Advanced Systems Lab Report

Autumn Semester 2018

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Grading

Section	Points
1	
2	
3	
4	
5	
6	
7	
Total	

1 System Overview (75 pts)

Following is a description of the class structure of the Middleware:

- `MW` - responsible for accepting incoming socket connections, instantiating the `Writer` threads, and for enqueuing each request.
- `Request` - this class represent a request object, it contains the request's type and measures (presented below).
- `Worker` - each `Worker` establishes a socket connection with the memchached servers, dequeues a request, performs load balancing, and process the request (sends to servers, handle responses and collects some statistics.
- `Statistic` - container for all measured statistics.
- `Writer` - when shutting down the Middleware, it collects all the statistics from each `Worker`, aggregates them and save them to disk.

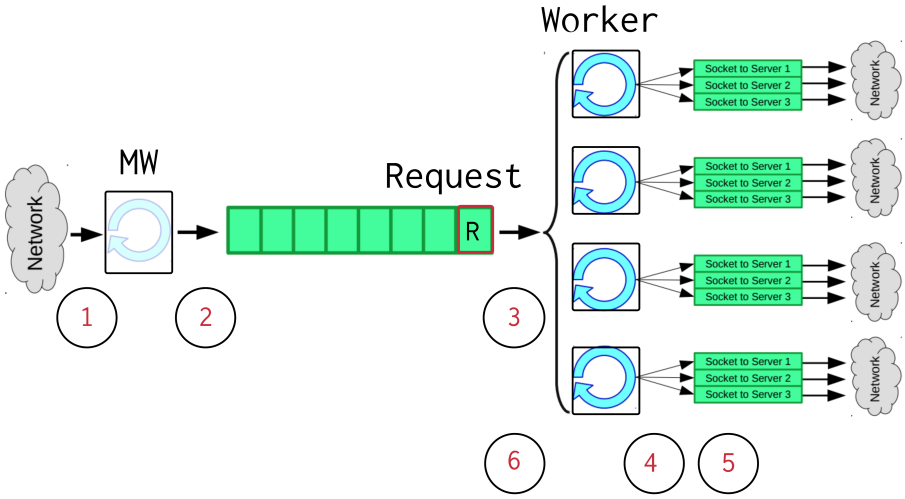


Figure 1: Middleware architecture.

The Middleware is instrumented at six points (shown in Fig.1):

1. R_c - Request created
2. R_e - Request enqueued
3. R_d - Request dequeued
4. R_f - Request forwarded to memcached instances.
5. R_r - Response received from memcached instances.
6. R_a - Request answered to memtier instance.

1.1 Load Balancing

In order to guarantee that each server gets the same amount of jobs, each request's key gets hashed to a specific index that identify a memcached instance.
This is done by method `getServerFromKey` in `Worker` class, and further tested in class `LoadBalancer` of package `test.java.asl`. Following is the result of a test with 1M random strings and 10 servers:

```
Server 0 got 100047 jobs.
Server 1 got 100172 jobs.
Server 2 got 99590 jobs.
Server 3 got 99714 jobs.
Server 4 got 100506 jobs.
Server 5 got 100081 jobs.
Server 6 got 99962 jobs.
Server 7 got 100221 jobs.
Server 8 got 99809 jobs.
Server 9 got 99898 jobs.
```

This indeed shows that the distribution is uniform and that each memcached instance receives the same amount of requests as the others.
NOTE: This is done only for `GET` and *non-sharded* `MULTI-GET`s requests, as `SET`s need to be replicated, and *sharded* `MULTI-GET`s are splitted across memcached instances.

1.2 The system

There are two main components, the `MW` and the `Worker`s. They communicate between each other using a dynamic-sized queue where requests are passed in.

1.3 The queue

The queue is designed to grow as much as needed although in practice it can only grow to the number of clients memtier is using. A fixed-sized queue may have done the job as well, but having a dynamic-sized one has less impact on the memory usage.

1.4 Non-blocking IO

The Middleware communicate both with the clients and the memcached instances via the `java.NIO.SocketChannel`'s library. In `MW`'s constructor `Worker`'s are instantiated and started. Each `Worker`, connects to the memcached instances in a non-blocking fashion.

1.5 Request Protocol

Each request is assumed to be well-formed, and only the first character is checked in order to determine the request type. As a request may be sent into multiple chunks, it is essential to read it without losing any byte. Thisis done by saving the partial content of the `ByteBuffer` the `SocketChannel` has written to, into a `ByteArrayOutputStream`. A request is assumed to be completed when the last bytes are equals to`"\r\n"`. The same assumption is done for responses from the memcached instances, by checking `"STORED\r\n"` or `"END\r\n"`.

1.6 Handling incoming connections

The Middleware listens for incoming connections by memtier clients. This is achieved by using the `java.NIO` package that allows non-blocking IO operations on multiple channels. A `Selector` monitors channels for changes and signal them in a `SelectionKey` object, which contains a set of keys registered with the channel.
Whenever a `SelectionKey`'s interest is set on `ACCEPT`, a `SocketChannel` connection can be established between the client issuing the request and the Middleware. After that, the interest of the `SelectionKey` is set to `READ`, waiting for data from the client.

1.7 Handling incoming requests

When the `SelectionKey`'s interest is set to `READ`, data is read from the `SocketChannel`. From this moment the Middleware starts recording the `responseTime` of the request (Point 1 in Fig.1). When the whole request has been read, it gets enqueued to a `BlockingQueue`, its `queueWaitingTime` is started (Point 2 in Fig.1), and the `SelectionKey`'s interest is set to `WRITE`.

1.8 Forwarding requests

When a new request is ready to be processed by a `Worker`, before sending it to the memcached instances, some operations take place (shown in Fig.1.8):

- The request's `queueWaitingTime` is stopped (Point 3 in Fig.1).
- The request gets copied into a `pendingRequest` object.
- Based on its type, a `multiRequest` object gets created.

Then, when the first entry of the `multiRequest` object gets sent, the `pendingRequest`'s `serviceTime` is started (Point 4 in Fig.1).

1.9 Handling responses

When handling an incoming response each `Worker` does the following:

- Checks if the response is completed
- Increments a counter of the number of responses received, and compares it with the size of the `multiRequest` object created for that `pendingRequest` (expected number of responses).
- Then, in case it has received the expected number of responses:
  - Stops the `pendingRequest`'s `serviceTime` (Point 5 in Fig.1).
  - Creates a `Statistic` object that wraps `pendingRequest` measures.
  - Answers back to the client that issued the request.
  - Stops the `pendingRequests` `responseTime` (Point 6 in Fig.1).

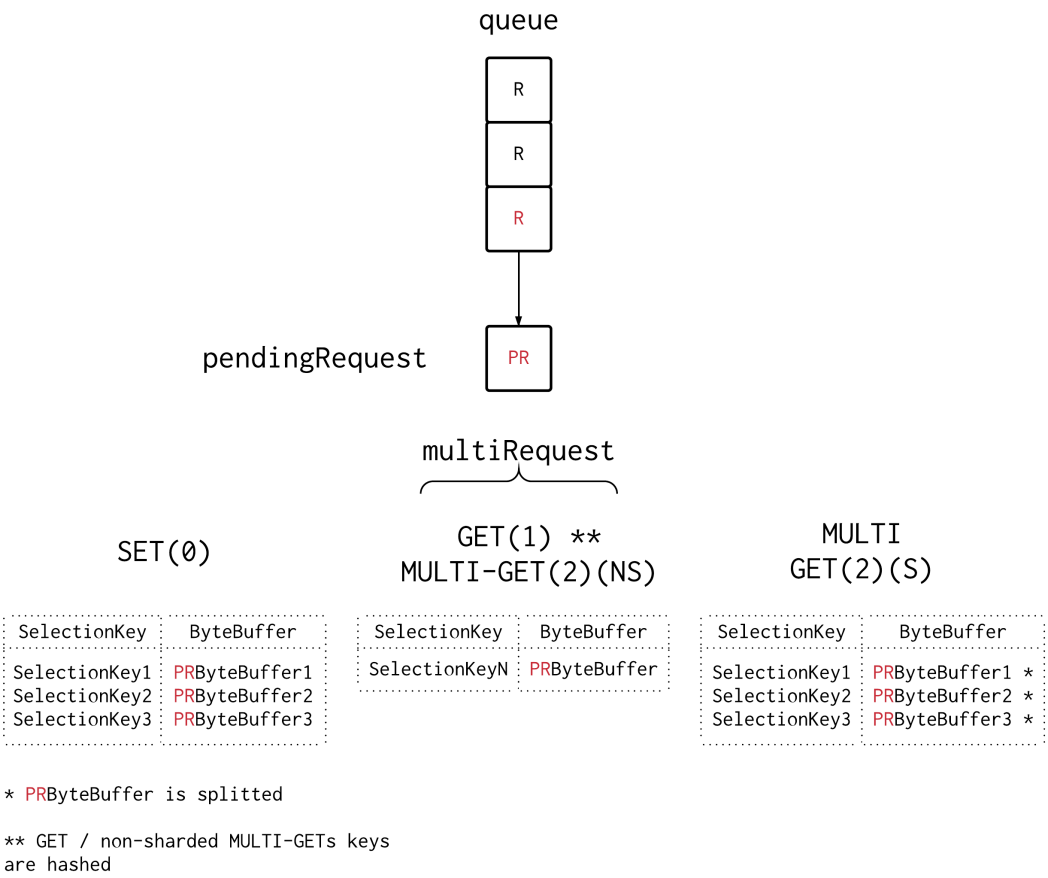


Figure 2: `loadRequest()` behavior.

1.10 Statistics

As already pointed out in 1.9, each `Worker` collects the following statistics:

- The current system's time (`ns`).
- The time the request spent in the queue (`ns`).
- The time elapsed between forwarding the first `multiRequest` and the last response (`ns`).
- The time elapsed between reading the request from the client and the last response (`ns`).
- The current queue size.
- The number of misses of the request.
- The number of keys in the request.

NOTE: All the time-related statistics are then converted in milliseconds (`ms`) when writing them to the logs.

2 Baseline without Middleware (75 pts)

In these experiments we study the performance characteristics of the memtier clients and memcached servers.

2.1 One Server

In this, and in each of the following sections, the number of virtual clients is intended to be the total number of clients in the system, if otherwise, it is emphasized the phrase *per thread*. Bottleneck analysis, and throughput/response time comparsions are shown in each *Explanation* section of each experiment, rather than in the Summary. The focus on the latter is in presenting how the maximum throughput configurations are determined.

2.1.1 Experiment Setting

There are 3 machines that generate write-only and read-only workloads. Each machine runs a single memtier instance with 2 threads, and from a minimum of 1, to 64 virtual clients *per thread* (see table below). The number of virtual clients is the only (tunable) parameter in this setting; it is expected that by raising it, both throughput and response time should grow respectively. The reason behind it is that by raising the number of clients, the server will spend less "idle/free time" between each successive request. The clients machines are connected to a server machine running a single, one-threaded, memcached instance. Each experiment runs for 70 seconds (measures take into account both warm-up and cool-down phases, excluding 10 secs), and is repeated for 3 times under the same exact conditions. By running this benchmark, we hope to find how much load can a single memcached instance sustain.

Number of servers	1
Number of client machines	3
Instances of memtier per machine	1
Threads per memtier instance	2
Virtual clients per thread	[1, 4, 8, 16, 24, 32, 40, 48, 64]
Workload	Write-only and Read-only
Multi-Get behavior	N/A
Multi-Get size	N/A
Number of middlewares	N/A
Worker threads per middleware	N/A
Repetitions	3 (70 secs, effective 60 secs)
Log Files Path	`experiments/baseline_no_mw_1_server/`
Processed Files Path	`experiments/baseline_no_mw_1_server/out/memtier_data.csv`

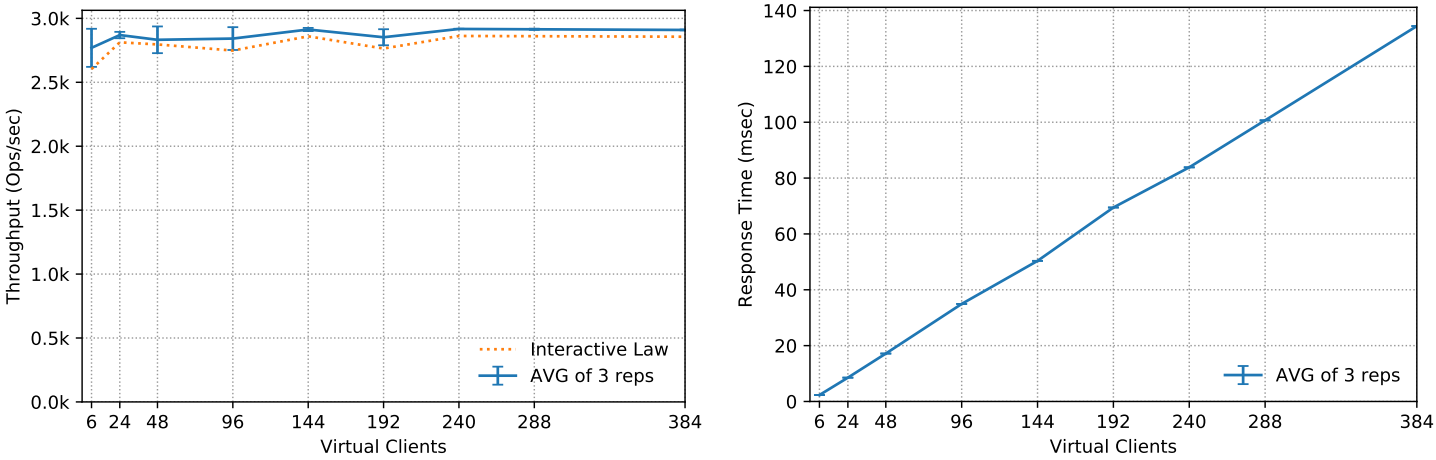
2.1.2 Explanation

The following plot shows how throughput and reponse time behave when increasing the number of virtual clients. The number of virtual clients on the `x-axis` of each plot represents the total number of clients in the system, e.g. the first tick at `VC=6` is the result of `1` virtual client per thread multiplied by the number of threads (`2`), instances(`1`), and client machines(`3`). For each quantity we plot the average measured value of the 3 repetitions, and the standard deviation from the mean as a confidence measure. Additionally as a sanity check, we plot the *Interactive Law* as a dotted line in the troughput plots. In this case it is computed as the invers of the measured response time multiplied by the total number of virtual clients. The throughput shown below is the sum of the throughputs of each memtier instance of each client, while the response time is the average response time of each client's machine.

Read-Only

Consider the throughput below: we can see pretty clearly that, for the whole virtual clients range, apart from `VCs=6`, (in which the memcached server is still **under-saturated**), it essentially remains constant at $\approx$ 3000ops/s. Suprisingly, increasing the number of virtual clients doesn't affect the throughput at all; the server is indeed saturated after 6 virtual clients. Although we have extended the range of virtual clients per thread to 64, we still cannot observe over-saturation of the server.
The same exact behavior can be double checked by looking at the response time plot. It grows almost linearly, confirming the fact that the server is saturated.
As for now, (without additional information both on the arrival rate of requests and the service rate at which they get processed), we cannot determine the bottleneck of the sytem. Either outbound load is limited by the client's bandwidth, or the server's peak performance in reading is 3k ops/s. In Section 2.2 we investigate how much workload a client machine can generate, that is the missing piece of the puzzle to conclude the bottleneck analysis.

