScript. A further drawback is that it cannot measure system throughput, and is thus not suited for reasoning about system performance. Further, related work also includes stochastic modelling of BFT protocols [25] and validations of BFT protocols through unit test generation [2]..

There are simulators which are dedicated to blockchain research, such as Shadow-Bitcoin [22], Bitcoin blockchain simulator [13], BlockSim [12], SimBlock [1] or ChainSim [33]. These tools mainly focus on building models that capture the characteristics of Proof-of-Work and thus can not easily be adopted or used for BFT protocol research.

Further, there are tools to emulate or simulate distributed applications: Mininet [15, 19] and Kollaps [14] are emulators that allow to create realistic networks (running real internet protocols) and real application code with time being synchronous with the wallclock. Naturally, both approaches provide less resource-friendly, a problem which was addressed later by Maxinet [35], which allows Mininet emulated networks to spawn over several physical machines. Kollaps is a scalable emulator, but also requires many physical machines for large-scale experiments. Moreover, ns-3 [26] is a resource-friendly and scalable network simulator, but it requires the development of an application model, and thus does not preserve application layer realism.

Phantom [17] uses a hybrid emulation/simulation architecture: It executes real applications as native OS processes, co-opting the processes into a high-performance network and kernel simulation and thus can scale to large system sizes. An advantage of this is that it preserves application layer realism as real BFT protocol implementations are executed. At the same time, it is resource-friendly and runs on a single machine. Through its hybrid architecture, Phantom resides in a sweet-spot between ns-3 (pure simulator) and Mininet (pure emulator): It still provides sufficient application realism for the execution of BFT protocols, but is more resource-friendly and scalable than the emulators are.

### Table 1. Comparison of different emulators and simulators in the context of BFT protocol research.

|                     | BFTSim [29] | BFT Simulator [34] | Kollaps [14] | ns-3 [26] | Mininet [15, 19] | Phantom [17] |
|---------------------|-------------|--------------------|--------------|-----------|-----------------|--------------|
| application layer realism | ✗          | ✗                  | ✓            | ✓         | ✓               | ✓            |
| realistic networking  | ✓           | ✓                  | ✓            | ✓         | ✓               | ✓            |
| scalability          | ✓           | ✓                  | ✓            | ✓         | ✓               | ✓            |
| resource friendliness  | ✓           | ✓                  | ✓            | ✓         | ✓               | ✓            |
| Byzantine attacker    | ✓           | ✓                  | ✓            | ✓         | ✓               | ✓            |

**R2** Can simulations help us to reason about the behavior of real BFT protocol implementations at larger scale?

Our contributions aim for supporting validations of novel BFT protocol implementations for their practical deployments in large-scale DLT systems. In the following, we summarize our main findings:

- We first compare existing simulators and emulators to analyze properties of an ideal evaluation tool in the context of BFT protocol research. A key finding is, that the state-of-the art is deficient as there is no resource-friendly evaluation tool to predict the performance (i.e., latency and throughput) of BFT protocols at a larger scale.
- We present a tool that automates large-scale simulations of unmodified BFT protocol implementations through the Phantom simulator [17] given a simple experimental description. For the first time, experiments with existing BFT protocol implementations can be effortless setup, configured and fed into a simulation engine (Sects. 3 and 4).
- We discovered that we can faithfully forecast the performance of BFT protocols because performance eventually becomes network-bound at a larger scale. Our evaluations compare results obtained from simulations with measurements of real protocol deployments (Sect. 5).

## 2 Related Work & Background

BFTSim [29] was the first simulator especially tailored for traditional BFT protocols like PBFT [10] or Zyzzyva [18]. Since these protocols were intended to be used for only small groups of replicas, the limited scalability of the simulator was at that time not an issue. However, it makes BFTSim impractical for the newer BFT protocols. BFTSim demands a BFT protocol to be modeled in the P2 language [21], which is somewhat error-prone when considering the complexity of, e.g., PBFT’s view change or Zyzzyva’s many corner cases. Although BFTSim allows the simulation of faults, it only considers non-malicious behavior and left the extension to more sophisticated Byzantine attacks for future work. It provides realistic networking using ns-2, and is resource-friendly as it runs on a single machine.

