

SOSP21 Artifact Evaluation Instructions

#617 Rabia: Simplifying State-Machine Replication Through Randomization

1.1 Summary

- We have four evaluations reported in the paper:
 - Performance without Batching: Table 1
 - Throughput vs. Latency: Figure 4
 - Varying Data Size: No table/figure (text only)
 - Integration with Redis: Figure 5

For these evaluations, we provide either the binaries (for competitors) or compile scripts.
- We have also provided all the necessary proof scripts for formally verifying our algorithm. See <https://github.com/haochenpan/rabia/tree/main/proofs>
- Rabia consists of x server VMs and y client VMs. In our evaluations, we have tested x = 3 or 5, and y = 1 or 3.
- Key parameters of Rabia that need to be configured are located in two files:
 - “[profileX.sh](#)” configurations -- adjust the parameters below in [deployment/profile/profile0.sh](#)
 - NServers -- the number of servers (n)
 - NFaulty -- the number of faulty servers (f)
 - NClients -- the number of clients
 - ClientTimeout -- the runtime of each client
 - ClientBatchSize -- the number of KV-store commands packed in a single client request
 - ProxyBatchSize -- the maximum number of client-batched requests packed in a single consensus object and hence stored in a single consensus slot
 - Other parameters that are not essential for the artifact evaluation: see comments in [deployment/profile/profile0.sh](#)
 - “[config.go](#)” configurations -- adjust the parameters below in [internal/config/config.go](#)
 - “[c.KeyLen](#)” and “[c.ValLen](#)” at line 162-163 need to be changed for the “Varying Data Size” test. These two parameters specify the lengths of keys and values of the KV-store, respectively
 - “[c.StorageMode](#)” at line 171 needs to be changed to “2” for the Rabia-Redis test. 2 stands for the MSET & MGET mode.

- Note: If the evaluation instruction asks you to change a file (i.e., config.go or profile.sh), please change that file on ALL VMs
- In the first few sets of experiments, we compare Rabia against EPaxos and Paxos using the EPaxos repo¹. We mainly edited two parts: (i) we fixed the way Go imports modules, and (ii) we modified the original codebase so that EPaxos and Paxos support the non-pipelining execution (to produce Table 1).
- EPaxos and Paxos do not provide an easy way to adjust parameters; hence, we create several branches, one for each combination of the parameters that we use. We will specifically mention which branch to use².
- In the last set of experiments, we compare Rabia against our implementation of synchronous replication on Redis and RedisRaft.
- Our paper reported data collected on Google Cloud Platform (GCP). Here, we explain how to replicate it on CloudLab. We expect the data to be a little bit off, because computation and communication resources, such as CPU specifications, memory frequencies, network bandwidths, and network stability, are different in two platforms. Among these, network stability affects the numbers the most. For example, CloudLab has average RTT roughly 0.13 ms, whereas GCP has average RTT roughly 0.25 ms. Due to the property of Rabia, the performance improvement due to the lower RTT is not as great as Paxos and EPaxos.
- One set of evaluations (Figure 4c in the paper) might be difficult to achieve on CloudLab, because it does not provide multiple availability zones. We originally conducted the experiments on Google Cloud Platform (GCP), see steps to run at section 2.2.
- For the reviewers' convenience, we have a video walkthrough of section 2.1: <https://youtu.be/LPjyibkhgYc>

1.2 Setup on CloudLab: General

- Instantiate the following [profile](#), which consists of three server VMs and three client VMs with these VMs being connected with each other on the experiment network.
- We used 2-core server VMs to collect our data, where each core ran 2 threads (i.e., 4 vCPU). Hence, it is necessary to disable 12 cores on server VMs to provide a comparable specification, since the smallest raw machine has 16 cpus on CloudLab (8 cores, 2 threads per core).

¹ <https://github.com/efficient/epaxos>

² The modified EPaxos and Paxos can be found at <https://github.com/zhouaea/epaxos-single> for non-pipelined version, and <https://github.com/zhouaea/epaxos> for pipelined version.

- Follow the steps below to disable cores on server VMs:
 - Run as super user
 - `sudo su`
 - To check CPU status
 - `lscpu`
 - To disable 6 cores (Note: All cpus except cpu0 can be disabled)
 - `echo 0 > /sys/devices/system/cpu/cpu2/online`
 - `echo 0 > /sys/devices/system/cpu/cpu3/online`
 - `echo 0 > /sys/devices/system/cpu/cpu4/online`
 - `echo 0 > /sys/devices/system/cpu/cpu5/online`
 - `echo 0 > /sys/devices/system/cpu/cpu6/online`
 - `echo 0 > /sys/devices/system/cpu/cpu7/online`
 - `echo 0 > /sys/devices/system/cpu/cpu10/online`
 - `echo 0 > /sys/devices/system/cpu/cpu11/online`
 - `echo 0 > /sys/devices/system/cpu/cpu12/online`
 - `echo 0 > /sys/devices/system/cpu/cpu13/online`
 - `echo 0 > /sys/devices/system/cpu/cpu14/online`
 - `echo 0 > /sys/devices/system/cpu/cpu15/online`
- Note: If needed, you can re-enable a core by doing
 - `echo 1 > /sys/devices/system/cpu/cpu1/online`