Figure 3: Plots for baseline with one server (read-only)



Write-Only

When testing for write-only workloads we observe a completely different behavior with respect to what seen above. Here the throughput follow our initial assumption and grows as the number of virtual clients increases. We can see that at `VCs=240` we reach saturation. We can explain the fact that we reach saturation at a much higher number of VCs compared to the read-only workload, simply because the service rate at which the server process write-only requests, is higher than when reading. This is investigated and further confirmed when measuring service time for different workloads inside the middleware in Section 3.1. With no surprise, the response time plot reflects the measured throughput: we have an initial under-saturated phase until `VCs=240`, for which the rate $\frac{r_t}{\texttt{VC}}$ monotonically decreases. After that point, the rate stays almost constant, suggesting a flattening:

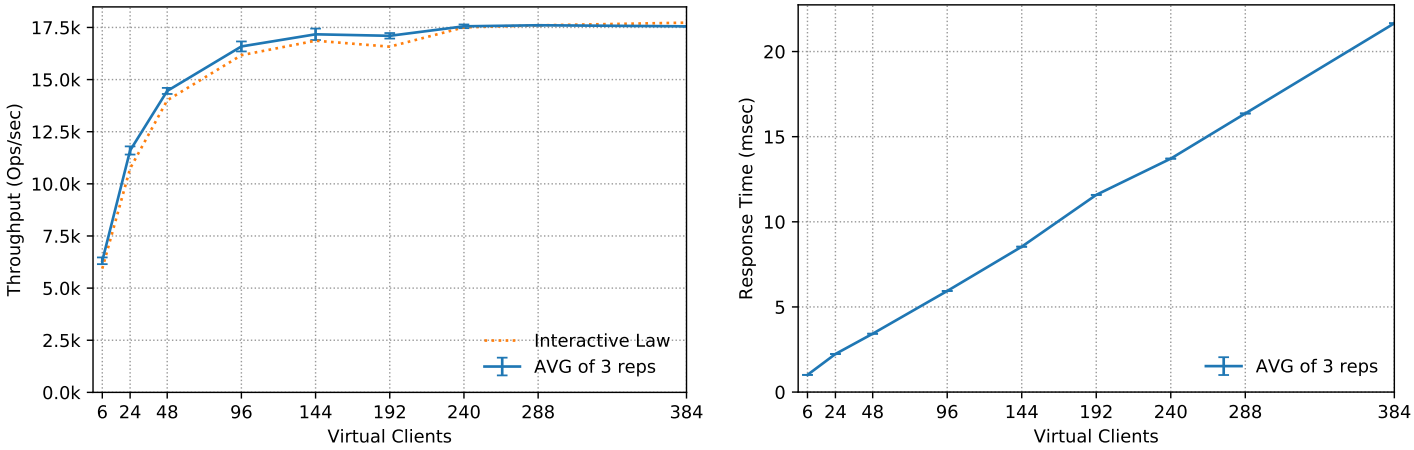
$$\frac{2.5}{24} =\approx 0.1$$

$$\frac{4}{48} =\approx 0.08$$

$$\frac{6}{96} =\approx 0.06$$
$$\frac{12}{192} =\approx 0.06$$
$$\frac{14}{240} =\approx 0.058$$
$$\frac{22}{384} =\approx 0.057$$

In addition, by looking at the interactive law, we can observe that it follows the throughput line precisely, concluding the analysis for the experiment.

Figure 4: Plots for baseline with one server (write-only)



2.2 Two Servers

2.2.1 Experiment Setting

There is a single client machine that generates write-only and read-only workloads. The machine runs two different memtier instances with 1 thread, and from a minimum of 1, to 32 virtual clients (see table below). The number of virtual clients is again, the only (tunable) parameter in this setting; it is expected that by raising it, both throughput and response time should grow accordingly. We connect each client's instance to 2 different server machines running a single, one-threaded, memcached instance. The same exact conditions on the number of repetions, duration and measurement stated before still hold. By running this benchmark, we hope to find how much load can a single memtier client produce before saturation.

Number of servers	2
Number of client machines	1
Instances of memtier per machine	2
Threads per memtier instance	1
Virtual clients per thread	[1, 4, 8, 16, 24, 32]
Workload	Write-only and Read-only
Multi-Get behavior	N/A
Multi-Get size	N/A
Number of middlewares	N/A
Worker threads per middleware	N/A
Repetitions	3 (70 secs, effective 60 secs)
Log Files Path	`experiments/baseline_no_mw_2_server/`
Processed Files Path	`experiments/baseline_no_mw_2_server/out/memtier_data.csv`

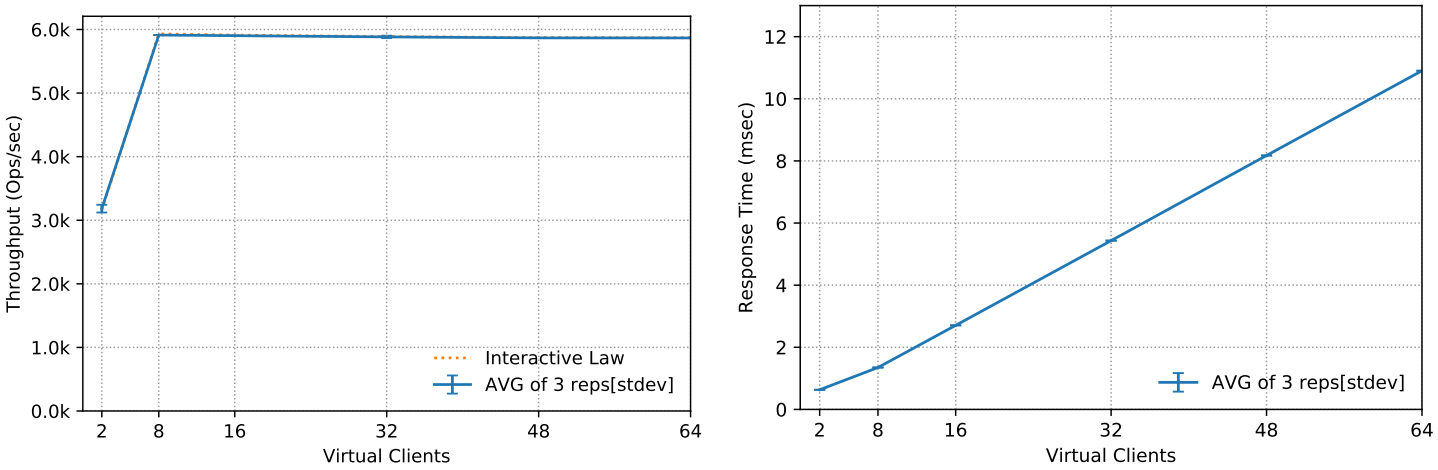
2.2.2 Explanation

Once again we plot both throughput and response time as a function of the total number of clients. It is interesting to note how these quantities are measured. The response time is the mean response time of each memtier instance, for each client machine, for each repetition. The throughput is the sum of the throughputs measured in each instance, summed over the number of client machines, and averaged between each repetition. The error measure introduced is again the standard deviation from the mean value in all repetitions.

Read-Only

The throughput presents an interesting behavior: as before, we observe that it flattens early on, at `VCs=8`, reaching saturation at $\approx$ 6k *ops/s*. From that point on, the system seems to begin to over-saturate, as the throughput slightly decrases.
In Section 2.1 we have 3 clients connected to one server, reaching peak performance at $\approx$ 3k *ops/s*, this suggests that now that we have a single client that can read 6k *ops/s* from two servers, that the bottleneck when reading is effectively the service rate at which a single memcached instance process incoming requests. The response time, after a sub-linear growth between the first and second virtual clients grows linearly, confirming saturation.

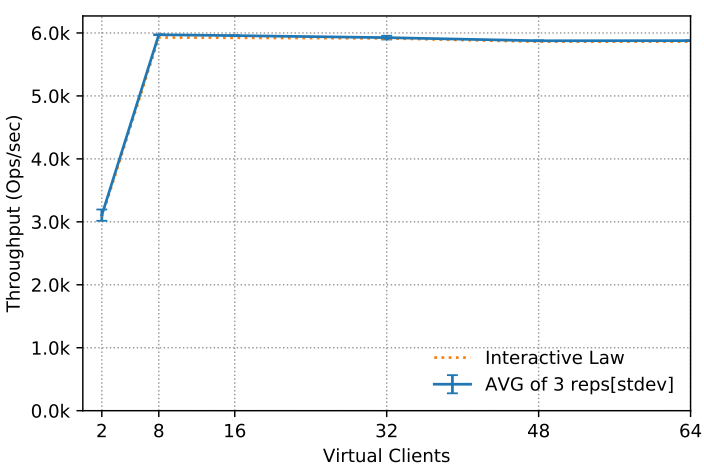
Figure 5: Plots for baseline with two servers (read-only)

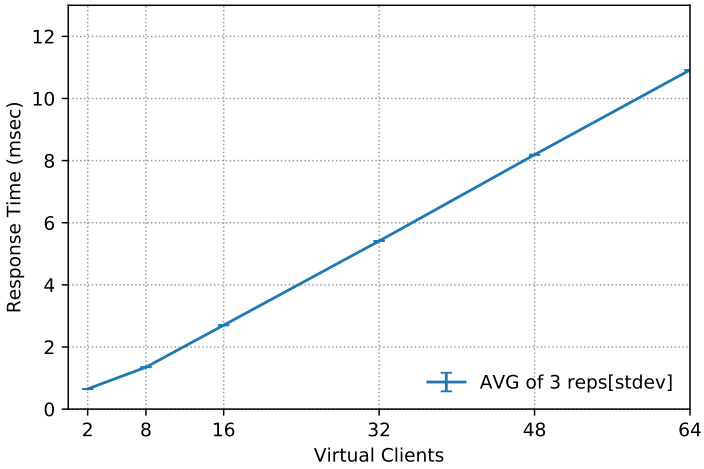


Write-Only

The throughput is almost identical to the read-only workload. Again a pretty fast flattening at `VCs=8`. Let's compare it with the one in Section 2.1: there, we have 3 clients writing to a single server, reaching an $\approx$ 18k *ops/s* peak performance), meaning an approximate throughput per client of 6k *ops/s*. Now by doubling the number of servers, a single client still produces 6k *ops/s*. Thus, we can conclude that the bottleneck is the maximum arrival rate of incoming write-only request from a single client machine, limited at 6k *ops/s*.

Figure 6: Plots for baseline with two servers (write-only)

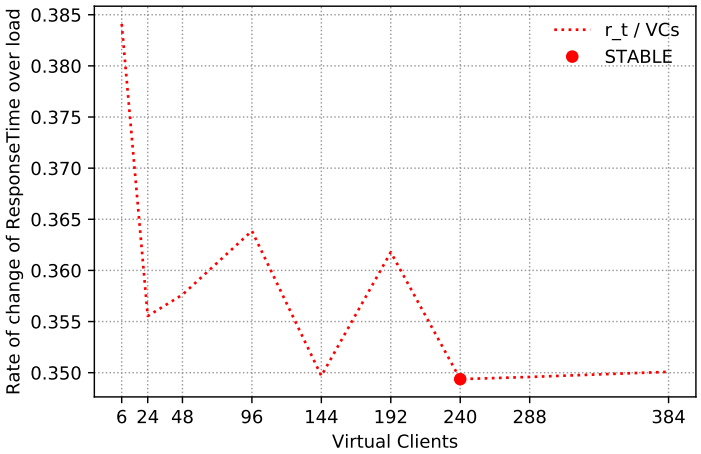




2.3 Summary

Following, the maximum throughput of each experiment for both write-only and read-only workload is shown. In order to determine what is the maximum throughput configuration, we additionally plot the rate of change of the response time over the generated load and pick the configuration from which the rate reaches an horizontal asyntote. Before that point the response time can grow sub-linearly, even oscillating (in the read-only case). So, we choose the first stable virtual client which rate stays almost flat for the entire range of virtual clients to represent the maximum throughput configuration in our system.

Figure 7: Plots for baseline with one server (Rate of change of response time over load, left: read-only, right: write-only)



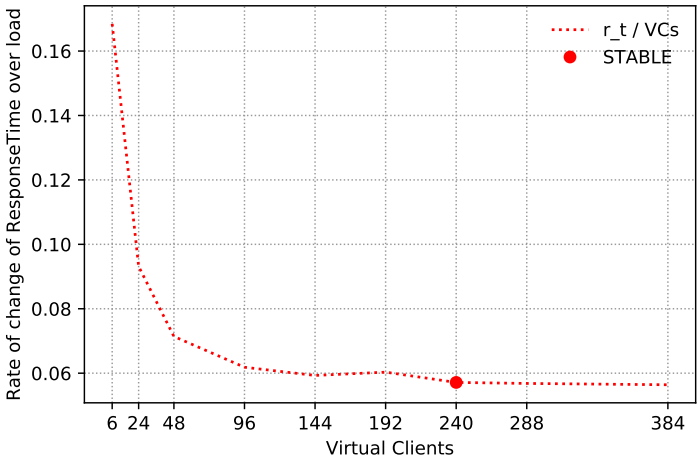
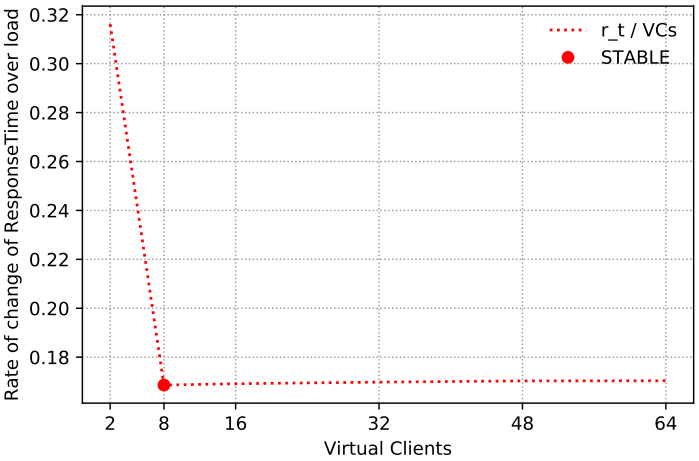
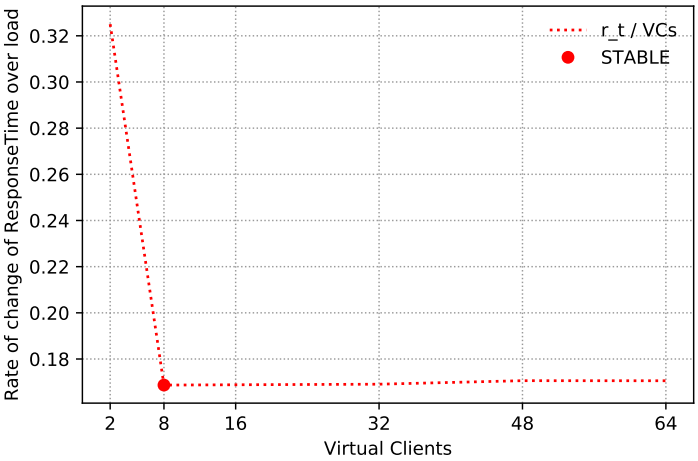


Figure 8: Plots for baseline with two servers (Rate of change of response time over load, left: read-only, right: write-only)





Maximum throughput of different VMs.

	Read-only workload	Write-only workload	Configuration gives max. throughput
One memcached server	2.88k ops/s	17.5k ops/s	40 VCs per thread (240 total clients)
One load generating VM	5.87k ops/s	5.98k ops/s	4 VCs per thread (8 total clients)

When performing write-only operations, each client machine cannot issue more than $\approx$ 6k *ops/s*. Given that the object size is `4096B`, the maximum throughput achievable is approximately 24 MB/s. When reading data from the memcached servers, the bottleneck is given by the number of operations a server sends back to the client. Benchmarks indicate that a single memcached machine cannot send more than $\approx$ 3k *ops/s*, or 12 MB/s.

3 Baseline with Middleware (90 pts)

In this set of experiments we test the performance of the Middleware/s. We measure and display the results both at the client, and inside the middleware, and compare them. Additionally, in order to gain a better insight on the internal performance breakdown of the middleware, and run analysis on the components, we present the statistics introduced in Section 1.10.

3.1 One Middleware

3.1.1 Experiment Setting

There are 3 clients machine generating both write-only and read-only workload. Each client machine runs a single memtier instance with 1 thread, and from a minimum of 1, to 64 virtual clients (see table below). Each client machine is connected to the the middleware, which is connected to a single, one-threaded, memcached machine. Essentially we are tuning the load the clients produce, and the service rate at which the middleware dispatches request between client and server machines.