Recently, a BFT simulator was presented by Wang et al. [34] which demonstrated resource-friendliness, high scalability, and comes with an attacker module which includes a pre-defined set of attacks (partitioning, adaptive, rushing).
As shown in Table 1, there is no perfect solution for simulating BFT protocols at scale yet. If we require both resource-friendliness and scalability, which we think are necessary characteristics to evaluate scalable BFT protocols in an inexpensive way, then only the BFT Simulator of Wang et al. [34] and Phantom [17] are viable options. Comparing these two, we decided to build our evaluation toolchain on top of Phantom, because it allows to plug and play BFT protocol implementations and can measure system throughput.

### 3 Preliminaries: Phantom

Phantom uses a hybrid simulation/emulation architecture, in which real, unmodified applications execute as normal processes on Linux and are hooked into the simulation through a system call interface using standard kernel facilities [17].

In Phantom, a network topology (the environment) can be described by specifying a graph, where virtual hosts are nodes and communication links are edges. The graph is attributed: For instance, virtual hosts specify available uplink/downlink bandwidth and links specify latency and packet loss. Each virtual host can be used to run one or more applications. This results in the creation of real Linux processes that are initialized by the simulator controller process as managed processes (managed by a Phantom worker). The Phantom worker uses LD_PRELOAD to preload a shared library (called the shim) for co-opting its managed processes into the simulation (see Figure 1). LD_PRELOAD is extended by a second interception strategy, which uses seccomp for cases in which preloading does not work [17].

The shim constructs an inter-process communication channel (IPC) to the simulator controller process and intercepts functions at the system call interface. While the shim may directly emulate a few system calls, most system calls are forwarded and handled by the simulator controller process, which simulates kernel and networking functionality (for example the passage of time, I/O operations on file, socket, pipe, timer, event descriptors and packet transmissions) [17].

### 4 A Simulation Toolchain for BFT

Large-scale simulations of BFT protocols with Phantom requires additional tooling support. This is mainly because of the following reasons: First, Phantom requires to generate realistic and large network topologies for an arbitrary system size and the characteristics of their communication links should ideally resemble real-world deployments. This is crucial to allow realistic simulation of wide-area network environments. Second, we need aid in setting up the BFT protocol implementations for their deployment, since bootstrapping a BFT protocol in Phantom involves many steps that can be tedious, error-prone and protocol-specific. This means, for instance, the generation of protocol-specific runtime artifacts like cryptographic key material, or configuration files which differ for every BFT protocol. Third, in the process of developing and testing BFT algorithms, different combinations of protocol settings result in numerous experiments to be conducted. Since Phantom simulations run in virtual time, they can take hours, depending on the host system’s specifications. For the sake of user experience and convenience, we find it is necessary for experiments to be specified in bulk and ran sequentially without any need for user-intervention. Fourth, we may want to track and evaluate resources needed during simulation runs, such as CPU utilization and memory usage. Fifth, when Phantom produces results, they are resided in the file system and for convenience we want to aggregate measurements of several simulations and map these to diagrams displaying to-be-specified metrics like throughput or latency.

These reasons led us to develop Delphi-BFT, a tool on top of Phantom to simplify and accelerate the evaluation of unmodified BFT protocol implementations.

**Architecture**

Delphi-BFT is composed of several components (see Fig 2) and follows a modular architecture, in that it is not tailored to a specific BFT protocol, but is easily extensible.