1.3 Setup on CloudLab: Rabia

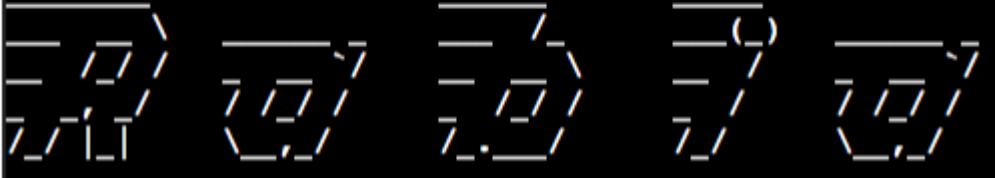
- Install Rabia by entering the commands (blue texts) below on EACH VM
 - # 0. use root
 - `sudo su`
 - # 1. download the project to the default path (see section 1.3)
 - `mkdir -p ~/go/src && cd ~/go/src`
 - `git clone https://github.com/haochenpan/rabia.git`
 - # 2. install Rabia and its dependencies
 - `cd ./rabia/deployment`
 - `./install/install.sh`
 - # note: this may take a while (3~5 mins), as the script is getting all the dependencies, including Redis and RedisRaft
 - # 3. check the installation:
 - `cd ./run`
 - # the default parameter runs a Rabia cluster on a single machine for 20 seconds (see the note below)
 - `./single.sh`
 - # inspect the performance statistics; one should see a few lines of file output
 - `cat ../../result.txt`
 - # remove logs, result.txt, and the built binary

- `. clear.sh`
- Note: if Rabia starts successfully, you should see the following:

```

root@ms1222:~/go/src/rabia/deployment/run# . single.sh
network = 1 successfully connected to all servers
network = 0 successfully connected to all servers
network = 2 successfully connected to all servers
all servers and clients are connected

```



1.4 Setup on CloudLab: Non-Pipelined Paxos and EPaxos (Table 1)

- Note: You only need to perform these steps if you're evaluating Table 1. For other EPaxos/Paxos evaluation, we provide binaries in the Rabia repository.
- Make sure Rabia is properly installed. Follow the instructions in Section 1.3. This step is critical as it provides the go binary and python3.8 needed for testing.
- Install Paxos/EPaxos (NP) by entering the commands below on EACH VM
 - # 0. use root
 - `sudo su`
 -
 - # 1. download the project to the default path (see section 1.3) and switch to the Paxos (NP) or EPaxos (NP) branch. Assuming you already have ~/go/src
 - `cd ~/go/src`
 - `git clone https://github.com/zhouaea/epaxos-single.git && cd epaxos-single`
 - `git checkout paxos-no-pipelining-no-batching OR git checkout epaxos-no-pipelining-no-batching`
 - # 2. compile Paxos or EPaxos (on each VM) (This will not output anything if successful.)
 - `cd ~/go/src/epaxos-single`
 - `. compilePaxos.sh OR . compileEPaxos.sh`

1.5 Setup on CloudLab: Paxos and EPaxos

- Note: You only need to perform these steps if you're evaluating Table 1. For other EPaxos/Paxos evaluation, we provide binaries.

- Install Paxos/EPaxos by entering the commands below on EACH VM. This will only be used for Table 1 experiments.
 - # 0. use root
 - `sudo su`
 -
 - # 1. download the project to the default path (see section 1.3) and switch to the Paxos (NP) or EPaxos (NP) branch. Assuming you already have ~/go/src
 - `cd ~/go/src`
 - `git clone https://github.com/zhouaea/epaxos.git && cd epaxos`
 - `git checkout paxos-no-batching OR git checkout epaxos-no-batching`
 -
 - # 2. compile Paxos or EPaxos (on each VM)
 - `cd ~/go/src/epaxos`
 - `. compile.sh`
- Note: If Paxos/Epaxos compiled correctly, you should see
Built Master
Built Server
Built Client
- For all experiments besides those done for Table 1, please follow the instructions below to launch the exact binary of EPaxos and Paxos for each evaluation below.

2.1 Performance without Batching (Table 1)

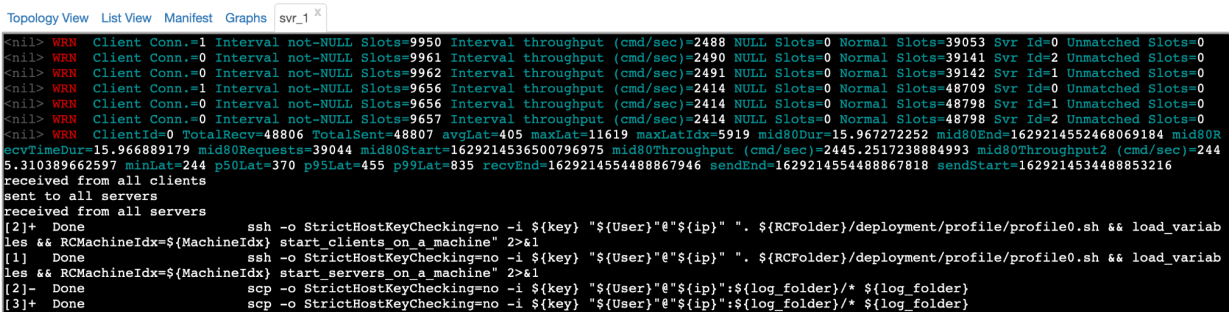
2.1.1 Rabia

- Configure VMs
 - System setup: three Rabia server VMs and one client VM. This experiment uses only one client VM; our profile provides three so that it's easier to run other experiments.
 - Make sure all the steps in "Setup on CloudLab: General" and "Setup on CloudLab: Rabia" are completed on ALL VMs
 - Make sure you're in the folder of `~/go/src/rabia`
 - Configure the following parameters by editing [deployment/profile/profile0.sh](#) on ALL VMs
 - Find the [experiment network ip address](#) of all three server VMs and one client VM that you chose to work on.
 - Note: these IPs usually appear as 10.10.1.x in CloudLab (see section below titled *Note: Find "experiment network IP" on Cloudlab*)
 - Fill ServerIps with 3 server VMs' internal IPs. e.g.,
 - `ServerIps=(10.10.1.1 10.10.1.2 10.10.1.3)`
 - Note: white space between each pair of IPs
 - Fill ClientIps with the client VM' internal IPs. e.g.,
 - `ClientIps=(10.10.1.1)`