Number of servers	1
Number of client machines	3
Instances of memtier per machine	1
Threads per memtier instance	2
Virtual clients per thread	[1, 4, 8, 16, 24, 32, 64]
Workload	Write-only and Read-only
Multi-Get behavior	N/A
Multi-Get size	N/A
Number of middlewares	1
Worker threads per middleware	[8, 16, 32, 64]
Repetitions	3 (70 secs, effective 60 secs)
Log Files Path	`experiments/baseline_mw_1_mw/logs`
Processed Files Path	`experiments/baseline_mw_1_mw/out/memtier_data.csv`

3.1.2 Explanation

We plot throughput and response time as measured at the client and inside the middleware, for an increasing number of both virtual clients and worker threads.
The measurements conducted in the middleware are grouped in five-seconds windows for a total of 14 per experiment ($70.0/5.0 = 14$). Everytime a request has been processed, and a response has been sent back to the client machines, the measurements for the specific request, and a snapshot of the system components, gets saved and later, processed and logged.
Measurements taken inside the middleware, do not include the latency between the client machines and the middleware, so there's a gap between the two, that remains constant and negligible ($\approx 2ms$).

Read-Only

As in Section 2.1, the throughput plot shows a flattening at $\approx$ 3k op/s starting from `VCs=24`. The presence of the middleware doesn't seem to affect the performance at all, moreover we cannot spot any differences when changing the number of worker threads inside the middleware. The unique possible explanation, (as we can exclude the fact that the client machines are the bottleneck, from what we have concluded in Section 2.3), is again. the fact that a single memcached machine cannot send back more than 3k ops/s of read-only requests.

Figure 9: Plots for baseline with one Middleware (read-only CLIENT)

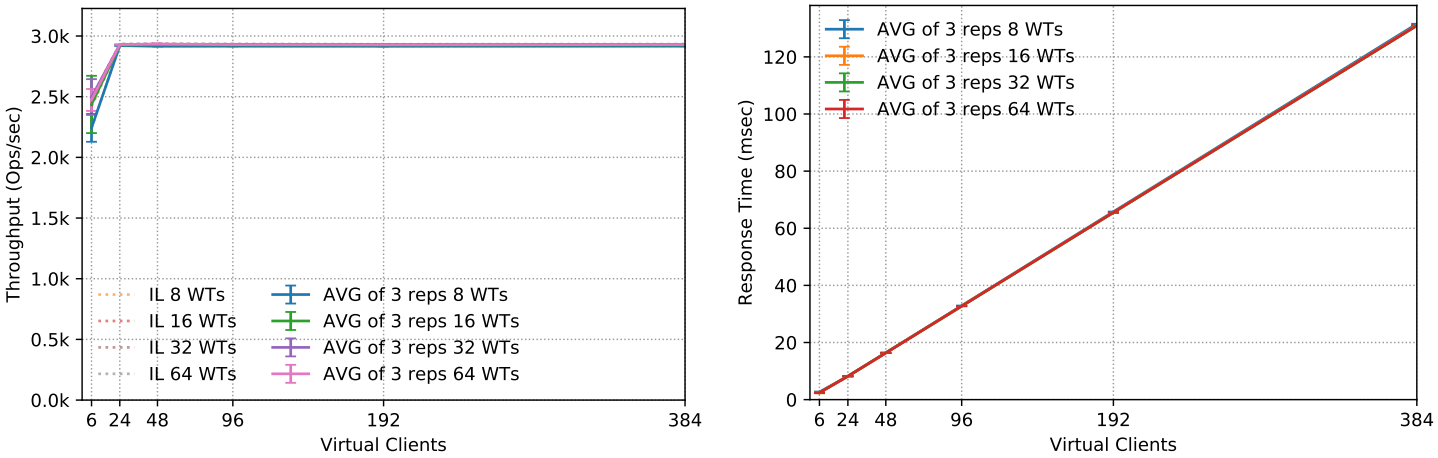
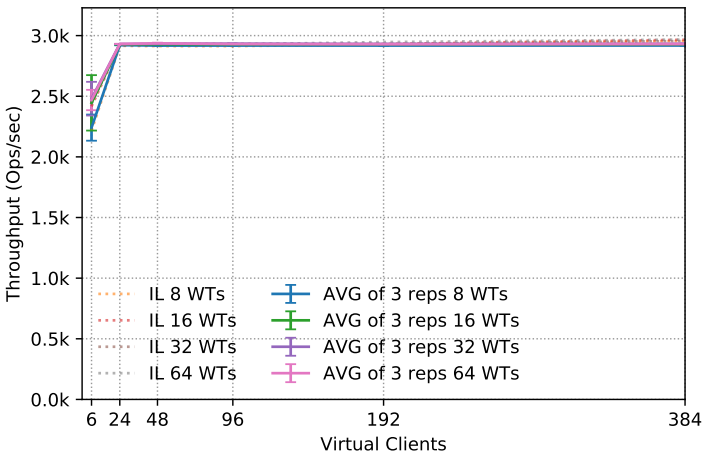


Figure 10: Plots for baseline with one Middleware (read-only MIDDLEWARE)



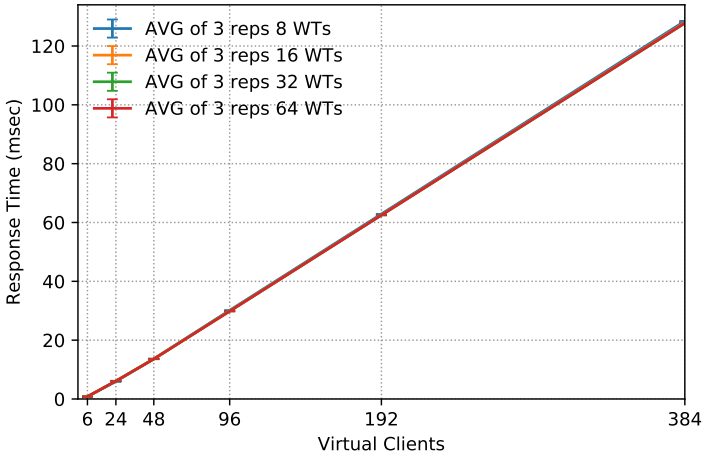
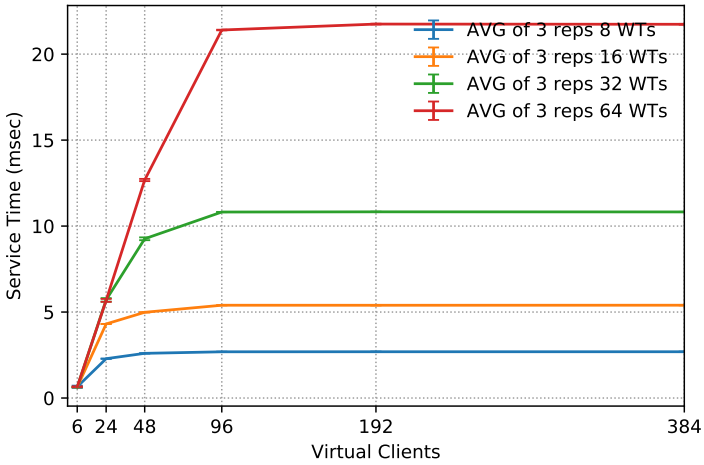
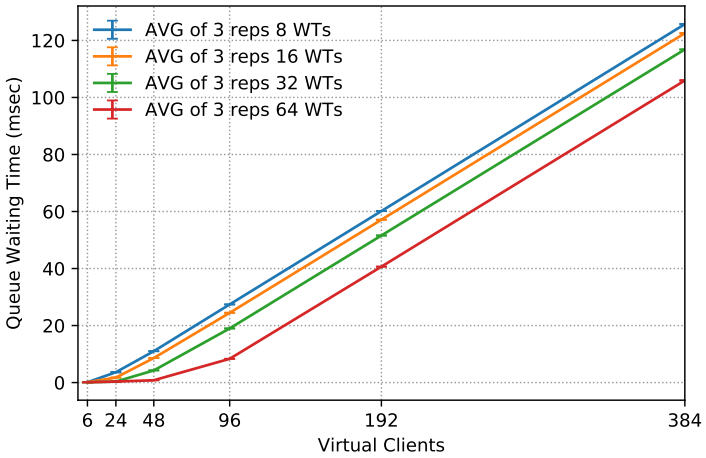


Figure 11: Plots for baseline with one Middleware, Service Time and Queue Waiting Time (read-only MIDDLEWARE)





Write-Only

As expected, increasing the number of worker threads in the middleware, results in an increase of the throughput. Even though, for every distinct worker thread configuration, we observe a distinct throughput behavior, there's a common treat that each configuration seems to manifest. In fact we can clearly identify and split the plot in two phases: one that goes from 6 to 192 `VCs`, and another one, that goes from 192 to 384 `VCs`. In the former (under-saturated phase), the configurations with 16, 32 and 64 workers, behave almost identically (apart from when we reach `VCs=96`, where we observe a difference of $\approx$ 500-600 ops/s). The latter phase (saturated) shows a much larger difference in performance for different worker threads configurations. We observe a clear distinction between 8 and 16 worker threads, and between 16 and 32, but not as much between 32 and 64 worker threads. Comparing this plot to the one in Section 2.1, we can cleary see that the presence of the middleware seems to have an impact on the throughput (saturation starts at 12k ops/s, before $\approx$ 18k ops/s). The difference is around 30%.

Figure 12: Plots for baseline with one Middleware (read-only MIDDLEWARE)

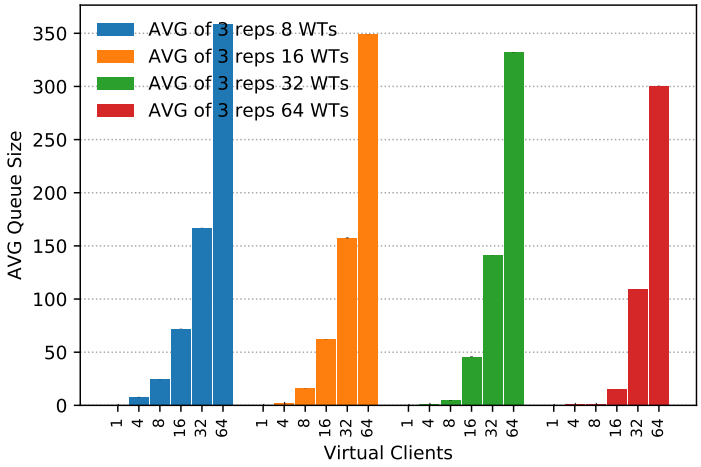


Figure 13: Plots for baseline with one Middleware (write-only CLIENT)

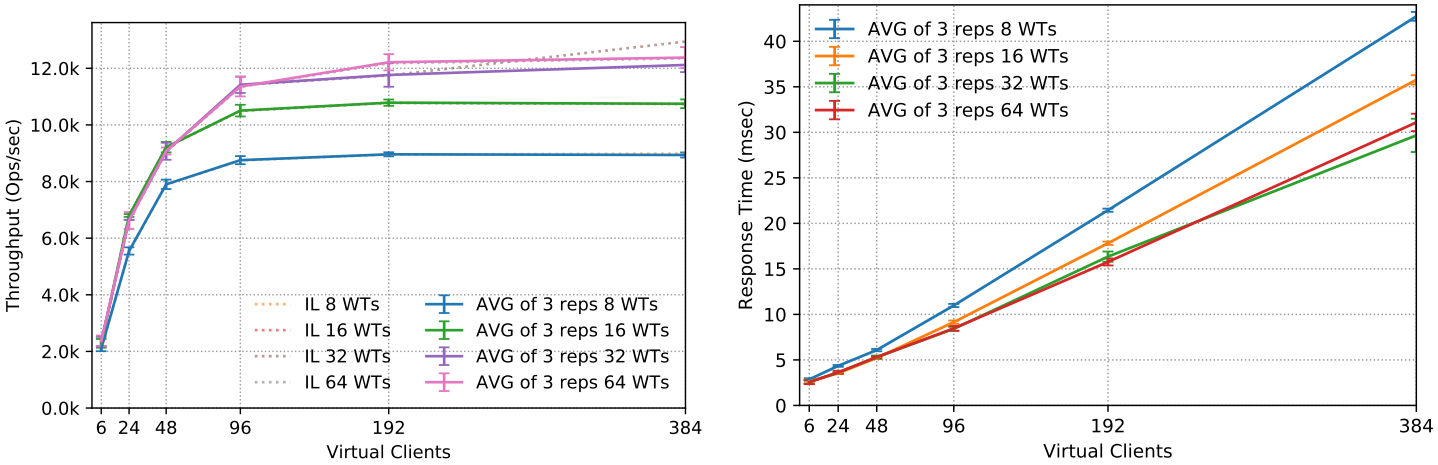


Figure 14: Plots for baseline with one Middleware (write-only MIDDLEWARE)

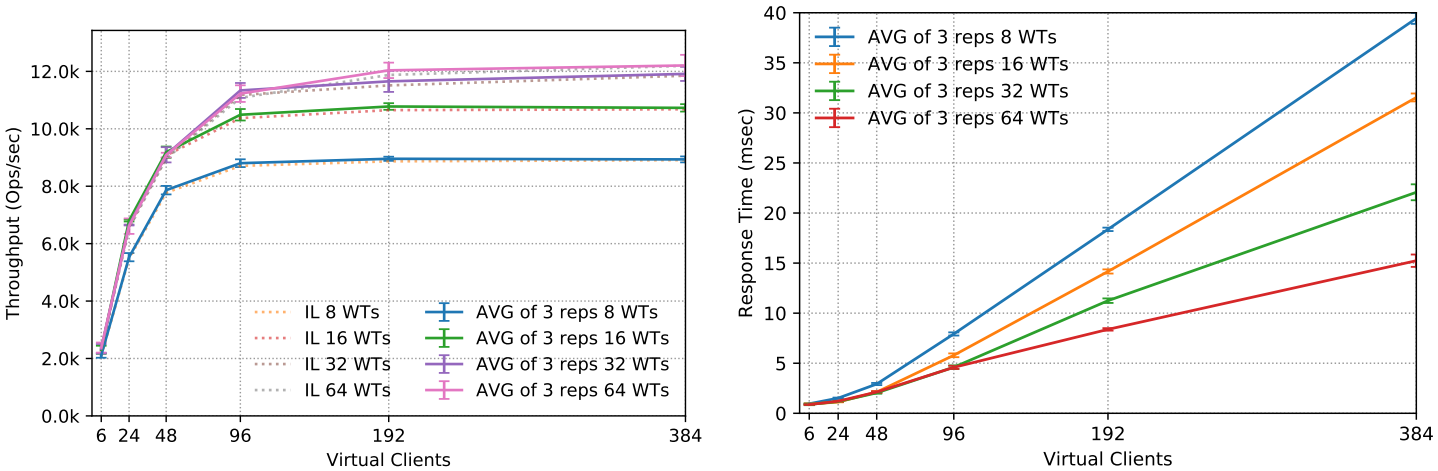


Figure 15: Plots for baseline with one Middleware, Service Time and Queue Waiting Time (write-only MIDDLEWARE)