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1 Code open-source available at https://github.com/Delphi-BFT/tool.
**Table 2.** BFT protocols that we employed for our evaluation.

| framework   | BFT protocol | language | repo on github.com |
|-------------|--------------|----------|-------------------|
| libhotstuff [36] | Hot-Stuff     | C++      | /hot-stuff/libhotstuff |
| themis [27]   | PBFT         | Rust     | /ibr-ds/themis   |
| bft-smart [6]  | BFT-SMaRt    | Java     | /bft-smart/library  |

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**Orchestrator.** The toolchain is administered by an orchestrator that manages all tools, i.e., preparing an environment, configuring runtime artifacts for a BFT protocol, and initializing a resource monitor. The orchestrator invokes protocol connectors to set up a BFT protocol and loads experiments description files which contain a set of experiments to be conducted for the specified BFT protocol. Finally, it starts Phantom, once an experiment is ready for its execution.

**Environment Generator.** The environment generator creates network topologies as complete graph for any system size. The network topologies resemble realistic deployment scenarios for a LAN or WAN setting. To create network graphs with network links reflecting a realistic geographic dispersion of nodes, the environment generator employs a cloudcomponent, which retrieves real round-trip latencies between all AWS regions from Cloudping. This allows the tool to create network topologies which resemble real BFT protocol deployments on the AWS cloud infrastructure.

**Protocol Connectors.** For each BFT protocol implementation that we want to simulate, it is necessary to create protocol configuration files and necessary keys. Since protocol options and cryptographic primitives vary depending on the concrete BFT protocol, we implement the protocol-specific setup routine as a tool called protocol connector, which is invoked by the orchestrator. A connector must implement the methods `build()` and `configure()`. This way, it is simple to extend our toolchain and support new BFT protocols, as it only requires writing a new protocol connector (in our experience this means writing between 100 and 200 LoC).

**Resource Monitor.** The orchestrator initializes a resource monitor to collect information on resource consumption (like allocated memory and CPU time) during simulation runs and also the total simulation time. The user can use these statistics as indicators towards a possible need for vertically scaling the host machine and as rough estimates for the necessary resources to run larger simulations.

**Plotter.** Results are stored to the file system by Phantom. They can be aggregated and mapped to specific diagrams for specifiable metrics like latency of throughput. For instance, it can create diagrams that display the performance of a BFT protocol for increasing system scale which aggregate several simulation runs for an increasing $n$ (or any other variable).

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5.1 **HotStuff at Increasing System Scale**

In our first evaluation, we try to mimic the evaluation setup of the HotStuff paper [36] to compare their measurements with our simulation results. Their setup consists of more than hundred virtual machines deployed in an AWS data center; each machine has up to 1.2 GB/s bandwidth and there is less than 1 ms latency between each pair of machines (we use 1 ms in the simulation). The employed batch size is 400. We compare against two measurement series: “p1024” where the payload size of request and responses is 1024 bytes and “10ms” with empty payload, but the latency of all communication links is set to 10 ms. Our goal is to investigate how faithfully the performance of HotStuff can be predicted by regarding only the networking capabilities of replicas, which manifests at the point where the network becomes the bottleneck for system performance.

**Observations.** We display our results in Figure 3. The simulation results for the payload experiment indicate a similar trend as the real measurements, where performance starts
to drop for \( n \geq 32 \). For a small sized replica group, the network simulation predicts higher performance: 200k tx/s. This equals the theoretical maximum limited only through the 1 ms link latency which leads to pipelined HotStuff committing a batch of 400 requests every 2 ms. The difference in throughput decreases once the performance of HotStuff becomes more bandwidth-throttled (at \( n \geq 32 \)). We also achieve close results in the "10ms" setting: 80 ms in the simulation vs 84.1 ms real, and 20k tx/s in the simulation vs. 19.2k tx/s real for \( n = 4 \); but with an increasing difference for higher \( n \), i.e., 84 ms vs. 106 ms and 19k.2 tx/s vs. 15.1k tx/s for \( n = 128 \).