- Let Controller be the first server VM's IP:some unused port, e.g.,
 - **Controller=10.10.1.1:8070**
- Replace the “run_once” function call at the bottom of [deployment/run/multiple.sh](#) to the followings (the result looks like the figure below):
 - **run_once \${RCFolder}/deployment/profile/profile_sosp_table1.sh**

```
source ../profile/profile0.sh # required, load the variables and functions
run_once ${RCFolder}/deployment/profile/profile_sosp_table1.sh
```

- Run Rabia
 - At the first server VM (which will act as the controller of the experiment):
 - **cd ~/go/src/rabia/deployment/run**
 - **. multiple.sh**
 - After 120-150 seconds, the run should be over. An example output is shown below.



```
Topology View List View Manifest Graphs svr_1 x
<nll> WRN Client Conn.=1 Interval not-NULL Slots=9950 Interval throughput (cmd/sec)=2488 NULL Slots=0 Normal Slots=39053 Svr Id=0 Unmatched Slots=0
<nll> WRN Client Conn.=0 Interval not-NULL Slots=9961 Interval throughput (cmd/sec)=2490 NULL Slots=0 Normal Slots=39141 Svr Id=2 Unmatched Slots=0
<nll> WRN Client Conn.=0 Interval not-NULL Slots=9962 Interval throughput (cmd/sec)=2491 NULL Slots=0 Normal Slots=39142 Svr Id=1 Unmatched Slots=0
<nll> WRN Client Conn.=1 Interval not-NULL Slots=9656 Interval throughput (cmd/sec)=2414 NULL Slots=0 Normal Slots=48709 Svr Id=0 Unmatched Slots=0
<nll> WRN Client Conn.=0 Interval not-NULL Slots=9656 Interval throughput (cmd/sec)=2414 NULL Slots=0 Normal Slots=48798 Svr Id=1 Unmatched Slots=0
<nll> WRN Client Conn.=0 Interval not-NULL Slots=9657 Interval throughput (cmd/sec)=2414 NULL Slots=0 Normal Slots=48798 Svr Id=2 Unmatched Slots=0
<nll> WRN ClientId=0 TotalRecv=48806 TotalSent=48807 avgLat=405 maxLat=11619 maxLatIdx=5919 mid80Dur=15.967272252 mid80End=1629214552468069184 mid80R
ecvTimeDur=15.966889179 mid80Requests=39044 mid80Start=1629214536500796975 mid80Throughput (cmd/sec)=2445.2517238884993 mid80Throughput2 (cmd/sec)=244
5.310389662597 minLat=244 p50Lat=370 p95Lat=455 p99Lat=835 recvEnd=1629214554488867946 sendEnd=1629214554488867818 sendStart=1629214534488853216
received from all clients
sent to all servers
received from all servers
[2]+ Done ssh -o StrictHostKeyChecking=no -i ${key} "${User}"@"${ip}" ". ${RCFolder}/deployment/profile/profile0.sh && load_variab
les && RCMachineIdx=${MachineIdx} start_clients on a machine" 2>&1
[1] Done ssh -o StrictHostKeyChecking=no -i ${key} "${User}"@"${ip}" ". ${RCFolder}/deployment/profile/profile0.sh && load_variab
les && RCMachineIdx=${MachineIdx} start_servers on a machine" 2>&1
[2]- Done scp -o StrictHostKeyChecking=no -i ${key} "${User}"@"${ip}":${log_folder}/* ${log_folder}
[3]+ Done scp -o StrictHostKeyChecking=no -i ${key} "${User}"@"${ip}":${log_folder}/* ${log_folder}
```

- Check [result.txt](#) in [~/go/src/rabia](#) of the controller VM to retrieve performance statistics. You may see a bunch of numbers separated by commas in the file.
- You can copy them to a Google Sheet, select the first column, and click "Data" -> "Split text to columns" -> "Separator: Comma" to get a human-readable presentation.
- Note: the other evaluation for Rabia basically follows the same recipe. We will explicitly specify the parameters that need to be changed and the profile to be used.

Note: Find “experiment network IP” on CloudLab

- Find the [experiment network ip address](#) of the desired node in your rspec manifest.
- First, find the description of your machine by looking for a <node> tag with the attribute client_id=<your_machine_name>.
- Inside the node tag, look for <interface>, and inside it you should see an <ip/> tag. The attribute address will give you the machine's experiment network ip. 2. The address likely has the format 10.10.1.x.

```

Topology View List View Manifest Graphs svr_1 svr_2 svr_3 cli_1
<rspec xmlns="http://www.geni.net/resources/rspec/3" xmlns:emulab="http://www.protogeni.net/resources/rspec/ext/emulab/1" xmlns:tour="http://www.protogeni.net/resources/rspec/ext/emulab/1" client_id="svr_1" exclusive="true" component_manager_id="urn:publicid:IDN+utah.cloudlab.us" >
  <node xmlns:emulab="http://www.protogeni.net/resources/rspec/ext/emulab/1" >
    <sliver_type name="raw-pc" >
      <disk_image name="urn:publicid:IDN+emulab.net+image+emulab-ops:UBUNTU18-64-STD" />
    </sliver_type>
    <hardware_type name="m510" />
    <interface client_id="svr_1:eth1" component_id="urn:publicid:IDN+utah.cloudlab.us+interface+ms1004:eth1" sliver_id="urn:publicid:IDN+utah.cloudlab.us+sliver+10" >
      <ip address="10.10.1.1" type="ipv4" netmask="255.255.255.0" />
    </interface>
    <emulab:vnode name="ms1004" hardware_type="m510" />
    <host name="svr_1.zhouaea-103917.hyflowtm-PG0.utah.cloudlab.us" ipv4="128.110.217.119" />
    <services>
      <login authentication="ssh-keys" hostname="ms1004.utah.cloudlab.us" port="22" username="zhouaea" />
      <emulab:console server="boss.utah.cloudlab.us" />
      <emulab:recovery available="true" />
    </services>
  </node>
</rspec>