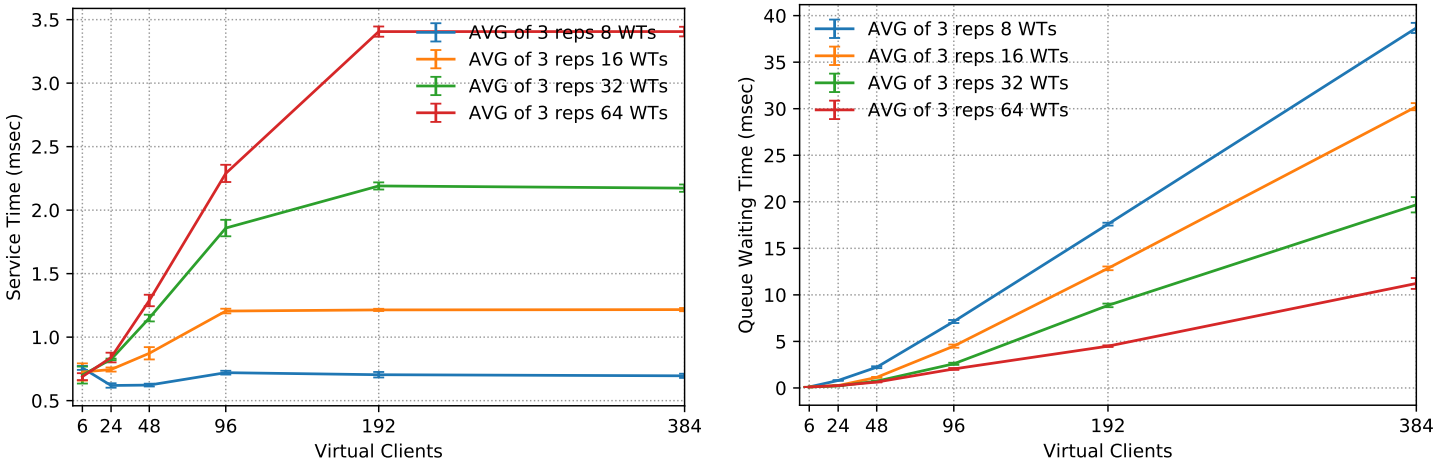
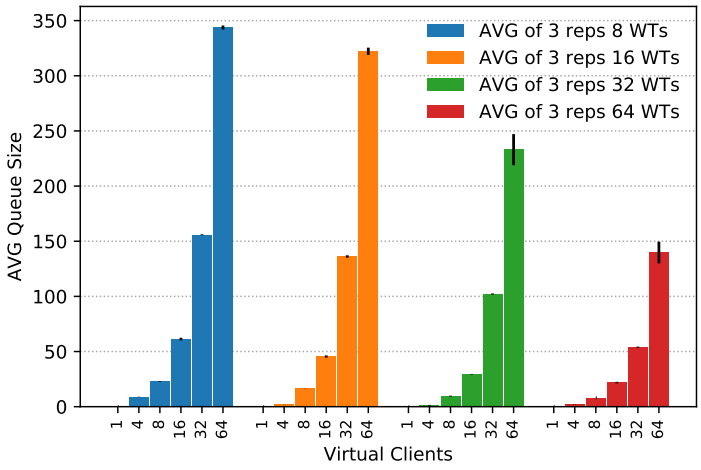


Figure 16: Plots for baseline with one Middleware, Average Queue Size (write-only MIDDLEWARE)



3.2 Two Middlewares

3.3 Experiment Setting

This experiment is similar to the previous one, apart from the fact that here we introduce a new middleware machine. Again, we have 3 load generating machines that run 2 single-threaded instances of memtier. Each instance connects to a different middleware, which itself, connects to one single-threaded memcached machine. Also in this experiment, we change the number of worker threads inside the middlewares to see how that impacts the overall performance.

Number of servers	1
Number of client machines	3
Instances of memtier per machine	2
Threads per memtier instance	1
Virtual clients per thread	[1, 4, 8, 16, 32, 64]
Workload	Write-only and Read-only
Multi-Get behavior	N/A
Multi-Get size	N/A
Number of middlewares	2
Worker threads per middleware	[8, 16, 32, 64]
Repetitions	3 (70 secs, effective 60 secs)
Log Files Path	`experiments/baseline_mw_2_mw/logs`
Processed Files Path	`experiments/baseline_mw_2_mw/out/memtier_data.csv`

3.3.1 Explanation

We plot throughput and response time as measured at the client and inside the middleware, for an increasing number of both virtual clients and worker threads.
The same conditions on the measurements presented in Section 3.1, still hold. Here, we need to take into account the fact that we have an additional middleware, thus any measure done in one middleware needs to be properly treated. By this we mean that depending on the measurement that we are analyzing, we might either take the average between the two Middlewares (e.g. response time, service time, and queue waiting time), or some over (e.g. throughput). It is relevant to mention how such measures are computed, because, as we will see, they might be source for minor imprecisions in the plots.

Read-Only

The client throughput seems to reflect the behavior seen in Section 2.1, showing a flattening at $\approx$ 3k op/s starting from `VCs=24`. If we look at the middleware plot, we still observe the same behavior, this time though, we observe a difference between 8 and 16 worker threads, and between them and 32 and 64. The configurations with 8 and 16 worker threads, exceed 3k ops/s. Now, we know that that's not possible, the reason for that is again that when reading we are limited by the memcached server at 3k ops/s. This is due to both the fact that time measurements inside the middleware are smaller than the one measured by the clients, and to the systematic error introduced when taking the average between the two. The difference between the clients and the middlewares plots can be spotted also by looking at their response time/load. In the one measured by the clients, every worker thread configuration is collinear, whereas in the middleware, we have distinct lines for 8 and 16 workers: indeed their value is lower, causing the throughput to grow and pass the 3k ops/s barrier.

Write-Only

As in the read-only case, we reach the same maximum performance presented in Section 2.1. It's the configuration with 64 worker threads that reaches $\approx$ 17,5k ops/s. From 6 to 24 virtual clients, every worker thread configuration behaves the same, from 48, we start to see a clear distinction between 8, 16, and 32 and 64, and at 96 there's no overlap in performance. Again, as before, we can individuate two main phases: the under-saturated one that goes from 6 to 192 `VCs`, and a second one, (saturated phase).The plot in Section 2.1 also shows that the point of switch of the two phases starts at `VCs=192/240`. Furthermore, for the configuration with 64 worker threads, the response time shown in Figure 21 is the same as the one in Figure 4. If we compare the client's and the middleware's plots, we can see that they show a consistent behavior between each other, even though, the client's one, both with 8 and 64 worker threads, has a considerable high `sttdev` ($\approx 3.6ms$). Especially in the case of 64 worker threads, we noticed

Figure 17: Plots for baseline with two Middlewares (read-only CLIENT)

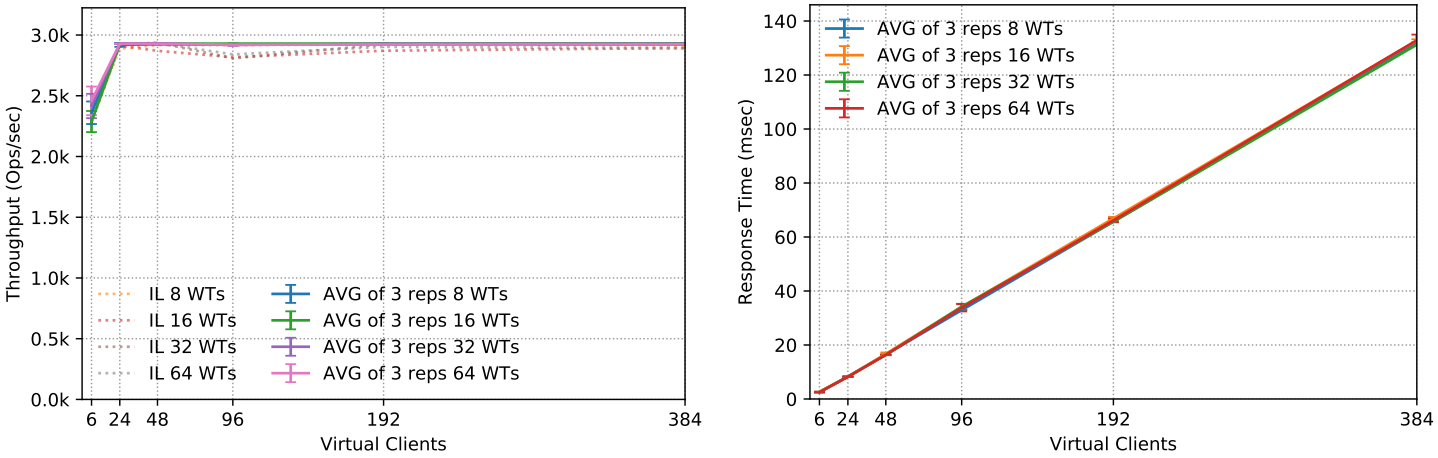


Figure 18: Plots for baseline with two Middlewares (read-only MIDDLEWARE)

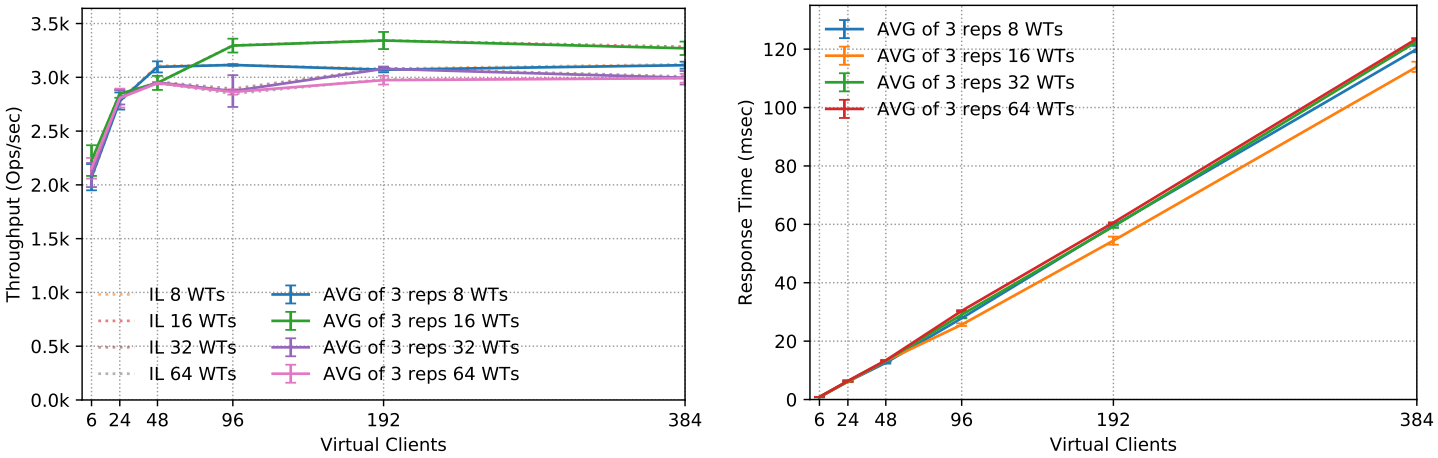


Figure 19: Plots for baseline with two Middlewares, Service Time and Queue Waiting Time (read-only MIDDLEWARE)

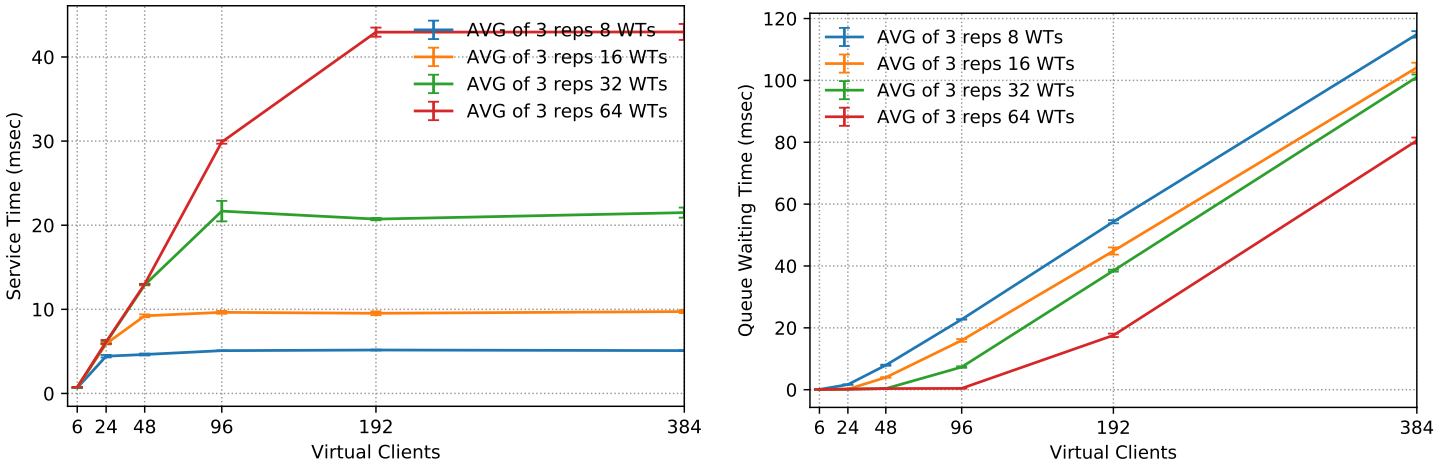
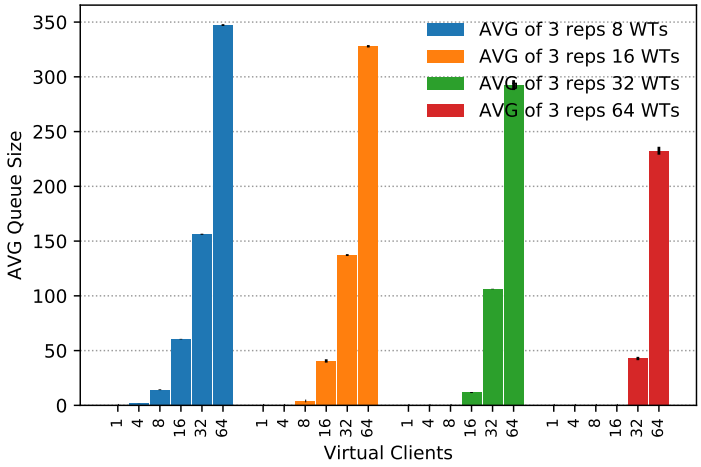


Figure 20: Plots for baseline with two Middlewares (read-only MIDDLEWARE)



the effect of a high `stddev` in the response time, that is visible in the throughput graphwith a `stddev` of $\approx$ 1.5k *ops/s*. The interactive law is almost collinear with the measured throughput in both client and middleware plots; for the client case, the computation is still the one presented in Section 2.1, while for the middlewares it has been computed as mentioned in Section 3.1, with the unique difference that in this configuration we need to asjust the computation of the number of jobs in the system, so having 2 middlewares, we sum up each middleware's measured number of jobs:

```
# Little's Law for the number of jobs in the system
jobs =  df.loc[(ratio, wt, vc), 'Jobs'].T.sum().mean() / 70.0  *
        df.loc[(ratio, wt, vc), 'ResponseTime (ms)'].unstack().T.mean().mean() / 1000
il[i] = (1 / values[i]) * 1000 * (jobs / clients)
```

The number of jobs recorded in each middleware is summed up, and then the average of the repetitions gets computed. Then we divide by the total duration of each experiment and we obtain an approximation on the arrival rate λ, that we multiply by the average time a request spends in the middleware (waiting + serviced = response time). then we simply divide by the number of physical client machines connected to the middleware, and multiply it by the inverse of the measured response time for a distinct configuration of worker threads and virtual clients. Note that both measured times are converted to *seconds*, that is the reason we divide by 1000.

3.4 Summary

Based on the results obtained we can derive the following.

For the Baseline with one Middleware, for a read-only workload, the bottleneck is the memcached instance, which cannot output more than 3k *ops/s*, or $\approx 12MB/s$. For the write-only workload the bottleneck is the middleware, we can see a relevant drop in performance compared to Section 2.1.