**Resource Usage.** Further, we investigate how resource utilization, i.e. memory usage and simulation time, grows with an increasing system scale. We run our HotStuff "10ms" simulations (which display a somewhat steady system performance for increasing system scale) on an Ubuntu 20.04 VM with 48 GB memory and 20 threads (16 threads used for simulation) on a host with an Intel Xeon Gold 6210U CPU at 2.5 GHz. We observe that active host memory and elapsed time grow with increasing system scale (see Fig. 4). We think it should be feasible to simulate up to 512 HotStuff replicas with a well-equipped host (with e.g., 64 GB RAM).

### 5.2 BFT-SMaRt under Geographic Dispersion

Next, we experiment with geographic dispersion of BFT-SMaRt replicas, where each replica is located in a distinct AWS region. Our experimental setup is thus similar to experiments found in papers that research on latency improvements [4, 5, 30]. We employ a \( n = 4 \) configuration and choose the regions Oregon, Ireland, São Paulo and Sydney for the deployment of a replica and a client application each. We run clients one after another, and each samples 1000 requests without payload and measures end-to-end latency, while the leader replica (in Oregon) measures the system’s consensus latency. Further, we create an experiment with 1000 requests to compare our simulation results with real measurements.

**Observations.** We notice that consensus latency is slightly higher in the simulation (373 ms vs. 249 ms), and further, the simulation results also display slightly higher end-to-end request latencies in all clients (see Figure 5). The deviation between simulated and real execution is the lowest in Oregon (1.3%) and the highest in São Paulo (3.5%).

### 5.3 PBFT at Increasing System Scale

We run simulations with 1KiB payload with Themis [27] (a Rust-based implementation of PBFT) to compare the results against our HotStuff simulation results.

**Observations.** PBFT initially outperforms HotStuff, but then its throughput decreases more swiftly (as can be seen in the sharper curve in Figure 6). At \( n = 128 \), PBFT achieves up to 9.3k tx/s while HotStuff achieves up to 20k tx/s.

### 6 Future Work

**Extending Evaluations.** For future work, we intend to extend our evaluations to more BFT protocols, in particular, to evaluate the effectiveness of different communication strategies, like Gosig [20] (gossip) or Kauri [24] (tree-based) and compare them with the results obtained from Hot-Stuff (star-based) and PBFT (clique). In particular, we can explore the performance of these protocols under different network characteristics and for an increasing system scale. A high-level simulation model previously studied the effect of different message exchange patterns of BFT protocols [28] but it lacks applicability for reasoning about real system metrics.

**CPU Model.** We think a CPU model could improve simulation results for evaluations of either (1) small sized replica groups or (2) experiments with empty payload – in both cases the CPU may be the dominating factor and not the network. Up to now, we use Phantom only as a network
simulator and all computations, such as creating or verifying signatures, take no time. It might be possible to capture most of the computational work by only modeling a few methods, in particular, the cryptographic primitives (like in BFTSim [29]). Currently, Phantom plans the introduction of a CPU model as a future milestone for development and we will try to utilize it to improve our simulation results.

**Attacker Model.** Moreover, we have in view to introduce an attacker model to reason about the impact of attacks on system performance. For this reason, we seek inspiration from the Twins [2] methodology, a recent approach for validating BFT protocols: Twins is an unit test case generator that can simulate Byzantine attacks by duplicating cryptographic identities of replicas (which then leads to forgotten protocol states, or equivocations) and it can be quite useful in a simulator to explore a variety of attacking scenarios.

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Appendix

In this section, we first define the properties that we used to create our comparison of evaluation tools (Sect. A). Further, we explain how to (B) reproduce this paper’s simulation results on your own machine, (C) create your own experiments to run on our toolchain, and (D) connect your own BFT protocol implementation with our toolchain by writing a protocol connector.