```

2.1.2 Paxos (NP) and EPaxos (NP) -- NP stands for Non-Pipelining version

- You need to run the following steps twice. One for Paxos (NP) and the other for EPaxos (NP).
- System setup: three paxos/epaxos (NP) server VMs and one client VM. You can use the same VMs used in the Rabia test.
- Follow Section 1.4 to manually create binaries and switch to the correct directory and branch ([paxos-no-pipelining-no-batching](#) or [epaxos-no-pipelining-no-batching](#))
- System setup: three server VMs and one client VM
- Configure Master
 - Choose one of your server VMs to be the master server. The other two will be replicas.
 - Edit [runMasterServer.sh](#) in [~/go/src/epaxos-single](#)
 - Set MASTER_SERVER_IP equal to the server machine's experiment network IP address (see section above titled *Note: Find "experiment network IP" on Cloudlab*).
- Configure Replicas
 - You need to perform the following on the other two replicas
 - Find its experiment network ip address.
 - Edit [runServer.sh](#) in [~/go/src/epaxos-single](#)
 - Set MASTER_SERVER_IP equal to the master server VM's experiment network IP address.
 - Set REPLICA_SERVER_IP to the current server VM's experiment network IP address.
- Configure the Client
 - Edit [runClient.sh](#) in [~/go/src/epaxos-single](#)
 - Set MASTER_SERVER_IP equal to the master server VM's experiment network ip address.
- Run Paxos (NP) or EPaxos (NP)
 - In your master server VM, run [. runMasterServer.sh](#) in [~/go/src/epaxos-single](#)
 - In every replica server VM, run [. runServer.sh](#) in [~/go/src/epaxos-single](#)
 - Once all servers are connected, you should see messages from rpc.Register and the message

Replica id: x. Done connecting to peers

- Alternatively, you may see the error below. If this is the case, you did not input the network ip addresses correctly in one or more machines. Type `. kill.sh` in each server VM to terminate server processes and retry the configuration steps above.

```
[signal SIGSEGV: segmentation violation code=0x1 addr=0x18 pc=0x560ac5]
goroutine 56 [running]:
genericsmr.(*Replica).waitForPeerConnections(0xc00027c000, 0xc000096480)
    /root/go/src/epaxos-single/src/genericsmr/genericsmr.go:196 +0x105
created by genericsmr.(*Replica).ConnectToPeers
    /root/go/src/epaxos-single/src/genericsmr/genericsmr.go:127 +0x9f
```

- Finally, run `. runClient.sh > run.txt` in the terminal of your client VM.
 - After a couple of seconds, press the enter key a few times on your keyboard.
 - You should see a bunch of DONE messages, equal to the number of NClients specified.
 - You can also use the `ps` command to check for pending clients.
 - Verify the contents of `run.txt`. It should contain a list of start and end times.
 - You'll know `runClient.sh` failed if any client in NClients outputs `Error connecting to replica 0` after a timeout period of around 1 minute.
- Analysis
 - Dependencies:
 - We use python3.8 for our analysis scripts, which should have been downloaded when you installed Rabia.
 - Note: our latency analysis script requires the numpy package, which should have been downloaded when you installed Rabia. If it somehow did not get installed, we have provided a shell script in the repo that will install pip and numpy for python3.8 that can be run with `. download_numpy.py`
 - Latency and throughput analysis:
 - In your client VM, run `. calculate_throughput_latency.sh`. This will run both `latency_analysis.py` and `throughput_analysis.py`
 - You may get an error from `calculate_throughput_latency.sh` if you run it before `runClient.sh` has terminated, or if `runClient.sh` failed.
 - Note:
 - If you see `SyntaxError: Non-ASCII character '\xc2'` in file `latency_analysis.py` on line 21, but no encoding declared; see <http://python.org/dev/peps/pep-0263/> for details. It's likely because you're using python 2 instead of python 3.

2.1.3 Paxos and Epaxos

- Note: the workflow for EPaxos/Paxos is different from the one for EPaxos (NP) and Paxos (NP)