For the Baseline with two Middlewares, for a read-only workload, the bottleneck is still the memcached instance that cannot output more than 3k *ops/s*, indeed we doubled the number of middlwares compared to Section 3.1, but the throughput doesn't seem to be affected at all, so it seems correct to blame the server for it. In the write-only workload, we reach a similar performance as in Section 2.1, the two middlewares don't affect performances, plus we know from Section 2.2 that a single client machine cannot send more than 6k *ops/s* write-only

Figure 21: Plots for baseline with two Middlewares (write-only CLIENT)

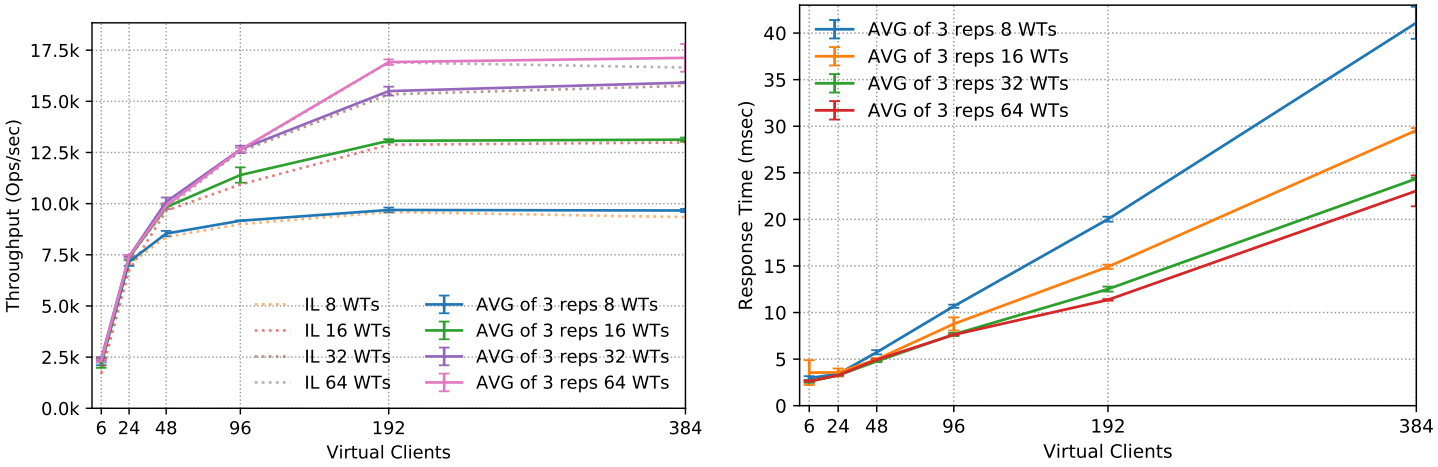
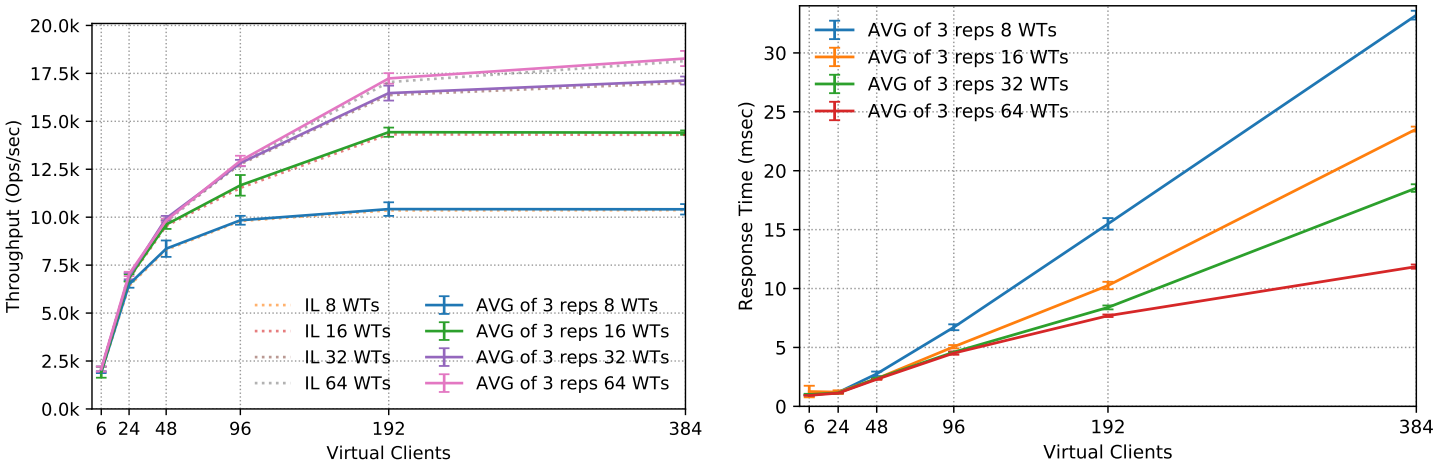


Figure 22: Plots for baseline with two Middlewares (write-only MIDDLEWARE)



requests, thus having 3 clients and reaching $\approx$ 18k *ops/s* we can conclude that the bottleneck for this setup are the client machines.

Maximum throughput for one middleware.

	Throughput	Response time	Average time in queue	Miss rate
Reads: Measured on middleware (`32 VCs` per thread)	2.92k *ops/s*	13.66 *ms*	0.85 *ms*	0.0
Reads: Measured on clients (`32 VCs` per thread)	2.97k *ops/s*	16.22 *ms*	n/a	0.0
Writes: Measured on middleware (`32 VCs` per thread)	12.5k *ops/s*	15.81 *ms*	10.42 *ms*	n/a
Writes: Measured on clients (`32 VCs` per thread)	12.7k *ops/s*	16.38 *ms*	n/a	n/a

Maximum throughput for two middlewares.

	Throughput	Response time	Average time in queue	Miss rate
Reads: Measured on middleware (`64 VCs` per thread)	2.95k *ops/s*	62.12 *ms*	22.15 *ms*	0.0
Reads: Measured on clients (`32 VCs` per thread)	2.92k *ops/s*	64.32 *ms*	n/a	0.0
Writes: Measured on middleware (`64 VCs` per thread)	16.8k *ops/s*	8.25 *ms*	2.48 *ms*	n/a
Writes: Measured on clients (`64 VCs` per thread)	17.8k *ops/s*	11.43 *ms*	n/a	n/a

Figure 23: Plots for baseline with two Middlewares, Service Time and Queue Waiting Time (write-only MIDDLEWARE)

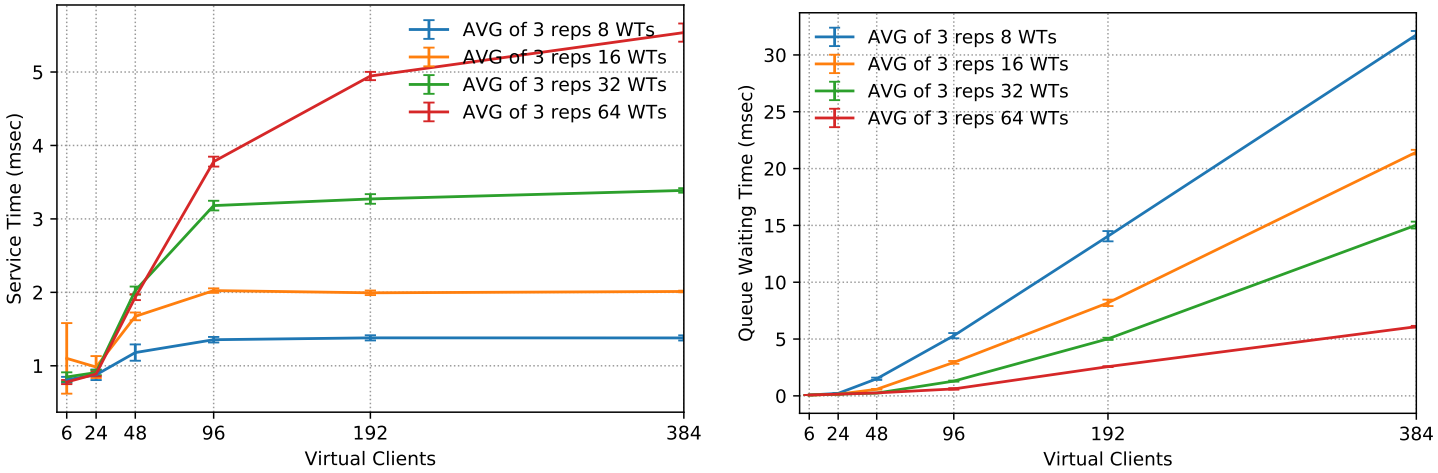
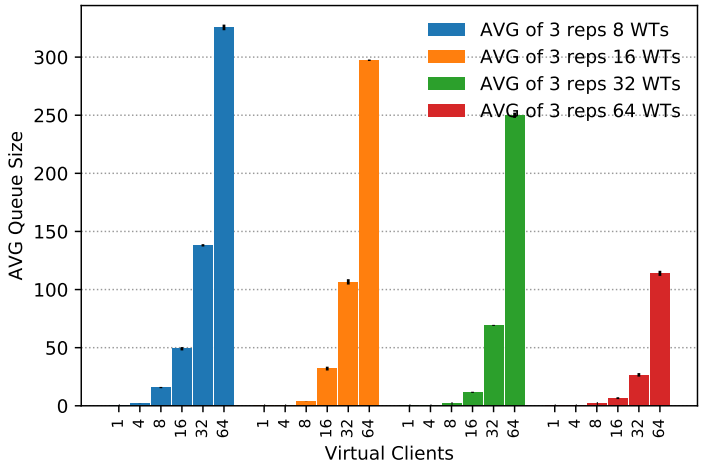


Figure 24: Plots for baseline with two Middlewares, Average Queue Size (write-only MIDDLEWARE)



4 Throughput for Writes (90 pts)

4.1 Full System

Experiment Setting

In this experiment we study the performance of the whole system when writing data. The setup is the same as the one with two Middlewares in Section 3.2, we just increase the number of memcached machines to 3. Note that since we do not read data, we also do not need to populate the memcached servers.

Number of servers	3
Number of client machines	3
Instances of memtier per machine	2
Threads per memtier instance	1
Virtual clients per thread	[1, 4, 8, 16, 24, 32, 64]
Workload	Write-only
Multi-Get behavior	N/A
Multi-Get size	N/A
Number of middlewares	2
Worker threads per middleware	[8, 16, 32, 64]
Repetitions	3 (70 secs, effective 60 secs)
Log Files Path	`experiments/throughput_for_writes/logs`
Processed Files Path	`experiments/throughput_for_writes/out/memtier_data.csv`

4.1.1 Explanation

The throughput plot is similar to the one in Section 3.2. Here we have thripled the number of servers, and throughput has noticeably decreased, at a point which it looks really similar to Section 3.1. This decrease is noticed also by looking at the measured response time. We can see how here, the maximum response time is $\approx 50\ ms$, (vs $\approx 40\ ms$ as in Figure 22), and moreover, for every worker thread setup, the response time is shifted upwards, and at `VCs=384`, the difference between 8 and 64 worker threads is of $\approx 10\ ms$, smaller than the $\approx 15\ ms$ above. This difference in response time is due to the fact that the service time in this setting has raised considerably: in the case of 8 workers we observe a growth of $\approx 1\ ms$, while with 64, more than $3ms$. Being the service time higher, each incoming request into the middleware spends more and more time waiting in the queue. This can be seen by comparing Figure 15 and Figure 27. We observe a constant increase of $\approx 10\ ms$ for every worker thread configuration. One can see how, for 8 and 16 worker threads the system is saturated already at `VCs=96`. With 32 worker threads the saturation point is reached with `VCs=144`, and with 64, at `VCs=192`. Another evident behavior at those same point of saturation, is evident in the queue size plot: it starts to scale linearly as the workload increases, further confirming that the system is indeed saturated.

Write-Only

Figure 25: Plots for throughput for writes (write-only CLIENT)

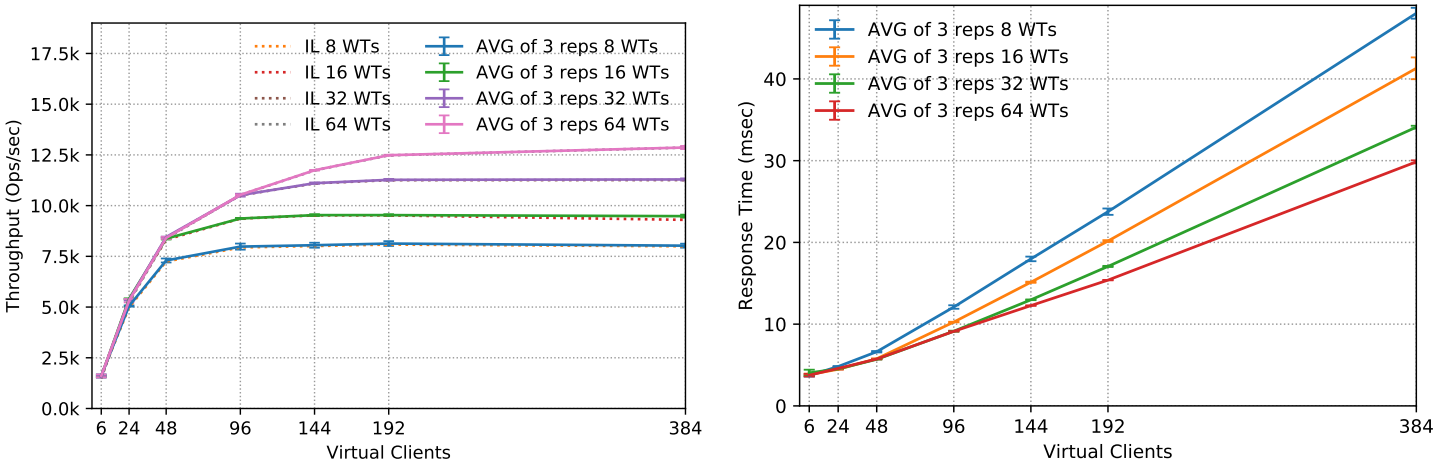


Figure 26: Plots for throughput for writes (write-only MIDDLEWARE)

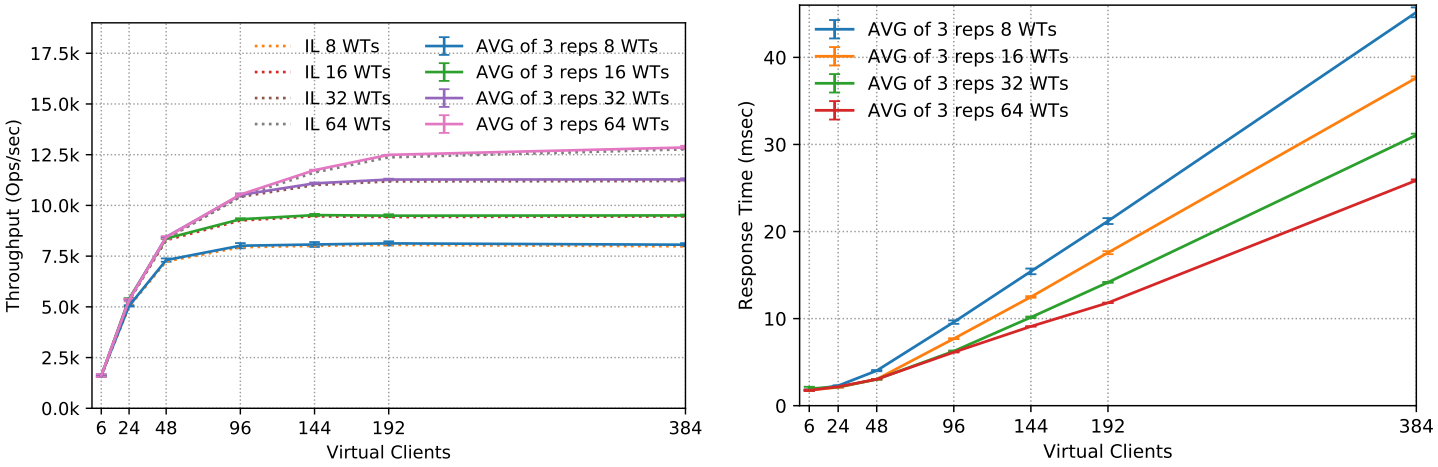
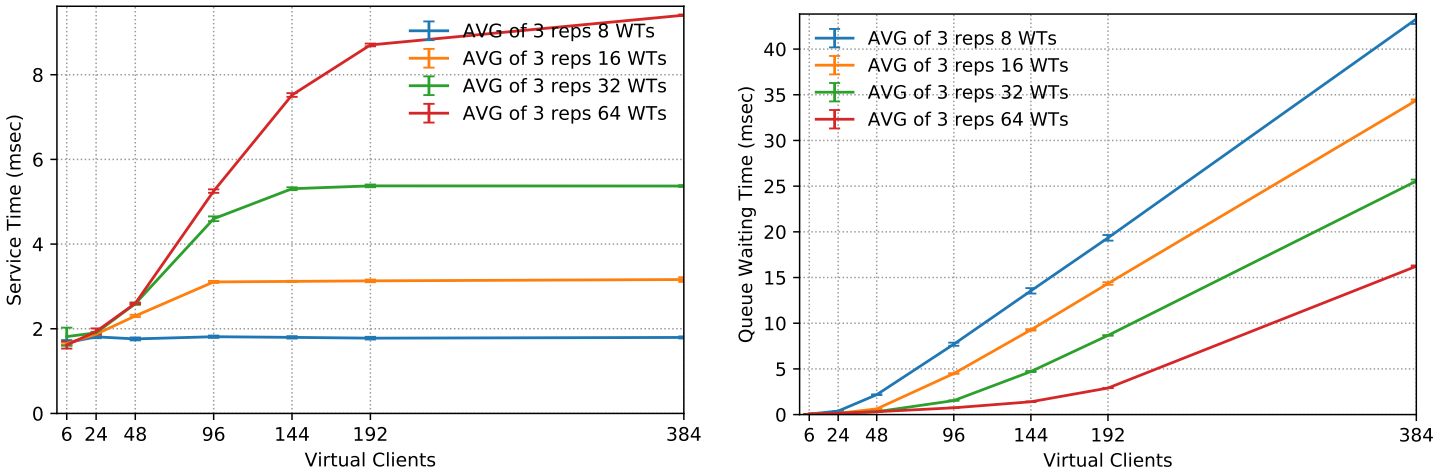