A Properties of an Ideal Simulator for BFT Research

In the following, we briefly explain a set of distilled properties that we employed to create our comparison:

- **Realism**: The simulator allows us to reason about the real protocol behavior fairly enough. We can distinguish this further into the characteristics of realistic networking and application layer realism (which means the application model of a BFT protocol matches its implementation).
- **Scalability**: The simulator can handle up to the magnitude of over $10^5$ of nodes executing the BFT protocol and can also handle the geographic dispersion of nodes, i.e., by maintaining a large network topology.
- **Resource friendliness**: To conduct experiments, it is not necessary to have many physical machines at hand.
- **Reproducibility**: Repeated runs give similar results (or even the same results in the case of simulation runs which can be deterministic).
- **Experimental controllability**: It is simple to study isolatable factors, e.g., controlling the environment, or parameters of the protocol.
- **Fault induction / Byzantine attacker**: The simulator provides support to induce faults, for instance, dropping messages, crashing nodes or more complex, in particular malicious attacking behavior orchestrated by an attacker.

The first five properties are favorable for any simulations of distributed systems. If models use re-implementation or if simplifications are used, then application layer realism is hard to achieve. This is because BFT protocols are generally difficult to implement, and a re-implementation (that may even simplify the protocol) can easily induce bugs (a fact that is also stressed in BFTSim [29]). To counteract this, BFT-Simulator compares execution traces of real deployments with traces from the simulation for validation (the authors are aware that this gives no strict guarantees for correctness) [34].

The last property deserves explanation: It seems desirable to also evaluate BFT protocols in an adverse environment, such as when a portion of nodes becomes faulty. To our best knowledge, BFTSim only supports benign faults (i.e., faulty replicas staying silent [29]), while the BFT Simulator from Wang et al. [34] also supports some more sophisticated attacks (such as partition, adaptive and rushing attacks [34]). The generic simulators and emulators which were not crafted for BFT research do not consider a global Byzantine attacker.

Reproducibility and experimental controllability are important but seem to be provided by most if not all simulators and emulators so these properties are not used in our comparison.

B Reproduce our Results

Our evaluation results can be reproduced. First, it is necessary to clone our toolchain repository and follow the setup instructions in the README file. For best compatibility, we recommend (and currently use) Ubuntu 20.04 LTS and Shadow v2.2 (the newest version as of time of writing) and Node version 16.3.0. If you want to simulate specific BFT protocols like HotStuff, Themis or BFT-SMaRt you will need to install their dependencies, too.

A series of experiments (like the "p1024" experiment row with increasing $n$) is specified in an experiments description file, in yaml format. The structure and description is easy to understand. For instance, an experiment for Hotstuff with 128 replicas looks like this:
duration: 30 s
parallelism: 16
useShortestPath: false
network:
  bandwidthUp: 10 Gbits
  bandwidthDown: 10 Gbits
  latency:
    uniform: true
    replicas: 1000 us
    clients: 1000 us
replica:
  replicas: 128
  blockSize: 400
  replySize: 1024
client:
  clients: 16
  numberOfHosts: 2
  startTime: 0 s
  outStandingPerClient: 175
  requestSize: 1024

const processName = 'my-app'; // replace with the name of your protocol app!

function getProcessName() { return processName; }

function getExecutionDir() {...}

function getExperimentsOutputDirectory() {...}

async function build(replicaSettings, clientSettings, log) {...} // Mandatory

async function configure(replicaSettings, clientSettings, log) {...} // Mandatory

async function getStats(log) {...} // Optional, called after simulation

module.exports = {build, configure, getStats, getProcessName, getExecutionDir, getExperimentsOutputDirectory};

### Listing 1. Stubs of a BFT protocol connector.

The geographic distribution of replicas can be simply specified by passing a mapping of regions and the number of replicas to be placed in the respective region such as:

```javascript
['us-west-1': 1, 'eu-west-1': 1, 'sa-east-1': 1, 'ap-southeast-2': 1]
```

We think it is easy to adapt our experiment description files. However, some care needs to be taken. In the following, we want to share some insights we made:

**Duration:** This is one of the most important parameters because it has a big impact on resource consumption of simulations. It is better to use short durations to keep the overall simulation time short.