- You need to run the following steps twice. One for Paxos and the other for EPaxos.
- System setup: three paxos/epaxos server VMs and one client VM. You can use the same VMs used in the Rabia test.
- Follow Section 1.5 to manually create binaries and switch to the correct directory and branch ([paxos-no-batching](#) or [epaxos-no-batching](#))
- Configure Each VM:
 - Choose one of your server VMs to be the master server.
 - **On each VM**, configure the following parameters by editing [base-profile.sh](#):
 - Fill ServerIps with 3 server VMs' IPs. e.g.,
 - [ServerIps=\(10.10.1.1 10.10.1.2 10.10.1.3\)](#)
 - Note: white space between each pair of IPs
 - Note: IPs should be [experiment network ip addresses](#), which usually appears as 10.10.1.x in CloudLab (see section above titled *Note: Find "experiment network IP" on Cloudlab*)
 - Fill ClientIps with the client VMs' IPs. e.g.,
 - [ClientIps=\(10.10.1.4\)](#)
 - Let MasterIp be the first VM's IP, e.g.,
 - [MasterIp=10.10.1.1](#)
- Run Paxos or EPaxos
 - Finally, run [. runPaxos.sh](#) or [. runEPaxos.sh](#) (depending on the branch) on your master VM only. You should see a relatively constant flow of messages in your terminal.
 - If all works correctly, there will be n client logs inside the [/logs](#) directory in your master machine.
 - If something doesn't work correctly, run [. kill.sh](#) and try to execute again.
 - Alternatively, you can manually search and kill processes
 - Use [ps](#) to find active processes
 - Use [kill -9 <pid>](#) to kill a process
- Analysis
 - Dependencies:
 - This script uses python3.8, which should have been downloaded when you installed Rabia.
 - For throughput/latency analysis, run [python3.8 analysis.py ./logs](#)
 - If you get the error below, you didn't supply [./logs](#) as an argument
 - Traceback (most recent call last):
 - File "analysis.py", line 164, in <module>
 - infos, disconnects = analysis_epaxos_logs()
 - File "analysis.py", line 100, in analysis_epaxos_logs
 - params = get_experiments(argv[1])
 - IndexError: list index out of range
 - If successful, this will output a variety of different statistics. You can find the relevant statistics as clientp50Latency: x, clientp99Latency: x, throughput: x.

2.2 Throughput vs. Latency (Figure 4)

2.2.1 Rabia

- Figure 4a, 4b
 - System setup: three server VMs and three client VMs
 - Following the steps in “Performance without Batching,” run Rabia on CloudLab with profile [profile_sosp_4abc.sh](#):
 - i. Make sure [ServerIps](#), [ClientIps](#), [Controller](#) are adjusted in the way described in “Performance without Batching”
 - ii. Replace the “run_once” function call at the bottom of deployment/run/multiple.sh to the followings:
 - 1. [run_once \\${RCFolder}/deployment/profile/profile_sosp_4abc.sh](#)
 - Adjust the number of clients (parameter NClients) manually after a run to produce a series of data points (the exact numbers are in the profile, which range from 20 to 500).
 - Copy the content of [result.txt](#) to a Google Sheet, check the columns of median latency and 99-percentile latency.
Note: You may need to split your pasted data into columns by clicking Data > Split text to columns
- Figure 4c (this experiment requires multiple availability zones, which unfortunately is not supported by CloudLab but available on GCP)
 - System setup: three server VMs and three client VMs
 - i. 3 server VMs one in [us-east-1-b](#), one in [us-east-1-c](#), and the last in [us-east-1-d](#)
 - ii. 3 server VMs: e2-highmem-4 instances (Intel Xeon 2.8GHz, 4 vCPUs, 32 GB RAM)
 - iii. 3 client VMs in [us-east-1-b](#), each with 30 vCPUs and 120 GB RAM
 - iv. OS for all VMs: Ubuntu-1604
 - Following the steps in “Performance without Batching,” run Rabia on GCP with profile [profile_sosp_4abc.sh](#) (see the note at the end of this file).
 - i. Make sure [ServerIps](#), [ClientIps](#), [Controller](#) are adjusted in the way described in “Performance without Batching”
 - ii. Replace the “run_once” function call at the bottom of deployment/run/multiple.sh to the followings:
 - 1. [run_once \\${RCFolder}/deployment/profile/profile_sosp_4abc.sh](#)
 - Adjust the number of clients (parameter NClients) manually after a run to produce a series of data points (the exact numbers are in the profile, which range from 20 to 500).
 - Copy the content of [result.txt](#) to a Google Sheet, check the columns of median latency and 99-percentile latency.
Note: You may need to split your pasted data into columns by clicking Data > Split text to columns

- Figure 4d
 - System setup: five server VMs and three client VMs
 - Instantiate the provided [profile](#)
 - Following the steps in “Performance without Batching,” run Rabia on CloudLab with profile [profile_sosp_4d.sh](#):
 - i. Make sure [ServerIps](#) (previously 3 entries, now 5 entries), [ClientIps](#), [Controller](#) are adjusted in the way described in “Performance without Batching”
 - ii. Replace the “run_once” function call at the bottom of deployment/run/multiple.sh to the followings:
 1. [run_once \\${RCFolder}/deployment/profile/profile_sosp_4d.sh](#)
 - Adjust the number of clients (parameter NClients) manually after a run to produce a series of data points (the exact numbers are in the profile, which range from 20 to 500).
 - Copy the content of [result.txt](#) to a Google Sheet, check the columns of median latency and 99-percentile latency.
 Note: You may need to split your pasted data into columns by clicking Data > Split text to columns

2.2.2 EPaxos, Paxos

- Figure 4a, 4b
 - System setup: three server VMs and three client VMs
 - On each VM, open the [paxos-batching](#) or [epaxos-batching](#) folder with `cd ~/go/src/rabia/epaxos/figure-4/paxos-batching` or `~/go/src/rabia/epaxos/figure-4/epaxos-batching`, respectively.
 - Configure Each VM:
 - i. Choose one of your server VMs to be the master server.
 - ii. **On each VM**, configure the following parameters by editing [gre](#):
 1. Fill [ServerIps](#) with 3 server VMs' IPs. e.g.,
 - a. [ServerIps=\(10.10.1.1 10.10.1.2 10.10.1.3\)](#)
 - b. Note: white space between each pair of IPs
 - c. Note: IPs should be [experiment network ip addresses](#), which usually appears as 10.10.1.x in CloudLab (see section above titled *Note: Find “experiment network IP” on Cloudlab*)
 2. Fill [ClientIps](#) with the client VMs' IPs. e.g.,
 - a. [ClientIps=\(10.10.1.4, 10.10.1.5 10.10.1.6\)](#)
 3. Let [MasterIp](#) be the first VM's IP, e.g.,
 - a. [MasterIp=10.10.1.1](#)
 - iii. In our paper, we run the Paxos/EPaxos configuration 9 times with varying clients (ranging from 20 to 500). [profile0.sh](#) contains code to run with 20 clients, while [profile8.sh](#) will run with 500 clients. To choose which profile