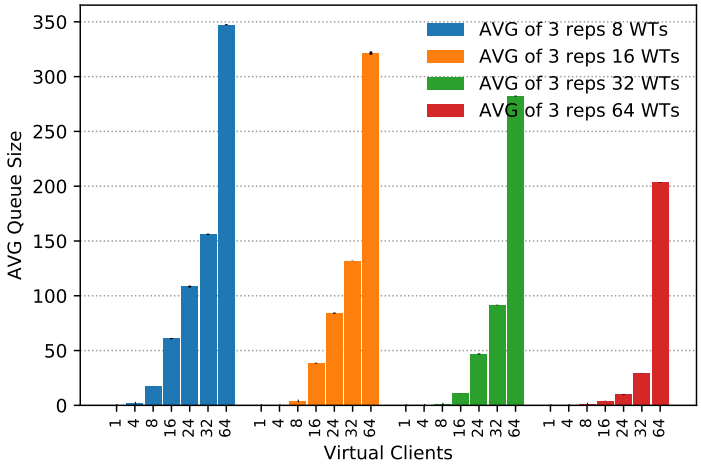
Figure 27: Plots for throughput for writes, Service Time and Queue Waiting Time (write-only MIDDLEWARE)



4.2 Summary

Based on the results of this experiment we can derive the following. In this configuration, when just performing write-only requests, the bottleneck are the two middlewares, more precisely, is the number of worker threads. The reason that supports this claim can be found by comparing Figure 26 and Figure 22. In the latter, both middleware are connected to only one memcached instance, reaching a maximum trhoughput of $\approx$ 18k ops/s. Now, both middlewares are connected to 3 memcached instances, so if the middlewares would not represent a bottleneck we should reach a theoretical throughput 3 time bigger, but we don't, indeed we measure a substantial decrease. This can be explained by the fact that there's some overhead when worker threads switch from a job to another, and also that when we perform writes, we need to wait for all 3 answers from the servers.

Figure 28: Plots for throughput for writes, Average Queue Size (write-only MIDDLEWARE)



Maximum throughput for the full system

	WT=8	WT=16	WT=32	WT=64
Throughput (Middleware)	8.3k *ops/s* `16 VCs` per thread	9.6k *ops/s* (`32 VCs` per thread)	11.3k *ops/s* (`32 VCs` per thread)	12.9k *ops/s* `64 VCs` per thread
Throughput (Derived from MW response time)	8.3k *ops/s*	9.6k *ops/s*	11.3k *ops/s*	12.9k *ops/s*
Throughput (Client) (max config is same as MW)	8.3k *ops/s*	9.5k *ops/s*	11.3k *ops/s*	12.9k *ops/s*
Average time in queue	12.35 *ms*	9.04 *ms*	5.85 *ms*	3.11 *ms*
Average length of queue	49.4	41.4	30.9	17.6
Average time waiting for memcached	1.77 *ms*	2.62 *ms*	3.85 *ms*	5.29 *ms*

5 Gets and Multi-gets (90 pts)

5.1 Experiment Setting

This set of experiments aims to measure and analyze the performance of the middleware when dealing with multi-GET requests. There are 3 client machines running 2 single-threaded instances of memtier generating multi-GET workloads (as depicted in the table below). Each instance is connected two one of the two middlewares (each to a different one) with the maximum throughput configuration. Each middleware is connected to 3 memcached machines running a single-threaded memcached instance each. We are interested in generating two types of multi-GET requests (sharded and non-sharded), and compare their effect on the overall system. We plot the throughput as measured in the middlewares, (not considering the number of *hits/s*), the average response time and its (25th, 50th, 75th, 90th and 99th) percentiles, and the distribution of response times (for the case of 6 keys) as measured by both memtier clients and the middlewares.

Maximum Throughput Choice

For this particular case, since we are more concerned on the performances when reading rather than writing (which consitutes for a small fraction of the total of operations, $\approx \frac{1}{3 \cdot 6 \cdot 9}$), having no comparable setting (no experiment with 2 middlewares connected to 3 servers, apart from Section 4), the maximum (stable) throughput considered is the one reached in 3.2, obtained with 64 worker threads.

5.2 Sharded Case

Number of servers	3
Number of client machines	3
Instances of memtier per machine	2
Threads per memtier instance	1
Virtual clients per thread	2
Workload	ratio=1:<Multi-Get size>
Multi-Get behavior	Sharded
Multi-Get size	[1, 3, 6, 9]
Number of middlewares	2
Worker threads per middleware	64 (MAX throughput config)
Repetitions	3 (70 secs, effective 60 secs)
Log Files Path	`experiments/multigets_sharded/logs`
Processed Files Path	`experiments/multigets_sharded/out`

5.2.1 Explanation

By looking at the troughput plot, we can spot how the more keys we have in each request, the more the throughput decreases, starting from $\approx$ 3k ops/s for the case of 1 key, to $\approx$ 2k ops/s for the case with 9 keys. If we multiply the throughput by the number of keys, we obtain the number of $hits/s$ for each key configuration; that means approximately (3k, 8.4k, 14.4k, 17.5k) $hits/s$ for 1, 3, 6, and 9 keys respectively. Thus we notice a gain in overall read performance by increasing the number of keys in a request. When the number of keys is 3, for instance, compared to having 1 key, we almost thriple the number of $hits/s$ by thriplicating the number of servers we actually read from.
This gain though, doesn't seem to grow linearly if we compare the $hits/s$ with 3, 6 and 9 keys. With 6 keys, we are doubling the number of request for each of the 3 servers, and we obtain a slightly less number of $hits/s$ (8.4k $\cdot 2 =\approx$ 16.8k $-$14.4k = 2.2k of difference). Same for 9 keys, (8.4 $\cdot 3 =\approx$ 25.2k $-$17.5k = 7.7k of difference). The fact that the gain is not linear is better explained by looking at the reponse times for each key. We can see how the average response time grows from $\approx 1.8ms$ to $5.8ms$ and how by increasing the number of keys, the percentiles also do. If we look at those for 1 and 3 keys, we observe how similar they are, meaning that the gap between the two average response times is explained by the latency of the 3 servers, instead of 1. Then if we compare 3 keys with 6, and 9 keys, we see a larger difference (especially for the 99th percentiles). This means that by increasing the load of each server, the service time also grow accordingly. In fact, if we break down the response time into the waiting time spent inside the queue, and into the time spent in service, we notice how effectively, the service time for 6 and 9 keys grows much more than in the case with 3 keys(Figure 30).

5.3 Non-sharded Case

5.4 Experiment Setting

The only parameter that changes is the sharded flag, the rest of the configuration is the same as in the sharded case.

Figure 29: Plots for multigets sharded, (Throughput MIDDLEWARE)

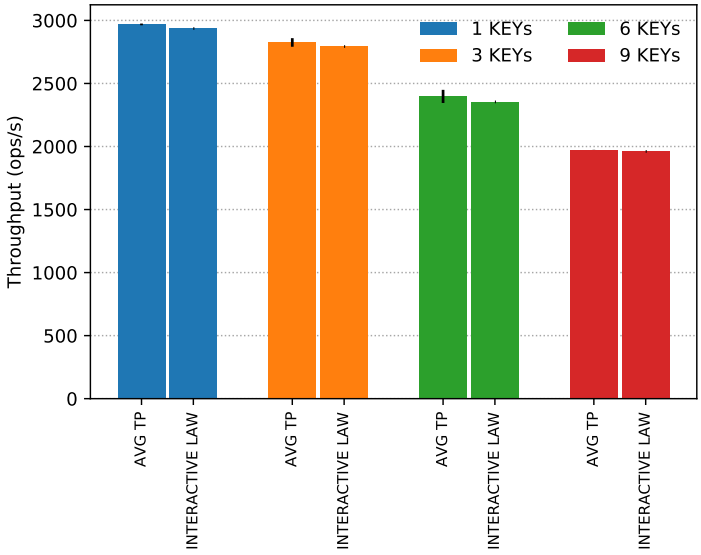
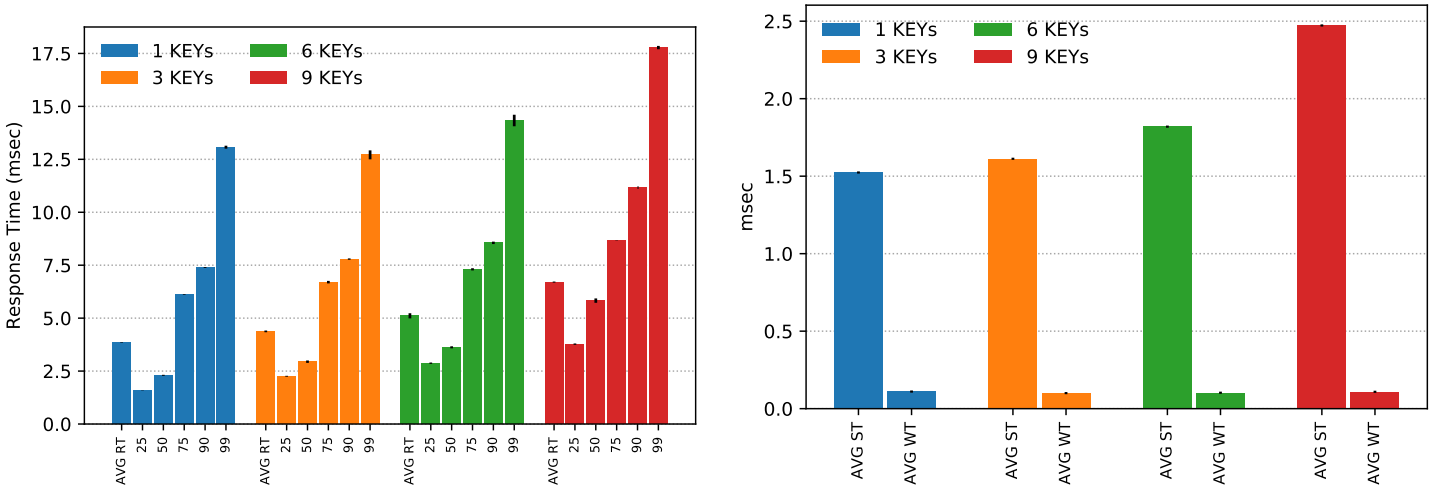


Figure 30: Plots for multigets sharded, (Response Time CLIENT, Response Time composition MIDDLEWARE)



Number of servers	3
Number of client machines	3
Instances of memtier per machine	2
Threads per memtier instance	1
Virtual clients per thread	2
Workload	ratio=1:<Multi-Get size>
Multi-Get behavior	Non-Sharded
Multi-Get size	[1, 3, 6, 9]
Number of middlewares	2
Worker threads per middleware	64 (MAX throughput config)
Repetitions	3 (70 secs, effective 60 secs)
Log Files Path	`experiments/multigets_non_sharded/logs`
Processed Files Path	`experiments/multigets_non_sharded/out/memtier_data.csv`

5.4.1 Explanation

We analyze the throughput plot as we have done for the sharded case. So if we consider the number of $hits/s$ again we approximately have: (2.75k, 7.5k, 6k, 16.2k) $hits/s$ for (1, 3, 6 and 9) keys respectively. For 1 key, the standard deviation seems higher than before, but we still get a close measure. That can be said also for the other keys, although by growing the number of keys, the difference compared to the sharded case seems to be in the range of 1k to 2k $hits/s$ Interestingly, how the average response time doesn't grow much the same as in the sharded case. We notice a growth of the 75th, 90th, and 99th percentiles by $\approx$ 2-3 ms. This growth is noticeable if we look into the response time composition plot: here we can see how both service time and waiting time have slighlty raised compared to the sharded case.

Figure 31: Plots for multigets non sharded, (Throughput MIDDLEWARE)

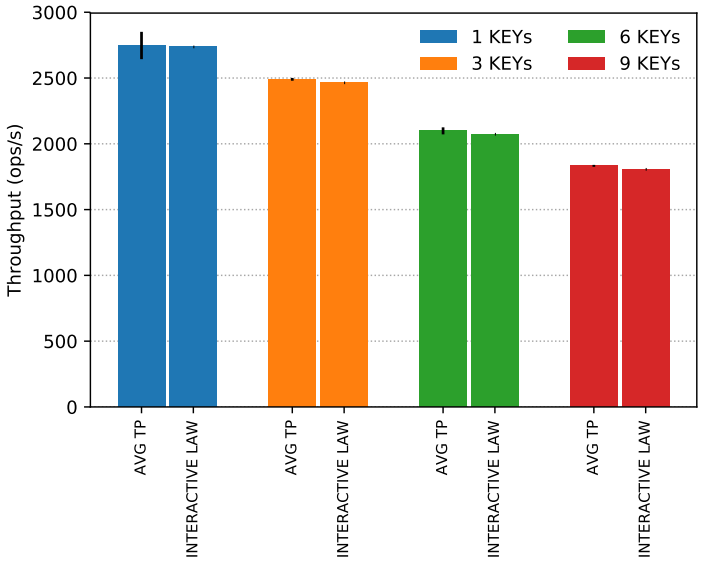
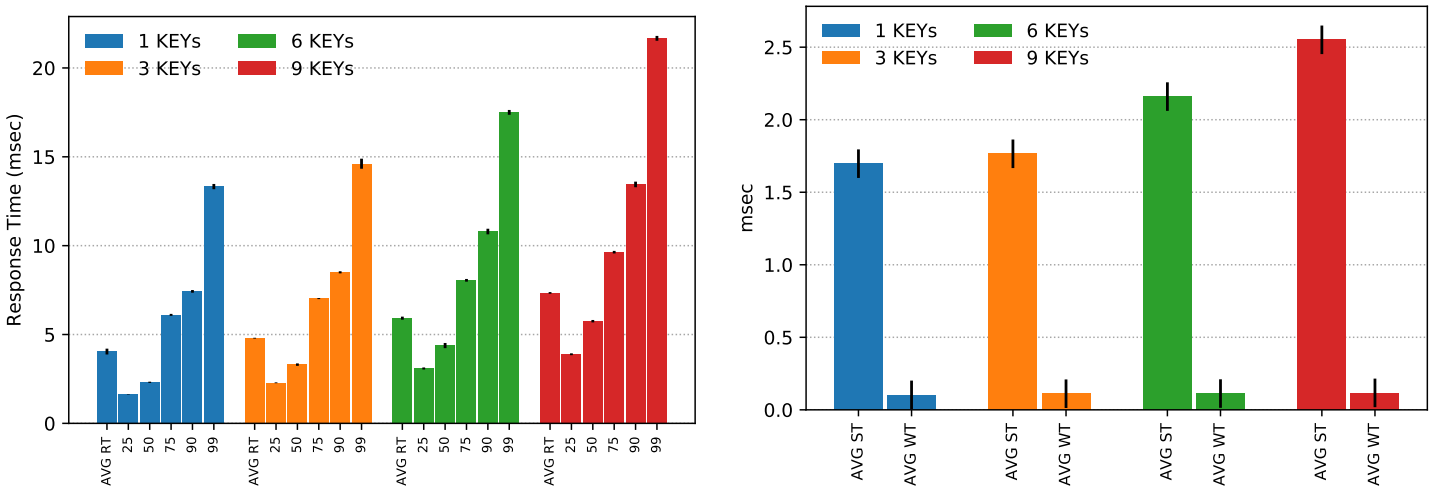