**Parallelism:** Make sure to set this parameter to utilize multicore systems and speed up simulations.

**BlockSize and OutStandingRequestsPerClient:** In HotStuff, if the number of in-flight requests is too low to fill the blocks, then HotStuff replicas just wait for more requests (which wont arrive). In this case the system halts and the simulation fast-forwards and terminates. It is better to overestimate the number of inflight requests for HotStuff.

We put a folder called examples/serial22 on the repository that contains all experiments description files that we used for the evaluation section of this paper. We also provide all of our data sets as a reference. After following the README, you can run simulations by typing in a shell:

```
  npm run simulation -- examples/hotstuff/hs3-aws.yaml
```

This will create a data set called results.csv in your experiments directory.

### C Create your own Experiments

It is also easy to setup experiments that simulate AWS deployments. Here is an example:

```javascript
proclonName: bftsmart
protocolConnectorPath: ./connectors/bftsmart.js
experiments:
  - 4replicasAWS:
      misc:
        duration: 1200 s
        parallelism: 16
        useShortestPath: false
      network:
        bandwidthUp: 1 Gbit
        bandwidthDown: 1 Gbit
        latency:
          uniform: false
          replicas: ['us-west-1': 1, 'eu-west-1': 1, 'sa-east-1': 1, 'ap-southeast-2': 1]
        clients: ['us-west-1': 1]
    replica:
      replicas: 4
      blockSize: 100
      replicaInterval: 100
      replySize: 0
      stateSize: 0
      context: false
      replicaSig: nosig
    client:
      clients: 1
      threadsPerClient: 1
```

```javascript
opPerClient: 2000
requestSize: 0
startTime: 30 s
clientInterval: 0
readOnly: false
verbose: false
clientSig: true
```

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Moreover, we recommend reading the documentation of parameters\(^3\) and we also recommend to use \texttt{tmux} to run your simulations in the background.

**D Simulate your own BFT Protocol Implementation**

You can implement your own BFT protocol connector by implementing the stubs \texttt{build}, \texttt{configure}, \texttt{getExecutionDir} \texttt{getProcessName} and \texttt{getExperimentsOutputDirectory} as shown in Listing 1. Your connector can optionally also implement a method \texttt{getStats} to automatically parse logs and put the results in a comma separated value file. Experiment description files have to adhere to a certain format:

```plaintext
protocolName: #name of your protocol
protocolConnectorPath: #path to your connector
experiments: #Array describing the experiments
  -expr: #description of an experiment
    misc: #miscellaneous settings
    duration: #duration of the experiment
    useShortestPath: #default is false
    parallelism: # multi-core awareness
    network:
      bandwidthUp: ..
      bandwidthDown: ..
      latency:
        uniform: (true|false)
        # if true:
        replicas: #inter-replica
        # latency ex. 1000 us
        clients: #client-replica
        # latency ex. 1000 us
        # else:
        replicas: #Array describing
        # AWS hosts format region: host
        clients: #Array describing
        # AWS hosts format region: host
        #OR: a uniform client-replica latency
    replica:
      #This is for protocol- and replica-specific
      # configs; will be passed to your connector.
    client:
      #This is for protocol- and client-specific
      # configs; will be passed to your connector.
```

You may leverage the `.env` file to make your experiment description files and your connectors more concise.

**E Determinism in Phantom**

Throughout the simulation, Phantom preserves determinism: it employs a pseudo-random generator, which is seeded from a configuration file to emulate all randomness needed during simulation, in particular the emulation of \texttt{getrandom} or reads of \texttt{/dev/*random}. Each Phantom worker only allows a single thread of execution across all processes it manages so that each of the remaining managed processes/threads are idle, thus preventing concurrent access of managed processes’ memory [17].

\(^3\)http://shadow-github.io/docs/guide/shadow_config_spec.html