- is being executed, edit the second line of `runBatchedPaxos` or `runBatchedEPaxos` in each machine.
 - Run Paxos or EPaxos
 - i. **On the master VM**, run `. runBatchedPaxos` or `. runBatchedEPaxos`. You should see a relatively constant flow of messages in your terminal.
 - ii. If all works correctly, there will be n client logs inside the `/logs` directory in your master machine.
 - 1. If something doesn't work correctly, run `. kill.sh` and try to execute again.
 - 2. Alternatively, you can manually search and kill processes
 - a. Use `ps` to find active processes
 - b. Use `kill -9 <pid>` to kill a process
 - Analysis
 - i. Dependencies:
 - 1. This script uses python3.8, which should have been downloaded when you installed Rabia.
 - ii. For throughput/latency analysis, run `python3.8 analysis.py ./logs`
 - iii. If you get the error below, you didn't supply `./logs` as an argument
 - 1. Traceback (most recent call last):
 - 2. File "analysis.py", line 164, in <module>
 - 3. infos, disconnects = analysis_epaxos_logs()
 - 4. File "analysis.py", line 100, in analysis_epaxos_logs
 - 5. params = get_experiments(argv[1])
 - 6. IndexError: list index out of range
 - iv. If successful, this will output a variety of different statistics. You can find the relevant statistics as `clientp50Latency: x, clientp99Latency: x, throughput: x`.
- Figure 4c (this experiment requires multiple availability zones, which unfortunately is not supported by CloudLab but is available on GCP)
 - System setup: three server VMs and three client VMs
 - i. 3 server VMs one in `us-east-1-b`, one in `us-east-1-c`, and the last in `us-east-1-d`
 - ii. 3 server VMs: e2-highmem-4 instances (Intel Xeon 2.8GHz, 4 vCPUs, 32 GB RAM)
 - iii. 3 client VMs in `us-east-1-b`, each with 30 vCPUs and 120 GB RAM
 - iv. OS for all VMs: Ubuntu-1604
 - With Rabia installed on machines in GCP, follow the instructions for "Figure 4a, 4b." The only difference is that instead of using experiment network ips, you will use GCP's internal network IPs.
- Figure 4d
 - System setup: five server VMs and three client VMs

- With Rabia installed on machines in Cloudlab, follow the instructions for Figure 4a, 4b. The only difference is that instead of configuring 3 server ips, you need to configure 5.

2.3 Varying Data Size (No Figure or Table)

2.3.1 Rabia

- System setup: three server VMs and three client VMs
- The base configuration for comparison (the setup of that produces Figure 4a) uses 16B key-value pairs. For this section, change the size to 256B: at each VM, in [internal/config/config.go](#), at line 162-163, set
 - `c.KeyLen = 128, c.ValLen = 128`
- Following the steps in “Performance without Batching,” run Rabia on CloudLab with profile [profile_sosp_vd.sh](#):
 - Make sure [ServerIps](#), [ClientIps](#), [Controller](#) are adjusted in the way described in “Performance without Batching”
 - Replace the “run_once” function call at the bottom of `deployment/run/multiple.sh` to the followings:
 - `run_once ${RCFolder}/deployment/profile/profile_sosp_vd.sh`
- Run Rabia according to the “Run Rabia” steps in “Performance without Batching.”
- Copy the content of `result.txt` to a Google Sheet, check the first column for throughput

2.3.2 EPaxos, Paxos

- System setup: three server VMs and three client VMs
- On each VM, open the [paxos-batching-data-size-256B](#) or [epaxos-batching-data-size-256B](#) folder with `cd ~/go/src/rabia/epaxos/varying-data-size/paxos-batching-data-size-256B` or `~/go/src/rabia/epaxos/varying-data-size/epaxos-batching-data-size-256B`, respectively.
- Configure each VM
 - Choose one of your server VMs to be the master server.
 - In each machine, configure the following parameters by editing [base-profile.sh](#):
 - i. Fill `ServerIps` with 3 server VMs' IPs. e.g.,
 1. `ServerIps=(10.10.1.1 10.10.1.2 10.10.1.3)`
 2. Note: white space between each pair of IPs
 3. Note: IPs should be [experiment network ip addresses](#), which usually appears as 10.10.1.x in CloudLab (see section above titled *Note: Find “experiment network IP” on Cloudlab*)
 - ii. Fill `ClientIps` with the client VMs' IPs. e.g.,
 1. `ClientIps=(10.10.1.4, 10.10.1.5 10.10.1.6)`
 - iii. Let `MasterIp` be the first VM's IP, e.g.,
 1. `MasterIp=10.10.1.1`