Figure 32: Plots for multigets non sharded, (Response Time CLIENT, Response Time composition MIDDLEWARE)



5.5 Histogram

Figure 33: Plots for multigets sharded, (Response Time Distribution CLIENT & MIDDLEWARE)

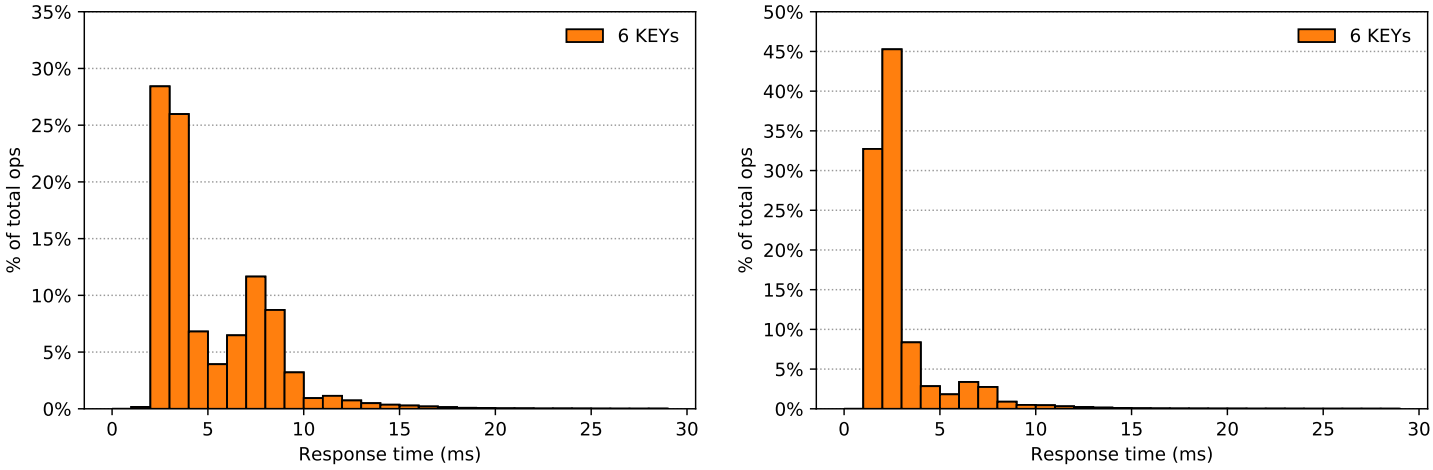
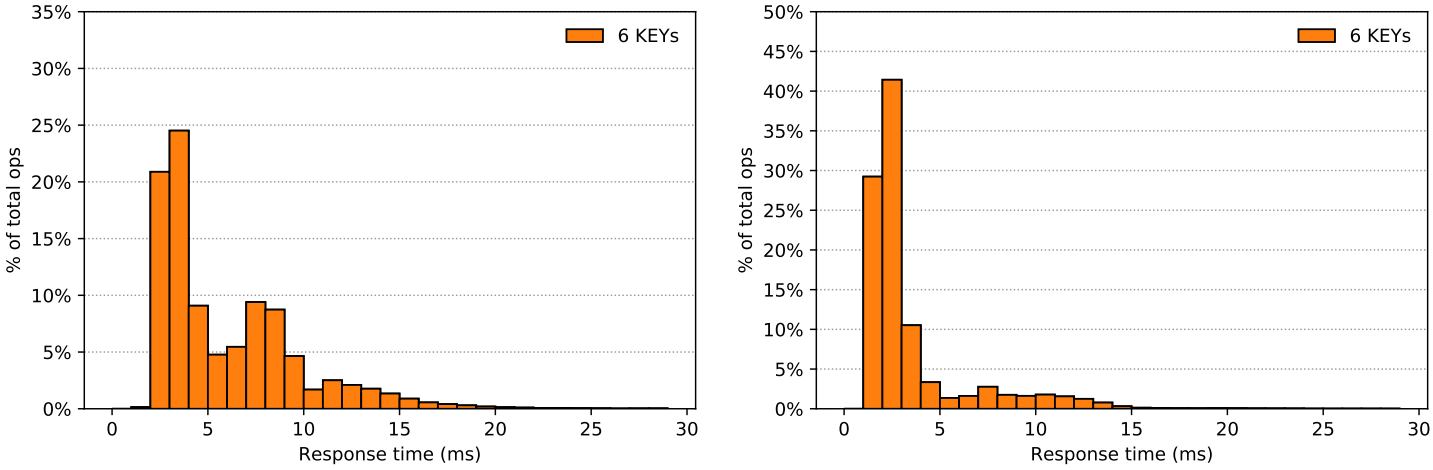


Figure 34: Plots for multigets non sharded, (Response Time Distribution CLIENT & MIDDLEWARE)



We plot the distribution of the response times measured for the 6-key configuration at the clients and inside the middlwares. For both the client and the middleware, the distribution is obtained as the aggregate distribution of all runs with 6 keys. We show just the first $30ms$ interval for visual purposes, (as it would be too spreaded and flatconsidering the whole distribution). The number of bins is 30, so each bin covers a $1ms$ interval. Visually there seems to be not too much difference if we compare the sharded and non sharded scenarios, although the non-sharded one present higher bars in the 10-15 interval range. If we compare the client plots with the middleware, we can see the difference in the measured response time (depicted in Section 3.1, as the shift in the bars.

5.6 Summary

Based on what presented above we derive the following.
Sharding, seems to be the preferable option with 1, 3, 6 and 9 keys (no relevant difference with 1 key). From plotting the composition of the response times, we have seen that majority of the time a multi-GET request spends inside the system is given by the service time of the servers. From that, it seems that the sharding operation inside the middleware is almost irrelevant in the composition of the response time, (beacuse service time timing starts when the request leaves the middleware).

6 2K Analysis (90 pts)

We perform a $2^k r$ experimental analysis to investigate the effect of ($k = 3$) **factors**, namely:

- The number of memcached servers
- The number of middlewares
- The number of worker threads per middleware

and study the effects of each of them on throughput and response time respectively (**response variables**).

6.1 Experiment setting

There are 3 machines that generate write-only and read-only workloads. Then based on the number of middlewares (1 or 2), each client machine runs (1 or 2) instances of memtier, each with 32 virtual clients and (2 or 1) threads respectively. In the case of two memtier instances per machine, each of them connects to a different middleware. Each middleware runs either (8 or 32) worker threads, and is connected to either (2 or 3) mecached machines. We measure both throughput and response time for each workload (read-only and write-only). We investigate experimental errors by replicating each experiment 3 times ($r = 3$), so the response variable, is simply the average between each repetition. Based on results on experiments in Section 3.1, we do expect the number of middlewares and the number of worker threads, to have relevant impact on the response variables. Furthermore, we do assume that the effects of the factor are additive and that measurements error are independent and follow a normal distribution.

Number of servers	1 and 3
Number of client machines	3
Instances of memtier per machine	1 (1 middleware) or 2 (2 middlewares)
Threads per memtier instance	2 (1 middleware) or 1 (2 middlewares)
Virtual clients per thread	32
Workload	Write-only and Read-only
Multi-Get behavior	N/A
Multi-Get size	N/A
Number of middlewares	1 and 2
Worker threads per middleware	8 and 32
Repetitions	3 (70 secs, effective 60 secs)
Log Files Path	`experiments/2k_analysis/2k_analysis_1_mw_1_server/logs`, e.g. with 1 mw and 1 server
Processed Files Path	`experiments/2k_analysis/out`

6.2 Model

We model the response variable y as

$$y = q_0 + q_A x_A + q_B x_B + q_C x_C + q_{AB} x_A a_B + q_{AC} x_A x_C + q_{BC} x_B x_C + q_{ABC} x_A x_B x_C + \epsilon \quad (1)$$

where x_A, x_B, x_C are defined as

$$x_A = \begin{cases} -1 & \text{if 1 server} \\ 1 & \text{if 3 servers} \end{cases}$$

$$x_B = \begin{cases} -1 & \text{if 1 middleware} \\ 1 & \text{if 2 middlewares} \end{cases}$$

$$x_C = \begin{cases} -1 & \text{if 8 worker threads} \\ 1 & \text{if 32 worker threads} \end{cases}$$

and $q_0, q_A, \ldots q_{ABC}$, and ϵ (**experimental error**) are the parameters to be computed with the *Sign Table Method*.

6.3 Results

We perform the analysis both on the throughput and on the response time for both read-only and write-only workloads. Results consider two scenarios: one in which the load of the system is low (under-saturated) and the maximum throughput configuration (saturated).

Throughput

Read-Only

Table 1: Sign Table Method for read-only workload (Throughput)

i	**I**	**A**	**B**	**C**	**AB**	**AC**	**BC**	**ABC**	y_1	y_2	y_3	$\hat{y}$
1	1	-1	-1	-1	1	1	1	-1	2919.15	2924.77	2926.62	2923.51
2	1	-1	-1	1	1	-1	-1	1	2938.38	2941.38	293985	2939.87
3	1	-1	1	-1	-1	1	-1	1	2931.00	2930.24	2936.23	2932.49
4	1	-1	1	1	-1	-1	1	-1	2930.93	2935.77	2943.00	2936.57
5	1	1	-1	-1	-1	-1	1	1	2208.15	2100.92	2105.38	2138.15
6	1	1	-1	1	-1	1	-1	-1	2329.69	2279.54	2379.46	2329.56
7	1	1	1	-1	1	-1	-1	-1	4051.39	4144.38	3912.92	4036.23
8	1	1	1	1	1	1	1	1	4391.15	4464.54	4362.77	4406.15
	3080.32	147.21	497.54	72.72	496.12	67.61	20.78	23.85	Total/8			

In Table **??**, each row represents one combination of the factors (x_A, x_B, x_C), the last column is the average throughput and, the last row in the table shows the coefficients $(q_0, q_A, \ldots q_A BC)$ that solve the system of equations. Table **??** summarizes the strength of variation of throughput. Each row represent the sum of the squares of the factors, their interaction, as well as:

- SSO is the sum squares of q_0
- SSY is the sum of squares of the response variable
- SSE is the sum of squares of the experimental error
- SST is the total sum of the squares

Table 2: Allocation of variations for read-only workload (Throughput)

Sum	Value	% / SST
SS0	227720480.01	N/A
SSA	520078.21	4.10%
SSB	5941174.89	46.88%
SSC	126921.12	1.00%
SSAB	5907350.45	46.61%
SSAC	109716.16	0.87%
SSBC	10362.15	0.08%
SSABC	13650.31	0.11%
SSE	45129.63	0.356%
SST	12674382.93	100.00%
SSY	240394862.94	N/A

Table 3: Confidence Intervals, read-only workload

I	A	B	C	AB	AC	BC	ABC
3057.33	124.22	474.56	49.74	473.14	44.63	-2.20	0.87
3103.30	170.19	520.53	95.70	519.11	90.60	43.76	

Write-Only

Table 4: Sign Table Method for write-only workload (Throughput)

i	I	A	B	C	AB	AC	BC	ABC	y_1	y_2	y_3	$\hat{y}$
1	1	-1	-1	-1	1	1	1	-1	7513.69	7467.46	7527.77	7502.97
2	1	-1	-1	1	1	-1	-1	1	10299.85	10494.08	10384.38	10392.77
3	1	-1	1	-1	-1	1	-1	1	10539.31	11077.77	11350.31	10989.13
4	1	-1	1	1	-1	-1	1	-1	15661.00	15949.92	15640.54	15753.82
5	1	1	-1	-1	-1	-1	1	1	4942.85	4501.46	5197.00	4880.44
6	1	1	-1	1	-1	1	-1	-1	7163.38	6809.62	6746.46	6912.49
7	1	1	1	-1	1	-1	-1	-1	6719.23	7008.00	7159.15	6962.13
8	1	1	1	1	1	1	1	1	10302.61	10609.69	10622.93	10511.74
	9238.19	-1921.49	1816.02	1654.52	-395.78	-259.1	424.06	-44.67	Total/8			

Table 5: Allocation of variations for write-only workload (Throughput)

Sum	Value	% / SST
SS0	2048257859.79	N/A
SSA	88610741.10	36.298%
SSB	79150214.73	32.4%
SSC	65698408.15	26.91%
SSAB	3759450.90	1.54%
SSAC	1611218.53	0.66%
SSBC	4315794.32	1.768%
SSABC	47880.88	0.02%
SSE	928128.86	0.38%
SST	244121837.47	100.00%
SSY	2292379697.26	N/A

Table 6: Confidence Intervals, write-only workload

I	A	B	C	AB	AC	BC	ABC
9133.96	-2025.71	1711.79	1550.29	-500.01	-363.33	319.83	-148.89
9342.41	-1817.26	1920.24	1758.74	-291.56	-154.88	528.28	59.56

ResponseTime

Read-Only

Table 7: Sign Table Method for read-only workload (Response Time)

i	I	A	B	C	AB	AC	BC	ABC	y_1	y_2	y_3	$\hat{y}$
1	1	-1	-1	-1	1	1	1	-1	62.73	62.47	62.54	62.58
2	1	-1	-1	1	1	-1	-1	1	62.01	61.87	61.47	61.68
3	1	-1	1	-1	-1	1	-1	1	63.30	63.26	63.14	63.23
4	1	-1	1	1	-1	-1	1	-1	62.57	62.45	62.33	62.45
5	1	1	-1	-1	-1	-1	1	1	78.62	85.91	83.73	82.75
6	1	1	-1	1	-1	1	-1	-1	60.64	63.64	61.04	61.77
7	1	1	1	-1	1	-1	-1	-1	42.02	41.22	44.16	42.46
8	1	1	1	1	1	1	1	1	32.84	32.94	33.53	33.10
	58.77	-3.74	-8.46	-3.99	-8.78	-3.60	1.45	1.45	Total/8			

Table 8: Allocation of variations for read-only workload (Response Time)

Sum	Value	% / SST
SS0	82882.74	N/A
SSA	336.41	7.102%
SSB	1716.28	32.4%
SSC	382.12	8.067%
SSAB	1852.14	39.101%
SSAC	310.21	6.549%
SSBC	50.74	1.071%
SSABC	50.50	1.066%
SSE	38.44	0.812%
SST	4736.85	100.00%
SSY	87619.6	N/A