- In our paper, we run the Paxos/EPaxos configuration 9 times with varying clients (ranging from 20 to 500). [profile0.sh](#) contains code to run with 20 clients, while [profile8.sh](#) will run with 500 clients. To choose which profile is being executed, edit the second line of [runBatchedPaxos](#) or [runBatchedEPaxos](#) in each machine.
- Run Paxos or EPaxos
 - On the **master VM**, run [. runBatchedPaxos.sh](#) or [. runBatchedEPaxos.sh](#). You should see a relatively constant flow of messages in your terminal.
 - If all works correctly, there will be n client logs inside the [/logs](#) directory in your master machine.
 - i. If something didn't work correctly, run [. kill.sh](#) and try to execute again.
 - ii. Alternatively, you can manually search and kill processes
 1. Use [ps](#) to find active processes
 2. Use [kill -9 <pid>](#) to kill a process
- Analysis
 - Dependencies:
 - i. This script uses python3.8, which should have been downloaded when you installed Rabia.
 - For throughput/latency analysis, run [python3.8 analysis.py ./logs](#)
 - If you get the error below, you didn't supply [./logs](#) as an argument
 - i. `Traceback (most recent call last):`
 - ii. `File "analysis.py", line 164, in <module>`
 - iii. `infos, disconnects = analysis_epaxos_logs()`
 - iv. `File "analysis.py", line 100, in analysis_epaxos_logs`
 - v. `params = get_experiments(argv[1])`
 - vi. `IndexError: list index out of range`
 - If successful, this will output a variety of different statistics. You can find the relevant statistics as `clientp50Latency: x, clientp99Latency: x, throughput: x`.

2.4 Integration with Redis (Figure 5)

2.4.1 Sync-Rep (Synchronous replication using standalone Redis)

- There are two configurations:
 - (i) Sync-Rep (1): two VMs, one as the Redis leader and the other as a follower; and
 - (ii) Sync-Rep (2): three VMs, one as the Redis leader and the other two as followers.
 - Note: We run clients on follower VMs to force the system to have one RTT so that it's compatible with SMR-based approach.
- Configuration
 - On each VM, complete the following steps:

- Follow the steps in “Setup on CloudLab: Rabia” to clone Rabia and install necessary dependencies, including Redis. Following the steps in “Performance without Batching”
 - # Clone code for Sync-Rep
 - `cd ~/go/src`
 - `git clone https://github.com/YichengShen/redis-sync-rep.git`
 - `cd redis-sync-rep`
- Configure IP of master VM in [config.yaml](#)
- Start Redis server: You could configure the current VM either as a master or a replica.
 - configure as a master
 - `./deployment/startRedis/startServer.sh`
 - configure as a replica
 - `./deployment/startRedis/startServer.sh replica`
 - Note: if run successfully, you should see
OK
PONG
- Run Sync-Rep
 - Change the following parameters in [config.yaml](#) to produce the lower bar
 - `NClients=1` and `ClientBatchSize=1`
 - On one of the follower VMs, run the main program
 - `go run main.go`
 - Change the following parameters in [config.yaml](#) to produce the taller bar
 - `NClients=15` and `ClientBatchSize=20`
 - On one of the follower VMs, run the main program
 - `go run main.go`

2.4.2 Redis-Rabia

- System setup: three server VMs and three client VMs
- For each of the three Rabia **server VMs**, start a stand-alone Redis instance on the VM (n server requires n Redis instance), and start a client to monitor the Redis:
 - # on server-0
 - `src/redis-server --port 6379 --appendonly no --save "" --daemonize yes`
 - `src/redis-cli -p 6379`
 - # on server-1
 - `src/redis-server --port 6380 --appendonly no --save "" --daemonize yes`
 - `src/redis-cli -p 6380`
 - # on server-2
 - `src/redis-server --port 6381 --appendonly no --save "" --daemonize yes`
 - `src/redis-cli -p 6381`
- Adjusting the [StorageMode](#) in [config.go](#) on all VMs

- In `config.go`, adjust the `c.StorageMode` in `loadRedisVars()` to 2: use Redis' MGET and MSET commands only
Note: path to the file: `internal/config/config.go`
- Following the steps in “Performance without Batching,” run Rabia on CloudLab with profile `profile_sosp_5a.sh` to generate the low bar:
 - Make sure `ServerIps`, `ClientIps`, `Controller` are adjusted in the way described in “Performance without Batching”
 - Replace the “run_once” function call at the bottom of `deployment/run/multiple.sh` to the followings:
 - `run_once ${RCFolder}/deployment/profile/profile_sosp_5a.sh`
- After a run, you may want to type `keys *` in each redis-cli's terminal to see whether keys are written to the DB.
Note: this operation takes a significantly long time if there are many keys.
- Finally, run `flushall` to truncate the DB to prepare for the next clean run.
- Following the steps in “Performance without Batching,” run Rabia on CloudLab with profile `profile_sosp_5b.sh` to generate the high bar:
 - Make sure `ServerIps`, `ClientIps`, `Controller` are adjusted in the way described in “Performance without Batching”
 - Replace the “run_once” function call at the bottom of `deployment/run/multiple.sh` to the followings:
 - `run_once ${RCFolder}/deployment/profile/profile_sosp_5b.sh`
- After a run, you may want to type `keys *` in each redis-cli's terminal to see whether keys are written to the DB.
Note: this operation takes a significantly long time if there are many keys.
- Finally, run `flushall` to truncate the DB to prepare for the next clean run.
- **Note: If you need to re-run the previous evaluation, reset `StorageMode` in `config.go` to 0 on all VMs after these runs.**

2.4.3 Redis-Raft

- **Install Redis-Raft**

Note: These instructions assume you have the Rabia project cloned on the standard Cloudlab profile (deployment/env/cloudlab)

- `sudo su && cd`
 - `# clone the project to root`
 - `git clone https://github.com/RedisLabs/redisraft.git`
 - `# install the project's build deps`
 - `cd ~/go/src/rabia/redis-raft && . install.sh`
 - `# build the project to generate redisraft.so binary.`
 - `. build.sh`
- **Run Redis-Raft**

- System setup: three VMs -- Redis-Raft supports clients running on server VMs, so we did not use separate client VMs.
- This script assumes port 5001 is open and unused. You may use any free port you like.
- HOST (1..n) represents the internal IP. (See section above titled Note: Find “experiment network IP” on Cloudlab)
- RedisRaft recommends an odd number of nodes in a cluster. We have tested on 3.
- **Steps**
- On the first VM (this will act as the leader), type:
 - `redis-server --bind <HOST 1> --port 5001 --dbfilename raft1.rdb --loadmodule ~/redisraft/redisraft.so raft-log-filename raftlog1.db addr <HOST 1>:5001 &`
 - `redis-cli -h <HOST 1> -p 5001 RAFT.CLUSTER INIT`
 - `redis-cli -h <HOST 1> -p 5001 RAFT.CONFIG SET raft-log-fsync no`
- In subsequent two VMs, type:
 - `redis-server --bind <HOST n> --port 5001 --dbfilename raft<n>.rdb --loadmodule ~/redisraft/redisraft.so raft-log-filename raftlog<n>.db addr <HOST n>:5001 &`
 - `redis-cli -h <HOST n> -p 5001 RAFT.CLUSTER JOIN <HOST 1>:5001`
 - `redis-cli -h <HOST n> -p 5001 RAFT.CONFIG SET raft-log-fsync no`
- **To view the performance, in a new terminal on a leader VM, type**
 - `redis-benchmark -h <HOST 1> -p 5001 -t set,get -c 500 -n 1000 -d 16 -P 100 -q`
- **To kill the cluster and wipe the rdb files associated with the nodes:**
 - `cd ~/go/src/rabia/redis-raft/multiple && . multiple_kill.sh`
- **Known issue:**
- As mentioned in the paper, Redis-Raft is still in the experimental mode. So you might observe the issue of constant leader election. An example output is as follows:

```
24543:M 10 Aug 2021 14:35:18.142 * <redisraft> State change: Election starting, node is now a candidate, term 118
24543:M 10 Aug 2021 14:35:18.142 * <redisraft> Cluster Membership: term:118 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
notimeout=9337~--go/src/rabia/redis-raft/multiple redis-cli -h 10.10.1.1 -p 5001 RAFT.CONFIG SET raft-log-fsync no 10 Aug 2021 14:35:19.445 * <redisraft> State change: Election starting, node is now a candidate, term 119
24543:M 10 Aug 2021 14:35:19.445 * <redisraft> Cluster Membership: term:119 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:20.748 * <redisraft> State change: Election starting, node is now a candidate, term 120
24543:M 10 Aug 2021 14:35:20.748 * <redisraft> Cluster Membership: term:120 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:21.951 * <redisraft> State change: Election starting, node is now a candidate, term 121
24543:M 10 Aug 2021 14:35:21.951 * <redisraft> Cluster Membership: term:121 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:23.755 * <redisraft> State change: Election starting, node is now a candidate, term 122
24543:M 10 Aug 2021 14:35:23.755 * <redisraft> Cluster Membership: term:122 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:25.458 * <redisraft> State change: Election starting, node is now a candidate, term 123
24543:M 10 Aug 2021 14:35:25.458 * <redisraft> Cluster Membership: term:123 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:26.961 * <redisraft> State change: Election starting, node is now a candidate, term 124
24543:M 10 Aug 2021 14:35:26.961 * <redisraft> Cluster Membership: term:124 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:28.264 * <redisraft> State change: Election starting, node is now a candidate, term 125
24543:M 10 Aug 2021 14:35:28.264 * <redisraft> Cluster Membership: term:125 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:30.268 * <redisraft> State change: Election starting, node is now a candidate, term 126
24543:M 10 Aug 2021 14:35:30.268 * <redisraft> Cluster Membership: term:126 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:31.971 * <redisraft> State change: Election starting, node is now a candidate, term 127
24543:M 10 Aug 2021 14:35:31.971 * <redisraft> Cluster Membership: term:127 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:33.574 * <redisraft> State change: Election starting, node is now a candidate, term 128
24543:M 10 Aug 2021 14:35:33.574 * <redisraft> Cluster Membership: term:128 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:34.776 * <redisraft> State change: Election starting, node is now a candidate, term 129
24543:M 10 Aug 2021 14:35:34.776 * <redisraft> Cluster Membership: term:129 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:36.279 * <redisraft> State change: Election starting, node is now a candidate, term 130
24543:M 10 Aug 2021 14:35:36.279 * <redisraft> Cluster Membership: term:130 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:37.381 * <redisraft> State change: Election starting, node is now a candidate, term 131
24543:M 10 Aug 2021 14:35:37.381 * <redisraft> Cluster Membership: term:131 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:38.483 * <redisraft> State change: Election starting, node is now a candidate, term 132
24543:M 10 Aug 2021 14:35:38.483 * <redisraft> Cluster Membership: term:132 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:40.086 * <redisraft> State change: Election starting, node is now a candidate, term 133
24543:M 10 Aug 2021 14:35:40.086 * <redisraft> Cluster Membership: term:133 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
24543:M 10 Aug 2021 14:35:41.790 * <redisraft> State change: Election starting, node is now a candidate, term 134
24543:M 10 Aug 2021 14:35:41.790 * <redisraft> Cluster Membership: term:134 index:498 nodes: id=1308345182,voting=1,active=1,addr= id=1787412747,voting=1,active=1,addr=10.10.1.3:5001 id=776826545,voting=1,active=1,addr=10.10.1.5:5001
```