Table 9: Confidence Intervals, read-only workload

I	A	B	C	AB	AC	BC	ABC
58.10	-4.41	-9.13	-4.66	-9.46	-4.27	0.78	0.78
59.44	-3.07	-7.79	-3.32	-8.11	-2.92	2.12	2.12

Write-Only

Table 10: Sign Table Method for write-only workload (Response Time)

i	I	A	B	C	AB	AC	BC	ABC	y_1	y_2	y_3	$\hat{y}$
1	1	-1	-1	-1	1	1	1	-1	20.16	22.01	20.56	20.91
2	1	-1	-1	1	1	-1	-1	1	11.71	9.43	11.99	11.04
3	1	-1	1	-1	-1	1	-1	1	15.60	14.74	14.06	14.80
4	1	-1	1	1	-1	-1	1	-1	9.00	8.75	8.85	8.87
5	1	1	-1	-1	-1	-1	1	1	35.89	34.65	34.07	34.87
6	1	1	-1	1	-1	1	-1	-1	22.1	23.53	21.51	22.38
7	1	1	1	-1	1	-1	-1	-1	25.4	24.73	24.24	24.79
8	1	1	1	1	1	1	1	1	15.76	15.10	15.03	15.30
	19.12	5.21	-3.18	-4.72	-1.11	0.77	0.87	-0.12	Total/8			

Table 11: Allocation of variations for write-only workload (Response Time)

Sum	Value	% / SST
SS0	8772.45	N/A
SSA	652.66	43.361%
SSB	243.05	16.147%
SSC	535.30	35.563%
SSAB	29.54	1.962%
SSAC	14.35	0.953%
SSBC	18.02	1.197%
SSABC	0.33	0.022%
SSE	11.95	0.794%
SST	1505.18	100.00%
SSY	10277.63	N/A

Table 12: Confidence Intervals, read-only workload

I	A	B	C	AB	AC	BC	ABC
18.74	4.84	-3.56	-5.10	-1.48	-1.15	0.49	-0.49
19.49	5.59	-2.81	-4.35	-0.74	-0.40	1.24	1.26

6.4 Summary

Data results of the analysis for the throughput and response time do look similar. For the read-only workload the primal factors that count for the variation in throughput and response time are the number of middlewares and the interaction between the number of middlewares and the number of servers. It is also visible by just looking at the measured throughput in Table **??**. We can see how from row 4 the trhoughput decreases when we raise the number of memcached instances, and in row 6 it doubles thanks to the presence of another middleware, which itself, doesn't seem to make a difference when the number of servers is equal to 1, confirming our bottleneck analysis derived in Section 3. The write-only workload results show a different behavior compared to the read-only case. Here, the primal factors that contribute the most in the change of the response variable are:

- the number of servers $\approx 35 - 40\%$

- the number of middlewares $\approx 20 - 25\%$
- the number of worker threads $\approx 30 - 35\%$

From what we have concluded in Section 3.1 the bottleneck of the system was the number of worker threads of the middleware, indeed in Section 3.2 by having 2 middlewares we are able to write as in Section 2.1, reaching maximum throughput achievable by the load of the machine ($\approx 17.5 kops/s$), then in Section 4, where the number of servers is now 3, we have registered a decrease in throughput similar to Section 3.1. In conclusion, results of the analysis show a consistent behavior to what has been found out in the previous eexperiments.

7 Queuing Model (90 pts)

In this section we model our system with different techniques using some particular measurements recorded inside the middleware, to predict the behavior of the internal state of the system, and compare it, with the actual values.

In this section we introduce the following notation to describe the relevant factors that we take into consideration:

- τ is the interarrival time between two successive requests
- λ is the arrival rate
- μ is the service rate
- ρ is the utilization factor
- ϱ is the probability of queueing
- r is the response time
- s is the service time
- w is the queue waiting time
- n is the total number of jobs in the system ($n = n_q + n_s$)
- n_q is the total number of jobs waiting in the queue
- n_s is the total number of jobs being served

7.1 M/M/1

In this section we model our system based on the results of Section 4 for each worker thread configuration. In the M/M/1 model ther is only a single queue and a single server ($m = 1$). The model assumes that the τ's are IID, (follow a Poisson distribution: meaning constant rate and independence between each sample), and that jobs get enqueued in a single queue from where they get taken out and serviced in a First Come, Fist Served fashion. Another assumption of the model is that, it is closed, meaning that no flow can enter from outside; thus we can already take the throughput as a measure of λ, (indeed memtier machines issue new request upon receiving an answer back for the current request being serviced). In order to conduct further analysis we need to estimate the service rate μ. We could either:

- compute the service rate as the inverse of the mean service time. If we would choose this approach, we would need to into account that we are running two middlewares with 64 worker threads so we should normalize the service time by dividing it for $(\#mws \cdot \#wts)$ so 128 in this case.
- use the maximum measured throughput as lower bound on the service rate. This is justified by the fact that the average throughput is always less or equal the average service rate in our system, given the fact that wait some idle in the queue. Moreover there's some overhead created by switching jobs, so it seems a fair reasonable measure.

We try both approaches and compared the results in the following Section. As λ depends on the number of virtual clients, we choose to report the results we obtain for two configurations: one with `VCs=24` (under-saturated system), and one with `VCs=384` (saturated system).

Table 13: Results of the M/M/1 queue model for 24 `VCs`. Service rate is tha max throughput measured. Gray values represent actual measurements.

	WT = 8	WT = 16	WT = 32	WT = 64
Arrival rate (λ)	5.04k ops/s	5.4k ops/s	5.3k ops/s	5.3k ops/s
Average time waiting for memcached	2.29 ms	2.11 ms	2.14 ms	2.117 ms
Service Rate (μ, from adjusted service time)	5073 $reqs/s$	5439 $reqs/s$	5377 $reqs/s$	5390 $reqs/s$
Utilization (ρ)	0.99	0.99	0.98	0.98
Mean # of jobs in the system ($E[n]$)	199.8 $reqs$	143.04 $reqs$	237.67 $reqs$	92.14 $reqs$
Mean # of jobs in the queue ($E[n_q]$)	198.8$reqs$	141.04 $reqs$	236.67 $reqs$	91.15 $reqs$
Mean response time ($E[r]$)	39.5 ms	26.4 ms	44.35 ms	17.2 ms
Mean waiting time ($E[w]$)	39.3 ms	26.3 ms	44.19 ms	17.09 ms
Mean # of jobs in the system ($E[n]$)	$\approx$ 0.11 $reqs$	$\approx$ 0.15 $reqs$	$\approx$ 0.28 $reqs$	$\approx$ 0.43 $reqs$
Mean # of jobs in the queue ($E[n_q]$)	1.3 $reqs$	2.7 $reqs$	5.8 $reqs$	13.8 $reqs$
Mean response time ($E[r]$)	1.53 ms	1.98 ms	3.75 ms	5.8 ms
Mean waiting time ($E[w]$)	0.16 ms	0.27 ms	0.81 ms	1.44 ms

Table 14: Results of the M/M/1 queue model for 384`VCs`. Service rate is tha max throughput measured. Gray values represent actual measurements.

	WT = 8	WT = 16	WT = 32	WT = 64
Arrival rate (λ)	8.06k ops/s	9.5k ops/s	11.2k ops/s	12.8k ops/s
Average time waiting for memcached	1.79 ms	3.16 ms	5.37 ms	9.4 ms
Service Rate (μ, from adjusted service time)	8.18k $reqs/s$	9.5k $reqs/s$	11.36k reqs/	12.9k $reqs/s$
Utilization (ρ)	0.98	0.99	0.98	0.98
Mean # of jobs in the system ($E[n]$)	83.96 $reqs$	278.5 $reqs$	282.2 $reqs$	203.4 $reqs$
Mean # of jobs in the queue ($E[n_q]$)	82.9 $reqs$	277.5 $reqs$	139.02 $reqs$	167.4 $reqs$
Mean response time ($E[r]$)	10.41 ms	29.3 ms	12.4 ms	13.11 ms
Mean waiting time ($E[w]$)	10.29 ms	29.2 ms	12.32 ms	13.03 ms
Mean # of jobs in the system ($E[n]$)	5.2 $reqs$	5.1 $reqs$	14.96 $reqs$	4.73 $reqs$
Mean # of jobs in the queue ($E[n_q]$)	347.36 $reqs$	321.46 $reqs$	282.2 $reqs$	203.4 $reqs$
Mean response time ($E[r]$)	45.17 ms	37.6 ms	31.05 ms	25.87 ms
Mean waiting time ($E[w]$)	43.29 ms	34.3 ms	25.56 ms	16.23 ms

7.2 M/M/m

In this section we model the system as a combination of m independent services processing requests out of a single queue. The same assumption of the M/M/1 model do still hold, apart

from the obvious number of services, and we use again, data from Section 4. Being the M/M/m model suited for modeling systems that have more parallel independent components, we should expect results to be more accurate than the M/M/1 model. The choice of the input parameters is done by taking again the throughput as a measure for the arrival rate, and for the service rate, we compute it as the inverse of the service time, and we multiply m by 2 in order to take into account the fact the there are 2 middlewares.

Table 15: Results of the M/M/m queue model for 24 `VCs`

	WT = 8	WT = 16	WT = 32	WT = 64
Arrival rate (λ)	5.04k ops/s	5.4k ops/s	5.3k ops/s	5.3k ops/s
Average time waiting for memcached	2.29 ms	2.11 ms	2.14 ms	2.117 ms
Service Rate (μ)	552 $reqs/s$	534 $reqs/s$	524 $reqs/s$	516 $reqs/s$
Utilization (ρ)	0.57	0.31	0.15	0.08
Probability of queuing (ϱ)	0.03	$3.14\ e-8$	$1.24\ e-29$	$5.17\ e-91$
Mean # of jobs in the system ($E[n]$)	9.17 $reqs$	10.1 $reqs$	10.2 $reqs$	10.3 $reqs$
Mean # of jobs in the queue ($E[n_q]$)	0.04 $reqs$	$1.45\ e-8$ $reqs$	$2.35\ e-30$ $reqs$	$4.54\ e-92$ $reqs$
Mean response time ($E[r]$)	39.5 ms	26.4 ms	44.35 ms	17.2 ms
Mean waiting time ($E[w]$)	39.3 ms	26.3 ms	44.19 ms	17.09 ms
Mean # of jobs in the system ($E[n]$)	≈ 0.11 $reqs$	≈ 0.15 $reqs$	≈ 0.28 $reqs$	≈ 0.43 $reqs$
Mean # of jobs in the queue ($E[n_q]$)	1.3 $reqs$	2.7 $reqs$	5.8 $reqs$	13.8 $reqs$
Mean response time ($E[r]$)	1.53 ms	1.98 ms	3.75 ms	5.8 ms
Mean waiting time ($E[w]$)	0.16 ms	0.27 ms	0.81 ms	1.44 ms

Table 16: Results of the M/M/m queue model for 384`VCs`

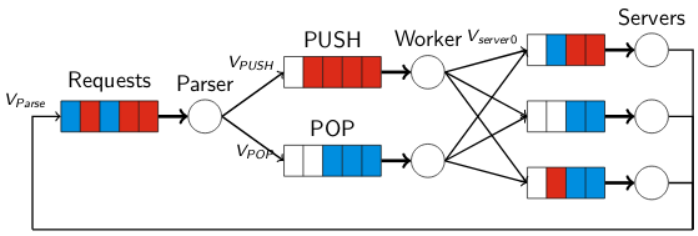
	WT = 8	WT = 16	WT = 32	WT = 64
Arrival rate (λ)	8.06k ops/s	9.5k ops/s	11.2k ops/s	12.8k ops/s
Average time waiting for memcached	1.79 ms	3.16 ms	5.37 ms	9.4 ms
Service Rate (μ)	557.1 $reqs/s$	316.12 $reqs/s$	186.16 req/s	106.32 $reqs/s$
Utilization (ρ)	0.90	0.92	0.94	0.94
Probability of queuing (ϱ)	0.61	0.64	0.56	0.41
Mean # of jobs in the system ($E[n]$)	20.22 $reqs$	40.06 $reqs$	70.67 $reqs$	128.01 $reqs$
Mean # of jobs in the queue ($E[n_q]$)	5.75 $reqs$	9.99 $reqs$	10.08 $reqs$	7.09 $reqs$
Mean response time ($E[r]$)	2.51 ms	4.22 ms	6.26 ms	9.95 ms
Mean waiting time ($E[w]$)	0.71 ms	1.05 ms	0.89 ms	0.55 ms
Mean # of jobs in the system ($E[n]$)	5.2 $reqs$	5.1 $reqs$	14.96 $reqs$	4.73 $reqs$
Mean # of jobs in the queue ($E[n_q]$)	347.36 $reqs$	321.46 $reqs$	282.2 $reqs$	203.4 $reqs$
Mean response time ($E[r]$)	45.17 ms	37.6 ms	31.05 ms	25.87 ms
Mean waiting time ($E[w]$)	43.29 ms	34.3 ms	25.56 ms	16.23 ms

7.3 Network of Queues

In this section we model the system as a newtwork of queues, in order to find out the Utilization factor of each component, using data from Section 3.1 and Section 3.2.

Our model consists of a *Parser* that takes jobs from the queue, process them and send them to the *Workers*, which are connected to a single *Server*. Again, our system is a closed system, meaning the outflow of the *Server* goes back to the *Parser*, thus the V_{ratio} of the *Server* and the *Parser* are the same (=1). The V_{ratio} of the workers component is computed as the probability of a request to get to a specific *Worker* w, which in the case of one middleware is $\frac{1}{\texttt{WTs}}$, and $\frac{1}{2\texttt{WTs}}$, for two middlewares. We can compute the throughput of each component by multiplying the V_{ratio} of each component by the measured throughput. To obtain the utiliazion of each factor we need the service time measured inside the analyzed component. Here we do not have such measures, so we have tried to approximate the service time of the Workers as the service time measured on the middleware. Results (especially in the read-only case) do not seem to be sound with what presented in the above sections, merely because we are effectively using a poor measure of the service time of each worker. Following results for the partial analysis are shown:

Figure 35: Network of Queues: note that our model consists of just one queue per parser, and 64 worker threads, and just a single server



Baseline with one Middleware

Table 17: Network of Queues, results of partial analysis Baseline with one Middleware

Workload	Read-Only	
Worker Threads	32	
Virtual Clients	4	64
Throughput (ops/s)	2930.21	2931.97
ServiceTime (ms)	5.70667	10.8233
VisitRatio Server	1	1
Throughput Server (ops/s)	2930.54	2932.92
VisitRatio Worker	0.03125	0.03125
Throughput Worker (ops/s)	91.5794	91.6538
ρ **Worker**	0.522613	0.991999
VisitRatio Parser	1	1
Throughput Parser (ops/s)	2930.54	2932.92

Table 18: Newtork of Queues, results of partial analysis Baseline with one Middleware

Workload	Write-only	
Worker Threads	32	
Virtual Clients	4	64
Throughput (ops/s)	6648.28	11912.9
ServiceTime (ms)	0.823333	2.17333
VisitRatio Server	1	1
Troughput Server (ops/s)	6668.08	12260.1
VisitRatio Worker	0.03125	0.03125
Throughput Worker (ops/s)	208.377	383.13
ρ **Worker**	0.171564	0.832669
VisitRatio Parser	1	1
Throughput Parser (ops/s)	6668.08	12260.1

Baseline with two Middlewares

Table 19: Network of Queues, results of partial analysis Baseline with two Middlewares

Workload	Read-Only	
Worker Threads	32	
Virtual Clients	4	64
Throughput (ops/s)	2933.95	2925.82
ServiceTime (ms)	5.92167	21.965
VisitRatio Server	1	1
Throughput Server (ops/s)	2935.15	2932.54
VisitRatio Worker	0.015625	0.015625
Throughput Worker (ops/s)	45.8617	45.8209
ρ **Worker**	0.271578	1.00646
VisitRatio Parser	1	1
Throughput Parser (ops/s)	2935.15	2932.54

Table 20: Newtork of Queues, results of partial analysis Baseline with two Middlewares

Workload	Write-only	
Worker Threads	32	
Virtual Clients	4	64
Throughput (ops/s)	7432.59	15805.7
ServiceTime (ms)	0.921667	3.72333
VisitRatio Server	1	1
Troughput Server (ops/s)	7479.23	15933.7
VisitRatio Worker	0.015625	0.015625
Throughput Worker (ops/s)	116.863	248.964
ρ **Worker**	0.107709	0.926976
VisitRatio Parser	1	1
Throughput Parser (ops/s)	7479.23	15933.7